SHEBA: The Surface Heat Budget of the Arctic Ocean

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Central to almost all aspects of Arctic system science is the problem of projecting the variations of Arctic climate during the next 100 years and beyond. Such projections are based on simulations performed with global numerical models of the climate system that represent the atmosphere, the oceans, land surfaces, the snow cover, and the sea ice cover. These simulations indicate that physical processes occurring in the Arctic ocean–atmosphere–ice system produce climate feedback mechanisms involving thermodynamic coupling of the sea ice, snow cover, and Arctic clouds. Two key processes are the ice–albedo and cloud–radiation feedback mechanisms. These feedbacks strongly influence the simulated Arctic climate; however, there is wide variation in the response of different climate models to perturbations, such as enhanced atmospheric greenhouse gases. Through its effect on the circulation of the atmosphere and ocean, the high sensitivity of the Arctic climate extends the uncertainty surrounding future climate scenarios to hemispheric and global scales.

The uncertainties associated with Arctic climate sensitivity have long been recognized by the Arctic research community. The combination of the importance of the Arctic sea ice cover to climate and the uncertainties of how to treat the sea ice cover led directly to SHEBA: the Surface Heat Budget of the Arctic Ocean. SHEBA is a large, interdisciplinary project that was developed through several workshops and reports. SHEBA was governed by two broad goals: understand the ice–albedo and cloud–radiation feedback mechanisms and use that understanding to improve the treatment of the Arctic in large-scale climate models. The SHEBA project was sponsored _jointly by the National Science Foundation's Office of Polar Programs Arctic System Science program and the Office of Naval Research's High Latitude Dynamics program. From a programmatic perspective, it was critical that SHEBA be an interdisciplinary experiment: one where a diverse group of researchers come together, each bringing their own particular expertise, to work on the common goals of the program. Achieving this interdisciplinary teamwork was one of the major successes of SHEBA.

Background

The ice–albedo feedback is a straightforward concept. The albedo is simply the fraction of the incoming sunlight that is reflected. Interestingly, snow has the largest albedo of any naturally occurring material on earth, while water has one of the smallest. The snow-covered sea ice reflects most (about 80%) but not all of the incident sunlight. This absorbed sunlight leads to melting, which in turn lowers the albedo, resulting in more absorbed sunlight, increasing melting, and the process continues. The ice–albedo feedback has been understood qualitatively for over 100 years. The challenge for SHEBA was to quantitatively define it in a form suitable for large-scale climate models. The ice–albedo relationship is significant because it is a positive feedback, so a small change can be amplified into a large difference.

The cloud–radiation feedback is more complex. During the long night of the Arctic winter, clouds act as a blanket, trapping thermal radiation and warming the surface. However, in summer, the sun is up, and clouds have two opposing effects on the surface heat budget: again, they act as a blanket, but they also act as an umbrella, reducing the amount of sunlight and cooling the surface. Prior to SHEBA we did not know even qualitatively— let alone quantitatively—which of these cloud effects is stronger, or whether Arctic cloud variables tend to increase or decrease in response to changes in the surface heat budget. Knowledge of these relationships is essential to evaluating the net interaction between Arctic clouds and the ice cover.

Ice Station SHEBA near the beginning of the drift on 28 October 1997. The Canadian Coast Guard Icebreaker Des Groseilliers *served as a base of operations for the field experiment. The huts housed scientific equipment and logistical supplies.*

The SHEBA program was divided into three phases. The first phase was directed towards analyzing existing data sets, formulating models, and determining the key knowledge gaps. During Phase 1 it became clear that the major obstacle to understanding the feedback mechanisms was a lack of a comprehensive, integrated set of observations, and most importantly a set of observations that extended over an entire annual cycle. This identified need led directly to the centerpiece of Phase 2: the year-long drift of Ice Station SHEBA. Phase 3 is currently underway and is directed towards analysis of the field results and model development.

Ice Station SHEBA

On 2 October 1997, the Canadian Coast Guard icebreaker *Des Groseilliers* stopped in the middle of an ice floe in the Arctic Ocean, beginning the year-long drift of Ice Station SHEBA. For the next 12 months, until 11 October 1998, Ice Station SHEBA drifted with the pack ice from 75°N, 142°W to 80°N, 162°W. At any given time, there were 20–50 researchers at Ice Station SHEBA. During the year over 200 researchers participated in the field campaign, spending anywhere from just a few days to the entire year.

