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. Our long-term goal is to develop accurate formulations of the major ice-albedo feedback processes which are suitable for inclusion in climate and general circulation models.

OBJECTIVES

We are investigating a variety of specific problems related to the interaction of shortwave radiation with the ice and ocean. The work addresses the following general 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 issues are being addressed through a combination of field measurements, laboratory observations and theoretical modeling. Field data in support of this work were collected 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 D.K. Perovich and colleagues from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and focused on: (1) documenting the temporal evolution and spatial variability of 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, (2) soot

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14. ABSTRACT
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. Our long-term goal is to develop accurate formulations of the major ice-albedo feedback processes which are suitable for inclusion in climate and general circulation models.

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loading of the snow to determine whether contaminants generated by the ship might alter the normal albedo and melt cycle, and (3) ground-based and aerial ice surveys to obtain a statistical picture of spatial variability and fractional area covered by individual ice types within the SHEBA region. Such data will play an important part in obtaining regional estimates of shortwave input to the ice and ocean, lateral melting on floe edges, and melt pond evolution, and in the understanding of ice-albedo feedback processes in the Central Arctic.

Complementing the field observations were an extensive series of structural and optical measurements carried out in laboratory sea ice samples under a wide range of temperatures (-2 to –34 °C). These data have been used to develop and test a model that relates structural and optical properties in sea ice. Such a model is needed to provide a general 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. Analysis and interpretation of the experimental data were made possible through development of a two-dimensional Monte Carlo model which allows us to investigate how horizontal variability affects radiative transfer in sea ice. The model will also be used in the analysis of vertical irradiance profiles collected in bore holes during the SHEBA Project.

WORK COMPLETED

Work during the past year has focused on the summer melt season, in particular, on: (1) characterizing the seasonal evolution of surface albedo and mass balance of the ice cover, (2) understanding processes which determine surface melt pond coverage and its impact on albedo, (3) analysis of spatial variations in summer surface temperatures, (4) continued testing and development of the structural-optical model of sea ice, (5) studies of how melt ponds affect the transmission and absorption of solar radiation in the surrounding ice, and (6) enhancement and testing of our two-dimensional Monte Carlo model of radiative transfer in sea ice. Results from this work are presented in six journal papers which are either in press, submitted, or in the final stages of preparation.

RESULTS

Evolution of Surface Albedo

Results of our soot analysis show that the ice was sufficiently clean (about 4.5 ngC/g) that the measured SHEBA albedos should be representative of the Central Arctic. A paper describing these results is in press in the *Journal of Geophysical Research* (*JGR*). Field measurements showed that the albedo of bare ice remained surprisingly constant (0.6-0.7) throughout the melt season because of a surface scattering layer which was continually regenerated. Melt ponds, on the other hand, experienced a progressive decrease in albedo due to increasing brine volume and decreasing numbers of vapor bubbles in ice beneath the ponds. Typical changes are illustrated in Fig. 1. These results indicate that floe-scale albedos are largely determined by pond fraction and pond albedos. Comparison with results from Soviet drifting stations confirms that floe-scale albedo decreases during SHEBA were abnormally strong, presumably because of the thinness of the ice and the extended duration of the melt season in 1998. We believe that the processes observed at SHEBA hold in general, and efforts are underway to produce a practical parameterization of regional changes in albedo for use in large-scale models. Another paper describing this work is also in press in *JGR*.

Mass Balance Cycle

Seasonal mass changes were measured at 135 locations that included examples of the principal ice types present in the SHEBA region. Although the SHEBA winter was slightly colder than average, the melt season of 1998 was significantly longer. This led to substantial thinning of the ice cover. Typically, 2 m ice experienced a net loss of about 75 cm over the annual cycle from October 1997 to October 1998.

