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Ocean-to-ice heat flux at the North Pole environmental observatory

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[1] Data from drifting buoys deployed in April, 2002, as part of the North Pole Environmental Observatory project have been analysed to estimate ocean heat flux in the time period from 1 May 2002 to 11 Mar 2003. Prior to late January, the observatory remained in deep water, but subsequently drifted directly over the Yermak Plateau, a relatively shallow feature north of Svalbard. While over deep water, heat flux was dominated by storage and release of solar energy in the ocean boundary layer during summer. The most likely annual average value for 2002 was 2.6 W m^{-2}, less than previous determinations in the western Arctic. Over Yermak Plateau, heat flux at the interface came from mixing of warmer water into the boundary layer from below. When the observatory was in water with depths less than 1200 m, the average heat flux was around 22 W m^{-2}. *INDEX TERMS:* 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4572 Oceanography: Physical: Upper ocean processes; 4594 Oceanography: Physical: Instruments and techniques. **Citation:** McPhee, M. G., T. Kikuchi, J. H. Morison, and T. P. Stanton, Ocean-to-ice heat flux at the North Pole environmental observatory, *Geophys. Res. Lett.*, *30*(24), 2274, doi:10.1029/2003GL018580, 2003.

1. Background

[2] The existence of perennial sea ice depends on a delicate energy balance in which heat flux from the underice boundary layer (UBL) plays a central role [*Maykut and Untersteiner*, 1971]. The main sources of ocean heat flux are (i) summer insolation through open leads, thin ice, and melt ponds [e.g., *Perovich and Maykut*, 1990; *Maykut and McPhee*, 1995; *Perovich and Elder*, 2002]; and (ii) upward turbulent mixing of heat from warmer water residing below the well mixed UBL [*McPhee et al.*, 1999]. In the western deep Arctic Basin, summer insolation appears to dominate as the primary source of ocean (basal) heat flux over advection and upward mixing of sensible oceanic heat. It thus serves as a principal factor in the ice-albedo feedback, wherein increased melting lowers aggregate albedo, leading to enhanced absorption of solar energy, and so on.

[3] The North Pole Environmental Observatory (NPEO) is designed to track and understand ongoing changes in the Arctic environment, as well as provide a long-term data and infrastructure resource for other polar science and climate investigations. First established in 2000, NPEO includes an automated drifting station of buoys fixed to the sea ice, an ocean mooring, and airborne hydrographic surveys. A primary task is to monitor UBL characteristics and ocean heat flux in the eastern Arctic to better understand the energy and mass balance of multiyear ice as it drifts toward the marginal ice zone of Fram Strait. Data discussed here are from the 2002 deployment of Japan Marine Science and Technology Center buoy J-CAD 4, and the Naval Postgraduate School surface flux buoy. In order to observe oceanographic conditions up to 250 m depth, the J-CAD 4 buoy includes six pairs of temperature and salinity sensors (SBE37IM), plus a downward looking ADCP, and meteorological sensors. The NPS flux buoy is designed to measure current shear, and vertical fluxes of momentum, heat, and salt in the upper UBL.

[4] The NPEO buoy cluster was deployed in April, 2002, and continued transmitting data into the summer of 2003. It drifted (Figure 1) slowly southward from its deployment near the North Pole for most of the 2002 summer, meandered in the deep water north of Yermak Plateau in the early winter, then headed southwest across the Yermak Plateau in February and early March, 2003. By the end of March it was exiting the Arctic through Fram Strait and was less than 50 km from diffuse pack ice in the marginal ice zone. In this work we restrict consideration to data from day 2002:125 to 2003:70, which we use to investigate basal heat flux from insolation during the summer of 2002, as well as energetic mixing of heat from below the UBL when the buoy cluster drifted across Yermak Plateau.

2. Methods and Data

[5] Measurements of turbulent heat flux and Reynolds stress near the interface made during a series of polar field projects performed beginning in the mid-1980s demonstrated that turbulent heat flux could be reasonably well expressed as the product of interfacial friction velocity and elevation

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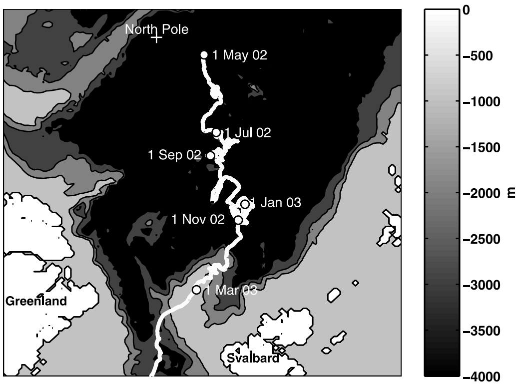