Conducting a year-long sea ice experiment provided daunting scientific and logistic challenges: low temperatures, high winds, ice breakup, demanding instruments, and polar bears. It was truly a unique opportunity to observe with our eyes, as well as our instruments, the changes that a sea ice cover undergoes over the course of an annual cycle. For much of the year the ice was covered by snow. The average snow depth was about 35 cm, and the surface was uniform and had a large albedo. This was all changed by the onset of melt. The surface was transformed into a highly variegated mixture of bare ice, melt ponds, and open water, and the albedo decreased substantially.

Of course, the field program was much more than visual observations and personal impressions. There was an intense measurement program designed to obtain a complete, integrated time series of every possible variable defining the state of the "SHEBA column" over an entire annual cycle. This column is an imaginary cylinder stretching from the top of the atmosphere through the ice into the upper ocean. Observations included longwave and shortwave radiative fluxes; the turbulent fluxes of latent and sensible heat; cloud height, thickness, phase, and properties; energy exchange in the boundary layers of the atmosphere and ocean; snow depth and ice thickness; and upper ocean salinity, temperature, and currents. This year-long, integrated data set provides a test bed for exploring the feedback mechanisms and for model development.

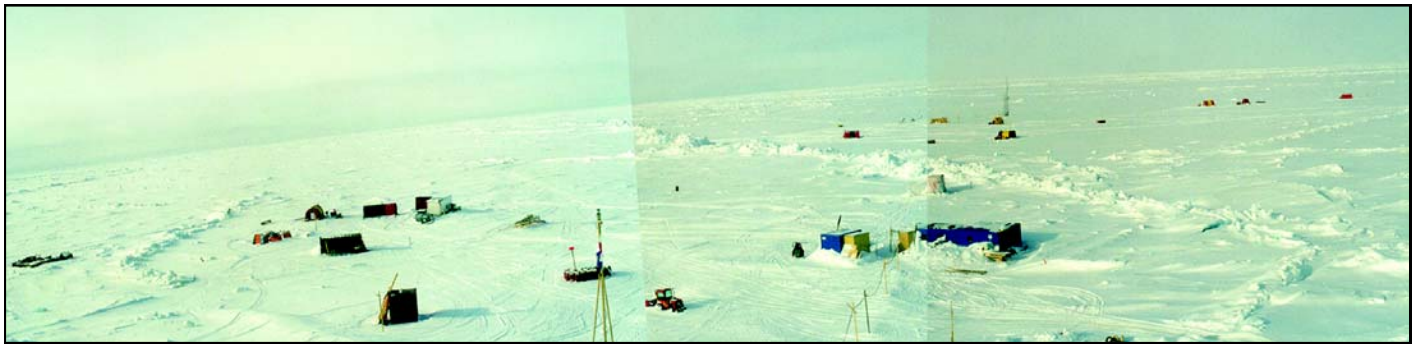
Results

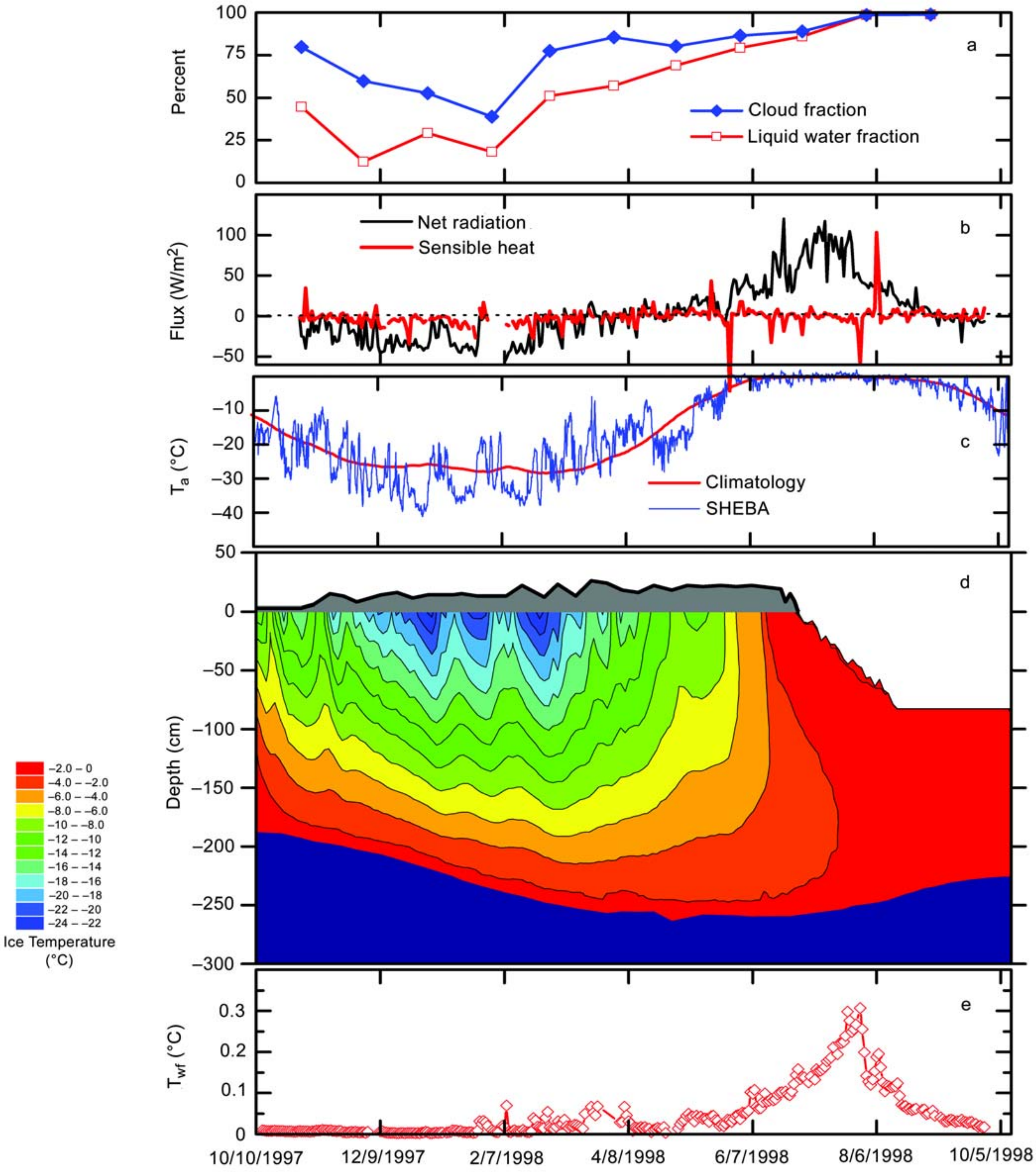
Cloud fraction and occurrence of liquid water in the cloud were monitored using a combination of radar and lidar. Clouds were pervasive at SHEBA. Even in midwinter the sky was overcast at least 40% of the time, and in the summer there was almost continuous overcast. There was cloud liquid water present throughout the year, with liquid fractions of nearly 100% in summer and approximately 20% in winter.

The net surface radiation flux (that is, the net surface longwave plus net surface shortwave irradiance) was negative during the winter. In winter there was little to no incident solar radiation, and the radiation flux was dominated by longwave radiation. The large changes in the radiative flux were due to clouds. The net radiative flux was large and negative under clear-sky or high-cloud conditions. Under low clouds the net radiation was much smaller in magnitude. By April the increasing contribution of solar radiation resulted in the net radiative flux shifting from negative to positive. The net radiative flux reached a maximum of 130 W/m^2 in mid-July, when incident shortwave radiation was large, the surface albedo was relatively small, and there were low clouds present with warm air aloft. This confluence of factors resulted in both the net shortwave and the net longwave fluxes being positive.

