Optical Properties of the Arctic Upper Water

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ABSTRACT. Optical properties of the Arctic Upper Water have been measured from Fletcher's Ice Island, T-3, in the Arctic Ocean. Beam transmittance for various wavelengths and the upwelling and downwelling irradiance have been measured to a depth of 120 metres. In the spectral region of maximum transmittance the beam transmittance was found to be 93.1 per cent per metre and the diffuse attenuation coefficient for irradiance was 0.0444 per metre. The data show that the Arctic Upper Water, in early May before the snow cover on the ice has cleared, is optically uniform and very clear.

RÉSUMÉ. *Propriétés optiques de l' "Arctic Upper Water"*. L'auteur a étudié les propriétés optiques de l'(a masse océanique dite) *Arctic Upper Water* à partir de l'île de glace de Fletcher T-3, dans l'océan Arctique. Il a mesuré la transmission de faisceau pour différentes longueurs d'onde et le rayonnement en remontée et en enfoncement, jusqu'à une profondeur de 120 mètres. Dans la région spectrale où la transmission est maximale, la transmission de faisceau est de 93,1 pour cent par mètre et le coeffcient d'atténuation pour le rayonnement diffus est de 0,0444 par mètre. Les données recueillies révèlent qu'au début de mai, avant que la couverture neigeuse sur la glace ne soit disparue, l'*Arctic Upper Water* est optiquement uniforme et très transparente.

РЕЗЮМЕ. *Оптические свойства арктического верхнего бьефа.* Оптические свойства верхнего бьефа были измерены с ледяного острова Флетчера (Т-3) в Северном Ледовитом Океане. Прохождение луча в различных длинах волн и распространение излучения вверх и вниз были измерены до глубины 1200м. В спектральной области максимального пропускания прозрачность составляла 93,1 процент на метр и коэффициент ослабления излучения на рассеяние был 0,0444 на метр. Полученные данные показывают, что в начале мая, когда снежный покров льда ещё не растаял, верхний бьеф оптически однороден и очень чист.

INTRODUCTION

Coachman (1968, 1969) has reviewed recent knowledge of the physical properties of the Arctic Ocean. The optical measurements reported below were made in the Arctic Upper Water; a relatively thin (~200 m.) and well mixed upper layer of water characterized by low salinity and temperature. The interface layer of the Arctic Upper Water is cold, being at or near freezing. Within the Canada Basin a slight temperature maximum is found at 75 to 100 metres owing to the intrusion of Bering Sea water. The salinity is reported to be uniform at about 31‰ from the surface to about 50 metres, then increasing to over 34‰ at 200 metres (English, 1961).

As pointed out by Coachman (1969) "the Arctic Ocean is probably no less complex than any of the world's oceans, but its ranges of property values are less and hence the complexities are reflected as smaller variations of the values in space and time." This should also be true of variations in the optical properties

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of the Arctic Ocean waters whose optical properties are relatively insensitive to variations in temperature and salinity. On the other hand, the optical properties of ocean water are particularly sensitive to the presence of dissolved or suspended material in the water (Tyler 1961). Thus in general, away from the influence of land, variations in those properties are principally caused by variations in primary productivity. Since primary productivity in the Arctic Ocean is low in relation to other ocean areas, it is expected that variations in the optical properties of the waters will be correspondently small except during the short arctic productivity season.

The optical measurements reported below were obtained in early May, under roughly 5 metres of ice and 30 centimetres of snow, well before the onset of summer productivity. Thus these measurements should be typical of the Arctic Upper Water for most of the year. In addition, the apparent physical uniformity of the Arctic Upper Water suggests that the optical studies reported below may be representative over the full geographical range of these waters. However, this wide temporal and spatial applicability of the optical data reported herein is an assumption based on the reported physical uniformity and low productivity and should be treated with due caution. Also, it is to be expected that the optical properties of the Arctic Upper Water will show variations during the summer productivity season and as the edge of the ice pack or land is approached.

