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RESEARCH PAPER

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Effects of seston on ultraviolet attenuation in Lake Biwa

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Abstract We examined the attenuation of underwater ultraviolet (UV) radiation and photosynthetically available radiation (PAR) in Lake Biwa, Japan, at offshore and inshore sites and under contrasting stratification and mixing regimes. There were large spatial differences in the water column transparency to both wavebands, despite little change in concentrations of dissolved organic carbon (DOC). The 1% of surface irradiance depth varied from 0.3 to 2.7 m at 305 nm, from 0.8 to 6.3 m at 380 nm, and from 2.3 to 12.8 m for PAR. Both PAR and UV transparency declined abruptly in the South Basin of the lake when a typhoon caused the resuspension of sediments. The water column ratio of UV to PAR increased by 30% at all stations over the course of a 3-week sampling period associated with the general increase in phytoplankton concentrations. At several sites, the diffuse attenuation coefficient for UV radiation deviated substantially from that predicted from UV-DOC models. A significantly positive linear relationship was found between UV attenuation (K_d determined with a profiling UV radiometer) and the beam attenuation coefficient at 660 nm as measured by transmissometer. These results indicate that scattering and absorption by particulate matter can reduce UV transparency to below that inferred from DOC concentrations, and that current UV-exposure models should be modified to incorporate this effect.

Key words Absorption · Biooptics · Colored dissolved organic matter · Photosynthetically available radiation · Particulates · Scattering · Ultraviolet radiation

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Introduction

Ultraviolet (UV) radiation is the most reactive waveband of solar radiation in the underwater environment and has a broad range of photochemical and photobiological effects in marine and freshwater ecosystems (Whitehead and de Mora 2000; Vincent and Neale 2000). The advent of commercially available instruments to measure underwater UV radiation has led to a rapid expansion of information concerning the factors that control UV exposure in natural aquatic environments, although the time scales of change and their effects are still poorly understood. In lakes, rivers, and the coastal ocean, UV radiation is attenuated by colored dissolved organic matter (CDOM), the yellow, humic substances that are mostly derived from catchment vegetation and soils, as well as by suspended particles and water itself (Bukata et al. 1995). However, several studies (Scully and Lean 1994; Morris et al. 1995; Laurion et al. 1997; Rae et al. 2001) have emphasized the dominant role played by CDOM and have developed attenuation models that depend exclusively on this component or a correlate, such as dissolved organic carbon (DOC). This level of control is important for answering questions on global change, because climate can influence catchment hydrology and vegetation and in this way cause major changes in the export of CDOM to receiving waters. Such climate effects may cause greater variations in underwater UV exposure than stratospheric ozone depletion (Schindler et al. 1996; Pienitz and Vincent 2000).

Recently, several studies have found significant deviations from published models relating UV attenuation to DOC concentration or CDOM absorption. These deviations have been attributed to significant attenuation due to scattering (Smith et al. 1999) or to absorption by particulate components (Hodoki and Watanabe 1998; Laurion et al. 2000), and they imply that current models need to be modified to incorporate the biooptical effects of particulate material.

Our first objective in the present study was to define the extent of spatial and temporal variation in the underwater

UV and PAR environment in Lake Biwa, Japan. Our measurements were conducted during the typhoon season in late summer, when the lake is subject to large variations in wind-forcing, and when nuisance algal blooms are sometimes observed. Our second objective was to determine to what extent these variations could be attributed to CDOM versus other light-attenuating components of the water column. For this part of the study, the earlier measurements were complemented by a spatial survey of UV attenuation and CDOM-related properties. Our results imply that the standard models based only on DOC or CDOM have a reduced predictive capability for Lake Biwa and other lakes in which light-scattering and absorption by the seston play a significant role in UV attenuation.

Materials and methods

Study sites

The temporal variation of irradiance attenuation was measured at four stations (S, B, 9, and N) every 2 days from August 24 to September 12, 1993, during the BITEX experiment (details in Frenette et al. 1996). In September 1997, a synoptic survey of irradiance attenuation was undertaken at eight stations distributed throughout the lake (Fig. 1) to encompass the broadest spread of biooptical conditions: Akanoi Bay (two stations), S, N, 4, Shiozu Bay, Kaizu Bay, and Nagahama Harbor.

