The Underwater Photic Environment of a Small Arctic Lake

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ABSTRACT. The underwater light field in a small arctic lake on Victoria Island, Northwest Territories, was examined. Downward radiance was found to be bimodal, with transmission peaks at 480 and 640 nanometres (nm, or 10^{-9}m). Upward radiance was similar near the surface, with peaks at 480 and 620 nm, but became unimodal with depth and shifted to 580 nm near the bottom. Diurnal variation in the underwater downward and upward irradiance of PAR (photosynthetically active radiation) was approximately two orders of magnitude. The spectral quality of light transmission also changed over this 24 hour period. Unimodal transmission of red light occurred in the early morning (1:00 and 5:00) and late evening (22:00), while bimodal transmission of blue-green and red light was observed during the day (9:00-17:30). $K_d(z_m)$, the vertical attenuation coefficient for downward irradiance at the midpoint of the euphotic zone, was relatively insensitive to changes in solar elevation. Diurnal variation in the reflectance of PAR differed from that predicted by previous simulation models, while the inverse relationship between reflectance and the absorption coefficient was in agreement with these same models. Gilvin, humic material-dissolved iron complexes, algal fucoxanthin, chlorophyll a and tripton all contribute to the attenuation of light and are responsible for the unique underwater spectral transmission in Keyhole Lake.

Key words: arctic, limnology, underwater light, diurnal variation, spectral quality, irradiance, radiance

RÉSUMÉ. L'environnement photique sous-marin d'un petit lac arctique sur l'Isle Victoria, Territoires du Nord-Ouest a été examiné. La radiance descendante a eu un spectre bimodal avec deux pics de transmission à 480 et à 640 nanomètres (nm ou 10^{-9}m). La radiance ascendante a été semblable près de la surface avec les mêmes deux pics (480 et 620 nm) mais avec une augmentation de la profondeur la transmission est devenue unimodale et a été déplacé près du fond vers 580 nm. La variation quotidienne de l'irradiance sous-marine descendante et ascendante de la PAR (la radiation disponible pour la photosynthèse) a été à peu près deux ordres de grandeur. La qualité spectrale de la transmission lumineuse a également changé pendant cette période de 24 heures. Une transmission unimodale de la lumière rouge a eu lieu tôt le matin (1:00 et 5:00) et tard le soir (22:00) tandis qu'une transmission bimodale de la lumière bleue-verte et rouge a été observé durant le jour (9:00-17:30). $K_d(z_m)$, le coefficient vertical d'atténuation de l'irradiance descendante au milieu de la zone photique, n'a pas vraiment changé avec des changements de l'élévation solaire. La variation diurne de la réflexion de la PAR s'est différé de celle prédit par des modèles de simulation précédents tandis que le rapport inverse entre la réflexion et la coefficient d'absorption a été en accord avec ces mêmes modèles. La matière organique dissoute, les composés de matière organique - fer dissout, la fucoxanthine des algues, le chorophylle a et le tripton contribuent tous à l'atténuation de la lumière et sont responsable pour l'unique transmission spectrale sous-marine dans le lac Keyhole.

Mot clés: arctique, limnologie, lumière sous-marine, variation diurne, qualité spectrale, irradiance, radiance

INTRODUCTION

As sunlight penetrates the surface of natural waters, its attenuation with depth is brought about by a combination of scattering and absorption processes. The factors primarily responsible for this attenuation are the water itself, dissolved organic matter (gilvin or "Gelbstoff"), suspended non-living particulate matter (tripton), the photosynthetic biota (phytoplankton and macrophytes where present), bacterioplankton and zooplankton (Furch *et al.*, 1985; Hulburt, 1945; Kirk, 1976, 1985; Robarts and Zohary, 1984; Ruttner and Sauberer, 1938; Tilzer, 1980; Westlake, 1980). The transmission of light underwater and its spectral composition have been found to vary with depth, location and season (Dubinsky and Berman, 1979; Kirk, 1977a; Roemer and Hoagland, 1979).

Maximum transmission of light underwater can vary across the entire visible spectrum. Crater Lake, the closest freshwater equivalent to distilled water, has an average maximum transmission near 420 nm (Tyler and Smith, 1967). Lakes having a relatively high phytoplankton biomass tend to transmit better in the green part of the spectrum (Yentsch, 1960; Jewson, 1977; Schanz, 1986). As the concentration of gilvin and tripton increases in fresh waters, transmission maxima of underwater light shift to the yellow and red parts of the spectrum (Kirk, 1976, 1985; Visser, 1984).

Studies of the underwater photic environment in marine systems are numerous (Jerlov, 1951; Højerslev, 1975; McFarland and Munz, 1975; Morel, 1982). Freshwater systems have been less studied (Talling, 1971; Spence *et al.*, 1971; Kirk, 1977b, 1979; Bowling *et al.*, 1986), while detailed investigations of the underwater light climate in arctic lakes are virtually absent. Some arctic studies have during the course of their limnological surveys measured relative transparency using a secchi disc (McLaren, 1964; Oliver, 1964), determined extinction coefficients for broad regions of the visible spectrum (Hobbie, 1962; Schindler *et al.*, 1974), or have presented limited downward photosynthetically active radiation spectra (Kalff, 1967; Schindler *et al.*, 1974).

The objective of this study is to provide a detailed description of the underwater light field of a small arctic lake (Keyhole Lake) and, in addition, to investigate diurnal variation in the intensity and spectral quality of this unique photic environment. This work is part of a continuing ecosystem study (Hunter, 1970; Johnson, 1976, 1983; Vanriel, unpubl. data) relating to primary production, trophic level energy dynamics and arctic charr production in this lake.

