OPTICAL PROPERTIES OF THE MCMURDO DRY VALLEY LAKES, ANTARCTICA

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The optical properties of the ice and water columns of lakes of the McMurdo Dry Valleys are described. Attenuation of light is dominated by the effects of the permanent ice cover, which reduces incident irradiance between 78 and 99%. The ice cover also imparts a strong blue to blue-green bias to its spectral distribution. Attenuation by ice can be highly variable over short time and distance scales. This is related to the nature of incident light (direct or diffuse), ice temperature (which affects crystal structure), snow cover, solar angle, and the amount of sediment and air spaces within the ice. Transmission is highest in ice at low temperature, with diffuse incident irradiance, in the absence of snow and at low sediment and bubble contents. Within the water columns, most attenuation is due to water itself. The lakes typically have extremely low concentrations of dissolved yellow substances. In some strata, phytoplankton and suspended sediments can make significant impacts on water clarity. This is particularly evident in the deep chlorophyll-*a* layers in some lakes. Overall, the lakes of the McMurdo Dry Valleys can be characterized as being extreme shade environments, with what light there is being in the blue or blue-green portion of the spectrum. The demands that this environment imposes on phototrophs is briefly discussed.

INTRODUCTION

The optical properties of inland waters are highly variable and reflect properties of both the lake itself and, often more importantly, its catchment. Lakes of the McMurdo Dry Valleys are end members of the limnological spectrum for several reasons, many of which are discussed in other chapters of this volume. First, they are permanently covered with 3 to 4 m of ice. This feature alone sets them apart from most other lakes on the planet, even those at the same latitude in the arctic [*Adams et al.*, this volume]. Second, the inflows are generated only by melting glacier ice, rather than snow-melt or liquid precipitation [*Conovitz et al.*, this volume]. Third, the catchments are essentially devoid of vegetation. Fourth, many are in closed drainage basins (endorheic drainage), and with small inflow volumes exhibit long hydraulic residence times. Finally, lack of exposure to wind induced mixing and the presence of strong salinity gradients result in many lakes having highly stratified water columns [*Spigel and Priscu*, this volume].

In general, nutrient concentrations in the inflowing streams are low at the point of entry to the lakes [*Howard-Williams et al.*, 1986]. Low trophogenic zone nutrient concentrations support low phytoplankton population densities [*Priscu*, 1995], and biological attenuation of light is weak. Because glacier melt in the McMurdo Dry Valleys is a relatively slow process [*McKnight et al.*, this volume], suspended sediment loads in most of the streams are usually low. There are, however, a few inflows with seasonally high suspended sediment loads [*Howard-Williams et al.*, 1986; *Webster et al.*, 1996] but these streams are the exception rather than the rule. Streams in glacier-fed catchments with no vegetation may be expected to have low concentrations

TABLE 1. General Characteristics of the McMurdo Dry Valley Lakes Considered in this Chapter. m.a.s.l. = Meters Above Mean Sea Level

Lake	Elevation (m.a.s.l.)	Depth (m)	Drainage	Notes
Fryxell	17	18	Endorheic	Meromictic
Bonney west	60	40	Endorheic	Meromictic
Bonney east	60	40	Endorheic	Meromictic
Hoare	73	34	Endorheic	Proglacial, some mixing
Vanda	123	75	Endorheic	Meromictic
Miers	240	20	Exorheic	Meromictic
Wilson	100?	>100	Endorheic	Meromictic, proglacial

of dissolved organic matter [*McKnight et al.*, 1991], a major attenuating component of light in aquatic ecosystems [*Hutchinson*, 1957; *Kirk*, 1994]. The combination of low suspended solids and poorly developed terrestrial dissolved organic carbon (DOC) sources might be expected to result in highly transparent lakes.

Perennial ice cover has a profound effect on both the quality and quantity of the light available for photosynthesis [*Priscu*, 1991; *Neale and Priscu*, this volume; *McKay et al.*, 1994,]. The ice cover can be clear or contain wind-blown sediments, gas bubbles, and crystal structures within it which attenuate light by absorption and scattering. Lake ice is therefore highly variable in appearance: clear, white, blue, or even brown [*Adams et al.*, this volume]. Ice rapidly attenuates light at the red end of the spectrum, thus shifting the wavelengths of the light which enters the water column below [*Palmisano and Simmons*, 1987].

Because of its influence on preventing mixing of the water column of the lakes, a second effect of the ice cover is to enhance water column stability to the point of exhibiting meromixis because of low turbulence which is insufficient to mix old salt layers (Table 1) [*Spigel and Priscu*, this volume]. This allows a series of "attenuating layers" to develop as discrete vertically stratified zones of organisms or particulate matter. For instance, Lakes Vanda, Fryxell, and Bonney have layers of phytoplankton in relatively high concentrations at some depth below the underside of the ice, associated with discrete nutrient supply near the oxycline [*Vincent*, 1988; *Priscu*, 1995]. These Deep Chlorophyll Maxima (DCM) should selectively attenuate light more rapidly than the water column above and below and also alter the downwelling spectrum producing a distinct change in transmittance profiles. In temperate lakes, such deep blooms are sensitive to minor changes in water column turbidity and irradiance [*Vincent*, 1983]. The locations of the DCM in dry valley lakes must also be partly dependent on the clarity of the overlying water column [see *Vincent*, 1981].

This paper provides a review of existing data and compilations of both new and existing data in which the optical properties of the lakes of the McMurdo Dry Valleys are compared. The macro- and micro-scale structure of light attenuation in each lake is examined to determine the influence of suspensoid layers on the light regime at depth. The implications of this for photosynthetic organisms is discussed.

INFLUENCE OF THE PERENNIAL ICE COVER

By far the most important attenuating layer in the lakes is the ice cover. Attenuation of light by this layer has been the subject of detailed study on sea ice in the McMurdo Sound region [*Buckley and Trodahl*, 1987; *Trodahl et al.*, 1989] and on some of the lakes [e.g., Lake Hoare, *Palmisano and Simmons*, 1987; *McKay et al.*, 1994; Lake Bonney, *Priscu*, 1991; *Adams et al.*, this volume; *Fritsen et al.*, this volume].

Attenuation by the ice cover results from absorbance within the ice and reflection at the surface and within the ice, and varies markedly between lakes (Table 2). Lake Vanda's ice cover is the thinnest (Table 2) and most transparent (K_{ice} = 0.6 m^{-1}) resulting in approximately 13% of incident Photosynthetically Active Radiation (PAR: 400–700 nm) reaching the water column below the ice. In contrast, the ice cover of Lake Fryxell (K_{ice} = 1.1 m^{-1}) transmits only 1% of incident PAR to the water column. Total attenuation coefficients of the ice cover provide a limited insight into the processes which influence the amount of light reaching the water column, since there can be considerable

TABLE 2. Summary Table of Attenuation of Incident Irradiance by the Ice Cover (K_{ice} is the Extinction Coefficient for the Ice Cover), Mean Ice Thickness at the Time of Transparency Measurements, and Ice Transparency (% PAR Transmitted) in the Dry Valley Lakes in Mid Summer (November to January).

Lake		K_{ice}	Thickness (m)	n	% incident of PAR under ice	n	References
Vanda	mean	0.60	3.4	9	13.17	11	*Goldman et al.,* 1967
	range	0.49–0.67	3.1–4.5		5.2–20		*Seaburg et al.*, 1983
							Vincent and Vincent, 1982
							Parker et al., 1982
							Priscu, 1989
							This study
							Vincent, 1988
Bonney	mean	0.85	4.3	3	2.73	3	*Goldman et al.,* 1967
(East lobe)	range	0.76–0.98	4.0–4.5		1.7–3.3		*Seaburg et al*., 1983
							Parker et al., 1983
							Spigel, unpublished
							Priscu, 1991
Hoare	mean	1.08	3.95	6	1.59	6	*Seaburg et al*., 1983
	range	0.96–1.33	2.6–5.5		0.5–2.8		*Palmisano and Simmons,* 1987
							Parker et al., 1982
							Hawes and Schwarz, unpublished
Fryxell	mean	1.08	4.3	5	1.34	5	*Parker et al.,* 1982
	range	1.0–1.21	3.8–4.6		0.5–3.2		*Vincent,* 1981
							Priscu, 1989
							Vincent, 1988

variation in surface albedo and attenuating properties within the ice itself.