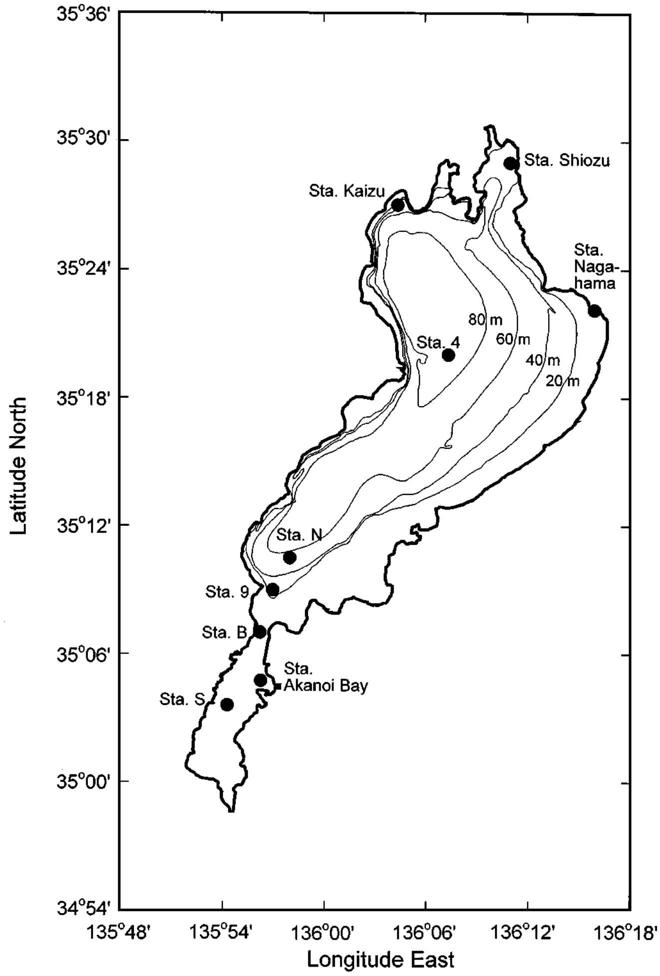

Fig. 1. Distribution of profiling sites in Lake Biwa during the UV-synoptic and BITEX sampling programs

Radiometric profiling

The PUV-500 instrument (Biospherical Instruments; San Diego, CA, USA) provided a measure of cosine-corrected downwelling UV at 305, 320, 340, and 380 nm (full bandwidth at half maximum of 8–10 nm) and of downwelling, cosine-corrected PAR (400–700 nm). The instrument also recorded depth and temperature. The radiometer was slowly lowered through the water column of each station while measurements (>10 per meter) were recorded on a portable computer. Diffuse attenuation coefficients, $K_d(\lambda)$ (m^{-1}), were calculated by linear regression of the natural logarithm of $E_d(\lambda, z)$ versus depth. PAR or UV transparency (m) was calculated as $1/K_d(\lambda)$.

Seston and CDOM measurements

Chlorophyll *a* concentration (Chl *a*) was estimated from in vivo fluorescence measured using a Sea Tech fluorometer (WET Labs, St. Philomath, OR, USA). The fluorometer calibration was established from Chl *a* determination (Frenette et al. 1996) of samples from selected depths. A further measure of seston concentrations was provided by transmissometry profiles. The beam attenuation coefficient at 660 nm (c, m^{-1}), was measured by a Sea Tech transmissometer equipped with a 25-cm cell. Values at 1 m depth in the water column at each site were converted from percent transmittance (%T) by the formula $-\ln(\%T/100)/0.25$. The profiles showed that the top few meters of the water column were well mixed, and that subsurface or 1-m samples were likely to be representative of the surface layer where the UV profiling was performed. During the 1997 survey, near-surface samples for the CDOM analyses were filtered under low vacuum pressure through Whatman GF/F filters. The samples were then stored in amber glass bottles at 4°C until analysis. DOC concentrations in the samples were determined with a Shimadzu (Kyoto, Japan) TOC Analyzer Model 5050 fitted with an ASI-5000 autosampler. For CDOM absorptivity, a_{CDOM} (m^{-1}), the samples were refiltered through 0.22 μm Sartorius cellulose acetate filters. a_{CDOM} was measured every 2 nm over the wavelength range 250–820 nm using a 1-cm, acid-cleaned, quartz cuvette in a Hewlett Packard (Palo Alto, CA, USA) 8452A diode array spectrophotometer.

