ABSORPTION COEFFICIENTS OF ICE FROM 250 TO 400 NM

Donald K. Perovich and John W. Govoni

Reprinted from

Geophysical Research Letters

Volume 18, Number 7, July 1991

GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 7, PAGES 1233-1235, JULY 1991

ABSORPTION COEFFICIENTS OF ICE FROM 250 TO 400 NM

Donald K. Perovich and John W. Govoni

U.S. Army
Cold Regions Research and Engineering Laboratory

Abstract. Absorption coefficients for pure bubble-free ice are a critical element in theoretical efforts to determine levels of ultraviolet radiation reaching marine biota in and under a sea ice cover. A 3-m block of ice was used to measure these coefficients from 250 to 400 nm. Absorption coefficients were found to increase from 0.092 m^{-1} at 400 nm to 0.665 m^{-1} at 250 nm. Values in the ultraviolet were shown to be comparable to visible results from 580 to 720 nm. This suggests that existing data on the interaction of visible light with snow and sea ice can be used as a first-order estimate of ultraviolet optical properties.

Introduction

Over the past several years there has been a growing concern about stratospheric ozone depletion during the austral spring in Antarctica. Since stratospheric ozone filters out the UV-B component (280–320 nm) of the solar spectrum, a major by-product of ozone depletion is an increase in levels of biologically damaging radiation at the surface of the earth [Lubin et al., 1989; Frederick and Snell, 1988]. A critical question is how much of this ultraviolet light reaches biological organisms. Answering this question for marine biota in the polar regions is complicated by the presence of a sea ice cover. To date, field measurements of ultraviolet light transmission through sea ice have been extremely limited [Trodahl and Buckley, 1990], though ample data for sea ice and snow are available at visible wavelengths [Grenfell and Perovich, 1984; Perovich et al., 1986; Warren, 1982]. Because of the temporal and spatial variability of a sea ice cover, radiative transfer models are used to obtain representative estimates of light transmission [Perovich, 1990; Grenfell, 1983]. Spectral absorption coefficients of pure ice are a fundamental component of such radiative transfer models. Warren [1982] points out that while accurate measurements of absorption coefficients have been made in the visible and much of the near-infrared, data at ultraviolet wavelengths are not available. Lacking such measurements, efforts to model ultraviolet light transmission through sea ice [Trodahl and Buckley, 1989] have used absorption coefficients based on values for water. In this paper we address this deficiency by presenting absorption coefficients for pure bubble-free ice from 250 to 400 nm.

The Experiment

Our approach to determining spectral absorption coefficients of ice at ultraviolet wavelengths is similar to that used in the visible and near-infrared by Grenfell and Perovich [1981]. Based on the similarity in absorption coefficients for water and ice in the visible and reported values for water in the ultraviolet [Smith and Baker, 1981], the ice was expected to be quite transparent between 250 and 400 nm. Because of this transparency a long ice sample was required to provide sufficient attenuation for an accurate determination of the absorption coefficient. In principle, to measure only absorption losses, there would be no scattering in the ice block. In practice, our goal was to minimize scattering by growing an ice block that was free of air bubbles and had large ice crystals.

The ice block was grown in a 0.3 × 0.3 × 3.0-m tank. The tank had Plexiglas walls and the base consisted of an aluminum beam with cooling coils embedded in it. The tank was filled with doubly distilled deionized water, which was changed every few days during freezing to remove dust and particulates and reduce the air content. The tank was placed in a coldroom set slightly above the freezing point, and cold (–30°C) freon was circulated through the coils in the base. In this fashion we were able to grow the ice from the base of the tank upward. Four stirrers were placed in the water so that, as the ice froze and air came out of solution, the bubbles were swept from the ice surface, leaving the ice free of bubbles. The ice was grown very slowly (10–20 mm/day) to assist in the air rejection and to increase the size of the crystals. The resultant ice block consisted of vertically oriented crystals that extended the entire height of the block and were on the order of 50–150 mm across. A close inspection indicated that the ice was free of air bubbles and other impurities, though some of the grain boundaries between ice crystals were faintly visible.

