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The SIMMS Program: A Study of Change and Variability within the Marine Cryosphere

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ABSTRACT. This paper describes the scientific context of an experimental program for an eight year study of change and variability within the marine cryosphere in the Canadian Arctic and summarizes the field program since its inception in 1990. The focus is on understanding the process linkages between the atmosphere, cryosphere and ocean at the sea ice interface and in establishing a method by which these processes can be modeled numerically. Remote sensing plays a significant role as a major source of temporally and spatially consistent data in this relatively inaccessible region. In this program, we combine *in situ* measurement of geophysical characteristics of the sea ice interface, electromagnetic radiation interactions with the interface, and numerical modeling of marine cryosphere processes operating across this interface. Our primary objective is to observe and simulate the mechanisms that may contribute to change and variability. We conclude by proposing a conceptual spatial signature of an icescape as the basis for integration of these processes and illustrate how remote sensing data can be used to identify these functional signatures.

Key words: Canadian Arctic, marine cryosphere, remote sensing, atmosphere-cryosphere interactions, snow and sea ice

RÉSUMÉ. Cet article décrit le contexte scientifique d'un programme expérimental consistant en une étude portant sur une période de huit ans des changements et de la variabilité au sein de la cryosphère marine dans l'Arctique canadien, et il résume le programme de terrain depuis sa création en 1990. On se concentre sur la compréhension des liens entre les processus à l'oeuvre, à l'interface de la glace de mer, qui impliquent l'atmosphère, la cryosphère et l'océan, ainsi que sur l'élaboration d'une méthode permettant de faire une modélisation numérique de ces processus. La télédétection joue un rôle important comme source principale de données cohérentes sur les plans temporel et spatial provenant de cette région relativement inaccessible. Dans ce programme on combine les mesures *in situ* des caractéristiques géophysiques de l'interface de la glace de mer, les interactions du rayonnement électromagnétique avec l'interface et la modélisation numérique des processus de la cryosphère agissant à cette interface. Notre objectif premier est d'observer et de simuler les mécanismes qui peuvent contribuer au changement et à la variabilité. On conclut en proposant sur le plan conceptuel une signature spatiale d'un panorama glaciaire comme base d'intégration de ces processus, et on illustre la façon dont les données obtenues par la télédétection peuvent servir à identifier ces signatures fonctionnelles.

Mots clés: Arctique canadien, cryosphère marine, télédétection, interactions atmosphère-cryosphère, neige et glace de mer

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INTRODUCTION

The state of the environment exhibits change and it exhibits variability. From theory, we have known for decades that certain actions of humankind can be of such a magnitude that they can change the state of the environment. The difficulty has been detection of that human-induced change in an integrated system that undergoes natural change and variability.

Such is the case with the consequences of CO_2 and other radiatively active gases. These can cause the virtual greenhouse effect of warming with increasing gas concentrations from anthropogenic sources. From numerical models we can anticipate a warming for the globe as a whole over the next century if present rates of gas injection continue, but to date the forecast warming is less than the natural variability, or the statistical noise, of the temperature signal. This variability may be the result of naturally recurring events such as El Niño and La Niña, or irregular events such as the eruption of Mt. Pinatubo in the Philippines which resulted in a detectable global cooling over the latter half of 1992.

The conundrum that results from attempts to reconcile models and observations makes it difficult to discuss human adaptation to change and variability. The models tempt the uninitiated with hard numbers that can be entered into economic models, geopolitical scenario analysis and policy development. Yet, the abrupt reality of an anomalously wet summer that may be traced to a volcano not considered in the models can breed chaos. We are in the difficult position of knowing that the future may be drastically different from the present, and having to prepare plans to adapt to it, but with only an imperfect view of the mechanisms at work. The operative word is uncertainty, and we must plan to adapt by responding to various levels of uncertainty.

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For the globe, we can predict within reason the specific temperature increase over the next century from the virtual greenhouse gases given specific rates of emission. We can identify the sources and levels of uncertainty. These data may be used with other planning and economic models—at that scale. Unfortunately, the level of uncertainty increases several-fold when we consider specific geographic areas. This is because of the inherent limitations of the numerical models. Nowhere is this uncertainty as great as in the polar regions. The model results exhibit the greatest divergence in these regions as a consequence of the limited understanding of the processes; hence, the primitive nature of the parameterization of those processes. Furthermore, the effects of a perturbation, such as a warming in southern latitudes, may be amplified in the polar regions because of positive feedbacks among the atmosphere, cryosphere and hydrosphere (LeDrew, 1992). The detailed nature and strength of these feedbacks are unknown. There may be a variety of negative feedbacks also in effect in some unexplained fashion. Canada has a significant responsibility in this field of inquiry, not only because of the great expanse of land and ocean subject to these uncertainties, but also because it has great potential for human habitation, resource development and creation of transportation and communication technologies and policies in the polar regions. We must be able to make informed decisions.

In this paper we describe a research program directed specifically at reducing these uncertainties through systematic field observation, use of remotely sensed information and numerical modeling. This has been known as the SIMMS program which stands for the Seasonal Sea Ice Monitoring and Modeling Site. Five years of field work have been supported through the Institute for Space and Terrestrial Science at the University of Waterloo. The intent is to have a science program that will characterize the temporal variability and, perhaps, change of the processes at the atmosphere–cryosphere–hydrosphere interface and incorporate these processes into improved models of atmospheric analysis. Here we provide the conceptual framework and linkages for the more detailed research results of the SIMMS program presented in this volume.

