Refractive indices of water and ice in the 0.65- to 2.5-μm spectral range

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New accurate values of the imaginary part, k, of the refractive index of water at $T = 22$ °C, supercooled water at $T = -8$ °C and polycrystalline ice at $T = -25$ °C are reported. The k spectrum for water in the spectral region 0.65–2.5 μm is found to be in excellent agreement with those of previous studies. The k values for polycrystalline ice in the 1.44–2.50-μm region eliminate the large uncertainties existing among previously published conflicting sets of data. The imaginary part of refractive index of supercooled water shows a systematic shift of absorption peaks toward the longer wavelengths compared with that of water at warmer temperatures.

Key words: Refractive index, optical constant, near-infrared, ice, water.

1. Introduction

Refractive indices of water and ice play a special role in the field of atmospheric science. They must be known if the radiative properties of clouds and haze are to be determined. It has been recognized that the cloud feedback mechanism is one of the most important and least understood climate mechanisms[1–5] that may significantly modify currently predicted warming[6–8] resulting from the increase of atmospheric greenhouse gases. An accurate calculation of the cloud radiative parameters is not possible without a precise knowledge of the refractive indices of water and ice in the spectral range of solar (0.25–4.0-μm) and terrestrial (3–150-μm) radiation.

Refractive indices used most frequently in atmospheric applications are those listed in the Hale and Querry[9] compilation of the refractive indices of water and in Warren's[10] compilation of indices of refraction of ice. A major effort was devoted to the determination and parameterization of the cloud radiative properties with an error not larger than a few percent. At the same time it was assumed that the refractive indices of such common materials as water and ice are known with a high degree of accuracy. Those who not only use the tables but also study carefully the analysis given in the text of the above-mentioned compilations are well aware that this is not true. The uncertainty in the imaginary part of the refractive index (which determines the absorption of radiation) is significant especially in the case of ice,[10] where it can reach as high as 100% in some spectral regions.

One of the regions of large uncertainty is in the near-infrared part of the solar spectrum. Warren's[10] compilation of the refractive indices of ice is based in this range on measurements done in the early- and mid-1950's[11,12] on ice in the temperature range $-30°$ to -78 °C. The estimated uncertainty[10] of the compilation in this region is a factor of 2.

To reduce the uncertainty in the imaginary part k of the refractive index of ice in the near-infrared region, we have performed new accurate measurements in the 1.45–2.5-μm spectral region. Although our primary goal was to obtain new accurate values of k for ice, we have also measured k for water. The latter measurement was made to test the experimental equipment (k for water is known with a must higher accuracy than that of ice) and procedures.

The measured k values for water differ by as much as 15% from those listed by Hale and Querry[9]; however, they are in good agreement with those obtained by Palmer and Williams[13] and Downing and Williams.[14] We present new measurements of k for supercooled water at -8 °C. Obtained refractive indices (imaginary parts) of ice differ as much as 22% from those listed by Warren.[10]

This paper is divided into four parts. In Section 2 we describe the experimental setup and discuss the

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procedure used to measure k for water and ice. In Section 3 we present new results for water and ice, and Section 4 provides a discussion of the results and suggestions for future work.

2. Experimental Setup and Procedures

The transmission measurements through water and ice were carried out with a Bomem DA3.02 Fourier-transform infrared spectrometer at a spectral resolution of 16 cm^{-1}. The instrument has an absolute wavelength calibration. During the course of the measurements, no adjustment of the light intensity was necessary for 100% transmission to be obtained in the spectral regions where the absorption is negligible.

We derived the Lambert absorption coefficient, α, of freshly distilled filtered water, using the ratio of transmittances obtained with different absorption path lengths. In this way, reflection losses occurring at the air–window and window–water interface and absorption losses caused by the windows of the absorption cell were exactly canceled out. Optical path lengths d in water ranging from 100 μm to 20 cm were selected in such a way that α could be determined from transmittance values varying from 20% to 60%.

Measurements of α of supercooled water and polycrystalline ice were taken in a temperature-controlled cryostat with sample temperatures ranging from +22 °C to −40 °C. For the case of ice and supercooled water, at a given path length α was calculated by using the ratio of the transmittance taken below 0 °C temperature to that at 22 °C. Using our previous measurements of absorption coefficient of water at 22 °C, we determined the absorption coefficient at subzero temperature. Using this method, we found that reflection and absorption losses caused by the cell windows were eliminated. Optical path lengths varying between 100 μm and 2 cm were used for supercooled water, while those for ice were between 116 and 269 μm.

We utilized the following procedure for the formation of ice sample. A droplet of water was placed between two optical windows in such a way that the droplet was free to expand during cooling in the direction normal to the thickness of the sample. Using the above procedure, we found that the water thickness was nearly the same as that of ice.

We obtained an α spectrum by calculating the average spectrum of a set of as many as 20 α spectra collected under the same experimental conditions. The corresponding error can be evaluated by using the standard deviation of the same set of α spectra and the uncertainty in the path length.

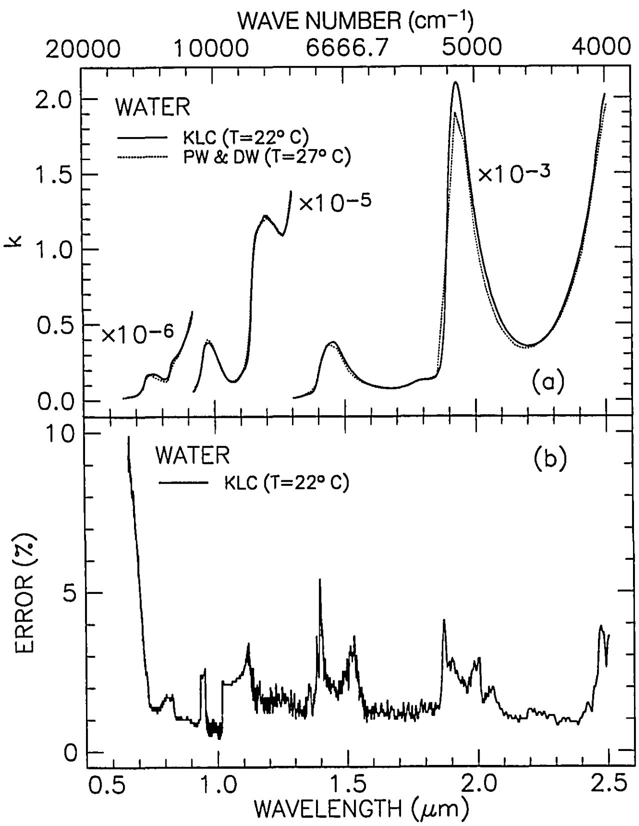

Fig. 1. (a) Imaginary part of the refractive index, k, of water: the present work (KLC, solid curves) at T = 22 °C and the PW and DW data (dashed curves) at 27 °C. (b) Standard deviation of k for water at T = 22 °C.

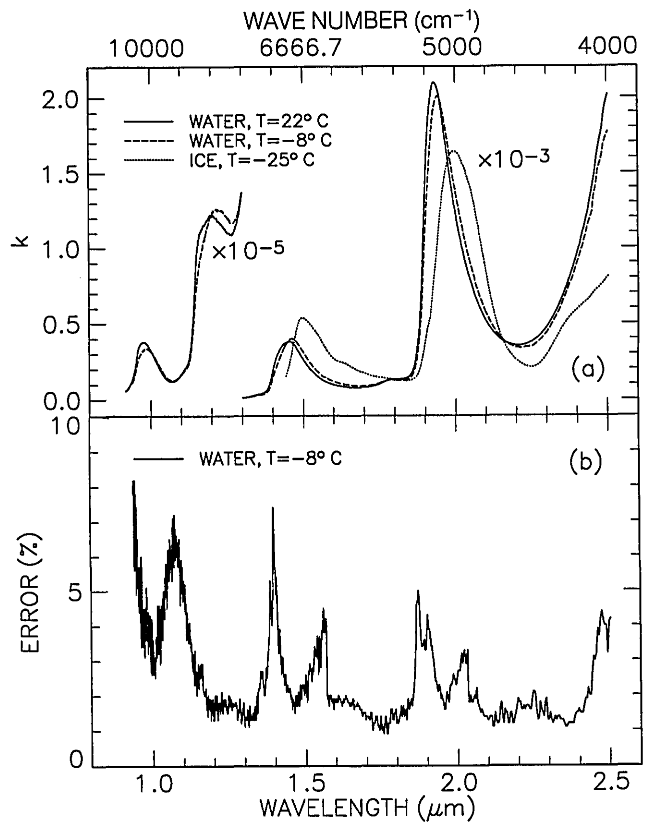

Fig. 2. (a) Imaginary part of the refractive index of water at T = 22 °C (solid curves), supercooled water at T = −8 °C (longer-dashed curves), and polycrystalline ice at T = −25 °C (shorter-dashed curves). (b) Standard deviation of k for supercooled water at T = −8 °C.