Once a block of bubble-free ice was successfully grown, the coldroom temperature was lowered to below freezing and the optical measurements were made. A 300 W Xenon arc lamp was used as an ultraviolet light source. The beam from this lamp was collimated using a 75-mm-diameter quartz lens. The detector used a diffraction grating to split the spectrum and then focused it on a 252-element silicon photodiode. The spectral range of the detector was from 216 to 406 nm, though low light levels and light leakage from longer wavelengths precluded using data from wavelengths less than 250 nm.

First a reference measurement [$I_o(\lambda)$] was made without the ice block after aligning the source and detector to give the maximum reading. The ice block was then moved into the beam, and another set of measurements was made of the light transmitted through the block [$I(\lambda)$]. Spectral absorption coefficients [$K(\lambda)$] were calculated from these data using the formula for a purely absorbing medium,

$$K(\lambda) = \frac{-1}{H} \ln \left(\frac{I(\lambda)}{\left[I_o(\lambda)\,(1 - R_f(\lambda))\,(1 - R_b\,(\lambda)) \right]} \right)$$

where H is the length of the ice block, and $R_f(\lambda)$ and $R_b(\lambda)$ are

Paper number 91GL01642

the Fresnel reflection coefficients at the front and back of the block, respectively. The imaginary part of the index of refraction was also calculated using the absorption coefficient and the expression $n_{im} = \lambda K(\lambda)/(4\pi)$ [Born and Wolf, 1959]. Since the ice was polycrystalline, there was a small amount of scattering from the crystal boundaries, which, as was the case for Grenfell and Perovich [1981], was primarily in the forward direction. To compensate for this scattering, a Teflon diffusing element was used on the detector to enhance light collection. This small amount of scattering and slight deviations in the experimental alignment resulted in some variability in the ice transmission measurements.

Because of this variability, 13 separate sets of absorption coefficient measurements were made. Mean values of absorption coefficients for these cases are plotted in Figure 1, along with error bars denoting 90% confidence levels. Uncertainties were due to repeatability of the $I_0(\lambda)$, $I(\lambda)$ measurements at long wavelengths and to instrumental noise and low light levels at short wavelengths. Errors due to multiple internal reflections were negligible. Absorption coefficients monotonically increase from 0.092 m^{-1} at 400 nm to 0.665 m^{-1} at 250 nm, corresponding to a decrease in e-folding length from 10.9 to 1.5 m.

Discussion

In Figure 2 these ultraviolet absorption coefficients for ice are compared to previously reported values for pure water [Smith and Baker, 1981] and for pure ice in the far ultraviolet [Minton, 1971] and at visible wavelengths [Grenfell and Perovich, 1981]. Though no measurements of absorption coefficient are available between 185 and 250 nm, values must decrease sharply by more than an order of magnitude. In the ultraviolet, absorption coefficients for ice are larger than those reported for pure water, though the curves appear to converge at shorter wavelengths. No spectral features are evident from 250 to 400 nm for either ice or water. There is good continuity between the ice absorption coefficients in the ultraviolet and in the visible, as the upward trend in absorption coefficient between 450 to 400 nm previously reported by Grenfell and Perovich [1981] is continued in the ultraviolet. A rough symmetry is evident in the ice data, with absorption coefficients from 400 to 250 nm corresponding to those between 580 and 720 nm. The absorption coefficients of pure bubble-free ice from 250 to 400 nm and the imaginary part of the index of refraction are summarized in Table 1 along with the visible wavelength that has the same absorption coefficient. If we neglect the effects of biological organisms on radiative transfer and assume no spectral variation in scattering, the optical properties of fresh ice, sea ice, and snow from 250 to 400 nm should be similar to those from 580 to 720 nm. Thus the large data base of observations and theoretical modeling results available at visible wavelengths can be used to generate first-order estimates of the interaction of ultraviolet light with snow and sea ice.

