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THE SUMMERTIME THERMOHALINE EVOLUTION OF AN ARCTIC LEAD: HEAT BUDGET OF THE SURFACE LAYER

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1. INTRODUCTION

Leads and polynyas play an important role in coupling the atmosphere with the Arctic Ocean. The focus of this paper is on the summer season when the net surface heat flux is dominated by solar insolation that heats the upper ocean and melts ice and snow. Meltwater flowing into leads from surrounding ice floes causes vertical density stratification which inhibits turbulent mixing and traps heat in a shallow surface layer. If this surface layer does not extend below the bottom of the surrounding ice floes, the trapped heat is available for melting the sides of ice floes and for transfer to the atmosphere and deeper ocean. If the heat is transported below the surrounding ice floes, it may also be used to melt the undersides of the floes.

The ratio of side to bottom melt of ice floes determines the strength of an albedo-feedback mechanism which in turn controls the evolution of the average surface area covered by ice and open water. If the side (or lateral) melt is large, the fractional area covered by open water increases as the summer season progresses and the solar insolation into the ocean also increases because the albedo of a water surface is much lower than an ice floe surface. If side melt is small, the fractional area covered by open water remains small and solar heating of the upper ocean is modest.

The objective of this paper is to describe the heat budget of the fresh surface layer which forms at the surface of Arctic leads in summer. One of the components of this budget is the heat flux used to melt the surrounding ice floes. The melt rate associated with this heat flux will be compared to observations of the melt rate of an adjacent floe.

2. OBSERVATIONS

We participated in the Surface Heat Budget of the Arctic (SHEBA) field experiment in the Beaufort Sea. Measurements were made from lead edges and from a small boat. Measurements included: 1) incoming and outgoing solar radiation over leads and 2) vertical profiles of temperature, salinity and optical properties on vertical sections across and around the perimeter of leads. In this paper we focus on observations of temperature (T) and salinity (S) made in a lead, named Nanook, from 7 June to 8 August, 1998. This lead was located near the SHEBA ice camp that drifted from 77.0N, 166.7W to 78.6N, 158.7W during this period. Observations were made for several hours nearly every day with Seabird CTDs deployed from a small boat. Two CTDs were used, one mounted on the bow which measured T and S at a depth of about 15 cm while the boat was underway, and the second which profiled to a depth of several meters while slowly towed by the boat. The perimeter of the lead was mapped by the use of two GPS units, one on the boat and the second on an adjacent ice floe. The average area of the lead was 12,000 m^2 and the average length of the perimeter was 800 m (Days 185 to 199). The maximum distance across the lead was approximately 200 m.

Several investigators made atmospheric measurements during SHEBA. These included wind speed and direction, temperature, humidity, downward solar irradiance and downward longwave irradiance. The primary source of atmospheric measurements used for this paper is Andreas, Fairall, Guest, and Persson. When there were gaps in their measurements, these were filled with measurements made by the SHEBA Project Office (Moritz). These atmospheric observations were combined with our measurements of lead surface temperature and surface albedo to estimate exchanges of heat between the lead surface and the atmosphere (see below).

Perovich and his colleagues measured the rate of lateral melting of a floe adjacent to the lead. This melt rate was compared to the melt rate inferred from the heat budget of the fresh surface layer heat (see below).

3. SUMMER CYCLE

The summer cycle is illustrated in Figure 1. At the beginning of the summer season T and S were nearly uniform within an upper mixed layer approximately 30 m in depth with T close to the freezing point. This mixed layer formed during the previous winter under the influence of wind-forced ice motion, surface cooling, and brine rejection associated with ice formation. As solar insolation increased during the summer, the total surface heat flux into the lead and surrounding ice floes changed from net cooling to net heating which melted ice and snow. The meltwater formed a fresh surface layer with temperature above freezing. The near-surface temperature of Nanook lead was consistently above freezing after 21 June. By 11 July the average temperature of Nanook lead at a depth of 15 cm ranged