SITE DESCRIPTION

Keyhole Lake is located at 69°22'45" N latitude and 106°14' W longitude on Victoria Island, Northwest Territories. It is found in a shallow valley at an elevation of 27.4 m above sea level. The only input is from melting of the active surface layer, which provides a continuous filtered summer water supply.

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METHODS

Water samples were taken with a Van Dorn type sampler at a depth of 0.5 m at four locations in Keyhole Lake on 28 and 29 July 1985. The water quality parameters that were analyzed are found in Table 1. Analytical methods used were those of Stainton *et al.* (1977) with the following modifications: alkalinity — Gran titration; chloride, sulphate and organic acids — ion chromatography; total dissolved nitrogen and total dissolved phosphorus — ultraviolet photocombustion and chlorophyll *a* — the solvent used was methanol (P. Vanriel, pers. comm. 1986). Turbidity was measured on site with a Hach Ratio turbidity meter (model no. 18900-00). Estimates of the dissolved colour or gilvin concentration as g_{440} (Kirk, 1976) were calculated as 2.303 A/0.1 m^{-1}, where A was the measured absorbance of a membrane-filtered (Whatman GF/C glass fibre and Millipore GS 0.22 μm filters) water sample in a 10 cm cuvette.

Underwater downward and upward irradiances for PAR were measured on 21, 22 and 30 July 1985 at the deepest point in the pelagic zone (6.5 m). The instrument used to record irradiance was a LI-COR LI-185 quantum meter and a LI-192S underwater quantum sensor. The spectral quality of the underwater light was measured concurrently as radiance with an underwater spectroradiometer. A complete description of this wide-angle radiance meter is found in Heinermann and Ali (1988).

TABLE 1. Water quality analysis of Keyhole Lake water on 28 and 29 July 1985

Parameter	Mean (S.E.)*
Alkalinity[a]	1330 (7.0) μeql^{-1}
Calcium[a]	13 500 (40) μgl^{-1}
Chloride[a]	22 500 (300) μgl^{-1}
Chorophyll *a*[a]	0.6 (0.02) μgl^{-1}
Conductivity at 25°C [a]	214.5 (1.0) μScm^{-1}
Dissolved inorganic carbon[a]	1600 (71) μgl^{-1}
Dissolved iron[a]	40 (0) μgl^{-1}
Dissolved organic carbon[a]	395 (12) μgl^{-1}
Dissolved oxygen[b]	9.28 (0.50) mgl^{-1} at 8.94 (0.01) °C
Gilvin (g_{440})[c]	0.60 (0.07) m^{-1}
Magnesium[a]	9380 (20) μgl^{-1}
Manganese[a]	<20 μgl^{-1}
Organic acids[a]	32 (11.7) μeql^{-1}
pH[a]	(8.04-8.12) range
Potassium[a]	1180 (40) μgl^{-1}
Primary productivity[b]	2.3 (0.86) mgCm^{-3}day^{-1}
Secchi disc[a]	2.9 (0.6) m
Sodium[a]	12 280 (350) μgl^{-1}
Soluble reactive phosphorus[a]	1 (0) μgl^{-1}
Soluble reactive silicon[a]	148 (3) μgl^{-1}
Sulphate[a]	6250 (250) μgl^{-1}
Suspended carbon[a]	1162.5 (362) μgl^{-1}
Suspended nitrogen[a]	157.8 (45.6) μgl^{-1}
Suspended phosphorus[a]	7.75 (0.48) μgl^{-1}
Total dissolved nitrogen[a]	440 (35) μgl^{-1}
Total dissolved phosphorus[a]	15 (1) μgl^{-1}
Turbidity[c]	5.09 (0.04) NTU
Water temperature[a]	11.0 (0) °C

[a]Data from Van Riel (unpubl.).
[b]Data from Hunter (1970).
[c]Data from this study.
*Number of samples = 4, except for secchi disk and gilvin, where n = 2.

Irradiance and radiance series were recorded at 0 m (just below the water surface) and at 1 m intervals to the bottom. Measurement of a complete vertical profile required 10-15 min. The effect of boat shadow was eliminated by lowering the measuring device on the sunny side of the boat by hand to the desired depth. A measurement of in-air downward quantum flux was taken at the beginning of each downwelling and upwelling series to ensure that little variation in incident radiation was occurring over the measurement interval. All recordings were started only under cloudless skies and taken within 1 h of the sun's maximum altitude. Diurnal variation in the underwater light flux and spectral quality was investigated over a 24 h period at 1 m depth and hourly intervals on 24-25 July 1985. With the downwelling (E_d) and upwelling (E_u) irradiance data obtained at each interval, the downward (K_d) and upward (K_u) vertical attenuation coefficients, as well as irradiance reflectance values ($E_u E_d^{-1}$), were calculated. Solar elevations were computed using the method described by Kirk (1983). An estimation of the absorption (a) and total scattering coefficients (b) from the diurnal measurements followed the procedure outlined by Kirk (1981a).

RESULTS

The water quality analysis of Keyhole Lake water is presented in Table 1. Nutrient element levels in Keyhole Lake were low and conductivity was moderate. During sampling the water column was completely mixed and isothermal at 11°C. Chlorophyll *a* concentrations were also very low. pH values indicate that the lake was basic in nature. Turbidity was moderate and gilvin concentrations were low.

