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Surface heat fluxes and subsurface heat content at a site over the southeastern Bering Sea shelf, May–July 1996

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Abstract

Observations from a surface mooring, in a weak-flow regime over the southeastern Bering Sea shelf, were used to derive surface heat fluxes for the period May–July 1996. Changes in heat content of the water column also were determined from subsurface temperature measurements. Agreement of net surface heat flux and change in heat content was within 2%. This result provides additional evidence that heat advection and diffusion are small in this region.

1. Introduction

The southeastern Bering Sea shelf is a region of very weak baroclinic flow (Fig. 1). This feature was clearly demonstrated by current measurements and hydrographic sections, starting in 1975, as part of the Outer Continental Shelf Environmental Assessment Program, which was administered by the National Oceanic and Atmospheric Administration for the Bureau of Land Management. Kinder and Schumacher (1981) and Schumacher and Kinder (1983) presented evidence for this weak flow. Later, Coachman (1986) and Stabeno et al. (2001) published comprehensive studies.

Reed (1978) used data over the shelf from mid-June to early August 1976 and found that the change in heat content of the water column, during the major period of heating, equaled the surface heat exchange as derived by empirical formulae (discussed below). Of the surface fluxes, 88% was from insolation. This situation resulted from the weak winds (a mean of $4\,\mathrm{m\,s^{-1}}$), substantial cloud cover (0.93), and small air–sea temperature differences. Estimates also showed that heat advection and diffusion were no more than $\sim 5\%$ of the surface heat flux.

The present study uses results for May–July 1996, from a site near the region investigated by Reed (1978). The location of the site, mooring 2, is shown in Fig. 1, as well as a schematic of the climatological mean circulation from Reed and Stabeno (1996). All of the atmospheric and oceanic variables needed for a heat budget study were measured, except for cloud cover, which was derived from measured insolation by an empirical formula discussed below.

2. Data and methods

2.1. Instruments and measurements

A surface mooring (mooring 2; Fig. 1) has been deployed each year, typically from late April to mid-September, from 1995 to the present. Details

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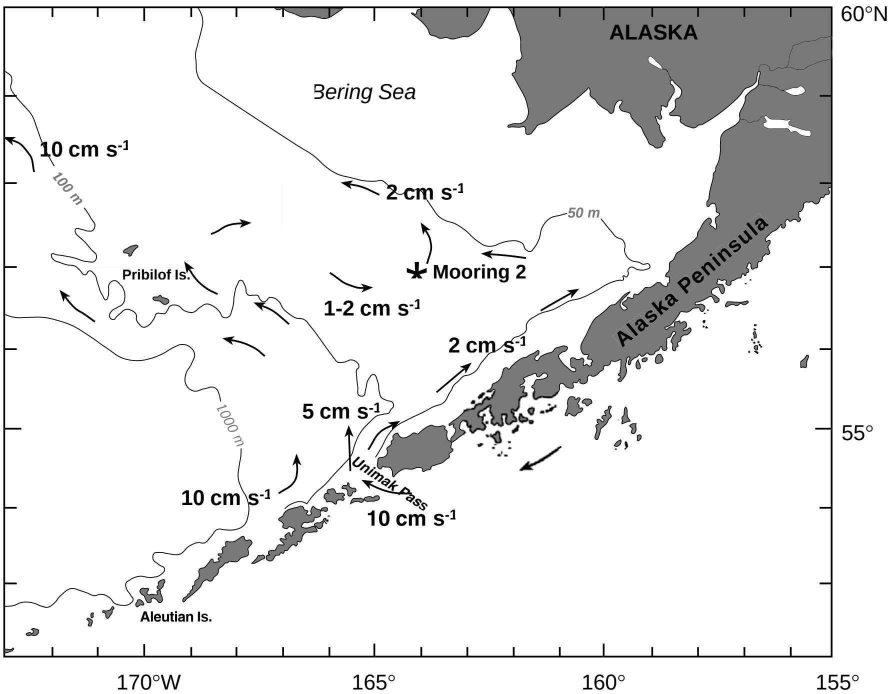

Fig. 1. Location of mooring 2 over the southeastern Bering Sea shelf. A schematic of the climatological sea surface circulation, from Reed and Stabeno (1996), is also shown.

about the mooring are contained in Stabeno et al. (1998). The surface buoy was a 2.3 m diameter fiberglass toroid, connected by chain to a tether and an anchor at 72 m. The float could move horizontally ~60 m.