Table 1. Imaginary Part of the Refractive Index, k, and the Standard Deviation of k for Water at $T = 22\ °C$, Supercooled Water at $T = -8\ °C$, and Polycrystalline Ice at $T = -25\ °C$ in the Spectral Range From 4000 to 6920 cm^{-1}

		Water				Ice	
		$T = 22\ °C$		$T = -8\ °C$		$T = -25\ °C$	
Wave Number (1/cm)	Wave Length (μm)	k	Error (%)	k	Error (%)	k	Error (%)
4000	2.5000	2.00×10^{-3}	3.6	1.76×10^{-3}	4.3	8.04×10^{-4}	6.0
4020	2.4876	1.87×10^{-3}	3.3	1.68×10^{-3}	4.1	7.72×10^{-4}	4.7
4040	2.4752	1.71×10^{-3}	3.9	1.56×10^{-3}	4.3	7.44×10^{-4}	3.8
4060	2.4631	1.56×10^{-3}	3.1	1.42×10^{-3}	3.8	7.20×10^{-4}	3.8
4080	2.4510	1.40×10^{-3}	2.0	1.25×10^{-3}	3.0	6.91×10^{-4}	3.0
4100	2.4390	1.27×10^{-3}	1.4	1.17×10^{-3}	2.3	6.61×10^{-4}	2.1
4120	2.4272	1.17×10^{-3}	1.4	1.08×10^{-3}	2.2	6.40×10^{-4}	2.0
4140	2.4155	1.07×10^{-3}	1.4	9.94×10^{-4}	1.8	6.21×10^{-4}	1.9
4160	2.4038	9.84×10^{-4}	1.2	9.20×10^{-4}	1.5	5.99×10^{-4}	1.6
4180	2.3923	9.05×10^{-4}	1.0	8.50×10^{-4}	1.5	5.77×10^{-4}	1.5
4200	2.3810	8.35×10^{-4}	0.8	7.81×10^{-4}	1.3	5.54×10^{-4}	1.3
4220	2.3697	7.70×10^{-4}	0.9	7.31×10^{-4}	1.2	5.27×10^{-4}	1.4
4240	2.3585	7.11×10^{-4}	0.9	6.73×10^{-4}	1.1	4.97×10^{-4}	1.5
4260	2.3474	6.75×10^{-4}	1.0	6.19×10^{-4}	1.2	4.61×10^{-4}	1.7
4280	2.3364	6.07×10^{-4}	0.9	5.70×10^{-4}	1.3	4.20×10^{-4}	1.8
4300	2.3256	5.64×10^{-4}	1.0	5.31×10^{-4}	1.3	3.81×10^{-4}	2.1
4320	2.3148	5.24×10^{-4}	0.9	4.90×10^{-4}	1.3	3.40×10^{-4}	2.3
4340	2.3041	4.89×10^{-4}	0.8	4.55×10^{-4}	1.5	3.03×10^{-4}	2.7
4360	2.2936	4.60×10^{-4}	1.0	4.26×10^{-4}	1.4	2.72×10^{-4}	3.3
4380	2.2831	4.34×10^{-4}	1.1	4.01×10^{-4}	1.4	2.46×10^{-4}	3.6
4400	2.2727	4.12×10^{-4}	1.1	3.80×10^{-4}	1.7	2.28×10^{-4}	3.9
4420	2.2624	3.95×10^{-4}	1.0	3.63×10^{-4}	1.3	2.16×10^{-4}	4.1
4440	2.2523	3.80×10^{-4}	1.2	3.48×10^{-4}	2.1	2.10×10^{-4}	4.3
4460	2.2422	3.70×10^{-4}	1.1	3.45×10^{-4}	1.7	2.12×10^{-4}	4.3
4480	2.2321	3.62×10^{-4}	1.2	3.43×10^{-4}	1.7	2.17×10^{-4}	4.3
4500	2.2222	3.56×10^{-4}	1.1	3.37×10^{-4}	1.7	2.27×10^{-4}	4.2
4520	2.2124	3.53×10^{-4}	1.2	3.35×10^{-4}	1.6	2.38×10^{-4}	3.9
4540	2.2026	3.53×10^{-4}	1.3	3.41×10^{-4}	1.8	2.54×10^{-4}	3.7
4560	2.1930	3.54×10^{-4}	1.3	3.43×10^{-4}	1.7	2.71×10^{-4}	3.4
4580	2.1834	3.59×10^{-4}	1.0	3.52×10^{-4}	1.3	2.93×10^{-4}	3.1
4600	2.1739	3.64×10^{-4}	1.0	3.61×10^{-4}	1.5	3.17×10^{-4}	3.0
4620	2.1645	3.73×10^{-4}	1.0	3.72×10^{-4}	1.2	3.48×10^{-4}	2.7
4640	2.1552	3.83×10^{-4}	0.9	3.89×10^{-4}	1.6	3.83×10^{-4}	2.4
4660	2.1459	3.96×10^{-4}	1.0	4.08×10^{-4}	1.4	4.28×10^{-4}	2.2
4680	2.1368	4.13×10^{-4}	1.0	4.31×10^{-4}	1.4	4.85×10^{-4}	2.0
4700	2.1277	4.32×10^{-4}	1.0	4.58×10^{-4}	1.2	5.50×10^{-4}	1.8
4720	2.1186	4.54×10^{-4}	1.1	4.87×10^{-4}	1.1	6.28×10^{-4}	1.6
4740	2.1097	4.80×10^{-4}	1.2	5.23×10^{-4}	1.4	7.19×10^{-4}	1.6
4760	2.1008	5.09×10^{-4}	1.1	5.61×10^{-4}	1.3	8.20×10^{-4}	1.5
4780	2.0921	5.43×10^{-4}	1.3	6.03×10^{-4}	1.4	9.30×10^{-4}	1.2
4800	2.0833	5.80×10^{-4}	1.3	6.47×10^{-4}	1.4	1.02×10^{-3}	3.3
4820	2.0747	6.20×10^{-4}	1.5	7.00×10^{-4}	1.5	1.13×10^{-3}	3.0
4840	2.0661	6.65×10^{-4}	1.6	7.50×10^{-4}	1.7	1.23×10^{-3}	2.9
4860	2.0576	7.20×10^{-4}	2.0	8.25×10^{-4}	1.9	1.32×10^{-3}	2.7
4880	2.0492	7.77×10^{-4}	1.8	8.91×10^{-4}	1.8	1.40×10^{-3}	2.5
4900	2.0408	8.31×10^{-4}	2.0	9.54×10^{-4}	2.0	1.45×10^{-3}	2.1
4920	2.0325	8.96×10^{-4}	1.8	1.03×10^{-3}	3.1	1.52×10^{-3}	2.2
4940	2.0243	9.69×10^{-4}	1.7	1.11×10^{-3}	3.1	1.55×10^{-3}	2.1
4960	2.0161	1.05×10^{-3}	1.5	1.19×10^{-3}	2.9	1.59×10^{-3}	2.1
4980	2.0080	1.13×10^{-3}	2.5	1.28×10^{-3}	2.8	1.63×10^{-3}	2.2
5000	2.0000	1.23×10^{-3}	2.9	1.37×10^{-3}	2.7	1.64×10^{-3}	2.2
5020	1.9920	1.33×10^{-3}	2.5	1.46×10^{-3}	2.4	1.64×10^{-3}	2.0
5040	1.9841	1.44×10^{-3}	2.7	1.56×10^{-3}	2.5	1.63×10^{-3}	2.4
5060	1.9763	1.56×10^{-3}	2.5	1.68×10^{-3}	2.3	1.59×10^{-3}	2.4
5080	1.9685	1.68×10^{-3}	2.0	1.77×10^{-3}	1.8	1.52×10^{-3}	2.2
5100	1.9608	1.80×10^{-3}	2.1	1.87×10^{-3}	1.9	1.42×10^{-3}	2.5
5120	1.9531	1.92×10^{-3}	2.0	1.95×10^{-3}	1.8	1.31×10^{-3}	2.7
5140	1.9455	2.02×10^{-3}	2.1	2.00×10^{-3}	2.0	1.16×10^{-3}	3.6

(Table continued)

Table 1. (continued)

