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 major factor in amplifying variations that occur 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 Arctic 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 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; 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. During Fall 1997, CRREL personnel surveyed the primary SHEBA floe and deployed a variety of instrumentation. Over 120 hot wire ice thickness gauges were installed at various sites on the floe, including young ice, melt ponds and pressure ridges. Continuously recording instrument packages were deployed at several sites where ice temperature profiles, ice growth rates and snow depths were monitored throughout the SHEBA year. Routine observations carried out during the winter focused on monitoring changes in ice thickness and snow depth.

While we believe it is possible to predict ice growth rates, salt fluxes to the ocean and heat exchange with the atmosphere during the freezing season for essentially any thermal forcing and any thickness of snow and undeformed ice, numerous uncertainties exist during the summer melt season and fall freeze-up when changes in ice conditions and optical properties are rapid and the impact of ice-albedo feedback processes are greatest. For this reason, our field efforts were focused on these two important periods. Two UW investigators (T.C. Grenfell, B. Light) carried out measurements at the drift station from May-September 1998. The spring effort was directed primarily towards obtaining detailed information on the state of the ice and snow cover at the onset of the melt season. Summer observations were carried out on several different ice types where the focus was on measuring 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. Because of the possibility that soot and particulates generated by the ship might alter the albedo and melt cycle of the surrounding ice, periodic particulate measurements were made 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. 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, melt pond fraction, floe size distribution, floe perimeter and surface reflectivity. 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 effects. 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 warm 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 model will be used in the analysis of the experimental data and to develop optical parameterizations that are suitable for use in our 4-stream radiative transfer model. Because *in situ* measurements of microstructure are impractical in warm first-year ice, thin section data from ongoing laboratory studies will be used to characterize the structure of major ice types and consequent effects on radiative transfer.

WORK COMPLETED

Work during FY98 was focused on three general areas: (1) design, construction and testing of specialized field equipment needed for the summer field program at SHEBA, (2) collection of surface heat and mass balance data over a complete melt cycle, and (3) development and refinement of theoretical techniques needed for interpretation of SHEBA field data. New instruments successfully deployed during SHEBA included: (1) an integrating-sphere cosine collector for measurements of spectral albedo, (2) a radiation detector that allowed us to obtain vertical profiles of downwelling shortwave radiation within and beneath the ice, and (3) an improved soot sampling apparatus to quantify the amount of contaminants in the ice and snow.

We spent over 8-man months on the ice collecting data at the SHEBA station, beginning before the onset of the melt season and continuing until after the fall freeze-up. Large amounts of data were acquired on: total and spectral 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 and meltwater transport. In contrast to most earlier efforts, we were able to obtain albedo data that spanned the ultraviolet, visible and optical infrared (e.g. Fig. 1a). We were also able to obtain time series of the optical and physical property data throughout the summer (e.g. Fig. 1b) for all major categories of ice present in the SHEBA region. A detailed soot survey was carried out just before the onset of the melt season with additional samples taken sporadically over the summer. Samples of sediment-laden ice were collected for size distribution analysis.