The effect of changes in winter cloud conditions was also manifested in surface temperatures, with the low-cloud regime resulting in surface temperatures 10–20°C higher than the clear-sky or high-cloud regime. The annual average air temperature at Ice Station SHEBA was only 0.6°C lower than the regional climatological average temperature. There were, however, several differences in the annual cycle of temperature. Comparing the climatological and SHEBA air

Views from the bridge of the CCGC Des Groseilliers *on 17 April 1998 and 8 August 1998.*





Selected annual cycle time series results from the SHEBA column: a) cloud fraction and occurrence of liquid water in the cloud; b) daily averaged net radiation fluxes; c) Ice Station SHEBA and climatological air temperatures; d) snow depth (gray-shaded area), ice thickness (blue-red and red-white boundaries), and ice temperature (color contours); and e) elevation of ocean mixed layer temperature above the freezing point.

temperature time series shows that the SHEBA year was relatively cool in winter and warm in spring. Most pronounced was the difference in the summer melt season. The SHEBA melt season was quite long, lasting almost 80 days, compared to an average of only 55 days. This long melt season had significant consequences for the ice mass balance.

The mass balance was measured at more than 100 sites. The snowpack accumulated slowly over nine months and then melted rapidly in only a few weeks in June. Rain on 29 May 1998 marked the start of the surface melt season. The annual cycle of ice thickness was similar at all sites, though there was considerable spatial variability in the magnitude of the mass balance. The cold front propagated down into the ice during fall, finally initiating bottom growth in November. There was a steady increase in ice thickness throughout the winter, with a gradual tapering in the spring. In the summer the ice was isothermal at its melting point. On average at SHEBA there were about 0.5 m of ice growth in winter and 0.64 m of surface melt and 0.62 m of bottom melt in summer. There was a substantial net thinning of the ice at the SHEBA measurement sites of 0.75 m during the SHEBA year.

