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CORRESPONDENCE

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SIR,

Rheological contrast between Pleistocene and Holocene ice in Barnes Ice Cap, Baffin Island, N.W.T., Canada: a new interpretation

That Wisconsin-aged ice is mechanically softer than Holocene ice, at least in the Northern Hemisphere, is widely recognized. This characteristic was apparently first observed in bore-hole deformation experiments on Barnes Ice Cap, Baffin Island, Canada (Hooke, 1973). At comparable stresses, shear-deformation rates in a layer of bubbly white ice at the base of Barnes Ice Cap were found to be ~2.5 times faster than in overlying blue ice. Subsequently, stable-isotope data demonstrated that the Pleistocene-Holocene transition lay at the boundary between the white and blue ice (Hooke, 1976; Hooke and Clausen, 1982). Additional bore-hole deformation studies in the late 1970s and early 1980s confirmed this rheological contrast, and suggested that the white ice might deform as much as 25 times faster than the blue ice (Hooke and Hanson, 1986). During this same time period, bore-hole deformation experiments on Devon Ice Cap (Paterson, 1977, p. 53-54), on Aggasiz Ice Cap (Fisher and Koerner, 1986), and at Dye 3 in south Greenland (Dahl-Jensen and Gundestrup, 1987) documented a similar softness of Pleistocene ice.

Because the white ice on Barnes Ice Cap was exceptionally bubbly, particularly in comparison with the overlying blue ice, its softness was originally attributed to the high bubble content (Hooke, 1973, p. 432-33). The contrast in bubble content was sufficient to produce a density difference of 0.05 Mg/m^3 which, based on extrapolation of creep data from snow and low-density ice (Mellor and Smith, 1967, fig. 4), seemed to be quantitatively sufficient to explain the contrast in rheology. Thus, although Paterson (1977, p. 54) drew an analogy between the softness of the Pleistocene ice in Devon and Barnes Ice Caps, Hooke (1981, p. 670) argued that different processes must be involved, as no corresponding bubble or density contrast was found in the Devon Island ice core.

Recent experimental results obtained by Gao and Jacka (in press) now suggest that Hooke's interpretation was wrong. Using tests in unconfined uniaxial compression, Gao and Jacka found that there was no significant change in minimum strain-rate over a density range from 0.83 to 0.91 Mg/m^3 (Fig. 1). This suggests that the rheological contrast between Pleistocene and Holocene ice in Barnes Ice Cap should be attributed to factors other than the density contrast. In particular, the cause of this rheological contrast in Barnes Ice Cap may be the same as the cause in the Devon and Aggasiz Ice Caps and Greenland ice sheet. If future laboratory tests in simple shear, preferably extending to tertiary creep, should fail to show a contrast in rheology over the density range mentioned, this interpretation would be strengthened.

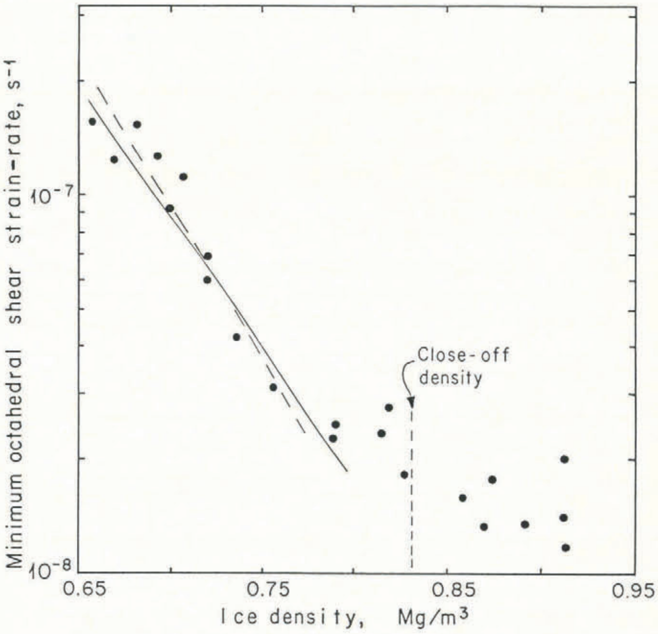

Fig. 1. Variation in minimum octahedral shear strain-rate with initial ice density (modified from Gao and Jacka (in press)). Slopes of solid and dashed lines are based on tests of Mellor and Smith (1966) and Haefeli and von Sury (1975), respectively.

TABLE I. SUMMARY OF CHEMICAL ANALYSES OF BARNES ICE CAP ICE, ppm (ANALYSES BY R.A. SOUCHEZ IN 1973 AND 1974)

	Na	*K*	*Ca*	*Mg*	*Cl*
Holocene ice	0.024 ± 0.010	0.012 ± 0.007	0.010 ± 0.015	0.002 ± 0.001	<0.05
Pleistocene ice	0.049 ± 0.043	0.043 ± 0.045	0.244 ± 0.231	0.044 ± 0.043	0.1 ± 0.1

Values shown are mean value and standard deviation. For the Holocene ice, three samples were collected. Each was sampled three times, making nine analyses. For the Pleistocene ice, seven samples were collected and each was sampled three times, making 21 analyses.

