ARCTIC SYSTEM SCIENCE • OCEAN-ATMOSPHERE-ICE INTERACTIONS

SHEBA

a research program on the

Surface Heat Budget of the Arctic Ocean

Science Plan

Report Number 5

July 1996

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Edited by

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EXECUTIVE SUMMARY

The Surface Heat Budget of the Arctic Ocean (SHEBA) is an interdisciplinary, interagency research project designed to enhance understanding of the thermodynamic coupling between the atmosphere, the sea ice, and the ocean. SHEBA is motivated by the large discrepancies among simulations by global climate models (GCMs) of the present and future climate in the Arctic and by uncertainty about the impact of the Arctic on climate change. These problems arise from an incomplete understanding of the physics of vertical energy exchange within the ocean/ice/atmosphere system. To address this problem, the SHEBA project is focused on enhancing understanding of the key processes that determine ice albedo feedback in the Arctic pack ice and on applying this knowledge to improve climate modeling.

Primary sponsorship of the SHEBA project is provided by the NSF Arctic System Science Program and the ONR High Latitude Program. In addition, the SHEBA experiment is being designed in collaboration with the Submarine Science Ice Experiment (sponsored by a consortium of federal agencies led by ONR), the NASA FIRE III program, the DOE ARM program, the NASA Polar Research Program, and the NASA-sponsored EOS-POLES and RADARSAT projects. International collaboration is coordinated under the auspices of the Arctic Climate System Study of the World Climate Research Programme. (See Appendix A for definitions of acronyms.)

The project has five strategic objectives:

(1) To develop accurate physical and mathematical relationships between the state of the ice cover and albedo, for any given incident shortwave radiation

(2) To determine how the state of the ice cover changes in response to forcing from the atmosphere and the ocean

(3) To relate the surface forcing to conditions within the atmospheric and oceanic boundary layers

(4) To extend the relationships determined in Objectives 1–3 from local scales to the aggregate scales suitable to climate models

(5) To establish a basic data set suitable for developing and testing climate models that incorporate the processes SHEBA is proposing to study.

To achieve these objectives, the SHEBA project will conduct a multiseason field experiment starting in the autumn of 1997 or the spring of 1998 in the pack ice of the Arctic Ocean. This field experiment will be complemented by remote sensing and modeling analyses. The field observations will emphasize the physical processes associated with interactions among the radiation balance, mass changes of the sea ice, the storage and retrieval of heat in the mixed layer of the ocean, and the influence of clouds on the surface energy balance. The modeling effort is designed to provide insight into the mechanisms that affect climate change and to improve the parameterizations of crucial air/sea/ice interactive processes in GCMs. Geophysical data products derived from satellite-borne sensors and analyses derived from operational assimilation models will be used to provide the large-scale context for the SHEBA field experiment.

In view of the multitude of observations that might be of interest, the field measurements have been divided into four priorities reflecting scientific importance as well as technical, logistical, and fiscal constraints:

Priority 1 - Core data: the minimum data necessary to constitute a viable project

Priority 2 - Essential data: data which, together with the core data, constitute a complete project

Priority 3 - Desirable data: data that augment the scientific value of the project but are not essential

Priority 4 - Ancillary data: data that are not required to achieve the scientific objectives of SHEBA but that have intrinsic value and can be obtained at no cost to SHEBA.

A comprehensive list of the measurements and their priorities is given in Appendix C. The core data consist of the following items:

- *Standard surface weather*: pressure, wind, temperature, humidity, sky cover, rain, visibility
- *Snow*: horizontal profiles of depth, density, skin temperature, local and regional albedo
- *Ice*: albedo, transmittance, thickness profiles, mass changes (top and bottom), lateral melting, temperature (skin and internal), salinity, thickness distribution function
- *Melt ponds*: area, depth, melt rate, albedo, drainage patterns (including flushing), light transmission, freeze-up
- *Surface radiation*: downwelling and upwelling streams, shortwave and longwave, total and spectral
- *Clouds*: amount and type, base height, base temperature
- *Atmospheric structure*: temperature and humidity, as functions of height
- *Atmospheric boundary layer*: turbulent heat fluxes
- *Oceanic boundary layer*: sensible heat flux, heat storage, depth of pycnocline.

The need to aggregate the point and column measurements taken at the field station into the larger surface and volume elements resolved by atmosphere and ocean models presents an intrinsic problem. The SHEBA field experiment is designed to acquire measurements sufficient to estimate the key variables and processes on both the local (point) scale and the aggregate scale.

Important modeling applications of the core data are as follows:

- *Albedo feedback.* The onset of surface melting leads to a positive feedback, i.e., to further enhancement of the melting rate. Owing to its influence on ice thickness, the albedo parameterization plays a dominant role in the thermodynamic part of sea ice models. Direct observations of the effects of snow cover, surface topography, and ice concentration on the evolution of summertime albedo are needed to develop accurate albedo formulas suitable for GCMs.
- *Differential melt-rate and modification of the thickness distribution.* Owing to several factors, the thinnest ice has the lowest albedo, thus eliminating each year much of the ice that has formed during the preceding winter and spring. Along with dynamic effects, this thermodynamic modification of the ice thickness distribution must be included in interactive models.
- *Ocean heat flux.* Most of the heat flux from the ocean to the ice is derived from shortwave radiation stored in the mixed layer during summer. This flux must be

calculated as a internal GCM variable from the ice melt rate, solar heating, and turbulent transfer. Data are needed to test models that simulate this process.

- *Uneven distribution of shortwave radiation energy absorbed at the surface.* This energy is transformed and used to warm and melt snow and ice, to enlarge brine pockets, and to warm the ocean. In a near-equilibrium annual cycle, this energy must be returned to the environment with a phase lag that varies from process to process. A complete set of observations during the crucial part of the year (March–November) is needed to unravel the details of these unevenly distributed energy fluxes.
- *Atmospheric structure.* Rawinsonde observations are needed to enable comparisons between the structure of the real atmosphere at a grid point and the structure predicted by atmospheric models.
- *Radiation modeling.* Direct observations of the downwelling streams of radiation at the surface—acquired simultaneously with rawinsonde, radar, and microwave radiometer measurements of cloud structure, mass, particle distribution, temperature, and humidity—are needed to develop improved algorithms for calculating radiative transfers and surface fluxes in GCMs.

The field station will be established in a region of the Beaufort Sea, 300–500 km north of the Alaskan coast. The Plan includes two options for the research platform: an icebreaker frozen into the ice or a camp on an ice floe. Using an icebreaker as a research platform offers the intrinsic advantage of greater safety and operation over a full annual cycle, but the cost of this option may exceed that of an ice floe camp. If a suitable icebreaker can be chartered at sufficiently low cost, the field experiment will be deployed during autumn 1997 and will be removed at freezeup 1998. Since several of the core measurements are of diminished interest during the winter, an ice floe camp of 8 months duration (March to October, 1998) is deemed both scientifically satisfactory and financially feasible. This logistics option will be adopted if a suitable ship cannot be reserved during 1996.

All operational support services will be provided by a Logistics Office. The general coordination of science planning, coordination among principal investigators, liaison with the Logistics Office, establishment of data policies, workshops, status reports, and other activities supporting the conduct of an integrated research program will be the responsibility of a Project Office and its Director.

The SHEBA project is divided into three phases. Phase I, currently under way, includes the analysis of existing data, preliminary modeling studies, technology development, and planning to develop and refine the experimental design. Phase II, 1997–1999, will include the field experiment, initial analysis of the new observations, and initial development of detailed process models. Phase III, 2000–2003, will include further analysis and process modeling, the development of models of the surface heat budget on aggregate scales, and development of GCM parameterizations for application in simulating the Arctic and global climate. A timeline for the SHEBA project is presented in Section 9.

1. INTRODUCTION

This document describes the Surface Heat Budget of the Arctic Ocean (SHEBA) project, the motivation behind it, relevant physical processes and modeling, its scientific objectives, and the plan for their achievement. The intended audience includes prospective SHEBA principal investigators, agency program managers, operations and logistics managers, and others with an interest in the Arctic climate. This document builds on the scientific background and rationale for SHEBA presented earlier in a prospectus (Moritz et al., 1993) available from the SHEBA Project Office.

The goal of the SHEBA project is to enhance quantitative understanding of the thermodynamic coupling between the atmosphere and the ocean in the presence of a sea ice cover in order to improve the representation of important high-latitude processes in global climate models (GCMs). Primary sponsorship of the SHEBA project is provided by the NSF Arctic System Science Program and the ONR High Latitude Program. In addition, the SHEBA experiment is being designed in collaboration with the Submarine Science Ice Experiment (sponsored by a consortium of federal agencies led by ONR), the NASA FIRE III program, the DOE ARM program, the NASA Polar Research Program, and the NASA-sponsored EOS-POLES and RADARSAT projects. International collaboration is coordinated under the auspices of the Arctic Climate System Study of the World Climate Research Programme. (See Appendix A for definitions of acronyms.)

The project is divided into three phases. Phase I (1995–1997) consists of technology development, analysis of existing data sets, modeling, satellite studies, and experiment planning. Phase II (1997–1999) is a long-term, surface-based, process-oriented experiment addressing the sea-ice albedo feedback mechanism in the perennial ice zone. The heart of this mechanism is the strong connection between the state of the ice cover and the albedo, or ratio of reflected solar radiation to incoming solar radiation. Snow-covered ice reflects most incoming solar radiation (i.e., has an albedo near 1). Open water absorbs almost all incoming radiation (i.e., has an albedo near 0). Bare ice and melt ponds absorb intermediate amounts of solar radiation. During summer, radiation heats the ice and upper ocean, causing snow and ice to melt and the albedo to decrease, which leads to additional heating and melting. To quantify the physics of the sea-ice albedo feedback mechanism, the field experiment will investigate how sea-ice characteristics respond through the seasons to changing radiative and sensible heating from the atmosphere and the ocean. The measurements will document how heat absorbed in leads and melt ponds and stored in the upper ocean affects the state of the ice and the way it interacts with the boundary layers of the ocean and the atmosphere.

On a global scale, sea-ice albedo feedback involves changes in the climatological position of the ice edge and adjustments in the poleward heat transport by the atmosphere, in addition to changes in the thickness, albedo, and temperature of ice within the central Arctic Ocean (Budyko, 1969; Sellers, 1969; Schneider and Dickinson, 1974; Kellogg, 1975). SHEBA has been designed to focus specifically on the processes contributing to ice albedo feedback within the perennial ice zone. SHEBA will thus complement research projects that focused mainly on the marginal ice zone, such as MIZEX and CEAREX, and projects focusing on improving GCM simulation of poleward heat transport, such as AMIP.

Although the primary focus of SHEBA is ice albedo feedback, the field experiment will also address aspects of cloud radiation feedback. This is because the two feedback mechanisms are related, many of the measurements are complementary, and the SHEBA field experiment provides a platform that is useful for cooperating programs. Results of the surface-based experimental program will be extended to larger spatial scales by incorporating remote sensors aboard aircraft, satellites, and submarines, operational assimilation models, and basic modeling studies. The coupling processes that determine the ice albedo feedback mechanism and their impact on the climate system will be examined primarily through modeling and the analysis of large scale data sets during Phase III (2000–2003), exploiting the data and results of Phase II.

Section 2 explains the motivation behind the SHEBA project. Section 3 is a basic primer on the physical processes involved. Section 4 gives the strategic objectives, and Section 5 details the experimental program designed to meet those objectives. Section 6 addresses modeling topics. Sections 7–10 are devoted to administrative details. A list of the acronyms used in the Plan is given in Appendix A, and a list of symbols in Appendix B. Because of the variety of measurements that could be of interest, the field program has been divided into four priorities, based on scientific importance and technical and fiscal constraints. A detailed discussion of the priorities and the measurements involved is contained in Appendix C.

2. MOTIVATION

There is much concern about anthropogenic impacts on climate, especially those associated with increasing concentrations of atmospheric carbon dioxide (CO_2) and other "greenhouse" gases. This problem is discussed at length in the Scientific Assessment of the International Panel on Climate Change, or IPCC Assessment (Houghton et al., 1990). There is mounting pressure for the scientific community to provide a sound basis for assessing quantitatively the magnitude, timing, and spatial patterns of global warming associated with increased CO_2. More generally, the prospect of global warming has added urgency and relevance to research aimed at predicting climate variations on time scales of decades to centuries.

2.1 Unresolved Questions

Our understanding of the global climate is limited by serious, unresolved questions regarding the role of the polar regions. Numerical GCM experiments generally show that CO_2-induced warming is amplified by the retreat and thinning of Arctic Ocean sea ice and that the magnitude of global warming is much greater at high northern latitudes. The qualitative reasons for this are straightforward: (1) ice and snow are highly reflective of solar energy, and (2) sea ice presents a formidable barrier to sensible and latent heat transfer between the ocean and the atmosphere. At high latitudes the first factor is self-reinforcing, i.e., it provides positive feedback. The second factor provides a mechanism through which enhanced melting in one season shows up as a large temperature increase in another season. These factors are determined by the surface heat budget, the ice mass balance, and their effects on surface albedo and temperature. On the time scales of climatic change, perturbations to surface temperature and albedo also affect the formation, albedo, emissivity, and internal structure of clouds, with potentially important consequences.

As summarized in the IPCC Assessment and discussed in the SHEBA prospectus (Moritz et al., 1993), current GCMs produce widely discrepant simulations of the present Arctic climate and predictions of the high-latitude response to a CO_2 doubling. These discrepancies indicate that our ability to predict the future climate of the Arctic is open to serious question.

This state of affairs is particularly important for the NSF ARCSS program, because GCMs are the primary tools used to synthesize and integrate knowledge of basic physical processes and to address questions concerning the Arctic climate of the future. Our ability to understand and predict the climate of the Arctic, the impact of climate change on the Arctic system, and the role of the Arctic system in global change is limited by our knowledge of the processes that determine ice albedo feedback. If we are to simulate the dynamics of Arctic and global climate with confidence, better models of these processes must be implemented in GCMs. The ultimate purpose of SHEBA is to develop, test, and improve models of the processes that determine the sea ice mass balance, the surface energy balance, and their effects on surface radiative properties, to implement these models in GCMs, and to investigate the consequences for the Arctic climate system as part of the ARCSS (SIM) modeling effort.

2.2 Results of Previous Studies

Despite the wide quantitative variability in GCM simulations, nearly all GCMs predict amplified greenhouse warming in the Arctic. It is natural to ask whether such warming is being observed. Unfortunately, data that might isolate an initially small anthropogenic signal (embedded in natural climate variability) are very limited in the Arctic, both temporally and spatially, and therefore studies looking for clear greenhouse warming trends are as yet inconclusive. Kahl et al. (1993) report no significant trend in Arctic Ocean surface temperatures over the past 40 years. Analysis of data gathered from several sources from 1961 to 1990 led Chapman and Walsh (1993) to conclude that the summertime extent of Arctic sea ice had decreased by a small but significant amount, while there was no discernible trend in wintertime extent. They found significant warming over most high-latitude land areas but little change over the Arctic Ocean and, in fact, a significant cooling over Greenland. The lack of warming and relatively small ice retreat may indicate that present GCMs overemphasize the sensitivity of climate to high-latitude processes. On the other hand, Johannessen et al. (1995) argue that satellite passive microwave imagery shows a significant decrease in Arctic ice extent during the period 1978 to 1987, followed by a more rapid decrease from 1987 to 1994.

Simulations of the climate response to a transient CO_2 increase of 1% per year for 100 years were performed by Manabe et al. (1991), using a global, coupled ocean/atmosphere GCM. Their results show a poleward amplification of surface temperature change. A large fraction of this change took place during the second half of the 100-year simulation. Therefore, the absence of large trends over the past 50 years does not guarantee that the Arctic climate will remain stable in the future. Recent calibration of the oxygen-isotope "paleothermometer" indicates relatively much larger swings in glacial-to-Holocene temperatures in the Arctic than at lower latitudes, consistent with most climate modeling (Cuffey et al., 1995).

It is also possible that a global warming signal will appear first in variables less easily observed than surface temperature or ice extent. Winter ice extent, for example, may be controlled by the continents encircling the Arctic Basin and by the position of a few major oceanic fronts. A general thinning of sea ice or a change in the distribution of leads might be more appropriate measures of climate change than anomalies of temperature and ice extent. The Arctic Ocean is a complex heat exchanger in which a cold halocline separating the polar surface water from warmer deeper water over much of the Arctic Basin plays a critical role by limiting heating of the ice by the warm deep water. Recent oceanographic measurements have documented a surprising increase in the area dominated by relatively warm Atlantic water immediately below this halocline. If this oceanic warming indicates a climatic trend, then it will ultimately affect the ice cover, complicating the problem of predicting Arctic climate.

The scientific community is at an important crossroad with respect to understanding the relationship between global climate and the polar regions. On one hand, we know that the GCMs do not accurately simulate the present climate of the Arctic, yet they are essentially unanimous in finding that air/sea/ice interaction must play a large role in CO_2-induced climate change. On the other hand, we know that our knowledge is too sparse to document current climate trends in the Arctic, perhaps to the point of not even knowing which are the most important system variables. Even if the necessary monitoring systems were in place, it might be decades before trends associated with anthropogenic changes could be distinguished from natural variability.

2.3 The SHEBA Response

Despite problems posed by analyses of the Arctic climate record, and practical limitations on the number of global climate simulations that can be performed, it remains true that if the enhanced Arctic warming and reduction of sea ice simulated by state-of-the-art models are realized during the next century, there will be enormous implications for the social, economic, and ecologic systems of the Arctic and the adjacent upper mid-latitudes. The need to assess climate change is immediate. The result is a mandate to improve our understanding and predictive capability of the impact of sea ice on climate.

The SHEBA project is focused on the physical processes that determine ice albedo feedback over the Arctic Ocean and will also contribute to our knowledge of how these processes interact with clouds. This emphasis is consistent with the science priorities established for the Ocean/Atmosphere/Ice Interactions (OAII) component of the ARCSS program (Moritz et al., 1992). In the following sections, we describe the key processes involved in these interactions and the strategy of the SHEBA project for investigating them.