OBJECTIVES

Within the SIMMS program we attempt to understand the physical mechanisms that give rise to the major processes operating across the ocean–sea ice–atmosphere (OSA) interface. We work within a collaborative research framework where there are numerous individual research programs. In general, the long term collaborative goals of SIMMS can be articulated by five interrelated objectives. Objectives 1 to 3 are directly addressed within the SIMMS field programs and objectives 4 and 5 are an evolution of these observational investigations into more regional and hemispheric studies. Specific research questions being addressed within each of the SIMMS objectives provide further detail to the type and range of science investigations being pursued.

Objective 1: *To understand the physical nature of snow and sea ice over a continuum of space and time scales.*

This objective involves extensive *in situ* measurement of surface geophysical variables that are necessary for studies of OSA change and variability. The problem here is that we have a reasonably accurate picture of snow and sea ice geophysical characteristics only for limited time and space scales. If we are to eventually separate change from variability we will need a better understanding of this variability in space and time.

Specific research questions are directed both at the snow on the sea ice and the sea ice itself. With sea ice we are concerned with questions such as: What is the shape and size of the inclusions of ice, air, and brine within the sea ice? How do these partial concentrations change as a function of depth in the sea ice, age of the ice, and metamorphic state of the sea ice? What sea ice characteristics are required to develop robust numerical models for sea ice growth and ablation? With the snow cover on sea ice we are interested in questions such as: What are the relative concentrations of brine, ice and air within the snow volume and how are these concentrations affected by metamorphic state and the type of ice upon which the snow cover is deposited? How does snow grain morphology (indices of shape and size) change as a function of time and depth within the snow volume, and what are the metamorphic processes responsible for this change? How are snow grain morphology and density related to the thermodynamic history of deposition and what snow characteristics can be inferred from the sea ice catchment area topography?

Objective 2: *To understand how the major fluxes of energy and mass are partitioned within the OSA interface.*

This objective involves extensive *in situ* measurement of all components of the surface energy balance, collected coincidentally in space and time with the physical measurements described above. The problem is that we have only a rudimentary understanding of the relationship between sea ice types and fluxes of energy or mass. Implementation of this knowledge in numerical models is restricted to only the most fundamental of approaches.

Specific research questions are directed at radiative, conductive and turbulent fluxes within the sea ice ablation and accretion seasons. Within this objective we are concerned with questions such as: What is the role of shortwave energy in ablation and accretion processes? How is the interaction of shortwave energy partitioned into reflection, absorption, and transmission, given different snow and sea ice conditions? What are the feedback mechanisms between net longwave emission and cloud cover? What is the relationship between skin temperature and the boundary layer atmospheric temperature near the surface under various states of turbulence within the boundary layer? What is the relationship between snow and sea ice microstructure and conductive fluxes? How do different oceanic and atmospheric heat sources and/or sinks affect the overall sign and magnitude of the conductive fluxes? How do each of the major fluxes combine in the specification of the overall energy regime at the surface under different sea ice and atmospheric advection processes?

Objective 3: *Inversion of geophysical properties and energy fluxes from remote sensing data.*

This objective links 1 and 2 above with *in situ* observations of how various frequencies of electromagnetic energy interact with a snow-covered sea ice volume within various temporal and spatial ranges. Simultaneous observations of fluxes and electromagnetic (EM) variables are used in combination with numerical models of EM interactions to develop a better understanding of how various forms of remote sensing data may be used to estimate energy fluxes or the condition of pertinent geophysical variables within the volume. Development of an appropriate inversion methodology is also seen as a possible beneficial aspect of linking remote sensing data to regional and hemispheric models of atmospheric processes over the OSA interface. The use of remote sensing data is an obvious development of the modeling of the heat flow through ice for a variety of ice types by Maykut (1978, 1982).

Research questions, specific to this objective, deal with four general frequencies of EM energy: visible (0.4. to 0.7 μm), near infrared (0.7 to 1.2 μm), thermal infrared (9.0 to 11.0 μm), and microwave (mm to cm wavelength range). Within SIMMS we are concerned with questions such as: Can specific frequencies of EM energy be used to determine the microstructure of snow and sea ice within a fixed range of spatial and temporal attributes? Can EM observations be used to determine surface energy balance values? What are the limitations and application ranges for these energy balance inversion methods? Can observations within a particular frequency range (e.g., microwave) be used to infer the nature of interaction at another range of EM frequencies (e.g., visible)?

Objective 4: *Numerical Model Validation and a Study of the Scale of Processes.*

An evolution of objective 3 is to use surface energy flux estimates, generated from the remote sensing data, to study the appropriateness of various parameterizations within numerical models of the OSA interface. Of particular importance in this phase is an understanding of the scale of feedback processes that can be effectively modeled in hemispheric-scale simulations. For example, the open water leads (cracks in the ice) that comprise 3% of the Arctic pack ice account for almost all of the heat flux from the ocean to the atmosphere in the winter season. How can this process be adequately represented in a grid-point model? Other relevant questions include: How can two-dimensional input data be effectively utilized in uni-dimensional heat flow models? How can the aggregation of scales be handled through both remote sensing of estimated energy fluxes and implementation of this information within two-dimensional models? What is the appropriate scale for observing surface energy balance properties, and how is this scale dependent on the scale of the particular OSA process of interest?