		Water				Ice	
		$T = 22\ °C$		$T = -8\ °C$		$T = -25\ °C$	
Wave Number (1/cm)	Wave Length (μm)	k	Error (%)	k	Error (%)	k	Error (%)
5160	1.9380	2.08×10^{-3}	2.3	2.00×10^{-3}	2.3	9.91×10^{-4}	4.7
5180	1.9305	2.10×10^{-3}	2.2	1.95×10^{-3}	2.3	8.38×10^{-4}	5.4
5200	1.9231	2.06×10^{-3}	2.3	1.82×10^{-3}	2.7	6.82×10^{-4}	7.0
5220	1.9157	1.96×10^{-3}	2.5	1.66×10^{-3}	3.3	5.53×10^{-4}	9.2
5240	1.9084	1.78×10^{-3}	2.7	1.44×10^{-3}	3.8	4.84×10^{-4}	11.0
5260	1.9011	1.49×10^{-3}	2.9	1.17×10^{-3}	4.3	4.00×10^{-4}	14.7
5280	1.8939	1.10×10^{-3}	2.4	8.83×10^{-4}	3.2	2.98×10^{-4}	10.4
5300	1.8868	7.31×10^{-4}	2.7	5.91×10^{-4}	3.5	2.33×10^{-4}	9.9
5320	1.8797	4.75×10^{-4}	2.8	3.90×10^{-4}	3.5	1.87×10^{-4}	9.1
5340	1.8727	3.21×10^{-4}	4.0	2.69×10^{-4}	4.9	1.56×10^{-4}	10.6
5360	1.8657	2.34×10^{-4}	3.6	1.98×10^{-4}	4.7	1.42×10^{-4}	10.4
5380	1.8587	1.89×10^{-4}	1.9	1.65×10^{-4}	2.6	1.33×10^{-4}	11.0
5400	1.8519	1.64×10^{-4}	1.4	1.45×10^{-4}	1.9	1.26×10^{-4}	11.9
5420	1.8450	1.48×10^{-4}	1.4	1.34×10^{-4}	1.9	1.26×10^{-4}	12.3
5440	1.8382	1.42×10^{-4}	1.3	1.29×10^{-4}	1.7	1.23×10^{-4}	13.0
5460	1.8315	1.37×10^{-4}	1.1	1.26×10^{-4}	1.3	1.23×10^{-4}	12.1
5480	1.8248	1.34×10^{-4}	1.2	1.25×10^{-4}	1.4	1.25×10^{-4}	10.9
5500	1.8182	1.33×10^{-4}	1.4	1.24×10^{-4}	1.6	1.26×10^{-4}	11.4
5520	1.8116	1.32×10^{-4}	1.5	1.25×10^{-4}	1.6	1.28×10^{-4}	10.2
5540	1.8051	1.33×10^{-4}	1.2	1.26×10^{-4}	1.3	1.30×10^{-4}	9.8
5560	1.7986	1.31×10^{-4}	1.2	1.26×10^{-4}	1.2	1.31×10^{-4}	10.0
5580	1.7921	1.31×10^{-4}	1.4	1.27×10^{-4}	1.5	1.33×10^{-4}	9.9
5600	1.7857	1.30×10^{-4}	1.3	1.27×10^{-4}	1.3	1.35×10^{-4}	9.3
5620	1.7794	1.27×10^{-4}	1.5	1.26×10^{-4}	1.6	1.37×10^{-4}	8.3
5640	1.7731	1.23×10^{-4}	1.2	1.23×10^{-4}	1.2	1.38×10^{-4}	8.1
5660	1.7668	1.18×10^{-4}	1.0	1.19×10^{-4}	0.8	1.39×10^{-4}	8.2
5680	1.7606	1.11×10^{-4}	1.4	1.14×10^{-4}	1.4	1.40×10^{-4}	8.0
5700	1.7544	1.06×10^{-4}	1.1	1.09×10^{-4}	1.1	1.42×10^{-4}	7.6
5720	1.7483	1.01×10^{-4}	1.2	1.05×10^{-4}	1.2	1.45×10^{-4}	7.0
5740	1.7422	9.59×10^{-5}	1.0	1.01×10^{-4}	1.0	1.48×10^{-4}	7.0
5760	1.7361	9.19×10^{-5}	1.1	9.74×10^{-5}	1.1	1.49×10^{-4}	7.2
5780	1.7301	8.87×10^{-5}	1.3	9.50×10^{-5}	1.3	1.52×10^{-4}	6.4
5800	1.7241	8.61×10^{-5}	1.1	9.30×10^{-5}	1.2	1.54×10^{-4}	6.5
5820	1.7182	8.39×10^{-5}	1.0	9.15×10^{-5}	1.1	1.59×10^{-4}	5.9
5840	1.7123	8.19×10^{-5}	1.3	9.01×10^{-5}	1.5	1.63×10^{-4}	5.4
5860	1.7065	8.04×10^{-5}	1.1	8.94×10^{-5}	1.4	1.67×10^{-4}	5.5
5880	1.7007	7.97×10^{-5}	1.2	8.94×10^{-5}	1.4	1.72×10^{-4}	5.3
5900	1.6949	7.89×10^{-5}	1.3	8.92×10^{-5}	1.5	1.78×10^{-4}	4.7
5920	1.6892	7.84×10^{-5}	1.0	8.93×10^{-5}	1.5	1.82×10^{-4}	4.8
5940	1.6835	7.82×10^{-5}	1.1	8.97×10^{-5}	1.5	1.87×10^{-4}	4.7
5960	1.6779	7.79×10^{-5}	1.2	9.00×10^{-5}	1.6	1.92×10^{-4}	4.1
5980	1.6722	7.82×10^{-5}	1.3	9.08×10^{-5}	1.7	1.97×10^{-4}	4.2
6000	1.6667	7.85×10^{-5}	1.4	9.16×10^{-5}	1.7	2.05×10^{-4}	4.2
6020	1.6611	7.91×10^{-5}	1.1	9.29×10^{-5}	1.7	2.11×10^{-4}	3.5
6040	1.6556	7.97×10^{-5}	1.4	9.40×10^{-5}	1.9	2.16×10^{-4}	3.5
6060	1.6502	8.09×10^{-5}	1.1	9.56×10^{-5}	1.7	2.23×10^{-4}	3.4
6080	1.6447	8.20×10^{-5}	1.2	9.72×10^{-5}	1.7	2.29×10^{-4}	3.4
6100	1.6393	8.29×10^{-5}	1.3	9.86×10^{-5}	1.8	2.35×10^{-4}	3.5
6120	1.6340	8.44×10^{-5}	1.2	1.00×10^{-4}	1.9	2.40×10^{-4}	3.2
6140	1.6287	8.63×10^{-5}	1.4	1.03×10^{-4}	1.9	2.44×10^{-4}	3.3
6160	1.6234	8.79×10^{-5}	1.2	1.05×10^{-4}	1.9	2.47×10^{-4}	3.2
6180	1.6181	9.00×10^{-5}	1.1	1.07×10^{-4}	1.7	2.49×10^{-4}	3.2
6200	1.6129	9.23×10^{-5}	1.2	1.11×10^{-4}	1.9	2.53×10^{-4}	2.8
6220	1.6077	9.44×10^{-5}	1.5	1.13×10^{-4}	1.9	2.59×10^{-4}	2.9
6240	1.6026	9.70×10^{-5}	1.0	1.17×10^{-4}	1.8	2.66×10^{-4}	3.1
6260	1.5974	1.00×10^{-4}	1.2	1.20×10^{-4}	1.8	2.74×10^{-4}	2.8
6280	1.5924	1.03×10^{-4}	1.0	1.24×10^{-4}	1.9	2.84×10^{-4}	2.8
6300	1.5873	1.07×10^{-4}	1.2	1.29×10^{-4}	1.9	2.97×10^{-4}	2.7
6320	1.5823	1.11×10^{-4}	1.2	1.34×10^{-4}	1.9	3.11×10^{-4}	2.7

(Table continued)

Table 1. (continued)