Since the incident flux and the spectral distribution of the downwelling and upwelling light in Keyhole Lake were similar on 21, 22 and 30 July 1985, only the data for 30 July are presented. A description of the spectral distribution of the photic environment on this date will be followed by an examination of the diurnal changes in the underwater light field.

In Figures 1a and 1b, bimodal spectra are evident in the upper 1 and 2 m of the downward and upward radiances respectively. Transmission maxima are found near 480 nm (blue-green light) and 640 nm (red light). As depth increases the spectra become unimodal, with a loss of the short wavelength component and a shift to long wavelength transmission. In Figure 1b, blue-green light transmission appears slightly greater than red light penetrance near the surface. In addition, the long wavelength peak is located near 620 nm. Near the bottom unimodal spectra are again found, with maximum transmission occurring near 580 nm. Measured upward radiance curves extended over a smaller range of wavelengths (less wide) than downwelling ones.

Figures 2a and 2b present the diurnal variation in the downward and upward irradiances of PAR on 24 and 25 July 1985. Even though at this latitude on these dates there are about 22 h 12 min of daylight, the sun's altitude does change substantially (maximum altitude was 33.3° for 24 July) and results in a variation in the underwater light flux of more than three orders of magnitude. Increases and decreases in irradiance are monotonic except for noticeable changes in the measurements at 13:30 and 17:00 Alberta Summer Time (20:30 and 24:00 Greenwich Mean Time), where the sun was
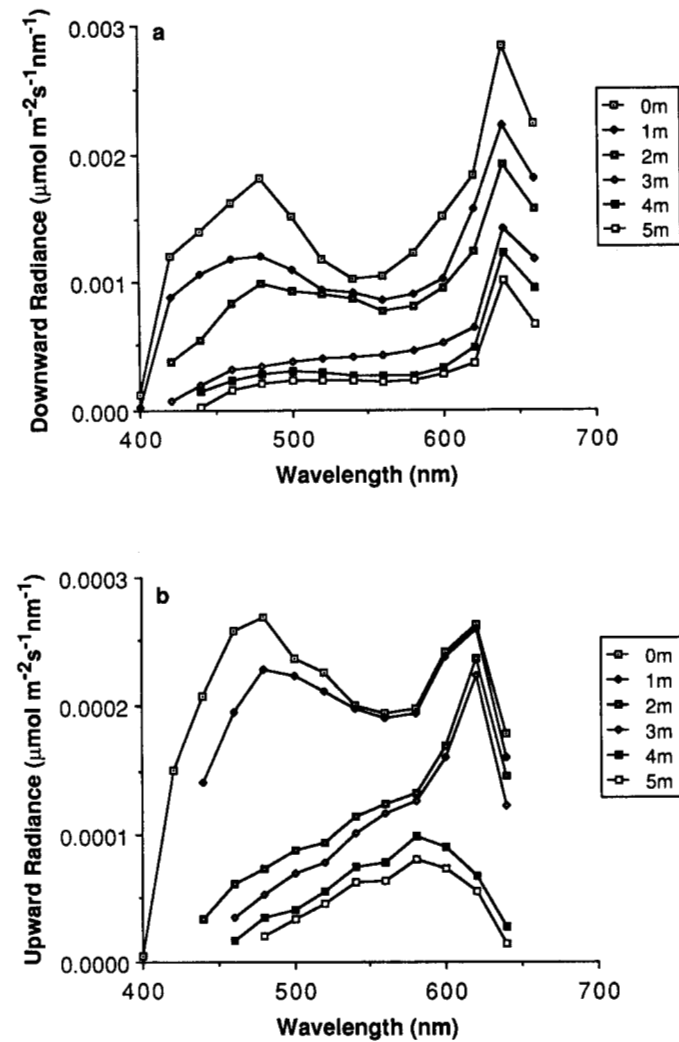
FIG. 1. Downward (a) and upward (b) radiance at each depth in Keyhole Lake on 30 July 1985. Note the bimodal spectral distribution in the upper 2 m and 1 m of downward and upward radiance respectively.
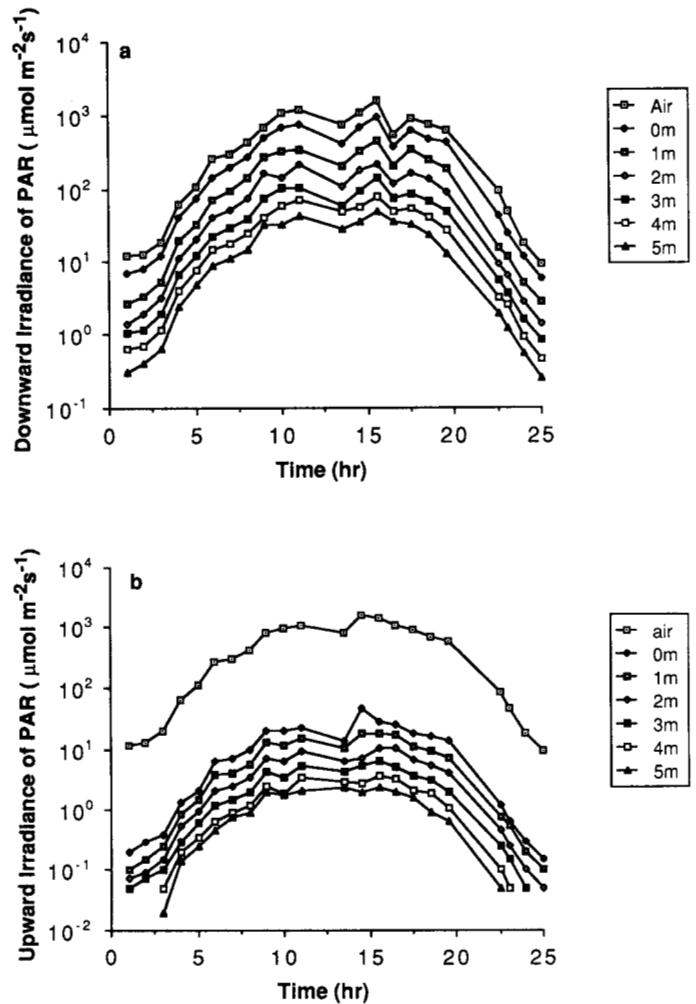

