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Observations of Ultraviolet Light Reflection and Transmission by First-Year Sea Ice

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Abstract. As part of a comprehensive program investigating the electromagnetic properties of sea ice, measurements were made of the optical properties of young ice and first-year sea ice at ultraviolet wavelengths. Young sea ice observations were made in a specially designed sea ice pond at the Cold Regions Research and Engineering Laboratory (Hanover, NH), while first-year sea ice was examined in the Chukchi Sea and Beaufort Sea near Barrow, Alaska. The results indicated that, in general, albedo increased with increasing wavelength from 305 to 380 nm, with values for first-year ice in the 0.4 to 0.6 range. Transmittance through bare first-year ice was roughly 0.5 to 2 percent. Extinction coefficients for bare sea ice were between 2 and 4 m^{-1} and decreased with increasing wavelength. The presence of a snow cover had a profound impact on ultraviolet light levels under sea ice, with even a thin (0.1-m-thick) snow cover reducing transmitted ultraviolet light by more than an order of magnitude. Observed transmittances indicated that the attenuation of ultraviolet light by sea ice and snow was greater than that of the photosynthetically active radiation.

Introduction

There has been considerable concern in recent years over the potential biological impact of enhanced levels of ultraviolet radiation at the surface of the earth resulting from decreases in the amount of stratospheric ozone. This concern is particularly pronounced in the Antarctic seas, where there is a great degree of ozone depletion and a large amount of highly productive marine biota (Smith, 1989; Lubin et al., 1992). A recent study by Smith et al. (1992) examined the impact of enhanced ultraviolet light levels on photosynthesis in the water column in the Bellingshausen Sea, Antarctica. This work indicated that ultraviolet radiation penetrated to ecologically significant depths in the water column and that enhanced levels were associated with decreases in primary productivity. There is growing concern about ozone depletion and enhanced ultraviolet light levels in the Arctic as well.

Over much of the region potentially affected by enhanced ultraviolet radiation, assessing the biological impact is complicated by the presence of a sea ice cover. This sea ice cover is home to a rich sea ice microbial community (Palmisano and Sullivan, 1983; Garrison et al., 1986; Smith et al., 1988; Cota et al., 1991). In this case an understanding of the interaction of ultraviolet light with the sea ice cover is critical; however there have been few studies investigating the interaction of ultraviolet light with sea ice. Trodahl and Buckley (1989) assumed ultraviolet absorption coefficients for ice were similar to those for water and theoretically investigated temporal changes in transmitted ultraviolet light under sea ice in McMurdo Sound, Antarctica. Perovich and Govoni (1991) measured the absorption coefficients of pure, bubble-free fresh ice from 250 to 400 nm. Perovich (1993) used these absorption coefficients to extrapolate visible wavelength sea ice extinction coefficients into the ultraviolet in order to compute estimates of ultraviolet light transmission through Antarctic sea ice. These theoretical estimates indicated that the presence of a sea ice cover caused a significant reduction in the amount of ultraviolet light transmitted and that UV-B light was attenuated more than visible light.

Field observations of the reflection and transmission of ultraviolet light by a sea ice cover are scarce. Trodahl and Buckley (1990) monitored ultraviolet light transmitted through 1.7-m-thick first-year sea ice in McMurdo Sound. They found that ultraviolet transmittances were a few percent in late October, then decreased by an order of magnitude to a few tenths of a percent over the next few weeks as the ice warmed and the surface layer drained, increasing the turbidity of the sea ice.

To augment this limited observational database, laboratory and field observations of ultraviolet albedos and transmittances were made. This paper reports results from three bare sea ice cases (0.33-m-thick young sea ice, 1.25-m-thick first-year sea ice, and 1.75-m-thick first-year sea ice), along with a snow-covered sea ice case. In addition to the albedos and transmittances, extinction coefficients calculated using a two-stream formulation are reported.