3. BACKGROUND

3.1 Radiation/Climate Feedback Processes in the Arctic

A quantitative physical understanding of the surface energy balance, the sea-ice mass balance, surface radiative properties, and interactions between the sea ice and the oceanic and atmospheric boundary layers is essential for accurately simulating the present-day Arctic climate and for predicting its response to perturbations. The primary mechanisms through which these processes affect climate are ice albedo feedback and cloud radiation feedback. To realize significant improvements in models that simulate Arctic climate, the processes that determine these feedbacks must be investigated in detail. The ice albedo feedback mechanism figures prominently in the conceptual design of SHEBA and its *in situ* measurement program. The cloud radiation feedback mechanism will be addressed primarily by the ARM and FIRE programs, in cooperation with SHEBA.

3.1.1 Ice albedo feedback

The possible importance of ice albedo feedback to climate change has been recognized since the 19th century, when Croll (1875) hypothesized that if the climate warms, snow and ice cover will decrease, leading to a decrease in surface albedo, an increase in the absorption of solar radiation at the Earth's surface, and consequent further warming. Since that time, albedo feedback, and sea-ice albedo feedback in particular, has proved to be quite important in numerous simulations of global warming (Manabe and Stouffer, 1980; Spelman and Manabe, 1984; Washington and Meehl, 1986; Dickinson et al., 1987; Ingram et al., 1989; Manabe et al., 1991; Schlesinger and Jiang, 1991; Rind et al., 1995).

Albedo is defined as the ratio of the upward shortwave irradiance at the surface to the incident shortwave irradiance. Thus defined, albedo refers to radiation variables integrated over wavelengths, azimuth angles, and zenith angles. It follows that albedo depends on the optical properties of the surface and on the spectral and angular distribution of the incident radiation. In most GCMs, albedo is parameterized as a simple function of the physical state of the surface, ignoring its dependence on the incident radiation. Yet this dependence is significant for sea ice and open water. More general models express the spectral bidirectional reflectance distribution function (BRDF) as a function of the state of the surface. In this document, we follow the common practice of GCM modeling by referring to ice albedo feedback as though albedo is a function of surface properties only, but with the understanding that the SHEBA measurements, analysis, and modeling studies will treat BRDF as a function of surface state. Alternatively, the albedo can be thought of as a function of surface state, given the incident radiation.

We focus here on the sea-ice albedo feedback characteristic of the central Arctic pack ice. Figure 1 is a schematic illustrating the key processes. There are two main components:

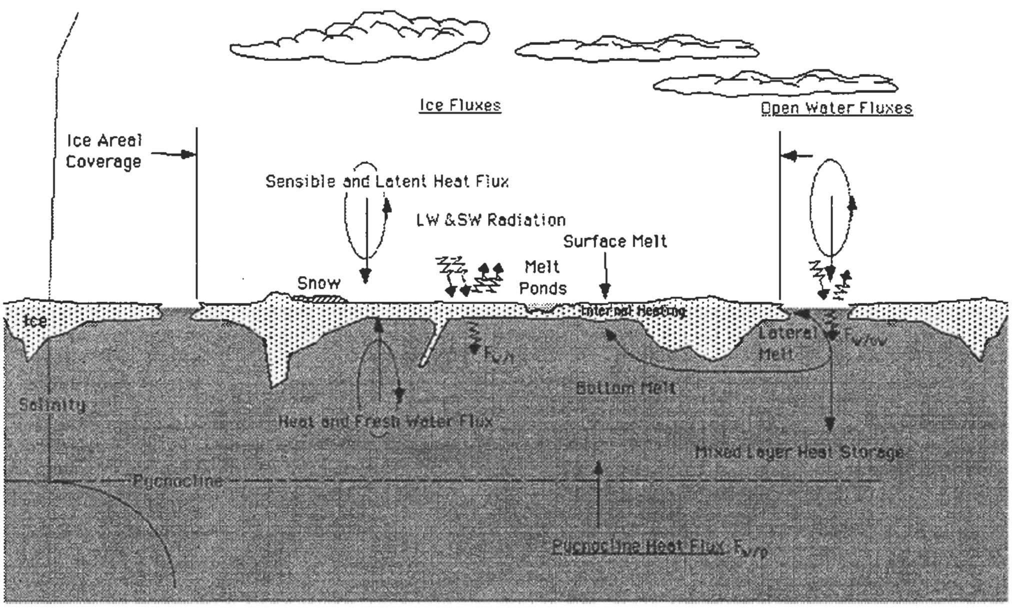

Figure 1. Schematic of ice albedo feedback of pack ice. There are two main components: (1) Melting at the ice surface tends to decrease ice surface albedo, and (2) the albedo of ice is greater than that of water, so decreasing the fraction of ice coverage decreases the albedo of the aggregate ice/water surface. The albedo of the ice surface depends on several factors, including ice thickness, snow coverage, and melt pond coverage. The radiant heating over open water $F_{w/ow}$ is absorbed in the water. This is augmented by radiative heat coming through the ice, $F_{w/i}$, and by heat coming from the deep ocean through the pycnocline, $F_{w/p}$. The ocean portion of the feedback depends on how the total heat entering the mixed layer, F_w, is partitioned among storage within the mixed layer, ice edge melting, and ice bottom melting (Rind et al., 1995).

(1) Melting at the surface tends to decrease the albedo by removing the snow cover and deepening and widening the melt ponds, and (2) the albedo of ice and snow is greater than that of water, so decreasing the fraction of ice coverage increases the amount of energy absorbed at the surface. These factors cause two principal feedback loops: an ice-surface loop, in which radiation modifies the albedo of the ice surface, and an ocean loop, in which melting modifies the albedo by changing the area of the ocean surface covered by ice.

The albedo of the ice surface depends on several factors, including surface optical properties, ice thickness, snow coverage, and melt-pond coverage (Zubov, 1945; Bryazgin, 1959; Grenfell and Maykut, 1977; Grenfell and Perovich, 1984; Shine et al., 1985; Barry et al., 1989; Lindsay and Rothrock, 1994; Perovich, 1994; Barry, 1996). Albedo exhibits the largest and most significant temporal and spatial variability during the melt season, when incoming shortwave radiation is large. Springtime heating melts snow, which decreases the albedo of the surface. The melt water soaks the remaining snow and collects in ponds, thereby substantially lowering the average albedo of the pack ice. Heat flux to the surface of bare ice causes additional melting, and thin ice melts completely. In this way, the aggregate albedo of the ice/open-water system decreases significantly.

The ocean portion of the feedback loop depends on how heat entering the mixed layer is partitioned among storage within the mixed layer, ice-edge melting, and ice-bottom melting (Rind et al., 1995). We know that polar mixed layers can store considerable heat (i.e., support mixed-layer temperatures well above freezing). Badgley (1961) was first to recognize that the difference between ice bottom accretion/ablation and heat conduction in the ice can be used to estimate the vertical flux of sensible heat in the mixed layer of the ocean. Based on Untersteiner's (1961) observations of ice temperature, Badgley estimated that heat flux to have an annual average of about 2 Wm^{-2}. This number was later supported by the model calculations of Maykut and Untersteiner (1971). Over much of the Arctic, however, the mixed layer is decoupled thermodynamically from the deep warm water in the Atlantic layer by the cold halocline. Thus the portion of the ocean heat flux originating in the radiative flux through leads and thin ice (Maykut, 1982) is a substantial fraction of the total. Maykut and McPhee (1995) estimated the oceanic heat flux to the underside of the ice during the 1975–1976 AIDJEX experiment, and found it to vary seasonally, reaching 40–60 Wm^{-2} during summer. They also found significant spatial variability in the flux on the 100-km separation scale of the AIDJEX stations. Their results imply that during AIDJEX most of the incoming solar radiation absorbed in leads was mixed rapidly downward, some of it residing in the mixed layer for weeks to months. This heat storage blurs the distinction often made in large-scale ice models between solar heating in leads and heat entering the mixed layer from below. Because the incident shortwave radiation decreases rapidly from July to September, the strength of ice albedo feedback is affected by any time lag between the absorption of shortwave radiation and the melting and change in albedo caused by the absorbed energy.

The partitioning of the shortwave radiation absorbed in the upper ocean between bottom melting and edge, or lateral, melting is poorly known. Stratification in the summer may trap heat in the upper few meters of the water column in leads. This would tend to increase lateral melting. When the floe size is small, the ratio of edge area to bottom area is significant, and the lateral melt has a greater effect on ice coverage (Steele, 1992). Ocean turbulence will mix the heat downward under the ice, enhancing bottom melt. This melting decreases the aggregate albedo when it completely disintegrates thin ice.

Coupled ice/ocean models have been recently used to examine the impact of more realistic ocean heat flux parameterizations (e.g., McPhee, 1987, 1994; Mellor and Kantha, 1989; Holland et al., 1996), but at present the ocean side of the albedo feedback loop is parameterized crudely in most GCMs. In the simplest and most common approach, the mixed layer is assumed to remain at freezing as long as ice is present, and the incoming solar radiation is partitioned immediately into edge and bottom melting in some prescribed ratio (Parkinson and Washington, 1979; Varvus, 1995). Zubov (1945) showed that partitioning to edge melting alone produces unrealistic exponential growth in lead area, and ice/ocean boundary layer studies have shown that heat deposited near the surface may be mixed efficiently by turbulence. In a recent GCM sensitivity study, Rind et al. (1995) considered an additional, conductive transfer mode that allows heat storage in the mixed layer and demonstrated that the partitioning of solar ocean heating in GCMs has a significant impact on simulated northern-hemisphere ice extent in CO_2 doubling experiments.

It is well recognized that GCM formulations of the sea-ice mass balance, surface energy balance, surface radiative properties, and clouds are highly simplified parameterizations of a complicated system. Although available observations document the overall climatological components of the surface energy budget of undeformed, perennial ice, they are inadequate to diagnose and understand the interactive processes by which the heterogenous air/sea/ice system adjusts to external perturbations. The magnitude and even the sign of the overall thermodynamic response of the Arctic climate system to such perturbations depend critically on the mutual adjustments of the oceanic mixed layer, sea ice of various thicknesses, leads, clouds, and the atmospheric temperature structure. This state of affairs has already motivated efforts to develop more sophisticated descriptions of the sea-ice mass balance and the complex interactions between the atmosphere and ocean when sea ice is present. However, to judge the realism of these descriptions, and their impact on climate sensitivity, requires a coordinated effort to obtain comprehensive data sets that document the processes during large changes in the ice cover and to integrate the observations with models.

SHEBA will address the problem by providing quantitative information on (1) how the surface heat balance is affected by melt ponds, ice thickness, surface characteristics, and disposition of solar heating in and near leads; (2) how the surface mass balance responds to this complex heat balance; (3) how the surface mass balance affects the evolving radiative properties such as albedo and temperature; and (4) how the detailed workings of these local processes affect the spatial averages and statistics needed for relatively coarse model grids.

3.1.2 Cloud radiation feedback

An important climatological feature of the Arctic Ocean is the occurrence of extensive, multilayered, low-level stratus clouds (Marshunova, 1961; Huschke, 1969; Hahn et al., 1988). These clouds have large effects on the surface heat budget, especially during the late spring and summer when the mean cloudiness exceeds 85% and the incident shortwave radiation is large.

Herman and Goody (1976) explain the predominance of low-level, multilayered clouds in terms of air mass modification as follows. Relatively warm, moist air from surrounding continents and oceans cools to the dew point temperature as it advects northward over the melting pack ice. Layering can develop as shortwave photons are absorbed within the cloud (owing to absorption by water vapor, enhanced by multiple scattering from cloud particles), providing an energy source to evaporate droplets in an interior layer. This mechanism depends to some extent on the small diurnal variation of shortwave radiation that obtains at high latitudes during summer.

It is well known that clouds have a significant impact on the surface energy balance of pack ice. Data presented by Doronin (1969) for the central Arctic, for example, indicate that during May–July the shortwave radiation incident on the ice/ocean surface is greater by approximately 110 W m^{-2} under clear skies than under overcast skies, whereas the net longwave radiative loss from the surface is greater under clear skies by approximately 60 Wm^{-2}. At a surface albedo of 0.45, typical of summer pack ice, the contributions of these shortwave and longwave perturbations to the surface energy balance nearly cancel. This illustrates that the impact of clouds on the surface energy balance of sea ice in summer is highly dependent on the surface albedo.

During winter there is an insignificant amount of shortwave radiation, and the net surface longwave radiation is less sensitive to clouds than during summer because the surface temperature is free to adjust. In winter, the net radiation loss under reportedly clear skies is greater by approximately 30 W m^{-2} than under overcast skies (Doronin, 1969). Since reported winter cloudiness averages about 0.65 over the Arctic Ocean, imposing clear skies at this season might enhance the surface energy losses by about 20 W m^2.

In a general climate-change scenario, caused for example by a doubling of CO_2, the cloudiness need not remain constant. If cloudiness increases over the pack ice during May–July, then it may damp out some of the positive ice-albedo-feedback effect on the surface energy budget by decreasing the incident shortwave radiation. By contrast, a decrease in cloudiness may tend to amplify the ice albedo feedback.

In the Herman and Goody (1976) model, the formation and layering of clouds result from two interactions with the surface: cooling of the air mass and absorption of reflected shortwave radiation. Therefore, it is plausible to consider feedback loops involving the surface radiation balance and clouds.

In both winter and summer, the driving mechanism is the modification of air masses arriving from lower latitudes. In a general climate-change scenario, this supply of warm, moist air can be expected to change in a manner that is only partly determined by what goes on in the Arctic. Many possibilities can be entertained. The surface can influence the clouds through changes in surface albedo and surface temperature. As long as some ice is present, the summer surface temperature cannot vary much, and the clouds may be influenced primarily by the amount of shortwave radiation reflected from the surface.

Clouds directly affect the net shortwave and longwave fluxes at the surface by scattering and absorbing shortwave radiation and strongly absorbing longwave radiation. The extent to which a cloud layer increases the net longwave radiation beneath it depends on the temperature at or near the bottom of the cloud and on the size and type of particles in the cloud. At the same time, the clouds decrease the incident shortwave radiation because of backscattering and the enhancement of absorption by multiple scattering due to the cloud particles. Changes in the surface radiation balance affect the near-surface inversion and the stability of the atmospheric boundary layer, modifying the sensible and latent heat fluxes as well. Clouds also produce precipitation which influences the depth of the snow cover and the fresh water balance of the ice.

Interactions between clouds and the surface radiation balance are influenced by the low temperature and specific humidity and the frequent occurrence of temperature inversions. Several factors affect the surface/cloud radiation exchange, including cloud morphology and the vertical distributions of temperature, water vapor, ice content, particle size, and phase. For example, perturbations in the atmospheric radiation balance may arise from increased concentrations of greenhouse gas and aerosol. Changes in the surface radiation balance of the snow and ice should modify the length of the melt season and the equilibrium thickness of the ice (Maykut and Untersteiner, 1971). Changes in cloudiness, surface temperature, and fraction of open water will modify fluxes of radiation and sensible and latent heat, which will modify the atmospheric temperature, humidity, and dynamics.

The sensitivity of surface and top-of-atmosphere (TOA) radiation fluxes to variations in Arctic cloud characteristics has been examined by Schweiger and Key (1994) and Curry et al. (1996a). They showed that the net surface radiation flux increases with increasing cloud amount, increasing condensed-water amount, and decreasing cloud-particle size. These results are based on calculations in which the vertical profiles of temperature and humidity do not change in response to the changes imposed in cloud parameters. In partially coupled calculations, the effect of clouds on the net surface radiation flux in the Arctic is generally opposite to that in lower latitudes. Although the full cloud radiation feedback mechanism is complicated and poorly understood, Curry et al. (1996a) estimate that it is positive in the Arctic, which is contrary to the negative cloud feedback estimated globally (Cess et al., 1989). Several cloud aerosol feedback processes in the Arctic have been proposed, although there is no suitable data set with which to test them (e.g., Curry, 1995; Blanchet and Girard, 1995).

To gain a better quantitative understanding of how clouds interact with the surface energy budget, SHEBA is collaborating with the DOE ARM and NASA FIRE III programs. The combined efforts of SHEBA, ARM, and FIRE will produce a new data set that simultaneously documents the surface energy budget over the complex pack ice (SHEBA), the relationship between atmospheric radiative fluxes and atmospheric structure (ARM), and the formation and radiative properties of clouds (FIRE).

3.2 Status of Arctic Climate Modeling

In GCMs, many of the details of the state of the ocean/ice surface are neglected. In the model of Manabe et al. (1991), for example, the pack ice is represented at each model grid point (resolution approximately 500 km) by two variables: ice thickness h and surface temperatures T_s. The albedo is a simple function of h and T_S which asymptotes to 0.8 for cold, thick ice and to 0.1 for ice of zero thickness at the melting point. For ice states of intermediate h and T_s, the albedo varies between the asymptotes. Experiments with more detailed models suggest that these simplifications are too drastic (Shine et al., 1985; Barry et al., 1993; Bitz et al., 1996). For example, Curry et al. (1995) examined the sea-ice albedo feedback mechanisms associated with local thermodynamic and dynamic processes occurring within the multiyear ice pack, employing a number of different one-dimensional sea-ice models. The magnitude of the positive ice albedo feedback simulated as the response to a prescribed perturbation of the surface sensible heat flux increased with the inclusion of melt ponds and diminished with the inclusion of an ice thickness distribution and ridging parameterization.

The direct response of 1-D thermodynamic models (without feedback to the atmosphere or ocean) to perturbation of the surface sensible heat flux has been summarized by Curry et al. (1995). There are very large differences between the response of 1-D and 2-D ice models to heat-flux perturbations. Part of the discrepancy arises from the fact that the 2-D ice models utilize variations of the Semtner 0-level thermodynamics, which makes the models much less sensitive than models that include more vertical resolution. Ice dynamics also play an important role. Modeling efforts that include a sea-ice thickness distribution (Flato and Hibler, 1995; Björk, 1992; Schramm et al., 1996) are bringing together the physics used in the 1-D and 2-D ice models. It remains a challenge to integrate the physics involved in ice dynamics and thermodynamics to provide a realistic determination of the ice albedo feedback processes acting on the aggregate scale of a GCM grid cell.

