# Year on Ice Gives Climate Insights

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# Year on Ice Gives Climate Insights

Research involving a yearlong drift with the ice pack in the Arctic Ocean witnessed surprisingly thin ice at the start and even thinner ice at the end. Also, the extent of open water during the summer of 1998 in the Beaufort and Chukchi Seas was the greatest of the past 2 decades.

As the ice is melting from under your feet there is an understandable tendency to blame global warming. But the project, known as the Surface Heat Budget of the Arctic Ocean (SHEBA), though motivated by climate change, was not designed to detect global warming. Definitive climate change pronouncements can not be made based on a single experiment.

Rather, the interdisciplinary scientific party aboard and around the Canadian Coast guard icebreaker *Des Groseilliers*—Ice Station SHEBA (Figure 1)—was looking at feedback processes that govern the thermodynamics of the ice pack. Large-scale general circulation models indicate that Arctic sea ice may be a sensitive indicator of climate change and that feedback processes associated with the ice cover are not well understood. One of our significant findings was that Arctic summer clouds warm the surface and enhance ice melting.

We knew that clouds have two opposing effects on the surface heat budget. They act as an umbrella for solar radiation, reducing the incident shortwave radiation, and they act as a blanket for thermal radiation, increasing the net longwave radiation flux at the surface. However, prior to SHEBA we did not know which effect was greater. Preliminary results indicate that, for the pervasive low cloud conditions of the SHEBA summer, the blanket effect dominates.

Meanwhile, the annual cycle of albedo was found to be a combination of a smooth, gradual seasonal trend and rapid fluctuations caused by synoptic weather events such as rain and snow. Albedos were highest in the spring, decreased sharply when melting began in late May and early June, and decreased even more as the snow melted and ponds began to form.

Findings such as these put SHEBA on the road to fulfilling its first goal, to understand the ice albedo and cloud radiation feedback mechanisms. Next up is to apply this understanding to improve large-scale climate models [*Moritz et al.*, 1993].

Other data, on differential ice motion, also proved important and has already been incorporated into models. A granular sea ice model has been developed to simulate the ice pack around the field site, and some data from the SHEBA column—an imaginary cylinder from the top of the atmosphere down through the ice into the upper ocean—is already being used in single column models [*Pinto et al.*, 1999]. This modeling has shown the importance of including atmospheric changes and ice dynamics to accurately represent the ice thermodynamics. Simulations of large eddies have established that winter leads affect both the atmosphere and the ocean.

Overall we obtained an extraordinary data set describing in detail the properties of the atmosphere, ice, and ocean over an entire annual cycle. We now know a great deal about a particular place for a particular year. The true legacy of the project will lie in how these data are used to understand the feedback mechanisms and to improve models so that we can accurately simulate any site in the Arctic Ocean for any year.

## Freezing a Ship

To obtain the sort of high quality data set that we did, we followed in the footsteps of F. Nansen, freezing a ship into the ice and drifting with the pack for a year. The icebreaker served as the base of operations, with a camp and instruments located nearby on the ice. Between October 2, 1997, and October 11, 1998, Ice Station SHEBA meandered from 75°N, 142°W to 80°N, 162°W, traveling a distance of over 2800 km with a net displacement of 770 km (Figure 2). Daily drift distances ranged from as little as a few hundred meters to more than 30 km.

Spending a year on the ice provided formidable scientific and logistic challenges: low temperatures, high winds, ice drift, recalcitrant instruments, and polar bears. But there were also significant scientific and personal rewards. The insights came early and often. At the very beginning, while trying to find an ice floe to be the experimental site, we discovered that the ice was approximately 1 m thinner than expected. A concurrent submarine survey confirmed this, showing a mode of 0.9 m in the ice thickness distribution for the region surrounding Ice Station SHEBA.

Oceanographic measurements made at this time found that the upper ocean was warmer and fresher than 20 years earlier [*McPhee et al.*, 1998]. Isotope tracer measurements using $Be^7$ established that this heat was derived from insolation during the preceding summer and not input from below nor accumulation during prior summers. Taken together, these observations suggest that a significant amount of melting occurred during the summer of 1997.

