Review of radiation absorption coefficients for clear ice in the spectral refion 0.3 to 3 microns

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REVIEW OF RADIATION ABSORPTION COEFFICIENTS FOR CLEAR ICE IN THE SPECTRAL REGION 0.3 to 3 MICRONS

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REVUE DES COEFFICIENTS D'ABSORPTION DE RAYONNEMENT POUR LA GLACE CLAIRE DANS LA RÉGION SPECTRALE DE 0.3 A 3 MICRONS

SOMMAIRE

Des données ont été colligées dans la littérature technique sur le coefficient d'absorption de la glace pure et sans faille en fonction de la longueur d'onde, pour cette partie du spectre solaire variant entre 0.3 à 3 μm. Les meilleures valeurs sont présentées sous forme de graphique ainsi que des valeurs pour l'eau. On inclut une liste d'articles publiés jusqu'à 1967.

NATIONAL RESEARCH COUNCIL OF CANADA
DIVISION OF BUILDING RESEARCH

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ABSTRACT

Information has been collected from the literature on the radiation absorption coefficient of pure flawless ice as a function of wavelength, for the range (0.3 to 3 μm) of the solar spectrum. Best values are presented in graphical form along with values for water.

A list of articles published up to 1967 is included.

REVIEW OF RADIATION ABSORPTION COEFFICIENTS FOR CLEAR ICE IN THE SPECTRAL REGION

by

L. E. Goodrich

In studies of the heat balance over natural ice and snow surfaces, the absorption of solar radiation within the material is an important consideration. The literature contains many references to measurements of absorption and transmission coefficients in ice (natural as well as laboratory-grown). Many of the data, however, are inexact or inconsistent for a variety of reasons. Results presented by different authorities differ by as much as a factor of 100. The mention of a simple experiment performed by Lyons and Stoiber (1959) will suffice to illustrate the difficulty of such measurements: "...a polished ice surface was frosted by a breath of air; transmissivity of the sample dropped from 90 to 3 per cent."

Of the two compendiums of data known to the author (Lyons and Stoiber, 1959; Minsk, 1964*), the first gives results only for the visible region and the second is essentially concerned with the electromagnetic region of the spectrum. The spectral region of interest for studies of the solar radiation balance over natural snow and ice covers is the visible-near infrared (roughly the band 0.3 μm to 3 μm). This review was initiated in the hope of finding new observations not contained in these collections.

A search was made of all materials held in the National Science Library and the library of the Division of Building Research. A number of recent Russian papers were obtained from the American Library of Congress. Principal bibliographic sources were the following four publications:

(1) U.S. Army Cold Regions Research and Engineering Laboratory Bibliography

* L. D. Minsk, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. Private Communication.

(2) Glaciological Notes

(3) Arctic Bibliography

(4) Meteorological Abstracts

ABSORPTION IN CLEAR, FLAWLESS ICE

The absorption of radiation in clear, flawless homogeneous ice follows closely the well-known Bouguer-Lambert exponential law

$$I(Z) = I_o^{-\alpha Z}$$

where

I_o = intensity of radiation incident at the surface

$I(Z)$ = intensity of transmitted radiation at depth Z

α = absorption coefficient.

The absorption coefficient is directly related to the nature of the atomic and molecular bonds and their associated energy levels and is, therefore, strongly dependent on wavelength.

The absorption coefficient has been measured by various authors for different regions of the spectrum. Experimental results show a considerable scatter, owing largely to the difficulty of properly taking into account reflections at the surface.

RESULTS OF LITERATURE SEARCH

One of the earliest workers to obtain data on the absorption coefficient for clear ice was Bode (1909), who worked with laboratory-prepared thin specimens (obtained by freezing a thin water layer between glass plates). The results he obtained for the spectral absorption are given in Table I.

TABLE I

ABSORPTION COEFFICIENT OF ICE (Bode)

Ice 1 mm thick		
λ, μm	% absorbed	α, cm^{-1}
1.0	93.0	26.6
1.5	97.5	34.8
2.0	99.0	46.0
2.3	98.0	39.3
2.5	99.5	53.1

Bode concluded that the absorption curve for pure ice was not essentially different from that for water. The magnitudes of the values obtained, however, were criticized by many authors including Sauberer (1959) who, in discussing Bode's results, pointed out the serious discrepancy at λ = 1.0 micron (Bode obtained $\alpha = 26.6\ cm^{-1}$ whereas values of $\alpha = 0.3\text{-}0.5\ cm^{-1}$ are obtained by four other workers for both ice and water). It might be noted, however, that with this one exception, all other values given by Bode are in excellent agreement with those for water and are virtually identical with those of Aschkinass quoted in Dorsey (1940), and shown in Fig. 1.