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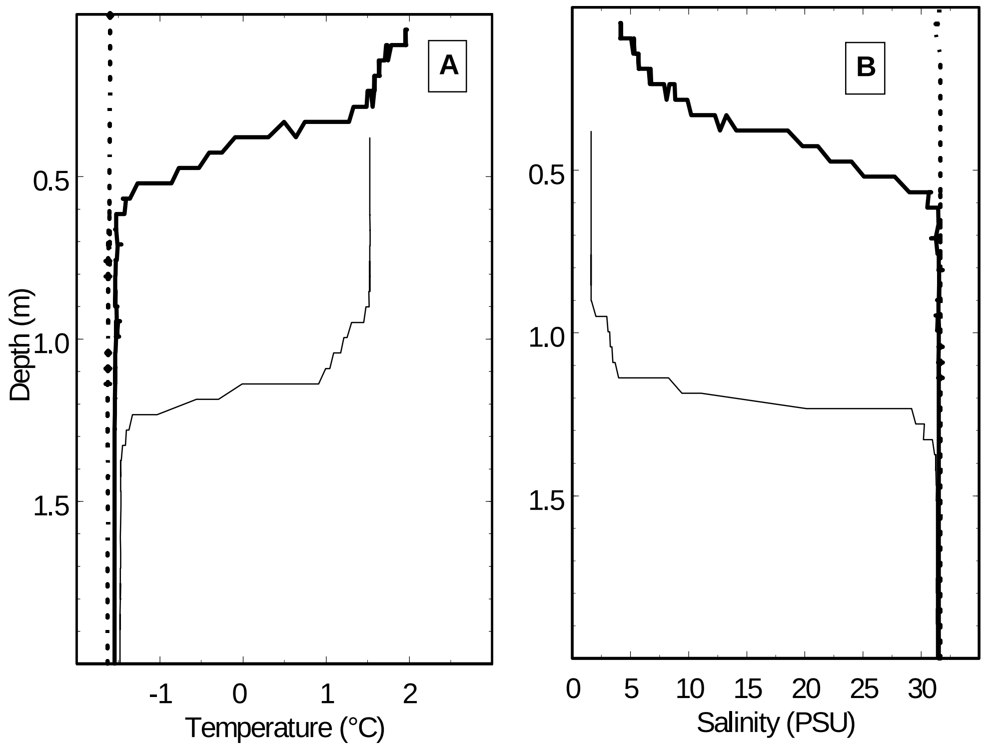

Figure 1. Temperature (A) and Salinity (B) profiles within the upper 2 m of Nanook lead. Profiles collected on June 19 (dotted line), July 11 (thick line), and July 22 (thin line) are shown.

from 0.9 to 2.2 C with a mean of 1.6 C. The thickness of this warm, fresh layer was approximately 0.5 m and surface salinity was about 4 psu (Figure 1). As summer progressed, the modified layer deepened to 1.2 m and salinity decreased to a uniform 2 psu in the upper 0.9 m (Figure 1). On 28 July winds increased to 15 m/s and remained near this level during most of the following day. The wind stress caused ice motion and turbulent mixing which was sufficiently energetic to deepen the surface mixed layer to 15 m as observed on 1 August. Following this date, the melt rate was not sufficient to reestablish a persistent, low-salinity layer at the surface.

4. HEAT BUDGET

The heat budget of the fresh surface layer was estimated for the period 4 to 18 July (Year Day 185 to 199). There was a persistent fresh layer during this period that gradually deepened (Figure 2A). The fresh layer reached a maximum depth of 1.2 m just after the end of the period. The depth of the fresh layer did not exceed 1.2 m because the depth of the surrounding ice floes was less than 1.2 m by 18 July and melt water flowed beneath the ice following this date.

