Experimental and Theoretical Studies of Ice-Albedo Feedback Processes in the Arctic Basin

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LONG TERM GOALS

Our overall goal is to develop a quantitative understanding of processes that collectively make up the *ice-albedo feedback mechanism*. This mechanism is generally believed to be a key factor in amplifying natural variations within the earth's climate system. To achieve this understanding, we need to learn how shortwave radiation is absorbed and distributed in the ice pack and upper ocean, then assess the effects of this distribution on the regional heat and mass balance of the ice cover. Complicating the problem are a variety of issues related to the extreme sub-grid scale variability of the Arctic ice cover and to how such variability can be accounted for in large-scale models. Ultimately, we plan to develop and test appropriate techniques for accurately incorporating ice-albedo feedback processes into climate and general circulation models.

OBJECTIVES

While we are investigating a variety of specific problems related to the interaction of shortwave radiation with the ice and ocean, our immediate focus is on answering the following questions:

(1) How is shortwave radiation that enters the ice-ocean system partitioned between reflection, surface melting, internal heat storage, and transmission to the ocean, and how is this partitioning affected by the physical properties of the ice, snow cover, melt ponds and distribution of contaminants?

(2) What is the areal distribution of ice, ponds and leads in perennially ice-covered regions; how does this distribution vary with time; and how does it affect area-averaged heat and mass fluxes?

(3) What are the crucial variables needed to characterize ice-albedo feedback processes and their effect on the heat and mass balance of the ice pack, and how accurately can they be treated through simplified models and parameterizations?

APPROACH

These questions are being addressed through a combination of field measurements, laboratory observations and theoretical modeling. Field data in support of this work were collected continuously over a complete annual cycle (Oct 1997 to Oct 1998) at the SHEBA Drift Station in the Central Beaufort Sea. Measurements were carried out jointly with investigators (D.K. Perovich, J.A. Richter-Menge, W.B. Tucker III and M. Sturm) from the U.S. Army Cold Regions Research and Engineering

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Laboratory (CRREL) as part of a group project funded by ONR. Also closely involved in the summer efforts was Dr. H. Eicken (Geophysical Institute, University of Alaska, Fairbanks) who was supported through NSF. Two UW investigators (T.C. Grenfell, B. Light) carried out measurements at the drift station from May-September 1998, work that focused on documenting the temporal evolution and spatial variability of such quantities as albedo, absorption and storage of solar energy by the ice, light transmission to the ocean, pond coverage, and mass changes in various types of sea ice. Periodic particulate measurements were also made to determine whether soot and particulates generated by the ship might alter the albedo and normal melt cycle of the surrounding ice during the spring and summer.

An important objective of this program is the application of information obtained from local process and time evolution studies to the estimation of areally-integrated heat and mass fluxes. For this purpose, we conducted numerous surveys that should give us a statistical picture of the spatial variability within individual ice types as well as quantitative information on the fractional area covered by these categories within the SHEBA region. Surface-based surveys were conducted routinely during the spring and summer to sample albedo, snow and ice properties, melt pond depth and area, lead temperature and salinity, ice surface topography and freeboard level. Helicopter surveys were also made throughout the summer to look at local and larger-scale variations in ice concentration, lead width, pond fraction, surface temperature and reflectivity, floe size, and floe perimeter. Such data will play an important part in obtaining regional estimates of shortwave input to the ocean, lateral melting on floe edges and melt pond evolution. When combined with corresponding data from the atmosphere and ocean, these data should lead to a much more complete understanding of ice-albedo feedback processes in the Arctic.

Process-oriented modeling will be carried out to supplement and augment the field studies. Field data on ice structure and optical properties will be combined with laboratory data to develop and verify a model that relates structural and optical properties in sea ice. Such a model is needed to provide an accurate description of radiative transfer in sea ice and will form the basis for modeling efforts to predict the optical evolution of the ice cover during the summer melt season. A Monte Carlo radiative transfer model for sea ice has been developed that will be used in the analysis of the experimental data and in the formulation of optical parameterizations suitable for use in conventional radiative transfer models. Because *in situ* measurements of microstructure are impractical in warm first-year ice, thin section data from ongoing laboratory studies are being used to characterize the internal structure and consequent effects on radiative transfer in such ice.