Accurate simulation of the mean annual cycle and the variability of the present-day Arctic climate is an important guide to modeling perturbed climates. To promote systematic evaluations and comparisons of GCMs, the Atmospheric Model Intercomparison Project (AMIP) was organized in 1990 (Gates, 1992). Approximately 30 GCMs have completed a 10-year simulation using observed, monthly averaged values of sea-surface temperature and sea-ice extent. Using the AMIP results, Tao et al. (1995) found zonally and seasonally averaged modeled temperatures to have a range of 8°C during summer and 17°C during winter. A limitation of the AMIP comparisons is that all the experiments use identical, prescribed, annually periodic sea ice as a lower boundary condition, so the model discrepancies are related to ice albedo feedback only insofar as they inform about poleward heat transport. The melting and thinning of sea ice which is so influential in the CO_2 doubling experiments is absent. In an intercomparison of 14 GCMs, Boer (1992) found large variations in simulated surface temperature and tropospheric temperature. All of the models predicted too much precipitation in the Arctic, and their predictions of the net surface heat flux varied widely.

Detailed analyses of the Arctic climatology used in the NCAR Community Climate Model (CCM) have been presented by Battisti et al. (1992) and Tzeng and Bromwich (1994). Battisti et al. found that for the incoming solar radiation and outgoing longwave radiation simulated at the top-of-atmosphere (TOA) by CCM Version 1 (CCM1) were too large because of errors in the simulated Arctic surface temperature and cloudiness. Over the Arctic Basin, CCM1 simulated large amounts of low clouds in winter and almost none in summer, opposite to what is actually observed. Battisti et al. also found that the wintertime anticyclone in the Beaufort Sea was not simulated by CCM2. This may be due to unrealistically thin sea ice (prescribed) which permits too much heat exchange between the ice and the atmosphere. Tzeng and Bromwich (1994) found that upgrading the boundary layer parameterization in CCM2 improved the simulation of the summertime cloud fraction in the Arctic Ocean.

Lynch et al. (1995) have performed winter and summer simulations of the Alaskan Arctic climate, using the Arctic Regional Climate System Model (ARCSyM) (Walsh et al., 1993). The model predicts spatial patterns that are generally consistent with synoptic observations, although biases appear because of the relatively low evaporation rates resulting from interactions between the modeled cloud/radiation scheme and the surface processes, particularly over land. The inclusion of sea-ice dynamics has a substantial impact on the ARCSyM simulations.

It remains difficult to evaluate the performance of GCMs of the Arctic because of inadequate data on the processes that determine ice albedo feedback and the mismatch between the highly simplified GCM representations of the state of sea ice and clouds and the complicated variability that occurs in nature. Even the crudest tests, such as simulating the basic features of an annual cycle, cannot be accomplished satisfactorily because of uncertainties in the components of the surface energy balance and cloud properties.

Although more sophisticated and potentially realistic models of sea ice and Arctic clouds exist, testing them, and implementing them as GCM parameterizations, requires new, comprehensive measurements of the sea-ice energy balance, mass balance, and surface radiative properties, together with simultaneous data on the ocean and atmospheric boundary layers.

3.3 Summary of Climatological Observations in the Arctic

There is a long history of productive field experiments that are related to the SHEBA project, beginning over a century ago with the drift of the research vessel *Fram* (1893–1896). This history includes a series of Soviet drifting stations operating from 1937 through 1989, several U.S. drifting stations beginning with the International Geophysical Year (1957–1958), the Arctic Ice Dynamics Joint Experiment (AIDJEX) in 1975–1976, and numerous shorter experiments focused on specific topics (e.g., ALEX, FRAM I through FRAM IV, MIZEX, AIWEX, CEAREX, LEADEX, SIMI, SIMMS, and AOS). Aircraft campaigns have been conducted to study Arctic clouds (Herman and Curry, 1984; Curry and Herman, 1985; Tsay and Jayaweera, 1984). These experiments and campaigns, together with associated theoretical and modeling studies, have been documented in scientific articles, books and special journal editions, including works by Nansen (1902), Pritchard (1980), and Untersteiner (1986) and special issues of the *Journal of Geophysical Research* (March 1983, June 1987, March 1991, March 1995).

Of the modern studies, the SHEBA project is similar to AIDJEX in duration and logistical scope. AIDJEX comprised an array of four manned ice stations surrounded by a constellation of data buoys which drifted for over a year in the Beaufort Gyre north of Alaska. AIDJEX differed from SHEBA, however, in several ways. Its goals were to understand the dynamical response of the ice pack to spatial variations in forcing, e.g., finding the constitutive law relating strain or strain rate to ice stress. The energy and mass balances of the ice pack, their response to time-dependent forcing, and their effect on surface radiative properties were not central issues in AIDJEX. In the intervening two decades, experimental capabilities have advanced remarkably. Many new technologies have been developed, including satellite remote sensing and navigation, ARGOS data buoys, sophisticated research aircraft instrumentation, ocean profiling and turbulence instruments, portable field spectroradiometers, Fourier-transform infrared radiometers, and powerful field-deployed computers.

The unique aspects of the SHEBA field experiment are its scientific focus on the processes associated with ice albedo feedback, its unprecedented coordination among atmosphere, ice, and ocean studies, and its plan to field state-of-the-art, multidisciplinary measurement systems for an extended period. A large amount of useful data has been obtained from previous field experiments, and appropriate technology has been developed and tested. However, a comprehensive data set of simultaneous and contiguous observations remains unavailable, thereby severely limiting the development and evaluation of climate models. Such a data set is needed to understand the physical processes of air/sea/ice interactions, to develop and test parameterizations suitable for climate models, and to evaluate satellite remote sensing algorithms.

4. STRATEGIC OBJECTIVES

The premise of the SHEBA experiment is that the state of the surface of the Arctic Ocean and its albedo are determined by the thermodynamic and dynamic forcing by the atmosphere and ocean. If this seemingly simple premise is true, and if global climate models can predict the appropriate forcing parameters, the ice albedo feedback can be simulated accurately. The SHEBA field experiment will be designed to measure the state of the ice and the forcing from the atmosphere and ocean in one area over large seasonal changes. The measurement will document the important variables on both local and aggregate scales. The measurements will be extended spatially by remote sensing and modeling. From these measurements, SHEBA will address the first three of five strategic objectives:

Objective 1: To develop accurate physical and mathematical relationships between the state of the ice cover (State) and albedo, for any given incident shortwave radiation (ISWR):

$$\text{Albedo} = f_1(\text{State, ISWR}) \quad (1)$$

Objective 2: To determine how the state of the ice cover changes in response to forcing from the atmosphere and the ocean:

$$d(\text{State})/dt = f_2(\text{State, Albedo, Forcing}) \quad (2)$$

Objective 3: To relate the surface forcing to conditions within the atmospheric and oceanic boundary layers:

$$\text{Forcing} = f_3(\text{ABL, OBL}) \quad (3)$$

where the symbols f_1, f_2, and f_3 denote the functional relationship.

In equations (1) and (2), the albedo (or more generally, BRDF) has been distinguished from the other surface state variables because of its central role in the feedback loop. To a large extent, the left-hand side of equation (2) is an expression of the change in ice mass balance and morphology. For example, in models wherein the sea-ice thickness distribution $g(h)$ represents the state of the ice pack, the left-hand side would be $dg(h)/dt$ (Thorndike et al., 1975). In this case, forcing terms on the right-hand side would include thermodynamics and ice deformation. The thermodynamic forcing is determined essentially by the surface heat budget and constitutes the main focus of the SHEBA project. The necessary ice deformation information will be monitored also during the SHEBA project, using RADARSAT and ERS-1 SAR image pairs, ARGOS buoy positions and analyzed geostrophic wind fields.

Indicating the important ties between the measurement and modeling elements of the SHEBA project is straightforward. If objectives 1–3 are met, their essence can be incorporated into GCMs with equations of the form (1)–(3). Then, if the GCMs predict the conditions at the outer edge of atmospheric and oceanic boundary layers, and if they use existing knowledge to predict the dynamically forced changes in $g(h)$, they should represent ice albedo feedback more accurately.

The questionable link in the preceding scenario is whether the state of the surface is determined uniquely by the surface forcing. It may be that the exact state is inordinately sensitive to conditions at an earlier time. The time at which ice begins to melt, for example, may depend sensitively on snow accumulated during the previous fall or on whether neighboring ice is heavily rafted and ridged. If this is true, and the albedo is sufficiently sensitive to ice state, it may be impossible to simulate the albedo accurately without much more detailed GCMs. Testing this link requires comparison of local and area-averaged, measured albedos with albedos estimated using the relationships developed in Objectives 1–3. Therefore, we also have a fourth objective:

Objective 4: To extend the relationships determined in Objectives 1–3 from local scales to the aggregate scales suitable to climate models.

From the SHEBA measurements at various scales, we will estimate the minimum spatial aggregation scales at which averages of the state variables become statistically stationary. These scales will determine the minimum useful grid scale for pack ice points in a GCM. If the predicted and measured states and albedos cannot be reconciled at some scale greater than or equal to the aggregate scale, the premise will be false for practical purposes, and we will know that more detail is necessary in GCMs.

The final objective concerns the legacy of the SHEBA field experiment:

Objective 5: To establish a basic data set suitable for developing and testing climate models that incorporate the processes SHEBA is proposing to study.

5. SHEBA EXPERIMENTAL PROGRAM

Measured on a scale of kilometers, multiyear sea ice moves as a coherent element for periods comparable to the duration of the SHEBA field experiment. That is, individual features and ice types, including ridges, hummocks, melt ponds, and modes of the sea-ice thickness distribution function, are recognizable over time intervals of a month to a year. Changes in the water masses beneath the ice occur relatively slowly compared with changes in the air masses and clouds, which may occur on time scales of hours to days. These factors imply that the ice cover and to some extent the upper ocean provide the "memory" of the system under study, while the atmosphere provides most of the time-dependent forcing on this system.

The primary base for the field measurements will be a drifting ice station. This choice allows the research station to follow the "memory" (ice) variables as they change in response to measured forcing. The SHEBA ice station will be located near the middle of the Beaufort Sea in the vicinity of 75°N, 145°W, where the average ice advection and the effects of dynamics (relative to thermodynamics) on the ice cover should be relatively small. Also, the heat flux from the deep ocean to the ice is very low in this region. This choice facilitates the investigation of the air/sea/ice processes responsible for ice albedo feedback (the signal) with minimum impact from other processes (noise) affecting ice conditions. The low advection in this location is also a logistical advantage, because the distance between the station and its shore base is likely to remain reasonably stable during the experiment period.

5.1 Experiment Design

The field program is designed to address specific scientific questions regarding the relationship of physical processes to the thermodynamic coupling and feedbacks between the atmosphere, ice, and upper ocean. Thus it is a "process oriented" experiment, and the experimental site might be anywhere that typical features are likely to occur: ice of varying thickness, age and morphology, leads, melt ponds, and snow cover.

Existing observations of the Arctic Ocean surface make it abundantly clear that surface temperature (in winter), surface albedo (in summer), and ice thickness (year round) exhibit large variations on horizontal scales of tens to hundreds of meters, far smaller than a grid cell of even the highest-resolution global climate model. For purposes of discussion, we denote this scale as the "local scale." The other scale of interest to SHEBA is the "aggregate scale," which is the minimum scale necessary to obtain area distribution functions of the variables. The analysis of Rothrock and Thorndike (1980), for example, implies that the aggregate scale for average ice thickness is about 20 km. The local and aggregate scales may be different for different variables, such as ice concentration, ice temperature, clouds, and atmospheric radiation. A major challenge in the design of the SHEBA field experiment is to bridge the gap between surface measurements made at the local scale and the aggregate scale at which the results become relevant to climate modeling.

The spatial scales of the measurements obtained during the SHEBA field experiment are determined by the intrinsic spatial variability of the parameters, modeling requirements, and logistical and budget constraints. Based on these considerations, the SHEBA measurement program will focus on scales of

(1) < 10 km, or the local scale. These measurements will be centered at a drifting ice camp. Time-series measurements will be conducted from the surface, with the aim of documenting local physical processes in detail for major ice types that typify the area under a variety of atmospheric conditions. This data set will provide the foundation for improving parameterizations of surface fluxes, surface radiative properties, processes involved in the ice mass balance, and relevant processes in the upper ocean.

(2) 10–100 km, the aggregate scale and also the scale of a high-resolution GCM grid cell. The aggregate-scale measurements will be made from a variety of platforms, such as satellites, aircraft, helicopters, and submarines. Observations and modeling on this scale are geared toward understanding spatial variability in the ice cover and in the atmospheric and oceanic boundary layers and how this variability affects the behavior of the system on the aggregate scale. This will provide information needed for evaluating parameterizations and subgrid-scale models developed for use in GCMs. Time averages of some atmospheric and oceanic quantities made on the local scale will serve in some cases to approximate the time-averaged aggregate quantities.

Observations are required for each of the following ice and surface types: first-year and multiyear ice, blue ice, white ice, hummocks, ridges, melt ponds, and leads. During special observing periods, surface variability, horizontal transport processes on the subaggregate scale, and problems of spatial averaging will be addressed.

The temporal sampling program has two parts. The first consists of simultaneous time-series measurements of the atmosphere, sea ice, and upper ocean variables maintained for the full duration of the experiment. This part will monitor the time evolution of the surface state, the albedo, and the forcing functions over large interseasonal changes. Time-series information will be derived from local measurements and area-aggregate measurements. Repeat surveys and remote sensing measurements will underpin the area-aggregate time series. Of particular interest is the time evolution of the ice thickness distribution, the melt pond distribution, and the summer ice concentration, all of which have important effects on the aggregate-scale albedo and temperature.

The second part consists of one-time surveys and Intensive Observing Periods (IOPs). The IOP measurements are designed to support the analysis and modeling of relatively short-lived phenomena. IOP measurements can be local or can be surveys to extend the short-duration observations beyond the local scale. IOPs are planned to study spatial variations in surface characteristics during the summer melt season, horizontal variability of turbulent fluxes, heat and salt budgets of the upper ocean, and interactions between the atmosphere, ocean, and ice in the presence of leads.

The layout of the SHEBA surface measurements is illustrated schematically in Figures 2 and 3. Figure 2 illustrates the possible types of instrumentation that could be used to sample the sea ice, snow cover, oceanic mixed layer, and atmospheric boundary layer on local and aggregate scales. Figure 3 illustrates the horizontal distribution of the measurement sites, including the main core-time-series station and the distributed local heat and mass balance stations.

Aircraft, submarine, and satellite remote sensing measurements will extend the scope of the SHEBA measurement program to greater spatial and temporal scales. Such measurements will contribute to Objective 4 and will be used in model development and evaluation.

5.2 Measurement Priorities

The domain of interest to the SHEBA project can be divided into three vertical zones (Figure 4): (1) a Surface Zone including the ice and thin surface layers in the atmosphere and ocean, (2) a Boundary Zone consisting of the atmosphere and ocean boundary layers, and (3) an Outer Zone extending beyond the boundary layer regions. The core measurement program is centered on the Surface Zone. This is the zone where the thermodynamic inputs determine the surface energy balance and where the ice properties change in response. Local measurements in the Surface Zone are affected by horizontal variability on length scales of 1–1000 m. The coupling between the surface fluxes and the rest of the atmosphere and ocean occurs in the Boundary Zone. This zone extends to the base of the ocean mixed layer and to a height of approximately 1 km in the atmosphere, depending on cloud cover and stratification. The Outer Zone includes the ocean pycnocline through which heat is exchanged with the deeper ocean and the region in the atmosphere whose properties affect the surface longwave and shortwave radiation (approximately 0 to 8 km). The important horizontal variations in this zone occur on scales larger than 1 km.

Priority 1 observations are core time series (CTS) measurements that will provide a fundamental, if limited, description of the parameters relevant to the surface heat and mass balance of sea ice and the surface radiative properties (Objectives 1, 3, and 4). Priority 1 measurements are largely confined to the Surface Zone, with a few in the Boundary Zone. Priority 2 observations are essential measurements that are needed to enhance the understanding of how surface fluxes modify the ice (Objective 2), to relate surface forcing to conditions in the Boundary Zone and the Outer Zone (Objective 3), and to extend local observations to the aggregate scale (Objective 4). In some cases, priority 2 observations extend priority 1 observations to higher spatial and temporal resolutions. Priority 3 observations are desirable measurements that examine details of the surface heat balance or that are directed at understanding the processes causing changes within and outside the Boundary Zone. Priority 4 observations are ancillary measurements that would complement SHEBA but are not vital to achievement of the primary goal. A detailed, prioritized list of the measurements is presented in Appendix C.