The components of the heat budget of the fresh layer include: 1) absorbed shortwave radiation (difference between solar radiation entering the surface and exiting the base of the fresh layer), 2) net longwave radiation entering the surface (difference between downward and upward longwave radiation just above the surface), 3) sensible heat exhange between the surface and the atmosphere, 4) latent heat of evaporation loss from the surface, 5) heat storage in the fresh layer, and 6) heat loss from the fresh layer used to heat and melt the ice of surrounding floes.

The measured average downward shortwave radiative flux for Year Days 185 to 199 was 239 Wm^{-2}. Assuming a constant albedo of 0.067 (Pegau and Paulson, 2001), an average of 16 Wm^{-2} was reflected and backscattered to the atmosphere. The average transmitted through the base of the fresh layer was 101 Wm^{-2} and the average absorbed by the fresh layer was

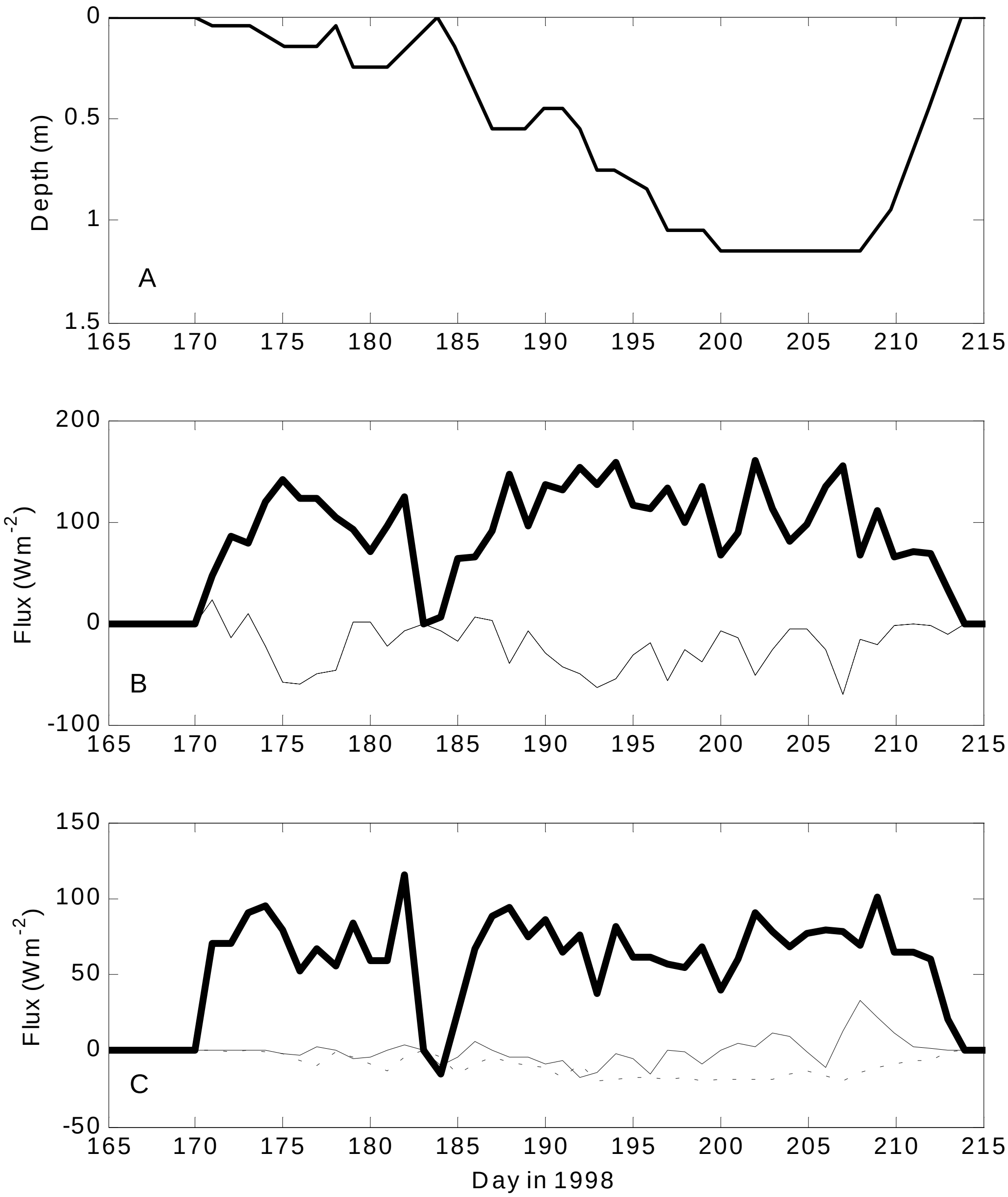

Figure 2. The depth of the freshwater layer (salinity < 29 PSU) is shown in panel A. Panel B shows the shortwave radiation absorbed in the freshwater layer (bold) and the sum of the sensible, latent, and net longwave radiation (thin). Panel C shows the heat loss due to molecular diffusion at the fresh-salt water interface (dashed), the rate at which heat is stored in the fresh layer(thin solid), and the sum of all heat fluxes (bold) that represents the amount of heat used to melt ice. All heat fluxes apply to the freshwater layer only and positive values represent a flux into the layer, negative fluxes are out of the layer.

122 Wm^{-2}. Absorption was estimated from measurements of optical properties and an expression for downward irradiance consisting of the sum of four exponential terms (Pegau, 2001). The time series of absorbed shortwave radiation is shown in Figure 2B.

The measured average downward longwave radiative flux for Days 185 to 199 was 294 Wm^{-2}. The average upward longwave radiative flux from the lead surface was 319 Wm^{-2}, estimated from measurements of surface temperature and the Stefan-Boltzmann equation. The emissivity was assumed to be 0.97. Tthe average net downward longwave radiative flux was –25 Wm^{-2}.

The average (Days 185 to 199) sensible and latent heat fluxes from the atmosphere to the lead surface (downward) were 5 and 3 Wm^{-2}, respectively. These fluxes were estimated by use of bulk formulas suggested by Andreas and Murphy (1986). The time series of the sum of net radiative, sensible and latent heat fluxes is shown in Figure 2B.