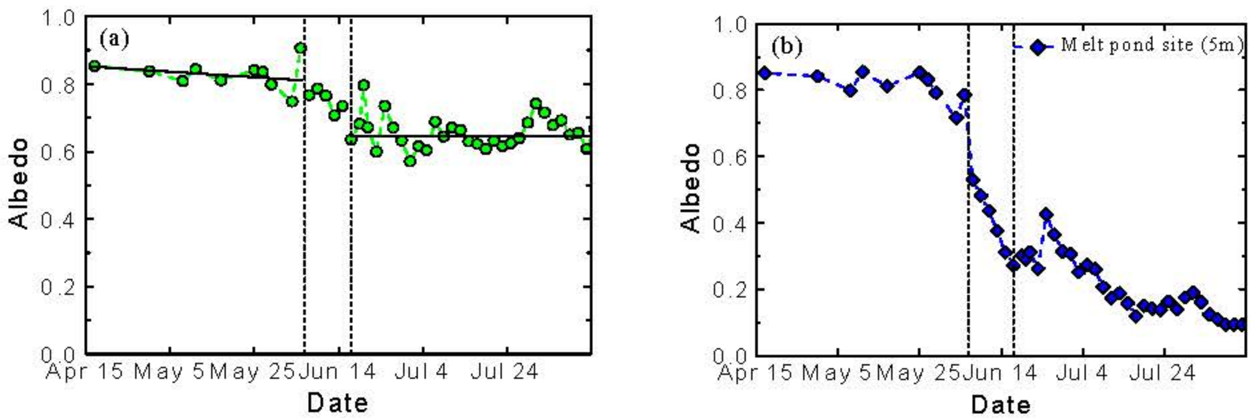

Figure 1. Time series of wavelength-integrated albedos for selected white ice (a) and melt pond (b) sites. Vertical dashed lines show transition to full summer melt conditions. Solid lines in (a) indicate trends. The summer albedo is 0.65. Fluctuations result from periods of snowfall and heavy melting.

The average bottom ablation of 62 cm was surprising large – more than twice the amount reported from previous experiments. Local input of solar radiation to the ocean through leads was not sufficient to account for the observed bottom ablation. Light transmitted through melt ponds, and even bare ice, probably contributed substantially to solar heating of the upper ocean and bottom ablation. A detailed description of these results has been submitted for publication in *JGR*.

Hydraulic Controls of Summer Arctic Pack Ice Albedo

A study of the hydrological balance of summer sea ice was carried out to investigate its effects on regional albedos. The observations were carried out during SHEBA and continued on first-year ice near Barrow AK. We show that Arctic summer sea-ice albedo is strongly dependent on the areal fraction of surface melt ponds, which are currently either ignored or ill described in large-scale models. The present study indicates that prediction of summer pack ice albedo is as much a hydraulic problem as an optical problem, with melt pond area controlling the spatial and temporal variability of albedo. The extent of the pond coverage depends critically on a detailed balance between the surface ablation rates, the ice topography and its permeability. Particularly during the early melt season, pond water level variations are directly translated into substantial changes in pond area and albedo over very short time scales. The entire range of observed pond fractional areas falls within a 0.2 to 0.4 m range in surface elevation, with differences of a few centimeters resulting in doubling or halving of pond fractions. A paper describing these results has been submitted for publication in *JGR*.

Regional Surface Temperature Observations of the Summer Ice Pack

Observations with a helicopter-mounted, Heimann Kt-19 infrared photometer (8-14 microns) are being combined with concurrent photography to determine temperature differences between ice, ponds, and leads throughout the summer. The results have strong implications for lateral ablation and thermal energy stored in the upper layers of the ocean. A Matlab program has been developed to analyze aerial photographic imagery and determine relative concentrations of ice, ponds, and open water observed by the Kt-19. This produces a spatial trace that can be compared directly to the Kt-19 swath (Fig. 2). The field of view of the Kt-19 is convolved with the surface features allowing us to back out the thermal contrast between ice and water over a wide area at regular intervals over the melt season.