FIG. 2. Diurnal variation in the (a) downward and (b) upward irradiance of PAR in Keyhole Lake on 24 and 25 July 1985. Solar elevations at measurement times are: 01:00 (–5.8°), 02:00 (–3.9°), 03:00 (–0.9°), 04:00 (3.1°), 05:00 (7.6°), 06:00 (12.6°), 07:00 (17.7°), 08:00 (22.6°), 09:00 (26.9°), 10:00 (30.3°), 11:00 (32.5°), 13:30 (31.6°), 14:30 (28.7°), 15:30 (24.8°), 16:30 (20.2°), 17:30 (15.2°), 18:30 (10.1°), 19:30 (5.3°), 22:00 (–3.9°), 23:00 (–5.8°), 24:00 (–6.4°) and 25:00 (–5.8°).

partially obscured by a thin cloud cover. The greatest incident downward flux was found at 15:30. The upward irradiance displayed a similar pattern of change and was about one order of magnitude less intense than the downward flux.

Diurnal changes in the spectral quality of the underwater photic environment are shown in Figures 3a and 3b. Measurements of the downward and upward radiance at 1 m depth are displayed at approximately 4 h intervals. In Figure 3a, a slightly greater transmission of red light is apparent in the early morning (1:00 and 5:00) and late evening (22:00), while blue-green penetrance increases during the day (9:00-17:30). This resulted in a bimodal distribution, with maxima found at 500 and 640 nm. Similar trends were found in the upward radiance; however, the blue-green peaks were much less important at 9:00 and 17:30.

With the downward irradiance data a downwelling attenuation coefficient for PAR (K_d) was calculated. The mean value of K_d for the entire water column on 24 and 25 July 1985 was 0.657 (S.E. 0.042). In addition, $K_d(z_m)$, the vertical attenuation coefficient for downward irradiance at the depth where irradiance is 10% of that found just beneath the surface (the

midpoint of the euphotic zone, 4 m) and the average K_d have been computed for each time interval and presented with respect to solar elevation (β) in Figures 4 and 5a. Figure 4 shows $K_d(z_m)$ to be relatively insensitive to changes in solar altitude, whereas the average K_d appears to be somewhat larger at low and high solar elevations (Fig. 5a). During the 24 h measurement period the average K_u was quite variable and did not change in any recognizable pattern with the sun's varying position (Fig. 5b).

Reflectance values for PAR just below the surface (0 m) and at z_m (4 m) are shown as a function of solar elevation in Figures 6a and 6b respectively. In Figure 6a there is a small increase in reflectance when the solar altitude increases. However, at z_m, large increases were seen in reflectance up to 5° above the horizon, while further increases in the sun's height resulted in little directed change in reflectance (Fig. 6b). The data agree well with a third order polynomial regression equation (R=0.87). Very similar trends were seen at 3 and 5 m, while similar but more variable patterns were found at 1 and 2 m.

The estimated absorption and scattering coefficients are plotted as a function of solar elevation in Figures 7 and 8
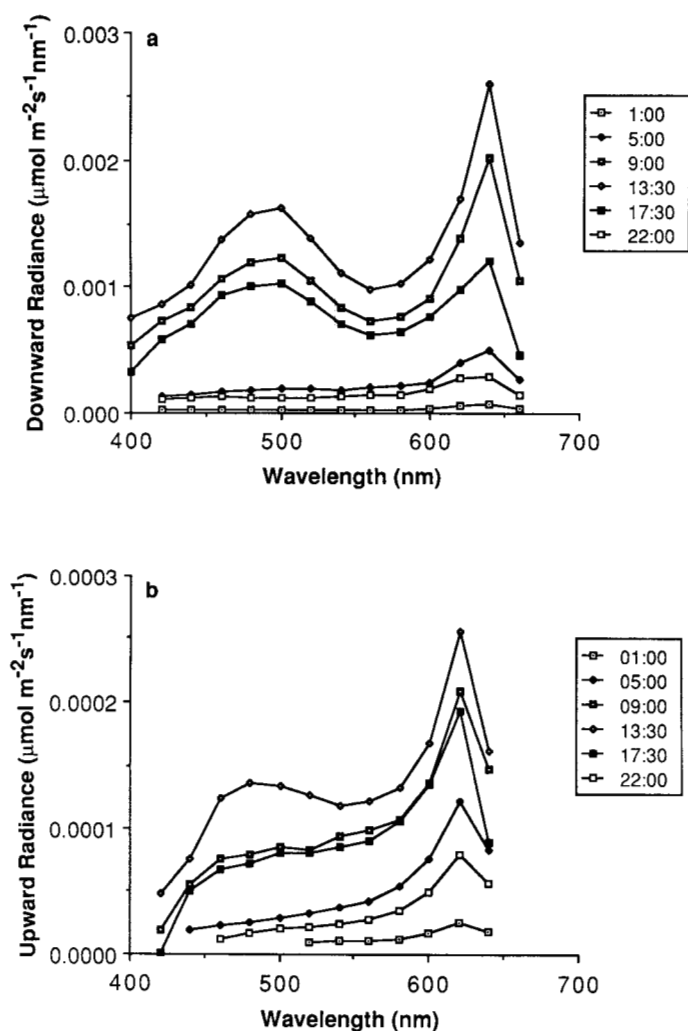
FIG. 3. Diurnal variation in the spectral distribution of (a) downward and (b) upward radiance at 1 m for various times on 24 July 1985. Times listed are Alberta Summer Time (AST), which is equivalent to Greenwich Mean Time (GMT) minus 7 h. Note the loss of the bimodal spectral distribution in the evening and early morning. See legend of Figure 2 for solar elevations.