Bosschieter and Errera (1937a, b) studied the infrared absorption spectra of water and ice but did not provide exact thickness data so that calculation of absorption coefficients is not possible.

J.W. Ellis and R.M. Vanderberg (1954) studied the absorption spectrum of ice in the near infrared, as well as the dispersion. Although their data do not permit the calculation of absorption coefficients, their work (covering visible to 2.3 μm) showed conclusively that there is no essential difference between absorption for the e-ray and the o-ray, contrary to results presented much earlier by Plyler (1924). This conclusion also agrees with that of other recent workers.

Kalitin (1935, 1936), working in the field with clear flawless pond ice and using a spectrophotographic method, obtained the results given in Table II.

TABLE II

ABSORPTION COEFFICIENT OF ICE (Kalitin)

$\lambda, \mu m$	Average for blocks of 10 cm thickness		One block 107 cm thick	
	I/I_o	α, cm^{-1}	I/I_o	α, cm^{-1}
0.332	0.97	0.0030	0.46	0.0072
0.346	0.96	0.0041	0.46	0.0072
0.366	0.99	0.0010	0.51	0.0063
0.392	0.99	0.0010	0.52	0.0061
0.416	0.98	0.0020	0.54	0.0058
0.438	0.99	0.0010	0.52	0.0061
0.446	0.98	0.0020	0.55	0.0056

The data refer to absorption of diffuse radiation. They are considered by Sauberer (1938) and others to be too large.

Lyons and Stoiber (1959) published a compendium of data covering the literature up to 1959, including some results of their own experiments performed on laboratory specimens up to 11.2 cm thick using a spectrophotographic method (Table III).

TABLE III

ABSORPTION COEFFICIENT OF ICE (Lyons and Stoiber)

λ, μm	α, cm^{-1}
0.4 to 0.8	0.000x to 0.00x
0.806	0.035
0.904	0.056
0.988	0.097
1.104	0.061

They conclude that Sauberer's values for the visible region are about right and are probably better than those of Kalitin.

Lyubomirova (1962a) obtained for river ice, described as "quite transparent ice (like glass), through which one could read; density is 0.92 cm", the value 0.002 cm^{-1} for the integral absorption coefficient. Measurements were made using a pyranometer with maximum sensitivity in the range 0.4 to 0.6 microns, and thus the value 0.002 cm^{-1} can be taken as referring to the visible spectrum.

Mantis (1951) presented data obtained by Sauberer (1950) and Kalitin (1935) and from this calculated absorption coefficients. A collection of data by Minsk* is concerned for the most part with the microwave and radio frequency range of the spectrum although data from Dorsey (1940), and Sauberer (1950) are quoted for the visible region and parts of the near infrared. The near infrared data are incomplete, especially the important region between about 0.7 μm and 1.5 μm.

Ockman (1957, 1958), in a thorough study of the infrared and Raman spectra of single crystals and thin films reviewed the literature up to 1957.

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* See previous footnote.

He concluded also that Plyler's result to the effect that there is a large difference in absorption for the e- and o-ray could not possibly be correct. He presented graphs (his results) of the absorption coefficient using polarized light for single crystals. The graphs show the e- and o-ray curves as being nearly identical.

The curves for the o-ray have been replotted in Fig. The curve labelled 0_1 refers to a single crystal 1.0500 cm thick; curve 0_2 refers to a crystal 0.0102 cm thick. The data for both curves were taken at -29°C.

Plyler (1924), working with specimens cut from large blocks of ice, measured absorption coefficients for polarized light. His conclusion that the e-ray is absorbed much more strongly than the o-ray has been discredited by later work of others. Plyler's values for both the e- and o-ray are presented (as quoted in Lyons and Stoiber (1954) and corrected by reference to the original paper) in Table IV.

TABLE IV

ABSORPTION COEFFICIENT OF ICE (Plyler)

λ, μm	α, cm^{-1} e-ray	α, cm^{-1} o-ray
0.75	1.02	0.030
0.81	1.12	0.072
0.85	1.02	0.030
0.92	1.16	0.060
0.95	1.02	0.060
1.02	1.47	0.072
1.10	1.20	0.050
1.20	2.55	1.06

Sauberer (1938), using photocells, studied clear flawless ice plates (from the Lunzer Untersee) in the visible-near infrared region. His results, which are generally considered to be among the most reliable (Lyons and Stoiber), are given in Table Va.