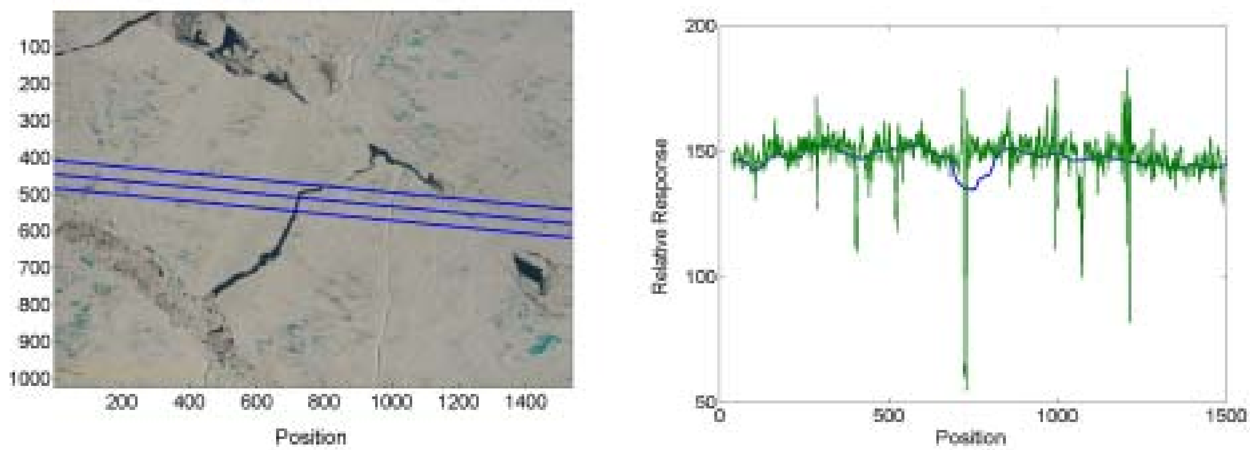

Figure 2. (a). Path of Kt-19 observations across ice pack. Outer blue lines show the field of view. Position is given in pixels. The width of the image is about 860 m. (b) The green line shows the contrast response along the center line of (a) while blue line shows the convolution of the field of view with the contrast response along the swath defined by the outer two blue lines.

Structural-Optical Studies

To model interactions between solar radiation and the ice pack, we must first understand how environmental conditions affect the structure and, hence, the optical properties of the ice. Changes in the structural and optical properties of first-year (FY) sea ice have been measured in the laboratory over a wide range of temperatures (-2 to –33 °C) and used to test predictions from a structural–optical model of the ice (Fig. 3). A specialized, 2-D Monte Carlo model was developed to infer scattering coefficients for the ice samples. The models have successfully taken into account effects of changes in temperature, brine volume, vapor bubbles and precipitated salts on spectral transmission and reflectivity. A paper describing results of the structural observations has been accepted for publication in *JGR* and another paper on the 2-D Monte Carlo model is nearing completion.

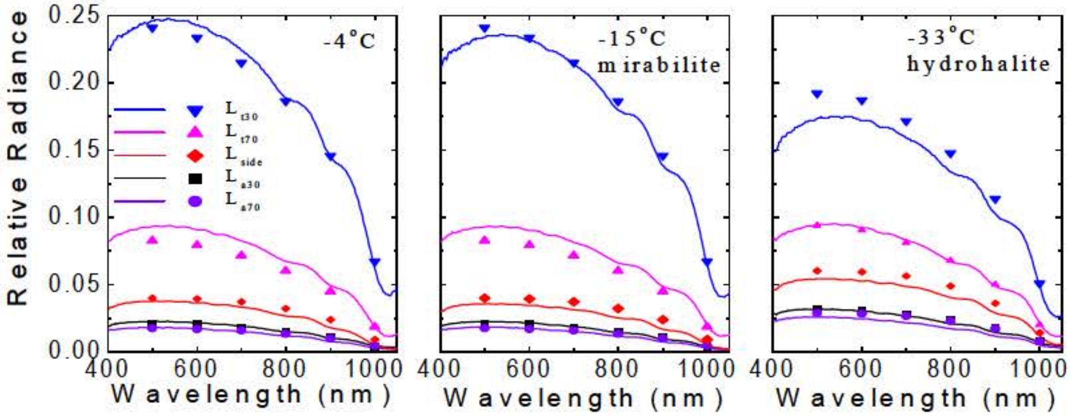

Figure 3. Comparison of observed (symbols) and modeled (solid lines) radiances for FY ice at –4, -15 and –33 °C. The sample contained precipitated mirabilite crystals at –15 °C and hydrohalite crystals at –33 °C. Transmitted (L_t) and reflected (L_a) radiances were measured at 30° and 70° from nadir.