Objective 5: *Ocean–Sea Ice–Atmosphere (OSA) Change and Variability.*

As an evolution of the preceding objectives we will focus on how the knowledge garnered in objectives 1 through 4 may be used in understanding the causal linkages between the atmosphere and the sea ice. In its simplest form this could be articulated as "Does the atmosphere lead the sea ice or does the sea ice lead the atmosphere" (Walsh and Johnson, 1979)? At a more detailed level we are concerned with the direction and magnitude of feedback linkages that operate across the interface under various seasonal and advective conditions. We anticipate that developing an understanding at this level will assist in separating issues of variability from change. Through the judicial use of numerical model sensitivity trials we hope to focus on the issues of parameter selection and scale. These results will then lead back into the preceding objectives as a means of directing the research associated with objectives 1 through 3.

THE SIMMS SAMPLING PROGRAM

To date the SIMMS program has successfully conducted six field experiments: SIMMS'90 (15 May to 8 June), SIMMS'91 (13 May to 13 June), SIMMS'92 - spring (3 April to 30 June) and SIMMS'92 - fall (2 to 9 October), SIMMS'93 - spring (April to 30 June) SIMMS'93 - fall (12 October to 1 November). A typical sampling strategy is presented to allow the reader a general understanding of the coordinated nature of the SIMMS program.

At our current stage of research we are focusing on Objectives 1 through 3, described above. The sampling required to address these objectives requires a coupled *in situ* geophysical, energy balance, and remote sensing observational program. The principal remote sensing platform is the European ERS-1 synthetic aperture radar (SAR) satellite. We also acquire aerial remote sensing data from the X- and C-band CV-580 polarimetric radar of the Canada Centre for Remote Sensing (CCRS) and the X-band airborne system of Intera Technologies. Four orbital radiometers provide data in the visible, near infrared, thermal infrared, and passive microwave lengths (LANDSAT TM [Thematic Mapper]; SPOT [Systéme pour d'observation de la terre]; the U.S. National Oceanic and Atmospheric Administration AVHRR [Advanced Very High Resolution Radiometer]; and the SSM/I [Special Sensor Microwave/Imager]).

Data from these remote sensing systems are combined with *in situ* measurements of a complete set of variable descriptors characterizing the boundary layer (Table 1), snow (Table 2), and ice volumes (Table 3), through the seasonal transitions from winter to summer (spring program) or fall to winter (fall program).

Site Selection and Sampling

Two primary sampling domains are established: intensive, and extensive. The intensive sampling is conducted between Cornwallis Island and Griffith Island in Resolute Passage (Fig. 1). Intensive sampling is conducted at two sites: MYI (Multi-year ice site) and FYI (First-year ice site). Extensive