The author is unaware of any previously published measurements of beam transmittance in arctic waters. On the other hand, a few measurements of radiant energy under arctic sea ice have been reported. Zubov (1943) summarizes some early measurements of illumination under sea ice. The difficulties in assessing the correct spectral and geometrical response of underwater radiant energy collectors have been fully discussed by Tyler (1959) and Smith (1969). These works should be consulted when referring to early measurements of underwater radiant energy. Data obtained by English (1961) in July, measuring downwelling irradiance in a bandwidth centred at 425 nanometers, give diffuse attenuation coefficients of 0.107 per metre in open water and 0.140 per metre under a 3-metre thick ice floe. Merrifield (1964), measuring downwelling illuminance from a submarine, obtained diffuse attenuation coefficients in late July and early August ranging from 0.069 per metre to 0.123 per metre. The attenuation coefficients reported by English and Merrifield were obtained during the season of arctic primary productivity and hence are higher than the value reported below.

Neshyba *et al.* (1968) have reported light scattering *v.* depth in the Central Arctic Ocean using a helium-neon laser. His results show a variability in the relative light scattering of the order of 15 per cent in depths of less than 500 metres. In clear waters, where the ratio of scattering to absorption can be 0.2 or less, a 10 per cent change in the scattering coefficient causes less than a 2 per cent change in the total attenuation coefficient (Equation 2). Thus the uniformity in total attenuation coefficient, repeated below, is not inconsistent with the results of Neshyba.

EXPERIMENTAL INSTRUMENTS AND RESULTS

Beam Transmissometer

An underwater transmissometer, developed by Petzold and Austin (1968), was used to measure temperature and beam transmittance at 5 wavelengths. This instrument measures the transmittance of a cylindrically limited beam of artificial light, suitably filtered for a desired spectral bandwidth, over a folded one-metre pathlength. The measured transmittance, T, is related to the total volume attenuation coefficient, α, by

$$T = e^{-\alpha r} \tag{1}$$

where r is the pathlength. The total attenuation coefficient, α, accounts for losses from the beam due to both scattering, s, and absorption, a, where

$$\alpha = a + s \quad . \tag{2}$$

The mean wavelength and spectral bandwidth of the transmissometer measurements are fixed by the spectral transmittance of the selected filters, by the spectral response of the silicon detector, by the spectral output of the artificial light source, and by the spectral transmission of the water. Wratten filter numbers, and the corresponding mean wavelength, $\bar{\lambda}$, and full spectral bandwith at half maximum, $\Delta\lambda\frac{1}{2}$, used for the present work are given in the first three columns of Table 1.

TABLE 1. Beam transmittance data.

Wratten Filter	λ	$\Delta\lambda 1/2$	T %/m.	α 1/m.
98	449 nm	47 nm	90.7	0.0975
48	473 nm	88 nm	92.2	0.0812
45	488 nm	53 nm	93.1	0.0715
61	530 nm	54.5 nm	91.5	0.0888
21	580 nm	45.5 nm	84.5	0.1720

The beam transmittance, for $\bar{\lambda} = 488$ nanometers, as a function of depth is shown in Fig. 1. The upper 4½ metres show the transmittance of the hydrohole water which had been contaminated by previous research activity and is therefore of no significance in this study. Beneath the ice, the beam transmittance is constant to a depth of 46 metres, slowly decreases by about one-half of one per cent over the next 10 metres and then remains constant to a depth of 100 metres. Precise temperature versus depth measurements made from T-3 by S. Neshyba (private communication) during this same period show a uniform temperature of about −1.6°C. from the surface to 46 metres followed by a slight maximum of about −1.4°C. at 75 metres. These small changes in the temperature are presumably due to the intrusion of Bering Sea water as described by Coachman (1968, 1969). On Fig. 1, this intrusion is just barely perceptible within the accuracy of measurement of the present 1-metre pathlength transmissometer. As mentioned above, the total attenuation coefficient is not a sensitive measure of scattering in waters with low ratio of scattering to absorption. Thus significant changes in total scattering, and hence suspended particulate material, may go unnoticed in these measurements.

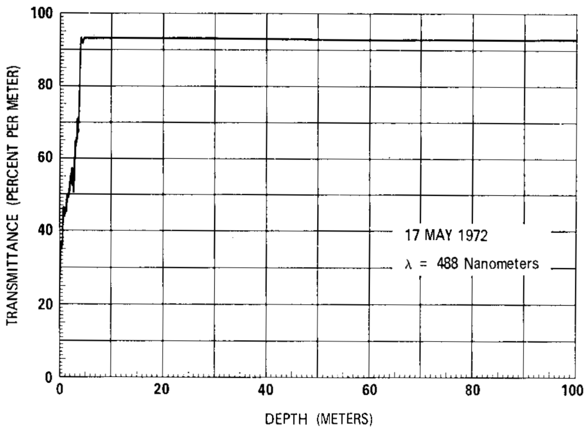

FIG. 1. Beam transmittance for λ = 488 nanometers as a function of depth. At 84°21′N., 85°24′W., water depth 1,803 m., 17 May 1972. Transmittance for depths less than 4.5 m. is within the hydrohole and does not represent natural conditions.