Model comparisons

The UV attenuation measurements in Lake Biwa were compared with three empirical models that relate the

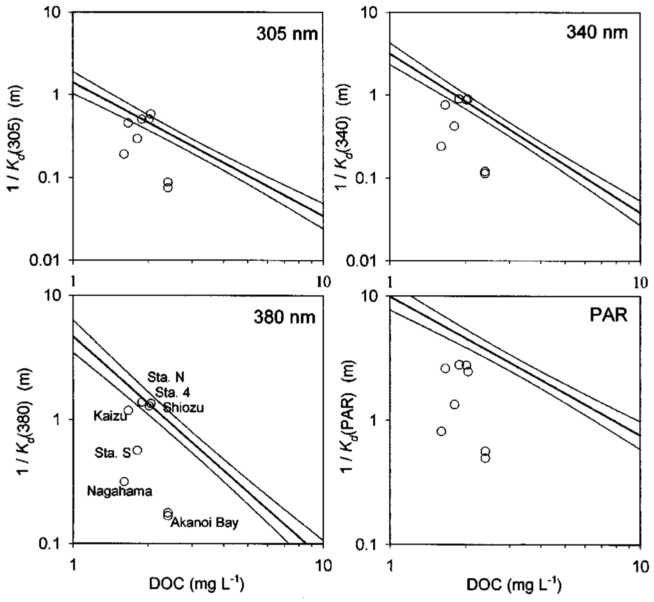

Fig. 2. Relationship between ultraviolet (UV) radiation or photosynthetically available radiation (PAR) transparency and dissolved organic carbon (DOC) in Lake Biwa. The regression lines (±95% confidence limits) are from the equations in Vincent et al. (1998) for high-latitude lakes

diffuse attenuation coefficient at a UV-B wavelength of 305 nm, $K_d(305)$, to DOC concentration, [DOC], or to CDOM absorption at 305 nm, $a_{\mathrm{CDOM}}(305)$:

$$K_d(305) = 10^{-(0.1481-1.6048\log[\mathrm{DOC}])} \quad (1)$$
$$K_d(305) = 2.76[\mathrm{DOC}]^{1.23} + 0.13 \quad (2)$$
$$K_d(305) = 2.62a_{\mathrm{CDOM}}(305) - 2.38 \quad (3)$$

Equation 1 is derived from the data in Vincent et al. (1998), which presents formulae for UV and PAR in terms of transparency, $1/K_d(\lambda)$. Equations 2 and 3 are from Morris et al. (1995).

Results

Irradiance attenuation versus DOC

The synoptic measurements showed that the transparency of Lake Biwa to UV and PAR varied spatially by an order of magnitude (Fig. 2). The 1% of surface irradiance depth varied from 0.3 to 2.7 m at 305 nm, 0.5 to 4.1 m at 340 nm, 0.8 to 6.3 m at 380 nm, and 2.3 to 12.8 m for PAR. DOC concentrations were consistently low and varied from 1.6 to 2.4 mg l^{-1}. There was no significant correlation between UV transparency and DOC, and for many of the stations UV transparency was much lower than that predicted from DOC using the equation $1/K_d(\lambda)$ in the statistical models developed by Vincent et al. (1998) for high-latitude lakes in which CDOM dominates attenuation (Fig. 2). PAR transparency was also lower than that predicted from DOC, indicating that unlike oligotrophic northern lakes, factors in addition to CDOM exert a major effect on PAR attenuation in Lake Biwa.