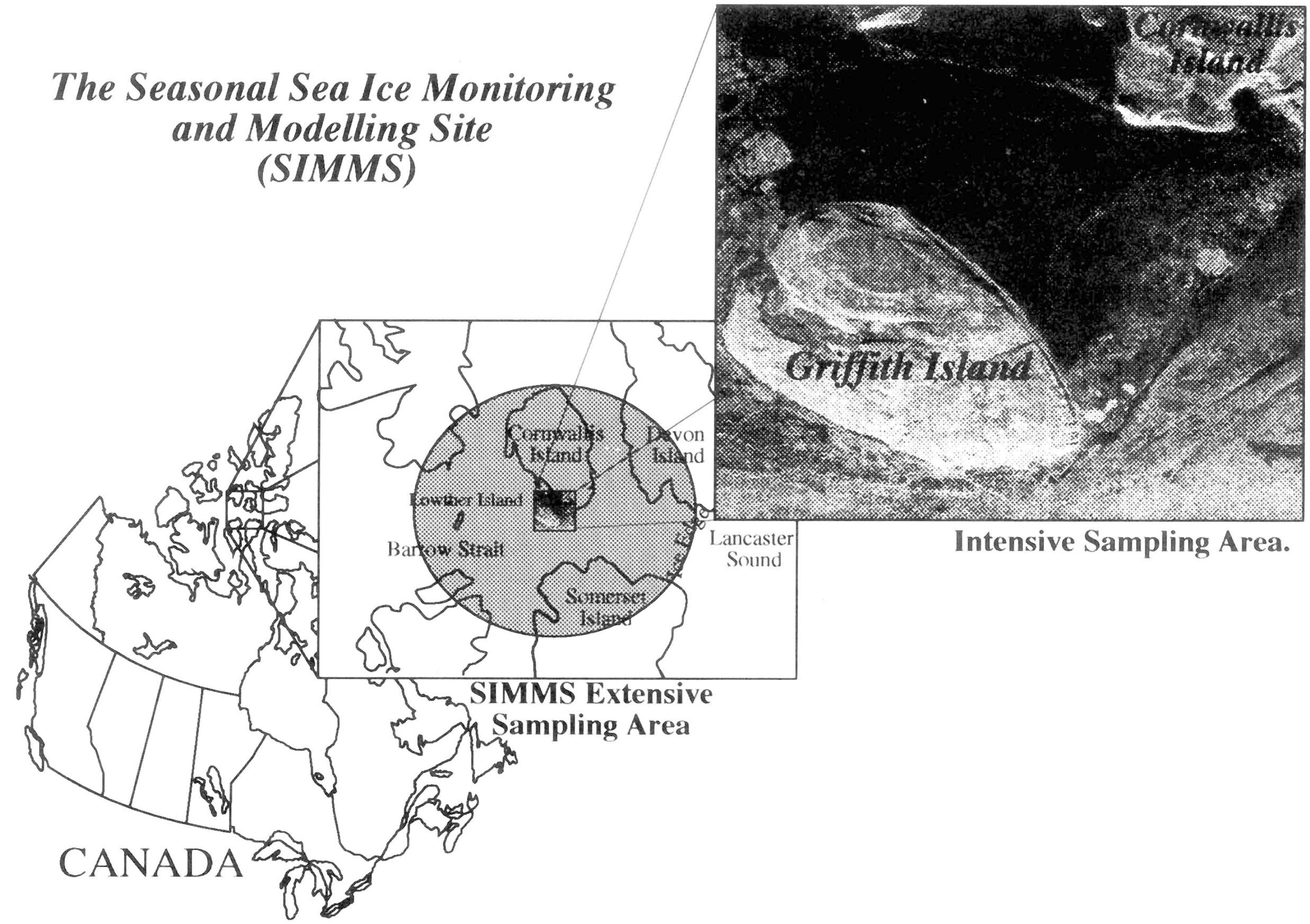

FIG. 1. SIMMS site location in the Canadian Arctic Archipelago, showing intensive and extensive sampling sites.

sampling is conducted by helicopter within a 100 km radius of Resolute Bay, NWT. General ice conditions are typical of the Canadian Arctic Archipelago. There is often multiyear ice within the extensive sampling region and in certain years the MYI site can be established within Resolute Passage. A polynya normally occurs at the edge of our extensive sampling area and large expanses of multiyear ice occur at the western edge of the extensive sampling area (Fig. 1). First-year ice conditions within the passage are typically 1.5 to 2.0 m thick with from 10 to 40 cm of snow cover. Multiyear ice can occur from relatively young forms (second or third year) through to old floes that have migrated out of the Arctic Basin on their way to Baffin Bay.

Intensive sites consist of a 300 m by 300 m square (Sample Site, Fig. 2) placed over a visibly homogeneous sea ice type. Twelve poles are augured into the ice; one at each corner and two along each side of the square sampling area. This separates the square into 9 segments numbered 1–9. Profiles are conducted, one along an x-axis and one along a y-axis. Snow pit sample sites are selected on the basis of a randomly stratified distribution on a segment number (i.e., 1–3 for each axis) then on a random integer between 1–100 (i.e., metres within a segment). Pits are excavated equidistant within each segment (i.e., 4 pits within each segment over 3 segments = 12 pits over the 300 m interval). Ten snow depths are obtained at equidistant intervals between each snow pit along the profile.

A twin intensive sampling area is partitioned using the same pole structure but with different colored flags. This area is off limits to snow machines and people and is located upwind of the sample site (Image Site, Fig. 2). The purpose of this area is to have a sector that can be imaged using ERS-1 and other orbital and aerial sensors as background signature.

Atmospheric Parameters

The height of the climatological boundary layer over a snow-covered sea ice surface varies seasonally, spatially and diurnally. For the purpose of SIMMS, characteristics of the boundary layer are measured within the turbulent surface layer at a high level of detail and only gross features of the planetary boundary layer (i.e., cloud parameters, temperature profiles, pressure, etc.) are taken. The turbulent surface layer is characterized using automated tower-based instrumentation at the MYI and FYI sites within the intensive sampling program. Planetary boundary layer conditions are obtained from the meteorological station at Resolute Bay and

TABLE 1. Boundary layer radiative and energy balance variables measured during SIMMS.

Variable	Symbol	Units	Instrument/Data Collection[1]
Cloud Type	–	type	RBWS and All-Sky photography.
Cloud Amount	–	tenths	RBWS and All-Sky photography.
Cloud Opacity	–	tenths	RBWS and All-Sky photography.
Sea Level Pressure	–	kPa	RBWS
Air Temperature	–	˚C	RBWS and at all IS and RS
Precipitation	–	cm	RBWS
Dewpoint Temp.	–	˚C	RBWS and at IS
Visibility	–	miles	RBWS
Water Equivalent	–	mm	RBWS
Wind Direction	–	degrees	RBWS and at IS
Wind Speed	–	kts	RBWS and at IS
Incident Shortwave Radiation	K↓	$W{\cdot}m^{-2}$	Pyranometer at IS (0.3 – 3.0 micrometres)
Net All-wave Radiation	Q*	$W{\cdot}m^{-2}$	Net Pyradiometer at IS (0.3 – 100 micrometres)
Reflected Shortwave	K↑	$W{\cdot}m^{-2}$	Pyranometer at IS (0.3 – 3.0 micrometres)
Spectral Reflectance	α	Percent	Spectroradiometer at all IS (0.3 - 1.1 micrometres)
Turbulent Fluxes	QH QE	$W{\cdot}m^{-2}$	Latent and sensible heat fluxes at the MYI and FYI Sites.
Photosynthetically Active Radiation	PAR	$\mu mol{\cdot}s^{-1}{\cdot}m^{-2}$	Incident and sub-snow PAR measurements at all IS & RS

[1]RBWS = Resolute Bay Weather Station; IS = Intensive Sites; RS = Remote Sites.