The structure of the ice cover of Lake Hoare, and its influence on light transmission, was studied in detail by *McKay et al.* [1994]. They found that the two major factors influencing light transmission were the amount of sediment (technically, sand and gravel) [*Adams et al.*, this volume] in the ice, and gas bubble density and alignment. The amount of sediment in the ice cover of Lake Hoare ranged from 0.2–2.0 g cm^{-2}, and most was concentrated in the upper 1 m of the ice cover. Variability in sediment concentration resulted in a three-fold variability in under-ice PAR on a spatial scale of meters [*Wharton et al.,* 1989]. In a recent study using a diver operated spectroradiometer we found that penetration of PAR through Lake Hoare ice varied almost tenfold from 0.6 to 5% also over distance scales of meters (authors' unpublished data). Below the sediment layer *McKay et al.* [1994] found the ice was very clear. Here the vertical alignment of bubbles coincides with the occurrence of vertically oriented [c-axis, sensu *Wilson,* 1981; *Adams et al.*, this volume] ice crystals which are several centimeters in diameter and extend for meters down through the ice.

Both absorption and scattering processes are important in the attenuation of PAR in lake ice. Absorption takes place within ice itself and in the entrapped wind-blown sand and gravel particles in the ice. The red end of the PAR spectrum is absorbed to the greatest extent by ice, while the specific wavelength

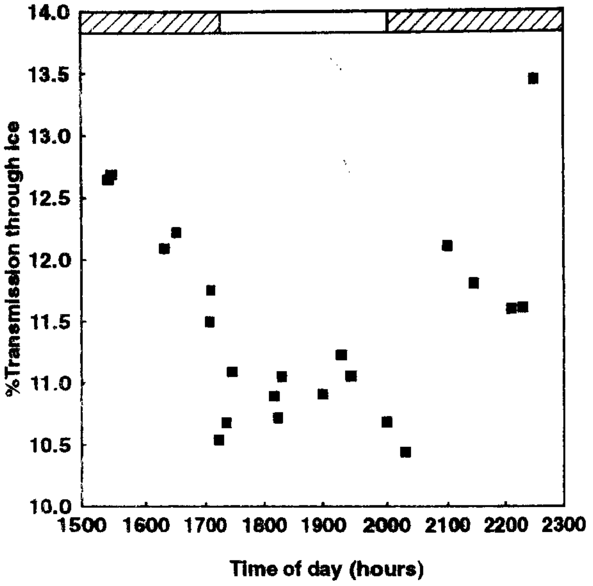

Fig. 1. Percentage transmission through 3.5 m of ice on Lake Vanda over an 8 hour period on 10 January 1996. The sky was cloudless between approximately 1700 and 2000 hrs. Shaded section of upper bar shows cloud cover.

absorbed by particles will depend on the type of particle. Organic particles may be expected to strongly absorb blue wavelengths. Scattering by particles, ice bubbles, and ice crystal structure also depends on the relative size of the scattering object and the wavelength of light [*Kirk*, 1994]. By increasing the path length for light, scattering can increase the probability of light absorption as well as that of reflectance [e.g., *Trodhal et al.*, 1989]. In the ice covers of similar thickness (Table 2) differences in light scattering will be due to particle concentrations, fractures, and bubble density rather than ice thickness alone. The relative importance of the absorption and scattering components imparted by the sediment particles in the ice versus those of other attenuating substances has not been determined and will vary greatly with ice type.

DIEL SHIFTS IN TRANSMISSION THROUGH ICE COVER

Lakes that are shaded by mountains for a period each day (e.g., Vanda, Bonney, Hoare) experience an abrupt daily change in total solar radiation [*Dana et al.*, this volume] and also a change from direct to diffuse radiation. Data from Lake Bonney show that the relative transmission through the ice almost doubles under diffuse light when compared to direct light [*Priscu*, 1991]. Changes in percent transmission over time scales of hours due to variations in cloud cover can also be seen which are comparable to the diel shifts from direct to diffuse light. Data for an 11 hour period on Lake Vanda (Figure 1) show an increase in transmission of the order of 1.3 times when conditions changed from bright sun to overcast. The net effect of this may be to decrease the temporal variance in PAR beneath the ice on a given day, since during periods of reduced incident radiation due to clouds, transmission will be highest. The mechanism for this is not yet clear as comparisons of spectral reflectance under diffuse and direct light for two different ice types show few differences (Figure 2).

SEASONAL CHANGES IN ICE TRANSPARENCY

Buckley and Trodahl [1987] demonstrated major shifts in the transparency of sea ice following an air temperature rise from –15°C to –5°C and the associated draining of surface brine. In the fresh water ice of the dry valley lakes, such changes in brine content will not occur, although seasonal changes in optical transparency have also been noted for Lakes Bonney, Vanda, and Hoare [*Priscu*, 1991; *McKay et al.*, 1994; *Wharton et al.*, 1989; authors' unpublished data]. For example,

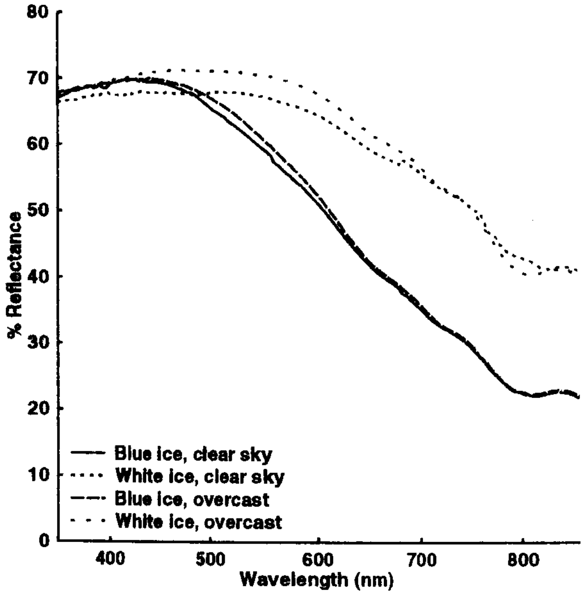

Fig. 2. Wavelength dependence of surface reflectance at the ice cover of Lake Hoare, December 1996. Data were collected with a LiCOR LI 1800 spectroradiometer suspended 1m above the ice to measure downward and upward irradiance in clear and overcast conditions.

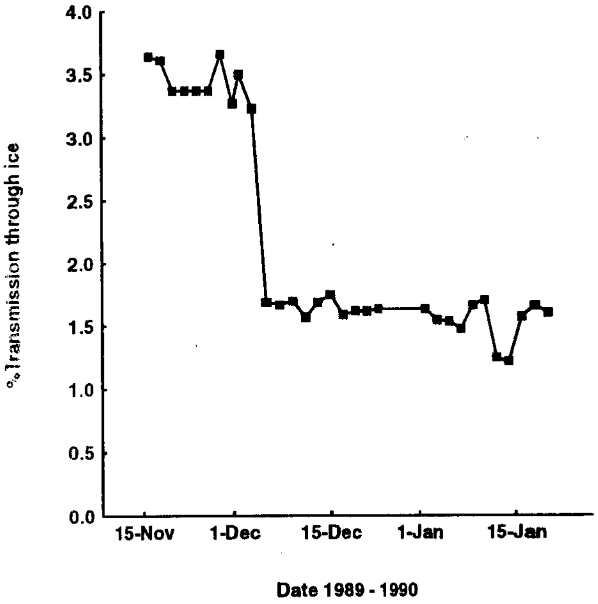

Fig. 3. Percent transmission of PAR through ice on Lake Bonney between November 1989 and January 1990 [redrawn from *Priscu*, 1991]. Transmission was computed from daily averages in PAR.

percent transmission dropped from 3.2 to 1.7% and attenuation increased from 0.8–0.98 m^{-1} in a week, coincident with visual observations of ice surface fracturing on lake Bonney (Figure 3) [*Priscu*, 1991]. Transmission apparently declined because of hoarfrost formation within near surface bubbles and fracturing along the grain boundaries of individual ice crystals with increasing ice temperature [*Adams et al.*, this volume].