WORK COMPLETED

Work during FY99 was focused in two general areas: (1) reduction and preliminary analysis of field data collected during SHEBA, and (2) laboratory and theoretical studies of the effects of ice structure on the transmission, absorption and scattering of solar radiation by sea ice. SHEBA data includes measurements of total and spectral surface albedos, light transmission to the ocean, irradiance profiles in the ice, surface and bottom ablation, melt pond coverage and evolution, temperature and salinity profiles in the ice and leads, lateral ablation on floe edges, snow depth, surface topography, soot content, freeboard level and meltwater transport. Time series of these quantities were obtained throughout the summer for all major categories of ice present in the SHEBA region. Whenever clouds were absent or sufficiently high, helicopter surveys were made of the ice cover around the ship out to distances of 30 km or more. Instruments flown on various flights included: an aerial mapping camera, video camera, spectral radiometer, infrared thermometer, digital camera and laser altimeter.

Together with D. Perovich and colleagues at CRREL, we have completed the basic reduction of all SHEBA heat and mass balance data. The reduced data are archived at JOSS (the Joint Office for Scientific Support) and are also being disseminated to the community on a CD-ROM ("SHEBA: Snow and Ice Studies") which includes documentation on instruments, observational techniques and environmental conditions along with sample graphs and photos. Also provided to the JOSS archive was an image library of over 3000 aerial photographs taken during 14 helicopter survey flights.

Laboratory work included optical and structural measurements carried out on a variety of first-year sea ice samples. Data on structurally-induced changes in light transmission and reflection were collected at temperatures between –2 and –30°C. High resolution microphotography allowed us to document corresponding changes in the size and number distributions of inclusions as small as 5 microns. Figs. 1a-c illustrate how brine pockets and vapor bubbles shrink in size when a sample is cooled from –15 to –25 °C. Precipitated salts of mirabilite and hydrohalite are visible in some of the brine tubes. Figs. 1d-f show dramatic increases in brine pocket size and reductions in number that take place during warming. Note that mirabilite crystals initially present in the bottom of the central brine tube have dissolved by the time temperature reaches –5 °C.

Construction and testing of a cylindrical Monte Carlo model for sea ice has been completed. The model produces excellent agreement with several other radiative transfer models for horizontally infinite domains. For finite cases, limited comparisons were made with a specialized, cylindrical radiative transfer model being developed at Los Alamos, again with excellent results. The model is presently being used in the interpretation of laboratory optical data collected from natural sea ice cores.

