Patterns of spatial and temporal variability of UV transparency in Lake Tahoe, California-Nevada

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[1] Lake Tahoe is an ultra-oligotrophic subalpine lake that is renowned for its clarity. The region experiences little cloud cover and is one of the most UV transparent lakes in the world. As such, it is an ideal environment to study the role of UV radiation in aquatic ecosystems. Long-term trends in Secchi depths showed that water transparency to visible light has decreased in recent decades, but limited data are available on the UV transparency of the lake. Here we examine how ultraviolet radiation varies relative to longer-wavelength photosynthetically active radiation (PAR, 400–700 nm, visible wavelengths) horizontally along inshore-offshore transects in the lake and vertically within the water column as well as temporally throughout 2007. UV transparency was more variable than PAR transparency horizontally across the lake and throughout the year. Seasonal patterns of Secchi transparency differed from both UV and PAR, indicating that different substances may be responsible for controlling transparency to UV, PAR, and Secchi. In surface waters, UVA (380 nm) often attenuated more slowly than PAR, a pattern visible in only exceptionally transparent waters with very low dissolved organic carbon. On many sampling dates, UV transparency decreased progressively with depth suggesting surface photobleaching, reductions in particulate matter, increasing chlorophyll *a*, or some combination of these increased during summer months. Combining these patterns of UV transparency with data on visible light provides a more comprehensive understanding of ecosystem structure, function, and effects of environmental change in highly transparent alpine and subalpine lakes such as Tahoe.

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1. Introduction

[2] Ultraviolet radiation (UVR) reaching the Earth's surface has increased substantially due to stratospheric ozone depletion [*Tevini*, 1993; *Young et al.*, 1993], and the ozone hole may take decades more to recover from anthropogenically induced depletion [*United Nations Environment Programme*, 2007]. UVB radiation (280–320 nm), the most biologically damaging wave band reaching Earth's surface, has been detected at depths of 60–70 m in the oceans near Antarctica [*Karentz and Lutze*, 1990; *Smith et al.*, 1992], and the three of the largest annual ozone holes on record have occurred since 2000 [*World Meteorological Organization*, 2006]. Increased climate warming may slow the recovery of stratospheric ozone in coming decades [*Shindell et al.*, 1999; *United Nations Environment Programme*, 2007] and alter allochthonous dissolved organic carbon (DOC) inputs in some inland waters [*Freeman et al.*, 2004]. Highly transparent alpine and subalpine lakes in regions with high solar radiation such as those on which this special issue is focused may be especially sensitive to UV-induced biological damage. This is due not only to their high transparency, but also to the decrease in the thickness of the atmosphere and consequent reduction of atmospheric aerosols and ozone that absorb the shorter more damaging wavelengths of UV before they reach the lake surface.

[3] Lake Tahoe, an ultra-oligotrophic subalpine lake located on the border between California and Nevada, USA, is renowned for its remarkable transparency. One of the most highly valued measures of Lake Tahoe's aesthetic quality is this high transparency that leads to its deep blue color [*Goldman*, 1988]. In recent decades, however, large declines in transparency have been measured in the lake [*Swift et al.*, 2006]. Secchi data collected continuously since 1967 have provided information on visible transparency of the lake at two locations: a nearshore station (Index station, maximum depth of 125 m) and a midlake station (maximum depth of 450 m; for a detailed map, see *Jassby et al.* [2003]). Initial annual mean Secchi depth was 31 m at the Index site when the program began in 1968; more recently this annual mean is closer to 21 m [*Swift et al.*, 2006]. These