Experimental Program

During a comprehensive laboratory and field program investigating relationships between the physical and electromagnetic properties of sea ice, we were afforded an opportunity to examine the interaction of ultraviolet radiation with sea ice and snow. The experimental program included studies of young sea ice and first-year sea ice. Experiments investigating young sea ice were conducted during January 1994 in a laboratory setting using a specially designed sea ice pond at the Cold Regions Research and Engineering Laboratory (Hanover, NH). Field observations of shorefast first-year sea ice were made at Point Barrow, Alaska, in April–May 1994. These observations were made at two sites within 20 km of each other, one in the Chukchi Sea and the other in the Beaufort Sea. There was a 0.10- to 0.20-m-thick snow cover at both sites. In order to make bare sea ice measurements a large 5-m by 10-m rectangular area was cleared at each site.

Ultraviolet measurements were made using a Biospherical Instruments PUV–500 ultraviolet radiometer. The instrument consisted of two components: a submersible unit that was placed under the ice to measure transmitted irradiance and a surface unit that measured incident and reflected irradiance. Each unit has five channels: four at single wavelengths of 305 nm, 320 nm, 340 nm, and 380 nm, plus an integrated channel measuring the photosynthetically active radiation (PAR). A typical measurement sequence consisted of measuring scans of incident and reflected irradiance with the above ice detector, then placing the submersible unit under the ice to measure

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transmitted irradiance, while continuing to monitor the incident irradiance. Irradiances were determined by averaging the results of five to ten scans. Transmitted irradiance was measured by mounting the submersible unit on a 1.3-m-long rotating arm and lowering it through a 0.25-m-diameter hole. Once placed beneath the ice a flotation collar caused the arm to rotate so that the instrument rested on the ice bottom, looking upward, sampling undisturbed ice away from the hole. Ultraviolet albedos were determined by taking the ratio of the reflected to the incident irradiance, and transmittances were computed by dividing the transmitted by the incident irradiance.

In conjunction with the optical observations, ice cores were analyzed to characterize the physical state and structure of the sea ice (Frankenstein and Gardner, 1967; Tucker et al., 1987). This characterization included vertical profiles of temperature, salinity, brine volume, density, and crystal structure. A qualitative assessment of the number of air bubbles in the sea ice was also made.

Results

The optical results for the three sites, along with the physical properties, are summarized in Table 1. The young ice, grown in the CRREL sea ice pond, was 0.33 m thick and was structurally composed of a few centimeters of frazil ice underlain by columnar ice. In the columnar ice the c-axes were in the horizontal plane and randomly oriented. The bulk salinity of the young ice was 5.3 ppt and the brine volume ranged from 3% to 8%. Two first-year sea ice sites were investigated in the field: 1.25-m-thick ice in the Chukchi Sea and 1.75-m-thick ice in the Beaufort Sea. The ice at the Chukchi Sea site was thinner due to a January storm locally sweeping the ice away and creating open water conditions, reinitializing the ice growth. At both sites the sea ice was composed mainly of highly oriented columnar ice. The columnar ice was strongly aligned with the c-axis horizontal and parallel to the shore, in the direction of the current. Salinities and brine volumes were roughly comparable for the two field cases. A qualitative examination of ice cores from both sites indicated that the surface layer of ice in the Chukchi Sea contained significantly more air bubbles than ice in the Beaufort Sea. An inspection of the bottom of the sea ice showed a considerable amount of biomass at the Chukchi site, while very little was evident at the Beaufort site.

Figure 1 summarizes ultraviolet albedos and transmittances for the three sites. Due to instrument difficulties the reflected irradiance at 320 nm was not measured, and hence the albedo at 320 nm was not calculated. The measurements were made under overcast skies and there was no significant direct beam contribution. Incident irradiances were relatively constant over the few minutes it took to make the measurements. Not surprisingly, the albedos are smallest for the thinnest sea ice, the 0.33-m-thick case, which was not optically thick. Both of the first-year sea ice cases were optically thick with optical thicknesses between 3.2 and 4.5. Since the sea ice was essentially optically thick in both cases, the albedo was not appreciably affected by the difference in ice thickness. In fact, albedos are larger for the 1.25-m-thick ice than for the 1.75-m-thick case. The variation in albedo between the two first-year sea ice cases was due to differences in the ice physical properties and structure. The surface layer of the 1.25-m-thick sea ice was composed of finer grained ice and had more air bubbles than the 1.75-m-thick case. The surface layer of sea ice is known to have a strong impact on the albedo (Grenfell and Maykut, 1977) and with more air bubbles and grain boundaries, the 1.25-m-thick ice had more scattering, and therefore larger albedos. The spectral shape of albedo shows an overall decrease with wavelength from 380 nm to 305 nm.