The upper oceanic mixed layer was close to the freezing point for much of the year from fall through winter into late spring. With the onset of summer melt, the combination of a decrease in ice albedo and an increase in the area of open water and ponded ice allowed significant amounts of sunlight to be absorbed in the upper ocean. This solar energy resulted in warming that continued through the summer, with the mixed layer reaching a peak temperature of 0.3°C in late July. After this, a storm caused significant ice motion and mixing of the water. The storm-associated mixing resulted in the increased ice bottom melt and a decrease in water temperature.

The analysis of the field data has provided many insights into the ice–albedo and cloud–radiation feedbacks. The seasonal evolution of areal surface albedo had five distinct phases, corresponding to the following surface conditions: dry snow, melting snow, pond formation, pond evolution, and fall freeze-up. To model the seasonal evolution of albedo accurately, it is necessary to accurately determine the timing of these transitions and to know the relative areas of ice, ponds, and open water. For the relatively low, wet cloud cover present at Ice Station SHEBA during the summer of 1998, the cloud–radiation feedback was positive. The net effect of the clouds was warming and enhanced surface ablation.

The SHEBA data set is fundamental to the legacy of the SHEBA field experiment. The analysis of the Phase 2 field results has been completed, and the results are archived at http://www. joss.ucar.edu/cgi-bin/codiac/projs?SHEBA. These data are available for the use of all interested researchers.

Modeling

Some of the smallest-scale modeling is focused on the interaction of radiation and sea ice. A model of radiative transfer in sea ice has been developed that uses the physical properties of ice measured at SHEBA and computes the radiation profile through an ice column. Radiation measurements through sea ice at SHEBA suggest that the horizontal scattering of light in sea ice can play a significant role in the light transmitted around and through melt ponds. The column radiation model can act as a tool to improve the treatment of radiation in large-scale models to account for melt ponds and impurities in ice such as sediment, brine, and bubbles.

Modeling of the upper ocean has provided insight and generated questions about some of the unique phenomena observed during SHEBA. A steady warming of the upper ocean was measured in June 1998, with temperatures elevated above freezing. The solar radiation is the dominant heat source to the surface; it was not clear how this energy was reaching the upper ocean. The fraction of open water was below 5% in June, which would absorb a relatively small amount of energy. The diurnal cycle of the heating was synchronous with the insolation, so a more remote heat source was ruled out. A model of the upper ocean heat balance suggests that 8% of the incoming solar radiation at the surface was absorbed in the ocean, but it is not yet clear how this energy was transmitted through the ice cover.

Parameterizing the atmospheric turbulent fluxes over sea ice has led to a new formulation of the drag coefficient appropriate for large-scale models. The high-frequency turbulence data from SHEBA show that as the ice surface melts in summer, and ice concentration decreases, the surface becomes rougher and the drag coefficient increases, peaking at about 60% ice concentration. The vertical edge effects from melting floes and the disintegrating ice pack appear to dominate the drag effect in summer.

Modeling the vertical column of air, ice, and upper ocean following the SHEBA camp (the SHEBA column) has led to improvements in global climate models, such as the parameterization of cloud liquid water content in the Community Climate System Model (CCSM). Using the lidar cloud measurements, the atmosphere profiles from balloonsonde data, and surface fluxes from the meteorology tower, the column model showed a bias of –20 W/m^2 in the total longwave and shortwave radiation at the surface, resulting from the cloud-radiation scheme in the CCSM. Correcting the radiative path for the cloud liquid water amounts found in SHEBA reduced this bias significantly. The impact of this correction on global CCSM simulations has been a significant improvement in the surface radiation in the Arctic, leading to more realistic ice and snow cover in the model.

Sea ice models of both the thermodynamics and dynamics observed during SHEBA have shown the importance of processes that have yet to be incorporated into global climate models. The thermodynamic sea ice model used in the CCSM has been used to simulate the cycle of growth and melt observed at SHEBA. Using the meteorological observations, including radiation, precipitation, and the upper ocean temperatures, the CCSM ice model simulates the growth and melt of ice without melt ponds to within an average of 5 cm. The evolution of albedo that reflects the appearance and growth of melt ponds is not yet included in the CCSM ice model, so the modeled albedo shows a sharp transition to summer melt. The lateral melting and the reduction in ice concentration during summer are highly dependent on the formulation of the ice–ocean heat flux and the model's formulation of dynamic lead opening. The dynamic forcing on the ice in summer creates open water leads and allows greater solar energy input to the upper ocean. This energy, in turn, creates greater lateral ice ablation and more open water, which is the local-scale ice–albedo feedback. The ice models of the SHEBA camp illustrate the interdependence of the dynamics and thermodynamics in the ice–albedo feedback and suggest that both must be represented appropriately in global climate models.