The surface float, which extended upward ~3 m, contained an Eppley Precision Spectral Pyranometer that measured solar radiation from ~0.3 to 2.8 μm, an R.M. Young model 05103 wind sensor, a Rotronics model MP100 air temperature/relative humidity sensor, and a Yellow Springs Instruments model 44006 thermistor that measured sea-surface temperature. Subsurface temperature was measured, with Seabird Electronics model SBE-16 Seacat temperature/conductivity sensors or Miniature Temperature Recorders constructed in our laboratory, at levels of 6, 8, 12, 15, 20, 24, 27, 31, 34, 39, 44, 50, 56, and 62 m. All sensors were calibrated in our laboratory or by the manufacturer a few months prior to and after use. Temperature accuracy was ~0.02°C.

The only year with complete data return was 1996. All other years had some incomplete surface observations. We have thus used observations during the period of major heating of the water column (May–July) in 1996.

2.2. Surface heat fluxes

Exchange of heat across the sea surface may be written as

$$Q_t = Q_s - Q_b - Q_e - Q_h, \quad (1)$$

where Q_t is the total or net exchange, Q_s is the solar radiation (insolation), Q_b is the net back or long wave (infrared) radiation, Q_e is the loss of latent heat through evaporation of water, and Q_h is the sensible heat loss.

The term Q_s is much larger than the other surface fluxes. As stated above, insolation was measured with a pyranometer and should be more reliable than the other fluxes, which were derived from empirical formulas. Having measured Q_s, we derived cloud cover (C, in tenths) from the relation

$$Q_s/Q_o = 1 - 0.62C + 0.0019\alpha, \quad (2)$$

where Q_o is the insolation under clear skies (Seckel and Beaudry, 1973), and α is the noon solar altitude (in degrees). Eq. (2), from Reed (1977), has been used widely (Weare et al., 1981; Josey et al., 1999) and appears to give reasonable results over various regions. Finally, the flux Q_s was reduced by 6% for reflected short wave radiation (Payne, 1972).

The net long wave radiation, Q_b, was derived from Efimova's formula (Budyko, 1974):

$$Q_b = \varepsilon\sigma T_s^4(0.254 - 0.00495e_a)(1 - 0.9C) + 4\varepsilon\sigma T_s^3(T_s - T_a), \quad (3)$$

where ε is the emissivity of the sea surface (0.98), σ is the Stefan–Boltzman constant (5.7×10^{-8} W m^{-2} K^{-4}), e_a is the air vapor pressure, and T_s and T_a are the absolute sea surface and air temperature, respectively. Moisan and Niiler (1998) used this formula, but with different cloud factors. It should be noted that others (Josey et al., 1999, for example) used the Berliand and Berliand formula (Budyko, 1974) with a nonlinear cloud factor. Our use of (3) is based on: (1) Reed's (1976) summary of measurements that indicated a factor of 1–0.9C for low stratus-stratocumulus clouds typical of high latitudes; and (2) the plausible results from Eq. (3) for the 1976 Bering Sea heat budget (Reed, 1978).

Finally, latent and sensible heat fluxes were computed from

$$Q_e = \rho LU(q_s - q_a)C_e \quad (4)$$

and

$$Q_h = \rho c_p U(T_s - T_a)C_h, \quad (5)$$

where ρ is the specific air density (1.3×10^{-3}), L is the latent heat of vaporization ($\sim 2.5 \times 10^6$ W s kg^{-1}), U is the wind speed (m s^{-1}), c_p is the specific heat capacity of air ($\sim 1 \times 10^6$ W s m^{-3} K^{-1}), q_s and q_e are the specific humidity of sea water and air, T_s and T_a are the sea and air temperature, and C_e and C_h are taken as 1.2×10^{-3} and 1.0×10^{-3}, respectively. These values, for the light winds here, are similar to Smith (1988), as well as to earlier results of Friehe and Schmitt (1976) used by Reed (1978). It should be noted that fluxes computed from monthly means of water and air properties were not significantly different than monthly means of computed daily fluxes.