The ultraviolet transmittance decreased with increasing thickness for the three cases. For the young sea ice, transmittances were approximately 20%, while they were 2% or less for the first-year sea ice cases. The transmittance decreases at shorter wavelengths, and this spectral dependence becomes more pronounced as the ice grows thicker. Our observed transmittances for 1.75-m-thick ice were comparable to, but somewhat lower than, values reported by Trodahl and Buckley (1990) for 1.7-m-thick, drained ice in McMurdo Sound (13 November case). Interestingly, the transmittance curves for the 1.25-m-thick and 1.75-m-thick cases appear to be converging as the wavelength increases. In fact transmitted PAR is greater for the 1.75-m case than for the 1.25-m case. We believe that this convergence in transmittance was primarily a result of the greater bottom biomass present at the 1.25-m-thick site. This higher biomass concentration was visually apparent in the bottom of the ice core and was also evident in the shape of the visible transmission spectrum. Compared to sea ice, the biomass is strongly absorbing, thereby reducing transmittance. The convergence in transmittance for these two cases indicates that the absorption due to the biomass was more pronounced as the wavelength increased towards the visible. Direct measurements of concentration of particulates and ice biota and their ultraviolet absorption spectra would be of great interest.

The impact of a snow cover on ultraviolet transmittance was investigated at the Beaufort Sea site at a location where the sea ice was covered by 0.17 m of snow. The top 0.02 m was low density new snow and the bottom 0.15 m was wind-packed snow composed of rounded grains approximately 1/2–1 mm in diameter. Transmittances were first measured for the ice with all of the snow present, then the new snow layer was removed, leaving wind-packed snow and sea ice, and finally the wind-

Table 1. Summary of ice ultraviolet and physical properties.

			Albedo					Transmittance				
H_i	S_b	v_b	305 nm	320 nm	340 nm	380 nm	PAR	305 nm	320 nm	340 nm	380 nm	PAR
Case 1: Young ice, 12 Jan, 1015, complete overcast—solar disk visible												
0.33	5.3	6.7	0.227	0.228	0.236	0.253	0.298	0.240	0.270	0.280	0.314	0.348
Case 2: First-year ice, 29 Apr, 1552, complete overcast—solar disk visible												
1.25	5.5	6.1	0.545		0.581	0.614	0.630	0.00696	0.01203	0.01326	0.02037	0.02910
Case 3: First-year ice, 5 May, 1540, complete overcast—solar disk not visible												
1.75	5.3	6.1	0.431		0.460	0.494	0.554	0.00262	0.00439	0.00630	0.01466	0.03548

H_i = ice thickness (m)
S_b = bulk salinity (ppt)
v_b = bulk brine volume (%)
PAR = photosynthetically active radiation