FIG. 4. Variation of the vertical attenuation coefficient for downward irradiance at the midpoint in the euphotic zone with solar elevation.

respectively. The absorption coefficient, even though being quite variable, appears to decrease as the sun's angle from the horizon increases (Fig. 7). The average absorption coefficient at z_m for the 24 h period was 0.31 (S.E. 0.01). On the other hand, the total scattering coefficient increases to the point where the sun meets the horizon and then it remains relatively stable with further increases in β (Fig. 8). The average scattering coefficient at z_m for the sampling interval was 1.22 (S.E. 0.10).

DISCUSSION

Water quality parameters in Keyhole Lake were somewhat variable but typically low and representative of a nutrient-poor water body. Based on chlorophyll a and primary productivity values, it may be classified as an oligotrophic lake. Greater values of Na^+, Mg^{++} and Mn^{++} were present, while smaller measures of silicon and primary productivity were recorded than have been reported from other arctic lakes (Livingstone, 1963; Hobbie, 1973). In terms of soluable reactive phosphorus, total dissolved phosphorus, dissolved organic carbon, suspended phosphorus, temperature and chlorophyll a, Keyhole Lake is similar to the Barrow Ponds in
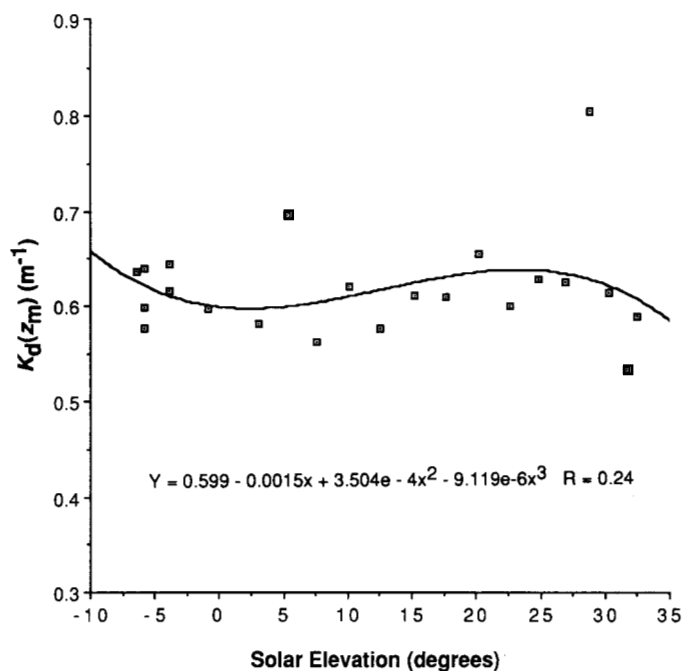
Alaska (Barsdate and Prentki, 1972), while in terms of soluable reactive phosphorus, K^+, SO_4^{--}, pH, conductivity, chlorophyll a and dissolved oxygen, it is similar to Char Lake, Cornwallis Island (Schindler *et al.*, 1974).

One obvious characteristic of the downward light transmission in Keyhole Lake is the loss of blue light with depth (Figs. 1a,b). This selective attenuation of blue light with depth has been observed by many workers (Verduin, 1982; Davies-Colley, 1983; Kishino *et al.*, 1984; Watras and Baker, 1988). It has often been attributed to absorption by gilvin found within the water column (Kirk, 1976). Gilvin concentrations in Keyhole are relatively low compared to other reported values (Kirk, 1983), but their contribution to this reduction may be substantial. No gilvin values from arctic waters have been reported, but recent measurements (Heinermann, unpubl. data) from other arctic lakes (Nauyuk Lake, g_{440} = 0.345 m^{-1}, Little Nauyuk Lake, g_{440} = 0.046 m^{-1}, Gavia Lake, g_{440} = 0.023 m^{-1}, Northwest Territories) show Keyhole Lake to have the highest gilvin concentrations measured so far. Tripton or inanimate suspensoids may also contribute to this loss of shorter wavelengths through absorption by insoluble humic material adsorbed on the surface of these particles (Hart, 1982; Kirk, 1985). A small reduction in blue light transmission may also be attributed to absorption by chrysophytes and diatoms in the water. These groups have a broad absorption band from 400 to 540 nm due to chlorophylls a and c, as well as fucoxanthin, which they possess (Owens, 1986)