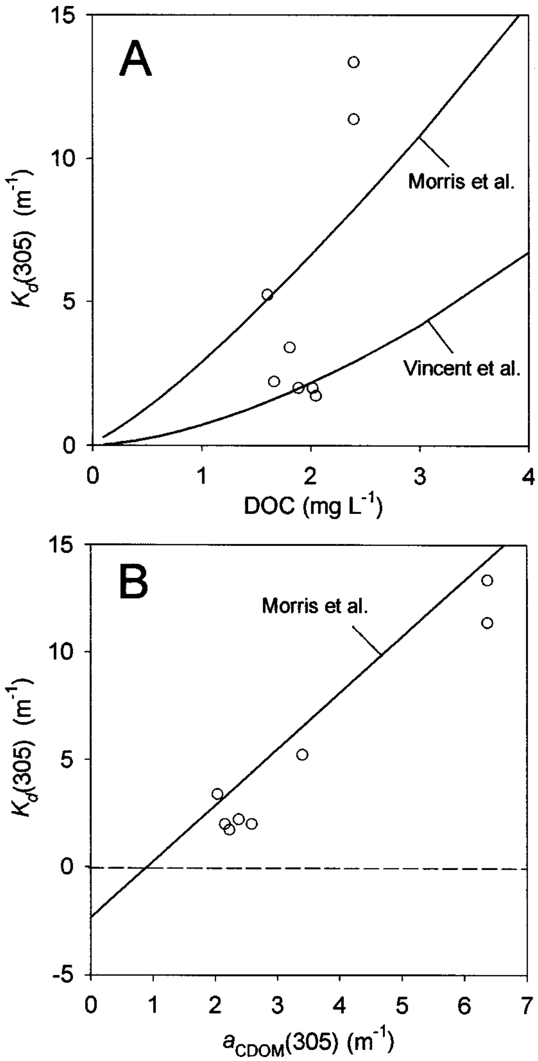

Fig. 3. Observed and predicted (from Vincent et al. 1998 and Morris et al. 1995) relationships between $K_d(305)$ and DOC and between $K_d(305)$ and a_{CDOM}

The models developed by Vincent et al. (1998) and Morris et al. (1995) to relate UV attenuation to DOC predict different $K_d(305)$ values (Eqs. 1 and 2; Fig. 3A), presumably reflecting differences in DOC optical properties or the influence of other optical parameters in the lakes included in their respective data sets. However, $K_d(305)$ in Lake Biwa was strongly correlated with $a_{CDOM}(305)$, and the correlative model (Eq. 3) of Morris et al. (1995) predicted the observed attenuation reasonably well (Fig. 3B). It should be noted, however, that this model has less predictive value at low $a_{CDOM}(305)$ values; the K_d intercept is negative, and small variations in a_{CDOM} near 1 m^{-1} predict large relative changes in K_d.

Scattering and particulate absorption influence on K_d

The time-series data set from BITEX showed large variations in PAR and UV attenuation among the four stations

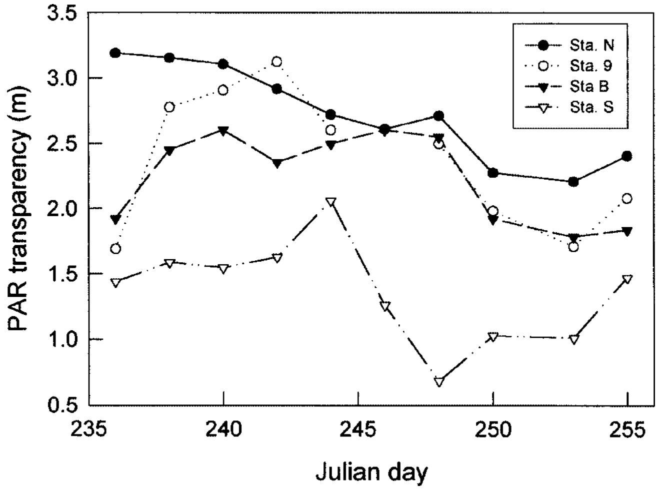

Fig. 4. Water column transparency to PAR ($1/K_d$(PAR)) at the four profiling stations during BITEX

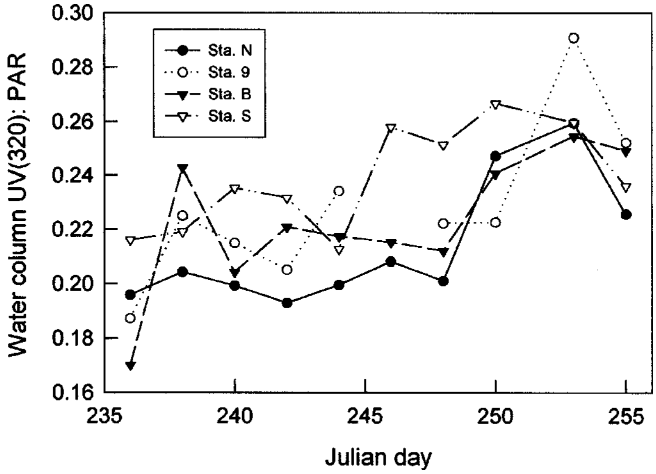

Fig. 6. Water column ratios of UV to PAR at the four stations during BITEX, calculated as in Laurion et al. (1997)