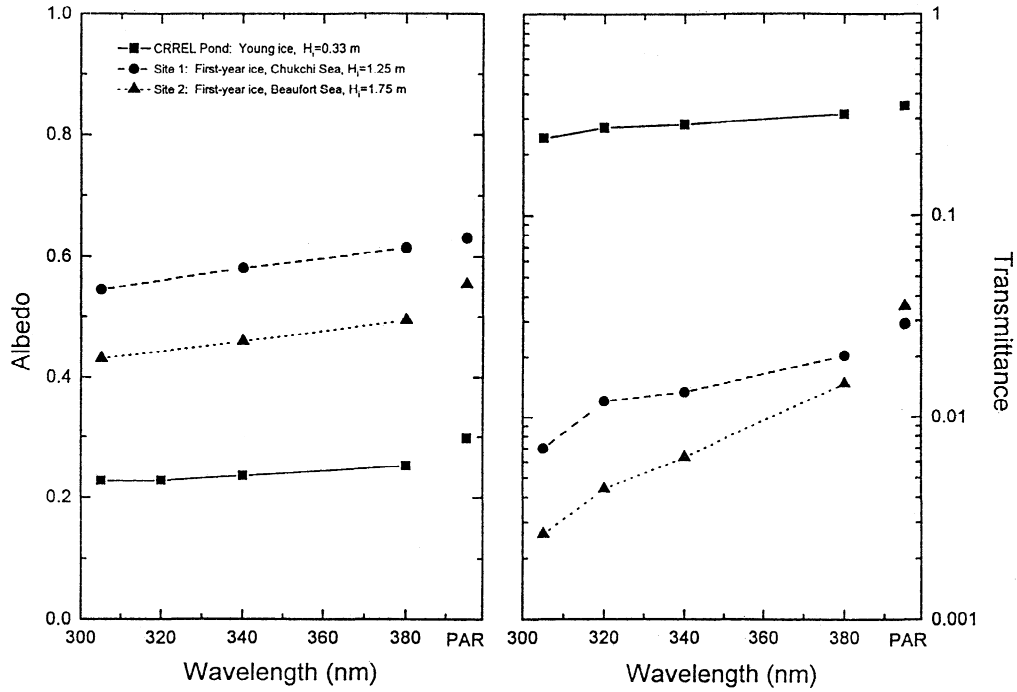

Figure 1. Ultraviolet albedo and transmittance for 0.33-m-thick young ice, 1.25-m-thick first-year ice, and 1.75-m-thick first-year ice. Values for photosynthetically active radiation (PAR) are plotted for comparison.

packed snow was removed and transmittance was measured for the ice-only case. Figure 2 summarizes ultraviolet transmittance for these three cases. The presence of a snow cover has a profound impact on ultraviolet transmittance. Adding 0.17 m of snow to 1.75-m-thick sea ice caused transmittance to be reduced by nearly a factor of 40. Even a small amount of new snow (0.02 m) reduced transmittance by one-third. Ultraviolet albedos for snow-covered sea ice were in the 0.90-0.95 range and increased slightly with increasing wavelength.

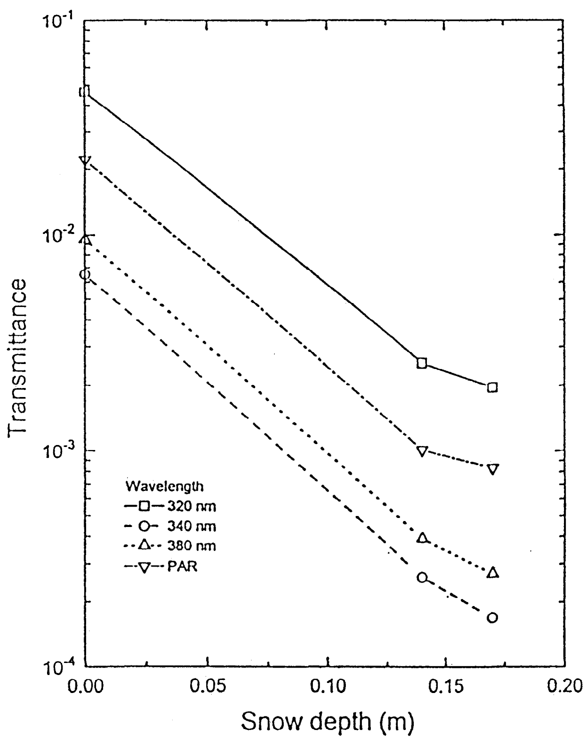

Figure 2. Ultraviolet transmittance for bare ice, ice covered by 0.15 m of wind-packed snow, and ice covered by 0.15 m of wind-packed snow and 0.02 m of new snow at 320 nm, 340 nm and 380 nm. PAR transmittances are plotted for reference. Light levels at 305 nm were too low to measure for the snow-covered cases.