TABLE 2. Snow variables measured during SIMMS.

Variable	Symbol	Units	Instrument/Data Collection
Snow Temp. Profiles	–	˚C	Thermistor Chain
Snow Depth	–	cm	Metre Stick
Snow Hoar Depth	–	cm	Metre Stick
Snow Hoar Salinity	–	ppt	Optical Salinometer
Snow Density	–	$kg{\cdot}m^{-3}$	Gravimetric Method
Snow Wetness	–	%Wv	Capacitance Plate
Snow Surface Roughness	–	mm, l	Surface Roughness Metre
General Snow Wall Properties	–		Digital analysis of layers, lenses, density and crystal sizes of each snow pit wall.
Snow Grain Size	–	mm	Crystallography
Snow Grain Shape	–	rounded/ faceted	Crystallography

TABLE 3. Ice variables measured during SIMMS'91

Variable	Symbol	Units	Data Collection
Ice Temp. Profiles	–	˚C	Thermistor Chain
Ice Salinity Profiles	–	ppt	Core Auger/Optical Salinometer
Ice Surface Salinity	–	ppt	Optical Salinometer
Ice Thickness	–	cm	Drill Auger
Surface Roughness	–	mm	Surface Roughness Meter
Microstructure	–	–	Digital analysis of core thin sections

during *in situ* sampling at the intensive sites (Table 1) using a tether-sond and an all-sky camera.

The intensive sites are manned permanently throughout the SIMMS experiment. Microclimate stations are erected at the MYI and FYI sites to measure the energy balance of these two ice types. Automated samples are recorded as averages over a 30 minute interval throughout the duration of the field experiment. Temperature profiles are acquired through the entire snow and sea ice volumes at 5 cm intervals. Ocean temperatures are acquired at 1 m beneath the ocean-ice interface. Sub-snow photosynthetically active radiation (PAR) measurements are coupled with surface radiation measurements at the MYI and FYI sites and recorded at 30 minute intervals. Incoming spectral irradiance and reflectance are monitored systematically. A tethered balloon is used to obtain estimates of the atmospheric boundary layer temperature and humidity profiles. All-sky photography is used to correlate the incoming shortwave irradiance field with ambient cloud conditions.

Snow Parameters

Two forms of snow pit sampling are conducted: crystal pits and grid pits. The structure and measurement parameters of both grid and crystal pits are consistent over each of the intensive and extensive sites (Table 2). At the crystal pits, automated snow and ice profile thermistor chains are used to obtain 30 minute averages of the temperature profiles. A 3 cm vertical resolution is used to obtain measures of snow grain morphological parameters (statistical moments of snow grain morphology and size), snow wetness, density and salinity. Incident spectral irradiance, reflectance and spectral albedo are measured coincident with the crystal pit sampling.

At the grid pits, snow depths and hoar depths are measured using a metre stick. Snow grain morphology is measured using the crystallography method employed at the crystal pits. Free water content is measured using a capacitance plate, snow density with a gravimetric method, and snow salinity with an optical salinometer. All samples are obtained at 3 cm beneath the air-snow interface.

Sea Ice Parameters

The principal vehicle for obtaining quantitative ice information is the snow pits described above. The structure of ice measure ments within the snow pit sampling (Table 3) is consistent over each of the intensive and extensive sites (Table 3). Ice surface salinities are collected at 3 cm into the ice surface. Ice cores are obtained under cold conditions from three points along each profile (beginning, middle, and end). Cores are interpreted in terms of ice temperature profiles and salinity profiles, and thin sections are photographed for statistics on the structural distribution of volume inhomogeneities with depth. Ice surface roughness is sampled in the same general location as the ice core sampling at the MYI and FYI sites. Microscale roughness is measured using the surface roughness meter. Mesoscale roughness is measured using transit surveying techniques or a system of ice roughness rods.

THE SIMMS RESULTS TO DATE

The papers that follow in this issue and other SIMMS results to date have provided incremental increases in our understanding

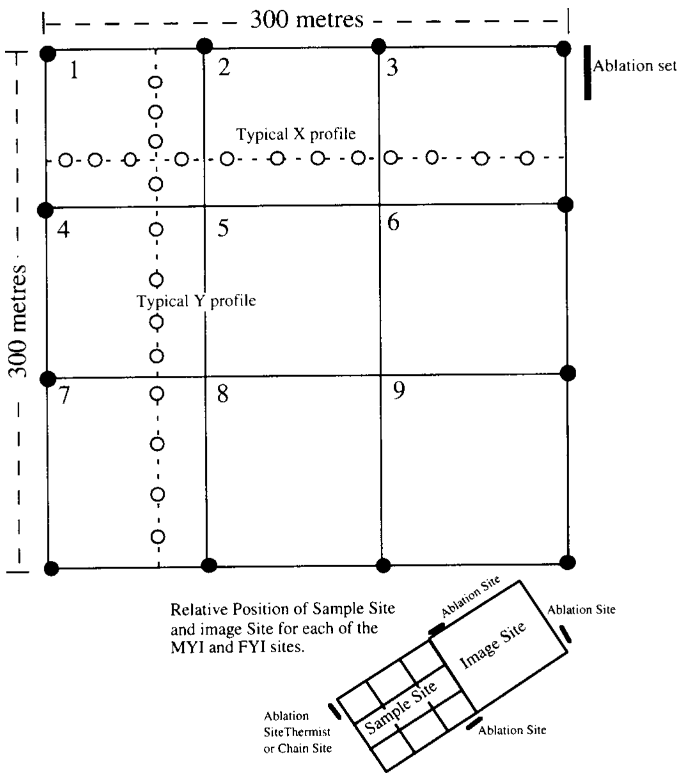

FIG. 2. Sampling scheme for the intensive sites.