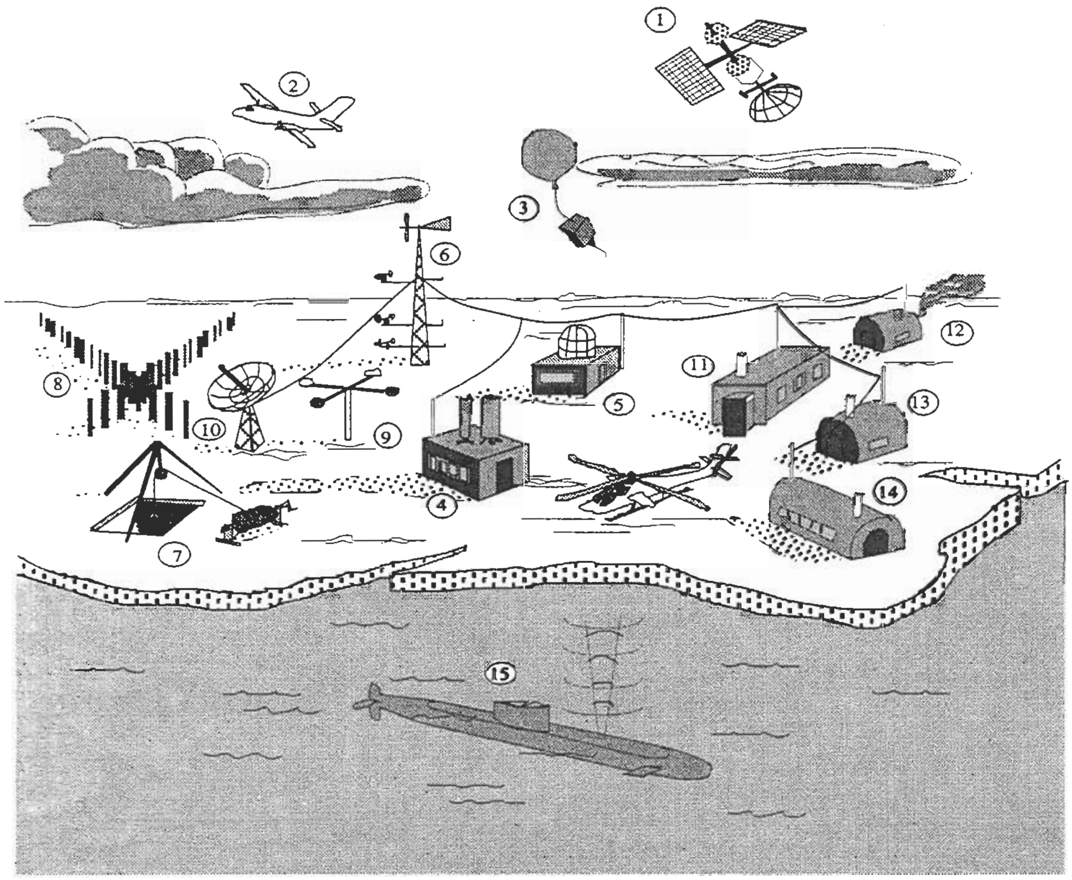

Figure 2. Sketch of a possible configuration of the SHEBA research camp on the pack ice. (1) Satellite for monitoring atmospheric structure and surface parameters; (2) research aircraft for surveys of atmospheric and surface parameters; (3) rawinsonde; (4) instrumentation to measure the spectral distribution of downwelling radiation; (5) all-sky camera, ceilometer, and other instrumentation to measure cloud properties; (6) meteorological tower; (7) hydrohole and winch for deployment/recovery of suspended oceanographic instruments and AUVs; (8) stakes representing the measurement of the ice and snow mass balance, and temperature and radiation in the ice interior; (9) radiometers; (10) communications antenna; (11) mess hall; (12) generator shed; (13) living quarters; (14) laboratory; (15) Submarine for surveying the ice thickness distribution. The cloud and radiation testbed instrumentation will be supplied by ARM. The research aircraft campaigns will be conducted by FIRE. The submarine data will be acquired as part of SCICEX. In the logistics option utilizing a ship frozen in the ice pack, the mess hall, laboratory, living quarters, and generators would all be aboard ship. (Figure provided by N. Untersteiner.)

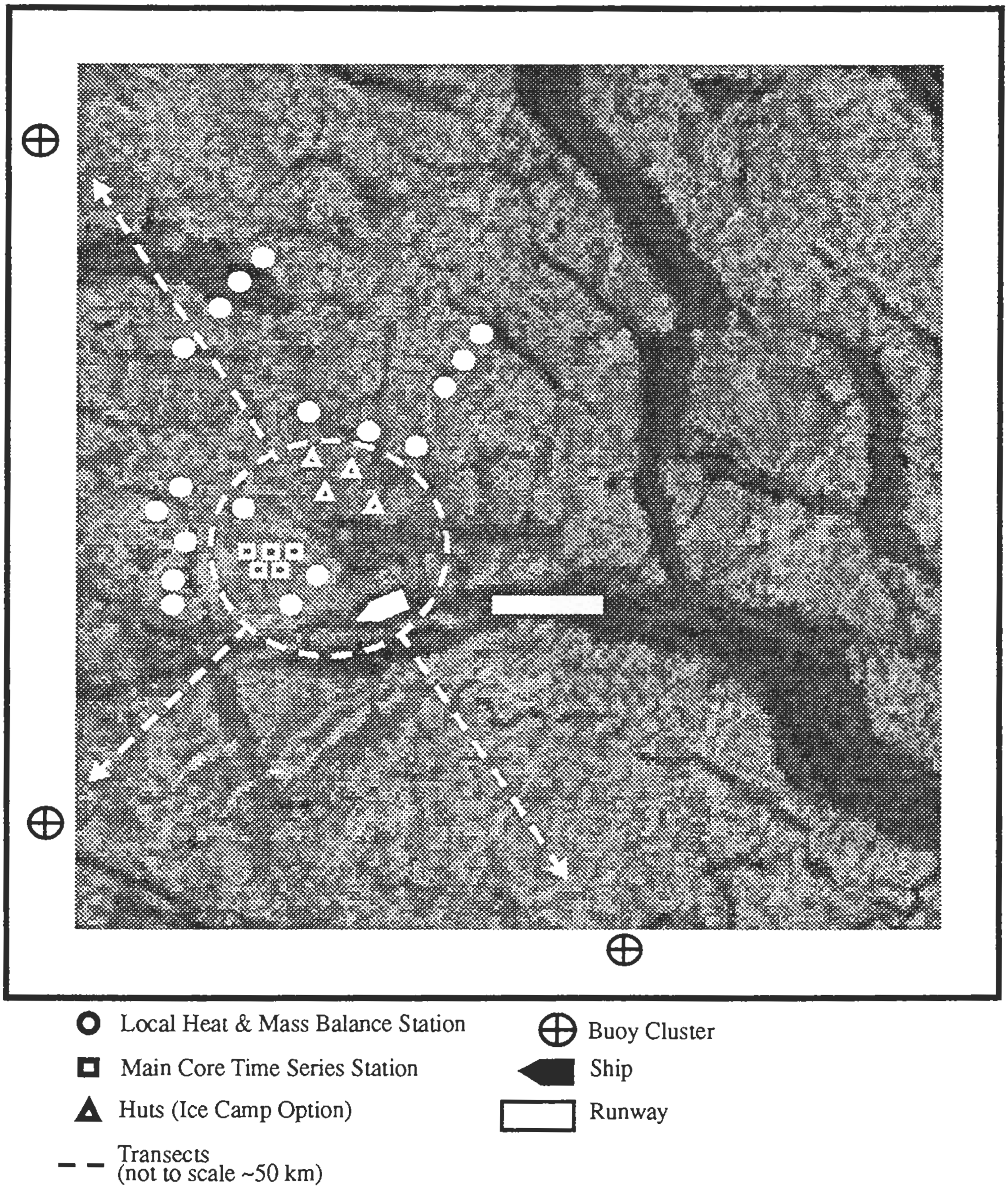

Figure 3. Schematic illustrating a possible arrangement of the SHEBA camp and elements of the measurement program. In the logistics option utilizing a ship frozen in the ice pack, the huts would be unnecessary. The background is a grey-scale image of pack ice in the Beaufort Sea, obtained by the ERS-1 SAR. The darkest, curvilinear features are leads covered with thinner, flatter ice than the floes. Intermediate grey tones are predominant over ice floes. The brighter tones within floes often indicate areas of deformed ice. The image shown is approximately 20x20 km. (Image courtesy of H. Stern.)

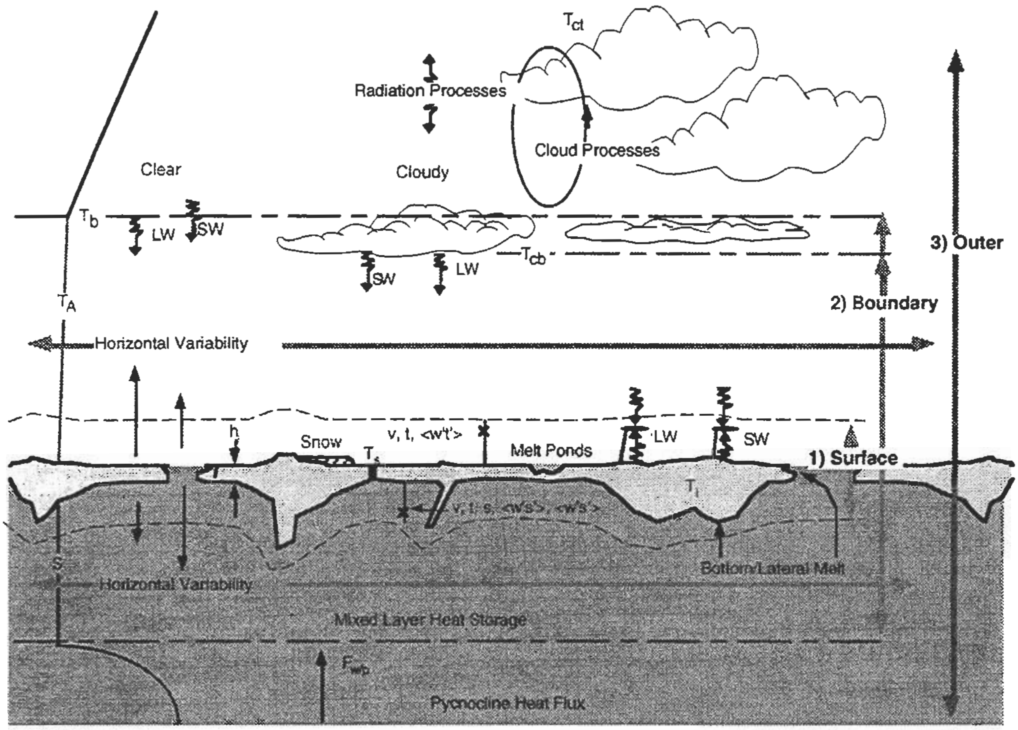

Figure 4. Schematic of the SHEBA measurement program. The Surface Zone is critical to the surface heat balance; most, but not all, priority 1 measurements are made there. It is important to understand processes in the Boundary Zone to extend the core measurements to larger, aggregate scales; many priority 2 measurements are in this zone. The Outer Zone includes measurements that address important questions beyond ice albedo feedback. The symbols are defined in Appendix B.

5.3 Local-Scale Measurements

The measurements at and near the ice camp are designed to answer specific scientific questions posed to guide the observational and modeling studies. The experiment is designed to allow investigators to test several hypotheses in the context of each scientific question. The questions and the strategies proposed to address them are based on a long series of past observational and modeling studies.

Individually, a number of the measurements have been made as part of other field programs. What is unique about SHEBA is the combined, comprehensive measurement effort designed to observe the various processes integral to the heat budget, the mass balance, and the radiative properties of the ice and the interactions between these processes. Because of these interactions, a deficiency in one measurement affects the application of related measurements. Similarly, to address an individual science question typically requires several different measurements. Therefore close cooperation and coordination in making these measurements is essential to the successful completion of the field program. This cooperation is needed not only within the disciplinary groups but also between the ice, ocean, and atmosphere measurement programs.

5.3.1 Heat budget, mass balance, and radiative properties of the ice cover

Areally integrated summer albedos for the Arctic ice pack are on the order of 0.45 (Lindsay and Rothrock, 1994). Early models (Maykut and Untersteiner, 1971) suggested that the absorption of such a large fraction of shortwave radiation would cause a horizontally uniform ice cover to melt completely during the summer. The fact that perennial ice covers much of the Arctic Basin indicates that nonuniformities associated with leads, melt ponds, ice thickness variations, and dynamic interactions alter the spatial and temporal utilization of this energy within the ice/ocean system. Quantitative details of how these factors affect the overall heat and mass balance of the ice pack are lacking. It is unlikely that climate models that neglect these factors can simulate ice albedo feedback accurately, even if the atmospheric structure and fluxes are known precisely. The representation and parameterization of these nonuniformities are crude in today's GCMs.

The greatest uncertainties in understanding and modeling ice physical processes lie in treating the effects of (1) melt ponds on the surface heat and mass balance, (2) solar heating of the mixed layer on the oceanic heat flux at the bottom of the ice and on lateral melting at floe edges, (3) thinner first-year ice on summer ice concentrations and shortwave energy transmission to the water, and (4) interactions between ice dynamics and thermodynamics. Ice modeling studies suggest that the inclusion of ice dynamics and variations in ice thickness tends to reduce the intensity of the ice albedo feedback, whereas the inclusion of differences in spatial albedo has the opposite effect. However, the processes that govern interactions between the various factors are not well understood, and systematic data are needed to evaluate the more sophisticated models.

Except for some winter lead observations (LEADEX Group, 1993), previous field measurements have focused on thick first-year and multiyear ice, ignoring the effects of thinner ice and leads on the regional heat and mass fluxes and on the overall evolution of the ice pack. The SHEBA ice-related measurements will determine the magnitude of these fluxes and will monitor how they change with time within an area of approximately 10 km^2. These changes will be related to concurrent thermal forcing and the physical properties of the ice pack. The basic approach will be to carry out complete heat, mass balance, and radiative measurements over each major type of ice within the region and then integrate these data, using information on the areal distribution of ice types, to obtain regional fluxes.

Of particular concern is the acquisition of a data set sufficient to describe from observations and reproduce from models the evolution of the ice thickness distribution and associated physical characteristics of the ice cover. Such a description will require data on the local-scale fluxes of heat, mass, and momentum at horizontal and vertical boundaries of floes within the experimental region, together with information needed to characterize the physical processes affecting these fluxes. Given the necessary forcing at the ice interfaces, an ice model that can reproduce the ice thickness distribution and associated physical characteristics of the ice would include the following processes: radiative transfer in the ice, evolution of melt ponds, water storage, evolution of snow characteristics, ice opening and closing, ridging processes, lead formation, new ice growth in leads, and accurate determination of interfacial turbulent fluxes for the aggregate of ice thicknesses and surface characteristics. Specific questions related to improved characterization of the snow and ice include the following:

(1) How is the annual cycle of ice growth and ablation affected by ice thickness, ice type, snow distribution, and surface melt water?

(2) How is shortwave radiation partitioned among reflection, surface melting, internal heat storage, and transmission to the ocean, and how is it affected by the physical properties of the ice, snow cover, melt ponds, particulates, and biological activity?

(3) What are the relationships between the optical properties and the physical properties of the ice and snow?

(4) How does pond volume and distribution depend on time and ice thickness? How do ponds affect the structural and optical properties of the underlying ice over a summer melt cycle? How is the surface melt water partitioned between runoff into leads and stored melt water that freezes in fall?

(5) How does surface topography affect wind redistribution of snow? What are the relationships between surface topography, snow depth, and melt pond distribution?

(6) How do mass changes in deformed ice differ from those in undeformed ice, and what is the long-term impact on the total ice mass at aggregate scales and larger?

The ice-related measurements will quantify critical processes that control the ice thickness distribution and associated physical characteristics of the ice and will determine the ice mass balance for the main floe. The ice-related measurements will be made in the vicinity of the main surface-flux measurement site. Many of the measurements, such as the ablation studies and the investigations of the partitioning of solar energy, must be obtained at more than one site to represent the local snow and ice conditions in the vicinity of the SHEBA ice camp. The following measurements will be made in the ice:

- time-series of ice thickness, internal temperature, and ablation/accumulation at the upper and lower surfaces
- lateral ablation/erosion rates around the perimeter of the main floe
- optical properties of the snow and major ice types, including irradiance at several levels inside the snow and ice
- time series of the reflection, absorption, and transmission of solar radiation
- vertical profiles of ice and snow properties
- snow depth, density, grain size, and salinity surveys
- surveys of melt pond areal extent, depth, volume, and runoff to the ocean
- pond evolution studies measuring changes in depth, area, volume, and temperature
- surface and under-ice topography at the primary floe.

Changes in the physical properties of the ice will be monitored at each of the heat and mass balance sites throughout the annual cycle. Intensive measurements will be required during the melt season because of the presence of melt ponds and highly variable optical properties. Detailed monitoring of ice morphology will be conducted on the local scale. Differences in ablation rate between ridge keels and undeformed ice are of special concern. Surface topography will be measured before, during, and after the melt season. In addition, a series of surveys will be made to measure ice thickness on the primary floe. Repeated aerial photographs of the primary floe and nearby areas will document the rapid morphological changes that occur during the summer.

5.3.2 Upper ocean properties and turbulent fluxes

To understand how the input of solar radiation affects the ice/ocean albedo feedback, the upper-ocean observational program is focused on the following questions:

(1) What are the sources and disposition of oceanic sensible heat and how do they affect the ice heat and mass balance?

(2) How do mean properties (velocity, temperature, salinity) of the mixed layer respond to surface momentum, heat, and salt fluxes? That is, what are the proper parameterizations relating mean properties to turbulent fluxes in the ice/ocean boundary layer?

(3) What controls the exchange of properties between the well-mixed layer and the underlying, stably stratified pycnocline?

Sampling the important temporal and spatial scales requires a variety of measurement techniques. In marked contrast to AIDJEX, technological developments make it feasible either to measure ocean fluxes directly by using covariance techniques or to estimate their values closely by measuring high-frequency (dissipation-scale) turbulent fluctuations. The capability to make accurate and continuous velocity, temperature, and salinity measurements has also increased dramatically. This offers a great advantage for closing the budgets of heat, salt, and momentum.

The observational strategy is to investigate questions 1–3 by combining a core time series (CTS) with shorter, intensive process studies. The CTS program will operate continuously for the duration of the drift station, providing most of the information required for a first-order characterization of how the ocean at one particular location affects the surface heat balance. Our minimum scenario for the CTS program consists of four types of measurements:

(1) three-dimensional velocity, temperature, and salinity in the upper ocean, with sufficient resolution to determine the Reynolds fluxes by direct covariance techniques

(2) profiles of temperature, salinity, and mean horizontal current velocity in the upper ocean

(3) horizontal variability of turbulent fluxes

(4) microstructure observations of boundary layer and pycnocline turbulent kinetic energy and thermal dissipation rates.

Techniques are well established for these four types of measurements, with a well-documented history of direct turbulent flux measurements in the boundary layer under drifting sea ice (e.g., McPhee, 1994; McPhee and Stanton, 1996).

Accurate conductivity-temperature-depth (CTD) instruments with automatically cycling, programmable winches can provide high quality temperature and salinity profiles (Morison et al., 1994). Acoustic Doppler current profilers (ADCPs) with various resolutions and ranges have been used repeatedly from drift stations (Pinkel et al., 1995; Muench et al., 1992). In the strongly stratified fluid below the mixed layer, where the small scales of turbulence often preclude direct measurement, microstructure profilers provide an alternative method for estimating turbulent fluxes by combining spectral energy levels in the high-wavenumber-dissipation range of the turbulence spectrum with mean gradients. Such profilers have been used extensively for measurements acquired at drifting stations (Padman and Dillon, 1987, 1991; Wijesekera et al., 1993; Robertson et al., 1995; McPhee and Stanton, 1996).