Since transmittance depends strongly on the thickness of the ice, a more useful thickness-independent quantity is the extinction coefficient. In this paper we follow the lead of earlier researchers (Grenfell and Maykut, 1977; Grenfell, 1979; Perovich, 1990; Perovich, 1993) and use a Dunkle and Bevans two-stream radiative transfer formulation to compute extinction coefficients from the irradiance observations. Ultraviolet extinction coefficients for the three cases are plotted in Figure 3. Values are in the 2 to 4 per meter range and decrease with increasing wavelength. These extinction coefficients represented values averaged vertically over the entire thickness of the ice and include extinction due to the ice as well as any material present in the ice. Extinction coefficients from the ice in the Chukchi Sea were affected by the additional absorption by the biomass present at that site.

Discussion

The field observations indicate that albedos for cold, bare, first-year sea ice are in the 0.4 to 0.6 range and that extinction coefficients lie between 2.5 and 3 m^{-1}. For thin (0.3 m), snow-free, young sea ice, ultraviolet transmittance is large, roughly 20%. The presence of even a thin snow cover was found to significantly reduce ultraviolet transmission. The observations of transmittance provide experimental confirmation that the biologically harmful ultraviolet radiation is attenuated by snow and sea ice more strongly than the beneficial PAR. This is in keeping with the theoretical findings of Perovich (1993).

The extinction coefficients determined for the three ice cases lie between the theoretical estimates for the interior of white ice and the surface scattering layer of white ice used to represent Antarctic sea ice by Perovich (1993). In all cases wavelength-integrated extinction coefficients for PAR are smaller than ultraviolet values, consistent with earlier theoretical estimates.

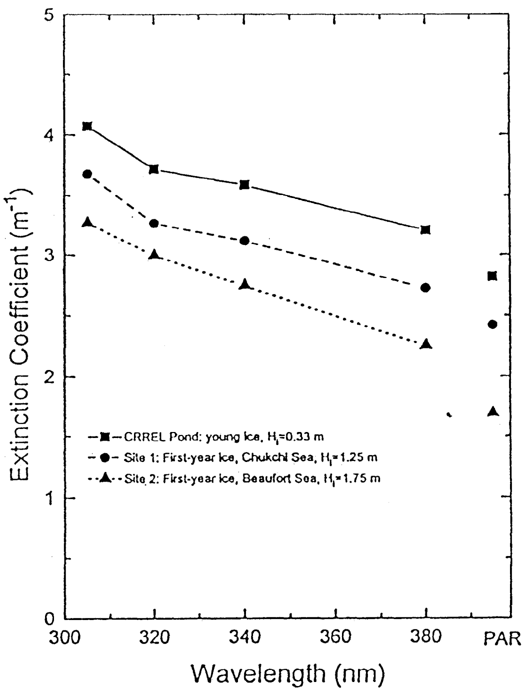

Figure 3. Ultraviolet extinction coefficients for young ice and for 1.25-m-thick and 1.75-m-thick first-year ice.

These results provide insight into the interaction of ultraviolet radiation with sea ice and snow, but are only a first step. Observations of the ultraviolet properties for different sea ice types and conditions are needed. Of particular importance are observations of Antarctic pack ice and observations of temporal changes during the onset of melt. Because of a larger amount of frazil and pancake ice, Antarctic pack ice differs structurally from Arctic sea ice (Weeks and Ackley, 1986) and may have different ultraviolet properties. Measurements are also needed of the ultraviolet absorption coefficients of biogenic material and other matter found in sea ice.

Recent field and laboratory observations (Ryan and Beaglehole, 1994) indicate that for algae growing on the bottom of 1.8-m-thick ice in McMurdo Sound the impact of ultraviolet radiation was small, and that further observations were needed before extrapolating these results to other cases. They also found that the peak intensity of the ultraviolet radiation had a greater biological impact than the accumulated dose did. Their findings emphasized the importance of conducting *in situ* studies under natural conditions. This highlights the need for combined bio-optical efforts addressing the prime concern of understanding the biological implications of the ultraviolet light transmitted into and through sea ice.

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