of each of the objectives described above. The significance and context of these results are described relative to each objective being addressed within SIMMS.

Objective 1: *To understand the physical nature of snow and sea ice over a continuum of space and time scales.*

Within SIMMS we have been primarily involved with observing snow and sea ice microstructure under various states of sea ice ablation and accretion. Results to date have illustrated that the snow cover on first-year sea ice is highly saline within both the spring and fall periods. The saline layer is restricted to within 1 to 5 cm of the ice surface and it contains higher fractions of salinity than does the ice surface (Barber *et al.*, 1992). First-year sea ice snow microstructure has been shown to vary as a function of depth and time with respect to both shape and size indices. Density profiles have been shown to follow the annual pattern of snow deposition and compaction. Snow depth distributions are a function of ice type, consolidation time, and ice surface roughness (Barber, 1993). The combination of brine volume and density have a compensatory effect on the complex dielectric constant within the snow cover resulting in the nearly linear profile of both permittivity and loss over the vertical dimension of the snow cover (Barber *et al.*, in press).

First-year sea ice, within the SIMMS study area, has been shown to consist of a thin layer of snow or frazil crystals over a predominantly columnar formation. The brine distribution shows higher concentrations within the surface layer with largely spherical inclusions. Columnar ice has lower relative concentrations of brine pockets than the frazil, and they tend toward a columnar structure. Multiyear sea ice consists of the two predominant phenomenological forms of melt pond and hummock ice. A thin layer of snow ice is often found at the surface of the columnar microstructure melt pond ice. Hummock ice consists of complex connections of air inclusions within an ice background near the surface. This structure becomes transformed to a less interconnected series of air bubble inclusions at greater depths within the hummock.

Our current research attempts to contrast the microstructure of snow cover and sea ice over a variety of ice type, growth stage and thermodynamic conditions. Both the snow and sea ice microstructure information is important for modeling the complex dielectric constant, developing physically realistic electro-magnetic interaction models, and providing initialization variables for energy balance investigations.

Objective 2: *To understand how the major fluxes of energy and mass are partitioned within the OSA interface.*

Results to date indicate that the individual components of the sea ice energy and radiation balances show large inter-annual and seasonal variability. Significant differences are also observed between multiyear and first-year sea ice types. Net all-wave radiation (Q*) balances are small except during periods of advanced snowmelt at which time energy totals increase in response to increases in absorbed solar radiation. We have found that the shortwave radiation balance becomes particularly important when the reflective component drops with advanced metamorphism of the snow cover. Details regarding the period of advanced snow melt differ depending on whether one considers first-year or multiyear ice types (Barber *et al.*, 1992). Conductive flux daily totals for first-year sea ice range from approximately 1.5 MJ/m^{-2} in the winter to near zero at the onset of snowmelt when diurnal temperature fluctuations are observed in the snow cover. Totals for multi-year sea ice are typically smaller, often an order of magnitude less.

In the fall, during periods of ice consolidation and rapid growth, the net energy available at the surface is controlled for the most part by the net infrared radiative exchange. Net energy losses are large despite daily conductive heat gains from the substrate in excess of 5 MJ/m^{-2} per day. The distribution of Q* is clearly bimodal with peaks corresponding to cloud-free and cloudy conditions. The differences between the surface radiative losses for overcast versus predominately cloud-free conditions approach 75 W/m^{-2}.

Objective 3: *Inversion of geophysical properties and energy fluxes from remote sensing data.*

Within SIMMS we have sampled geophysical and energy balance components *in situ* coincidentally with overflights of various remote sensing systems. Results within objective 3 show that surface temperature may be estimated using thermal wavelength remote sensing data (Key *et al.*, 1994) as long as atmospheric attenuation is accounted for in the inversion models. From work within objective 2 we found that the surface temperature provides a good proxy of the general direction and magnitude of the surface energy fluxes. Estimation of the shortwave surface albedo can be made using visible wavelength remote sensing data (De Abreu *et al*., 1994). These results show that surface albedo can be extracted under clear sky conditions after adjusting for the viewing geometry of the sensor and the attenuation of the intervening atmosphere. This investigation also highlights the need for an improved understanding of both the anisotropic nature of sea ice albedo and the role of the atmosphere in the attenuation of the incident and reflected solar radiation.

