Temperature dependence of beam scattering in young sea ice

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Laboratory measurements of the upward intensity distribution in young thin sea ice illustrate the variation of this distribution and peak intensity with growth temperature and ice thickness.
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Understanding the reflection and diffusion of light from and through sea ice is important for determining the energy flux in polar regions. Thin ice covers a significant area in the arctic in the marginal ice zone and occurs frequently as leads break open and refreeze. Laboratory measurements offer the ability to study young, thin ice safely and can be used to determine various optical properties that are important for radiative transfer. In this study measurements of the angular pattern of radiance exiting the surface of the ice when illuminated from below by a collimated beam were made. This can provide information on the radiance distribution in the ice volume and can be used to predict the radiance received by airborne radiance sensors that fly over the ice. This data set is also useful for validating future and current radiative transfer models in sea ice.

The ice was grown in a polyethylene plastic water tank, 1.1 m in diameter and 1.2 m deep, located in a temperature-controlled room in the U.S. Naval Ocean Systems Center Arctic Submarine Laboratory. The room temperature could be controlled to within +/−1° from 25°C to −40°C. A second room, maintained at ~0°C, contained a similar tank from which water was circulated into the ice tank. In this manner, water salinity control was maintained while the apparent volume of water under the ice was doubled. A third room was maintained at room temperature (~25°C) and contained most of the measurement instrumentation. The cold room tank had 30 cm of insulation on its side walls and rested on an insulating platform to reduce the heat flow from the sides and bottom of the tank. Thus ice formed from the water surface down as it would in the Arctic rather than on the tank sides. Filtered seawater was supplied through a pipeline from the ocean off San Diego.

A Spectra-Physics 148 air-cooled argon-ion laser in the laboratory room provided blue light (488 nm) that was transmitted into the cold room and into the tank on multimode optical fiber. A fiber-optic beam collimator in the tank collimated the light into a 1-cm-diameter beam with ~9-mrad divergence. The light exited the collimator in an upward direction and produced an ~2-cm-diameter spot on the bottom of the ice.

The receiver used was a fiber-optic collector (full angle 17°) mounted on a motorized cart traveling on a semicircular gonio track above the cold room tank. This field of view was chosen to permit light from the entire illuminated surface to be viewed. The gonio track was mounted such that the radiometer was directed at the center of the beam exit point on the ice below at all times. After collection optical fibers transported the light to a photomultiplier assembly (EG&G D-46AQ) in the warm instrument room for detection, digitization, and recording.

To monitor ice thickness a simple mechanical J-shaped gauge was vertically frozen into the ice surface. The gauge was drawn upward against the ice–water interface with the length of the J stem protruding above the ice surface to indicate thickness. Ice salinity was sampled at several depths in the ice at the conclusion of each temperature experiment. Salinity values (shown in Ref. 1) were typical of natural sea ice.[2] Vertical and horizontal ice sections were taken to observe the ice crystal and brine cell structures qualitatively.

The collector viewed a 15-cm-diameter spot on the surface when pointed in the nadir direction, greater when viewed at other angles. As the ice grew, the beam spot size on the surface also grew through beam spread processes. Beam spread data were collected at the same time[1] and used to filter data in this analysis. The beam spread is the radial function of irradiance above the ice. When the beam spread data had not fallen to 10% of its central value by the edge of the collectors field of view, these data were excluded. In this way the entire illuminated spot at the surface was viewed, and the angular intensity distribution exiting the ice was the radiometric parameter measured.

The intensity distribution exiting the ice depends on scattering in the ice (the internal radiance distribution) and on surface effects. If the light were perfectly diffuse in the ice (radiance distribution was isotropic) and the surface were smooth, the intensity measured would have a functional dependence proportional to the cosine of the zenith angle for the angles measured here. A rough surface would have the effect of making even collimated light look diffuse, thus giving it a cosine angular dependence.

The surface roughness of the ice is dependent on the air temperature at the ice–air interface. As the ice grows below the eutectic point, as in the −35°C case, brine is squeezed to the surface by expanding ice crystals in which it crystallizes, eventually resembling frost on the surface of the ice. This was brushed off prior to each measurement, leaving a fairly smooth surface. The brine extruded from the ice grown at −15°C did not crystallize and remained on the surface in liquid form. Thus the surface in this case contributed little to the angular distribution of the exiting light. The surface of the ice in the −25°C case resembled a mixture of the other two. The extruded brine was semi-solid and could neither be brushed off nor ignored.

Several example intensity distribution data sets for the angular range from zenith to 35° are shown in Fig. 1. Since

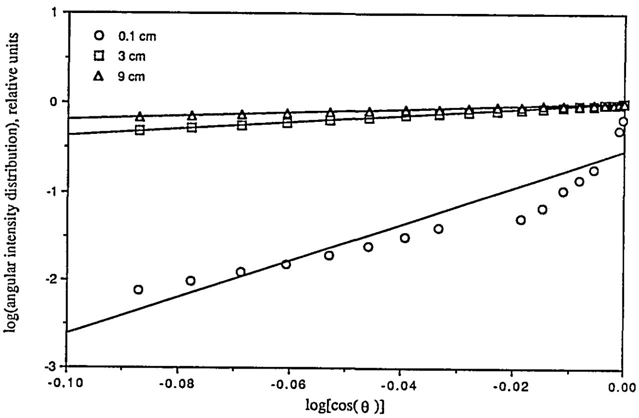

Fig. 1. Plot of log(intensity distribution) versus log[cos(θ)] for three sample ice thicknesses of ice grown at −15°C. The r^2 for the linear fits for ice thicknesses of 0.1, 3, and 9 cm were 0.857, 0.999, and 0.998, respectively.