A shift in the peak transmission of the upward radiance to shorter wavelengths with depth was observed on 30 July. This is similar to shifts in upward radiance found in temperate dystrophic waters (Heinermann and Ali, 1988). Upwelling spectra were found to be narrower than downwelling ones because they represent a part of the downward light from a greater depth (i.e., narrower spectral distribution) that has been redirected upwards by scattering (Kirk, 1985).
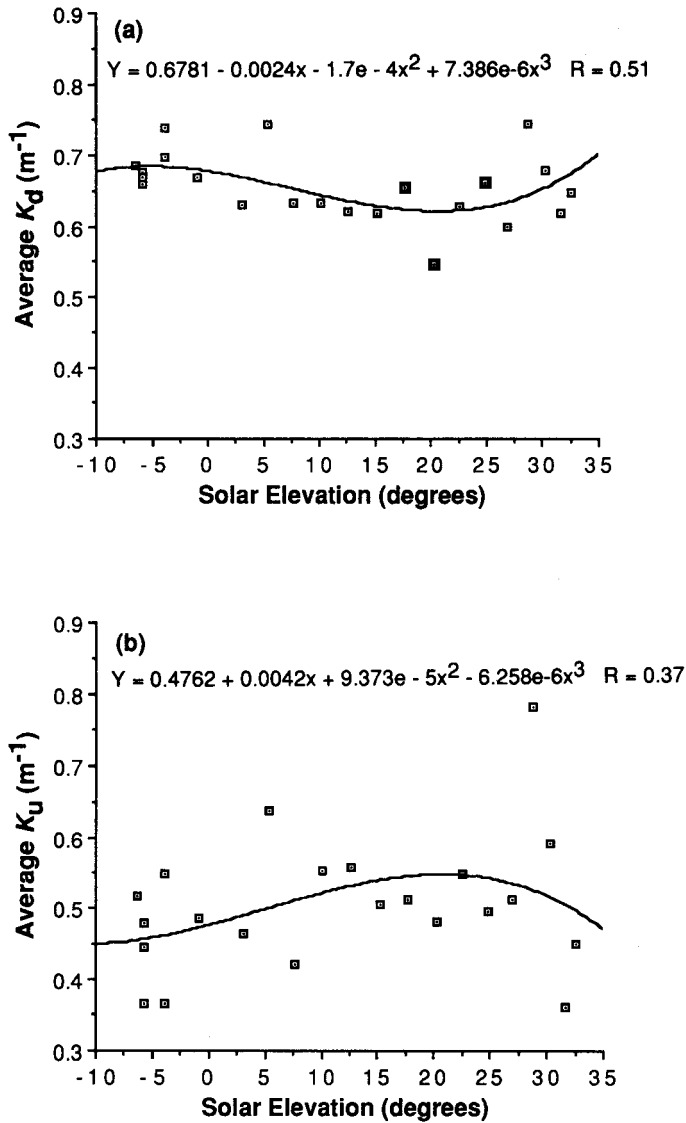
FIG. 5. Diurnal changes in the average K_d (a) and average K_u (b) with solar altitude.

FIG. 6. Solar elevation effects on (a) the reflectance just beneath the water surface (0 m) and (b) the reflectance at z_m.