2.3. Heat content

The heat content of the water column was determined from

$$H = \rho c_p \int T\,dz, \quad (6)$$

where ρ is the seawater density, c_p is the specific heat of seawater at constant pressure, T is the water temperature, and z is the vertical axis.

3. Results

3.1. Air and water properties

Fig. 2 presents daily mean observed values of wind speed, air temperature, sea-surface temperature, and insolation at mooring 2 for May–July 1996. Wind speed was 5.3 ± 1.8 m s^{-1} during May, 6.9 ± 2.4 m s^{-1} during June, and 5.9 ± 1.9 m s^{-1} during July. These values are all greater than that (4 m s^{-1}) during the June–August 1976 period (Reed, 1978). Fig. 2 indicates a general increasing trend of air temperature with time but with numerous deviations. Air temperatures were 2.8 ± 1.2, 5.1 ± 1.3, and 8.7 ± 1.2°C for May, June, and July, respectively. Sea-surface temperatures were 2.3 ± 1.2, 4.9 ± 0.7, and 8.3 ± 1.1°C for May, June, and July, respectively. Insolation was greatest in May, even though clear-sky values were greatest in June. The extreme high-frequency variations result mainly from rapid changes in cloud cover. Computed mean cloud cover, from the measured insolation and use of Eq. (2), was 0.79, 1.00, and 1.02 for May, June, and July, respectively. (The cloud cover was not greater than 1.0, but the atmospheric transmission was probably reduced additionally by fog, drizzle, rain, high humidity, or other factors.) The most unanticipated result is that May had lighter winds, clearer skies, and greater insolation than the "summer" months of June and July.