As described by Petzold and Austin (1968), the transmissometer was designed to keep the error due to forward scattered light less than a few tenths of one per cent. In addition, the instrument is equipped with an internal reference light path so that the calibration of the instrument can be checked while submerged. The overall inherent accuracy of the instrument, except in very turbid waters, is estimated to be less than ± 0.5 per cent of the transmittance measurement. If greater accuracy is desired, in waters where the transmittance is higher than 90 per cent per metre, a 2 or 3-metre pathlength transmissometer is necessary.

However, the contaminated water in the hydrohole used for this work may have been an added source of systematic error. It is imperative, in transmittance measurements, that the windows of the instrument remain clean. Even a light film of oil on the window surfaces can seriously affect the measurements. This is particularly serious when the measured transmittance is greater than 90 per cent per metre. Measurements of beam transmittance were made on 13 May 1972 taking great care to insure clean instrument windows. The hydrohole was then cleaned with detergent, flushed, and the measurements repeated on 17 May. The transmittance within the ice hole changed appreciably but the transmittance measured beneath the ice was the same, well within ± 0.5 per cent, at all wavelengths for the two days. This is good evidence that the reported values for beam transmittance beneath the ice are within the stated accuracy of ± 0.5 per cent. Nevertheless, it is possible that the actual systematic error could be as large as twice the inherent systematic error due to the contaminated water in the hydrohole.

Beam transmittance versus depth profiles at other wavelengths were similar to that shown for $\bar{\lambda}$ = 488 nanometers in Fig. 1. At all wavelengths the measured value of beam transmittance remained constant from the ice-water interface to 46 metres, slowly decreased by a few tenths of one per cent over the next 10 metres, and then remained constant to at least 100 metres. The transmittance for 5 separate wavelength bandwidths as measured from the ice-water interface to 46 metres is given in Table 1. The transmittance values reported are averages of a number of measurements made on two separate days. The volume attenuation coefficients, α, were calculated from the transmittances by means of equation 1.

A plot of transmittance versus wavelength indicates that the wavelength of maximum transmittance lies between 480 and 495 nanometers.

Arctic Irradiance Meter.

A high sensitivity irradiance meter, modified from an oceanographic illuminometer developed by Austin and Loudermilk (1968), was used to measure the up- and downwelling irradiance in the Arctic Upper Water under ice and snow. High sensitivity is essential because the sun's radiant energy is reduced many orders of magnitude in passing through the snow and ice cover of the Arctic Ocean.

Principal features of the arctic irradiance meter system are: an underwater cosine collector, an appropriately filtered RCA 4517 photomultiplier, a depth transducer, an above water cosine collector, and electronic circuitry capable of linearly recording five logs of photomultiplier response.

The geometrical response of the instrument was designed by means of a carefully constructed underwater cosine collector (Smith 1969) to measure downwelling, H(−), and upwelling, H(+), irradiance defined (Tyler and Preisendorfer 1962) as

$$H(-) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\theta=\pi/2} N(\theta,\phi) \cos\theta \, d\Omega \tag{3}$$

and

$$H(+) = \int_{\phi=0}^{2\pi} \int_{\theta=\pi/2}^{\theta=\pi} N(\theta,\phi) \cos\theta \, d\Omega \tag{4}$$

Here $N(\theta,\phi)$ is the radiance from the zenith angle, θ, and azimuthal angle, ϕ, and $d\Omega = \sin\theta d\theta d\phi$. The irradiance is a measure of the radiant power per unit area.

The spectral response of the arctic irradiance meter was selected in the field after the wavelength of maximum transmittance of the Arctic Upper Water had been approximated by use of the transmissometer. Because of the strong absorption properties of water, it is necessary to match the spectral response of the irradiance meter to the maximum transmittance of the water if serious systematic errors due to filter leakage are to be avoided (Tyler 1959). The photomultiplier bialkali photocathode spectral response combined with a Wratten No. 64 filter gives an instrument spectral response centred at 490 nanometers with a spectral bandwidth of 50 nanometers at half maximum. This spectral response is shown in Fig. 2 and was used for all irradiance measurements reported below.