It may also be possible to estimate the magnitude of the surface shortwave albedo using microwave remote sensing. This approach would have the advantage of continuous application despite the ubiquitous cloud cover typical of spring conditions that prevents the traditional use of visible satellite sensors. Results suggest (Barber and LeDrew, in press) that the seasonal evolution of microwave scattering (both modeled and observed) follows a pattern similar to the seasonal evolution of the shortwave surface albedo. The physical variable responsible for this relationship is the water, in liquid phase, within the snow cover (Gogineni *et al*., 1992; Garrity, 1992). Numerical models of the microwave interaction process have been used in a diagnostic capacity to develop a better understanding of the role of various snow and sea ice physical properties in determining specific microwave interaction mechanisms and in defining the nature of the relationship between microwave energy and solar wavelength energy (Barber and LeDrew, in press).

All of the remote sensing investigations conducted within SIMMS are directed at developing methodologies whereby we can invert surface energy balance variables from the remote sensing data. These surface energy balance properties would then be used in meeting objectives 4 and 5 of the SIMMS research program. Our current research goals are directed towards integrating various frequencies of EM energy and compositing high resolution SAR data to directly estimate surface energy fluxes.

Objective 4: *Numerical Model Validation and a Study of the Scale of Processes.*

Within the context of this question we wish to use numerical models of the atmosphere, coupled with information regarding the ice/water surface as lower boundary conditions, to understand the feedbacks between the atmosphere, cryosphere and ocean at a variety of spatial scales.

An example of the role of the feedbacks that has provided a focus for our work is the August reversal of the Beaufort Sea ice gyre. McLaren *et al*. (1987) have examined the monthly values of ice divergence and relative vorticity as well as the sea level pressure data in the polar basin for the 1979–85 period. Whereas for the annual mean, the ice exhibits the well known anticylconic motion in the Canadian basin associated with the clockwise Beaufort Sea ice gyre, there is consistently a protracted reversal in the ice motion in the late summer. This is evident as episodes of ice divergence and positive relative vorticity of the ice field for this region. Furthermore, these episodes appear to coincide with a low pressure system moving into the area which then becomes quasi-stationary rather than continuing as the typical migratory feature. The authors note that the occurrence of ice divergence and the concomitant reduced ice concentration would also explain the observations of thinning ice in the submarine sonar record in early August 1958 and 1970, lending force to the conclusion that this is a long-standing recurring feature.

LeDrew *et al*. (1991) used a quasi-geostrophic diagnostic model of the atmosphere and calculations of isentropic potential vorticity to understand the mechanisms of reversal. Specifically, the questions were: 1) What are the conditions that occur in the late summer to initiate such a phenomenon? Is there a specific atmospheric event that would suggest that the atmosphere is the forcing mechanism and that the ice is responding to it? and 2) What accounts for the stabilization of the low in the Canada Basin once it enters at this time when at other times of the year it would typically travel through the region as a migratory system? Is there feedback associated with some characteristics of the underlying surface that would contribute to the stabilization?

The flow diagram of Figure 3 summarizes the proposed processes. In August, the cooling of the stratosphere in the polar region signals a reversal of the summer clockwise circulation in the stratosphere to a winter counterclockwise circulation. This is associated with export of cyclonic vorticity from the stratosphere to the troposphere which initiates the development of the cold low pressure system. At this point a positive feedback loop emerges wherein the surface sea ice plays a significant role. The cyclonic circulation of the low induces divergence of the sea ice

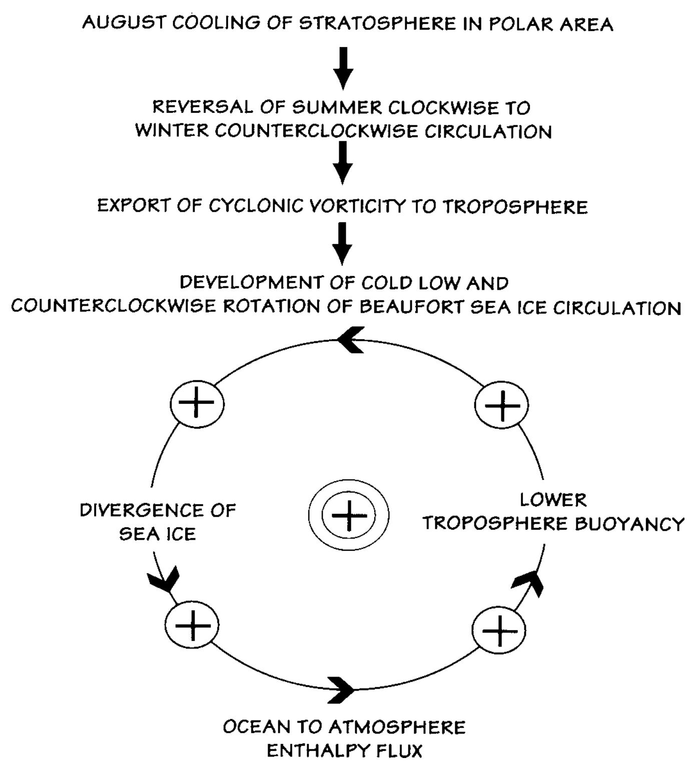

FIG. 3. A process schematic of the August Reversal of the Beaufort Sea Gyre. A positive sign in the feedback loop indicates that the sign of the triggering process, either positive or negative, is carried through to the next process. A negative sign would indicate the reverse. The entire loop is a negative feedback if there is an odd number of negative signs.

which can be observed as large areas of open water in the Canada Basin on NOAA imagery. There is an enhanced ocean–to–atmosphere heat flux from this open water into the core of the cold low that induces lower-tropospheric buoyancy. This buoyancy provides the vertical motion required to maintain the low pressure development for some time which will induce further divergence of the sea ice. The surface heat flux anomaly providing this buoyancy can originate in leads (cracks in the ice) that may be less than a kilometer in length; hence, the emphasis on a large scale in our SIMMS sampling design.