## The Annual Cycle

A major objective of the field experiment was to obtain a complete time series of parameters defining the state of the SHEBA column—the imaginary cylinder—over an annual cycle. Observations in the column included radiative and turbulent fluxes; cloud height, thickness,

*Fig. 1. Ice Station SHEBA on October 28, 1997. The huts in the foreground housed scientific equipment, and the Canadian Coast Guard icebreaker* Des Groseilliers *served as a base of operations.*

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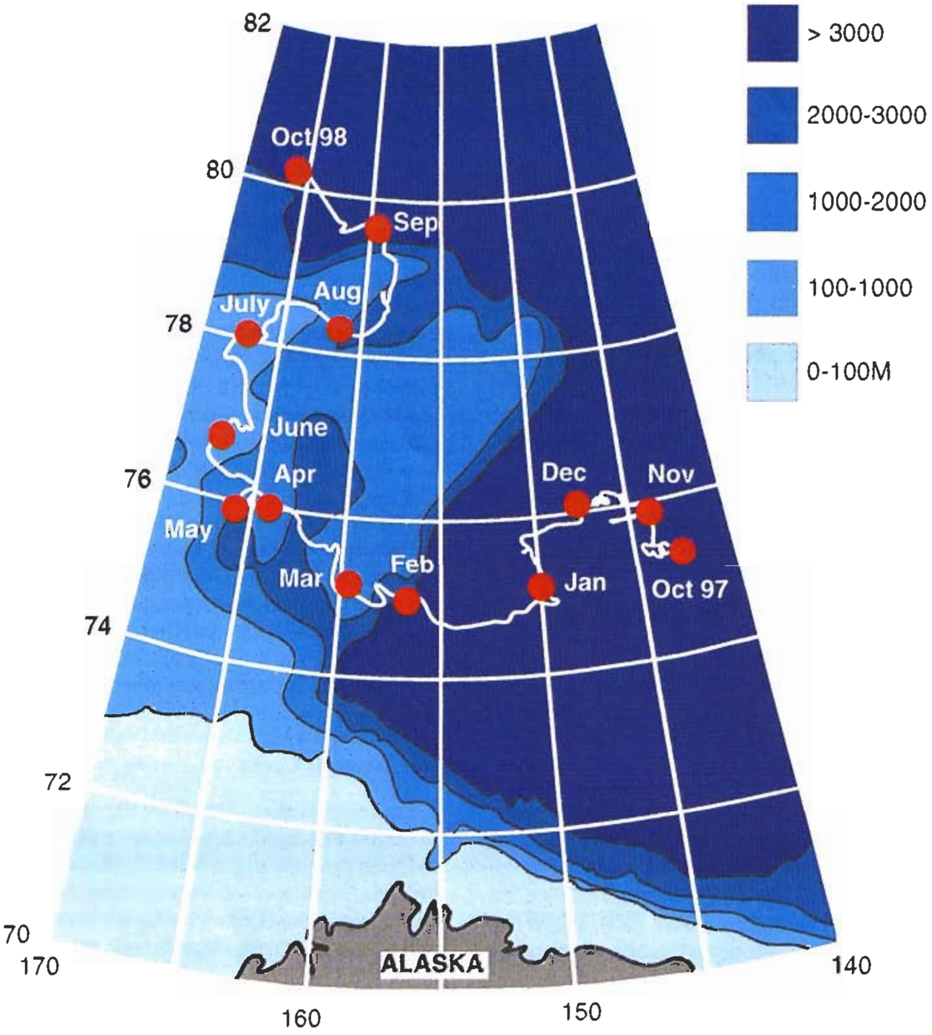

*Fig. 2. The drift track of Ice Station SHEBA from October 1997 to October 1998. Each dot represents the start of a month. The gray-shaded area at the bottom of the plot is the north coast of Alaska.*

and properties; energy exchange in the atmosphere and ocean boundary layers; snow depth and ice thickness; and upper ocean salinity, temperature, and currents.

A sampling of time series results from the SHEBA column is presented in Figure 3. A combination of radar and lidar was used effectively to monitor both cloud fraction and occurrence of liquid water in the cloud (Figure 3a). Though the Arctic Ocean is a desert, clouds were common at SHEBA. Makshtas et al. [1999] report that Arctic clouds have a bimodal distribution: the sky is usually either clear (cloud amounts 0-1 tenths) or overcast (cloud amounts 9-10 tenths). The cloud fraction reported by the lidar in Figure 3a can thus be interpreted as the fraction of the time that the sky is overcast.