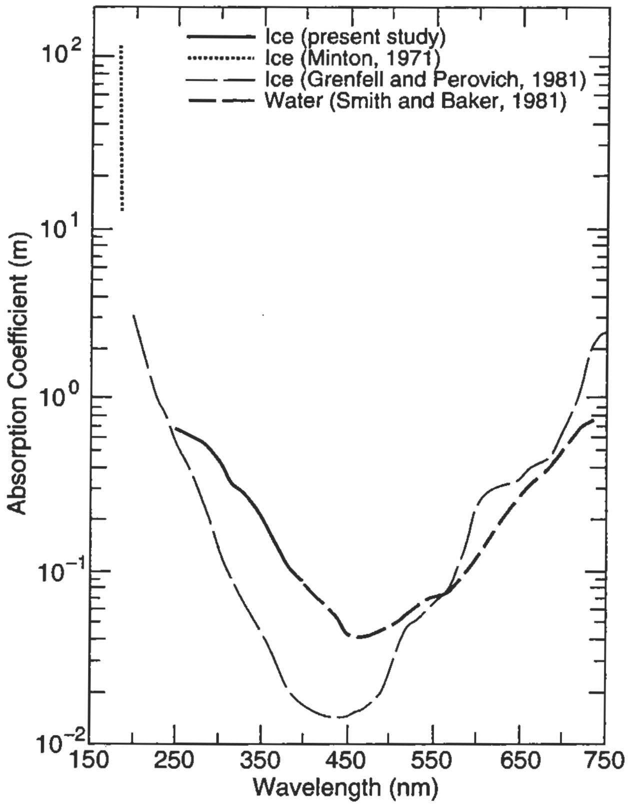

Figure 2. Spectral absorption coefficents for (—) pure bubble-free ice from 250 to 400 nm, (...) from 180 to 185 nm [Minton, 1971], (- -) from 400 to 750 nm [Grenfell and Perovich, 1981], and (– –) for pure water from 250 to 750 nm [Smith and Baker, 1981].

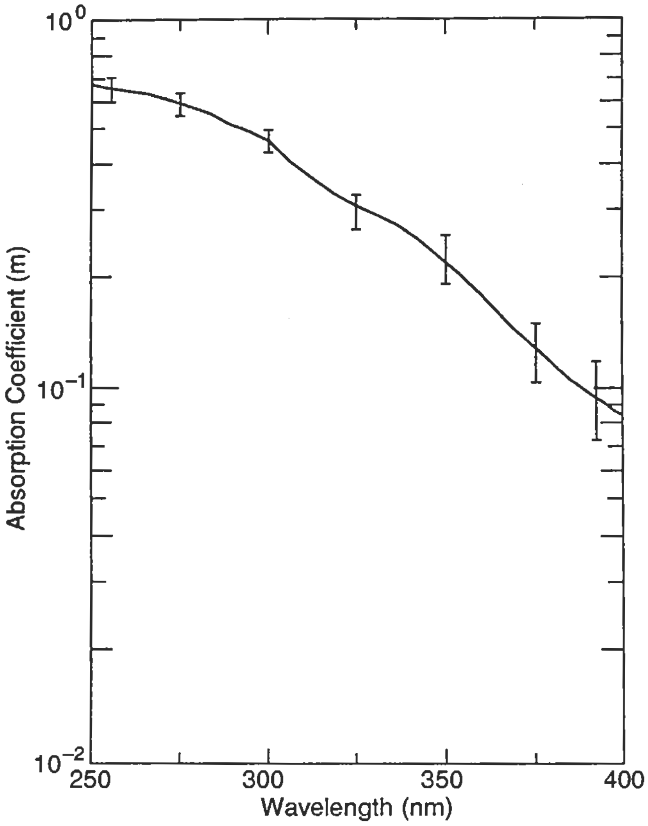

Figure 1. Spectral absorption coefficients of pure bubble-free ice from 250 to 400 nm. The error bars denote 90% confidence levels in the data.

Table 1. Spectral absorption coefficients (K) and the imaginary part of the index of refraction (n im) for pure bubble-free ice. The uncertainty denotes the 90% confidence level. Also reported is the corresponding visible wavelength with the same absorption coefficient.

