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IS OCEAN HEAT FLUX ENHANCED UNDER RAPIDLY GROWING ICE?

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1. INTRODUCTION

Direct measurements of turbulent heat flux in the boundary layer under sea ice have shown that the rate of heat transfer at the ice/water interface is controlled by molecular processes (McPhee et al. 1987). Evidence suggests that heat flux to melting ice in above freezing seawater is rate limited by salinity, since salt diffusivity is smaller than thermal diffusivity by a factor of nearly 200. Similar considerations of the double-diffusive character of the interface during freezing suggest that heat might be extracted from the water column faster under thin, rapidly growing ice, which would lead to substantial supercooling and frazil production if the mixed layer is near freezing (Steele et al.,1989). In models with several different ice thickness categories, this effect can have an appreciable impact on overall thickness if the frazil is mixed vertically in the upper ocean, then distributed evenly to the ice cover (Holland et al. 1997).

2. DOUBLE-DIFFUSIVE FLUXES

Dimensional analysis suggests that the exchange coefficient for turbulent heat flux at the ice/ocean interface, i.e., a dimensionless group

$$c_{\mathrm{h}} = \frac{\langle w'T'\rangle_0}{u_{*0}\delta T}$$

($\langle w'T'\rangle_0$ is the kinematic heat flux, u_{*0} is friction velocity at the interface, and δT is the change in temperature between the far-field and interface) is a function of Reynolds number, $Re = u_{*0}z_0/\nu$, where z_0 is the undersurface roughness length; and Prandtl number, $Pr = \nu/\nu_T$. Similarly, the exchange coefficient for salinity

$$c_{\mathrm{S}} = \frac{\langle w'S'\rangle_0}{u_{*0}\delta S}$$

should depend on Reynolds number and Schmidt number, $Sc = \nu/\nu_S$. Here, ν is kinematic viscosity, and ν_T and ν_S are molecular thermal and saline diffusivities, respectively. Several studies of heat flux under sea ice have shown that if there is a Reynolds number dependence of c_{h}, it is weak (McPhee et al. 1999). However, not much is known about the Prandtl (Schmidt) number dependence. In order to explain the unexpectedly slow melting of sea ice in relatively warm water of the marginal ice zone, McPhee et al. (1987) adapted an approach developed by Yaglom and Kader (1974) for describing heat and mass exchange in turbulent flow over hydraulically rough laboratory surfaces. An implication of the Yaglom-Kader work is that the ratio of exchange coefficients should vary approximately as $(\nu_T/\nu_S)^{2/3}$, which is about 30 for water near freezing. Thus melting is severely rate limited by the exchange of salinity at the ice/ocean interface.

If the converse holds, i.e., that during freezing heat is extracted from the water column faster than

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salt can be added, the possibility exists of rather intense supercooling when growth rates are high. This is illustrated by computation of ocean-to-ice heat flux as a function of conductive heat flux in an ice sheet floating in seawater initially at freezing. Results for two ratios are shown in Fig. 1A. As an example, if conductive heat flux is 20 W m^{-2} (corresponding to a negative ice temperature gradient of about 10 K m^{-1}), one might expect an ocean (basal) heat flux of about 8 W m^{-2}, if the Yaglom-Kader transfer coefficient ratio holds. If the ratio is unity, the ocean heat flux is much smaller, only that needed to maintain the seawater at its freezing temperature in response to the incoming salt flux.

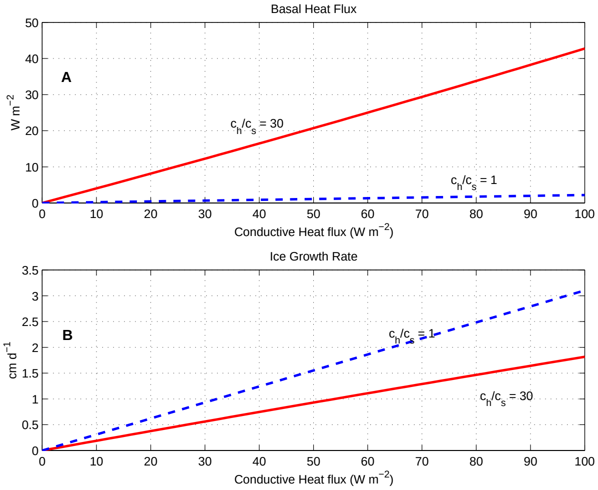

FIGURE 1. A.Heat flux from the ocean for growing ice, with two different ratios for the exchange coefficients. The difference between conductive flux (abscissa) and basal heat flux is latent heat released as ice grows. B. Corresponding ice growth rates.