Even in mid-winter, the sky is overcast at least 40% of the time; in summer the overcast is almost continuous. Surprisingly, there was cloud liquid water present throughout the year, even in winter. In spring and summer, the surface-based cloud observations were augmented by intensive aircraft surveys of cloud properties as part of a collaborative program on Arctic clouds [*Curry et al.*, 1999].

The winter atmospheric conditions at SHEBA exhibited two regimes largely defined by the effects of clouds on the net longwave radiation. There was a low-cloud regime and a high-cloud or no-cloud regime. Each regime produced distinctive responses in the lower atmosphere and in the snow and ice. For the low-cloud regime, the near-surface air temperatures were 10-20°C warmer, surface fluxes and stress were larger, and wind speeds were higher than the clear-sky or high-cloud regime.

The clouds appeared to be produced by both synoptic and mesoscale atmospheric baroclinic processes above the inversion, with temperature variations there smaller than those observed at the surface. Hence the radiative effects of the clouds control the temperature difference across the inversion and thereby produce most of the temperature variations at the surface. The process depends only on the horizontal temperature gradients (such as warm advection) in the free atmosphere for the baroclinicity to produce the clouds.

During winter, the net radiation—the net surface longwave plus net surface shortwave irradiance—was negative (Figure 3b). Our sign convention is that a negative radiative flux cools the surface. The total radiation became positive in early April because of the increasing contribution of shortwave radiation. It reached peak values of over 130 W m$^{-2}$ in mid-July, when the incident shortwave was large, the surface albedo was relatively small, low clouds were present, and warm air was aloft. During this period, both the net shortwave and the net longwave fluxes were positive.

Magnitudes of the monthly mean sensible heat fluxes—measured at five levels on a 20-m tower with sonic anemometers/thermometers—were small, varying from a winter range of -4 to -10 W m$^{-2}$ to summer values from -2 to + 2 W m$^{-2}$. Though small, the monthly variations in sensible heat appear to be directly related to the annual cycle of the surface and boundary layer air temperatures.

Near-surface atmospheric observations revealed episodes during SHEBA for which the Monin-Obukhov similarity theory did not hold, primarily because of nonstationarity and advection. Monin-Obukhov similarity theory is the foundation of boundary-layer meteorology. Its basic assumption is that the vertical turbulent fluxes of momentum and sensible and latent heat are constants with height near the surface and thereby provide scales that collapse any near-surface meteorological statistics into universal functions.

Comparing the 2-m air temperature at SHEBA with the climatological 2-m air temperature [*Martin and Munoz*, 1997] shows that the SHEBA station was relatively cool in winter and warm in spring (Figure 3c). Averaged over the year, the temperature at the ice station was 0.6°C less than the climatological 2-m air temperature derived from data from 1979 to 1996.

Nevertheless, the melt season at SHEBA was long, lasting nearly 80 days. By comparison, melt seasons observed at the several drifting ice stations of the former Soviet Union averaged 55 days and ranged from 20 to 83 days [*Lindsay*, 1998].

Snow depth increased quickly in the fall, then slowly through the winter, reaching an average depth of 34 cm in the spring (gray shaded area in Figure 3d). More than half of the snowpack consisted of depth hoar—larger, well-metamorphosed crystals. The snowpack