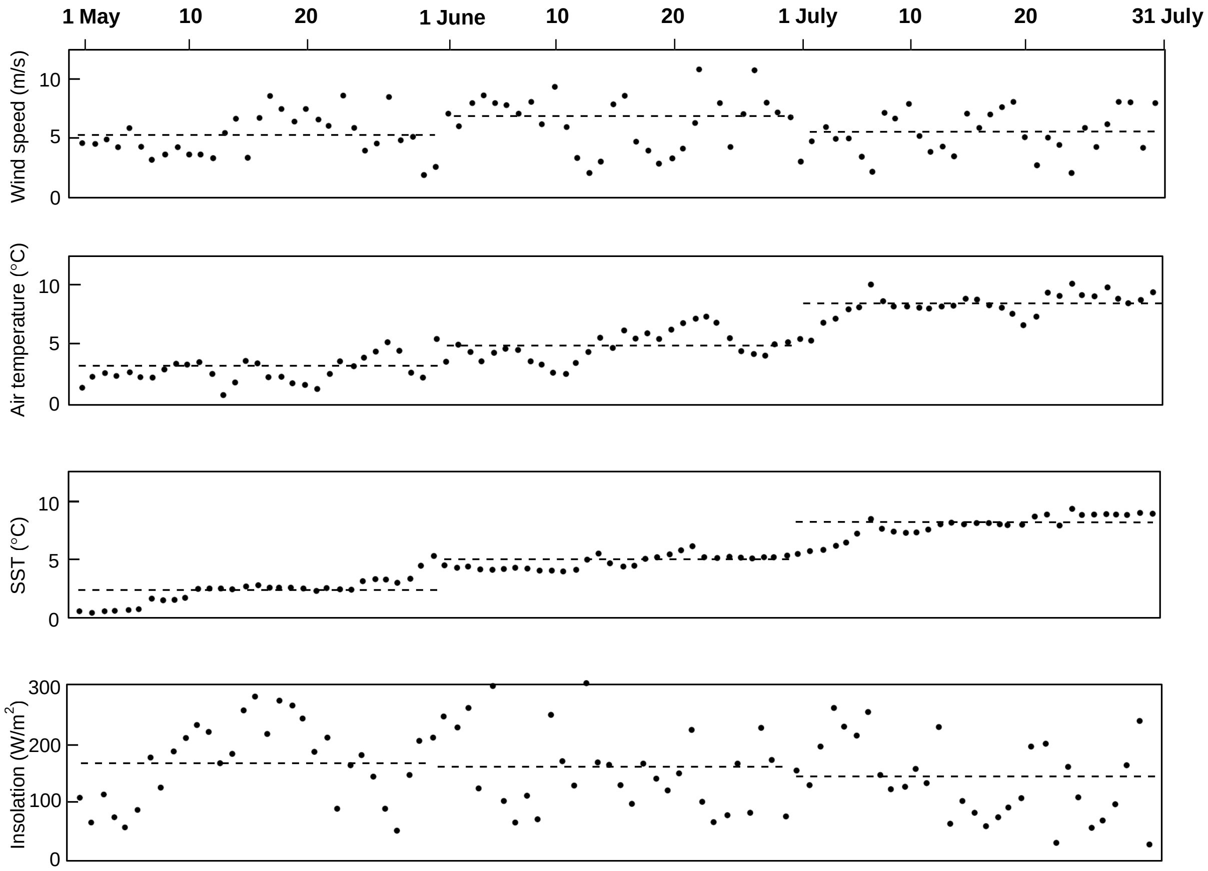

Fig. 2. Daily mean values of measured wind speed (m s^{-1}), air temperature (°C), sea surface temperature (°C), and insolation (W m^{-2}) at mooring 2, May–July 1996. The dashed lines indicate the monthly mean properties.

Considerable variability also exists on daily time scales as well as on the monthly scales given above. The mean diurnal standard deviations in wind speed, air temperature, and sea-surface temperature were 1.3 m s^{-1}, 0.4°C, and 0.2°C, respectively, with no significant difference in these values in May, June, and July 1996. There were, however, nearly ten-fold day-to-day differences in diurnal variability. Finally, these "event-scale" variations of wind-speed, air-temperature, and sea-surface temperature had weak correlations.

Bond and Adams (2002) have examined conditions during 1995–1999 in relation to a 40-year mean reanalysis of water properties and fluxes (Kalnay et al., 1996). Summer 1996 was near the climatological mean in most respects but had stronger than normal wind mixing much of the time and below normal insolation (by ~40 W m^{-2}) during the second half of June. The long-term mean summer surface heat flux (Q_t) was ~15% greater than our value (Table 1). This comparison

Table 1
Summary of observed and computed surface heat fluxes (in W m^{-2}) at Mooring 2 (56°52′N, 164°3′W), May–July 1996

	May	June	July	Mean
0.94 Q_s	173	157	148	159
Q_b	18	6	4	9
Q_e	9	16	9	11
Q_h	−4	−2	−3	−3
Q_t	150	137	138	142
$\partial H/\partial t$	141	156	137	145

The changes in heat content of the water column, $\partial H/\partial t$ (W m^{-2}), are also shown. The standard error of estimate in $\partial H/\partial t$ is ~2 W m^{-2}, or ~4 W m^{-2} at 95% confidence limits.

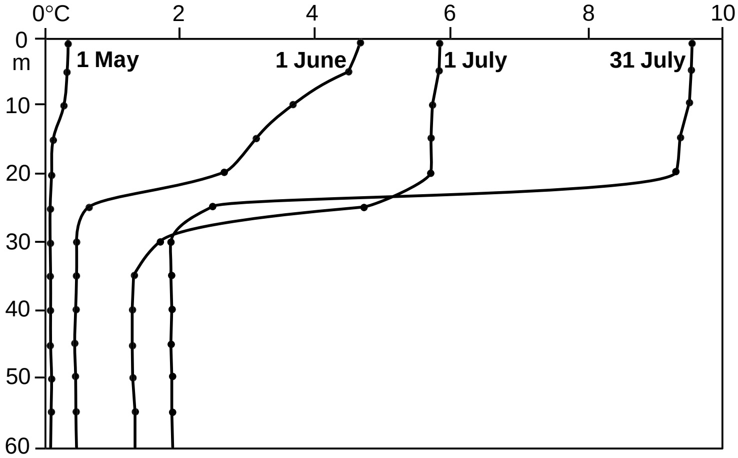

Fig. 3. Subsurface thermal structure (°C) at mooring 2, May–July 1996.

may not be very meaningful, however, because of the different methods used by Kalnay et al. (1996) and us. Results of Hermann et al. (2002) suggest that the reanalysis fluxes may be too high.