Our data for Lake Vanda also show a distinct seasonal change with transmission declining from 21% in September to 13% by mid summer and increasing again in January. As in the case of Lake Bonney, visual observations showed a change in ice appearance from blue in October/November to white in December, suggesting seasonal changes in light scattering.

Detailed analysis of the ice cover of Lake Hoare suggests that the decreased transparency is also due to deep warming of the ice and to the formation of light scattering Tyndall figures [*Mae*, 1975; *Walker*, 1986; *McKay et al.*, 1994]. Visual changes to the ice may be the "whitening" or apparent fine fracturing which occurs at this time as noted above for Lakes Bonney and Vanda.

Seasonal changes in transparency may follow a predictable sequence [*McKay et al.*, 1994]. Early in the season, ice is cold, completely frozen and percent transmission is at its highest. With increased radiative heating and Tyndall figure formation, scattering and internal absorption increase thereby reducing transmission. As summer progresses, ice melts and destroys the fine cracks and other scattering "structures" [see *Adams et al.*, this volume] and transmission increases. As winter approaches, ice temperature declines, cracks and fissures reappear and transmission decreases. Transmission varied over the summer in Lake Hoare by a factor of three.

INFLUENCE OF SNOW COVER

Snow cover on ice can significantly increase light attenuation. Thin snow cover (18 mm) on sea ice at McMurdo Sound has been shown to reduce transmission of all wavelengths in the PAR spectrum to 30% [*Trodahl and Buckley*, 1990]. Snow cover, with its high albedo, has been shown to be a major contributor to attenuation of light in ice covered maritime Antarctic lakes [*Hawes*, 1985] and in sub-Arctic lakes [*Adams*, 1978; *Roulet and Adams*, 1984; *Bolsenga et al.*, 1996]. However persistent snow cover is rare on most dry valley lakes and mainly affects underwater light regimes by increasing spatial and temporal variability (patchiness). Spatial variability in snow cover can result in an overestimation of average PAR transmission to the underlying water column if not corrected for [*Roulet and Adams*, 1984].

SPECTRAL INFLUENCE OF THE ICE COVER

Spectral Reflectance

Spectral reflectance for clear and white ice varies little over the PAR wavelengths [*Grenfell and Maykut*, 1977; *McKay et al.*, 1994], although for blue ice we have recorded a significant reduction in spectral reflectance between 500 and 700 nm (Figure 2). Albedo depends mostly on the amount of sediment in the ice [*McKay et al.*, 1994], the degree of fracturing [*Adams et al.*, this volume] and on whether the ice is smooth or irregular [*Goldman et al.*, 1967]. High sediment content reduces albedo, while fracturing and irregular surfaces lead to high values.

Spectral Attenuation and Transmission

Pure ice transmits in the blue region of the spectrum and strongly absorbs at wavelengths greater than 600

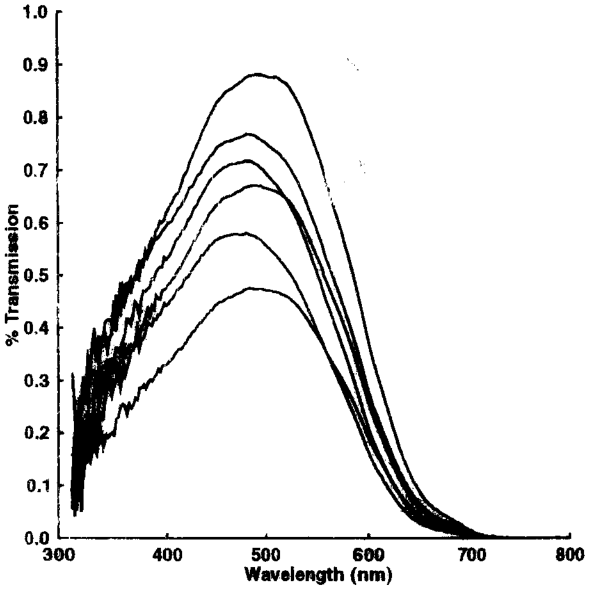

Fig. 4. Percent transmission through ice on Lake Hoare in December 1996 for the waveband 300–800 nm. Spectra were collected in clear sky conditions at six different positions by divers operating an LI 1800 spectroradiometer on the undersurface of the ice, well away from the dive hole.

nm. Maximum light transmission through the ice covers of lakes Hoare and Joyce occurred between 450 and 490 nm (Figure 4), consistent with earlier studies based on instruments with broad bandpass filters [*Palmisano and Simmons,* 1987; *Lizotte and Priscu,* 1992a; *Vincent,* 1988]. There is considerable variability in downward irradiance in the 450–550 waveband at different positions on Lake Hoare (Figure 4), further illustrating the patchiness in light transmission through an ice cover.

Seasonal changes in ice transparency described above have an influence on the spectral properties of the transmitted light [*Wharton et al.,* 1989]. Between November and January transmitted light in the waveband 400–600 nm declined relative to that at 700 nm probably due to increased scattering of blue light brought about by fracturing. Although the specific absorbance of red light by ice is much greater than that of blue light, short wavelengths are more subject to scattering.

It is interesting to note that seasonal changes in UV transparency of sea ice may be more marked than for PAR [*Trodahl and Buckley,* 1990]. Early season ice (when, incidentally, the ozone hole is at its maximum) is usually highly transparent to UV. High transparency at this time is due to low scattering, and short wavelength UV light is more prone to scattering than longer wavelengths. Although such studies are yet to done on dry valley lakes, we anticipate that scattering may also significantly influence UV transmittance through lake ice with a high early season UV transparency that reduces as ice fracturing increases.

THE WATER COLUMN

Bulk Attenuation

Gross differences in attenuation between the lakes can be summarized by the integrated water column attenuation coefficients for downwelling irradiance (K_d) and for scalar irradiance (K_o). Despite changes in instrumentation which affect estimations of irradiance [*Kirk,* 1994], comparisons of the relatively long term records for the lakes (1963-1996) suggest that attenuation coefficients vary more as a function of time and lake than as a result of instrumentation. Table 3 provides a compilation of attenuation coefficients for the lakes at different times and depths.

The lakes can be arranged on a gradient of attenuation coefficient from lowest to highest as follows: Vanda, Miers, Bonney, Hoare, Fryxell, Wilson. The data from Lake Wilson are based on one series of measurements taken in January [*Webster et al.,* 1996] and the extent of seasonal variability for this lake is not known. Coefficients span an order of magnitude among lakes from extreme clarity at Lake Vanda (K_d <0.05 m^{-1}) to relatively turbid Lake Wilson (K_d = 0.8 m^{-1}). Considerable variation in attenuation with depth is recorded (Table 3) because of discrete layers of attenuating materials. Attenuation coefficients measured over small depth intervals are particularly unreliable as indicators of integral attenuation in vertically structured lakes such as these. For example, although Hoare is considered to be more transparent than Fryxell [*Lizotte and Priscu,* 1992a], there have been higher values of K_o recorded in some layers in the former (Table 3).

Temporal Changes in Attenuation

There is little consistent evidence of a seasonal change in integral water column attenuation in dry valley lakes (Table 3). Attenuation in Lake Vanda, from just below the ice to 40 m, varied more between years than within a summer season (October-February). Data obtained with the same instrumentation show that K_o in 1993-1994 averaged 0.053 m^{-1} with a range of

0.046–0.060 (Table 3), as compared to 1995-1996 when it averaged 0.036 m^{-1} (range 0.033–0.037). Although K_0 increased to a maximum in late December 1993 in Lake Vanda this pattern was not evident in data from other years, nor could it be explained by changes in biotic attenuation as evidenced by chlorophyll-*a* concentration. In the upper layers of Lake Fryxell (5–12m) there was a gradual seasonal increase in attenuation in the water column from 0.528 to 0.621 between November 15, 1994 and January 18, 1995. Over the same period attenuation increased in the west lobe of Lake Bonney from 0.170 on November 6, 1994 to 0.214 on December 21, 1994 (Priscu, unpublished data). These increases are consistent with the period of glacial stream flow into the lakes.