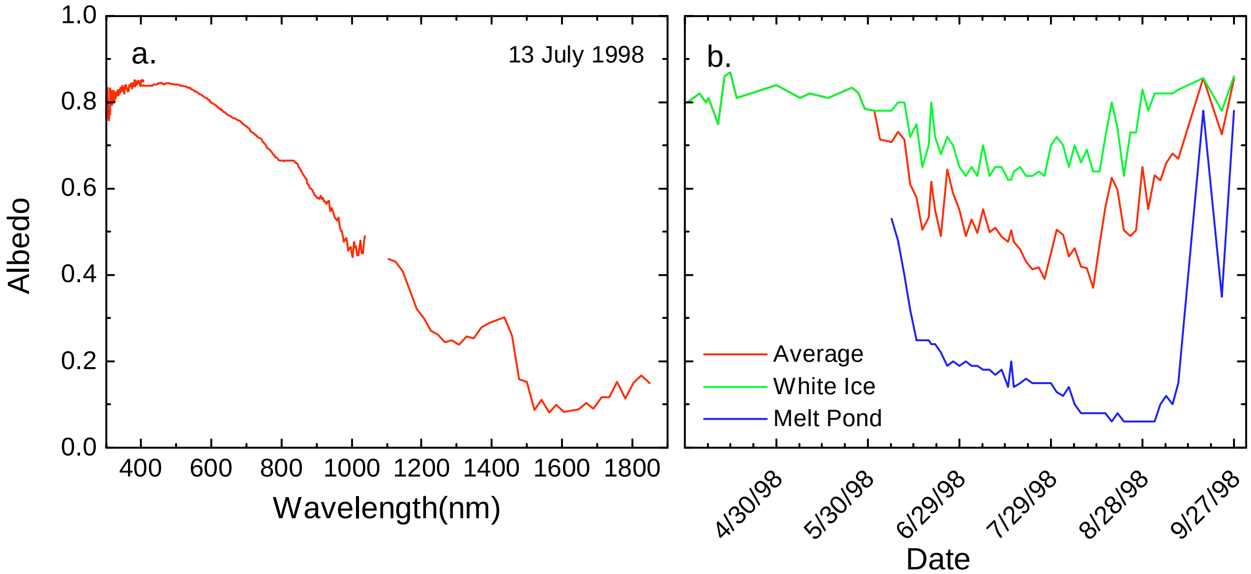

Figure 1. (a) Example of spectral albedos for melting, multiyear white ice observed in the ultraviolet, visible and infrared portions of the spectrum. (b) Time series of total albedo averaged along a 200 m transect line, together with average melt pond and white ice albedos along this same line.

Our microimaging system was used to study and document the structure of the surface scattering layer and of the interior of the ice. Measurements of freeboard level were made frequently at the main floe to estimate area-averaged mass changes and meltwater storage by the ice. Whenever clouds were absent or sufficiently high, helicopter surveys were made of the surrounding ice. Instruments flown on various flights included: an aerial mapping camera, video camera, spectralradiometer, infrared thermometer, digital camera and laser altimeter. Reduction and analysis of all these data are just beginning.

We are also working on ways to ways to determine structural/optical changes, heat storage, and light transmission in summer sea ice using Monte Carlo and multistream radiative transfer models. We are currently testing a cylindrical, multilayer Monte Carlo model that should allow us to determine vertical variations in the optical properties of the ice from radiation data collected in vertical boreholes during SHEBA. The model will also be used in the interpretation of optical data collected in the laboratory from natural sea ice cores. We have carried out preliminary measurements of the optical properties of first-year ice at warm temperatures and are working to extend our laboratory-based studies of temperature-induced changes in microstructure to include multiyear ice. Finally, we have published a paper discussing the theoretical treatment of light propagation in sea ice, and have in press a paper that describes how various types of included particulates affect radiative transfer in sea ice.

RESULTS

While we are only in the early stages of data reduction and analysis, there are several results of interest:

(1) Soot levels in regions where the heat and mass balance measurements were made appear to be too low (3-4 ng/g) to significantly affect melt rates or radiative transfer in the ice. This is important because it means that the presence of the ice station did not impact the natural melt cycle.

(2) Summer leads were stratified by meltwater runoff for weeks at a time, trapping substantial amounts of solar energy near the surface and causing about 5 m of lateral ablation on the edges of both first-year and multiyear floes. The surprising infrequency of downward mixing events suggests that lateral melting may play a more important role in the summer decay cycle than previously believed.

(3) Analysis of spatial variations in albedo show a linear relationship between melt pond fraction and total albedo (Fig. 2), indicating that regional albedos can be estimated from information on pond coverage. However, the slope and intercept of this relationship can change with time and ice type so that additional analysis of the full data set is needed to properly characterize spatial and temporal variability.