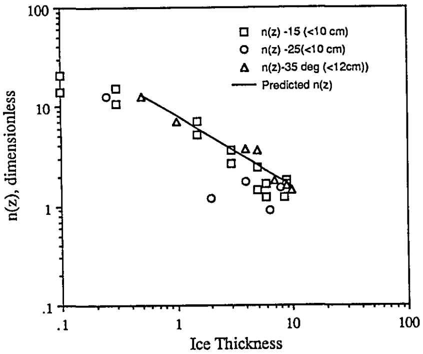

Fig. 2. Plot of derived $n(z)$ versus ice thickness for the three ice growth conditions and the previously derived fit to the $-35°C$ case. As the ice thickness increases, $n(z)$ should approach 1, completely isotropic.

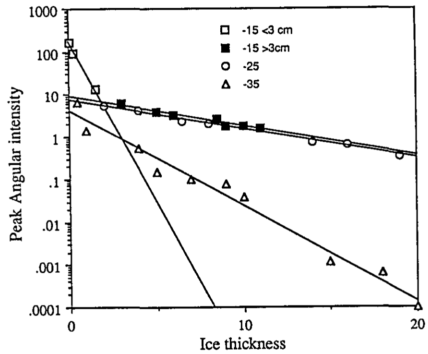

Fig. 3. Plot of peak angular intensity versus ice thickness, illustrating that the attenuations in the $-25°C$ and $-15°C$ cases are the same, while the $-35°C$ case varies significantly.

the form of the relationship for totally diffuse light is a cosine, the data were tested to determine whether an expression of the form

$$L(\theta, z) = L(0)\cos^{n(z)}(\theta)$$

would produce a satisfactory fit. Here θ is the angle from zenith, z is the ice thickness, and $n(z)$ is some function of ice thickness. $L(\theta, z)$ for each z was regressed against θ to determine the $n(z)$ for that z. For all growth temperatures, the initial measurements (<1 cm of ice) of L did not follow this cosine dependence well. The regression coefficients (r^2) for these cases were as low as 0.857, because the shape of the distribution was still characterized by the initial beam shape to a large extent. However, after the ice reached a thickness of 1 cm the cosine function fit quite well. In fact, for ice thicknesses 1 cm or greater, the r^2 were >0.977 (most >0.99).

The ice grown at $-35°C$ and $-15°C$ thus had a smooth surface in the angular range that we measured; the intensity distribution measured outside the ice can be related to the radiance distribution inside the ice. The ice grown at $-25°C$ exhibited a rough surface. This was evidenced in the data as it quickly approached a simple cosine response at relatively small ice thicknesses (2 cm).

The ice at $-35°C$ and $-15°C$ behaved similarly. As seen in Fig. 2, the exponent of the cosine relation decreased to 1 when the ice thickness increased. The $-15°C$ case approached 1 quicker than the $-35°C$ case, indicating that there is slightly more scatter at this growth temperature as noted by Gilbert and Schoonmaker.[1] However by 10 cm in both situations the distribution appears to be totally diffuse. These two growth temperatures were selected because they should exhibit the ice properties of two quite different growth conditions: $-15°C$ is above the eutectic point and $-35°C$ is below the eutectic point for sea ice. As can be seen in Fig. 2, the equation initially described for the $-35°C$ case,[3]

$$n(z) = 8.02z^{-0.705},$$

describes the situation within the noise and inhomogeneities of the measurement. However at >10 cm, the scattering in the ice is strong enough that the distributions should be considered isotropic for the angular ranges measured (0–35° in air).

The other parameter needed to characterize the distribution is the variation in the peak value, $L(0, z)$. These values were fit to equations of the form $L(0, z) = L(0, 0)\exp(-K_{\text{peak}}z)$; see Fig. 3. In these measurements there were two trends of note. First, the peak value for angles <4 cm thick for the $-15°C$ case had a decidedly different relationship than for >4 cm. The slope of the relationship below 4 cm is much steeper, indicating a much greater attenuation value ($K_{\text{peak}} = 1.732\ \text{cm}^{-1}$ for $z < 4$ cm and $K_{\text{peak}} = 0.165\ \text{cm}^{-1}$ for $z > 4$ cm). The mechanism for this is probably that below 4 cm the direct beam is dominant in these measurements, while above 4 cm the direct beam has been attenuated sufficiently to allow the diffuse beam to dominate. Second, in the measurements of the ice grown at $-35°C$, the slope is intermediate between the thin ice and thicker ice slopes given above ($K_{\text{peak}} = 0.513\ \text{cm}^{-1}$), and no clear distinction between a thin and thick ice situation is evident. The $-25°C$ case is extremely similar to the $-15°C$ case ($K_{\text{peak}} = 0.160\ \text{cm}^{-1}$). However, for this growth temperature no measurements were done at the very thin ice thicknesses (>3 cm); thus the functional behavior in this regime is undetermined.

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