The differences between years in Lake Vanda (Table 3) may be associated with small differences in chlorophyll-*a* and inorganic turbidity. Turbidity may be caused by the inflow from the Onyx River, which has a suspended solids concentration ranging from 2.7 to 130 mg m^{-3} [*Howard-Williams et al.*, 1986]. The Onyx River has a considerable effect on the water in the Lake Vanda moat at the east end of the lake. This area becomes markedly turbid following the onset of flow of the river. For instance, in 1993 at the time of initial river flow on January 1 there was no significant moat and the water beneath the seasonal moat ice had a K_d of 0.04 m^{-1}. By January 15 this had risen by a factor of six to 0.24 m^{-1}. However the river water remains largely confined to the moat and consequently has little effect on light attenuation within the main water body. The tendency for the inflowing river water to follow the moat is consistent with similar observations in Lake Fryxell [*McKnight and Andrews*, 1993]. The influence of meltwater streams is likely to be most marked in Lake Wilson. Here, the single large inflow stream in 1993-1994 was highly turbid, with a suspended solids concentration of glacial flour reaching 40 g m^{-3}; the lake had no moat during this period [*Webster et al.* 1996].

Reflectance

Reflectance [E_u (PAR)/E_d (PAR)] in Lakes Vanda, Bonney and Wilson ranges from 0.062 to 0.17. These values are all high and even in highly transparent Lake Vanda values have been recorded ranging from 0.062 to 0.092. Reflectance is largely from suspended inorganic material, and is usually higher in waters containing glacial flour than in other natural waters [*Howard-Williams and Vincent,* 1984]. It is likely to be a seasonally varying attribute, governed by the extent of river inflows. Of the dry valley lakes, Lake Wilson is the only one where a high suspended sediment (mostly glacial flour) concentration of up to 5.6 g m^{-3} has been recorded in the lake at a period of low river inflows [*Webster et al.,* 1996]. This compares with a concentration of <0.1 g m^{-3} in Lake Vanda throughout summer (authors' unpublished data). Not suprisingly Lake Wilson is the most turbid site, with a reflectance of 0.17.

Spectral Attenuation

Comparisons of spectral data obtained with a Biospherical Instruments MER 1000 spectroradiometer for Lakes Bonney, Hoare, and Fryxell [*Palmisano and Simmons,* 1987; *Lizotte and Priscu,* 1992a] with our data and those of *Vincent and Vincent* [1982] and *Goldman et al.* [1967] for Lake Vanda are presented as spectral attenuation coefficients ($K_d(\lambda)$) for three wavelengths in Table 4. Spectral attenuation coefficients across the PAR waveband for Lakes Hoare and Joyce are shown in Figure 5. These data were obtained using a diver operated LiCOR LI 1800 scanning spectroradiometer suspended 0.5 and 4.5 m below the ice cover. The most penetrating wavebands for Lakes Hoare and Joyce were for green light (490–500 nm) (Figure 5). A noticeable difference between the lakes was the relatively low attenuation at wavelengths below 470 nm in Lake Joyce compared to that in Lake Hoare. In Lake Fryxell, maximum penetration was between 520 and 580 nm [*Palmisano and Simmons,* 1987] whereas Lake Bonney passes blue-green light with the most penetrating waveband between 480 and 520 nm. Although full spectral data are not available for Lake Vanda the analyses with optical filters suggests that blue wavelengths (midpoint 420 nm) penetrate deeply (Table 4). With an attenuation coefficient at 420 nm of 0.066 m^{-1} , Lake Vanda is considerably more transparent to blue light than either Lakes Hoare or Joyce (cf. Figure 5).

Red light is strongly attenuated by the ice cover (see above) and the spectral composition of the PAR immediately beneath the ice is blue and green light (Figure 4). *Lizotte and Priscu* [1992a] suggested that the marked reduction of far red light (*ca.* 680 nm) under the ice means that natural fluorescence by phytoplankton at 683 nm will become an important source of long wavelengths at depth. This effect can be seen in a comparison of spectral scans for upward and downward irradiance flux in Lake Hoare (Figure 6). There is a

TABLE 3. Attenuation Coefficients for Discrete Depths in the Water Column.

Lake	Year	Depth (m)	K_o	K_d	Method*	Reference
Vanda	Jan-63			0.049	p	*Goldman et al.*, 1967
	Jan-63			0.042	p	*Goldman et al.*, 1967
	Feb-63			0.041	p	*Goldman et al.*, 1967
	Dec-80			0.050	c	*Vincent and Vincent*, 1982
	1980-1981			0.055	c	*Kasper et al.*, 1982
	Nov-93	3.5–40	0.055	0.052	s,c	This study
	Dec-93	3.5–40	0.060	0.05	s,c	This study
	Jan-94	3.5–40	0.051	0.055	s,c	This study
	Nov-94	3.5–40	0.033	0.04	s,c	This study
	Dec-94	3.5–40	0.045	0.05	s,c	This study
	Sep-95	3.5–40	0.035		s	This study
	Oct-95	3.5–40	0.036		s	This study
	Jan-96	3.5–40	0.037	0.034	s,c	This study
Hoare	Dec-82			0.164	p	*Parker et al.*, 1982
	Nov-94	4.5–22	0.127		s	This study
	Dec-94	5–22	0.219		s	This study
	Dec-94	4.5–22	0.173		s	This study
	Dec-94	4.5	0.420		PNF	This study
	Dec-94	11	0.120		PNF	This study
	Jan-95	4.5–22	0.216		s	This study
	Dec-96	10–18		0.17	c	This study
Fryxell	Nov-79	5–7.5		0.074	c	*Vincent*, 1981
	Nov-79	7. 5–9.5		0.250	c	*Vincent*, 1981
	Dec-90	7	0.275		s	*Lizotte and Priscu*, 1992
	Dec-90	8.5	0.352		s	*Lizotte and Priscu*, 1992
	Nov-94	5–11.5	0.528		s	This study
	Dec-94	5–12	0.549		s	This study
	Jan-95	5–12	0.621		s	This study
Bonney (west lobe)	Jan-63			0.141	p	*Goldman et al.*, 1967
	Nov-82			0.158	c	*Parker et al.*, 1982
	Nov-94	4.5–20		0.102	c	This study
	Dec-94	4.5–20		0.095	c	This study
	Jan-95	4.5–20		0.127	c	This study
Bonney (east lobe)	Nov–82			0.138	p	*Parker et al.*, 1982
	Dec–89	5–12	0.120		s	*Lizotte and Priscu*, 1992b
	Dec-89	12–20	0.106		s	*Lizotte and Priscu*, 1992b

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* The method of collection is indicated by p = irradiance photometer; s =scalar sensor; c = cosine corrected PNF = Biosphereical Instruments Corp. Profiling natural fluorometer.

TABLE 3. Attenuation Coefficients for Discrete Depths in the Water Column.

Lake	Year	Depth (m)	K_o	K_d	Method*	Reference
	Nov-90	6	0.143		s	*Lizotte and Priscu*, 1992
	Dec-90	6	0.138		s	*Lizotte and Priscu,* 1992
	Jan-91	6	0.246		s	*Lizotte and Priscu,* 1992
	Nov-90	10	0.094		s	*Lizotte and Priscu,* 1992
	Dec-90	10	0.107		s	*Lizotte and Priscu,* 1992
	Jan-91	10	0.195		s	*Lizotte and Priscu*, 1992
	Nov-90	17	0.118		s	*Lizotte and Priscu*, 1992
	Dec-90	17	0.109		s	*Lizotte and Priscu,* 1992
	Jan-91	17	0.125		s	*Lizotte and Priscu,* 1992
	Nov-94	4.5–22	0.095		s	This study
	Dec-94	4.5–22	0.095		s	This study
	Jan-95	4.5–22	0.127		s	This study
Wilson	Jan-93		0.800		c	*Webster et al.*, 1996
Miers	Jan-95		0.110		PNF	This study

TABLE 4. Spectral Values for Downward Attenuation.