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changes in water transparency are due mostly to changes before 1985. This long-term trend in transparency is believed to be due to an accumulation of materials in the lake, especially suspended inorganic sediments and phytoplankton [*Jassby et al.*, 2003; *Swift et al.*, 2006]. Transparency, traditionally measured by Secchi depth, may be responsive to many different processes and substances beyond chlorophyll [*Edmondson*, 1980; *Megard et al.*, 1980; *Lorenzen*, 1980]. Despite the extensive data on visible light in Tahoe, little is known about its UV transparency, if it is changing over time, or how it varies across spatial and seasonal gradients. Beyond being biologically important [*Williamson*, 1995], UV is highly sensitive to changes in the quantity and quality of dissolved organic carbon (DOC) [*Kirk*, 1994a; *Morris et al.*, 1995]. This sensitivity to changes in DOC makes UV a potentially sensitive indicator of environmental change at watershed, regional, and global scales. UV data may also permit earlier detection of trends of changing transparency than visible light due to its greater sensitivity to environmental changes. Although Lake Tahoe's small catchment area and long residence time may make it less susceptible to changes in DOC inputs from its catchment, the initially very low concentrations of DOC make Lake Tahoe vulnerable to even slight changes in DOC concentration [*Williamson et al.*, 1996].

[4] Here we examine the spatial and temporal variation in UV relative to photosynthetically active radiation (PAR), and Secchi transparency in Lake Tahoe. The purpose of our investigation is to better understand the potential role of UV in environmental change, both as an indicator of change, and as a mediator of change in aquatic ecosystem processes. We also demonstrate the utility of using a transparency depth ratio to characterize systematic changes in UV transparency vertically in the water column.

2. Site Description

[5] Lake Tahoe, located in the Sierra Nevada mountain range (39°N, 120°W), exhibits many characteristics that give it unusually high transparency. Lake Tahoe has a combination of great depth, small ratio of watershed area to lake area, and granitic basin geology that result in almost unparalleled transparency [*Jassby et al.*, 1994]. It has a surface area of 501 km^2, and the ratio of watershed area to lake area is 1.6 [*Hyne et al.*, 1972]. The maximum depth is approximately 500 m, and the mean depth is 333 m [*Gardner et al.*, 2000]. Hydraulic residence time is approximately 650–700 years [*Marjanovic*, 1989]. The lake is an oligomictic lake with the greatest depth of mixing in the late winter to early spring. The lake is free of ice the entire year. Tahoe develops a deep chlorophyll maximum (DCM) in midsummer, and the DCM has been getting shallower over time. In 2007, the depth of the DCM was about 55 m [*Tahoe Environmental Research Center* (*TERC*), 2008]. Over 85% of Lake Tahoe's watershed has been forested for the last few decades. The Upper Truckee River, which is the largest river input into Lake Tahoe, accounts for approximately 19% of the runoff entering the lake [*Marjanovic*, 1991]. This results in a predicted input of sediments over the entire lake in a 0–30 m stratum of 0.23 mg L^{-1} a^{-1} [*Jassby et al.*, 1999]. The Upper Truckee River input strongly influences bacterial and phytoplankton activity in the lake [*Jassby and Goldman*, 1974].

3. Methods

[6] We collected light profiles approximately monthly throughout 2007 with a Biospherical Instruments Cosine (BIC) radiometer (Biospherical Instruments Inc., San Diego, California, USA) that measured temperature, 305, 320, and 380 nm UV and PAR (400–700 nm) irradiance. The BIC is a medium bandwidth submersible radiometer. Depth resolution is 0.01 m. The UVR bands have a bandwidth of 8–10 nm measured as the full width at half maximum response (FWHM, the range between the two wavelengths at which response is 50% of the peak response). A deck cell simultaneously records the same UV and PAR wavelengths as the submersible cell in order to account for short-term changes in atmospheric conditions (clouds, aerosols, etc.). Profiles were taken at the Index site and the Midlake site. The Index site is located 0.3 km SE of Tahoe Pines, California, at 39°05.840′N, 120°09.300′W and the Midlake site is located near the center of Lake Tahoe, at 39°09.220′N, 120°02.120′. These sites have received consistent monitoring attention for several decades and Secchi depth time series are similar at both stations [*Jassby et al.*, 2003]. In May and July 2006 we collected BIC light profiles along transects beginning at the mouth of the Truckee River input, the largest input into Lake Tahoe, at the south end of the lake and extending outward into the center of the lake. The diffuse attenuation coefficient (K_d) for 305, 320, and 380 nm UV and PAR was calculated over the log linear portion of the irradiance versus depth data for all light profiles. Generally, the integration depth range was from the surface to the point at which transparency was determined visually and conservatively to be no longer log linear. However, PAR exhibited a non-log linear attenuation rate near the surface due most likely to the more rapid absorption of the longer red wavelengths [*Hargreaves et al.*, 2007]. This generally was observable in only the top 5–10 m of the water column. To avoid this region of spectral shift we estimated the PAR K_d from deeper waters below this region of non-log linear change.

