Blue ice and green ice

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In some mountainous regions in Antarctica, strong winds blow away the fallen snow and sublimate the firn, exposing areas of glacier ice, which are further ablated by sublimation. The exposed surface is often called "blue ice," but its appearance might be better described as "blue-white," because the ice contains numerous bubbles. Blue ice can occur wherever there is net ablation, which in coastal regions may be due more to melting than to sublimation. Antarctic blue-ice fields are of interest both as places to search for meteorites and as potential landing sites for wheeled aircraft; the blue-ice regions near the South Pole were catalogued by Swithinbank (1989). We measured the spectral reflectance at one of these sites (Mount Howe) in November 1992. The spectral reflectance is useful for understanding the energy budget of the ice surface and for remote sensing.

Pure ice is inherently blue because its wavelength of minimum absorption is 470 nanometers (nm) (Grenfell and Perovich 1981). In the visible region, ice therefore can be thought of as a filter that removes red light and transmits blue light; but because ice is a weak filter, only large blocks of ice [more than 1 meter (m) thick] appear colored to the eye.

Glacier ice is formed by compression of snow and, therefore, contains numerous bubbles that scatter light of all visible wavelengths. As the bubble content increases, the fraction of light reflected increases, and the perceived color changes from blue to white; that is, the color becomes less pure, as explained by Bohren (1983).

Our particular reason for measuring the spectrum of blue ice was for comparison with our previous measurements of a green iceberg (figure 2 of Warren et al. 1993). Green ice apparently forms by the freezing of seawater to the base of ice shelves. It differs from sea ice at the ocean surface, however, in that it contains almost no salt and no bubbles. The reason for the absence of salt and bubbles probably has to do with a difference in the mechanism of freezing at the base of an ice shelf vs. at the surface (Kipfstuhl et al. 1992). The ice is green because some of the dissolved organic matter in the seawater, which absorbs blue light, is incorporated into the ice as seawater freezes to the base of the ice shelf.

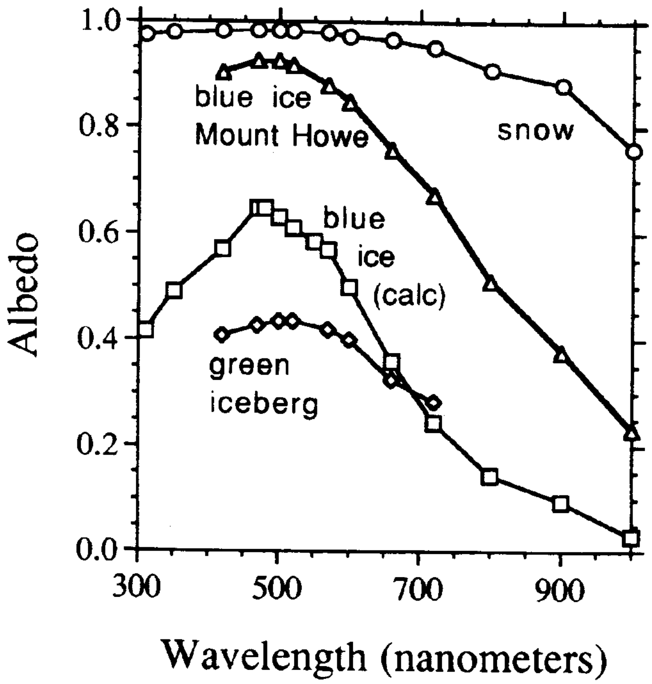
Our opportunity to measure the spectral albedo of blue glacier ice was on 17 November 1992 at Mount Howe (87°S 150°W). We used a portable spectrophotometer described by Grenfell, Warren, and Mullen (in press). Access to the site was by Twin-Otter aircraft, a 1-hour flight from the South Pole.

The photometer consists of a cosine collector in front of a silicon photodiode, with an intervening filter wheel containing 11 interference filters. Bandwidth (full width at half-maximum transmittance) was 10 nm for all filters. The photometer was suspended on a horizontal rod between two tripods and leveled such that the cosine collector was parallel to the horizon.

The atmospheric conditions were excellent for optical measurements. The sky was very clear, and two repeated spectral scans agreed to within 0.1 percent in both upward and downward fluxes. The albedo, or fraction of light reflected, is the ratio of the upward flux to the downward flux. The albedo is uncertain to a few percent; the largest likely source of error is a possible unmeasured deviation of the local surface slope away from horizontal, which can cause a bias in the measured albedo at large solar zenith angles, as explained by Grenfell et al. (in press). No slope was obvious at the measurement site. The measurements were made at 22:00 Greenwich mean time on 17 November, corresponding to a local time of noon at 150°W, so that the solar elevation angle was about 22°.

The figure shows the measured albedo as a function of wavelength for the blue ice, as well as that of snow and of a green iceberg. The albedo of the blue ice is surprisingly high due to the large number of bubbles. Other blue-ice areas with fewer or smaller bubbles will have lower albedos. The albedo of pure ice without bubbles would be just the Fresnel reflectance for an air-ice interface, which is 0.07 (independent of wavelength) for diffuse incidence, and 0.12 for a direct beam at elevation angle 22°. An albedo of 0.07 was used as an extreme lower limit for modeling the subsurface absorption of sunlight in blue ice (Brandt and Warren 1993), but the figure shows that 0.07 is far too low to represent natural blue-ice surfaces in Antarctica.

The reflectance spectrum of the green iceberg differs from that of the blue glacier ice in two respects: its peak wavelength is slightly longer (500–520 nm instead of 470–500 nm), and the reflectance is lower at all wavelengths. The green ice had some



Spectral albedo measured on blue-white ice below Mount Howe (87°S 150°W), on 17 November 1992, under direct sunlight at elevation angle 22°. Also plotted are the spectral albedos of snow at South Pole Station and of a green iceberg at 67°S 62°E (near Mawson Station), and a calculated spectrum for pure, infinitely thick blue ice with a scattering coefficient similar to that of the green ice. The spectrum of snow is from Grenfell et al. (in press); that of the green ice and calculated blue ice are from figure 2 of Warren et al. (1993).

cracks that scattered light, but it had almost no bubbles; therefore, the scattering coefficient was much lower than for blue glacier ice. For comparison to the green ice, the spectrum of a hypothetical blue ice with a scattering coefficient similar to that of the green iceberg was calculated using the method of Mullen and Warren (1988); it is also plotted in the figure. Because the blue-ice model used an unrealistically low bubble content, its calculated spectral albedo is probably lower than that of any natural surfaces of thick glacier ice. On the other hand, the spectrum of snow can be taken as an upper limit for the surfaces of glaciers and ice sheets.

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