The aim of the horizontal variability study is to quantify statistically how representative the CTS measurements are of surrounding conditions. Possible approaches include (1) deploying portable versions of flux-measuring equipment under several ice types and during all seasons near the main station for comparison with simultaneous CTS measurements, and (2) using autonomous underwater vehicles (AUVs) to map variations in temperature, salinity, and vertical velocity at several levels in a 1–2 km square box (Morison, 1996). Close coordination with ice investigators, especially in identifying ice types and undersurface morphology, will be required. Similar techniques may be used for investigating special phenomena, like internal wave drag during strong summer stratification (Morison et al., 1987; McPhee and Kantha, 1989).

Two additional IOPs are important:

- a summer lead study
- a summer/fall mixed-layer study.

Combined with observations of the ice at the edge and undersurface near open leads in the summer, the summer lead study will constitute a major effort to understand the disposition of solar heating in the summer ice/upper ocean system. Possible elements of the lead IOP measurement program include direct fluxes near the edge of the lead, turbulent kinetic energy, and thermal variance dissipation through the mixed layer and in horizontal sections perpendicular to the lead, time series of radiation attenuation in the water column, and effects of melting (stabilizing buoyancy flux) on boundary layer turbulence and ice/ocean heat exchange near the lead.

The summer/fall mixed-layer study will encompass the peak radiation input into the upper ocean and also capture the beginning of the fall freeze-up. During the fall freeze-up period, mixed-layer changes are rapid and substantial. Salt injected by freezing at the surface erodes the pycnocline, both by nonpenetrative convection and by active enhancement of turbulence forced by the surface buoyancy flux. Both may release summer heat trapped by the seasonal pycnocline associated with melt water. Measurements will include frequent vertical profiles of temperature, salinity, and velocity.

5.3.3 Surface fluxes and atmospheric properties

Determination of surface fluxes and the physical properties of the cloudy atmospheric boundary layer will be conducted in collaboration with the ARM and FIRE programs. This collaboration is outlined in Section 7.

Each of the components of the surface energy balance will be measured: incident, absorbed, transmitted, and scattered (upward) shortwave radiation; incident and emitted longwave radiation; surface ablation; surface heat conduction through ice and snow; surface-layer sensible and latent heat fluxes. Many of the measurements must be made at a number of distinct sites, chosen to represent the variety of snow and ice-surface conditions in the vicinity of the SHEBA ice camp. The following CTS measurements are required to document the surface energy balance and will be obtained at the main CTS station:

- downward and upward spectral irradiances, shortwave and longwave (ARM)
- spectrally integrated downward longwave and shortwave fluxes (ARM)
- surface layer wind speed, air temperature, and water vapor mixing ratio and surface roughness length (bulk determination of turbulent fluxes)
- covariances of heat, moisture, and velocity components (direct determination of turbulent fluxes)
- radiometric surface temperature (surface emitted longwave radiation)
- internal ice temperature profile (conductive flux)
- rainfall and snowfall rates
- surface accumulation and ablation.

Note that the total turbulent heat flux in the atmospheric surface layer can be calculated as a residual if the net radiation, heat conduction, and ablation are known. This provides a check on both the bulk and the direct turbulence measurements and extends the coverage beyond the sites where the latter measurements are available.

The following measurements, relevant to surface layer fluxes, are essential at each local energy and mass balance site:

- radiometric surface temperature
- BRDF and albedo (repeated surveys)
- surface ablation
- bottom ablation and accretion
- internal ice temperature profile.

Together with the air temperature, wind speed, and humidity, the downward radiation measurements at the CTS site and other sites constitute a basis for estimating the daily surface energy balance at each local site. During IOPs it is desirable to sample these fluxes directly, on the aggregate scale, and at individual sites, as a further consistency check.

In addition to the CTS at the ice camp, IOPs are needed to estimate surface turbulent fluxes over the aggregate scale. Andreas (1989), for example, reports a scintillation technique that can be used for this purpose, and research aircraft to be used by FIRE can measure turbulent eddy correlations.

To understand how clouds influence the surface fluxes, studies are needed of processes that control the formation, maintenance, and dissipation of boundary layer clouds, cloud microphysical and optical properties, processes that control the evolution of the temperature and humidity inversions, and interactions between the atmospheric boundary layer and the surface. This understanding is an important part of the foundation for improved parameterizations of the surface energy balance in GCMs.

The mechanisms of cloud formation in the Arctic boundary layer have been examined by Herman and Goody (1976; summertime stratus), Curry (1983; wintertime "diamond dust"), and Pinto and Curry (1995; convective plumes from leads). These studies have shown that modeled cloud characteristics are sensitive to surface radiative characteristics, large-scale atmospheric dynamics, turbulence parameterizations, cloud microphysical parameterizations, and interactions among radiative transfer, cloud microphysics, and turbulence. Large uncertainties in these processes and their parameterizations preclude accurate simulation of Arctic clouds in climate models.

Our present understanding of the surface energy budget and the processes that determine the fluxes motivates the following science questions related to the cloudy atmospheric boundary layer over the Arctic Ocean:

(1) What are the impacts of clouds on surface temperature, albedo, and fluxes of radiation, sensible heat, and latent heat?

(2) What are the relationships of the bulk turbulent flux coefficients and the albedo to the ice physical characteristics?

(3) How are the surface turbulent fluxes influenced by cloud and planetary boundary layer processes?

(4) How does the cloud radiative forcing vary seasonally?

(5) How are surface radiative fluxes affected by ice and water cloud particles?

(6) How do the extreme static stability and low atmospheric water vapor content of the Arctic lower troposphere affect the flow of energy across the air/sea interface?

(7) How are the shortwave radiative fluxes influenced by horizontal inhomogeneities in clouds and the highly reflecting snow/ice surface?

(8) How do clouds and the boundary layer structure interact with changes in surface state and temperature?

(9) What are the climatological properties of multiple cloud layers and how do they affect the surface fluxes?

(10) How is diamond dust formed and what is its radiative significance?

To address the question of how clouds influence the surface fluxes, observations are needed of the vertical structure of the atmosphere, particularly of low-level clouds and the atmospheric boundary layer. CTS measurements of low-level clouds and the atmospheric boundary layer allow the measured surface flux components to be interpreted in the context of the cloud and atmospheric properties. While the measurements emphasize the atmospheric boundary layer, the following measurements are required throughout the troposphere to distinguish the radiative effects on the surface of upper level clouds from those at lower levels:

- vertical profiles of atmospheric temperature, humidity and winds
- vertical profiles of ice and liquid water content, particle size and shape
- horizontal variability of clouds over the ice camp area
- vertical profiles of radiative fluxes in the lower atmosphere.

Several measurement strategies and platforms can be used to obtain vertical profiles. Rawinsondes are the traditional instrument used internationally for weather analysis and forecasting. The advantage of using radiosondes at the SHEBA station is that they can be used in the numerical forecasts and analyses for the Arctic. Ground-based, profiling, remote-sensing systems, such as wind profiler/RASS and lidar, have the advantage of continuous, high-resolution coverage up to about 2 km (Wolfe et al., 1993). A small, lightweight, tethered balloon system has been used to provide detailed soundings of the lowest 1 km. Cloud microphysical properties have been studied during previous experiments using combinations of ground-based remote sensors, such as Doppler radars, microwave and infrared radiometers, and lidars.

5.4 Aggregate-Scale Measurements

The aggregate-scale measurements will sample the average properties and the variability of the atmosphere, ice, and upper ocean over the 10–100 km scale. Aggregate-scale measurements are critical for

- assessing the statistical representativeness of ice camp measurements
- providing statistical representations of the property distributions within a single GCM grid cell
- estimating the lateral processes required to close the system of physical equations within a single GCM grid cell
- distinguishing spatial and temporal variability.

5.4.1 Ice properties

Although the measurements proposed for the ice camp constitute a basis for improved models of the summer decay season and local radiative transfer in different ice types, additional information is needed to obtain a more complete picture of the behavior of the aggregate region. To make the link between the measurements at the SHEBA ice station and the representation of ocean/atmosphere/ice processes in climate models, it is important to recognize that the energy balance, ice mass balance, surface radiative properties, and upper ocean salt balance are strongly influenced by the fractional areal coverages of thick ice, thin ice, melt ponds, and open water. Estimates of the ice thickness distribution, pond coverage, snow distribution, surface albedo distribution, surface temperature distribution, and floe size are needed for a region of approximately 50-km radius surrounding the ice camp.

Helicopter and fixed-wing aircraft will be used to survey ice characteristics on the 10–100 km scale, concentrating on the spring-summer transition and summer melt seasons. In addition to the research aircraft campaign conducted by FIRE III and routine surveys conducted with the aircraft from the camp, the SHEBA project is pursuing cooperative aircraft measurements with the NASA Polar Research Program. The objective of this cooperation is to assure aggregate-scale coverage of surface temperature, albedo, radiation fluxes, ice concentration, melt pond fraction, and other variables at approximately 2-week intervals from May through September 1998. The NASA P3s with appropriate instrumentation, and possibly other NASA aircraft, are relevant platforms for this cooperative effort. Aerial photographs will be acquired and analyzed to determine ice concentration, pond fraction, floe size distribution, and melt pond characteristics. Additional instrumentation such as shortwave radiometers, infrared thermometers, laser profilometers, and multiband scanners can be employed to estimate albedo, surface temperature, ice concentration, and deformed ice fraction on the aggregate scale. To document the time evolution of the surface on aggregate scales, it is important to acquire these survey data at time intervals of approximately 2 weeks throughout the spring and summer.

To a useful approximation, the sea-ice thickness distribution can be estimated from upward-looking sonar (ULS) measurements. ULS data will be acquired from submarines cruising beneath the pack ice as part of SCICEX in the fall of 1997, the spring of 1998, and possibly the fall of 1998. Each cruise could provide two or more "snapshot" surveys of the sea-ice draft distribution in the SHEBA aggregate area. An array of moored ULS instruments may be appropriate to provide time-continuous estimates of $g(h)$ over the full annual cycle of the SHEBA field experiment. These thickness distribution data could also be supplemented by laser profilometer observations obtained as part of helicopter and aircraft flights (Comiso et al., 1991).

Time series of ice divergence in the vicinity of the ice camp are needed to monitor the dynamic component of changes in the lead fraction and the ice thickness distribution. Direct measurements of the relevant deformation variables can be obtained from satellite-borne active microwave sensors (e.g., Stern et al., 1995). These quantities can also be calculated indirectly from strain-rate estimates using a mesoscale buoy array (Hibler et al., 1974; Richter-Menge et al., 1995). The SHEBA Project Office has established liaison with relevant remote sensing groups, including the RADARSAT Geophysical Processor System (RGPS) group and NASA's POLES project, to assure coverage during the experiment.

The key questions for this element of the ice-measurement program are

(1) How do leads and thinner ice affect the regional heat and mass balance, and how is this related to dynamic activity?

(2) What is the relative importance of leads, melt ponds, and thin ice in controlling solar heat input to the upper ocean, and how is this heat apportioned between vertical heat flux at the underside of the ice, lateral melting on floe edges, losses to the atmosphere, and heat accumulation in the water?

(3) What is the role of melt ponds in the regional heat and mass balance?

(4) How do spatial variations in these quantities affect regional heat and mass fluxes?

5.4.2 Upper ocean properties

During wind storms, it is not uncommon for sea ice to drift 30 km in a day. This displacement coincides with about twice the internal deformation radius (Rossby, 1938) for typical upper ocean conditions in the Arctic. Hence an ice station may drift from one type of near-surface water mass to another in the span of 1 day. Such behavior is well documented not only for drift over subsurface eddies (e.g., D'Asaro, 1988) but also for front-like variation in mixed-layer properties north of Fram Strait (McPhee, 1986). During the AIDJEX summer melt season, all four stations drifted across a sharp front in upper pycnocline structure with a horizontal extent over 200 km (Maykut and McPhee, 1995).

One consequence of the advective change in upper ocean properties during the 1975 AIDJEX summer was that despite a large influx of freshened melt water at the surface, the average salinity in the upper 50 m increased at all stations (Maykut and McPhee, 1995). Thus during this period of AIDJEX, advective effects in the upper 50 m overrode a very significant surface salinity flux. While it may be impractical to obtain measurements of the horizontal gradients required for continuous estimates of advective fluxes of heat and salt at the central station, it is important to have data on the mesoscale variability of upper ocean temperature and salinity structure and surface fluxes, and at least occasional "snapshots" of the upper ocean mesoscale temperature and salinity fields. To this end, we recommend the following as a minimum aggregate-scale ocean measurement program:

- a triangular array of buoy clusters measuring upper ocean temperature, salinity, currents, and turbulent flux at a spacing of approximately 100 km

  Technology for such buoys is well established, and they have been used in numerous programs. They will provide, for example, time series of the mesoscale variability in ocean heat flux, at least crude estimates of mean temperature and salinity gradients at the CTS site, and important data on temporal variations at particular locations as other elements of the array drift near previously occupied sites. Resources permitting, the buoy arrays should be supplemented with a smaller-scale triangle, or perhaps the interior of the 100-km triangle should be "peppered" with simple mixed-layer temperature-salinity buoys. Ice and atmosphere measurements should be coordinated closely with the ocean requirements in designing the remote buoys. The buoys will also provide data for ice deformation estimates, which will augment the RADARSAT SAR estimates. These data are needed to assess the impact of opening and closing on local insolation and vertical velocity in the upper ocean due to surface stress curl (Ekman pumping).The buoy-motion field should be well integrated with remote sensing tools such as visual imagery and the SAR RGPS motion fields.

- helicopter-borne surveys of upper ocean properties

  Techniques and equipment for rapid helicopter sampling of temperature, salinity, velocity shear, and other properties have been developed and used in several polar experiments (e.g., D'Asaro, 1988; Muench et al., 1992). The mesoscale array can be spanned with closely spaced stations in a short time, providing a near-synoptic sample. The surveys could be timed to coincide with other IOPs as appropriate and combined with buoy maintenance periods. In addition, the program should be closely coordinated with the SCICEX surveys (e.g., "calibrating" submarine-launched expendable CTD probes).

5.4.3 Surface fluxes and atmospheric properties

To document the surface energy balance on the aggregate scale we must (1) measure the components at a variety of sites representative of the surface types present, (2) determine the fraction of area covered by each surface type, and (3) aggregate these fluxes as averages and distributions weighted by the area covered by each surface type. Detailed measurements made over ice with different characteristics must be translated into a physical understanding of the statistical aggregate of each heat flux component over the distribution of ice and surface characteristics. Given the distributions of surface properties and ice thickness over the aggregate region, ancillary atmospheric information (such as atmospheric temperature, humidity, wind, and cloud characteristics) can be used to determine the corresponding distribution of surface fluxes over the region. Because of the nonlinear dependence of the heat-flux components on surface variables, substantial errors are possible if areally averaged ice properties are used in the flux formulas.

Airborne observations are needed to determine the horizontal variability of surface radiation fluxes and clouds, to understand the physical processes that couple the atmospheric boundary layer, clouds, and surface, and to provide a complete data set against which to test parameterizations in single-column models. Aircraft can measure both horizontal and vertical variability of the atmosphere and clouds at scales larger than those resolved from the ice camp and smaller than those resolved by satellite remote-sensing instruments. Airborne measurements of cloud properties are also useful for validation of ground-based and satellite remote-sensing measurements.

Two periods during which there are important interactions between the surface and the clouds are (a) mid-April through mid-June, which is the seasonal transition between ice-crystal clouds and water-phase clouds, and (b) August, when the summertime stratus regime is fully developed and the boundary layer is relatively turbulent and complex. These periods are the focus of possible aircraft campaigns proposed as part of FIRE III. The horizontal variability of clouds and surface radiative fluxes and the physical processes that occur in the cloudy boundary layer will be addressed by the following measurements:

- cloud microphysical characteristics: liquid and ice water contents, discrimination of phase in mixed-phase clouds, particle size distributions
- radiation characteristics: broad-band fluxes, direct and diffuse radiation
- meteorological parameters: temperature, humidity, and vector winds
- turbulence quantities: variances and covariances of temperature, humidity and velocities
- cloud properties and ice-surface characteristics, to be assessed with fixed and scanning radiometers and cameras.

Details of the measurements and modeling activities to be conducted by FIRE III PIs are described in the FIRE III Implementation Plan (Randall et al., 1996). SHEBA and ARM are collaborating in this effort. The NASA P3 and other NASA platforms are also relevant to this effort.

On the aggregate scale, the parameterization of surface radiation fluxes is challenging. It is necessary to determine the area-aggregate surface temperature and albedo and the area-aggregate downwelling fluxes of solar and infrared radiation. The second task is complicated by the fact that the horizontal variations in both sea ice and clouds affect these fluxes locally. Significant horizontal variability is caused by multiple reflections between a horizontally inhomogenous surface and the cloud field.

Horizontal variability in cloud characteristics on a scale of 10 km can arise from the edges of a large-scale cloud deck running through the domain, small-scale variability associated with turbulent motions, and local effects of the surface on cloud characteristics that are associated primarily with leads (Curry et al., 1996b). This horizontal variability of clouds can result in very complex radiative interactions with a highly reflecting and inhomogeneous surface, resulting in extreme small-scale variability in the downwelling shortwave radiative flux.

Instantaneous, aggregate fluxes obviously cannot be estimated accurately from single point measurements. The aggregate-scale surface fluxes can be estimated from aircraft measurements. Another approach is to estimate the area-aggregate, time-averaged down–welling fluxes from single-point, time-averaged measurements. It remains to be seen how accurate such estimates are for a range of time-averaging intervals over melting pack ice. In a mid-latitude experiment, time averaging helped but was not a panacea (Rossow and Zhang, 1995). However, since research aircraft will be available only for part of the SHEBA experiment, alternative schemes must be employed that make use of some combination of surface observations, available helicopter and fixed wing aircraft, satellite observations, and models. To infer the aggregate surface radiation fluxes will require some determinations of the cloud field over the region in conjunction with radiative transfer calculations. The accuracy of these alternate schemes can be tested by comparison with the aircraft observations when available.