[7] The diffuse attenuation coefficient (K_d) was calculated by the log linear function,

$$K_d = \frac{Ln\left(\frac{E_0}{E_z}\right)}{Z} \quad (1)$$

where (E_z) is irradiance at depth Z, (E_0) is irradiance at the surface, and K_d is the slope of the log linearized function [*Kirk*, 1994b]. The K_d was estimated from the linear portion of the log-transformed irradiance data. UV wave bands were often not log linear and residuals about the regression line often showed a consistent nonrandom pattern indicating a decreasing transparency with depth, particularly in summer months (Figure 1). To quantify how transparency changed with depth, we calculated the diffuse attenuation coefficient in (1) surface waters at the top of the profile, which was made from the surface on downward and including at least 20 data points (generally the depth range was from 0.0 m to about 2.0 m), and (2) in deeper waters, immediately above

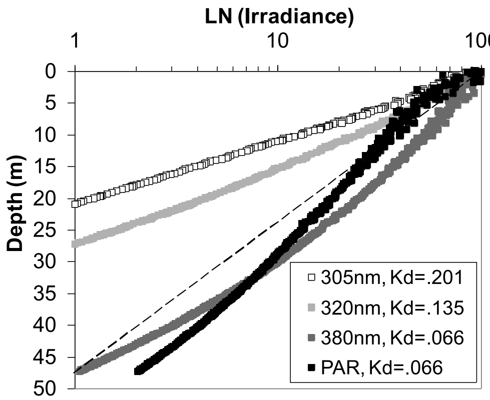

Figure 1. Irradiance-depth profiles for the midlake station collected 9 July 2007 showing non-log linear trends within the water column typical of many of the profiles. Note that PAR exhibits a spectral shift near the surface where PAR transparency is reduced quickly in the first few meters, and that 380 nm UVA attenuates more slowly than PAR in the surface waters. A dashed line connecting the 100% and 1% depths for 380 nm illustrates the curvature associated with many profiles (see Figure 2).

the depth where 1% of surface light remained to 20 data points shallower. Twenty data points were used because this range often was enough to produce a high R^2 value (>0.95), yet a small enough depth range to isolate changes in K_d with depth. We calculated a ratio of these two attenuation estimates (deeper K_d: surface K_d) what we hereafter refer to as the depth transparency ratio or DTR. This ratio is used to express how transparency varied within in the vertical water column seasonally, where values of DTR above one indicate that surface waters were more transparent than deeper waters and values less than one indicate that deeper waters were more transparent than surface waters.

[8] Because transparency is wavelength-dependent, seasonal changes in transparency were compared using the percent change relative to the initial sampling (earliest 2007 ordinal day) for both the Index and Midlake sites through time (Figure 2). Percent change in transparency is expressed as 1% depths (the depth at which 1% of surface irradiance remains), estimated from the K_d values [*Williamson et al.*, 1996]. For ease of comparison, changes in Secchi depth were also plotted as a percent change. In all cases, positive values indicate increasing transparency and negative values indicate decreasing transparency relative to the initial sampling date or location (in the case of inshore-offshore transects).

[9] Chlorophyll *a* data, particulate data, and Secchi depths were measured simultaneously to light profiles for most sampling dates. Chlorophyll *a* concentration was measured at a series of depths (0, 2, 5, 10, 15, 20, 30, 40, and 50 m) at the Index site. Chlorophyll *a* concentration was determined fluorometrically (Turner Designs fluorometer calibrated with pure chlorophyll *a*) after methanol extraction for particles collected from 100 ml water on GF/F filters. Secchi depth was measured with a 20 cm diameter white disk lowered from the shaded side of the boat. Suspended particles were counted using a Liquilaz LS-200 (Particle Measurement Systems Inc., Boulder, Colorado, USA). For comparisons of transparency to chlorophyll *a* concentration, the chlorophyll *a* concentration was estimated over the same depth range used to estimate transparency for UVB, UVA, PAR, and Secchi.