TABLE Va

ABSORPTION COEFFICIENT OF ICE (Sauberer)

Specimens 14 to 16 cm thick		
$\lambda, \mu m$	% transmitted	α, cm^{-1}
0.313	90.0	0.0011
0.350	95.0	0.0005
0.400	96.0	0.0004
0.450	95.0	0.0005
0.500	92.0	0.0008
0.550	88.0	0.0013
0.600	81.5	0.0020
0.650	71.0	0.0034
0.700	55.0	0.006
0.750	34.5	0.011
0.800	17.0	0.018

In the same study he also presented data on the infrared, and although he does not consider these to be very accurate, concluded that the infrared spectrum of ice is essentially the same as that of water (Table Vb)

TABLE Vb

ABSORPTION COEFFICIENT OF ICE (Sauberer)

Specimens 1 cm thick		
λ, μ m	% transmitted	α, cm^{-1}
0.8	97	0.030
0.9	91	0.044
1.0	73	0.315
1.1	85	0.163
1.2	22	1.514
1.3	19	1.661

The most reliable results found are presented in Fig. 1. With the exception of the curves for water in the visible region of the spectrum and the data of Sauberer and Ockman for ice, the lines drawn are not intended to represent the actual spectral curve, and are only included to make the graph more legible. The labelling is as follows.

For ice: (solid lines)

K_1: Kalitin (1935, 1936): average for blocks 10 cm thick (pond ice)

K_2: Kalitin (1935, 1936): one block 107 cm thick (pond ice)

L-S: Lyons and Stoiber (1959): laboratory specimens to 11.2 cm thick

0_1 : Ockman (1958): laboratory specimens 1.05 cm thick

0_2 : Ockman (1958): laboratory specimen film 0.0102 cm thick

S_1 : Sauberer (1938): lake ice 14 to 16 cm thick

S_2 : Sauberer (1938): lake ice 1 cm thick

The data for water (dotted line) are extracted from Dorsey (1940) and refer to the following authors quoted by him.

As : Aschkinass, E. (1895)

Co : Collins, J.R. (1922)

D-H: Lawson, L.H., and E.O. Hulburt (1934)

Dr : Dreisch, T. (1924)

Ew : Ewan, T. (1895)

Ho : Hodgman, C.D. (1933)

R-L: Goldhammer, D.A. (1913)

Sa : Sawyer, W.R. (1931)

Additional data for water (curve C-P) have been taken from Curcio and Petty (1951).

As may be seen in Fig. 1, the absorption spectrum of pure flawless ice is essentially similar to that of water for wavelengths corresponding to the solar radiation received at the earth's surface. Throughout the range 0.3 to 2.5 μm the two spectra agree within a factor of 10, and over much of the range the agreement is considerably closer.

Below 0.6 μm, the data plotted in Fig. 1 suggest a shift of the position of the absorption minimum for ice towards shorter wavelengths relative to the position of the same peak for water. Although the data for ice are insufficient to allow any firm conclusion, this does agree with Cassel (1936) (cited in Lyons and Stoiber 1959), who reported a shift towards shorter wavelengths in the ultraviolet.

All three curves for water (as, Ew, Sa) agree in showing a secondary peak at about 0.6 to 0.64 μm. That Sauberer's curve (S_1) does not show this behaviour may be due to a certain amount of internal reflection (his measurements were made on natural lake ice samples). The magnitude of the absorption coefficients for ice given by Sauberer, however, agree closely with the values for water in the wavelength range 0.6 μ m to 0.7 μ m.

The range 0.7μ m to 0.95μ m shows some conflict among the results of various authors. The data of Dreisch, quoted in Dorsey (1940), indicate an absorption minimum at about 0.9μ m. Such a minimum does not occur in the data of the other authors.

The data of Ockman (O_1) and of Sauberer (S_2) agree closely with the values for water over the range 0.95 μ m to 1.1μ m, whereas the values given by Lyons and Stoiber and by Plyler are smaller by a factor of about 5.

Beyond 1.1μ m the general agreement between the two spectra is evident. Ockman's data for ice shows the expected shift towards longer wavelengths due to lower temperature.

Although there is no data for ice beyond 2.6 μ m this is not important for heat-balance considerations. Values of the absorption coefficient are so large that essentially all the radiation in this spectral region is absorbed at the surface. Furthermore, the intensity of solar radiation of wavelength greater than 2.6 μ m is extremely small.

CONCLUSION

Data have been compiled from various sources on the spectral dependence of the absorption coefficient for clear flawless ice for the spectral region 0.3 to 3.0 microns. The original data or values of absorption coefficient calculated therefrom are presented in tabular form in the main text, along with comments. The data are assembled in graphical form in Fig. 1, which also shows values of absorption coefficient for water taken from Dorsey (1940).

It is concluded that the absorption coefficient of pure flawless ice is essentially similar to that of water in the spectral region corresponding to solar radiation. Data for ice in the wavelength range 0.7 μm to 0.95 μ m are somewhat incomplete and further measurements would be desirable.

