Estimates of ocean heat flux at SHEBA

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Received 2 October 2001; revised 11 March 2002; accepted 11 March 2002; published 15 May 2002.

[1] Observations of sea ice mass balance and temperature made during the year-long Surface HEat Budget of the Arctic Ocean (SHEBA) field experiment were used to calculate monthly estimates of the ocean heat flux for a variety of ice types. The ocean heat flux displayed a strong seasonal cycle, with values of a few W m$^{-2}$ from October through June followed by a steady increase in June and July. By the end of July the ocean heat flux for undeformed ice reached a peak value of about 33 W m$^{-2}$ during a period of substantial ice motion. The annual average ocean heat flux for multiyear ice ranged from 7.5 W m$^{-2}$ for undeformed ice to 10.4 W m$^{-2}$ for a melt pond to 12.4 W m$^{-2}$ for an old ridge. Annual averages measured at SHEBA were more than twice as large as values observed in 1975 during AIDJEX. INDEX TERMS: 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 1863 Hydrology: Snow and ice (1827); 4572 Oceanography: Physical: Upper ocean processes

1. Introduction

[2] Changes in the thickness and extent of the Arctic sea ice cover may be harbingers of climate change. A key element affecting the mass balance of sea ice is the transfer of heat from the ocean to the underside of the ice, the ocean heat flux \[ F_w \]. Examining undeformed multiyear ice, they found peak values as \( F_w \) salinity, and current, as well as estimating ice bottom roughness. measuring times series of vertical profiles of ocean temperature, balance \[ relatively simple measurements of ice temperature and mass SHEBA (Surface HEat Budget of the Arctic Ocean) field experi-

2. Observations and Methods

[4] There was an extensive mass balance measurement program during the SHEBA field experiment [Perovich et al., in press]. Five sites had thermistor strings to measure the ice temperature and thickness gauges to measure the ice mass balance. For convenience and consistency in nomenclature, each site was named after a city: Pittsburgh, Quebec, Seattle, Tuk, and Baltimore. The Pittsburgh mass balance site was relatively thick multiyear ice. Quebec was a multiyear hummock with a thin snow cover. In fall 1997 the Seattle mass balance site was an area of ponded multiyear ice with nearby hummocks. Seattle was also heavily ponded in summer 1998. The Tuk mass balance site was an old consolidated ridge that was 3–4 m thick at the beginning of the experiment. The Baltimore mass balance site was first-year ice. Ice at this site started growing in late August 1997 and was about 40 cm thick in mid-October 1997. Baltimore was heavily ponded in the summer of 1998, with many of the ponds melting all the way through to the ocean. The sites were located more than 100 m and less than 5 km from one another.

[5] The instrumentation at each mass balance site consisted of several thickness gauges, a thermistor string, and a datalogger. The thermistor strings were polyvinyl-chloride rods with thermistors spaced at 10-cm intervals. A vertical hole was drilled through the ice, and the thermistor string was installed so that it extended from the air through the snow, through the ice, and into the upper ocean. The accuracy of the thermistors was ±0.1°C. Thermistor measurements were recorded hourly and stored using a Campbell Scientific Inc. CR-10 datalogger. Hot-wire thickness gauges [Untersteiner, 1961; Perovich et al., in press] were used to measure ice accretion or ablation at the underside of the ice. Uncertainties in gauge readings were typically less than 0.5 cm. Gauges were read every 1–2 weeks during winter and every 4 days during summer.

[6] Ice temperature profiles, and measurements of ablation/ accretion at the ice bottom can be used to calculate the ocean heat flux by treating it as a residual of the conductive \( Q_c \), specific \( Q_s \), and latent \( Q_l \) heats of the ice:

\[ F_w = \frac{1}{\Delta t} (Q_c + Q_s + Q_l) \]  

\( Q \) represents heat fluxes integrated over a time period \( \Delta t \). The sign convention is that cooling, freezing, and upward heat flow are negative, while warming, melting, and downward heat flux are
The ocean heat flux is the residual of the other fluxes. Negative values represent cooling, freezing, and downward heat conduction. The ocean heat flux is the residual of the other fluxes.

The thermal conductivity of sea ice \((k_i)\) is defined using Untersteiner [1961] expression. The time integral in Equation (2) was numerically evaluated using a time step of 1 day. The derivative \(\partial T/\partial z\) was determined from a linear fit of observed temperatures across the reference level.

The specific heat \((Q_s)\) is the change in heat content of the ice and is

\[
Q_s = \rho \int c_i dT dz.
\]

where \(\rho\) is the ice density and \(c_i\) is the specific heat of sea ice. We used Schwerdtfeger's [1963] expression for the specific heat of sea ice.