[10] To further characterize vertical heterogeneity in transparency, the diffuse attenuation coefficient, K_d, was calculated on 1m intervals from the surface to the estimated depth at which 1% of surface irradiance remained (or the maximum depth sampled) for each profile at the Index site. Least squares linear regression was used to characterize the relationship between vertical changes in K_d and particulate matter, vertical changes in K_d with chlorophyll *a*, and vertical changes in particulate matter with chlorophyll *a*.

[11] Least squares linear regression was used to test if transparency (Secchi depth, UVB, UVA, and PAR) was related to chlorophyll *a* concentration at the Index site through time. We averaged chlorophyll *a* concentration over the relevant depth range used to calculate the diffuse attenuation coefficient for UVB, UVA, and PAR or Secchi depth and compared this chlorophyll *a* concentration to the diffuse attenuation coefficient for UVB, UVA, and PAR and to the Secchi depth. Least squares linear regression was also used to test if the transparency ratio was related to vertical changes in chlorophyll. A chlorophyll *a* ratio was calculated over the same two depth ranges used to calculate the transparency ratio.

[12] Particulates were quantified on several sampling dates, including the dates of the annually lowest transparency in 2007 for UVA and UVB (2 January 2007) and PAR (23 March 2007) and annually greatest transparency for UVA, UVB, and PAR (24 July 2007) at the Index site. Particulates were quantified within bins bounded by 0.5, 0.63, 0.79, 1.00, 1.41, 2.00, 2.83, 4.00, 4.76, 5.66, 6.73, 8.00, 11.31, 16.0 and 20.0 μm. Size ranges were combined to yield 0.5–1.00, 1.00–2.00, 2.00–4.00, and 4.00–20.0 over the depth range from 0 m to 50 m to facilitate comparison among size groups. Least squares linear regression was used to characterize the relationship between frequency of each size group and depth on the least and most transparent light profile dates.

4. Results

[13] Lake Tahoe was isothermal in the top 50 m (the maximum measured depth of light profiles) from January to February and surface water started to stratify in March. The lake was stratified from late June through September at about 20–25 m, and the stratification broke down in November (data not shown). Within the vertical water column UV transparency decreased smoothly and consistently with depth for most light profiles (Figure 1). This pattern was most pronounced for UVA in late summer (Figure 1). Transparency changed seasonally and the DTR from all UV wavelengths also showed strong seasonal changes (Figure 2). The DTR showed increasing values (i.e., surface waters becoming more transparent) until early August (day 220) and decreasing values thereafter at the Index site. A similar but more pronounced pattern occurred at the Midlake site, with a seasonal peak in early August (day 213).

[14] Transparency of all wavelengths showed strong seasonal variation throughout 2007 at both the Index and Midlake sites (Figure 2). UV transparency showed much