Wave Number (1/cm)	Wave Length (μm)	Water, T = 22 °C: k	Water, T = 22 °C: Error (%)	Water, T = −8 °C: k	Water, T = −8 °C: Error (%)	Ice, T = −25 °C: k	Ice, T = −25 °C: Error (%)
6340	1.5773	1.15×10^{-4}	1.4	1.39×10^{-4}	2.0	3.24×10^{-4}	2.5
6360	1.5723	1.19×10^{-4}	1.0	1.44×10^{-4}	2.0	3.42×10^{-4}	2.6
6380	1.5674	1.24×10^{-4}	1.6	1.46×10^{-4}	4.1	3.58×10^{-4}	2.3
6400	1.5625	1.30×10^{-4}	1.2	1.54×10^{-4}	3.8	3.75×10^{-4}	2.2
6420	1.5576	1.36×10^{-4}	1.4	1.63×10^{-4}	4.4	3.92×10^{-4}	2.4
6440	1.5528	1.44×10^{-4}	1.9	1.71×10^{-4}	3.8	4.08×10^{-4}	2.1
6460	1.5480	1.50×10^{-4}	1.9	1.81×10^{-4}	2.8	4.25×10^{-4}	1.8
6480	1.5432	1.57×10^{-4}	2.3	1.88×10^{-4}	3.0	4.37×10^{-4}	1.8
6500	1.5385	1.69×10^{-4}	2.2	2.00×10^{-4}	3.7	4.51×10^{-4}	2.0
6520	1.5337	1.78×10^{-4}	2.2	2.09×10^{-4}	3.1	4.62×10^{-4}	1.8
6540	1.5291	1.87×10^{-4}	3.5	2.23×10^{-4}	3.4	4.75×10^{-4}	1.9
6560	1.5244	1.95×10^{-4}	2.9	2.35×10^{-4}	2.6	4.87×10^{-4}	1.6
6580	1.5198	2.06×10^{-4}	2.8	2.48×10^{-4}	2.4	4.98×10^{-4}	1.5
6600	1.5152	2.18×10^{-4}	3.2	2.61×10^{-4}	2.7	5.09×10^{-4}	1.7
6620	1.5106	2.31×10^{-4}	3.0	2.75×10^{-4}	2.6	5.17×10^{-4}	1.6
6640	1.5060	2.45×10^{-4}	2.4	2.91×10^{-4}	2.1	5.27×10^{-4}	1.5
6660	1.5015	2.58×10^{-4}	2.5	3.04×10^{-4}	2.2	5.33×10^{-4}	1.5
6680	1.4970	2.73×10^{-4}	2.4	3.20×10^{-4}	2.2	5.38×10^{-4}	1.5
6700	1.4925	2.86×10^{-4}	2.4	3.33×10^{-4}	2.2	5.34×10^{-4}	1.6
6720	1.4881	3.05×10^{-4}	2.5	3.50×10^{-4}	2.3	5.27×10^{-4}	1.7
6740	1.4837	3.18×10^{-4}	2.0	3.61×10^{-4}	1.8	5.03×10^{-4}	1.6
6760	1.4793	3.32×10^{-4}	1.9	3.74×10^{-4}	1.8	4.71×10^{-4}	1.6
6780	1.4749	3.48×10^{-4}	2.2	3.85×10^{-4}	2.1	4.33×10^{-4}	2.0
6800	1.4706	3.58×10^{-4}	1.7	3.91×10^{-4}	1.6	3.86×10^{-4}	1.9
6820	1.4663	3.68×10^{-4}	2.2	3.97×10^{-4}	2.0	3.42×10^{-4}	2.6
6840	1.4620	3.77×10^{-4}	1.7	3.99×10^{-4}	1.7	2.99×10^{-4}	2.6
6860	1.4577	3.79×10^{-4}	1.9	3.95×10^{-4}	1.9	2.58×10^{-4}	3.1
6880	1.4535	3.79×10^{-4}	1.9	3.87×10^{-4}	1.9	2.20×10^{-4}	3.5
6900	1.4493	3.77×10^{-4}	2.0	3.80×10^{-4}	2.0	1.89×10^{-4}	4.3
6920	1.4451	3.74×10^{-4}	2.0	3.67×10^{-4}	2.1	1.60×10^{-4}	5.1

3. Imaginary Part of Refractive Index of Water and Ice

The results of the Kou–Labrie–Chylek (KLC) measurements for the case of water at 22 °C are shown in Fig. 1. We determined the imaginary part of the refractive index, k, from the absorption coefficient α, using the relationship $k = \lambda\alpha/4\pi$. We checked the results for internal consistency by comparing the k spectra obtained with different d values (different path length). When the transmittance values were in the range 15% to 80%, excellent agreement was found among spectra obtained with several different d values. Figure 1(a) also shows the k spectrum obtained from the data of Palmer and Williams[13] (PW) and Downing and Williams[14] (DW). To within PW and DW uncertainties, good agreement is found between the two spectra. Figure 1(b) shows the error of our measurements, which was calculated by using the standard deviation of the data and the uncertainty in the path length, d. The error spectrum typically varies between 1% and 2%, with some excursions above 3%. The error increases dramatically below 0.6 μm because of the weak absorption measured in the longest cell used. Recent measurements of Wieliczka *et al.*[15] that used a wedge-shaped cell are in considerable disagreement with our results for wavelengths shorter than 1.25 μm. The error of as much as a factor of 12 between the data of Wieliczka *et al.* and ours is caused by the high transparency of their very thin ($d \leqslant 22$ μm) water samples used in their study.

The k spectrum of supercooled water taken at an average temperature of −8 °C is shown in Fig. 2. The water temperature in the 2-cm-long cell was −4 °C. To our knowledge, this is the first reported measurement of the absorption coefficient of supercooled water. The k spectrum is similar to that of water; the main difference is that the k bands of supercooled water are shifted toward longer wavelengths than those of water measured at T = 22 °C. The k error spectrum, which varies in amplitude from 1% to 8%, is shown in Fig. 2(b).

The k spectrum of ice in the spectral range from 1.45 to 2.5 μm is also shown in Fig. 2(a). The k spectrum for ice exhibits absorption bands that are shifted toward longer wavelengths and have different strengths from those in the spectrum of water. Figure 3(a) shows a direct comparison between our measurement (KLC) of the ice spectrum and the spectrum obtained from Warren's[10] compilation. Good agreement is observed between the spectra.

Table 2. Imaginary Part of the Refractive Index, k, and the Standard Deviation of k for Water at $T = 22$ °C and $T = -8$ °C in the Spectral Range From 6940 to 15,000 cm^{-1}