Figure 1. Trajectory of the NPEO 2002 buoy cluster superimposed on the bathymetry.

of mixed layer above freezing [*McPhee*, 1992; *McPhee et al.*, 1999]:

$$\frac{H_f}{\rho c_p} = \langle w'T' \rangle_0 = c_H u_{*0} \delta T \tag{1}$$

where H_f is sensible heat flux at the interface; ρ is water density; c_p is specific heat of seawater; $\langle w'T' \rangle_0$ is the kinematic turbulent heat flux; c_H is a bulk heat transfer coefficient; u_{*0} is the interface friction velocity ($= \tau_0{}^{1/2}$ where τ_0 is kinematic stress); and $\delta T = T_\mathrm{ml}$-$T_\mathrm{f}(S_\mathrm{ml})$, where T_ml and S_ml are temperature and salinity in the well mixed boundary layer beneath the sea ice.

[6] Several methods exist for estimating interfacial friction velocity. We chose a method called Rossby similarity, adapted to ice drift relative to geostrophic (sea-surface tilt currents) at the ocean surface [*McPhee et al.*, 1999]:

$$\frac{\kappa \boldsymbol{V}}{\boldsymbol{u_{*0}}} = \log \frac{|u_{*0}|}{f z_0} - A - iB \tag{2}$$

where $\boldsymbol{V}$ is ice velocity relative to the surface geostrophic flow (2-d vectors are expressed as boldface complex numbers), κ is von Karman's constant (0.4), f is the Coriolis parameter, z_0 is the hydraulic roughness of the ice undersurface, and A and B are constants (for neutral static stability), with values 2.12 and 1.91, respectively. On the short time scales associated with individual storm events, ice drift velocity usually far exceeds geostrophic ocean current, and we assume that $\boldsymbol{V}$ is the actual ice velocity.

[7] The main sources of error in (1) are uncertainty in the bulk heat transfer coefficient, c_H, and in estimating u_{*0} from (2). Our best estimate of c_H is from turbulent heat flux and stress measurements made during the Surface Heat Budget of the Arctic (SHEBA) project [*McPhee*, 2002; *McPhee*, manuscript in preparation]. The result, $c_H = 0.0057 \pm 0.0004$, agrees well with previous determinations [*McPhee*, 1992; *McPhee et al.*, 1999]. The main source of error in (2) is the undersurface hydraulic roughness, z_0, which can range from hydraulically smooth ($\sim 5 \times 10^{-5}$ m) under fast ice, to several centimeters in the marginal ice zone [e.g., *McPhee*, 1990]. For undeformed multiyear ice at the SHEBA site, the most likely value was $z_0 = 0.006$ m [*McPhee*, 2002], but this estimate purposely excluded the contribution from pressure ridges or thin ice in frozen leads. A representative value for the type of multiyear ice on which drift stations (including NPEO) are sited is 0.01 m, with a probable range of $0.005 \leq z_0 \leq 0.03$ m.

[8] NPEO provided two options for determining mixed-layer *T*/*S* characteristics: the NPS flux buoy FSI temperature/conductivity probe nominally 4 m below the ice/water interface and the JAMSTEC J-CAD 4 uppermost SBE *T*/*C* pair, nominally at 25 m depth. Data were melded from both to get a continuous time series of δT for 2002 (Figure 2a).

[9] The frequent presence of inertial and tidal oscillations in ice velocity requires caution in selecting $\boldsymbol{V}$ in (2), because turbulent exchange at the interface depends on shear near the surface. High resolution ADCP data from NPEO confirm earlier results that the inertial component of shear near the interface is small compared with the wind driven part; i.e., the mixed layer and ice oscillate in phase. Similarly, if internal ice stress is negligible in the force balance, ice and upper ocean respond to the same tidal forcing, again with little shear. Hence, at any particular time we consider the velocity of the ice to comprise a combination of "mean" drift ($\boldsymbol{V_m}$) and inertial and tidal components:

$$\begin{aligned} V_{ice} = V_m + S_{cw} e^{-ift} + S_{ccw} e^{ift} + D_{cw} e^{-i\omega t} \\ + D_{ccw} e^{i\omega t} \end{aligned} \tag{3}$$

where f is the angular inertial frequency (close to the semidiurnal tidal frequency at high latitude); ω is the diurnal tidal frequency, $\boldsymbol{S_{cw}}$ ($\boldsymbol{S_{ccw}}$) and $\boldsymbol{D_{cw}}$ ($\boldsymbol{D_{ccw}}$) are complex coefficients describing the clockwise (counterclockwise) inertial and tidal oscillations, respectively, following *McPhee* [1988]. Friction velocity (Figure 2b) is then evaluated from (2), using $\boldsymbol{V_m}$, the ice velocity after removal of inertial and tidal components.