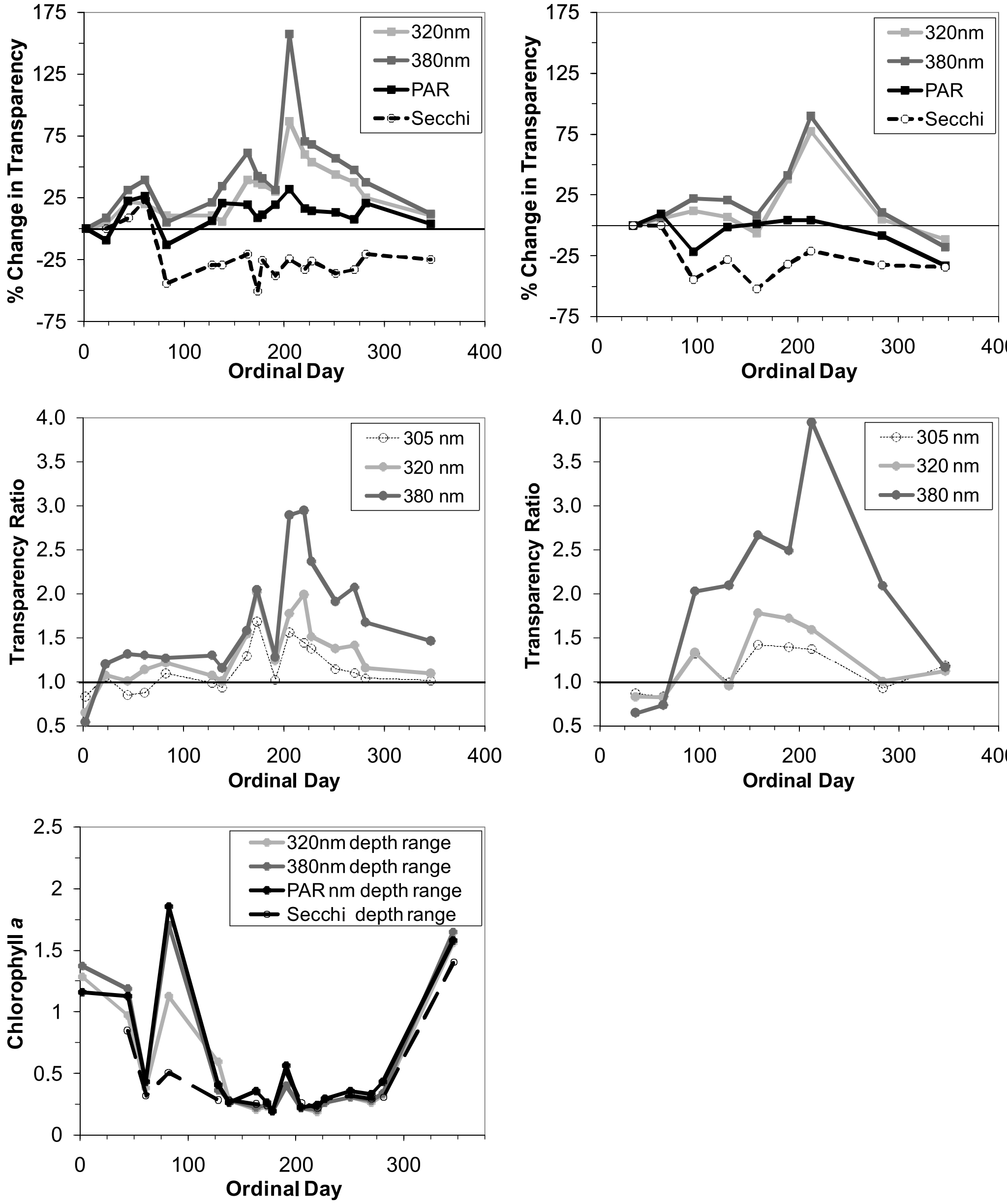

Figure 2. Seasonal changes in transparency, the transparency ratio, and chlorophyll *a* in Lake Tahoe at the (left) Index and (right) Midlake sites in 2007. (top) Percent changes in transparency of 320 nm, 380 nm, PAR, and Secchi depth expressed as a percent of the earliest collected profile in 2007 (2 January for Index, 5 February for Midlake) and plotted against ordinal day for both sites. Increasing values for 320, 380, PAR, and Secchi indicate increasing transparency, while decreasing values indicate decreasing transparency. Note that UV shows both stronger and different seasonal patterns than either PAR or Secchi, and that PAR and Secchi, though both based on visible light, give somewhat different patterns from each other. (middle) Seasonal changes in the transparency ratio used to quantify the systematic decrease in transparency with depth in 2007 at the Index and Midlake sites. Positive values indicate that surface waters are more transparent than deeper waters. Note that UVA shows the most pronounced changes of the three wave bands. The transparency ratio was significantly related to the chlorophyll *a* ratio for 320 nm ($R^2 = 0.58$, $p = 0.007$) and 380 nm UV ($R^2 = 0.75$, $p = 0.003$). (bottom) Changes in chlorophyll *a* seasonally at the Index site, calculated over the depth ranges used to measure transparency of 320 nm and 380 nm UV, PAR, and Secchi. Chlorophyll *a* was significantly inversely related to seasonal changes in 320 nm and 380 nm UV and PAR transparency, but not Secchi depth.