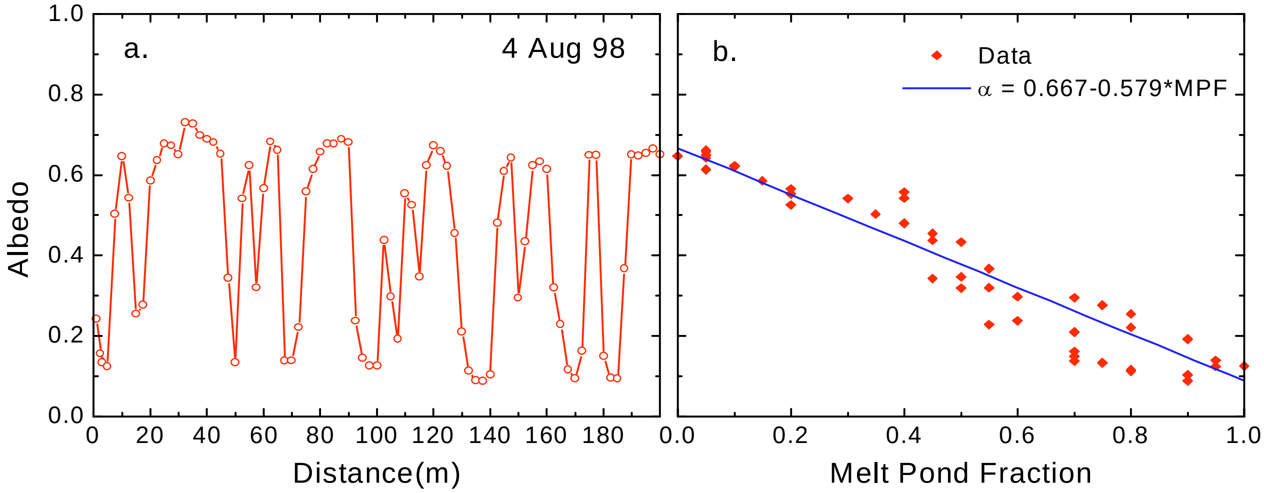

Figure 2. (a) Spatial variations in the total albedo of ponded multiyear ice in late summer. (b) Dependence of total albedo on melt pond fraction for the data shown in (a).

IMPACT/APPLICATIONS

Much of the data obtained during the field effort are unique and should provide the means to test a variety of 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, (3) the storage of solar heat in the water and its interaction with the ice cover, and (4) the seasonal evolution of the ice thickness distribution. Ultimately, we expect that this research will result in an improved understanding and treatment of ice-albedo feedback processes that can be used to enhance the accuracy of predictions made by large-scale climate and general circulation models.

TRANSITIONS

Our energy and mass balance data are fundamental to the interpretation of a wide range of atmospheric, oceanographic and remote sensing studies. Preliminary results have been incorporated into the SHEBA column dataset. Additional results will be provided to the SHEBA data bank as they become available.

RELATED PROJECTS

The work described above is part of a group project being carried out jointly with CRREL investigators who are funded under Contract N0001497MP30046. We are working closely with H. Eicken to link the optical results and assessment of regional albedos to the evolution of ice hydraulic properties as they pertain to the evolution of melt ponds and the microstructure of the upper ice layers. We also expect to be working closely with SHEBA ocean investigators (Morison and McPhee.; Paulson and Pegau) to study processes related to the recycling of solar energy absorbed by the ocean. In particular, we will be looking at how the state of the ice affects shortwave input to the water column, as well as at how this energy feeds back to alter ice concentration and thickness. Heat and mass balance data collected by this project will be used as input to modeling efforts funded under SCICEX, NASA-POLES, and SHEBA (D.A. Rothrock et al.; Lindsay et al.) that will calculate the ice thickness distribution within the SHEBA region throughout the experiment. Such information is needed by efforts to estimate regional fluxes from local observations. Achievement of the ultimate SHEBA objectives will require integration of the ice data with additional data on incident radiation, cloud conditions, turbulent heat fluxes, upper ocean conditions and remote sensing information. Accomplishing this integration will require cooperation with other SHEBA investigators funded by ONR and NSF.

PUBLICATIONS

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