Lake	Date	Depth (m)	Spectral K_d Values			Wavelength of most penetrating waveband	Reference
			440	520	680		
Vanda	Jan-63		0.038	0.055			*Goldman et al.*, 1967
	Jan-63		0.035	0.06			*Goldman et al.*, 1967
	Feb-63		0.031	0.058			*Goldman et al.*, 1967
	Dec-80		0.04	0.06	0.46		*Vincent and Vincent*, 1982
	Dec-93		0.056	0.085	0.712		This study
	Dec-94		0.051	0.039			This study
	Dec-94		0.066	0.07			This study
Hoare	Dec-82	6–14	0.418	0.282	0.715	515–542	*Palmisano and Simmons*, 1987
	Dec-82	3.7–6	0.372	0.271	0.625	515–542	*Palmisano and Simmons*, 1987
	Dec-82	2.7–9.8	0.264	0.241	0.486		*Palmisano and Simmons*, 1987
Fryxell	Dec-90	6–9	0.72	0.4	0.59	520–580	*Lizotte and Priscu,* 1992

Data from *Goldman et al.* (1967) were obtained using optical filters of 420 nm and 540 nm. *Vincent and Vincent* (1982) used optical filters with mid-points at 440, 520, and 680 nm. Remaining data were obtained using a MER 1000 Biospherical Instruments spectroradiometer with a band width of 10 nm.

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* The method of collection is indicated by p = irradiance photometer; s =scalar sensor; c = cosine corrected PNF = Biosphereical Instruments Corp. Profiling natural fluorometer.

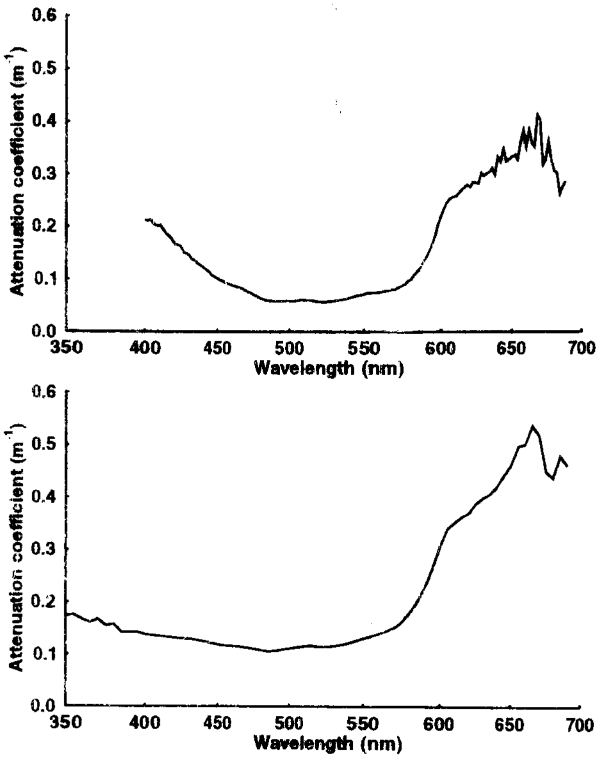

Fig. 5. Spectral attenuation coefficients for the upper 5m of the water columns of (A) Lake Hoare, and (B) Lake Joyce in December 1996. Data were collected as for Figure 4, with the instrument deployed at 4.5 and 9.5 m.

distinct peak in upward irradiance above 650 nm and centered on 680 nm. Reflectance at 680 nm was 0.35, consistent with a high proportion of red light due to chlorophyll-*a* fluorescence. The effect may be compounded by Raman emission, which occurs when predominantly blue-green downward irradiance undergoes a change to longer wavelengths when scattered [*Marshall and Smith,* 1990]. Raman emission shows up as an emission band roughly 100 nm on the long wavelength side of the exciting wavelength [*Kirk,* 1994]. However the position of the peak situated at 680 nm suggests that chlorophyll-*a,* rather than Raman emission dominates. In situ "production" of red light in the water column may be measurable in many other ice capped polar lakes and seas when ice covers are thick and the availability of red light from sunlight is negligible. Spectral reflectance data for Lake Hoare calculated from the data in Figure 6 shows a distinct peak centered around 680 nm, consistent with phytoplankton fluorescence and not Raman emission. Red light emission processes may explain the apparent decrease in spectral attenuation above 650 nm (Figure 5a) in Lake Hoare.

Scattering and Absorption

The relative importance of scattering and absorption in lake water can be assessed by comparing their respective coefficients [*Kirk,* 1994]. Scattering coefficients (b) for the upper waters of three dry valley lakes are generally higher than the absorption coefficients (a) (Table 5). The ratio of scattering to absorption was between 6.4 and 7.6 in Lakes Vanda and Fryxell, and between 2 and 4.8 in Lake Bonney (Table 5). In general, absorption coefficients of Antarctic lake waters are lower than those recorded for even alpine or high Arctic sites, and the small particle size of glacial flour will impart a high specific scattering coefficient [*Kirk,* 1994]

Factors Affecting Attenuation

Constituents of the water column such as phytoplankton, dissolved organic matter (yellow color), non-algal particulates as well as the water itself, influence absorption and scattering coefficients, which in turn determine the apparent optical properties such as K_d [*Kirk,* 1994]. In Lakes Bonney and Fryxell absorption was typically dominated by water (38–75%) with phytoplankton usually secondary (11–47%) and a

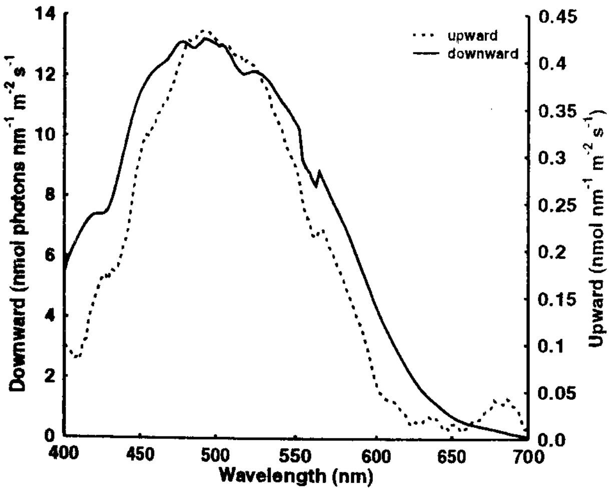

Fig. 6. Spectral scans of upward and downward irradiance (E_u (λ) and $E_d(\lambda)$) at a depth of 5.5 m in Lake Hoare (December 1996). Slight irregularities in the original scans have been smoothed by plotting the running averages over 10 nm band widths. Data were collected as for Figure 4.

TABLE 5. Absorption (a) and Scattering (b) Coefficients for the Upper Water Layers of Three Dry Valley Lakes.