Wave Number (1/cm)	Wave Length (μm)	Water, $T = 22$ °C, k	Water, $T = 22$ °C, Error (%)	Water, $T = -8$ °C, k	Water, $T = -8$ °C, Error (%)
6940	1.4409	3.69×10^{-4}	2.0	3.53×10^{-4}	2.2
6960	1.4368	3.66×10^{-4}	1.9	3.39×10^{-4}	2.1
6980	1.4327	3.54×10^{-4}	2.3	3.18×10^{-4}	2.6
7000	1.4286	3.44×10^{-4}	1.9	2.99×10^{-4}	2.4
7020	1.4245	3.30×10^{-4}	2.3	2.79×10^{-4}	2.9
7040	1.4205	3.13×10^{-4}	2.1	2.57×10^{-4}	2.7
7060	1.4164	2.97×10^{-4}	2.4	2.38×10^{-4}	3.2
7080	1.4124	2.77×10^{-4}	2.9	2.18×10^{-4}	3.9
7100	1.4085	2.50×10^{-4}	2.5	1.94×10^{-4}	3.5
7120	1.4045	2.20×10^{-4}	3.6	1.69×10^{-4}	5.1
7140	1.4006	1.89×10^{-4}	3.9	1.45×10^{-4}	5.4
7160	1.3966	1.55×10^{-4}	5.4	1.18×10^{-4}	7.5
7180	1.3928	1.22×10^{-4}	3.1	9.23×10^{-5}	4.8
7200	1.3889	9.70×10^{-5}	2.7	7.35×10^{-5}	4.2
7220	1.3850	7.94×10^{-5}	3.1	6.07×10^{-5}	4.7
7240	1.3812	6.58×10^{-5}	2.3	5.09×10^{-5}	3.7
7260	1.3774	5.68×10^{-5}	1.9	4.46×10^{-5}	3.3
7280	1.3736	5.07×10^{-5}	1.7	4.08×10^{-5}	2.7
7300	1.3699	4.60×10^{-5}	1.8	3.76×10^{-5}	2.8
7320	1.3661	4.30×10^{-5}	1.3	3.58×10^{-5}	2.2
7340	1.3624	4.04×10^{-5}	1.3	3.40×10^{-5}	2.1
7360	1.3587	3.84×10^{-5}	1.8	3.27×10^{-5}	2.5
7380	1.3550	3.66×10^{-5}	1.9	3.14×10^{-5}	2.5
7400	1.3514	3.48×10^{-5}	2.1	3.03×10^{-5}	2.7
7420	1.3477	3.32×10^{-5}	1.6	2.91×10^{-5}	2.2
7440	1.3441	3.09×10^{-5}	1.7	2.76×10^{-5}	2.2
7460	1.3405	2.88×10^{-5}	1.1	2.60×10^{-5}	1.5
7480	1.3369	2.70×10^{-5}	1.3	2.45×10^{-5}	1.6
7500	1.3333	2.50×10^{-5}	1.2	2.30×10^{-5}	1.6
7520	1.3298	2.33×10^{-5}	1.1	2.16×10^{-5}	1.3
7540	1.3263	2.16×10^{-5}	1.3	2.02×10^{-5}	1.5
7560	1.3228	2.01×10^{-5}	1.1	1.90×10^{-5}	1.3
7580	1.3193	1.88×10^{-5}	1.2	1.78×10^{-5}	1.3
7600	1.3158	1.75×10^{-5}	1.5	1.68×10^{-5}	1.6
7620	1.3123	1.65×10^{-5}	1.1	1.59×10^{-5}	1.1
7640	1.3089	1.55×10^{-5}	1.4	1.52×10^{-5}	1.5
7660	1.3055	1.47×10^{-5}	1.3	1.45×10^{-5}	1.4
7680	1.3021	1.40×10^{-5}	1.3	1.39×10^{-5}	1.4
7700	1.2987	1.34×10^{-5}	1.1	1.35×10^{-5}	1.2
7720	1.2953	1.29×10^{-5}	1.8	1.30×10^{-5}	1.8
7740	1.2920	1.25×10^{-5}	1.4	1.27×10^{-5}	1.5
7760	1.2887	1.21×10^{-5}	1.1	1.24×10^{-5}	1.3
7780	1.2853	1.19×10^{-5}	1.5	1.21×10^{-5}	1.6
7800	1.2821	1.16×10^{-5}	1.9	1.20×10^{-5}	1.9
7820	1.2788	1.13×10^{-5}	1.4	1.19×10^{-5}	1.6
7840	1.2755	1.12×10^{-5}	1.2	1.18×10^{-5}	1.4
7860	1.2723	1.10×10^{-5}	1.6	1.17×10^{-5}	1.7
7880	1.2690	1.09×10^{-5}	1.6	1.17×10^{-5}	1.7
7900	1.2658	1.09×10^{-5}	1.6	1.17×10^{-5}	1.7
7920	1.2626	1.09×10^{-5}	1.6	1.17×10^{-5}	1.7
7940	1.2594	1.10×10^{-5}	1.8	1.19×10^{-5}	1.8
7960	1.2563	1.10×10^{-5}	1.5	1.20×10^{-5}	1.6
7980	1.2531	1.10×10^{-5}	1.7	1.19×10^{-5}	1.9
8000	1.2500	1.11×10^{-5}	1.6	1.21×10^{-5}	1.7
8020	1.2469	1.12×10^{-5}	2.0	1.22×10^{-5}	2.0
8040	1.2438	1.13×10^{-5}	1.5	1.23×10^{-5}	1.6
8060	1.2407	1.14×10^{-5}	1.5	1.24×10^{-5}	1.6
8080	1.2376	1.14×10^{-5}	1.6	1.24×10^{-5}	1.7
8100	1.2346	1.15×10^{-5}	1.8	1.25×10^{-5}	1.8
8120	1.2315	1.16×10^{-5}	1.7	1.25×10^{-5}	1.8
8140	1.2285	1.17×10^{-5}	1.5	1.25×10^{-5}	1.8
8160	1.2255	1.17×10^{-5}	1.4	1.26×10^{-5}	1.6
8180	1.2225	1.18×10^{-5}	2.0	1.26×10^{-5}	2.1
8200	1.2195	1.18×10^{-5}	1.5	1.25×10^{-5}	1.7
8220	1.2165	1.20×10^{-5}	1.6	1.26×10^{-5}	1.8
8240	1.2136	1.20×10^{-5}	1.7	1.25×10^{-5}	1.8
8260	1.2107	1.21×10^{-5}	1.2	1.25×10^{-5}	1.3
8280	1.2077	1.21×10^{-5}	1.8	1.24×10^{-5}	2.0
8300	1.2048	1.22×10^{-5}	1.5	1.25×10^{-5}	1.8
8320	1.2019	1.21×10^{-5}	1.9	1.22×10^{-5}	2.0
8340	1.1990	1.22×10^{-5}	1.2	1.22×10^{-5}	1.3
8360	1.1962	1.22×10^{-5}	1.3	1.20×10^{-5}	1.5
8380	1.1933	1.21×10^{-5}	1.7	1.19×10^{-5}	1.9
8400	1.1905	1.20×10^{-5}	1.6	1.16×10^{-5}	1.7
8420	1.1876	1.19×10^{-5}	1.5	1.15×10^{-5}	1.6
8440	1.1848	1.18×10^{-5}	1.4	1.12×10^{-5}	1.6
8460	1.1820	1.17×10^{-5}	1.5	1.10×10^{-5}	1.8
8480	1.1792	1.16×10^{-5}	1.7	1.08×10^{-5}	2.0
8500	1.1765	1.15×10^{-5}	1.4	1.05×10^{-5}	1.7
8520	1.1737	1.15×10^{-5}	1.4	1.03×10^{-5}	1.7
8540	1.1710	1.13×10^{-5}	1.8	9.99×10^{-6}	2.2
8560	1.1682	1.12×10^{-5}	1.6	9.79×10^{-6}	2.1
8580	1.1655	1.11×10^{-5}	1.5	9.52×10^{-6}	2.0
8600	1.1628	1.10×10^{-5}	1.6	9.21×10^{-6}	2.2
8620	1.1601	1.08×10^{-5}	2.0	8.89×10^{-6}	2.7
8640	1.1574	1.05×10^{-5}	2.0	8.47×10^{-6}	2.9
8660	1.1547	1.01×10^{-5}	1.9	8.06×10^{-6}	2.7
8680	1.1521	9.54×10^{-6}	1.8	7.53×10^{-6}	2.6
8700	1.1494	8.68×10^{-6}	1.3	7.07×10^{-6}	2.2
8720	1.1468	7.84×10^{-6}	2.0	6.43×10^{-6}	2.8
8740	1.1442	6.86×10^{-6}	1.6	5.68×10^{-6}	2.4
8760	1.1416	5.92×10^{-6}	1.4	4.97×10^{-6}	2.1
8780	1.1390	5.05×10^{-6}	1.7	4.30×10^{-6}	2.4
8800	1.1364	4.26×10^{-6}	2.6	3.67×10^{-6}	3.3
8820	1.1338	3.64×10^{-6}	1.6	3.20×10^{-6}	2.2
8840	1.1312	3.18×10^{-6}	2.6	2.84×10^{-6}	3.2
8860	1.1287	2.84×10^{-6}	1.9	2.58×10^{-6}	2.7
8880	1.1261	2.59×10^{-6}	2.6	2.38×10^{-6}	3.3
8900	1.1236	2.43×10^{-6}	2.5	2.28×10^{-6}	3.4
8920	1.1211	2.30×10^{-6}	2.9	2.17×10^{-6}	3.7
8940	1.1186	2.18×10^{-6}	3.2	2.09×10^{-6}	3.9
8960	1.1161	2.09×10^{-6}	3.0	2.02×10^{-6}	3.8
8980	1.1136	2.07×10^{-6}	3.2	1.96×10^{-6}	3.9
9000	1.1111	1.99×10^{-6}	3.0	1.90×10^{-6}	4.4
9020	1.1086	1.91×10^{-6}	2.9	1.84×10^{-6}	3.7
9040	1.1062	1.83×10^{-6}	2.7	1.78×10^{-6}	4.8
9060	1.1038	1.76×10^{-6}	2.7	1.72×10^{-6}	5.0
9080	1.1013	1.69×10^{-6}	2.6	1.66×10^{-6}	4.8
9100	1.0989	1.63×10^{-6}	2.5	1.61×10^{-6}	5.2
9120	1.0965	1.55×10^{-6}	2.5	1.56×10^{-6}	4.8
9140	1.0941	1.49×10^{-6}	2.4	1.51×10^{-6}	5.9
9160	1.0917	1.44×10^{-6}	2.5	1.44×10^{-6}	5.3
9180	1.0893	1.39×10^{-6}	2.4	1.41×10^{-6}	4.6
9200	1.0870	1.35×10^{-6}	2.4	1.38×10^{-6}	6.3
9220	1.0846	1.31×10^{-6}	2.4	1.35×10^{-6}	6.4
9240	1.0823	1.27×10^{-6}	2.3	1.31×10^{-6}	6.1

(Table continued)

Table 2. (continued)