The unique feature of the underwater light environment is the presence of bimodal spectral distributions. This is a relatively rare occurrence and may be attributed to a couple of factors. First, dissolved organic matter in the water column may form complexes with dissolved iron (Shapiro, 1964, 1967; Mantoura et al., 1978). These humic material-metal ion compounds absorb strongly between 500 and 560 nm (C.G. Trick, pers. comm. 1989). The dissolved iron measured in this study (40 μgl⁻¹) is high enough so that when complexed with gilvin it would selectively produce the transmission troughs seen in downward and upward radiance spectra. With increases in depth and removal of short-wavelength light by gilvin the spectra become unimodal, with transmission maxima in the red end of the visible spectrum. A second, but less likely, possibility is the effect of algal populations on the transmission of underwater light. Dubinsky and Berman (1979) attributed the bimodal distribution of the downwelling spectral irradiance in Lake Kinneret to a *Peridinium* (Dinophyceae) bloom. Transmission peaks were found at 580 and 680 nm. These were stated to be the result of strong
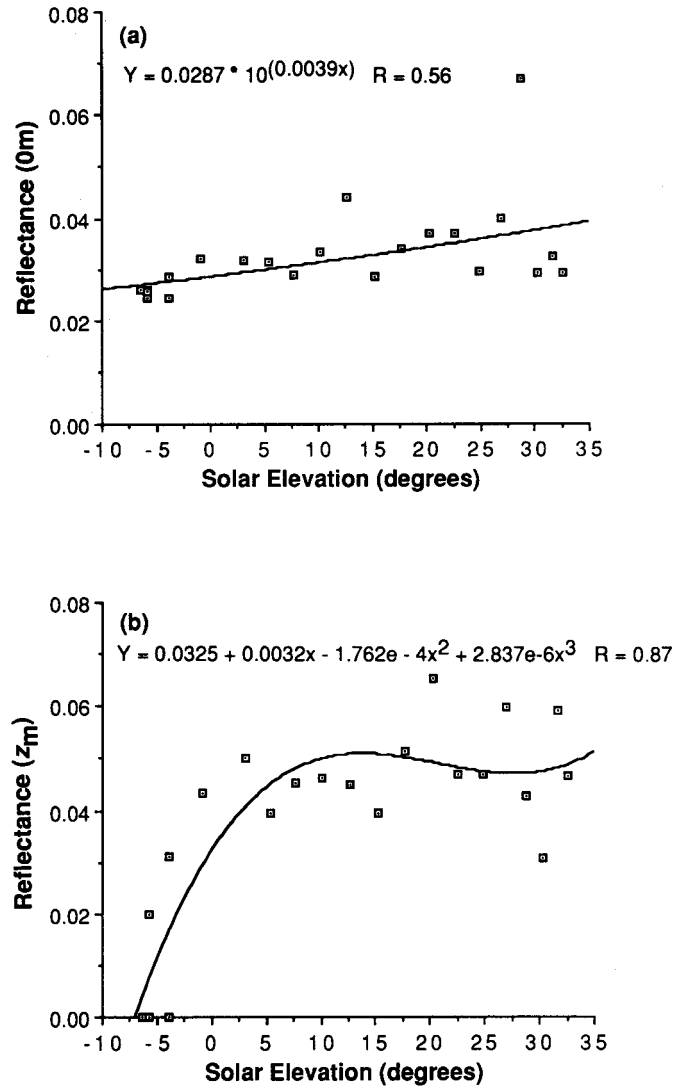
absorption by carotenoids between 440 and 470 nm and chorophyll *a* absorbance maxima near 450 and 650 nm. Kirk and Tyler (1986) and Bowling and Tyler (1986) have also found bimodal spectra in a tropical Australian and a Tasmanian lake respectively. They too attributed these distributions to chorophyll *a* absorption maxima. The absorption spectra of algal species have been shown to significantly affect the underwater spectral quality when the chorophyll *a* concentrations are greater than 10 mgm⁻³ (Talling, 1960; Kirk, 1977b). Below this level, Bowling et al. (1986) concluded that phytoplankton is unlikely to be a significant factor. Since chorophyll *a* levels in Keyhole Lake are very low, effects on light transmission would be minimal. This statement assumes that the vertical distribution of algal populations in the lake is uniform. This, however, was not verified. According to previous studies at Keyhole Lake (Hunter, 1970; Kling, unpubl. data), phytoplankton biomass was near its maximum for the year (29.13 mgm⁻²) during our sampling period, and the most abundant species for 1985, in order of importance, in terms of biomass were *Dinobryon cylindricum* (Chryso-
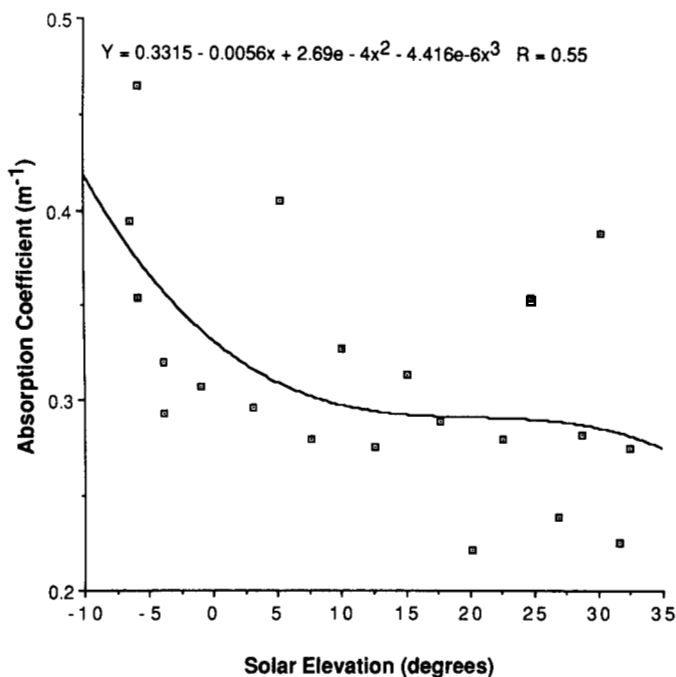
FIG. 7. Variation in the absorption coefficient with changes in solar elevation.
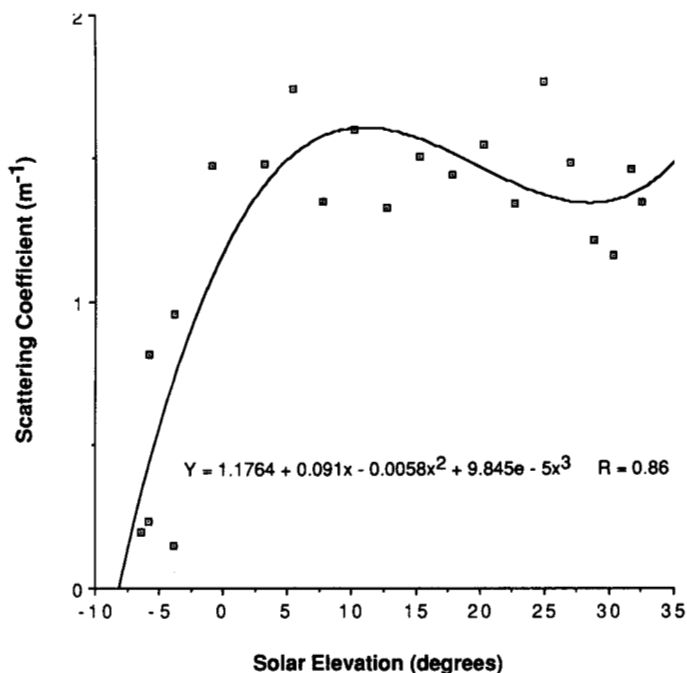

FIG. 8. Diurnal variation in the scattering coefficient with changes in solar altitude.

phyceae), *Diatoma elongatum*, *Asterionella formosa* and *Eunotia zasumensis* (Bacillariophyceae). Species such as *Dinobryon* are quite motile and may migrate upwards from the lake bottom in the mornings, thus being concentrated near the water surface at midday. Pigments such as xanthophylls found in these algae and, in particular, fucoxanthin absorb strongly in the 500-560 nm region (Kirk, 1983; Wetzel, 1983; Davies-Colley *et al.*, 1986). These two factors may account for the bimodal spectral distribution of underwater light in Keyhole Lake.