6. MODELING

6.1 Goals

The primary goals of the SHEBA modeling effort are as follows:

- to use field observations to develop detailed models of physical processes acting on the local and aggregate scale
- to construct improved parameterizations that can be incorporated in GCMs.

The scope of the SHEBA modeling effort, and the specific objectives through which its goals are to be realized, is related to the ocean/atmosphere/ice system to be modeled. This system is defined by three factors: (1) the spatial domain, (2) the physical quantities and processes that are relevant to the strategic objectives of SHEBA (Section 4), and (3) the spatial and temporal scales of variation of quantities over the domain. The system of interest for SHEBA modeling (Figure 5) is a vertical column encompassing the sea ice and extending from some depth in the Arctic Ocean and to some height in the atmosphere. The precise vertical limits of the column will vary, depending on the problem to be addressed, but in view of the strategic objectives, the ice/ocean, ice/atmosphere, and ocean/atmosphere interfaces are always included.

The physical processes of interest for SHEBA modeling are those related to the surface energy balance, the ice mass balance, the changing radiative properties of the ice/ocean surface, and the forcing functions in the oceanic and atmospheric boundary layers. These processes include radiative, advective, turbulent, and conductive heat transfer; melting, freezing, evaporation, and sublimation of water substance; and the evolution of variables that characterize the surface morphology.

The spatial and temporal scales are tied closely to the experiment's design. The SHEBA measurement program will follow the time evolution of a Lagrangian element of sea ice, representing the intersection of the column (Figure 5) with the surface (Figure 1).

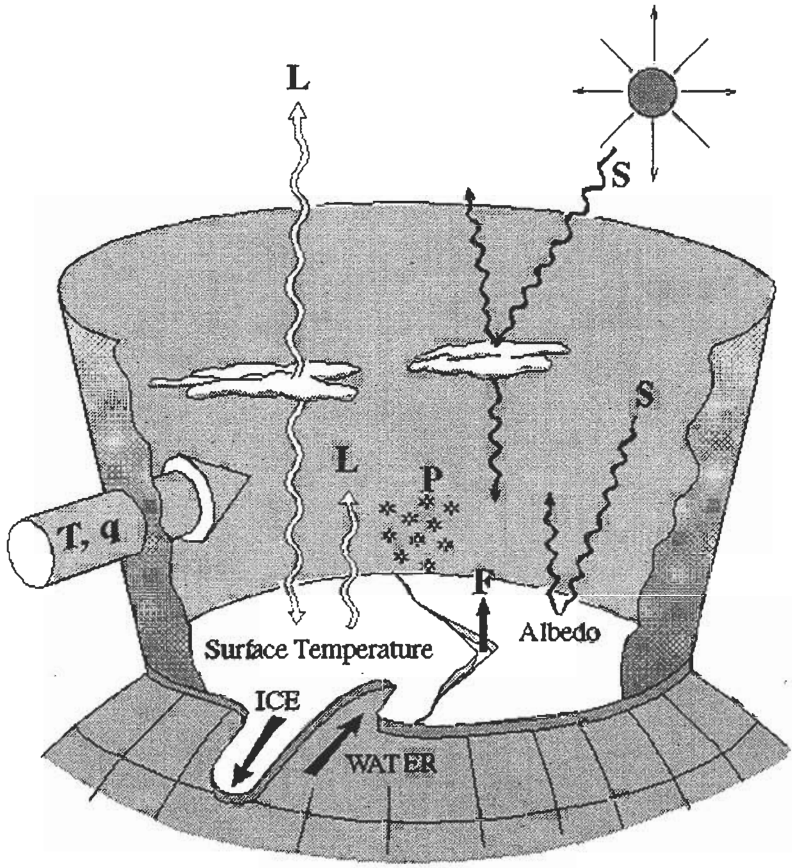

Figure 5. Schematic of the Arctic ocean/ice/atmosphere column relevant to the SHEBA modeling effort. The arrow labeled T,q represents the net advection of temperature (*T*) and humidity (*q*) into the column by eddy and mean motion. The solar and thermal infrared radiation fluxes are labeled S and L. The turbulent heat transfer through openings in the ice is labeled F. The stars labeled P represent precipitation. The tongues of ice and warm water symbolize net horizontal advection out of the column. In a single Arctic column of a global climate model, the horizontal advection of *T*, *q*, ice, and water would appear as flux divergence terms. (Figure provided by N. Untersteiner.)

The relevant spatial scales are the diameter of the base of the column and the horizontal scales that characterize variability *within* the column. An upper limit on the diameter of the column is set by the horizontal scale of a GCM grid cell, approximately 100–500 km. A lower limit on the within-column variability is set by the horizontal scale of local surface variables such as ice thickness, snow depth, melt pond depth, surface temperature, and surface spectral reflectance, approximately 1–1000 m. Matching the two scales requires that the within-column variability be integrated over the area in some manner. This requirement gives rise to the concept of an aggregate spatial scale—the minimum scale at which the integrated quantities converge closely to their full column values. Since the horizontal scale of a GCM grid cell is not determined by sea-ice properties, in principle the aggregate scale could be larger or smaller than the GCM grid cell. For at least some important variables, such as average ice thickness, the aggregate scale appears to be smaller than a GCM grid cell.

The temporal scales for the SHEBA measurement program range from approximately 1 hour to the annual cycle. The main temporal changes in the ice cover are expected to occur over time intervals of a few days to about 3 months (e.g., the melt season).

Within the context of the aggregate-scale (or GCM-scale) column, two sets of physical processes may be distinguished: vertical and horizontal. The vertical processes may involve both local and areally averaged behavior. The horizontal processes *within* the column represent subgrid-scale transfers of energy, mass, or momentum. For example, the differential absorption of shortwave radiation by high-albedo ice and low-albedo open water is, from the atmospheric point of view, a simple area aggregation vertical problem. However, from the ice mass balance point of view, it is important to know how the energy absorbed by leads is transported to the sides and bottoms of ice floes. This process is inherently a problem of lateral, subgrid-scale (or subaggregate-scale) transport, i.e., a horizontal problem.

Parameterizations of sea-ice processes, leads, ice/atmosphere coupling, and ice/ocean coupling are particular foci of the SHEBA modeling efforts. Candidate parameterizations are to be evaluated using measurements of both the forcing functions and the observed time evolution of the state of the ice, upper ocean, and atmospheric boundary layer. The models will be developed first for local processes and then be extended to simulate from first principles the evolving area-aggregate quantities.

Discrepancies between one model and another, and between model results and observations, depend on the physical formulations of the processes that determine ice albedo feedback in long-term integrations of GCMs. We adopt the approach that model parameterizations should be based on fundamental physical processes rather than on *ad hoc* empirical relationships. This is required to extend the utility of these parameterizations to other regions of the Arctic and for climate change scenarios.

The issue of documenting feedbacks in the Arctic climate system and incorporating the relevant processes into coupled models is addressed in the following way. The feedback processes described in Section 3 occur on a variety of time and space scales. The formation and evolution of a single melt pond, for example, is a small-scale, relatively high-frequency component of the ice albedo feedback mechanism. The action of an aggregate of processes related to surface albedo over a large region and long time periods produces the climatic-scale ice albedo feedback. While the annual cycle of surface albedo does not constitute a *climate change*, we can document the higher-frequency components of the ice albedo feedback and how these different components aggregate spatially and temporally. Similar examples can be given for the interaction between low-level Arctic clouds and the sea-ice surface. Therefore, although the seasonal change observed during SHEBA will not be a *climatic change* and will not constitute a direct observation of the climate scale feedbacks, it is nevertheless an aggregate of the essential physical processes that produces such feedback when acting over longer periods.

The approach of SHEBA is to develop models from first principles for the processes that affect ice albedo feedback, to distinguish different formulations of these processes, and to evaluate model improvements based on their performance in simulating fluxes and the time evolution of surface-state variables on time scales from 1 hour to 1 year. These parameterizations will be tested in partially coupled models against the time series of observations. Once these models are performing satisfactorily, climate feedback processes will be evaluated, and their magnitudes estimated through carefully designed fully coupled experiments.

The SHEBA measurement program is designed so that all of the forcing data and state variables will be monitored throughout the experiment (see Section 6.4).

6.2 Objectives by Scale

There are four broad objectives of the SHEBA modeling effort:

(1) Develop models of the fundamental physics of local processes

(2) Develop models of the aggregate quantities and properties

(3) Adapt the aggregate models as parameterizations for use in GCMs

(4) Assess the impact of parameterizations on the climate simulated by GCMs.

The SHEBA modeling program will address these objectives sequentially during Phase II and Phase III, with most of the modeling studies being conducted in Phase III. The impact on GCM simulations will be investigated by many modeling groups, partly supported by ARCSS (SIM), and will extend beyond the timeframe of SHEBA.

6.2.1 Fundamental physics models for local processes

Local processes can be measured by selecting sites that are typical of some general surface condition, for instance, relatively flat multiyear ice, relatively flat first-year ice, open water in a lead, a melt pond, etc. In many instances, these processes can be represented with one-dimensional, or horizontally uniform, models. All of the exchange and transport processes act in the vertical. Accurate models for local processes are an important step toward the more comprehensive models on the aggregate scale. It is most straightforward to link the observations to the modeling efforts at the local scale.

Models of the following local physical processes will be developed and evaluated using the following observations from the field program:

- radiative transfer in ice, leads, and the upper ocean
- evolution of surface albedo and physical properties of melt ponds
- local turbulent fluxes at the interfacial surfaces
- evolution of the mass and energy balance of the sea ice and snow cover
- bulk radiative transfer properties of the atmospheric boundary layer.

The relevant models include local-scale, single-medium models forced by observed boundary conditions. The local-scale, ice-related modeling effort aims to quantify critical processes that control the ice thickness and associated physical properties of the ice at local sites. The following questions will be addressed in this framework:

(1) How is the annual cycle of ice growth and ablation affected by ice thickness, ice type, snow distribution, surface melt water, and dynamic activity?

(2) How is shortwave radiation partitioned between reflection, surface melting, internal heat storage, and transmission to the ocean, and how is it affected by the physical properties of the ice, snow cover, melt ponds, particulates, and biological activity?

(3) What are the relationships between the optical properties and the physical properties of the ice and snow?

(4) What is the importance of surface topography in wind redistribution of snow? Are there relationships between surface topography, snow depth, and melt pond distribution?

(5) How do mass changes in deformed ice differ from those in undeformed ice, and what is the long-term impact on total ice mass within the Arctic Basin?

6.2.2 Modeling of the aggregate quantities and processes

The energy balance, ice mass balance, and upper ocean salt balance are influenced strongly by the distribution of surface characteristics and the fractional areal coverages of thick ice, thin ice, melt ponds, and open water.

Our models must reproduce the observed temporal variations in ice concentration, thin ice amounts, pond coverage, snow distribution, surface albedo, surface temperature, and floe size on the aggregate scale surrounding the ice camp. For many of the variables and processes associated with the sea ice and the oceanic mixed layer, a sound approach to bridging the gap between the local and aggregate scales is to define a region of the ocean surface whose size is commensurate with the aggregate scale and to specify the surface state as distribution functions. These functions represent the fraction of the total area covered by surfaces having a given range of temperature, albedo, or ice thickness. This approach was pioneered by Thorndike et al. (1975), who defined the ice thickness distribution $g(h)$ such that $g(h)dh$ is the fraction of the surface area covered by ice in the thickness range $(h, h+dh)$. Part of the ongoing Phase I research effort of SHEBA is to better define the aggregate scales for the physical quantities and fluxes that are central to the climate feedbacks that constitute the main focus of the SHEBA field experiment. A critical element of this effort is to develop and test models for the ice thickness distribution, emphasizing the thermodynamic terms. The following questions are central to this activity:

(1) How do leads and thinner ice affect the regional heat and mass balance, and how is this related to dynamic activity?

(2) What is the role of melt ponds in the regional heat and mass balance? How do pond volume and distribution depend on time and ice thickness? How do ponds affect the structural and optical properties of the underlying ice over the summer melt? What is the importance of surface water runoff into leads compared with stored melt water that freezes in the fall?

(3) How do leads, melt ponds, and thin ice control radiative heating of the upper ocean, and how is this energy apportioned between vertical heat flux at the underside of the ice, lateral melting on floe edges, loss to the atmosphere, and storage changes in the water?

The exchanges of energy and salt between the ice and ocean are important for the sea ice mass balance. This is a problem of coupling between local processes and lateral transports. Questions to be addressed here include:

(1) How is solar radiation stored in the upper ocean and returned to heat the ice from below?

(2) How does the fresh water associated with the summertime melting modulate the exchange of heat between the ocean and the ice?

(3) How does the ice thickness distribution influence the exchange of heat and salt between the ice and the ocean?

(4) How do nonlocal effects of pressure ridge keels modulate the exchange of heat and salt between the ice and the ocean?

The performance of the aggregate-scale models will be evaluated by prescribing the observed (measured) forcing on the models and comparing the statistical distribution (including areal average) of the local-scale variables that are predicted by the model with those that are measured during the field experiment. The results of these model studies will provide the foundation for the aggregate scale parameterizations that will be used in coupled models.

6.2.3 Development of parameterizations for aggregate- and GCM-scale quantities

The aggregate scales for many of the key climate variables in the Arctic are still smaller than the scale resolved in a full climate model. Hence an important part of the SHEBA modeling effort will be to build parameterizations that yield accurate large-scale averages for quantities that vary on smaller scales (e.g., albedo and surface energy fluxes). Such parameterizations give the state of the climate system on the temporal and spatial scales resolved by the climate model. These parameterizations will be developed by forcing the aggregate-scale models (which resolve the local-scale physics either explicitly or as area distributions) with the observed forcing and then determining the functional relationship between (1) the areal (aggregate) averaged quantities predicted by these models (also verified against the field data) and (2) the large-scale environmental state variables that are predicted explicitly by the climate models.

For practical reasons, each parameterization will be built and evaluated separately, requiring an aggregate model to be integrated for only one component of the system at a time (e.g., an atmospheric PBL model). The next step, and more stringent test of the parameterizations, is to employ them in a model that includes coupling between two or more media. The coupled model will be forced by the observed boundary conditions/fluxes, and the predicted variables compared with the observed variables (including comparing the observed areally averaged quantities with their simulated counterparts).

These modeling efforts are challenging because they depend on the successful aggregation of a number of parameterizations and on a complex observational strategy. The single-column model (SCM) serves as an analogue to a single column in a GCM. The SCM can be forced and evaluated using observations from the ice camp and spatial fields derived from measurements and analysis.

6.2.4 Impact of parameterizations on simulated climate and extension to larger scales

Once a model parameterization is judged to perform satisfactorily in the context of the single-domain hindcasts and SCM experiments for the SHEBA observation period, simulations will be performed using both regional Arctic atmosphere/sea-ice/upper ocean models (e.g., mesoscale models) and global models of the climate system. These studies will address feedbacks that occur within the Arctic climate system and feedbacks between the Arctic climate and the global climate.

Activities at the larger scales feed back into the smaller scales. A parameterization that provides acceptable results in an SCM may prove unsatisfactory in a 3-D model as interactions with large-scale dynamics come into play. In this case, it may be necessary to go back and re-evaluate the detailed process models. In addition, improvements in the 3-D models (regional and global) will result in improved 4-D data assimilation (FDDA) and thus in a more realistic data set with which to force and evaluate the SCM experiments.

6.3 Models and Model Strategy

Many of the specific modeling studies conducted in Phase II and Phase III of SHEBA/ ARCSS will emerge from individual PI proposals, evaluated in a competitive review process. Because of the innovative nature of such research, we cannot describe all of the details in this Science Plan. Here we provide *examples* of the type of modeling studies that will exploit the SHEBA data set and address the goal and objectives of SHEBA.

6.3.1 Local component models

The evolution of the thickness, internal temperature, and surface and internal radiative properties of a local snow/sea-ice column provides an example of the SHEBA hindcast problem. The initial conditions, and essentially local forcing functions, will be measured at specific sites. The local, vertical models will simulate heat conduction, heat absorption, heat scattering, transmission of radiation, melting, and internal changes of state in response to the forcing. Formulas for radiative properties, as a function of state, will produce time series of spectral reflectance, absorption, and so on. All of the hindcast time series will then be compared with the corresponding observed quantities. Such studies will serve to highlight and distinguish sources of discrepancies between the model and the data by isolating the vertical processes acting locally on various types of ice.

6.3.2 Aggregate-scale and single-column models

The variables and processes that must be determined on the aggregate scale are discussed in Section 6.2.2. The formulation of the aggregate-scale model will depend on the quantities to be simulated. However, it is likely that a product of the SHEBA modeling effort will be three models, one for each medium: "ice plus snow and melt ponds," "ocean," and "atmospheric boundary layer." Several submodels will contribute to the model of each medium. The ice model, for example, would incorporate models of ice thickness distribution, snow distribution, melt pond distribution, and radiative transfer in the ice. These media models can be evaluated by forcing with the boundary conditions observed during the SHEBA field program and comparing the (hindcast) evolution of the predicted state variables with the time series from the field experiment. These hindcasts of the media models are a prequisite to building parameterizations applicable to GCMs.

The SHEBA project will also need to develop a grand aggregate model in which the area fractions covered by open ocean and "ice plus snow and melt ponds" interact laterally.

It is worth noting that the design of the field experiment ensures that the aggregate scale of several key atmospheric processes will be resolved simply and over the entire duration of the experiment. This is because ice surface properties change slowly compared with atmospheric fluxes and properties. Hence most of the aggregate-scale atmospheric quantities that are crucial for the surface energy budget can be monitored throughout the field experiment by monitoring (on time scales of hours) the downward surface fluxes, cloud amount, total integrated liquid water, and (on the synoptic time scale) the tropospheric vertical temperature and humidity structure—all at the main CTS site.

These data provide the boundary conditions and state variables that are required to force and evaluate the cloud/boundary layer models. These models have been used successfully to ascertain the physics associated with the life cycle of subtropical stratus/strocumulus clouds. They are 2-D and 3-D LES models that include interactions between cloud microphysics and radiation (see, e.g., Wyant et al., 1996).