The impact of the supercooling tendency is to reduce the (congelation) growth rate at the interface (Fig. 1B). Supercooling of the water column is rarely observed with modern instrumentation, and is always small in magnitude, suggesting that any double-diffusive tendency must be rapidly relieved by growth of frazil crystals. If the frazil were more or less uniformly spread through the mixed layer by turbulence, then the double diffusion mechanism provides a “growth redistributor” which would inhibit the increase in thickness of thin ice, and by doing so, increase the overall ice growth (Holland et al. 1997).

3. SHEBA MEASUREMENTS

A SHEBA Intensive Observation Period (IOP) program was designed to evaluate the hypothesis that rapid growth enhances ocean heat flux by simultaneously measuring turbulent fluxes under thin (0.5 m) and thick (2 m) ice during freezeup in late Oct, 1997. In addition to the main SHEBA ocean turbulence mast, with instrument clusters at 4, 8, 12, and 16 m below the ice/ocean interface at “Ocean City,” a second mast was deployed with instrument clusters 2 and 4 m below smooth new ice about 50 cm thick near the station runway. The instrument clusters comprise 3-axis current meters and fast response thermometers with capability of measuring the temperature/vertical velocity covariance directly, as well as turbulent Reynolds stress (McPhee 1992).

The runway ice was not instrumented, but was similar in age and thickness to an instrumented frozen polynya about 3 km away named “Site Baltimore.” Ice temperature gradients and growth rate at Baltimore during the same period as the runway deployment (data courtesy of D. Perovich) suggested a conductive heat flux through half meter ice of roughly 20 W m^{-2}. Thus one might expect an easily measurable difference of several watts per square meter between the runway and main floe sites, if the exchange coefficient ratio was large (Fig. 1A).

At the runway site, two different 3-axis current meters were used: a standard partially ducted mechanical rotor system, identical to those on the main Ocean City mast installation, was positioned at 2 m below the ice, while a SonTek Acoustic Doppler Velocimeter (ADV) was used at the 4 m level. Before the IOP, the ADV was thoroughly tested at an installation about 30 m from the main mast, and provided quite similar results for turbulent stress and heat flux.

A comparison of results from the main mast (under thick ice of the primary floe) with the runway ADV instrument cluster on days 301 and 302 of 1997 (28-29 Oct.) is shown in Fig. 2. The flow was relatively steady, and there is reasonably good agreement between measured friction velocity: $u_* = (\langle u'w'\rangle^2 + \langle v'w'\rangle^2)^{1/4}$ at the two sites. The same is true of turbulent heat flux, with very small magnitudes and mean values close to zero. The results for Reynolds stress are somewhat surprising, however, in that the implied drag (U/u_*) is similar, whereas one might expect the smooth runway ice to have a considerably smaller drag coefficient. A possible explanation is that since the runway lead was relatively narrow, the lower runway cluster was beyond the internal boundary layer associated with the transition to the newer, smooth ice. Thus it would sense turbulence conditions "upstream" of the lead edge, typical of the multiyear pack ice. This interpretation is bolstered by the comparison of runway clusters at 2 m and 4 m (Fig. 3). The friction velocity and heat flux plots look similar only because values for the upper (2-m) cluster have been multiplied by ten in order to show detail. Increased stress at 4 m at time 302.8 coincides with a change in direction of the relative current, and an abrupt slowing of the mean current at that level. This probably resulted from flow obstruction by an irregular ice block at the floe/frozen lead boundary— but the disturbance apparently does not penetrate into the internal, "smooth" boundary layer.

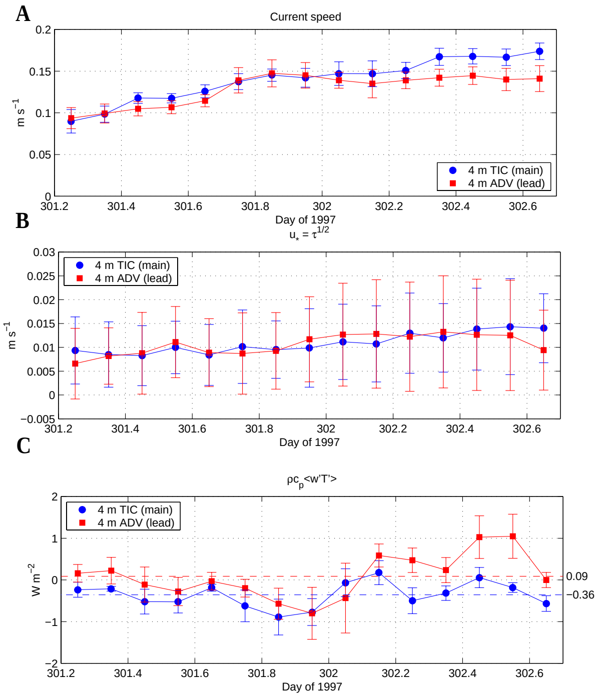

FIGURE 2. Comparison of Sontek ADV cluster data, positioned 4 m under 0.5-m thick ice at the SHEBA runway site, with the main mast TIC #1 data under 2-m thick ice. Symbols represent 2.4-h averages of 15-min flow realizations, with error bars indicating twice the sample standard deviation. A. Current speed. B. Friction velocity. C. Turbulent heat flux with mean values listed.