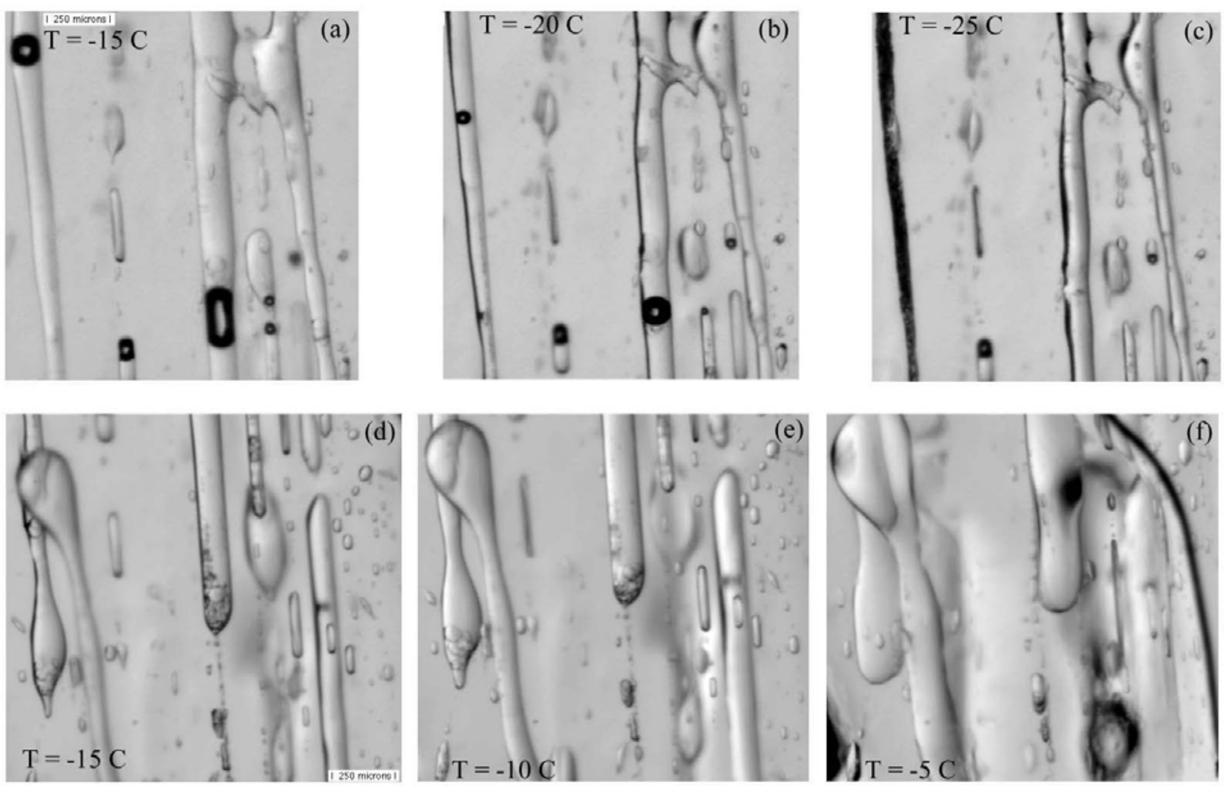

Figure 1. Temperature-dependent changes in the internal structure of first-year sea ice during cycles of cooling (a-c) and warming (d-f).

RESULTS

We are continuing to work on the analysis of data from SHEBA and the laboratory experiments. Interesting results to date include:

<u>Surface Albedo</u>. Fig. 2a shows seasonal changes in total albedo (α), spatially averaged along a 200 m survey line on the main SHEBA ice floe. Each point shown on the curve typically represents an average of about 100 separate α measurements. There are, of course, large α changes associated with the appearance and disappearance of the snow cover, but there is also a large, progressive decrease in α throughout the summer due almost entirely to changes in the state and optical properties of ponded ice. This can be seen in Figs. 2b and c. Fig. 2b shows the average spectral albedo (α_λ) of white ice along the survey line, while the vertical "error" bars show the range of values observed between 7 July and 14 August; Fig 2c shows corresponding values over shallow ponds. Continual breakdown and regeneration of a surface scattering layer produced an almost constant α_λ for white ice, while increasing brine volume and decreasing numbers of vapor bubbles in ice beneath the ponds caused a progressive reduction in α_λ. Changes in the standard deviation of α primarily reflect changes in extent and albedo of the melt ponds.

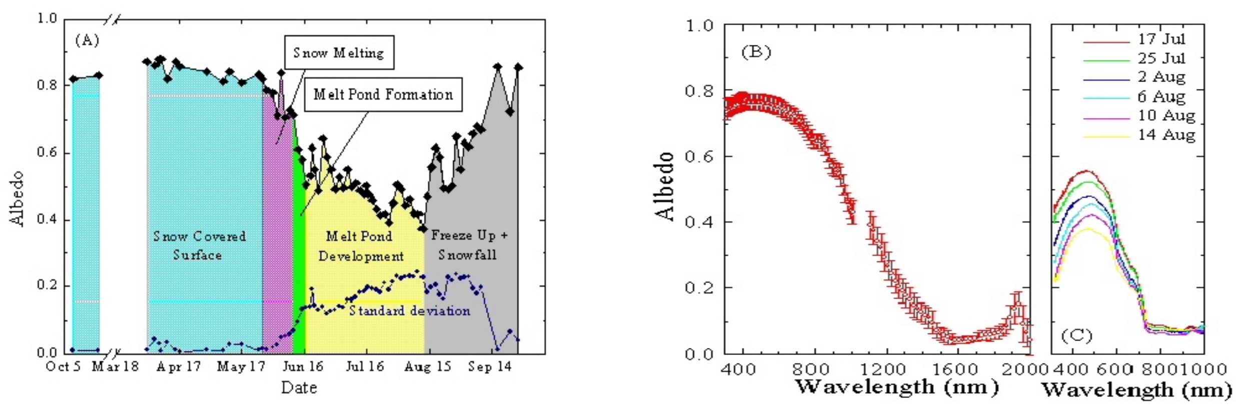

Figure 2. (A) Spatially-averaged, total albedos at SHEBA; (B) range and magnitude of spatially-averaged α_λ over white ice; (C) progressive change in α_λ observed over summer melt ponds

<u>Soot Measurements</u>. Fig. 3 shows the spatial distribution of soot in the snow around the ship at the end of May. Concentrations in regions where the heat and mass balance measurements were made (3-5 ngC/g) were essentially the same as background values measured tens of km away. Thus, the presence of the ship did not significantly affect the optical properties of the snow cover or its decay cycle. Nevertheless, model calculations indicate that this much soot could increase the melt rate of the sea ice by as much as 15-25% if it became concentrated near the upper surface of the ice when released from the snow. At this point we do not have any evidence of accelerated melting and suspect that much of the soot was carried away with the melt water, or transported more deeply into the ice.