Variations in the incoming solar radiation, due to changes in cloud cover and sun elevation, were monitored by measuring the downwelling illuminance incident on a horizontal plane 8 metres above the snow surface. Ideally, one should monitor the above-water radiant energy using the same spectral bandwidth that is used for the below-water measurements. However, since variations in the cloud cover do not change the relative spectral composition of the incoming solar radiation within the visible region of the spectrum more than a few per cent (Robinson 1966) the error due to non-ideal above-water monitoring is correspondingly small.

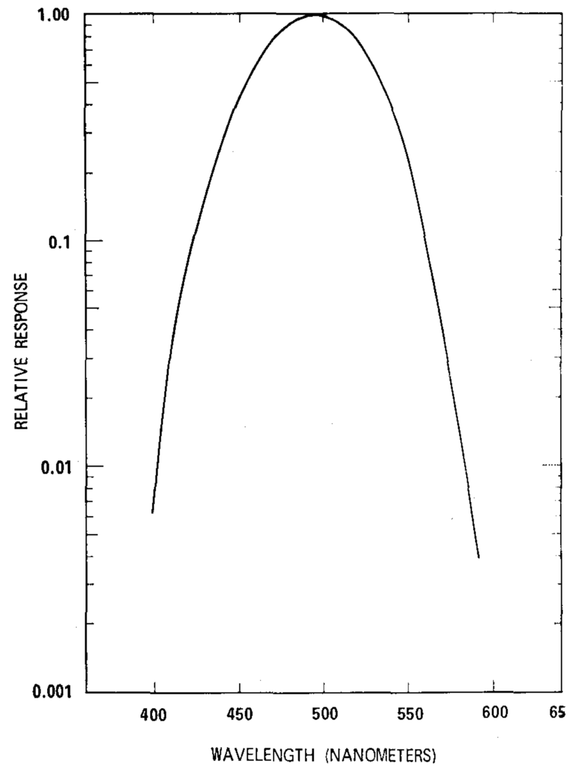

FIG. 2. Spectral response of Arctic Irradiance Meter. Bialkali photocathode (RCA 4517 photomultiplier, type 115 spectral response) covered with a Wratten No. 64 filter.

The ratio of the output of the underwater irradiance meter, covered by a neutral density 4.0 (Wratten No. 96) filter, to the output of the above water illuminometer was set to read 1.000 under relatively uniform overcast skies. From this ratio, the spectral responses of the above- and below-water instruments, the absolute calibration of the above-water illuminometer, and the known solar spectrum (Thekaekara 1970) a crude absolute calibration of the underwater instrument can be made. Thus it was determined that while the above-surface downwelling illuminance varied from 2.7 to 4.5 lumens per square centimetre, the above-surface radiant input within the spectral response bandwidth (Fig. 2) of the underwater unit varied from 3.16 to 5.30 milliwatts per square centimetre. The uncertainties in determining the above-surface radiant energy input within the spectral bandwidth of the underwater unit are estimated to be $\pm$ 15 per cent. Of more importance, the relative precision of the underwater irradiance measurements is better than $\pm$ 1 per cent. It is the relative precision of irradiance measurements that determines both the accuracy and precision of the irradiance attenuation coefficients, $K(\mp)$, and the reflectance coefficient, R.

From the downwelling irradiance the irradiance-attenuation coefficient (also called the diffuse attenuation coefficient) can be computed by

$$K(-) = \frac{-1}{H(-)} \frac{dH(-)}{dz} \tag{5}$$

A similar equation holds for the upwelling irradiance, H(+). The ratio of the upwelling to the downwelling irradiances at a specific depth is the irradiance reflectance for that depth,

$$R = \frac{H(+)}{H(-)} \tag{6}$$

For the optically uniform Arctic Upper Water, the irradiance attenuation coefficients, $K(\pm)$, and the irradiance reflectance, R, were found to be constant with depth.

The ratio of the down- and upwelling irradiances, $H_Z(\pm)$, to the illuminance above the snow and ice, H_O, as a function of depth, z, is shown in Fig. 3. These data were obtained under a cover of stratocumulus clouds which completely obscured the sun. It should be noted that the range of $H_Z(\mp)/H_O$ in Fig. 3 is from 10^{-5} to 10^{-9}. To the author's knowledge no previously published underwater radiant energy measurements have been made down to such low energy levels.