It is worth noting, however, that the change in fabric and crystal size across the Pleistocene–Holocene boundary is quite dramatic in Barnes Ice Cap (Hooke and Hudleston, 1980), and this is undoubtedly partially responsible for the rheological contrast. On the other hand, it is also worth noting that there is a chemical contrast between the Pleistocene and Holocene ice in Barnes Ice Cap similar to that found elsewhere at the Pleistocene–Holocene transition (Table I). These factors need to be taken into consideration in our attempts to explain this puzzling rheological contrast.

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SIR,

Estimating glacier melt from bulk-exchange coefficients

There are two ways to study ablation–climate relations. The first is to measure energy exchanges at the glacier surface and the second is to find simple correlations between ablation and selected climate elements. Supporters of the first approach claim that theirs is more physical, while supporters of the second are sure that their approach is more useful. Kuhn (1979) made an admirable step towards reconciling these approaches with his heat-transfer coefficient α, which is physically based and is useful for calculating sensible-heat flux from air temperature. The paper by Hay and Fitzharris (1988) can be similarly welcomed as describing physical models to estimate turbulent-heat fluxes from simple meteorological data, but Ambach (1986) has already done this in greater detail.

The calculation of sensible- and latent-heat fluxes by Ambach (1986) is based upon energy-balance data from the ablation area of the Greenland ice sheet (Ambach, 1963) and from the accumulation area (Ambach, 1977). Although the paper's title refers to nomographs, all assumptions are clearly presented so that the reader can choose between graphical and numerical methods. The sensible-heat flux Q_S for a Prandtl-type boundary layer over a melting glacier surface is given by:

$$Q_S = K_S b v_2 T_2 \qquad (1)$$

where b is the average atmospheric pressure at the site in question, v is wind speed, and T is air temperature. The subscript "2" denotes a measuring height of 2 m above the glacier surface. The coefficient K_S depends upon surface-roughness parameters z_{0W} and z_{0T}, referring respectively to wind and temperature profiles. Ambach (1986) gave different K_S values for snow and ice surfaces because of their differing surface roughness.

For a similar assumption of a melting glacier surface, Hay and Fitzharris (1988) expressed their sensible-heat flux Q_H by:

$$Q_H = \rho_a c_p K v_2 T_2 \qquad (2)$$

where ρ_a is the density of air, c_p is the specific heat of air at constant pressure ($1010\ \mathrm{J\,kg^{-1}\,deg^{-1}}$), and K is a dimensionless bulk-exchange coefficient for the surface layer. Equation (2) can be criticized as the site elevation is only implicit in the density ρ_a. This can be overcome by setting $\rho_a = \rho_0(b/b_0)$ where ρ_0 is the density of air ($1.29\ \mathrm{kg\,m^{-3}}$) at standard temperature and pressure, b_0 is standard air pressure (101 300 Pa), and b is the actual air pressure at the site which depends on elevation. Substituting into Equation (2) gives:

$$Q_H = \gamma K b v_2 T_2 \qquad (3)$$

where $\gamma = (\rho_0 c_p)/b_0$. The resemblance between Equations (1) and (3) is clear with:

$$K_S = \gamma K. \qquad (4)$$

For sensible-heat flux in $\mathrm{J\,m^{-2}\,s^{-1}}$ units, $K_S = 2.46 \times 10^{-5}$ for the assumptions of Ambach (1986), and $\gamma = 1.29 \times 10^{-2}$. Substitution of these into Equation (4) gives $K = 1.91 \times 10^{-3}$, which is lower than 3.9×10^{-3} found by Hay and Fitzharris for Ivory Glacier, New Zealand. However, in the latter case, the same bulk-exchange coefficients have been assumed for wind, temperature, and humidity profiles, which implies that the same roughness parameters are also assumed for the three quantities. The surface roughness on Ivory Glacier is 0.014 m, which is much greater than the 0.002 m assumed by Ambach (1986) for the wind profile over an ice surface. Substituting this greater roughness for both wind and temperature profiles into the Ambach model gives $K = 6.83 \times 10^{-3}$, which is higher than the value found by Hay and Fitzharris.

The above discussion indicates a factor-of-two agreement between the approaches of Hay and Fitzharris (1988) and Ambach (1986), which is very encouraging and supports the basic concept of a simple relation between sensible-heat flux and the product of temperature and wind speed as expressed by Equations (1) and (3). However, the aerodynamic assumptions by Ambach (1986) seem less restrictive than those of Hay and Fitzharris, and may therefore be more correct. More important, Ambach (1986) took account of the aerodynamic differences of snow and ice surfaces, e.g. the sensible-heat flux to a snow surface is only 70% of the flux to an ice surface with the same temperature and wind conditions. This is definitely needed for any serious attempt to explain the past behaviour of glaciers with high accumulation rates like Ivory Glacier.

My colleague and I have previously stressed the simple relation between ablation and temperature in analysis of our