Wave Number (1/cm)	Wave Length (μm)	Water, T = 22 °C, k	Water, T = 22 °C, Error (%)	Water, T = −8 °C, k	Water, T = −8 °C, Error (%)
9260	1.0799	1.24×10^{-6}	2.3	1.30×10^{-6}	6.1
9280	1.0776	1.23×10^{-6}	2.3	1.27×10^{-6}	6.3
9300	1.0753	1.21×10^{-6}	2.3	1.26×10^{-6}	6.7
9320	1.0730	1.20×10^{-6}	2.3	1.28×10^{-6}	6.6
9340	1.0707	1.20×10^{-6}	2.2	1.26×10^{-6}	5.8
9360	1.0684	1.20×10^{-6}	2.2	1.29×10^{-6}	7.0
9380	1.0661	1.21×10^{-6}	2.2	1.30×10^{-6}	6.8
9400	1.0638	1.22×10^{-6}	2.2	1.30×10^{-6}	5.2
9420	1.0616	1.23×10^{-6}	2.2	1.35×10^{-6}	5.8
9440	1.0593	1.26×10^{-6}	2.2	1.35×10^{-6}	6.2
9460	1.0571	1.28×10^{-6}	2.2	1.37×10^{-6}	6.5
9480	1.0549	1.31×10^{-6}	2.1	1.44×10^{-6}	5.5
9500	1.0526	1.35×10^{-6}	2.1	1.47×10^{-6}	5.3
9520	1.0504	1.39×10^{-6}	2.1	1.53×10^{-6}	5.9
9540	1.0482	1.43×10^{-6}	2.1	1.57×10^{-6}	5.2
9560	1.0460	1.49×10^{-6}	2.1	1.63×10^{-6}	4.8
9580	1.0438	1.55×10^{-6}	2.1	1.71×10^{-6}	5.8
9600	1.0417	1.61×10^{-6}	2.1	1.75×10^{-6}	5.4
9620	1.0395	1.67×10^{-6}	2.1	1.83×10^{-6}	5.4
9640	1.0373	1.74×10^{-6}	2.1	1.90×10^{-6}	4.3
9660	1.0352	1.81×10^{-6}	2.1	1.97×10^{-6}	5.0
9680	1.0331	1.89×10^{-6}	2.1	2.04×10^{-6}	4.8
9700	1.0309	1.96×10^{-6}	2.1	2.13×10^{-6}	3.7
9720	1.0288	2.05×10^{-6}	2.1	1.23×10^{-6}	3.8
9740	1.0267	2.14×10^{-6}	2.1	2.29×10^{-6}	4.5
9760	1.0246	2.22×10^{-6}	2.1	2.36×10^{-6}	3.2
9780	1.0225	2.31×10^{-6}	2.1	2.48×10^{-6}	3.2
9800	1.0204	2.40×10^{-6}	2.2	2.53×10^{-6}	4.5
9820	1.0183	2.50×10^{-6}	2.2	2.61×10^{-6}	3.7
9840	1.0163	2.58×10^{-6}	1.2	2.70×10^{-6}	4.1
9860	1.0142	2.66×10^{-6}	0.6	2.75×10^{-6}	3.9
9880	1.0121	2.74×10^{-6}	0.9	2.84×10^{-6}	3.4
9900	1.0101	2.83×10^{-6}	0.6	2.92×10^{-6}	3.7
9920	1.0081	2.92×10^{-6}	0.6	2.95×10^{-6}	3.1
9940	1.0060	3.01×10^{-6}	0.9	3.05×10^{-6}	2.7
9960	1.0040	3.09×10^{-6}	0.4	3.11×10^{-6}	3.0
9980	1.0020	3.16×10^{-6}	0.8	3.15×10^{-6}	2.7
10000	1.0000	3.24×10^{-6}	0.7	3.15×10^{-6}	3.2
10020	0.9980	3.31×10^{-6}	0.5	3.22×10^{-6}	3.3
10040	0.9960	3.38×10^{-6}	0.8	3.22×10^{-6}	4.4
10060	0.9940	3.45×10^{-6}	0.6	3.26×10^{-6}	3.1
10080	0.9921	3.50×10^{-6}	0.7	3.35×10^{-6}	2.7
10100	0.9901	3.57×10^{-6}	0.9	3.37×10^{-6}	4.3
10120	0.9881	3.62×10^{-6}	0.6	3.37×10^{-6}	3.8
10140	0.9862	3.67×10^{-6}	0.8	3.34×10^{-6}	4.1
10160	0.9843	3.71×10^{-6}	0.8	3.32×10^{-6}	3.2
10180	0.9823	3.74×10^{-6}	0.6	3.31×10^{-6}	3.9
10200	0.9804	3.76×10^{-6}	0.9	3.33×10^{-6}	3.8
10220	0.9785	3.78×10^{-6}	0.8	3.28×10^{-6}	4.0
10240	0.9766	3.78×10^{-6}	0.5	3.26×10^{-6}	4.1
10260	0.9747	3.77×10^{-6}	0.9	3.23×10^{-6}	4.1
10280	0.9728	3.75×10^{-6}	0.5	3.18×10^{-6}	3.0
10300	0.9709	3.72×10^{-6}	0.7	3.16×10^{-6}	4.5
10320	0.9690	3.69×10^{-6}	0.9	3.05×10^{-6}	3.8
10340	0.9671	3.66×10^{-6}	0.5	3.00×10^{-6}	3.4
10360	0.9653	3.61×10^{-6}	0.9	2.94×10^{-6}	5.1
10380	0.9634	3.55×10^{-6}	0.8	2.88×10^{-6}	5.2
10400	0.9615	3.47×10^{-6}	0.5	2.80×10^{-6}	3.3
10420	0.9597	3.35×10^{-6}	1.1	2.66×10^{-6}	5.2
10440	0.9579	3.19×10^{-6}	0.8	2.57×10^{-6}	5.2
10460	0.9560	2.99×10^{-6}	0.8	2.39×10^{-6}	4.8
10480	0.9542	2.75×10^{-6}	1.4	2.19×10^{-6}	4.6
10500	0.9524	2.48×10^{-6}	2.7	2.04×10^{-6}	5.4
10520	0.9506	2.25×10^{-6}	2.5	1.82×10^{-6}	6.2
10540	0.9488	2.04×10^{-6}	2.4	1.70×10^{-6}	7.5
10560	0.9470	1.86×10^{-6}	2.4	1.56×10^{-6}	4.8
10580	0.9452	1.72×10^{-6}	2.4	1.42×10^{-6}	7.1
10600	0.9434	1.58×10^{-6}	2.4	1.32×10^{-6}	9.0
10620	0.9416	1.47×10^{-6}	2.3	1.24×10^{-6}	6.5
10640	0.9398	1.36×10^{-6}	2.4	1.17×10^{-6}	7.8
10660	0.9381	1.26×10^{-6}	2.3		
10680	0.9363	1.16×10^{-6}	2.4		
10700	0.9346	1.09×10^{-6}	2.3		
10720	0.9328	1.02×10^{-6}	1.0		
10740	0.9311	9.49×10^{-7}	1.0		
10760	0.9294	8.83×10^{-7}	1.0		
10780	0.9276	8.22×10^{-7}	0.9		
10800	0.9259	7.68×10^{-7}	0.9		
10820	0.9242	7.22×10^{-7}	0.9		
10840	0.9225	6.80×10^{-7}	0.9		
10860	0.9208	6.45×10^{-7}	0.8		
10880	0.9191	6.15×10^{-7}	0.8		
10900	0.9174	5.90×10^{-7}	0.9		
10920	0.9158	5.68×10^{-7}	0.8		
10940	0.9141	5.50×10^{-7}	0.8		
10960	0.9124	5.34×10^{-7}	0.9		
10980	0.9107	5.21×10^{-7}	0.9		
11000	0.9091	5.09×10^{-7}	0.9		
11020	0.9074	4.98×10^{-7}	0.9		
11040	0.9058	4.88×10^{-7}	0.9		
11060	0.9042	4.80×10^{-7}	0.9		
11080	0.9025	4.71×10^{-7}	0.9		
11100	0.9009	4.63×10^{-7}	0.9		
11120	0.8993	4.55×10^{-7}	0.9		
11140	0.8977	4.48×10^{-7}	0.9		
11160	0.8961	4.41×10^{-7}	0.9		
11180	0.8945	4.34×10^{-7}	1.0		
11200	0.8929	4.27×10^{-7}	1.0		
11220	0.8913	4.20×10^{-7}	1.0		
11240	0.8897	4.13×10^{-7}	1.0		
11260	0.8881	4.06×10^{-7}	1.0		
11280	0.8865	3.99×10^{-7}	1.0		
11300	0.8850	3.92×10^{-7}	1.0		
11320	0.8834	3.84×10^{-7}	1.1		
11340	0.8818	3.78×10^{-7}	1.0		
11360	0.8803	3.71×10^{-7}	1.0		
11380	0.8787	3.64×10^{-7}	1.0		
11400	0.8772	3.57×10^{-7}	1.0		
11420	0.8757	3.52×10^{-7}	1.0		
11440	0.8741	3.45×10^{-7}	1.0		
11460	0.8726	3.40×10^{-7}	1.0		
11480	0.8711	3.35×10^{-7}	1.0		
11500	0.8696	3.29×10^{-7}	1.0		
11520	0.8681	3.25×10^{-7}	1.0		
11540	0.8666	3.21×10^{-7}	1.0		
11560	0.8651	3.17×10^{-7}	1.0		
11580	0.8636	3.13×10^{-7}	1.0		
11600	0.8621	3.09×10^{-7}	1.0		