Because the data will be collected continuously during the field experiment, models can be employed in a hindcast mode to simulate cases of each regime that is observed over the duration of the field experiment. Hence the models will be powerful tools for evaluating the physical processes that act during the life cycle of Arctic clouds. In addition, it may be possible to estimate directly the effect of the surface on cloud evolution because there will be time series extending several weeks for each of several different states of the sea-ice surface (snow covered, bare ice, ice and melt pond).

Once the parameterizations are built, they must be tested. The SCM retains the physics of vertical interactions that must be represented in climate models and is a convenient testbed. The SHEBA observations will be used to specify what is going on in neighboring columns and may or may not also be used to specify tendencies associated with parameterized processes other than those being tested. An SCM can test a single parameterization or a suite of parameterizations without the added complications and computational expense of a global climate model. However, an SCM has very demanding data requirements. Problems with the parameterization that involve large-scale multicolumn feedbacks cannot be detected using an SCM; they are best studied with a full climate model. The prototype atmospheric SCM experiment has been described by Randall et al. (1996). Bitz et al. (1996) describe a set of coupled atmosphere/ice SCM experiments.

The SCM strategy has been used by ARM at a Southern Great Plains site in Oklahoma (Stokes and Schwartz, 1994) and during TOGA COARE (Webster and Lukas, 1992). For SHEBA purposes, the appropriate vertical boundaries for the most comprehensive SCM are the tropopause and the ocean pycnocline. Partially coupled, more limited SCMs can be used to test specific subsets of parameterizations. For example, the aggregate response of the surface energy balance, mass balance, and surface radiative properties could be simulated with a SCM whose vertical extent corresponds to Zone 1 on Figure 4.

6.3.3 Large-scale climate models

Coupled atmosphere/ocean GCMs will be the ultimate tool to evaluate and interpret the climate feedbacks occurring in the Arctic and the extension of the influence of Arctic physical processes to the global climate system. Based on our current understanding of the performance of GCMs of the Arctic, improved model parameterizations are needed for clouds, the atmospheric boundary layer, sea-ice processes, and the oceanic mixed layer. The SHEBA project will use both global-scale models and Arctic regional models to evaluate the impact of individual parameterizations on the simulated Arctic climate. A major product of the large-scale modeling effort will be an assessment of the net effect on the simulated Arctic climate of the complete set of parameterizations that will be developed in the SHEBA project.

To address deficiencies in Arctic climate simulations, the Arctic Climate System Model (ARCSyM) has been developed (Walsh et al., 1993; Lynch et al., 1995). The ARCSyM is based on the NCAR regional climate model, but special attention has been paid to the inclusion of the ice phase in the atmosphere, in the ocean, and on land. ARCSyM can be applied on a regional basis to simulate the annual cycle observed during the SHEBA field experiment.

Global climate modeling is required to understand and predict the interactions and mechanisms that extend the influence of Arctic physical processes to the global climate system. An understanding of the role of the Arctic Ocean as a global heat sink requires accurate prediction of the heat content of the Arctic atmosphere and ocean. Accurate simulation of the Arctic heat sink requires accurate determination of the Arctic temperatures, which depend on sea ice and cloud characteristics, and their interactions with atmospheric and ocean dynamics. Another key feature that can be examined only in the context of a coupled global climate model is the export of relatively fresh water from the Arctic Ocean into the North Atlantic, the role that this export plays in modulating the North Atlantic Ocean thermohaline circulation, and the subsequent feedback onto the Arctic climate system. Accurate simulation of the fresh water export into the North Atlantic Ocean requires accurate simulation of ice thermodynamics and dynamics and the atmospheric and oceanic forcing of the sea ice.

Intercomparison of the Arctic climate simulated by existing and improved GCMs will be encouraged by preparation from the SHEBA observations of comprehensive summary data sets tailored to serve in the evaluation of model performance.

6.4 Data Requirements for Models and Model Evaluation

The SHEBA field experiment must produce an integrated data set that

(1) supports the analysis and interpretation of physical processes that determine the surface energy budget, the ice mass balance, and the surface radiative properties

(2) provides initial data, boundary conditions, forcing functions, and test data to support SHEBA modeling efforts.

The essential observations are noted below. Because of time lags in the coupled atmosphere/ice/ocean system, continuous time-series measurements are needed throughout the SHEBA field experiment. The following parameters are required for model initialization, testing, or forcing at the boundaries:

- vertical profiles of tropospheric temperature, humidity, wind velocity, and cloudiness
- bulk physical and radiative-transfer properties of clouds (including cloud base height and total liquid water content)
- vertical profiles of temperature, salinity, and currents in the upper ocean
- vertical profiles of horizontal advection of atmospheric temperature and humidity and large-scale atmospheric divergence
- horizontal distribution of heat and salt in the upper ocean

- areal statistics of the ice thickness distribution, lead fraction, snow cover, and melt pond properties
- local- and aggregate-scale albedo
- local and aggregate fluxes at the interface between the atmosphere and the ocean, the ice and the ocean, and the ice and the atmosphere. These fluxes include the sensible heat flux at the bottom of the ice floe, conduction in the ice, the latent heat flux due to ablation, and the surface radiative fluxes.

The most difficult aspect of conducting the atmospheric component of the SCM experiment is to determine the atmospheric advection into the cell and the large-scale divergence. To mitigate the problems associated with missing data, instrument errors, and incomplete spatial and temporal coverage, the SHEBA project will make use of the analysis products produced by data assimilation at the operational numerical weather prediction centers (NCEP and ECMWF). To receive the highest quality product during the experiment, the SHEBA Project Office is working with the weather centers to ensure that, whenever possible, the data that are collected in and around the Arctic Basin are included in producing the analysis product. These data include surface air temperature (from drifting buoys), air temperature (from satellite information and the SHEBA ice-camp rawindsondes), and humidity (from the ice-camp rawindsondes). In addition, data assimilation and interpolation procedures will be used to combine measurements from various sources (e.g., surface-based rawinsondes, wind profilers, aircraft dropsondes) to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields (see, e.g., Ooyama, 1987). Analysis products offer good spatial coverage and comprehensive information about the dynamical fields; they will play a very important role in driving SCMs.

While attempts will be made to minimize the effects of ocean advection when selecting the ice camp's location, advection of heat and salt into the column must be accounted for. It is important to have data on the mesoscale variability of the upper-ocean temperature and salinity structure and surface fluxes and to have at least occasional "snapshots" of the upper-ocean mesoscale temperature and salinity fields.

In conjunction with CAGES, the SHEBA project is working with NCEP and ECMWF to obtain a high-resolution research-quality analysis of the Arctic Ocean for the SHEBA year. It is a goal of ACSYS, stated in the ACSYS Implementation Plan, to provide improved analysis of the Arctic atmosphere, surface fluxes, and sea-ice characteristics. The intensive effort made for the SHEBA field experiment will provide the foundation for routinely producing improved analyses of the Arctic atmosphere and surface fluxes.

6.5 Sequence of Modeling Studies

The modeling studies are divided into the following four phases:

Phase I -	Preliminary modeling studies (1995–1997)
Phase II -	Use of detailed models of local processes and subgrid-scale lateral transports in conjunction with the field measurements (1997–1999)
Phase III -	Further process modeling, modeling of aggregate behavior and GCM parameterizations (2000–2003)

ARCSS-SIM - Further development of GCM parameterizations, implementation of SHEBA results in regional and global models, assessment of impacts on simulated climate (2001–2005).

7. MUTUAL COMMITMENTS: THE SHEBA, ARM, AND FIRE PROGRAMS

Complementary research initiatives are being developed between the SHEBA, ARM, and FIRE programs that address radiative transfer, the atmospheric boundary layer, and clouds over the Arctic Ocean ice pack in addition to the ice albedo feedback problem. While each program has distinct research objectives and measurement needs, they are united by at least the following items:

- All three programs share the goal of improving GCM performance at high latitudes with regard to radiative transfer and cloud behavior.
- All three programs require measurements of downwelling and upwelling radiation at the surface, boundary-layer structure (including clouds), and surface characteristics.
- All three programs are unable to afford the entire suite of measurements they need unless they collaborate with the others.

In the present context, the goals of these programs can be paraphrased as follows.

SHEBA: On scales ranging from local to GCM, document, understand and improve the capability to predict the surface energy balance, the resulting ice mass balance, and the associated changes in surface radiative properties in the high-latitude oceanic environment. Specifically within this context, the SHEBA project requires an understanding of radiative as well as sensible and latent heat fluxes at the top and bottom of the ice and of how clouds and other atmospheric and oceanic phenomena influence them.

ARM: Develop improved GCM algorithms for describing atmospheric radiative transport in the presence of liquid, mixed-phase, and ice clouds (including diamond dust) in the high-latitude oceanic environment. ARM's overall goals also embrace cloud formation and the evolution of surface optical properties at high latitudes, but its collaboration with SHEBA is focused on the more limited goal cited here.

FIRE: For the Arctic oceanic environment, improve our understanding of physical processes that couple clouds, radiation, chemistry, and the atmospheric boundary layer; improve our ability to sense clouds remotely from the surface and from satellites; and improve the treatment of cloud processes in cloud-scale models and GCMs.

The SHEBA field experiment involves measurements made during approximately one annual cycle at, above, and below the ocean surface from a manned station within the Arctic ice pack. In concept, the data set resulting from the combined effforts of SHEBA, ARM, and FIRE should be sufficiently comprehensive and detailed to achieve the goals of each of the participating programs. Close cooperation among the programs is required to assure that all necessary measurements are made and that the manner in which they are made will meet all requirements. Bringing about that level of cooperation is itself a challenging and elusive task. These programs have been working together for about 3 years to achieve this goal. They are now in the process of refining and documenting their agreements. These agreements will be documented by "Memoranda of Participation" (MOP) that are signed by the SHEBA Project Office and the appropriate representatives of the cooperating projects and organizations.

Other programs and organizations that have not been involved intimately in SHEBA planning also produce or can produce data or other products important to the success of the SHEBA project (POLES, RADARSAT, NASA-EOS, ECMWF, etc.). These programs and organizations are now also being consulted to negotiate the necessary additional agreements.

In particular, studies conducted by the NASA-EOS/POLES investigators and the RADARSAT investigators will provide aggregate-scale and regional-scale analyses of ice deformation, surface albedo, surface temperature, and surface fluxes for the region of the SHEBA ice camp. These investigators will also have access to the SHEBA data set for ground truth, verification, and assimilation studies.

8. PROJECT MANAGEMENT

The SHEBA Science Working Group (SWG) was established in April 1993 under the auspices of the NSF ARCSS OAII Science Steering Committee. The members of the SWG were chosen for their representation of relevant disciplines, major institutions expected to participate in SHEBA, and collaborating programs. The SWG is charged with developing plans for the SHEBA project based on input from the scientific community.

The SHEBA Interagency Group (IAG) is an *ad hoc* association of program managers from the member agencies of the Interagency Arctic Research Program Coordination (IARPC). The IAG coordinates SHEBA funding and interagency activities among NSF, DOE, ONR, and NASA. In particular, close coordination has developed among the SHEBA, DOE ARM, NASA FIRE III, ONR SCICEX, and EOS POLES programs.

The SHEBA Project Office (R. Moritz, Director) has been funded by the NSF ARCSS Program. The Project Office assists the SWG and SHEBA PI's by organizing meetings and workshops, printing and distributing SHEBA documents and information, coordinating data transfer and archival, and coordinating and disseminating logistics information. The SHEBA Project Office will develop MOPs with cooperating programs as appropriate and has overall responsibility to see that individual projects are integrated into the coordinated field experiment. The SHEBA Project Office will assure that PIs from SHEBA and collaborating programs have ready access to the extensive, quality-controlled data sets resulting from the SHEBA field experiment. The SHEBA Project Office interacts closely with the SHEBA Logistics Office (A. Heiberg, PI).

Selection of the PI's and science projects to participate in SHEBA will occur through a competitive process involving the review and evaluation of research proposals submitted in response to a sequence of Program Announcements published by the U.S. National Science Foundation, the U.S. Office of Naval Research, and other federal agencies. The funding for SHEBA from NSF-ARCSS and ONR is proceeding in three phases:

I. Technology development, analysis of existing data sets, preliminary modeling, satellite studies, and experiment planning (1995–1997).

II. Preparation for the field experiment, conduct of the field experiment, initial analysis and interpretation of field data, and initial development of process models (1997–2000).

III. Further data analysis and process modeling, development of aggregate-scale models, development and implementation of improved GCM parameterizations (2001–2003).

Evaluation of the Phase II proposals will be based partly on relevance of individual proposals to the SHEBA goals, objectives, and priorities. Coordination is required among the program managers, SWG, the Project Office, and the Logistics Office in selection of the Phase II projects to ensure that all essential measurements are made and that the proposed measurements are feasible and within budget. After selection of the Phase II projects by NSF-ARCSS and ONR, a SHEBA Science Team will be designated by the program managers together with lead PIs in the various disciplines. The coordination of the SHEBA field experiment will be organized by the lead PIs together with the Project Office. The ARCSS OAII Science Steering Committee will continue to be responsible for oversight and advisory functions for SHEBA as a project.

A SHEBA Operations Plan will be developed by logistics and operations personnel in consultation with the PI's and the SHEBA Project Office and will be printed and distributed by the Project Office in 1997.

9. DATA MANAGEMENT AND DISTRIBUTION

Development and maintenance of a comprehensive and accurate data archive is essential to the SHEBA project. Because SHEBA is designed as a multidisciplinary project with many investigators, varied instrumentation, and cooperating agencies, an integrated data-management activity is central to providing a useful data base that is easily accessible. The overall SHEBA data-management philosophy is to make the completed data set available to the world research community as soon as possible to improve understanding of the Arctic climate and its treatment in global models.

The SHEBA SWG has formulated the following data protocols:

- Open access to all SHEBA data sets will be ensured. This requires a data-management strategy that facilitates data exchange and investigators taking responsibility for making data available.
- The SHEBA project will take advantage of several existing data processing and archive centers to house the variety of data sets to be collected. These include NSIDC, NCAR, NASA/LaRC/DAAC, and ARM/ORNL. The MOPs will include cooperative agreements that establish unrestricted exchange and access of SHEBA data from all these locations.
- All investigators participating in the SHEBA project must agree to submit data promptly (within 1 year of the end of the field experiment) to the appropriate data center to facilitate the data processing, archival, and distribution. Data sets must be submitted to the archive in a usable format and with sufficient documentation to allow easy access and understanding by others. Appropriate statements of PI responsibility will be incorporated into the awards of SHEBA funding.
- The SHEBA Project Office has overall responsibility for developing and implementing an integrated data-management strategy and for coordination with the data and modeling centers.

- To ensure that the SHEBA data set is comprehensive, appropriate data will be acquired from NOAA, NASA, DOE ARM, and other organizations that are conducting relevant programs in conjunction with or of interest to SHEBA investigators.

The processing, quality control, validation, archival, and dissemination of SHEBA data will be distributed among many sites and several investigators, depending on the types and sources of data. The overall coordination of data-management issues will be the responsibility of the SHEBA Project Office.

During the field experiment and the period shortly after its completion, the following data-management needs are foreseen:

- an on-line SHEBA catalog during the field program that provides updates on project and equipment status and selected data of interest
- near real-time, on-line access to limited data sets for monitoring instrument performance and intercomparisons and evaluating the completeness of data sets
- access to operational and research data sets for preliminary analysis and for evaluating diagnostic analyses by SHEBA PIs during the field experiment
- special processing and quality control of specific data sets (field research and operational) to enhance data integration and analysis.

The SHEBA Project Office will gather a list of needs and requirements for special integrated or composite data sets to address different important facets of the SHEBA project.

The SHEBA project will take advantage of existing data archives for both project-related and important ancillary data sets. These ancillary data sets include satellite observations and products, analyses from the numerical weather-prediction centers, rawinsonde data from the surrounding region, and data from the surface-pressure buoy network. These archives and their relationship to SHEBA are described below.

(1) The National Snow and Ice Data Center (NSIDC) is the archive for all ARCSS data sets. NSIDC will be the final archive for the SHEBA data or have links to the other archives.

(2) The National Center for Atmospheric Research (NCAR) will archive a variety of global model output important to SHEBA goals and any relevant data from the NCAR aircraft.

(3) The Oak Ridge National Laboratory (ORNL) houses the long-term ARM data archive. A cooperative agreement is being developed between SHEBA and ARM to assure easy access to both ARM and SHEBA data sets by all SHEBA participants.

(4) The NASA Langley Research Center (LaRC) Data Analysis and Archive Center (DAAC) archives all FIRE data. SHEBA PIs will have access to all FIRE data obtained during the SHEBA experiment.

Details of SHEBA data-management tasks will be contained in a SHEBA Data Management Plan to be completed by July 1997. The timeline for the SHEBA project is shown in Figure 6.