3. Results

3.1. Summer Solar Heating

[10] Heat flux (Figure 3) was estimated via (1) for the period from 1 May to 31 Dec, 2002, during which time the

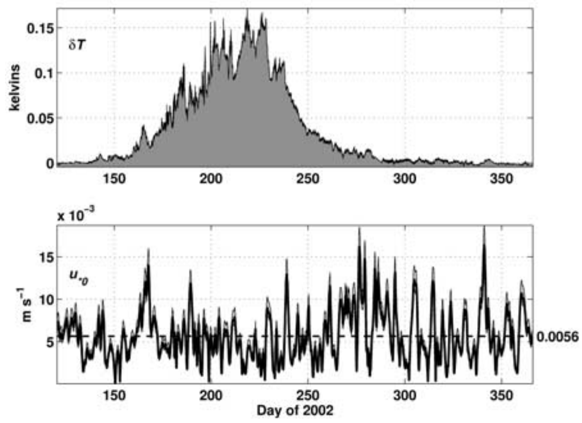

Figure 2. (a) $\delta T = T_{ml} - T_f(S_{ml})$ from mixed-layer T/S properties at NPEO during 2002. (b) Interfacial friction speed from (2). The solid curve is for $z_0 = 0.01$ m yielding mean value 0.0056. The shaded region shows the range for $0.005 \leq z_0 \leq 0.03$ m, for which mean values range from 0.0052 to 0.0065.

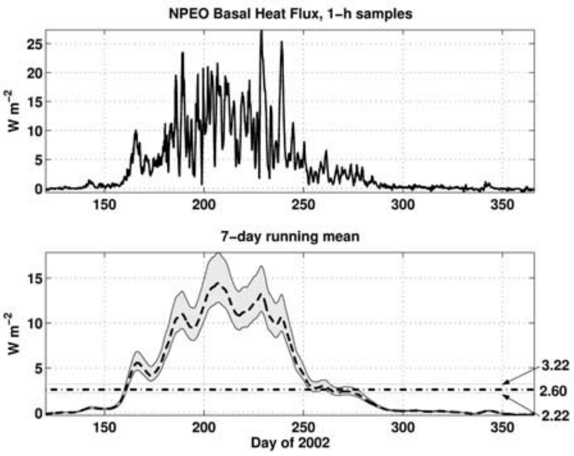

Figure 3. (a) Estimated ocean heat flux at the NPEO site for the period from 1 May to 31 Dec, 2002, from 1-h samples of mixed layer δT and u_{*0} with $c_H = 0.0057$ and $z_0 = 0.01$ m. (b) Heat flux time series smoothed with a 7-day boxcar filter (dashed curve). Shaded envelope indicates values with combined lower and upper limits of c_H and z_0 as described in the text. Straight lines show annual average heat flux for the expected value (dot-dashed) and upper and lower bounds (light), assuming zero heat flux from January through April.

NPEO remained in deep water over the Eurasian Basin and Barents Abyssal Plain. The maximum heat flux lagged solar zenith by about a month, reaching a peak in the smoothed time series around July 25 (Figure 3b). Prior to that time, the mixed layer absorbed solar energy faster than melting removed it. After July, as the solar angle decreased, melting outpaced insolation and the mixed layer cooled toward its freezing temperature, reaching very small thermal contrast by late October.