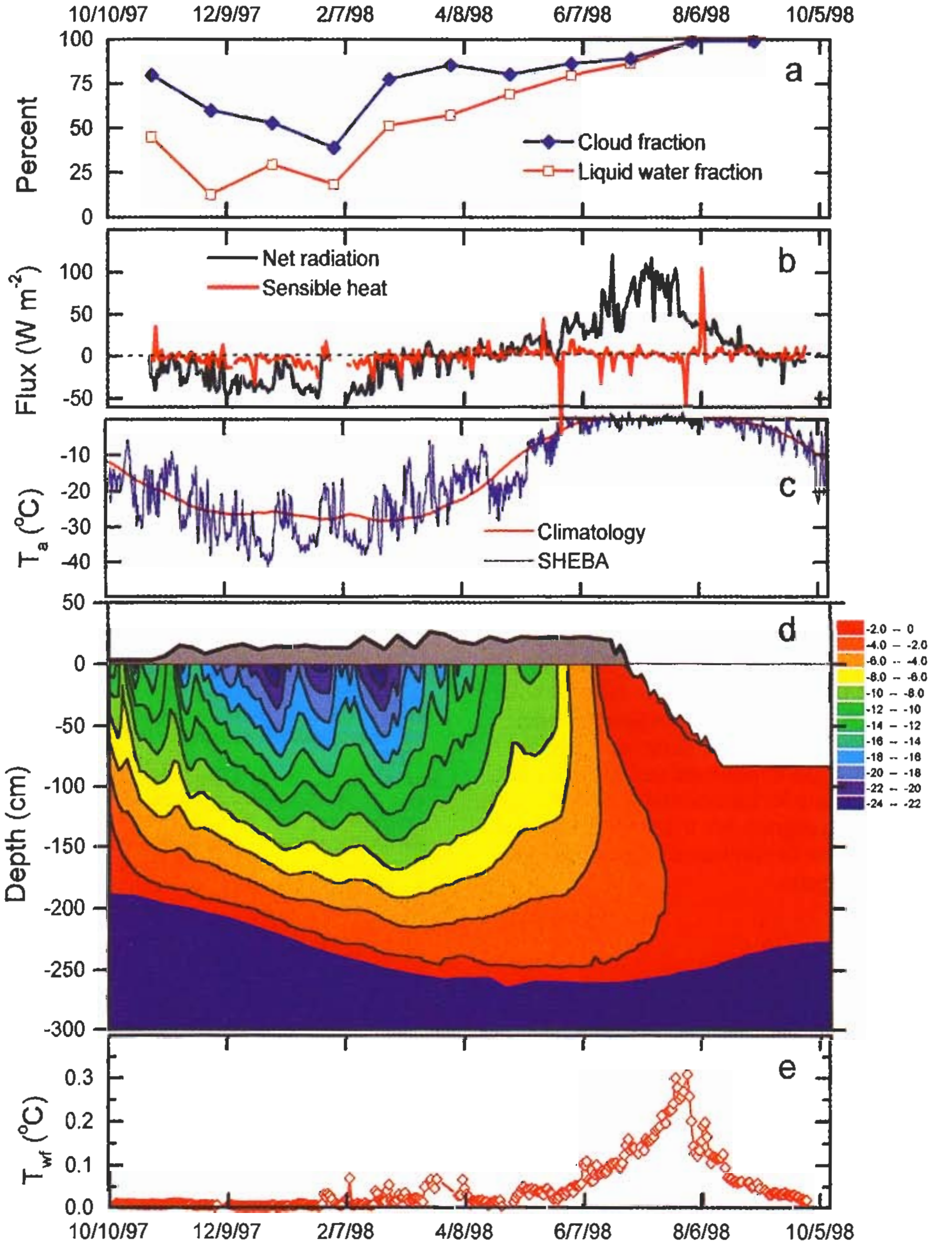

*Fig. 3. Annual time series results from the SHEBA column. a) cloud fraction and occurrence of liquid water in the cloud; b) daily averaged net radiation fluxes; c) air temperatures at Ice Station SHEBA and from climatology; d) snow depth (gray-shaded area), ice thickness (blue-red and red-white boundaries), and ice temperature; e) ocean mixed layer temperature relative to the freezing point.*

took 9 months to accumulate and essentially melted in only a few weeks. Ice growth started in November and continued until June.

Rain on May 29 marked the beginning of the melt season, which continued to late August for surface melting and early October for bottom melting. Melt ponds, areas where the surface meltwater collects, were pervasive from June through August, covering over 20% of the surface during the height of the melt season. These ponded areas have an albedo of only 0.2 to 0.4 compared to 0.6 to 0.7 for bare ice.

Undeformed multiyear ice in the SHEBA column grew 75 cm during winter (Figure 3d), but lost 70 cm through surface ablation plus 40 cm through bottom ablation during summer. Combining the growth and ablation gives a net ice thinning of 35 cm during the SHEBA year. This thinning came as a surprise, because we started with anomalously thin ice in October 1997 and had drifted over 500 km farther north by October 1998.