Two separate depth profiles of $H_Z(\mp)/H_O$ were obtained. For one (obtained within an hour of local noon) the irradiance above the surface, within the 50-nanometer bandwidth response (Fig. 2) of the underwater irradiance meter, varied over a range from 4.8 to 5.3 milliwatts per square centimetre. For a second (obtained between 1720 and 1805 local time) the above-surface irradiance, within the spectral response of the underwater instrument, varied over a range from 2.5 to 2.8 milliwatts per square centimetre. The two depth profiles of H_Z/H_O were identical within the precision of measurement and only the first is shown in Fig. 3. In addition, the ratio H_Z/H_O, monitored for half a day with the underwater instrument at a depth of 60 metres, remained constant within ± 2 per cent while the input above the ice and snow varied from 3.16 to 5.30 milliwatts per square centimetre.

Within the precision of measurement, the slopes of the down- and upwelling irradiances are linear and equal. The irradiance-attenuation coefficient, calculated by making a least squares straight line fit to the data of Fig. 3 and by using equation 5, is 0.0444 ± 0.0002 per metre for both down- and upwelling irradiance. The reflectance function, using equation 6, is 0.0189 ± 0.0006 for all depths, since the curves for H(+) and H(−) are parallel within the precision of measurement.

The departure of the data from a straight line, between the bottom of the ice and about 40 metres, is due to the perturbation of the under-ice radiant energy distribution due to the presence of the ice hole and hydrohut above the hole. Care was taken to prevent stray light from passing down our hydrohole or from other hydroholes within 100 metres of our work. Heat lamps pointing downward into a hydrohole about 30 metres from ours were found to make a 1 to 2 per cent change in the measured downwelling irradiance at 100 metres depth. Once unnatural light sources have been eliminated it remains only to make measurements deep enough so that the shadow perturbation of the hydrohut and ice hole becomes insignificant. For routine optical measurements under ice and snow, it would be useful to devise some technique of making measurements away from the influence of these perturbations.

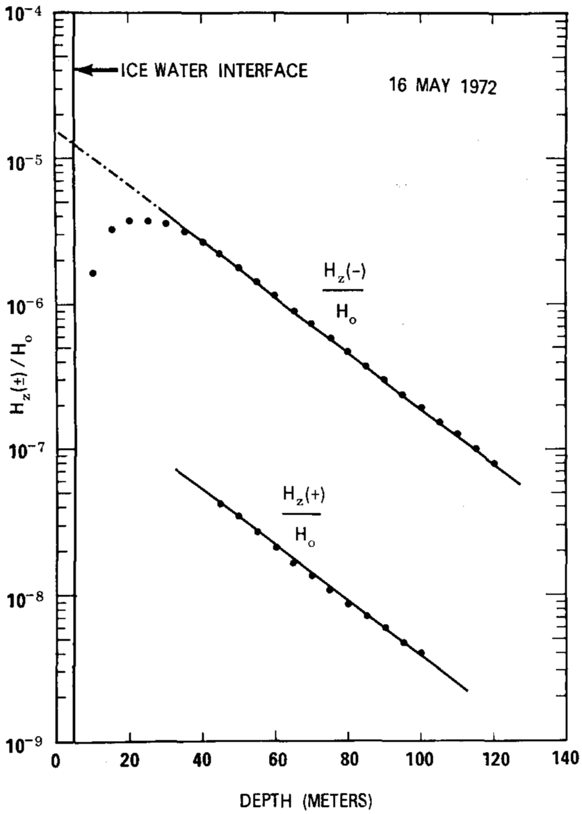

FIG. 3. Ratio of the down-, H_z (—), and upwelling, H_z (+), irradiance to the illuminance above the snow and ice, H_o, as a function of depth, z. Data taken 16 May 1972 within an hour of local noon at 84°21′N., 85°24′W., water depth 1,800 m. under approximately 5 m. of ice and 30 cm. of snow, including a few cm. of freshly fallen dry snow. The sun, at a calculated elevation of approximately 24°30′, was completely obscured by a cover of stratocumulus clouds. A ratio of 1.000 represents an input irradiance within the spectral bandwidth response (Fig. 2), which varied between 3.16 and 5.30 milliwatts per sq. cm. The straight lines are least square fits to the data below 40 m. The calculated slopes and zero depth intercepts of the straight lines are used to calculate the irradiance attenuation coefficient (equation 5) and the reflectance function (equation 6). $K = 0.0444 \pm 0.0002$ per m. and $R = 0.0189 \pm 0.0006$.