(Table continued)

Table 2. (continued)

Wave Number (1/cm)	Wave Length (μm)	Water, T = 22 °C k	Error (%)
11620	0.8606	3.06×10^{-7}	1.0
11640	0.8591	3.30×10^{-7}	1.0
11660	0.8576	2.99×10^{-7}	1.0
11680	0.8562	2.97×10^{-7}	1.1
11700	0.8547	2.93×10^{-7}	1.0
11720	0.8532	2.90×10^{-7}	1.0
11740	0.8518	2.86×10^{-7}	1.0
11760	0.8503	2.84×10^{-7}	1.1
11780	0.8489	2.84×10^{-7}	1.0
11800	0.8475	2.80×10^{-7}	1.0
11820	0.8460	2.77×10^{-7}	1.0
11840	0.8446	2.74×10^{-7}	1.1
11860	0.8432	2.71×10^{-7}	1.1
11880	0.8418	2.68×10^{-7}	1.0
11900	0.8403	2.64×10^{-7}	1.0
11920	0.8389	2.61×10^{-7}	1.1
11940	0.8375	2.57×10^{-7}	1.1
11960	0.8361	2.52×10^{-7}	1.1
11980	0.8347	2.46×10^{-7}	1.2
12000	0.8333	2.39×10^{-7}	1.3
12020	0.8319	2.29×10^{-7}	1.4
12040	0.8306	2.18×10^{-7}	1.6
12060	0.8292	2.05×10^{-7}	1.7
12080	0.8278	1.92×10^{-7}	1.7
12100	0.8264	1.82×10^{-7}	1.8
12120	0.8251	1.72×10^{-7}	1.8
12140	0.8237	1.65×10^{-7}	1.7
12160	0.8224	1.60×10^{-7}	1.7
12180	0.8210	1.56×10^{-7}	1.6
12200	0.8197	1.52×10^{-7}	1.6
12220	0.8183	1.50×10^{-7}	1.6
12240	0.8170	1.48×10^{-7}	1.6
12260	0.8157	1.46×10^{-7}	1.7
12280	0.8143	1.44×10^{-7}	1.7
12300	0.8130	1.43×10^{-7}	1.7
12320	0.8117	1.42×10^{-7}	1.7
12340	0.8104	1.41×10^{-7}	1.7
12360	0.8091	1.41×10^{-7}	1.7
12380	0.8078	1.40×10^{-7}	1.7
12400	0.8065	1.41×10^{-7}	1.7
12420	0.8052	1.41×10^{-7}	1.7
12440	0.8039	1.41×10^{-7}	1.7
12460	0.8026	1.42×10^{-7}	1.7
12480	0.8013	1.43×10^{-7}	1.7
12500	0.8000	1.43×10^{-7}	1.6
12520	0.7987	1.45×10^{-7}	1.7
12540	0.7974	1.47×10^{-7}	1.7
12560	0.7962	1.48×10^{-7}	1.7
12580	0.7949	1.49×10^{-7}	1.6
12600	0.7937	1.50×10^{-7}	1.6
12620	0.7924	1.52×10^{-7}	1.5
12640	0.7911	1.54×10^{-7}	1.6
12660	0.7899	1.55×10^{-7}	1.5
12680	0.7886	1.57×10^{-7}	1.5
12700	0.7874	1.58×10^{-7}	1.5
12720	0.7862	1.60×10^{-7}	1.4
12740	0.7849	1.62×10^{-7}	1.5
12760	0.7837	1.63×10^{-7}	1.5
12780	0.7825	1.64×10^{-7}	1.5
12800	0.7813	1.65×10^{-7}	1.4
12820	0.7800	1.67×10^{-7}	1.4
12840	0.7788	1.68×10^{-7}	1.3
12860	0.7776	1.69×10^{-7}	1.4
12880	0.7764	1.70×10^{-7}	1.4
12900	0.7752	1.70×10^{-7}	1.3
12920	0.7740	1.71×10^{-7}	1.4
12940	0.7728	1.71×10^{-7}	1.3
12960	0.7716	1.72×10^{-7}	1.3
12980	0.7704	1.73×10^{-7}	1.3
13000	0.7692	1.73×10^{-7}	1.4
13020	0.7680	1.73×10^{-7}	1.3
13040	0.7669	1.73×10^{-7}	1.2
13060	0.7657	1.74×10^{-7}	1.3
13080	0.7645	1.74×10^{-7}	1.3
13100	0.7634	1.74×10^{-7}	1.3
13120	0.7622	1.74×10^{-7}	1.3
13140	0.7610	1.74×10^{-7}	1.4
13160	0.7599	1.73×10^{-7}	1.3
13180	0.7587	1.73×10^{-7}	1.4
13200	0.7576	1.73×10^{-7}	1.3
13220	0.7564	1.73×10^{-7}	1.3
13240	0.7553	1.73×10^{-7}	1.3
13260	0.7541	1.72×10^{-7}	1.4
13280	0.7530	1.72×10^{-7}	1.4
13300	0.7519	1.71×10^{-7}	1.3
13320	0.7508	1.71×10^{-7}	1.4
13340	0.7496	1.70×10^{-7}	1.4
13360	0.7485	1.70×10^{-7}	1.4
13380	0.7474	1.69×10^{-7}	1.3
13400	0.7463	1.69×10^{-7}	1.4
13420	0.7452	1.68×10^{-7}	1.4
13440	0.7440	1.68×10^{-7}	1.4
13460	0.7429	1.67×10^{-7}	1.4
13480	0.7418	1.66×10^{-7}	1.5
13500	0.7407	1.65×10^{-7}	1.4
13520	0.7396	1.63×10^{-7}	1.5
13540	0.7386	1.61×10^{-7}	1.4
13560	0.7375	1.57×10^{-7}	1.5
13580	0.7364	1.53×10^{-7}	1.5
13600	0.7353	1.48×10^{-7}	1.7
13620	0.7342	1.43×10^{-7}	1.7
13640	0.7331	1.35×10^{-7}	2.0
13660	0.7321	1.28×10^{-7}	2.1
13680	0.7310	1.21×10^{-7}	2.2
13700	0.7299	1.14×10^{-7}	2.3
13720	0.7289	1.07×10^{-7}	2.5
13740	0.7278	1.02×10^{-7}	2.4
13760	0.7267	9.63×10^{-8}	2.5
13780	0.7257	9.20×10^{-8}	2.4
13800	0.7246	8.80×10^{-8}	2.5
13820	0.7236	8.45×10^{-8}	2.6
13840	0.7225	8.09×10^{-8}	2.7
13860	0.7215	7.75×10^{-8}	2.9
13880	0.7205	7.43×10^{-8}	2.8
13900	0.7194	7.11×10^{-8}	3.0
13920	0.7184	6.80×10^{-8}	3.2
13940	0.7174	6.51×10^{-8}	3.2
13960	0.7163	6.24×10^{-8}	3.5

(Table continued)

Table 2. (continued)