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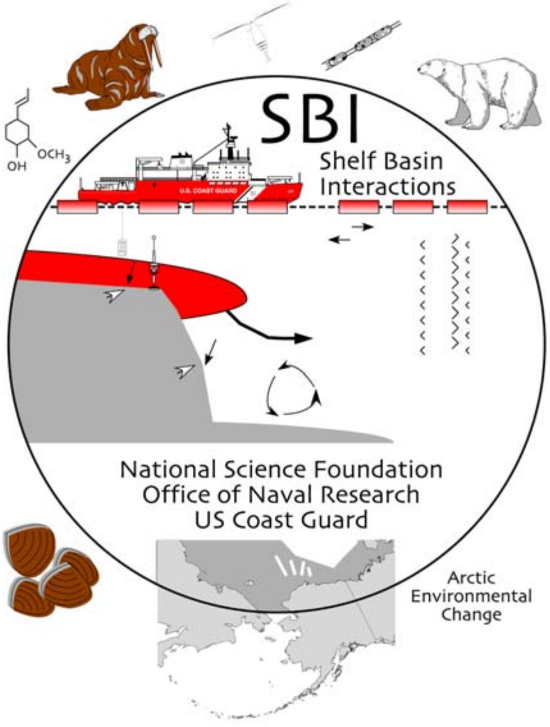
The Western Arctic Shelf–Basin Interactions Project

This article was prepared by Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Department of Ecology and Evolutionary Biology, The University of Tennessee, on behalf of all the SBI Phase II participants, who provided many of the concepts and results outlined in this article.

The National Science Foundation and the Office of Naval Research are supporting an interdisciplinary global change research study known as the Western Arctic Shelf–Basin Interactions (SBI) project. This project is part of the Ocean–Atmosphere–Ice Interactions component of NSF's Arctic System Science program. The goal of the SBI project is to improve our ability to assess the impacts of global change on the physical and biogeochemical connections among the western Arctic shelves, slopes, and deep basins. The SBI project focuses on shelf, shelf break, and upper slope water mass and ecosystem modifications, material fluxes, and biogeochemical cycles. The geographical focus is on the Chukchi and Beaufort Seas and adjacent upper slopes. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the Arctic shelves and the adjacent ocean basins. SBI therefore focuses on the outer shelf, shelf break, and upper slope, where it is believed that key processes control water mass exchange and biogeochemical cycles and where the greatest responses to climate change are expected to occur.



The SBI project consists of three phases over a 10-year period. Phase I (1998–2001) involved analyses of historical data, opportunistic field investigations, and modeling of specific regions and processes. SBI Phase II constitutes the field program taking place in the Bering Strait region and over the outer shelf, shelf break, and slope of the Chukchi and Beaufort Seas into the Arctic Ocean. Phase III will focus on the development of pan-Arctic models suitable for simulating scenarios of the impacts of climate change on shelf–basin interactions.

The SBI field program has been developed to focus on:

- Physical modifications of North Pacific and other waters on the Chukchi shelf and slope, and exchanges of these waters across the shelf and slope;
- Biogeochemical modifications of North Pacific and other waters over the Chukchi and Beaufort shelf and slope areas, with an emphasis on carbon, nutrients, and key organisms that represent the suite of trophic levels; and
- Comparative studies over the wide Chukchi and narrow Beaufort shelves and adjacent slopes to facilitate extrapolation and integration of the Western Arctic work to a pan-Arctic perspective. Integrated process and modeling studies of shelf–basin exchange processes and their sensitivity to global change will be an important methodology in this extrapolation. A physical–biological coupled model is being undertaken as part of the SBI study.

Through integrated field and modeling efforts, the SBI project is investigating the effects of glo-

Further information on the overall SBI project can be found on the SBI web site (http://sbi.utk.edu) or by contacting Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Marine Biogeochemistry and Ecology Group, Department of Ecology and Evolutionary Biology, The University of Tennessee, 10515 Research Drive, Suite 100, Bldg A, Knoxville, TN 37932; phone: 865-974-2592; fax: 865-974-7896; email: jgrebmei@utk.edu.