Lake	Date	Depth	Coefficient			
			a	b	b/a	
Vanda	1994-1995	5	0.014	0.103	7.45	This study
	1994-1995	12	0.023	0.173	7.45	This study
	1994-1995	25	0.021	0.162	7.6	This study
	1994-1995	30	0.022	0.167	7.45	This study
	1994-1995	40	0.02	0.13	6.5	This study
Fryxell	Dec. 1990		0.151	0.971	6.4	*Lizotte and Priscu,* 1992
	Dec. 1990		0.184	1.313	7.1	*Lizotte and Priscu,* 1992
Bonney (east lobe)	Nov. 1990	6	0.096	0.365	3.8	*Lizotte and Priscu,* 1992
	Dec.1990	6	0.098	0.316	3.2	*Lizotte and Priscu,* 1992
	Jan. 1991	6	0.205	0.402	1.9	*Lizotte and Priscu,* 1992
	Nov.1990	10	0.065	0.227	3.8	*Lizotte and Priscu,* 1992
	Dec. 1990	10	0.066	0.32	4.8	*Lizotte and Priscu,* 1992
	Jan. 1991	10	0.124	0.554	4.46	*Lizotte and Priscu,* 1992
	Nov. 1990	17	0.081	0.288	3.55	*Lizotte and Priscu,* 1992
	Dec. 1990	17	0.08	0.224	2.8	*Lizotte and Priscu,* 1992
	Jan. 1991	17	0.086	0.308	3.6	*Lizotte and Priscu,* 1992

variable contribution from dissolved organic matter (0.46%) [*Lizotte and Priscu,* 1992a]. In Lake Vanda the contributions to the absorption coefficient at 440 nm in the upper 20m of the water column showed that absorption was also dominated by water (54%) although particulate matter was more important (44%) than chlorophyll-*a* (1.2%). Although chlorophyll-*a* is the dominant pigment [*Lizotte and Priscu,* this volume], it is only one in an assemblage of different pigments in the phytoplankton [*Hoepffner and Sathyendranath,* 1992] and so may slightly underestimate the proportional contribution by phytoplankton. An analysis of absorbance due to dissolved organic matter (g_{440}) was carried out on samples collected in January 1996 in Lake Vanda and December 1996 in Lakes Hoare and Joyce. Dissolved organic matter (g_{440}) was not detectable in Lake Vanda at 10 and 38 m, and was 0.06 m^{-1} at 63 m depth. Values were slightly higher in Lakes Joyce (0.10–0.12 m^{-1} to 10 m depth) and Lake Hoare (0.15–0.25 m^{-1} to 16 m). Analysis of the 63 m data in Lake Vanda showed that dissolved color estimated by g_{440} contributed less than 1% to total absorption at 440 nm and will be less than this higher in the water column. This is consistent with a vegetation free catchment and little internal generation of DOC. The situation in Lake Vanda contrasts with Lake Fryxell and Bonney, where internal generation of DOC can be high despite a vegetation free catchment [*McKnight et al.,* 1991; *Lizotte and Priscu,* 1992a].

Optical Structure of the Water Column

Chemically stratified lakes are often characterized by layers of particulate and dissolved material associated with density layers. In the ice covered lakes of the dry valleys discrete density layers are particularly marked [*Spigel and Priscu,* 1996 and this volume]. Of the factors known to affect water clarity in such layers, chlorophyll-*a* is perhaps the most dynamic. Within Lake Vanda two well defined convection cells are found, one from 5–25 m depth and the other from 31–45 m depth [*Spigel and Priscu,* this volume]. The lower of these tends to have a slightly higher chlorophyll-*a* concentration than the upper. Well defined Deep Chlorophyll Maxima (DCM) are particularly well developed in Lakes Bonney, Fryxell, and

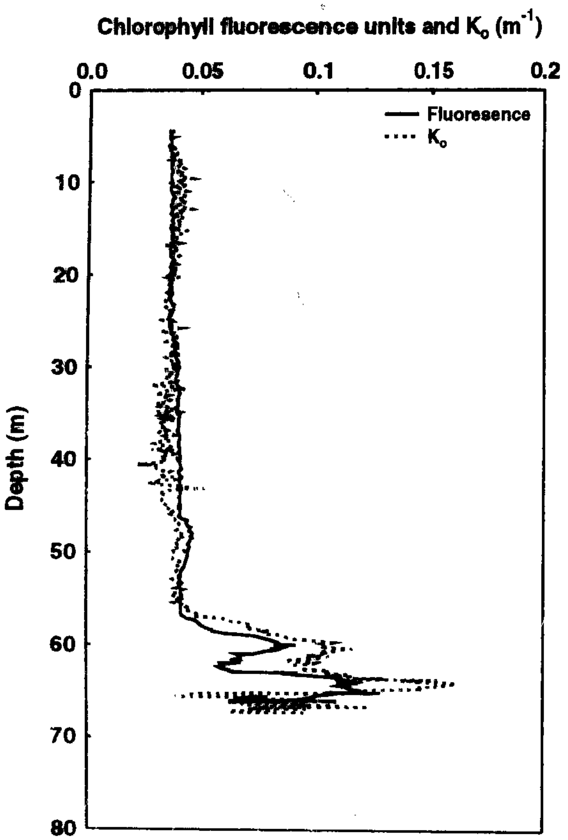

Fig. 7. Attenuation (K_0, dotted line) and upwelling natural chlorophyll-*a* fluorescence (relative units, solid line) over the depth profile in Lake Vanda. Data were obtained with a Biospherical Instruments Corp. PNF 300 profiler.

Vanda [*Vincent,* 1982; *Vincent and Vincent,* 1981; *Lizotte and Priscu,* 1992b; *Lizotte et al.,* 1996] usually associated with stable non-convecting layers where gradients of nutrients are sharp. The increased chlorophyll *a* and associated particulate matter in the DCM layers have a marked effect on attenuation of PAR.

The influence of the DCM on fine scale (30 cm) structure of K_0 in Lake Vanda is well illustrated in Figure 7, which shows chlorophyll-*a* fluorescence, measured using a Chelsea Instruments in situ fluorometer, and K_0, measured using a Biospherical Instruments PNF300 profiling fluorometer, with depth. The break between the upper and lower convecting cells at 25–30 m is evident in the fluorescence trace. Below 45 m vertical structure is more marked. The small fluorescence peak at 50 m, and the double peak in fluorescence at 60–65 m, was closely mirrored by K_0, which increased from 0.055 to 0.12 between 60 and 65 m. Not suprisingly, beam transmission in Lake Vanda (Figure 8) followed a similar but reciprocal pattern. In all cases vertical structure apparently recorded an increase in phytoplankton biomass in the DCM at 60–65 m depth. Sharp reductions in transmittance below 67 m depth may reflect the high biomass of non-chlorophyll containing bacteria [*Vincent,* 1988] or mineral precipitates (e.g., Fe and Mn-oxyhydroxides) at the oxycline [*Webster,* 1993; *Green et al.,* this volume].

In both lobes of Lake Bonney, chlorophyll-*a* appears to structure the K_0 profile within the trophogenic zone (Figure 9a, b). The general pattern down to 12 m follows that of the chlorophyll-*a* profile reported by *Lizotte and Priscu* [1994] and *Priscu* [1995] with maxima at 5 m and 12 m. The K_0 maximum near 25 m in the east lobe of Bonney (Figure 9a) reflects a non-photosynthetically active chlorophyll layer located below the chemocline, whereas the K_0 maximum at 24 m in the west lobe (Figure 9b) is caused by non-chlorophyllous matter (Priscu, unpublished). Not all dry valley lake exhibits a vertical zonation of optical properties. For example, Lake Miers shows relatively little optical structure in the water column

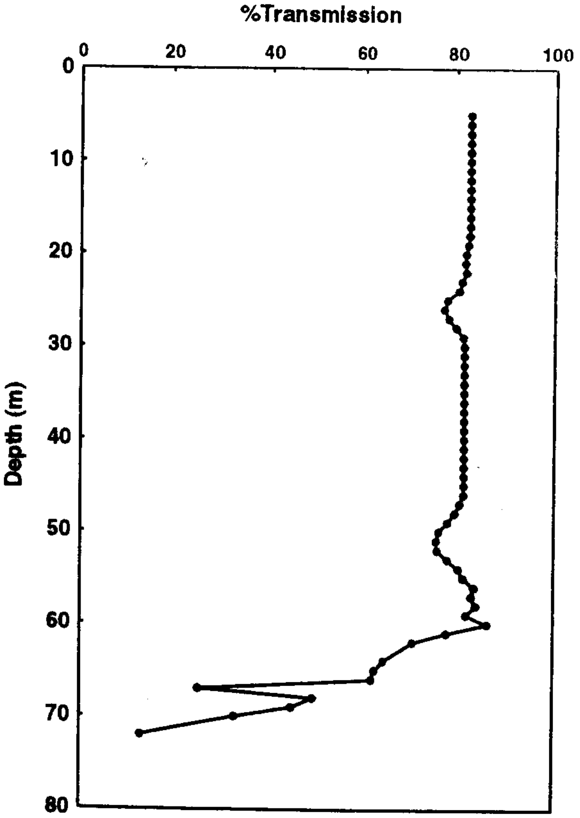

Fig. 8. Vertical profile of beam transmission in Lake Vanda measured at 1 m intervals.