Radiative Transfer Beneath Melt Ponds

Oceanographic data from SHEBA indicate that much more solar energy is absorbed by the mixed layer than predicted, bringing into question calculated rates of bottom ablation. The most likely reason for this is greater than expected energy transmission through melt ponds. We suspect that light attenuation by ponded ice has been overestimated in the past due to influences from the surrounding white ice. The 2-D Monte Carlo model was thus used to look at the spatial distribution of transmitted radiation beneath ponded ice. Results (Fig.4) show that the radiation field beneath ponds <6 m in diameter is always affected by the surrounding ice, causing extinction coefficients to be overestimated. Even large ponds will yield overestimates if measurements are made within 2-3 m of the pond edge. For smaller ponds on thick ice, over 40% of the transmitted energy at 475 nm exits beneath the neighboring ice. Previous estimates of melt pond extinction coefficients need to re-examined in light of these findings.

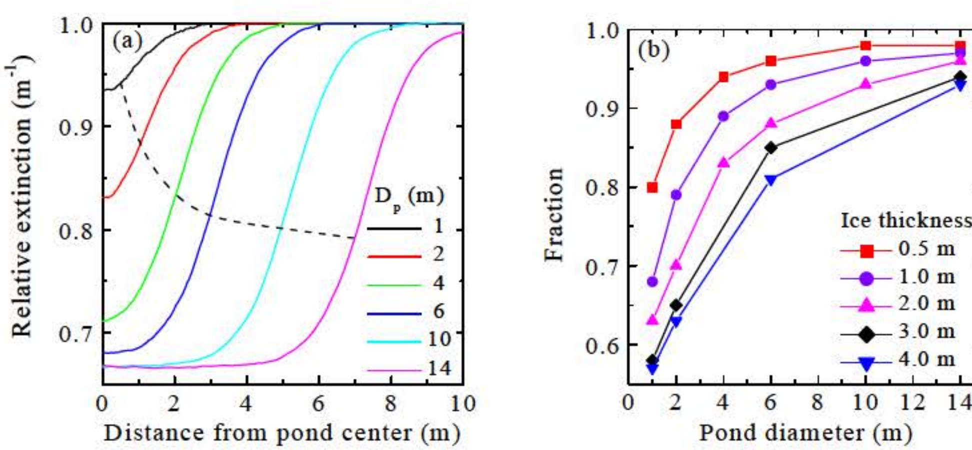

Figure 4. (a) Calculated extinction coefficients for 2m ice at 475 nm as a function of pond diameter (D_p) and distance from pond center. Dashed line shows location of pond edge. (b) Effect of ice thickness and pond diameter on fraction of total transmitted energy within geometric footprint of the pond.

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. The laboratory and theoretical studies also suggest that relatively simple parameterizations of radiative transfer in sea ice can be developed for large-scale modeling. We expect that these data and modeling results will lead to an improved understanding of ice-albedo feedback processes that can be used to enhance the accuracy of predictions made by climate models and GCMs.

TRANSITIONS

Our heat and mass balance data collected at SHEBA are archived in the JOSS database and also placed on a CD-ROM which has been widely disseminated to the community. We expect that these data will be used in a variety of process and column modeling studies by ourselves and other groups. Experimental results have been presented at numerous scientific conferences and written up in six journal papers.

RELATED PROJECTS

The work described above is part of a group project being carried out jointly with CRREL investigators funded under Contract N0001497MP30046. We are also working closely with other SHEBA Phase 3 investigators studying processes related to: (1) the recycling of solar energy absorbed by the ocean, (2) melt pond and ice cover evolution, and (3) energy exchange with the atmosphere. Data from this project will be used in modeling efforts funded under ONR, SCICEX, NASA-POLES, and NSF to calculate the ice thickness distribution and large-scale heat and mass fluxes.

PUBLICATIONS

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