Fig. 3 shows the changes in temperature in the water column during May–July 1996. In May, surface temperature increased from $<0.4°C$ to $>4.5°C$; temperature below 30 m increased by $<0.4°C$, however. In June, surface temperature increased by $\sim 1.1°C$, temperature at 30 m increased by $\sim 1.3°C$, and bottom temperatures increased by $\sim 0.9°C$. During July, surface temperature increased by almost 4°C, temperature at 25 m decreased by $>2°C$, and the water warmed by $\sim 0.6°C$ below 30 m. The total changes from 1 May to 31 July were $\sim 9°C$ at the surface and slightly less than 2°C at 30 m and below.

3.2. Surface fluxes

The measured and computed surface heat fluxes are listed in Table 1. The largest total heat flux (Q_t, 150 W m^{-2}) occurred in May. This resulted from relatively small cloud cover and light winds. In June and July, Q_b values were smaller than in May because of increased cloud cover then. June had the largest latent heat flux as a result of the strongest winds. For the entire May–July period, 0.94 Q_s is 87% of the sum of the absolute values of the fluxes.

Use of the Berliand and Berliand formula (Budyko, 1974) for Q_b, with a nonlinear cloud factor, as noted above and used by Josey et al. (1999) among others, would give values for Q_b of 42, 19, and 8 W m^{-2} for May, June, and July, respectively. These results would produce a mean of 23 W m^{-2}, rather than 9 W m^{-2} (Table 1). On the other hand, the Berliand and Berliand formula, with the cloud factor 1–0.9C, as used by Weare et al. (1981) for stratocumulus clouds, gives values of 22, 7, and 2 W m^{-2} for May, June, and July. The mean is 10 W m^{-2} versus our value of 9 W m^{-2} (Table 1). Suggestions of a nonlinear cloud factor appear to result from measurements over land (Budyko, 1974) but are not supported by some measurements at sea (Reed, 1976; Simpson and Paulson, 1979). As discussed above, we believe the method used here is more appropriate for conditions in the Bering Sea.

3.3. Changes in heat content and heat balance

Table 1 also lists the computed changes in heat content, derived by Eq. (6). For May, Q_t was 9 W m^{-2} greater than $\partial H/\partial t$; in June, Q_t was 19 W m^{-2} less than $\partial H/\partial t$; and in July, Q_t was 1 W m^{-2} more than $\partial H/\partial t$. For the mean, Q_t

was 2% less than $\partial H/\partial t$. This difference actually indicates good agreement considering that three of the fluxes were computed with empirical formulas. It should be noted that there were no temperature measurements in the deepest 10 m of the water column. If one extrapolates the curves in Fig. 3 to 70 m, mean $\partial H/\partial t$ becomes 153 W m^{-2}, and mean Q_t is 7% less than this value.

4. Conclusions

The combination of measured and derived surface heat fluxes and measured changes in heat content of the upper 60 m only differed by 2%, or 7% if one extrapolates the temperature curves 10 m to the ocean bottom. Reed (1978) found agreement within 5% during June–August 1976. It should be stressed, however, that the fluxes obtained here are more reliable than those derived in Reed (1978), which relied on scattered ships' weather reports and satellite images. Consequently, the relative importance of various processes determined here is more reliable than previously inferred.

Although currents were measured at the mooring, we lack information on horizontal thermal gradients in order to evaluate heat advection or diffusion. The currents themselves were only 1–2 cm s^{-1} toward the northeast, however. Based on results in Table 1, we infer that mean heat advection/diffusion was not greater than $\sim$5 W m^{-2}.

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