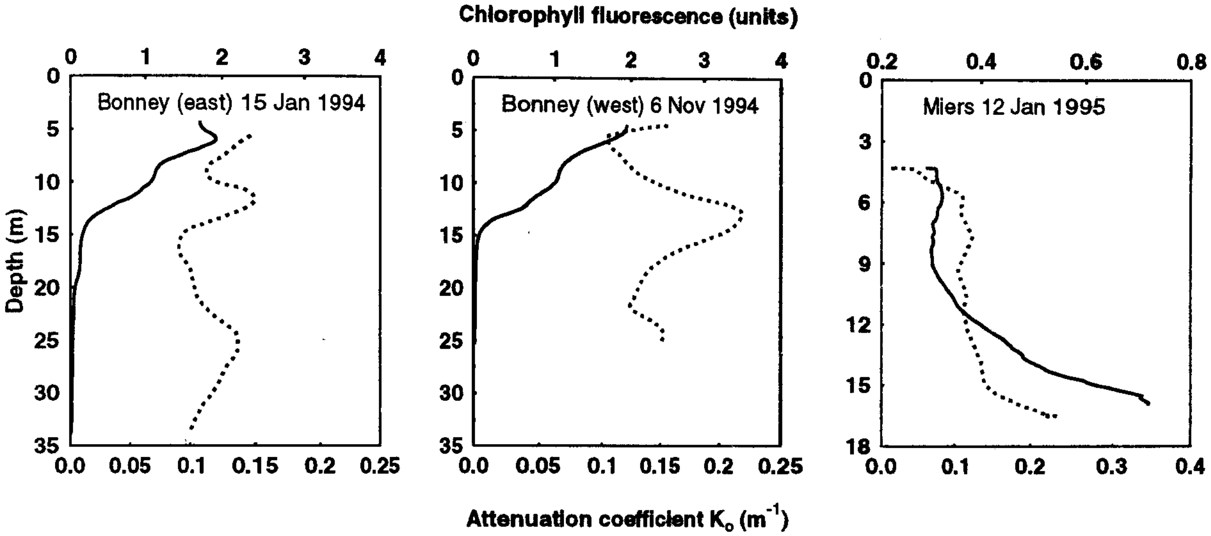

Fig. 9. Attenuation (K_0, dotted line) and upwelling natural chlorophyll-*a* fluorescence (solid line) in Lake Bonney (east lobe), Lake Bonney (west lobe) and Lake Miers. K_0 is in ln units m^{-1}; fluorescence is in relative units. Data were collected as for Figure 7.

(Figure 9c) with K_0 values remaining constant from 5 to 15 m, increasing gradually below this depth. Lake Miers also has little structure to its chlorophyll-a to a depth of 10 m, but shows a gradual increase in concentration with depth below this (Figure 9c).

IMPLICATIONS FOR PHOTOTROPHS

The optical properties of the ice cover and water columns of the McMurdo Dry Valley lakes regulate the quantity and quality of light which penetrates to a given depth. Ice cover has been shown to have an overwhelming effect in the amount of light which is present in these lakes, reducing incident PAR to 1–13% leading to the development of shaded aquatic ecosystems. The ice cover effects the spectral distribution of the PAR reaching the water column by effectively eliminating red light. The success of phototrophs under such conditions will depend on the efficiency with which they can capture and utilize available quanta [*Neale and Priscu*, 1995; *Neale and Priscu*, this volume; *Seaburg et al.*, 1983].

Low intensity of light available under ice selects for shade adapted phytoplankton and benthic algae [*Priscu*, 1989]. *Hawes and Schwarz* [in press] described the photosynthesis-light relationships of benthic algal/cyanobacterial mats and reported saturation light intensities in the region of 2–5% of incident irradiance. *Vincent* [1981] showed that photosynthesis of phytoplankton from Lake Fryxell (9 m) saturated at less than 1% incident irradiance and those from Lake Bonney require only 15–45 μmol photons m^{-2} s^{-1}, equivalent to approximately 2–8% of average daily incident PAR [*Lizotte and Priscu*, 1992b]. Despite the high degree of shade adaptation seen in these organisms, algal photosynthesis is rarely light saturated [*Vincent*, 1981; *Lizotte and Priscu*, 1992b].

Primary producers in the dry valley lakes appear to be specially adapted to utilize the under-ice spectrum [*Neale and Priscu*, 1995; *Neale and Priscu*, this volume]. The benthic communities are characterized by a high proportion of cyanobacterial taxa [*Hawes and Schwarz*, in press], which typically contain high concentrations of phycobilin pigments. High phycobilin contents have been observed in planktonic cyanobacteria in Lake Vanda, evident as a red-pink coloration seen under microscopic examination of fresh material. Phycobilins absorb maximally at 400–500 nm [*Rowan*, 1989], and are well adapted for harvesting the green light which penetrates the ice. *Vincent and Vincent* [1982] also commented on the possible significance of light quality on the relative distribution of the yellow pigmented alga *Ochromonas* immediately beneath the ice in Lake Vanda and the red pigmented *Chroomonas* at depth.

Despite the physical characteristics of the dry valley lakes that position them as end members of a limnological spectrum, there is still considerable variability among the lakes. A characteristic is the vertical structure in optical properties imposed by a series of attenuating layers. The topmost is the thick ice cover, which removes between 87 and 99% of incident PAR depending on the lake. Scattering is the dominant attenuating process within the ice. Selective removal of red light results in a spectral shift in the light transmitted to the water columns to predominantly shorter wavelengths. Attenuation by ice is variable and dependent on ice thickness, structure, and sediment content. Stable water columns, due to a lack of wind mixing under the ice, combined with meromixis confine phytoplankton populations to discrete depth layers each with its characteristic light spectrum. Phytoplankton and benthic autotrophs in dry valley lakes may be expected to be highly sensitive to light quality. Water column attenuation can vary by an order of magnitude due to differences in phytoplankton biomass and suspended solids concentration. The ratio of light scattering to absorption is high due to fine glacial flours which effectively scatter light, rather than to high concentrations of suspended solids per se. Relative to temperate and Arctic lakes, absorption is likely to play a smaller role in overall light attenuation because of the low concentrations of DOC in the inflowing waters. However the evidence shows that internally generated DOC from lake communities is significant at certain depths in some of the lakes (Lakes Fryxell and Bonney) further imposing a layered structure to the optical properties.

It is clear that light penetration is a key influence on primary production and consequently carbon production in these cold desert ecosystems. Owing to the tight association between light availability and primary production, these aquatic ecosystems are, perhaps more than most others, driven by their optical properties.

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REFERENCES

Adams, W. A., Effects of ice cover on the solar radiation regime in Canadian lakes. *Verh. Int. Ver. Limnol. 20,* 142–149, 1978.

Adams, E. E., J. C. Priscu, C. F. Fritsen, S. R. Smith and S. L. Brackman, Permanent ice covers of the McMurdo Dry Valley lakes, Antarctica: Bubble formation and metamorphism, this volume.

Bolsenga, S.J., M. Evans, H.A. Vanderploeg, and D.G. Norton, PAR transmittance through thick, clear freshwater ice. *Hydrobiologia 330*, 227–230, 1996.

Buckley, R. G. and H. J. Trodahl, Scattering and absorption of visible light by sea ice, *Nature, 326,* 867–869, 1987.

Dana, G.L., R.A. Wharton Jr., and T. Dubayah, Solar radiation in the McMurdo Dry Valleys, Antarctica, this volume.

Conovitz, P.A., D.M. McKnight, L.M. McDonald, A. Fountain, and H.R. House, Hydrologic processes influencing streamflow variation in Fryxell Basin, Antarctica, this volume.