The fact that this phenomenon has not been consistently observed throughout the 1980s, a decade of several record-breaking warm years, leads to several questions regarding the relation between atmospheric forcing, and sea ice and oceanographic processes at the regional level that are not addressed in general circulation models. These global-scale models, used in scenario analysis for future climate change, typically have a single albedo value assigned for all sea ice, and the dynamics of sea ice are considered in a very rudimentary fashion that would not allow for the feedbacks considered above. We anticipate that the type of modeling being pursued in SIMMS, using remote sensing and the knowledge of the surface energetics derived through objectives one through three, will provide more insight into regional scale processes.

Objective 5: *Ocean–Sea Ice–Atmosphere (OSA) Change and Variability.*

From our base-line data collected during SIMMS we will be able to examine the process linkages between the ocean, sea ice and cryosphere and determine the role of feedbacks and forcing variables. We have already experienced considerable inter-annual variability in those processes as evident in the seasonal progression of net radiation and date of initiation of ice melt. It would be presumptuous to say that we could identify change, however, over such a short period, but through our modeling we may be able to identify the mechanisms that may induce change.

Under this objective we are examining the historical archive of passive microwave radiometer data from the Scanning Multichannel Microwave Radiometer (SMMR) on the NOAA series of satellites and the recent Special Sensor Microwave Imager (SSM/I) of the Defense Meteorology Satellite Program. The total archive extends back to 1978 with minor disruptions. We are exploring new modes of image analysis with this archive. In the past the emphasis in remote sensing has been on spatial mapping at one or, at most, two points in time but we are looking at temporal mapping from the time series to classify patterns in the temporal anomalies of the sea ice type and extent for the entire polar basin. These temporal anomalies will be studied in terms of the diagnostic indicators that are products of our atmospheric numerical model, mentioned above, that will be run on a daily basis for the period of microwave observations. From these data sets we anticipate that we will be able to observe changes in the OSA processes that are related to the effect of sea ice. A concentration on processes may give us greater insight into potential change than may be possible from statistical analysis of the raw data. This work is at the formative stage.

DISCUSSION AND FUTURE DIRECTIONS

Implicit in our science plan and experimental design is the concept of a unit of the surface that behaves in a consistent and uniform manner for a variety of processes. We are measuring the detailed snow and ice microclimate and geophysical characteristics for such a hypothetical unit. The sampling structure provides a measure of confidence in this concept of a unit, and the extensive measurements at two sites provide some indication of the differentiation of units. The unit is not based upon one characteristic, such as surface roughness, but rather a suite of characteristics that may be used to define the integration of physical and biological processes contributing to the integrity of the unit.

The issue is somewhat analogous to the difference between looking for climate change or variability in a temperature record versus an amalgam of several potentially related signals which may provide a more definitive message that has been called a "fingerprint." We are looking for a spatial unit or signature that can be characterized by measurement at one scale, and subsequently be aggregated with other spatial forms to a different scale to describe a derived unit which can still provide the relevant process information for the modeling issue at hand.

The geographic heritage is rich in the concept of landscape: "… the most precise expression of geographic analysis is found in the map, an immemorial symbol" (Sauer, 1925:317). The task of geography was concerned with "… the critical system which embraces the phenomenology of landscape, in order to grasp in all of its meaning and color the varied terrestrial science" (Sauer, 1925: 319). The emphasis was on connectivity and integration of a variety of processes resulting in a consciousness of form. This form included the reality of union of physical and cultural aspects—it was the sum of all resources in an area. In fact, the concept of morphology originated with Goethe; this is a method of scientific inquiry based upon a defined philosophical position (Sauer, 1925).

Our thinking has changed considerably since the early part of this century as we have become deconstructionist in our quest towards ultimate understanding of the *element*. Yet we have returned to this notion of integration as is evident in the driving forces behind the International Geophysical Biological Program (IGBP), Global Change, and specific experiments such as BOREAS (Sellers, *et al.*, 1990). Interestingly, two of the reasons that such integration is now feasible are the development in computer technology so that we can model complex systems as integrated processes, and the availability of remote sensing so that we may observe and derive variables (some of which have been previously inaccessible on an ongoing basis) for large regions of the globe in a temporally and spatially consistent manner. The concept of total understanding and predictability of a spatial unit or signature of specific form has returned with remote sensing playing the role of the map in the earlier generation of studies.

For sea ice we propose to go beyond the phenomenological basis of the World Meteorological Organization classification of sea ice to the notation of a sea ice landscape or *icescape* that holds a conspicuousness of form as a consequence of a variety of processes operating together in a coherent fashion. These include the micrometeorology, snow and ice geophysics, biological linkages and their manifestation in the remotely sensed signal that may provide the basis for characterization of these processes from satellites, and their incorporation in numerical models of environmental change and variability. We anticipate that a major contribution of the SIMMS program will be the fundamental basis for the definition of an icescape and explicit description of the process linkages for a few examples that may have distinction in the remotely sensed imagery.

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