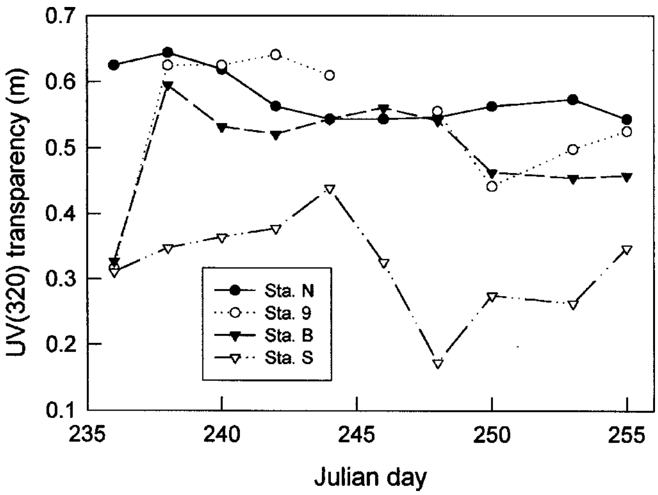

Fig. 5. Water column transparency to UV ($1/K_d$(320)) at the four profiling stations during BITEX

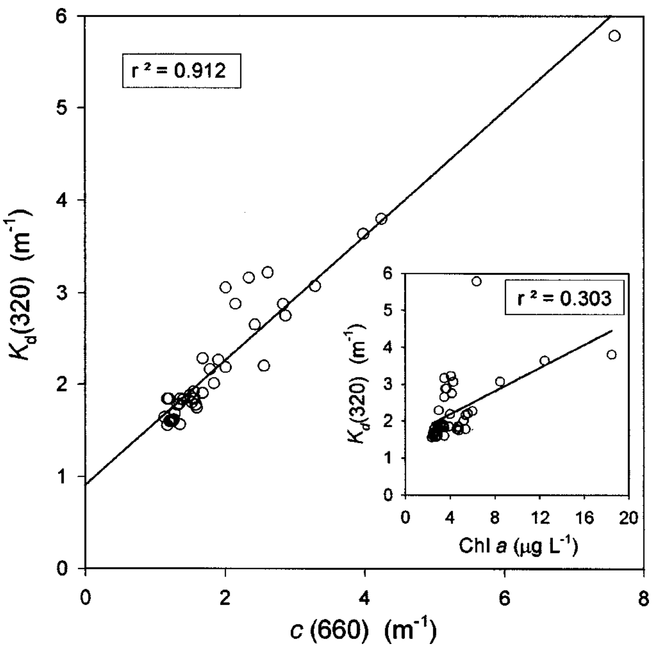

Fig. 7. Correlative relationship between K_d(320) and beam attenuation (c(660)) at 1 m depth for the BITEX data set. **Inset**: relationship between K_d(320) and Chl a at 1 m depth for the same sampling stations and period

and as a function of time. North Basin stations N or 9 were usually the most transparent to PAR (Fig. 4) and UV (Fig. 5), whereas transparency to both wavebands was consistently lowest at station S in the South Basin. Most of the temporal records for stations N, 9, and B show a general decrease in PAR transparency with time, reflecting a general increase in phytoplankton biomass over the sampling period (Frenette et al. 1996). Station S showed a very different pattern, with a general increase in PAR transparency up to day 244, followed by an abrupt decline associated with a major typhoon event and sediment resuspension (days 246–247). At this station there was a subsequent increase in PAR transparency over the final week of measurements (Fig. 4). UV followed a similar trend to PAR (Fig. 5); however, there was a general trend over the course of the BITEX sampling period toward an increase in UV to PAR exposure as indicated by the water column ratios for the two wavebands (Fig. 6). The lowest ratios were most commonly recorded at station N, which was also characterized by the lowest seston concentrations.

K_d(320) varied during the BITEX sampling period over the range 1.55–5.79 m^{-1}, which corresponds to 1% depths of 3.0 to 0.8 m. An unexpected, highly significant correlation was observed between K_d(320) and c(660) (Fig. 7). Because CDOM absorption is negligible at 660 nm, this correlation suggests that K_d(320) was strongly influenced by particulate matter absorption or scattering by organic and mineral particles. There was a weaker but significant correlation between $K_d(320)$ and Chl *a* (Fig. 7, inset), suggesting that phytoplankton cells were responsible for part of this increase.