For wavelengths greater than about 1 μ m the positions of the absorption peaks for ice are shifted to greater wavelengths relative to the positions of the same peaks for water. This is in accord with the expected shift due to temperature.

Below 0.7 μ m, the data plotted in Fig. 1 suggest a shift of the positions of the absorption maxima in the opposite direction. Although the data of Fig. 1 are insufficient to allow any firm conclusions, this does agree with Cassel (1936) (cited in Lyons and Stoiber (1959)), who reported a shift toward shorter wavelengths in the ultraviolet.

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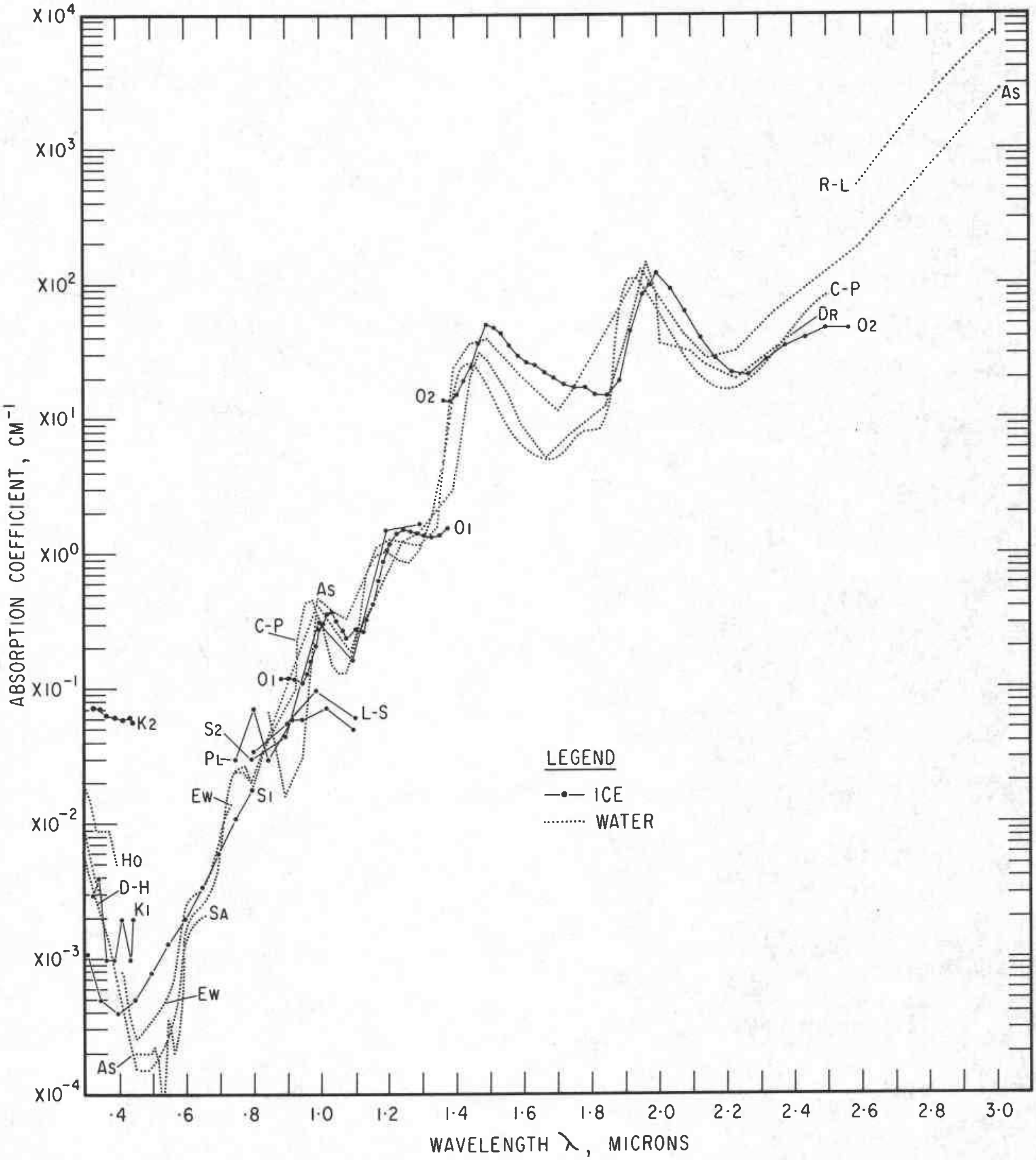

FIGURE I ABSORPTION COEFFICIENT OF PURE FLAWLESS ICE AND WATER

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