[11] We compared the NPEO results with previous summer manned drifts in other parts of the Arctic Ocean. The

Table 1. Heat Flux Parameters, Days 140–263

Station	Latitude	u_{*0} (m s^{-1})	δT (K)	H_f (W m^{-2})
NPEO '02	86° 20.4′	0.0052	0.065	7.5
SHEBA '98	78° 15.0′	0.0059	0.098	13.2
AIDJEX Big Bear '75	75° 29.4′	0.0054	0.081	10.8
Caribou	74° 52.2′	0.0052	0.071	9.1
Blue Fox	75° 44.4′	0.0055	0.095	13.0
Snowbird	75° 42.6′	0.0055	0.070	9.6

Arctic Ice Dynamics Joint Experiment (AIDJEX) maintained an array of four drift stations that drifted slowly SSE from the its deployment site in March, 1975, near the center of the Beaufort Gyre, during the 1975 summer. The SHEBA station, deployed near the same position in September, 1997, had drifted far to the northwest by the following (1998) summer. Using the same parameters ($c_H = 0.0057$, $z_0 = 0.01$ m) for each station, the estimated heat flux (smoothed with a 7-day running average) is shown in Figure 4. Mean values for the overlap period are listed for each station in Table 1.

3.2. Advective Heat Exchange Over Yermak Plateau

[12] The drift of the NPEO during the early months of 2003 (Figure 5) presents an interesting contrast to the remainder of the heat flux record, which was dominated by summer insolation. Time series for the first 70 days of 2003 (Figure 6) show that as the station drifted into shallow water (Figure 6d), mixed-layer temperature elevation increased (Figure 6c), reaching 0.4 K around day 50 (19 Feb 03), more than twice the summer maximum. Currents and ice drift over the Yermak Plateau are strongly affected by a mixed diurnal/semidiurnal tidal signal (solid curve in Figure 6e). Under the same assumptions as earlier, we derived the heat flux time series (Figure 6f). The highest temperature elevations and heat flux values coincide with shallow bathymetry and energetic tides, which combine to effect strong mixing between the surface and Atlantic water.

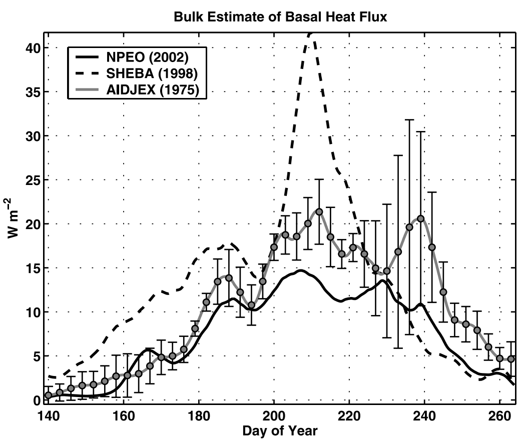

Figure 4. Comparison of NPEO heat flux with that at previous manned stations, estimated by the same method during times of the year when data overlapped. Error bars on the AIDJEX curve represent twice the standard deviation of values from the four stations.

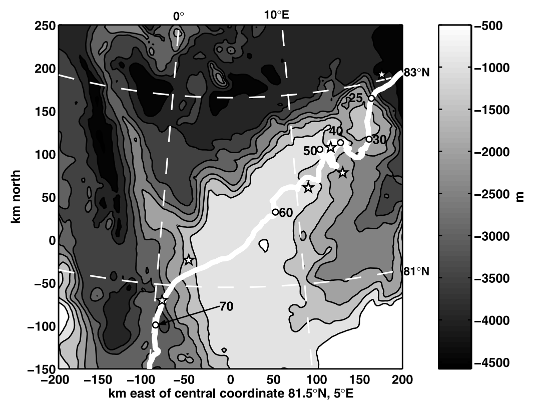

Figure 5. Drift track of NPEO from late January to mid March, 2003, superimposed on the bathymetry of the Yermak Plateau north of Fram Strait. Circles mark position at 0000UT on the day numbers shown. White pentagrams are positions of helicopter CTD stations during the 1989 CEAREX project [*Muench et al.*, 1992] that lay within 15 km of the NPEO trajectory.