DISCUSSION AND SUMMARY

The low values for the total volume attenuation and irradiance attenuation coefficients and their constancy with depth indicate that the Arctic Upper Water is very clear and uniform. The spectral α values given in Table 1 are relatively close to values obtained by Austin using the same instrument in the Sargasso Sea (Tyler *et al.* 1972). These low values, along with the knowledge that the wavelength of maximum transmittance lies within the 480 to 495 nanometer range, tentatively place the Arctic Upper Water into the clear natural water classification as described by Tyler *et al.* (1972). This would be close to water type IB as described by Jerlov (1968). Measurements of spectral irradiance (Tyler and Smith 1970) as a function of depth are required to classify a water type definitively.

The complete optical documentation of a natural water type requires measurements of the radiance distribution as a function of depth (Tyler and Preisendorfer, 1962; Smith, *et al.* 1970). However, since the radiant energy field under the clouds, snow, and ice has no strong specular component, the measured irradiance attenuation coefficient can be used as a very close (within the precision of the experimental results) approximation to the diffuse attenuation function for radiance. Making this assumption, a whole class of practical problems concerned with underwater visibility (Duntley 1962) can be treated using the data reported above.

For an object to be visually detectable, it must differ photometrically from its background in the direction of the sensor. Whatever difference does occur constitutes an optical signal. This optical signal at the object can be described by its inherent contrast (Duntley 1962) defined as

$$C_O = \frac{(N_T - N_B)}{N_B} \tag{7}$$

where N_T is the inherent radiance of the object and N_B is the inherent radiance of the background against which the object is seen. Once the inherent contrast has been determined, the equation of contrast reduction,

$$C_R = C_O \, e^{-(\alpha + K \cos \theta)r} \tag{8}$$

can then be applied to problems of the visibility of submerged objects. Here C_R is the apparent contrast seen by a sensor at a distance, r, along path a of sight and θ is the zenith angle between the vertical and the path of sight. The attenuation coefficients have been discussed above and shown to be $\alpha = 0.0715$ per metre and $K = 0.0444$ per metre at the wavelength of maximum transmittance for Arctic Upper Water. Using these data and equation 8, the apparent contrast can be calculated along any path of sight once the inherent contrast of the object has been determined.

Duntley (1962) has suggested rule-of-thumb sighting ranges for use when the human eye is used as the optical detector. For example, large dark objects, seen as silhouettes against a water background, can be sighted at the distance $4/\alpha$ when the path of sight is horizontal. Thus divers operating in the Arctic Upper Water, when there is sufficient natural light for visibility, should be able to see each other out to distances of roughly 56 metres.

The downwelling irradiance has been used as a measure of the energy available for photosynthesis. As can be seen, by extrapolating the downwelling irradiance curve in Fig. 3 up to the ice-water interface, the radiant energy has been reduced by roughly 5 orders of magnitude in passing through the snow and ice. If one assumes for a rough estimate that the albedo of the snow surface is 60 per cent (Larsson and Orvig 1962), that for dry snow K is approximately 18 per metre and that for ice K is approximately 0.9 per metre (see, for example, Greenbank 1945; Thomas 1962), then this reduction in radiant energy can be reasonably accounted for. Using these assumptions, the radiant energy is reduced roughly 3 orders of magnitude by the reflection from and by the transmission through 1/3 metre of snow. Transmission through 5 metres of ice reduces the radiant energy roughly 2 more orders of magnitude. Thus the ablation of the snow cover will cause an increase in the radiant energy under the ice of 3 or more orders of magnitude. This agrees with observations made by English (1961), who pointed out that the absence of snow greatly increased the amount of radiant energy available for photosynthesis.

The results reported above indicate that the Arctic Upper Water is optically very clear and uniform. Thus, once radiant energy succeeds in penetrating the icy cover of the Arctic Ocean, it may travel downward more than 50 metres while being attenuated an order of magnitude. More complete optical measurements will be required to determine the temporal and spatial extent of the clarity and uniformity of the Arctic Upper Water.

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