Fritsen, C. H., E. E. Adams, C. P. McKay, and J. C. Priscu. Permanent ice covers of the McMurdo Dry Valley lakes, Antarctica: Liquid water content, this volume.

Goldman, C. R., D. T. Mason, and J. E. Hobbie, Two antarctic desert lakes, *Limnol. and Oceanogr., 12,* 295–310, 1967.

Grenfell, T. C., and G. A. Maykut, The optical properties of ice and snow in the Arctic Basin. *J Glaciol 18,* 445–463, 1977.

Hawes, I., Light climate and phytoplankton photosynthesis in maritime Antarctic lakes, *Hydrobiologia 123*, 69–79, 1985.

Hawes, I., and A-M. Schwarz, Photosynthesis in benthic cyanobacterial mats from Lake Hoare, Antarctica, *Antarctic J. of the US,* in press.

Hoepffner, N., and S. Sathyendranath, Bio-optical characteristics of coastal waters: absorption spectra of phytoplankton and pigment distribution in the Western North Atlantic. *Limnol. Oceanogr. 37,* 1660–1679, 1992.

Howard-Williams, C., and W.F. Vincent, Optical properties of New Zealand lakes I: attenuation, scattering, and a comparison between downwelling and scalar irradiances, *Arch Hydrobiol. 19,* 318–330, 1984.

Howard-Williams, C., C. L. Vincent, P. A. Broady, W. F. Vincent, Antarctic stream ecosystems: variability in environmental properties and algal community structure. *Int. Revue ges. Hydrobiol., 71,* 511–544, 1986.

Hutchinson, G. E., *A Treatise on Limnology. I. Geography, Physics and Chemistry*. New York, John Wiley and Sons Inc. 1015 pp, 1957.

Kirk, J. T. O., *Light and Photosynthesis in Aquatic Ecosystems*. 2nd Edition, Cambridge University Press, Cambridge, 509 pp, 1994.

Lizotte, M. P., and J. C. Priscu, Spectral irradiance and bio-optical properties in perennially ice-covered lakes of the dry valleys (McMurdo Sound, Antarctica). Contributions to Antarctic Research III, *Antarctic Research Series, 57,* 1–14, American Geophysical Union, Washington, D.C., 1992a.

Lizotte, M. P., and J. C. Priscu, Photosynthesis-irradiance relationships in phytoplankton from the physically stable water column of a perennially ice-covered lake (Lake Bonney, Antarctica), *J. Phycol. 28,* 179–185, 1992b.

Lizotte, M. P., and J. C. Priscu, Natural fluorescence and quantum yields in vertically stationary phytoplankton from perennially ice-covered lakes. *Limnol. Oceanogr. 39,* 1399–1410, 1994.

Lizotte, M. P. and J. C. Priscu, Pigment analysis of the McMurdo Dry Valley lakes of Antarctica, this volume.

Lizotte, M. P., T. R. Sharp, and J. C. Priscu, Phytoplankton dynamics in the stratified water column of Lake Bonney, Antarctica. I: biomass and productivity during the winter-spring transition, *Polar Biol. 16,* 155–162, 1996.

Mae, S., Tyndall figures at grain boundaries of pure ice, *Nature 257,* 382–383, 1975.

Marshall, B. R., and R. C. Smith, Raman scattering and in-water ocean optical properties, *Appl. Opt. 29*, 71–84, 1990.

McKay, C. P., G. D. Clow, D. T. Anderson, and R. A. Wharton Jr., Light transmission and reflection in perennially ice-covered Lake Hoare, Antarctica, *J. Geophys. Res. 199,* 20,427–20,444, 1994.

McKnight, D. M. and E. D. Andrews, Hydrologic and geochemical processes at the stream-lake interface in a permanently ice-covered lake in the McMurdo dry valleys, Antarctic, *Verh. Internat. Verein. Limnol. 25,* 957–959, 1993.

McKnight, D. M., G. R. Aiken, and R. L. Smith, Aquatic fulvic acids in microbially based ecosystems - results from two desert lakes in Antarctica, *Limnol. Oceanogr. 36,* 998–1006, 1991.

McKnight, D. M., A. Alger, C. Tate, G. Shupe, and S. Spaulding, Longitudinal patterns in algal abundance and species distribution in meltwater streams in Taylor Valley, Southern Victoria Land, Antarctica, this volume.

Neale, P. J., and J. C. Priscu, The photosynthetic apparatus of phytoplankton from a perennially ice-covered Antarctic lake: acclimation to an extreme shade environment, *Plant Cell Physiol. 36,* 253–263, 1995.

Neale, P.J. and J.C. Priscu, Fluorescence quenching in phytoplankton of the McMurdo Dry Valley Lakes (Antarctica): implications for the structure and function of the photosynthetic apparatus, this volume.

Palmisano, A., and G. M. Simmons Jr., Spectral downwelling irradiance in an Antarctic lake, *Polar Biol. 7,* 145–151, 1987.

Priscu, J. C., Photon dependence of inorganic nitrogen transport by phytoplankton on perennially ice-covered antarctic lakes, *Hydrobiologia, 172,* 173–182, 1989.

Priscu, J. C., Variation in light attenuation by the permanent ice cap of Lake Bonney during spring and summer, *Ant. J. of the U.S.,* 223–224, 1991.

Priscu, J. C., Phytoplankton nutrient deficiency in lakes of the McMurdo Dry Valleys, Antarctica. *Freshwat. Biol. 34,* 215–227, 1995.

Roulet, N. T., and W. P. Adams, Illustrations of the spatial variability of light entering a lake using an empirical model, *Hydrobiologia 109,* 64–67. 1984.

Rowan, K. S., *Photosynthetic pigments of algae*. Cambridge University Press, New York, 334 p, 1989

Seaburg, K. G., M. Kasper, and B. C. Parker, Photosynthetic quantum efficiencies of phytoplankton from perennially ice covered antarctic lakes, *J. Phycol. 19,* 446–452, 1983.

Spigel, R. H., and J. C. Priscu, Evolution of temperature and salt structure of Lake Bonney, a chemically stratified antarctic lake, *Hydrobiologia 321,* 177–190, 1996.

Spigel, R.H., and J.C. Priscu, Physical limnology of the McMurdo Dry Valley Lakes, this volume

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

Trodahl, H. J., R. G. Buckley, and M. Vignaux, Anisotropic light radiance in and under sea ice, *Cold Regions Sci. and Techn. 16,* 305–308, 1989.

Vincent, W. F., Production strategies in Antarctic inland waters: phytoplankton eco-physiology in a permanent ice-covered lake, *Ecology 62,* 1215–1224, 1981.

Vincent, W.F. Phytoplankton production and winter mixing: contrasting effects in two oligotrophic lakes, *J. Ecol., 71,* 1–20, 1983.

Vincent, W. F., *Microbial ecosystems of Antarctica*, Cambridge University Press, 304 pp, 1988.

Vincent, W. F., and C. L. Vincent, Factors controlling phytoplankton production in Lake Vanda (77°S), *Can. J. of Fish and Aquat. Sci. 39,* 1602–1609, 1982.

Walker, J., The amateur scientist: exotic patterns appear in water when it is freezing or melting, *Scientific American 255,* 114–119, 1986.

Webster, J. G., Trace metal behavior in oxic and anoxic Ca-Cl brines of the Wright Valley drainage, Antarctica. *Chem. Geol. 112,* 255–274, 1993.

Webster J., I. Hawes, M. Downes, M. Timperley, and C. Howard-Williams. Evidence for regional climate change in the recent evolution of a high latitude pro-glacial lake, *Antarctic Science, 8,* 49–59 1996.

Wharton, R. A. Jr., G. M. Simmons Jr., and C. P. McKay, Perennially ice-covered Lake Hoare, Antarctica: physical environment, biology and sedimentation. *Hydrobiologia 172,* 305–320, 1989.

Wilson, A. T., A review of the geochemistry and lake physics of the Antarctic dry areas. *In* L. D. McGinnis (ed.), *Dry Valley Drilling Project, Antarctic Research Series 33,* 185–192. American Geophysical Union, Washington, D.C., 465 pp, 1981.

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