The flux of heat due to molecular conduction at the base of the fresh layer was estimated from observations of the temperature difference across the base. Based on these observations, a linear gradient over a vertical distance of 10 cm was assumed and the average (Days 185 to 199) flux out of the layer was 15 Wm^{-2}. The time series of the conductive flux is shown in Figure 2C.

The rate of heat storage in the fresh layer was estimated from observations and the time series is shown in Figure 2C. The storage flux averaged over Days 185 to 199 was 6 Wm^{-2}.

Given the heat flux components described above, the residual is a flux of heat from the lead used to melt the surrounding floes. The average (Days 185 to 199) residual used to melt ice was 67 Wm^{-2}. This corresponds to an average lateral melt rate of 0.24 m/day. The lateral melt rate measured by Perovich and his coworkers at a single location over the same period was 0.16 m/day. Given the uncertainty of whether a single measurement of lateral melt is representative, the agreement is satisfactory.

5. CONCLUSIONS

The summer cycle observed in Nanook lead illustrates the establishment of a fresh, warm, surface layer with very low surface salinity (2 psu) and temperature well above freezing (2 C). The strong vertical stratification associated with this layer inhibited mixing until near the end of July when a passing storm generated enough ice motion and turbulence to vertically mix the 1-m thick surface layer down to a depth of 15 m. The stratified surface layer may have limited the vertical transfer of heat to melt bottom ice, especially in the first part of the summer when the depth of the surface layer was less than the draft of surrounding ice floes. Hence the role of stratified surface layers in leads may be to apportion more heat to melting the sides of ice floes than to their bottoms.

The absorption of solar radiative flux dominates the heat budget of the fresh surface layer. The next largest term is the flux of heat from the fresh layer used to melt surrounding ice floes. The mean lateral melt rate of the surrounding floes estimated from the heat budget is in satisfactory agreement with the lateral melt rate observed at a single location.

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