<u>Summer Lead Temperatures</u>. An infrared thermometer (KT-19) was routinely flown during the helicopter surveys. Footprint size was about 80 meters or less, depending on helicopter altitude. The primary objective was to determine temporal and spatial distributions of lead temperatures in the region. These observations have now been reduced and atmospheric contributions removed. Fig. 4 shows that most lead temperatures remained near the freezing point of the ocean during the snow melt.

As leads became increasingly stratified, solar heat built up in the fresher surface layers and by late July reached temperatures nearly 4 °C higher than those in June. Except for water in small, newly-opened leads, heating and lateral ablation in larger leads appears to have been relatively uniform across the region.

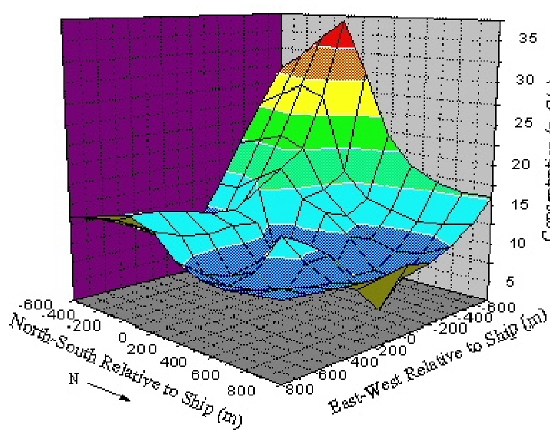

Figure 3. Spatial distribution of soot around the SHEBA ship at the end of May.

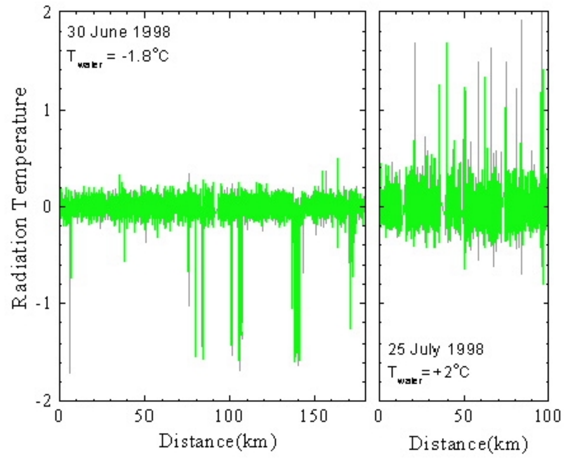

Figure 4. Surface temperatures observed along helicopter transects in late June and late July.

Structural-Optical Results. The observations show that brine pocket number densities average about 30 per mm^3, roughly an order of magnitude more than previously reported and indicating that brine pockets are responsible for much more scattering than expected. Vapor bubble number densities averaged 1.2 per mm^3 and were located almost exclusively in brine pockets. Brine pocket size ranged between 5 µm and 100 µm, while vapor bubbles ranged between 10 µm and 40 µm. The optical properties of cold ice were dominated by the presence of precipitated salts and those of warm ice by brine pocket geometry. Unexpectedly, there appear to be competing processes involving brine pocket enlargement and merging in warm ice that severely reduces temperature-dependent changes in the amount of light scattering.

IMPACT/APPLICATIONS

Data obtained during the field effort should provide the means to test theoretical models dealing with: (1) the transmission and absorption of light by the ice pack, (2) the role of leads and melt ponds in the regional heat and mass balance, and (3) the storage of solar heat in the water and its interaction with the ice cover. We expect this will lead to an improved understanding of ice-albedo feedback processes that can be used to enhance the accuracy of predictions made by large-scale climate models and GCMs.

TRANSITIONS

Our SHEBA heat and mass balance data are now archived on the JOSS database and are also being disseminated on CD-ROM. Preliminary results from this work have been presented in an EOS article and in more than a dozen presentations at scientific conferences in the past year. The data have been incorporated into the SHEBA column data set and will be used in a variety of process and column modeling studies.

RELATED PROJECTS

The work described above is part of a group project being carried out jointly with CRREL investigators funded under Contract N0001497MP30046. We also plan to work closely with a number of other SHEBA investigators studying processes related to: (i) the recycling of solar energy absorbed by the ocean, (ii) melt pond and ice cover evolution, and (iii) energy exchange with the atmosphere. Data from this project will be used in several modeling efforts funded under SCICEX, NASA-POLES, and NSF to calculate the ice thickness distribution and regional heat and mass fluxes in the SHEBA region.

PUBLICATIONS

Light, B., H. Eicken, G.A. Maykut and T.C. Grenfell, The effect of included particulates on the spectral albedo of sea ice, *J. Geophys. Res*, *103*, 27,739-27,752, 1998.

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