Wave Number (1/cm)	Wave Length (μm)	Water, $T = 22$ °C k	Error (%)
13980	0.7153	5.97×10^{-8}	3.5
14000	0.7143	5.72×10^{-8}	3.7
14020	0.7133	5.50×10^{-8}	3.8
14040	0.7123	5.27×10^{-8}	4.0
14060	0.7112	5.08×10^{-8}	4.3
14080	0.7102	4.89×10^{-8}	4.3
14100	0.7092	4.74×10^{-8}	4.5
14120	0.7082	4.59×10^{-8}	4.5
14140	0.7072	4.46×10^{-8}	4.6
14160	0.7062	4.34×10^{-8}	4.9
14180	0.7052	4.22×10^{-8}	5.0
14200	0.7042	4.12×10^{-8}	5.0
14220	0.7032	4.00×10^{-8}	5.2
14240	0.7022	3.90×10^{-8}	5.3
14260	0.7013	3.81×10^{-8}	5.5
14280	0.7003	3.72×10^{-8}	5.5
14300	0.6993	3.63×10^{-8}	5.5
14320	0.6983	3.55×10^{-8}	6.2
14340	0.6974	3.47×10^{-8}	6.0
14360	0.6964	3.40×10^{-8}	6.1
14380	0.6954	3.33×10^{-8}	6.4
14400	0.6944	3.27×10^{-8}	6.4
14420	0.6935	3.20×10^{-8}	6.7
14440	0.6925	3.15×10^{-8}	6.7
14460	0.6916	3.10×10^{-8}	6.9
14480	0.6906	3.04×10^{-8}	7.2
14500	0.6897	2.98×10^{-8}	7.0
14520	0.6887	2.94×10^{-8}	7.3
14540	0.6878	2.91×10^{-8}	7.4
14560	0.6868	2.87×10^{-8}	7.4
14580	0.6859	2.84×10^{-8}	7.7
14600	0.6849	2.82×10^{-8}	7.9
14620	0.6840	2.79×10^{-8}	8.1
14640	0.6831	2.76×10^{-8}	7.9
14660	0.6821	2.73×10^{-8}	8.2
14680	0.6812	2.73×10^{-8}	8.0
14700	0.6803	2.71×10^{-8}	8.1
14720	0.6793	2.69×10^{-8}	8.2
14740	0.6784	2.66×10^{-8}	8.1
14760	0.6775	2.64×10^{-8}	8.3
14780	0.6766	2.64×10^{-8}	8.6
14800	0.6757	2.61×10^{-8}	8.6
14820	0.6748	2.61×10^{-8}	8.7
14840	0.6739	2.58×10^{-8}	8.6
14860	0.6729	2.56×10^{-8}	9.0
14880	0.6720	2.55×10^{-8}	9.1
14900	0.6711	2.54×10^{-8}	8.9
14920	0.6702	2.53×10^{-8}	9.3
14940	0.6693	2.52×10^{-8}	8.8
14960	0.6684	2.48×10^{-8}	9.8
14980	0.6676	2.48×10^{-8}	9.2
15000	0.6667	2.47×10^{-8}	9.1

It seems that Warren's[10] estimate of an error as high as a factor of 2 was too pessimistic. The largest deviation between Warren's compilation and our measurements is ~22%, around a wavelength of 1.85 μm.

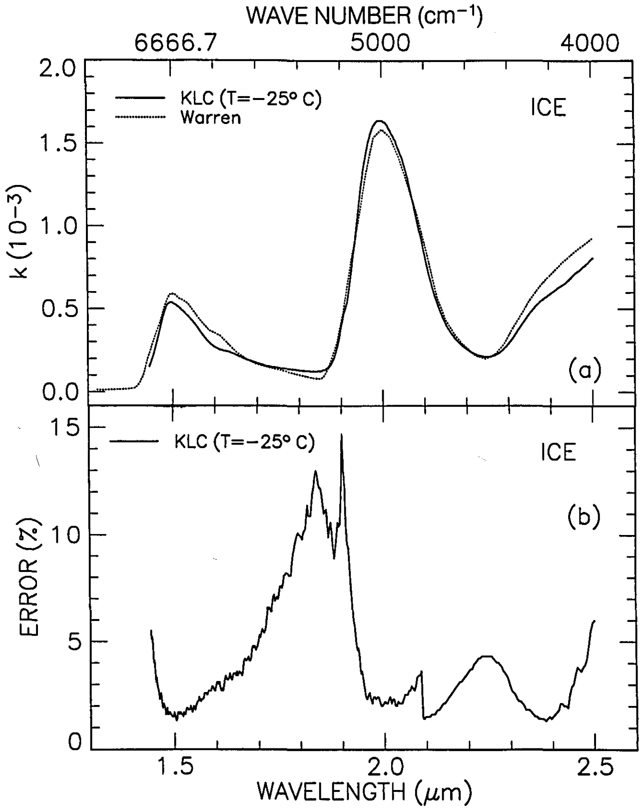

Fig. 3. (a) Imaginary part of the refractive index of polycrystalline ice at $T = -25$ °C from the present measurements (KLC, solid curve) and Warren's[10] compilation (dashed curve). (b) Standard deviation on k for polycrystalline ice at $T = -25$ °C.

The error k spectrum shown in Fig. 3(b) indicates that the error is largest in the 1.8–1.9-μm range, where the transmission is correspondingly high. The KLC data of k and error, which are shown in Figs. 1–3, are listed with wave-number intervals of 20 cm^{-1} in Tables 1 and 2.

4. Discussion

Good agreement between KLC data and data obtained by Palmer and Williams[13] and Downing and Williams[14] confirms the validity of the experimental techniques used in this study. The high quality of KLC data is also reflected in the very low standard deviation (typically 1–2%) presented in Fig. 1(b). For the first time to our knowledge, reported k spectrum of supercooled water at $T = -8$ °C is similar to that of water at $T = +22$ °C. The deviations are generally within 10% in the 1.0–2.5-μm spectral range. The absorption peaks of supercooled water are shifted slightly toward the longer wavelengths.

New accurate measurements of the imaginary part of the refractive index of polycrystalline ice taken at $T = -25$ °C and in the spectral range 1.44–2.5 μm are in surprisingly good agreement with Warren's[10] compilation, who has estimated an uncertainty of a factor 2 in k values for this spectral range. In his compilation, Warren used data collected by Ockman[12] on

102-μm-thick polycrystalline ice at $T = -29$ °C and by Reding[11] on 250-μm-thick polycrystalline ice taken at $T = -78$ °C. Reding's data are uncertain because they were corrected for the k temperature dependence and the ambiguous use of their vertical axis. Ockman's data and possibly Reding's data were not corrected for reflection losses at the interface. Discrepancies between KLC data and Warren's compilation are observed mainly near 1.50, 1.85, and 2.5 μm. The largest discrepancy occurs near 1.85 μm, at the minimum of the k spectrum. Reding's data used here were smoothed out by Warren to correct for the k temperature dependence. Our results have an uncertainty of 13% at the minimum because of the corresponding high transmission (79%) at the considered wavelength. New measurements with thicker ice samples will be required if we are to increase accuracy in this region and to extend the measurements toward shorter wavelengths.

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References

1. T. P. Charlock, "Cloud optics as possible stabilizing factor in climate," J. Atmos. Sci. **38,** 661–663 (1981).
2. R. C. J. Somerville and L. A. Remer, "Cloud optical thickness feedbacks in the CO_2 climate problem," J. Geophys. Res. **89,** 9668–9672 (1984).
3. R. T. Wetherald and S. Manabe, "Cloud feedback processes in a general circulation model," J. Atmos. Sci. **45,** 1397–1415 (1988).
4. G. L. Stephens, S. C. Tsay, P. W. Stackhouse, and P. J. Flatau, "The relevance of the microphysical and radiative properties of cirrus clouds to climate and climatic feedback," J. Atmos. Sci. **47,** 1742–1753 (1990).
5. J. F. B. Mitchell and W. J. Ingram, "Carbon dioxide and climate: mechanism of changes in cloud," J. Climatol. **5,** 5–21 (1992).
6. S. Manabe and R. J. Stouffer, "Sensitivity of a global climate model to an increase in the CO_2 concentration in the atmosphere," J. Geophys. Res. **85,** 5529–5554 (1980).
7. J. F. B. Mitchell, "The 'greenhouse' effect and climate change," Rev. Geophys. **27,** 115–139 (1989).
8. M. E. Schlesinger and J. F. B. Mitchell, "Climate model simulations of the equilibrium climatic response to increased carbon dioxide," Rev. Geophys. **25,** 760–798 (1987).
9. G. M. Hale and M. R. Querry, "Optical constants of water in the 200-nm to 200-μm wavelength region," Appl. Opt. **12,** 555–563 (1973).
10. S. G. Warren, "Optical constants of ice from the ultraviolet to the microwave," Appl. Opt. **23,** 1206–1225 (1984).
11. F. P. Reding, "The vibrational spectrum and structure of several molecular crystals at low temperature," Ph. D. dissertation (Brown University, Providence, R. I., 1951).
12. N. Ockman, "The infra-red and Raman spectra of ice," Adv. Phys. **7,** 199–220 (1958).
13. K. F. Palmer and D. Williams, "Optical properties of water in the near infrared," J. Opt. Soc. Am. **64,** 1107–1110 (1974).
14. H. D. Downing and D. Williams, "Optical constants of water in the infrared," J. Geophys. Res. **80,** 1656–1161 (1975).
15. D. M. Wieliczka, S. Weng, and M. R. Querry, "Wedge shaped cell for highly absorbent liquids: infrared optical constants of water," Appl. Opt. **28,** 1714–1719 (1989).