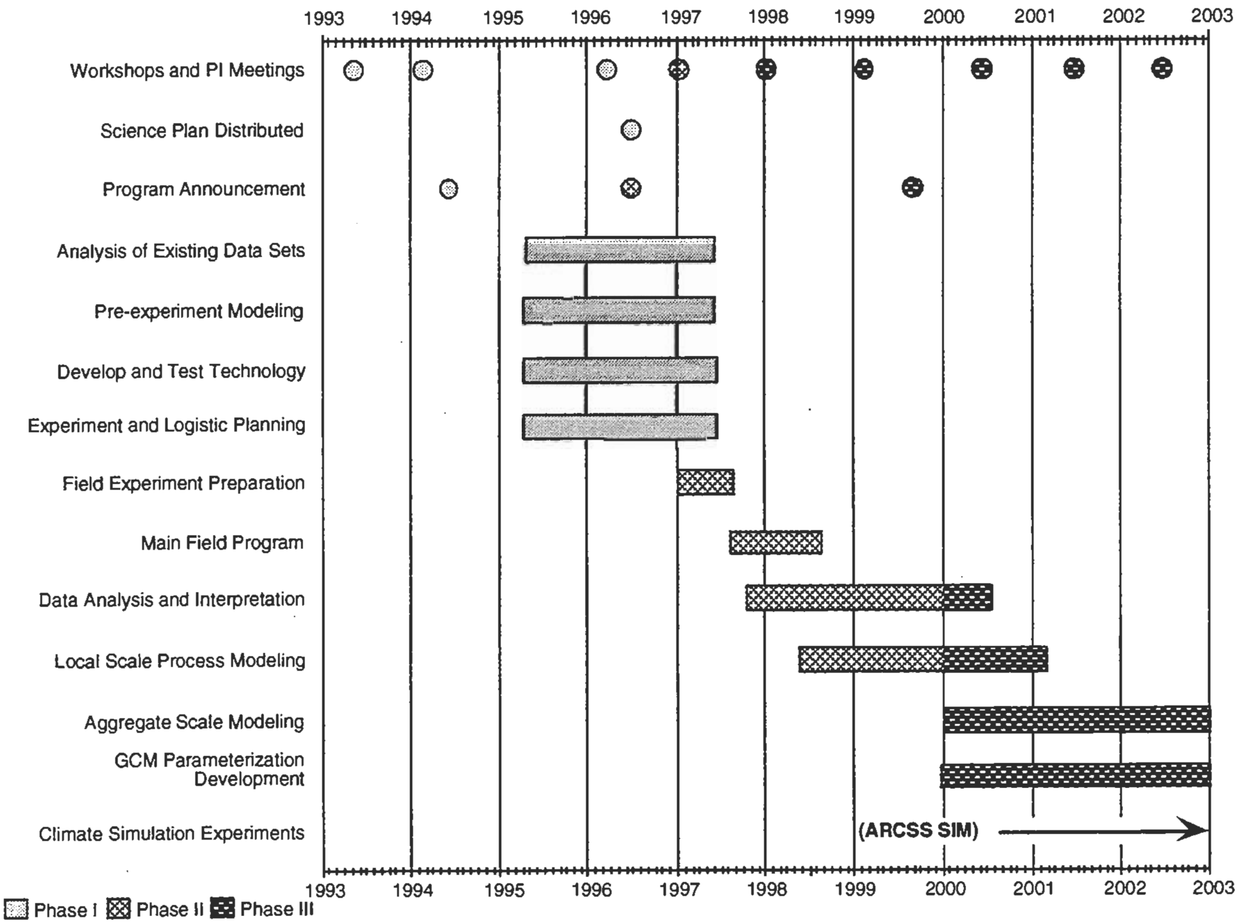

Figure 6. Timeline for the SHEBA project.

10. ICE STATION LOGISTICS

The SHEBA field experiment is scheduled to begin either in the fall of 1997 or the spring of 1998 and to continue through freeze-up in 1998. The measurement program is to be carried out at a temporary research station to be established on a multiyear floe in the Arctic ice pack.

Two logistics options have been considered. The fall 1997 deployment would involve a ship frozen into the ice pack for a 13-month drift. The spring 1998 deployment would involve aircraft landings on natural ice runways. In both options, most of the measurement program would be conducted from the ice floe surface (Figures 2 and 3).

The location of the camp will be determined by the following constraints:

- The ice floe and vicinity must be of sufficient size and variability to contain numerous surface features that vary in horizontal area and physical properties over the course of the experiment (such as bare ice, snow cover, melt ponds, leads, hummocks, ridges and ice of different thickness).
- The camp must be far enough from the continental shelf and from the ice margin to provide a stable ice platform over several seasons.
- The camp must be accessible by aircraft operating from North American coastal airports.

The scientific and operational considerations suggest that the optimal site for deploying the SHEBA camp is the eastern Beaufort Sea, perhaps in the vicinity of 77°N,135°W. Figure 7 illustrates the probable trajectory of a camp deployed at that location, taking into account the mean and variability of the sea-ice velocity documented by the Arctic Buoy Program during 1979–1993.

There is a considerable body of U.S.-based experience in deploying, maintaining and evacuating scientific ice camps of both short and long duration in this part of the Arctic Ocean, e.g., AIDJEX, AIWEX, LEADEX, and SIMI. This experience provides a solid basis for anticipating the operating conditions likely to be encountered during SHEBA and the techniques and resources needed to successfully conduct the measurement program.

The logistical constraints in combination with scientific objectives and budgetary constraints indicate an ice camp designed to support approximately 25 persons (of which approximately 17 would be scientists/technicians). At the SHEBA ice camp, there will be a continuing need for personnel to travel to specific sites chosen to represent typical ice and snow conditions. Some instrumentation can be installed and left at such sites (e.g., thermistor arrays, ablation stakes), and some instrumentation will need to be moved to the site for each period (e.g., spectral radiometers). Therefore the camp must be supplied with surface transport such as snow machines, rafts, and boats. To survey the area fraction covered by distinct surface types and to assist with deployment of ice and ocean instrumentation, a helicopter is required for a significant portion of the experiment. An autumn deployment will necessarily involve the use of a ship.

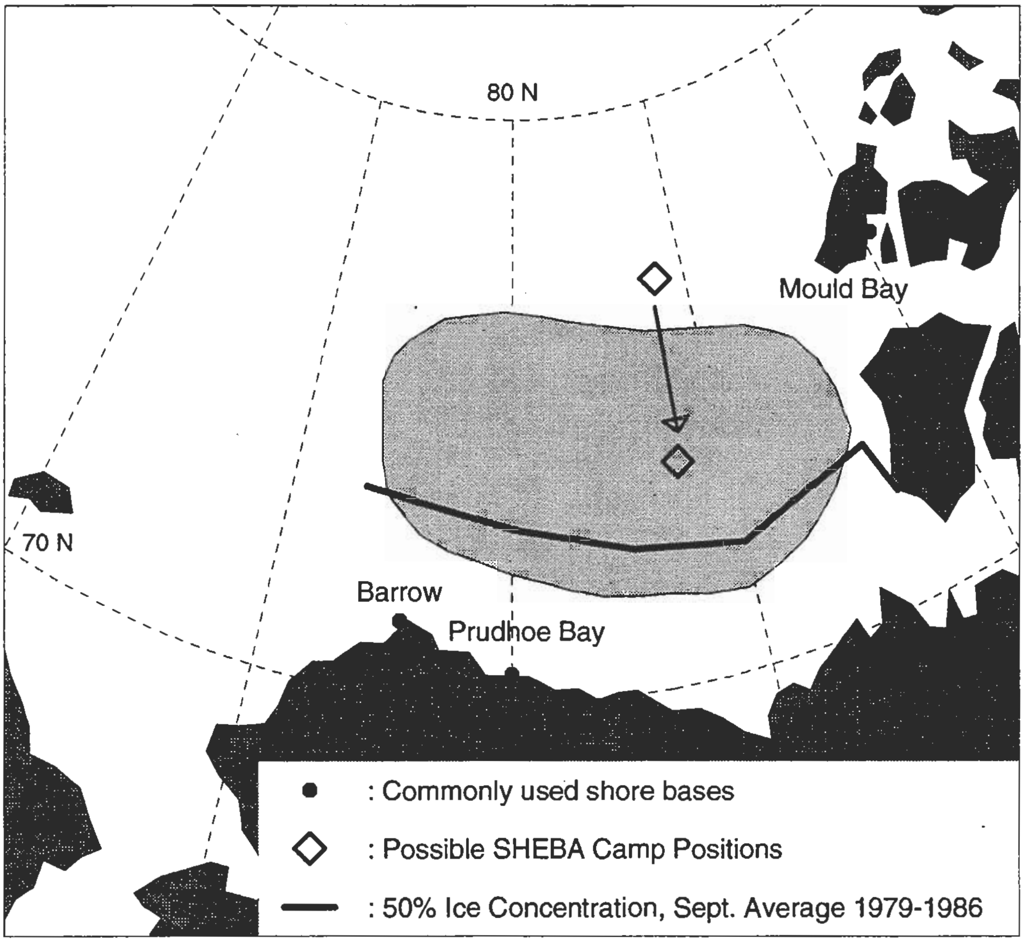

Figure 7. Sketch of possible deployment location (upper diamond) and 15-month drift (lower diamond and shaded region) of the SHEBA research camp. The lower diamond is the expected position of an ice floe located initially at the upper diamond after moving for 15 months in a randomly varying field of ice motion with realistic statistical mean and variance, based on the 15-year data set of the Arctic Data Buoy Program used to estimate the mean and variance of the ice velocity field. The average (1979–1986) location of the 50% ice concentration contour in September is indicated by the heavy curve, based on SMMR data.

In the ship option, a helicopter would be available to support research throughout the duration of the experiment. In the ice camp option, the helicopter would be present for approximately June–October. In both options, fixed-wing aircraft (Twin Otter type) will conduct routine flights to support crew rotations and supply needs during the seasons of sunlight, except during June–August. These routine flights would occur at 6–8 week intervals and involve approximately 5 days of flying. Science projects needing repeated sampling by fixed-wing aircraft will be coordinated with the routine flights to take advantage of this platform.

There are advantages and disadvantages to both the ship option and the ice camp option, including cost, probability of obtaining a full year's data set, staging of large/complex instrumentation, pollution of the measurement site by the platform, etc. These are still under discussion by the SHEBA SWG, the funding agencies, the logistics coordinator, and the Project Office. It is expected that a final decision will be made during 1996.

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APPENDIX A: Acronyms

ABL	Atmospheric Boundary Layer
ACSYS	Arctic Climate System Study (WCRP)
ADCP	Acoustic Doppler Current Profiler
AIDJEX	Arctic Ice Dynamics Joint Experiment
AIWEX	Arctic Internal Wave Experiment
ALEX	Arctic Lead Experiment
AMIP	Atmospheric Model Intercomparison Project (WCRP)
ANZFLUX	Antarctic Zone Flux
AOS	Arctic Ocean Section
ARCSS	Arctic System Science (NSF)
ARCSyM	Arctic Climate System Model
ARM	Atmospheric Radiation Measurement Program (DOE)
AUV	Autonomous Underwater Vehicle
BRDF	Bidirectional Reflectance Distribution Function
CAGES	Canadian GEWEX Enhanced Study
CCM	Community Climate Model
CTS	Core Time Series
CEAREX	Coordinated Eastern Arctic Experiment
CTD	Conductivity-Temperature-Depth
DAAC	Distributed Active Archive Center (NASA)
DOE	Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasting
EOS	Earth Observing System
ERS-1	European Remote Sensing, satellite 1
FDDA	Four-Dimensional Data Assimilation
FIRE III	First ISCCP Regional Experiment III (NASA)
GCM	General Circulation Model
IAG	Interagency Group
IARPC	Interagency Arctic Research Policy Committee
IOP	Intensive Observing Period
IPPC	International Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project (WCRP)
ISWR	Incident Shortwave Radiation
LaRC	Langley Research Center (NASA)
LEADEX	Lead Experiment
LES	Large Eddy Simulation
MIZEX	Marginal Ice Zone Experiment
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction (formerly NMC)
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
OAII	Ocean/Atmosphere/Ice Interaction (NSF-ARCSS)

OBL	Oceanic Boundary Layer
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
PI	Principal Investigator
POLES	Polar Exchange at the Sea Surface
RADARSAT	Radar Satellite
RASS	Radio-Acoustic Sounder System
RGPS	RADARSAT Geophysical Processing System Working Group (NASA)
SAR	Synthetic Aperture Radar
SCM	Single-Column Model
SHEBA	Surface Heat Budget of the Arctic Ocean
SIM	Synthesis Integration and Modeling (ARCSS)
SIMI	Sea Ice Mechanics Initiative
SIMMS	Seasonal Sea Ice Monitoring and Modeling Site (Canada)
SMMR	Scanning Multichannel Microwave Radiometer
SWG	Science Working Group
SCICEX	Submarine Science Experiment
TOA	Top-Of-Atmosphere
TOGA COARE	Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment
ULS	Upward-Looking Sonar

APPENDIX B: List of Symbols

F_w	Total heat flux into the ocean mixed layer
$F_{w/c}$	Contribution to F_w from radiation transmitted through the ice
$F_{w/ow}$	Contribution to F_w at open water surfaces
$F_{w/p}$	Contribution to F_w from below the mixed layer
$g(h)$	Sea ice thickness distribution function
h	Sea ice thickness
LW	Longwave irradiance
SW	Shortwave irradiance
s	Boundary layer salinity (ocean only)
T_A	Air temperature
$\mathrm{T_b}$	Temperature at the base of the inversion
T_{cb}	Temperature of the cloud base
$\mathrm{T_{ct}}$	Temperature of the cloud top
T_i	Ice internal temperature
T_s	Surface temperature
t	Boundary layer temperature
v	Horizontal velocity
w	Vertical component of velocity
$\langle w't' \rangle$	Turbulent sensible heat flux
$\langle w's' \rangle$	Turbulent salinity flux (ocean only)

APPENDIX C: Measurement Priorities

The SHEBA Science Plan describes a complete project to address the SHEBA goals and objectives. To make all of the measurements suggested in this Plan and to do all of the ancillary modeling and remote sensing may require a larger budget than will be available. Therefore, we have defined a priority scheme for the SHEBA measurement program. Four different priority levels are assigned, with priority 1 being the highest. The rationale for each priority level is briefly described here, along with the list of measurements. Measurements that will be made by programs collaborating with SHEBA are denoted by writing the program name in parentheses. While the entire annual cycle is of interest, observations during the summer melt period are critical, since this is the most important and poorly understood period for heat input to the ice.

PRIORITY 1 - Core Time Series (CTS) Measurements

These measurements will provide a fundamental, if limited, description of the parameters relevant to the surface heat and mass balance of the ice pack and the surface radiative properties. From these measurements, a parametric description linking atmosphere/ ocean forcing, ice state, and albedo can be obtained. This minimal description would lack some sophistication and its extension to larger scales would entail problems, but it would be sufficient to enhance significantly our understanding of the heat and mass balance of the ice cover and the processes that determine the ice albedo feedback mechanisms in the perennial pack ice. As illustrated in Figure 4, priority 1 measurements are confined largely to the Surface Zone, with a few measurements in the Boundary Zone.

Priority 1 CTS measurements at the ice camp, made relative to different ice thicknesses and surface types, include the following:

- downward spectral and wavelength-integrated irradiances (shortwave and longwave) (ARM)
- cloud bulk characteristics: cover, base, total water content (ARM)
- spectral and wavelength-integrated reflectance (albedo)
- surface-layer wind speeds, air temperature, "skin" surface temperature, and water vapor mixing ratio
- covariances of heat, moisture, and velocity components in the atmospheric surface layer (main CTS station)
- vertical profiles of atmospheric temperature, humidity and winds (rawinsondes, main CTS station)
- daily precipitation (both rain and snow)
- snow depth and density surveys
- ice thickness, internal temperature profile, and ablation/accumulation at upper and lower ice surfaces
- absorbed and transmitted solar radiation in the ice
- surveys of melt pond area
- profiles of temperature, salinity, and current in the upper ocean

- covariances of heat, salinity, and velocity components in the upper ocean (main CTS station)

Priority 1 process studies conducted at the ice camp include

- summer lead study measuring disposition of solar radiation absorbed in leads
- ridge study monitoring keel mass balance

Priority 1 aggregate scale studies include

- aerial surveys of surface characteristics: ice concentration, melt pond fraction, surface temperature, albedo, surface radiative fluxes, and surface height profiles.

PRIORITY 2 - Essential Measurements

These are additional measurements needed to understand the physics of how surface fluxes modify the ice (Objective 2), to relate surface forcing to conditions in the atmospheric and oceanic boundary layers (Objective 3), and to extend local observations to the aggregate scale (Objective 4). Data will be taken mainly in the surface and boundary layer zones. In some cases, priority 2 observations extend priority 1 observations to higher spatial and temporal resolutions. Many of the priority 2 measurements use highly sophisticated instrumentation and are labor intensive and will be done only during the "Intense Observing Periods."

Priority 2 CTS measurements, made at the ice camp, include

- vertical profiles of ice and liquid water content and particle size for clouds
- vertical profiles of atmospheric temperature, humidity, and wind at higher temporal and vertical resolution
- vertical profiles of salinity, temperature, density, and air volume in snow and ice
- optical properties and vertical irradiance distribution of the snow and major ice types
- aggregate scale ice deformation and velocity field (RADARSAT)
- microstructure observations of the ocean boundary layer and turbulent kinetic energy and thermal dissipation rates.

Priority 2 specific studies conducted in the vicinity of the ice camp include

- surface-based surveys of ice thickness
- pond evolution studies measuring changes in depth, area, volume, and temperature
- 2all freeze-up study (ice/upper ocean)
- horizontal variability of surface energy balance components
- horizontal variability of ocean turbulent fluxes
- surface and under-ice topography at the primary floe
- optical transmissivity in leads and the upper 30 m of the ocean.

Priority 2 aggregate scale studies include

- horizontal variability of heat, salt, heat flux, and current in the upper ocean
- snapshots and time evolution of the ice thickness distribution, snow cover, and melt pond characteristics (aerial surveys, sonar observations, submarine SCICEX missions).

PRIORITY 3 - Desirable Measurements

These include measurements that examine details of the surface heat balance or are directed at understanding the processes causing changes outside the boundary layer zones.

Priority 3 local ice camp measurements:

- vertical profiles of radiative fluxes in the lower atmosphere
- bidirectional reflectances of the snow/ice surface
- distribution, concentration and type of particulates present in the ice
- surveys of snow properties (grain size, thermal conductivity, salinity)
- observations of diamond dust.

Priority 3 process studies:

- winter lead study.

Priority 3 aerial surveys of atmospheric horizontal and vertical variability:

- cloud microphysical characteristics
- radiation characteristics
- aerosol characteristics
- turbulent quantities (temperature, humidity, velocity: variances and co–variances)
- cloud bulk properties.

PRIORITY 4 - Ancillary Measurements

These are measurements that would complement SHEBA but are not vital to achievement of the SHEBA goal and objectives.

Priority 4 local-scale measurements at the ice camp:

- vertical profiles of in-cloud vertical velocity variances
- vertical profiles of aerosol extinction
- surface measurements of aerosol composition and gaseous precursors
- vertical profiles of stable isotopes in snow and ice
- biological/turbidity coupling in the ice and ocean
- hydrographic measurements at greater depths
- measurements of ice and ocean chemistry
- spatial and temporal variations in the size, geometry, and distribution of air bubbles, brine pockets, and drainage tubes.

ARCTIC SYSTEM SCIENCE

Ocean-Atmosphere-Ice Interactions