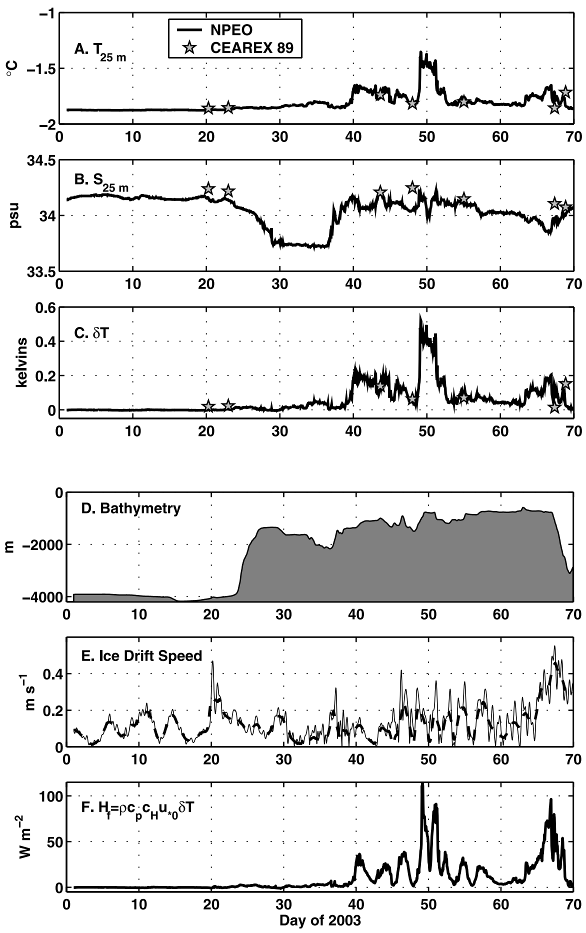

Figure 6. (a) Time series of temperature at 25 m from the JCAD-4 component of NPEO, during the first 70 days of 2003. Pentagrams show temperature at 25 m from CEAREX CTD stations positioned within 15 km of the drift track, plotted at the NPEO time of closest approach. (b) Same as A, except salinity. (c) Elevation of mixed layer temperature above freezing. (d) Bottom elevation along the drift track from the IBCAO bathymetry. (e) Ice drift speed from complex demodulation of hourly positions, showing total velocity (solid) and velocity without inertial and diurnal tidal components (dashed). (f) Inferred ice/ocean heat flux.

During the time the NPEO was in water less than 1,200 m deep over the Yermak Plateau, the average estimated heat flux (using the most likely values for z_0 and c_H) was about 22 W m^{-2}, comparable to the maximum values observed during the previous summer.

[13] During a late-winter CTD survey done by helicopter as part of the 1989 Coordinated Eastern Arctic Experiment (CEAREX), several shallow stations ($\sim$600 m) were obtained at locations near the NPEO drift track [*Muench et al.*, 1992]. Stations within 15 km of the 2003 drift, shown by pentagrams in Figure 5, were sampled at 25 m depth for comparison with the upper J-CAD 4 *T/S* values at closest approach. In all of the CEAREX profiles, this 25-m depth was within the upper well mixed layer. Pentagrams in Figure 6 mark the profile values at times when the NPEO drift passed closest to the CEAREX profile location. The CEAREX stations were taken 4–6 weeks later in the season.

4. Discussion

[14] During summer and early winter, 2002–2003, the NPEO station drifted over deep water in the Eurasian Basin and Nansen Absyssal Plain. Basal heat flux inferred from mixed-layer properties and ice drift speed followed a pattern of seasonal development remarkably similar to that observed at manned stations in widely separated locations in the Arctic (Canada Basin, Chukchi Borderland, Amundsen/Nansen Basin; Figure 4; Table 1) during different climatological regimes. For the same period spanning most of the summer, the average heat flux at NPEO was about 70% of the mean of the four AIDJEX station (10.7 W m^{-2}) and only about 57% of that inferred for SHEBA. The absolute differences are small, suggesting that the ice cover is sensitive to small differences in ocean heat flux [*Maykut and Untersteiner*, 1971]. Automated measurements of the accuracy we have obtained here are needed to track and understand these differences.

[15] Nearly all of the measured ocean heat flux over the deep Eurasian Basin was derived from insolation during the summer despite weakening of the cold halocline evident in the NPEO J- CAD data [*Morison et al.*, 2002]. Our result is consistent with the partial recovery of the cold halocline reported by *Boyd et al.* [2002].

[16] When the buoy cluster drifted over Yermak Plateau in early 2003, basal heat flux was dominated by mixing between the UBL and underlying warm water (Figure 6). The result is consistent with findings [*Padman and Dillon*, 1991; *D'Asaro and Morison*, 1992] from the Fram Strait region that the highest internal wave energies and pycnocline diffusivities occur over shallow bathymetry due to enhanced tidal forcing and the possible trapping of internal wave energy by reduced relative vorticity. Similar contrast was found during the SHEBA winter. Ocean heat flux increased dramatically when the station drifted out of the deep Canada Basin into shallow water over the Northwind Rise and Chukchi Cap. This reinforces the notion that such submarine features play a more important role in air-sea-ice exchange in the Arctic than their relative area might otherwise suggest.

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