Discussion

During periods of low seston concentration, UV penetrated deeply in Lake Biwa, with the 1% UV-B level (305 nm) as deep as 2.7 m, and the 1% UV-A (380 nm) level as deep as 6.3 m. Because the waters are characterized by relatively low DOC concentrations, a high water column transparency to UV is to be expected (Scully and Lean 1994; Morris et al. 1995; Laurion et al. 1997). However, during periods of phytoplankton development and storm-induced entrainment of bottom sediments, UV attenuation markedly increased in Lake Biwa. The UV synoptic measurements indicated that such changes were unrelated to shifts in total DOC, because the latter varied little between sites, despite large variations in UV transparency. Some variation was observed in CDOM during the synoptic, suggesting that changes in the absorption properties of DOC may contribute to the spatial and temporal variations in UV transparency in Lake Biwa.

On the basis of work partly conducted in Lake Biwa, Hodoki and Watanabe (1998) suggested that phytoplankton are likely to contribute significantly to UV attenuation in productive and non-humic water bodies. Our results are consistent with this conclusion, specifically the significant correlation we observed between $K_d(320)$ and Chl *a*. However, the stronger correlation between $K_d(320)$ and $c(660)$ found in the present study (Fig. 7) suggests that absorption by nonpigmented organisms or detritus and scattering by organic and mineral particles also contribute significantly to UV attenuation. At the 660-nm wavelength used in the transmissometer, the contribution of CDOM absorption to total beam attenuation is likely to be negligible relative to seston effects. Abiotic suspensoids have been previously identified as a significant control on PAR attenuation in Lake Biwa (Tsuda and Nakanishi 1988) and are likely to have been largely responsible for the major decrease in water column transparency to PAR at station S during the period of typhoon-induced sediment resuspension (Fig. 4). Such material may exert an effect on UV attenuation in a variety of lake types, but particularly those containing low CDOM concentrations. For example, Smith et al. (1999) found that total suspended solids values explained UV attenuation to a better extent than DOC in Lake Erie, a low-a_{CDOM} system. Similarly, in Lake Tekapo, a New Zealand lake characterized by high concentrations of glacial flour, UV transparency was much less than that estimated from its DOC concentration, leading Rae et al. (2001) to conclude that scattering rather than absorption exerts a dominant effect on the attenuation of short-wavelength irradiance in this low-a_{CDOM} lake.

The relative importance of scattering versus absorption for overall UV attenuation in Lake Biwa, cannot be assessed from the data presented here. However, since scattering is likely to dominate *c* measurements at 660 nm, the strong correlation between $K_d(320)$ and $c(660)$ suggests that scattering played a role in increasing the overall UV attenuation beyond that determined by absorption. Recent modeling analyses indicate that scattering by suspended material could contribute as much as 24% to the attenuation of UV (340 nm) in Lake Biwa, whereas absorption by particulate matter may contribute up to 37% (Belzile et al. 2001). The relative importance of scattering is likely to increase with increasing wavelength, because CDOM absorption declines exponentially with lambda, whereas scattering appears to decline more linearly (Belzile et al. 2001). This effect, in combination with the greater absorption of PAR relative to UV by the seston, is likely to have caused the general rise in UV to PAR ratios over the course of the BITEX sampling.

Although several studies have identified DOC as the most important factor controlling UV attenuation in natural freshwaters, some of the observed variability in UV attenuation has remained unexplained by this variable. Among-lake variation in the optical characteristics of DOC has been identified as one contributing factor. At low DOC concentrations, absorption and scattering by biotic and abiotic seston are likely to be additional factors contributing to the between-lake variability. The presence of intracellular UV-screening compounds, such as mycosporine-like amino acids, may give rise to a measurable contribution of phytoplankton cells to total UV absorption, for example, during nuisance algal blooms (Whitehead and Vernet 2000), and these effects are likely to be more pronounced in waters with low background UV attenuation by CDOM. Results from some large-scale mesocosm experiments in Lake Biwa suggest that cyanobacterial blooms may have such an effect in this body of water (J.-J. Frenette and A. Quesada, unpublished data).

The published DOC-K_d(UV) correlative relationships, such as Eqs. 1 and 2, are valuable tools to model UV attenuation in lakes. However, there are differences between models suggesting regional and lake-to-lake variations in bio-optical characteristics. Furthermore, the predictive value of such models is likely to be limited when DOC varies across a narrow range, and especially at low DOC concentrations. Biooptical models would be improved by incorporating estimates of UV absorption by particulate matter, for example, using the quantitative filter technique (Bricaud and Stramski 1990; Sosik 1999) and by inclusion of an index of scattering by the seston, such as nephelometric turbidity or beam *c* measured by transmissometry. Such information is incorporated in the most recent models that relate K_d(UV) to the combined effect of all absorption components plus scattering (Belzile et al. 2001).

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