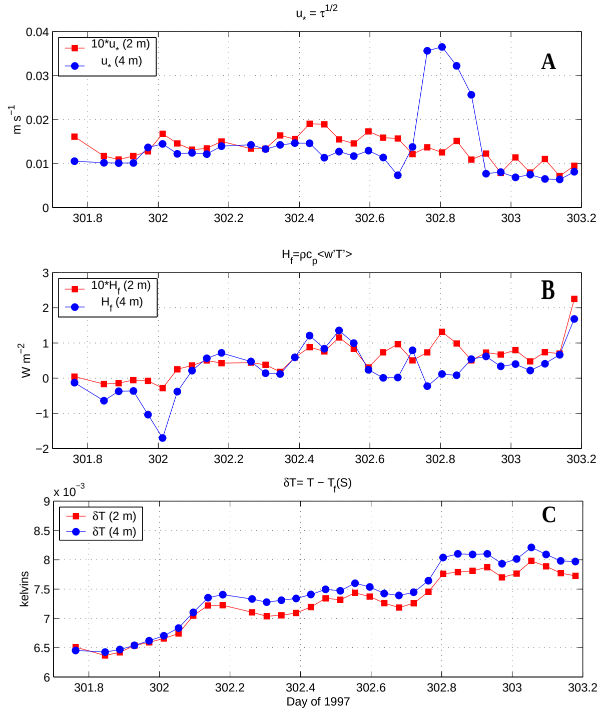

FIGURE 3. Hourly average values of friction velocity (A), turbulent heat flux (B), and temperature elevation above freezing (C) for the two instrument clusters on the runway mast. For the upper (TIC) cluster 2 m below the ice, u_* and H_f have been multiplied by ten for clarity. Factory calibrations were used for the SBE T/C sensors, leaving an uncertainty of several millidegrees in the absolute value for $\delta T = T - T_f(S)$

4. DISCUSSION

The results shown in Fig. 3 appear to bear directly on the question posed in the title. If in fact, the upper cluster lay within the internal boundary layer associated with the new ice, then it should be affected directly by any supercooling and/or frazil production. The magnitude of heat flux at 2 m, although showing the same trends as heat flux at 4 m, averages less than 0.1 W m^{-2} indicating that no $\langle w'T' \rangle$ covariance associated with downward flux of supercooled water occurred. This is also apparent in the small increase in temperature elevation above freezing (Fig. 3C), which follows the lower cluster.

The analysis is, of course, complicated significantly by the horizontal heterogeneity of the ice undersurface in the vicinity of the runway measurements. Nevertheless, the lack of any evidence for enhanced heat flux in the measurements under ice with a substantial conductive heat flux, indicates that during rapid ice growth any tendency toward double-diffusive supercooling is relieved quite near the interface. As it relates to heat and mass transfer at the interface, its impact would be hardly distinguishable from straight congelation growth.

5. REFERENCES

Holland, M. M., J. A. Curry, and J. L. Schramm, 1997: Modeling the thermodynamics of a sea ice thickness distribution 2. Sea ice/ocean interactions, *J. Geophys. Res., 102,* 23,093-23,107.

Steele, M., G. L. Mellor, and M. G. McPhee, 1989: Role of the molecular sublayer in the melting or freezing of sea ice. *J. Phys. Oceanogr., 19*, 139-147

McPhee, M. G., C. Kottmeier, J.H. Morison, 1999: Ocean heat flux in the central Weddell Sea in winter, *J. Phys. Oceanogr., 29,* 1166-1179.

McPhee, M.G., G.A. Maykut, and J.H. Morison, 1987: Dynamics and thermodynamics of the ice/upper ocean system in the marginal ice zone of the Greenland Sea. *J. Geophys. Res., 92,* 7017-7031.

McPhee, M.G., 1992: Turbulent Heat Flux in the Upper Ocean under Sea Ice, *J. Geophys. Res.,* ***97,*** 5365-5379.

Yaglom, A.M., and B.A. Kader, 1974: Heat and mass transfer between a rough wall and turbulent flow at high Reynolds and Peclet numbers. *J. Fluid Mech., 62,* 601-623.

6. ACKNOWLEDGMENTS

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