The latent heat \((Q_l)\) is

\[
Q_l = \rho \int q_m dz.
\]

The integrals over \(dz\) in equations (3) and (4) are from a reference level in the ice to the bottom of the ice. \(q_m\) is the heat needed to melt a parcel of ice and is calculated using Schwerdtfeger's [1963] relationship. \(Q_s\) and \(Q_l\) were numerically integrated over \(dz\) using a spacing of 5 cm.

The expressions for \(Q_s\), \(Q_l\), and \(Q_\ell\) were substituted into Equation (1) to determine \(F_w\). Both \(Q_s\) and \(Q_l\) depend on salinity, which was a complex and variable function of both position in the ice and time. Ice cores were taken at each thermistor site in the spring, but there was not a complete record of the evolution of the salinity profile near the bottom of the ice. Based on the measured profiles, an average value of 4 o/oo was used to represent the lower portion of the ice at all sites for the entire year. An average value of 900 kg m\(^{-3}\) was used for the sea ice density.

The major difficulty in this approach lies in precisely determining the amount of ice growth or melt at the bottom. The uncertainty in the thickness gauge measurements was ±0.5 cm, representing ±1.5 MJ m\(^{-2}\). The approach works best when averaging over long time intervals. For example, based on potential gauge error the uncertainty in ocean heat flux is 17.5 W m\(^{-2}\) for daily estimates, 2.5 W m\(^{-2}\) for weekly estimates, and 0.6 W m\(^{-2}\) for monthly estimates.

### Figure 1.
The annual cycle of monthly averages of ocean heat flux for undeformed multiyear ice (Pittsburgh). The shaded bars are the contributions from specific, latent, and conductive fluxes. Negative values represent cooling, freezing, and downward heat conduction. The ocean heat flux is the residual of the other fluxes.

### Figure 2.
Time series of ocean heat flux measured at Pittsburgh from March through October 1998. Monthly values, values are averaged over 4- to 8-day intervals, and error bars are plotted.
[Perovich et al., 1999]. Ice motion was rapid, as much as 25 km day$^{-1}$, further enhancing the ocean heat flux. This resulted in bottom melting of the ice, even though air temperatures were as low as $-30^\circ$C [Perovich et al., in press]. This episode was brief, and $F_w$ quickly dropped to background levels of 2–5 W m$^{-2}$.  

[14] From May through July the monthly averages show a steady monotonic increase in ocean heat flux, but the 4- to 8-day averages reveal a more complex structure with large fluctuations of tens of W m$^{-2}$. The heat content of the upper ocean mixed layer increased steadily and smoothly from late May through late July in a fashion that was consistent with solar heating [Maykut and McPhee, 1995; Perovich et al., 1999; Uttal et al., 2002]. Aside from a brief period at the beginning of June, there was a concomitant increase in $F_w$ from early May until early July. However, in the first half of July, $F_w$ dropped from nearly 20 to about 5 W m$^{-2}$. Then, in the last week of July, there was a rapid increase in $F_w$ from 10 to 35 W m$^{-2}$. This variability was a result of changes in ice dynamics. The ocean heat flux is a function of the heat content of the upper ocean and turbulent mixing in the boundary layer [McPhee, 1992]. In a simplistic sense we can consider floe speed as a surrogate for turbulent mixing. For much of July, conditions were quiescent and there was little ice motion. Consequently there was a decrease in the ocean heat flux. This changed at the end of the month as a storm hit SHEBA with 8- to 12-m s$^{-1}$ winds. Floe speed increased from 6 cm s$^{-1}$ on 26 July to 43 cm s$^{-1}$ on 29 July (Moritz, personal communication), and the ocean heat flux grew to 35 W m$^{-2}$.  

[15] The peak $F_w$ of 35 W m$^{-2}$ between 27 July and 31 July was followed by a steady decrease during the remainder of the experiment, as there was not enough energy available to sustain these peak heat fluxes. During the ocean heat flux peak, considerable heat was extracted from the mixed layer. Since the incident solar irradiance was steadily waning, this heat was not replaced, so the mixed layer gradually cooled.  

[16] This experiment provided the opportunity to transcend earlier efforts and explore the annual cycle of $F_w$ for first year inc, an old ridge and a melt pond. Monthly averages of $F_w$, determined at five sites, are presented in Table 1 and plotted in Figure 3. The dataset from the first-year ice site is abbreviated since the ice was heavily ponded, thinner than the other multiyear sites, and only 50 m from a lead. During the quiescent period in July the fresh meltwater runoff from the ice gradually filled the leads, eventually extending below the bottom of thinner ice [Pegau, pers. comm.; Richter-Menge et al., 2001]. This meltwater was strongly stably buoyant and insulated the ice from heat in the mixed layer. In addition, at the Seattle site in late July, an ice layer formed at the meltwater-seawater interface effectively reducing $F_w$ at the ice bottom to zero [Perovich et al., in press].  