Ultraviolet Wavelength (nm)	K (per meter)	n im	Uncertainty (% +/-)	Visible Wavelength (nm)
250	0.666	1.33E-08	7	714
255	0.650	1.32E-08	7	713
260	0.634	1.31E-08	7	712
265	0.625	1.32E-08	7	711
270	0.608	1.31E-08	7	710
275	0.585	1.28E-08	6	708
280	0.567	1.26E-08	6	706
285	0.544	1.23E-08	6	703
290	0.506	1.17E-08	7	698
295	0.488	1.15E-08	6	696
300	0.464	1.11E-08	6	693
305	0.419	1.02E-08	7	687
310	0.376	9.28E-09	8	677
315	0.345	8.65E-09	8	668
320	0.327	8.32E-09	9	663
325	0.299	7.73E-09	10	656
330	0.294	7.73E-09	11	655
335	0.275	7.34E-09	11	650
340	0.263	7.12E-09	12	647
345	0.235	6.46E-09	13	639
350	0.225	6.27E-09	14	635
355	0.194	5.49E-09	14	626
360	0.181	5.18E-09	15	622
365	0.158	4.58E-09	16	615
370	0.140	4.13E-09	17	609
375	0.127	3.79E-09	18	604
380	0.114	3.43E-09	19	596
385	0.106	3.25E-09	21	592
390	0.100	3.12E-09	22	588
395	0.095	2.99E-09	25	586
400	0.092	2.93E-09	28	584

Acknowledgments. This worked was funded by United States Army Cold Regions Research and Engineering Laboratory In-House Laboratory Independent Research (ILIR) funds.

References

Born, M., and E. Wolf, *Principles of Optics,* 3rd ed., 808 pp., Pergamon, New York, 1959.

Frederick, J.E., and H.E. Snell, Ultraviolet radiation levels during the Antartic spring. *Science, 241,* 438–440, 1988.

Grenfell, T.C., A theoretical model of the optical properties of sea ice in the visible and near infrared. *J. of Geophys. Res., 88,* 9723–9735,1983.

Grenfell, T.C., and D.K. Perovich, Radiation absorption coefficients of polycrystalline ice from 400–1400 nm. *J. Geophys. Res., 86,* 7447–7450, 1981.

Grenfell, T.C., and D.K. Perovich, Spectral albedos of sea ice and incident solar irradiance in the southern Beaufort Sea. *J. Geophys. Res., 89,* 3573–3580, 1984.

Lubin, D., and J.E. Frederick, C.R. Booth, T. Lucas, and D. Neuschuler, Measurements of enhanced springtime ultraviolet radiation at Palmer Station, Antarctica, *Geophys. Res. Let., 16,* 783-785, 1989.

Minton, A.P., The far ultraviolet spectrum of ice. *J. Phys. Chem., 75,* 1162–1164, 1971.

Perovich, D.K., G.A. Maykut, and T.C. Grenfell, Optical properties of ice and snow in the polar oceans, I. Observations. *Proc. Soc. Photo Opt. Instrum. Eng., 637,* 232–244, 1986.

Perovich, D.K., Theoretical estimates of light reflection and transmission by spatially complex and temporally varying sea ice covers. *J. of Geophys. Res., 95,* 9557–9567, 1990.

Smith R.C. and K.S. Baker, Optical properties of the clearest natural waters (200-800 nm). *Appl. Opt.,* 20, 177–184, 1981.

Trodahl, H.J. and R.G. Buckley, Ultraviolet levels under sea ice during the Antarctic spring. *Science, 245,* 194–195, 1989.

Trodahl H.J. and R.G. Buckley, Enhanced ultraviolet transmission of Antarctic sea ice during the Austral spring. *Geophys. Res. Let., 17,* 2177–2179, 1990.

Warren, S.G, Optical properties of snow. *Rev. Geophys. Space Phys., 20,* 67–89, 1982.

Warren, S.G., Optical constants of ice from the ultraviolet to the microwave, *Appl. Opt., 23, 8,* 1984.

(Received April 5, 1991;
accepted May 16, 1991.)