Both downwelling and upwelling radiance spectra showed a loss of the blue-green transmission maximum in the early morning and late evening. At these times the sun's position was relatively close to the horizon; as a result of this longer atmospheric path, shorter wavelength (blue and blue-green) light is more readily scattered and, thus, removed from the direct solar beam. Near sunset or sunrise, therefore, direct light becomes red-shifted (Nordtug and Melø, 1988; Kirk, 1983). This may account for the loss of the blue-green transmission maximum. On the other hand, at these low solar elevations indirect light (skylight), being richer in shorter wavelengths, makes up a larger proportion of the total irradiance (Nordtug and Melø, 1988). Without actual data concerning these parameters no simple relation can be drawn between solar altitude and spectral distribution of total irradiance.

The mean K_d for the entire water column and secchi disc readings for Keyhole Lake are similar to late July values for Lake Schrader, Alaska (K_d=0.59 and secchi disc=4 m, Hobbie, 1962) and to coefficients of some European north temperate lakes (e.g., Lake Esthwaite, K_d=0.59 and secchi disc=3.7 m, Macan, 1970; Lake Hampen, K_d=0.60 and secchi disc=3.7 m, Sand-Jensen and Søndergaard, 1981; Lake Vechten, K_d=0.60 and secchi disc=3.5 m, Steenberger and Verdouw, 1982). Lake Schrader is an oligotrophic lake (summer chlorophyll a=0.98 mgm^{-3}, while Lakes Esthwaite, Hampen and Vechten are mesotrophic (summer chlorophyll a > 2 mgm^{-3}). In terms of algal biomass, diatoms and blue-green algae predominate in Lakes Esthwaite and Hampen, green algae are most important in Lake Vechten and Chrysophyceae are the dominant group in Lake Schrader. Therefore only Lake Schrader is somewhat similar to the type of algal community found in Keyhole Lake.

The relative insensitivity of $K_d(z_m)$ to changes in solar angle in the moderately scattering waters of Keyhole Lake (average ba^{-1}=3.97) is in agreement with the characteristics of a "quasi-inherent" or "apparent" optical property of an aquatic medium, as discussed by Baker and Smith (1979) and simulated by Kirk (1984). The average K_d, on the other hand, displayed increases at low (13%) and high (22%) solar elevations. The former increase has been described by Kirk (1984); however, the increase in K_d when the sun was high in the sky remains somewhat problematic. The large variability shown by the average K_u with solar elevation changes does not allow any reasonable explanation.

The observations that reflectance just below the surface and at z_m increase with solar elevation are in opposition to calculations presented by Gordon *et al.* (1975), Kirk (1981b) and Kirk (1984). They found that reflectance values should decrease as β gets larger. These simulations may, however, not apply well to the relatively gilvin-poor, moderately turbid fresh water of Keyhole Lake.

An inverse relationship between reflectance and the absorption coefficient became apparent as solar elevation changed. As β increases, reflectance just below the surface increases (Fig. 6a), while the absorption coefficient decreases (Fig. 7). This inverse proportionality between R(0) and a has been shown by previous modelling studies (Gordon *et al.*, 1975; Kirk, 1984). The average absorption coefficient at z_m reported here is lower than values of a at z_m described for some Australian inland waters (Kirk, 1981a).

The scattering coefficient remained relatively stable while the sun was above the horizon, but a large decrease occurred as it dipped below the horizon. This decrease may result from the lack of a direct solar beam entering the water column. The average scattering coefficient at z_m in this study is similar to that reported for Corin Dam, a mesotrophic (chlorophyll a = 2.9 mgm^{-3}), slightly turbid (1.7 NTU) Australian lake.

In terms of the quality of its downward spectral transmission, Keyhole Lake appears to differ from other arctic lakes. Char Lake, on Cornwallis Island, transmits best in the blue-green (Schindler et al., 1974), while Lake Peters and Lake Schrader, in Alaska, have their greatest transmission in the green part of the spectrum (Hobbie, 1962, 1973). Red light penetration is very poor in these lakes and no bimodal spectral curves have been recorded.

When compared with other temperate and north temperate Canadian, American and European lakes, the underwater downwelling light spectra in Keyhole Lake are also quite different (see Chambers and Prepas, 1988; Watras and Baker, 1988). Its spectral quality only somewhat resembles that found in two eutrophic Albertan lakes (Lakes Cooking and Joseph; Chambers and Prepas, 1988). Therefore, the underwater photic environment of Keyhole Lake is unique among arctic, north temperate and temperate lakes.

CONCLUSIONS

Keyhole Lake is a slightly basic, monomictic arctic tundra lake. It is not very productive and nutrient poor. Although continuous light is present at this latitude during the summer, significant diel changes in the spectral quality and intensity of the underwater light field do occur. The spectral distribution of the downward and, to some degree, the upward radiance is bimodal and may be primarily attributed to absorption by humic material-dissolved iron complexes found in the water column. A second, and less important, contributor may be absorption by accessory pigments (namely xanthophylls) and photosynthetic pigments such as chlorophyll a found in phytoplankton species present at the time. The relative insensitivity of $K_d(z_m)$ to changes in solar elevation supports the idea that this parameter may be viewed as a "quasi-inherent" optical property. Diurnal variation in the reflectance of PAR differed from that predicted by previous simulation models, while the inverse relationship between reflectance and the absorption coefficient was in agreement with these same models. These data provide a quantitative and qualitative description of depth and diurnal variations in the unique arctic underwater photic environment of Keyhole Lake.

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