[19] There was a sharp increase in $F_w$ at the Seattle site in August, as well as a continued increase at the Quebec site. Mixing due to increased ice motion erased the stable surface layer at Seattle. Also, after the main SHEBA floe broke up during the divergence event in late July [Richter-Menge et al., 2001], the Quebec and Seattle sites were at the edges of floes. The sites were thus close to the heat source of relatively warm lead water at a time when this water was being mixed under the ice (Pegau, in press), resulting in a local enhancement of $F_w$. The other sites were at least a few hundred meters from the ice edge.  

[20] The annual average of the ocean heat flux was quite similar for the multiyear sites: 7.5 W m$^{-2}$ for Pittsburgh and 7.9 W m$^{-2}$ for Quebec. For the ponded ice at Seattle, the annual average was 10.4 W m$^{-2}$. The enhanced annual average at Seattle was the result of higher summer values of $F_w$, which were due to the nearby presence of a lead. The largest annual average ocean heat flux was 12.1 W m$^{-2}$ for the old ridge at Tuk. This provides quantitative support for the commonly accepted belief that ridge keels are areas of enhanced ocean heat flux [Maykut and McPhee, 1995].  

[21] Earlier measurements of ocean heat flux in the Beaufort Sea using the mass balance method have yielded annual averages of 3.5 W m$^{-2}$ in 1975 [ADIEITX; Maykut and McPhee, 1995] and 4.0 W m$^{-2}$ in 1993–1994 [Perovich et al., 1997]. The SHEBA values are two to three times larger than these prior results. The earlier experiments did not have any mid-winter peaks in ocean heat flux. However, the March 1998 $F_w$ peak only increased the annual average by about 1 W m$^{-2}$. The heat source of the relatively large ocean heat flux observed at SHEBA is not yet established. Maykut and McPhee [1995] determined that solar radiation input to the upper ocean through leads was the primary energy source of the ocean heat flux. However, SHEBA lead fractions were smaller [Perovich et al., in press] than those measured at

<table>
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<tr>
<th>Time interval</th>
<th>Multiyear (Pittsburgh)</th>
<th>Multiyear (Quebec)</th>
<th>Pondered (Seattle)</th>
<th>Ridged (Tuk)</th>
<th>First year (Baltimore)</th>
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<td>4</td>
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<td>12</td>
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<td>21</td>
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<tr>
<td>9/1/98 – 10/1/98</td>
<td>4</td>
<td>4</td>
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Figure 3. Time series of monthly values of ocean heat flux determined at five sites: thick multiyear ice (Pittsburgh and Quebec), ponded multiyear ice (Seattle), ridged multiyear ice (Tuk), and first-year ice (Baltimore).
AIDJEX, even though the ocean heat flux was much larger. The June through August ocean heat transfer to the bottom of undeformed multiyear ice was 153 MJ m$^{-2}$, representing 10% of the total solar radiation incident on the ice cover. We estimate that approximately two-thirds of this energy (110 MJ m$^{-2}$) was input to the ocean through leads, and some of this lead energy was lost to lateral melting of the ice floes. Because of the initially thin ice cover and large amount of summer ablation [Perovich et al., in press], SHEBA had a larger area coverage of melt ponds and had ice that was substantially thinner than AIDJEX. For the SHEBA ice conditions, significant amounts of solar radiation were transmitted to the ocean through ponds and bare, thin ice. This is a potential positive feedback mechanism, where thinning ice leads to increased solar radiation transmitted to the ocean, resulting in larger values of $F_w$ and enhanced bottom melting. Future work needs to quantify the contribution of solar radiation transmitted through the ice to the ocean heat flux.

4. Conclusions

[22] Temporally averaged values of ocean heat flux were determined over an annual cycle using ice temperature and mass balance data measured during the SHEBA field experiment. The ocean heat flux exhibited a strong seasonal dependence. With one brief exception, $F_w$ was only a few W m$^{-2}$ from November until May. The exception was a storm- and topography-induced upwelling event in March, when the five-day average of $F_w$ reached 37 W m$^{-2}$. Starting in May, there was a steady increase in the ocean heat flux, reaching a peak in late July and early August. There was significant variability in $F_w$ for different multiyear ice types. The value of 12.1 W m$^{-2}$ for an old ridge was the largest annual average $F_w$ observed during SHEBA for a melt pond. Peak monthly averages in summer were about 18 W m$^{-2}$ for undeformed multiyear ice and 32 W m$^{-2}$ for ponded ice and ridged ice. Values of $F_w$ observed during SHEBA were more than twice as large as those measured in 1975 during AIDJEX. Indications are that solar radiation transmitted through the extensive ponds and the relatively thin bare ice at SHEBA contributed substantially to the ocean heat flux.

[23] Acknowledgments. The authors thank H. Bosworth and J. Richter-Menge for their capable assistance during the SHEBA deployment phase. We also thank the crew of the *Des Groseilliers* and the SHEBA Logistics Office for their excellent support. This work was funded under Office of Naval Research Contract N0001401MP20022.

References