In general, the oceanic mixed layer was close to the freezing point 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, warming it. The warming continued through the summer and the mixed layer reached a peak temperature of 0.3°C in late July, when a storm caused significant ice motion and mixing of the water. A decrease in the water temperature and an increase in ice melt indicated that the storm transferred a portion of the heat stored in the water to the ice.

This summer warming of the upper ocean was even more pronounced in areas of open water (leads). During June and July, meltwater runoff from the ice produced a noticeable buildup of fresh water and heat in leads. By July 22, there was a 1.3 m thick warm, fresh surface layer with a temperature near 2°C and a salinity of only 2 practical salinity units. Until its depth exceeded the draft of surrounding ice floes, this stratified surface layer limited the transfer of heat from within the leads to the ice bottom. The late-July storm erased this stratified layer, after which there was not enough meltwater produced to reestablish it.

Another noteworthy feature of Figure 3e is the increase in mixed-layer temperature in March. This was not due to solar heating, but rather to entrainment of warmer deeper water as a storm rapidly moved the ice station into the shallower water on the Chukchi Cap.

## Horizontal Variability

If conditions were spatially uniform, the description provided by the SHEBA column would be sufficient. However, the atmosphere, ice, and ocean all exhibit considerable horizontal variability. Aerial, surface, and underwater surveys were conducted to assess this variability and extend the column measurements to larger scales. An extensive research aircraft program was undertaken from April through July to examine cloud properties, radiative fluxes, and ice surface conditions [*Curry et al.*, 1999]. These flights covered thousands of kilometers under a variety of cloud conditions.

In addition, helicopter surveys of ice concentration, pond fraction, and surface morphology were made approximately weekly from mid-May until the end of the experiment. Researchers ranged on foot and by snowmobile up to 10 km from the ship, to survey snow and ice properties and to service remote sites. These remote sites provided additional long-term data on snow and ice properties and time series of radiative and turbulent fluxes.

From 800 km overhead, the Canadian Radarsat satellite acquired 200 synthetic aperture radar (SAR) images of the SHEBA region over the course of the year. These dramatically illustrate the large-scale ice dynamics and surface features that provide the context for the SHEBA ice camp. U.S. Navy nuclear submarines, the USS *Archerfish* in October 1997 and the USS *Hawkbill* in August 1998, surveyed ocean properties as well as the thickness and bottomside topography of the ice cover as part of the submarine science program. The survey involved a 150 km wide pattern that was more than 1300 km in total length. The median ice thickness was 1 m and the mean was just 1.5 m, with 10% of the area covered by open water. An autonomous underwater vehicle made similar measurements on a smaller scale at the SHEBA camp.

In the albedo research, as melt progressed, the melt ponds deepened and became more numerous, resulting in a slow downward trend in albedo to a minimum spatially averaged value of 0.4, from the high of 0.8-0.9 in the spring. During the melt season a significant increase occurred in the spatial variability of the albedo. At the end of August, the albedo quickly increased with the onset of fall freezeup, as the ponds froze and the surface became snow covered. Key quantities defining the timing and the amplitude of the albedo cycle include the date melting begins, the duration of the melt season, the initial snow depth, and the evolution of the amount of open water and melt ponds.

From the sequence of Radarsat SAR images, the NASA-funded Radarsat Geophysical Processor System tracked the motion of the ice on a 5-km grid over a 200 x 200 km area centered on the SHEBA camp. The resulting differential ice motion, which was incorporated into models, shows divergence creating areas of open water and convergence forming ridges of ice blocks.

A seasonal change was observed in a key term in the ice momentum balance equation in that in winter internal ice stresses were considerable, while in summer they were essentially zero. Inertial oscillations of the ice cover were common during summer, though for the most part there was little direct impact on ice-ocean energy exchange, since the ice and mixed layer oscillated in phase.

Data analysis and theoretical modeling continues. Data are being archived at the Joint Office for Scientific Support (http://www.joss.ucar.edu/sheba/) and will be made available to the scientific community by the end of 2000. Other details about SHEBA are currently available on the SHEBA home page (http://sheba.apl.washington.edu/).

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