stronger seasonal variations than either PAR or Secchi depth, with 380 nm UVA varying the most seasonally at both sites (see Table 1 for seasonal K_d values). For example, UVA transparency at the Index site increased by 157% from the first sampling date on 2 January to the most transparent period on 24 July. The Index site which is nearer to shore

Table 1. Diffuse Attenuation Coefficient for Profiles Collected on Ordinal Days in 2007 at the Index Site and Midlake Site

	Diffuse Attenuation Coefficient K_d (m^{-1})			
Ordinal Day	305 nm	320 nm	380 nm	PAR
		Index Site		
2	0.296	0.224	0.121	0.087
22	0.293	0.216	0.111	0.096
44	0.255	0.184	0.092	0.071
61	0.252	0.187	0.087	0.069
82	0.269	0.202	0.115	0.100
128	0.291	0.203	0.100	0.082
138	0.296	0.212	0.090	0.072
163	0.233	0.161	0.075	0.073
173	0.238	0.164	0.085	0.080
178	0.236	0.165	0.086	0.078
191	0.242	0.172	0.092	0.073
205	0.175	0.120	0.047	0.066
220	0.204	0.140	0.071	0.075
227	0.209	0.146	0.072	0.076
251	0.219	0.156	0.077	0.077
270	0.229	0.163	0.082	0.081
281	0.246	0.179	0.088	0.072
346	0.247	0.203	0.108	0.084
		Midlake Site		
36	0.246	0.186	0.093	0.069
64	0.232	0.176	0.087	0.063
96	0.239	0.166	0.076	0.088
130	0.250	0.174	0.077	0.070
159	0.267	0.198	0.086	0.068
190	0.201	0.135	0.066	0.066
213	0.158	0.105	0.049	0.066
284	0.247	0.177	0.084	0.075
347	0.285	0.210	0.113	0.103

than the Midlake site, varied more than the Midlake site at all wave bands. Both sites exhibit a drop in transparency around ordinal days 75–100. Around day 75 (16 March), the lake was isothermal to below 140 m. Between the sampling just prior and just after this event, PAR transparency decreased 45%, while 380 nm UV dropped 32% and 320 nm UV dropped 8%. Seasonal patterns of variation in Secchi transparency appeared to mimic PAR transparency patterns; however, there was a critical difference. Secchi transparency was greatest early in the year and decreased thereafter while UV and PAR transparency was greatest in midsummer. Secchi transparency changed more in early spring than did either PAR or UV wavelengths, dropping 47% from 2 to 23 March (ordinal days 61 and 82) whereas at the Index site PAR, UVA, and UVB transparency dropped 45%, 32%, and 8%, respectively (Figure 2).

[15] PAR transparency was also not constant across depths within the water column, but the vertical patterns were distinctly different than the curvature associated with UV. PAR attenuated rapidly in the first few meters of the water column in all profiles (Figure 1). When transparency for UVA and PAR were estimated from more shallow surface waters (generally shallower than 20 m), the water was more transparent to UVA than to PAR. For example, on 9 July 2007 (profile in Figure 1), over the depth range 0–18 m the K_d for 380 nm was 0.066 m^{-1} and the K_d for PAR was 0.084 m^{-1}, but when PAR was integrated over deeper waters (6–26 m), the K_d for PAR was 0.066 m^{-1}. When transparency was estimated over the deeper portion of the water column, however, UVA transparency did not exceed PAR transparency, indicating that short-wavelength visible light penetrated more deeply than UV.

[16] Least squares linear regression showed that there was a significant positive relationship between the chlorophyll *a* ratio and the DTR for 320 nm ($R^2 = 0.58$, $p = 0.007$) and 380 nm UV ($R^2 = 0.75$, $p = 0.003$) at a seasonal basis, indicating that when the ratio was largest (and surface waters were more transparent than deeper waters), chlorophyll *a* was higher in deeper waters relative to surface waters. The DTR showed strong parallels with the seasonal changes in UV transparency at both sites (Figure 2). On the most and least transparent profile dates, a significant relationship between K_d and chlorophyll *a* concentration was observed only on 24 July 2007 (when the DTR was large and positive) for 305 nm (DTR = 1.56, $R^2 = 0.74$, $p = 0.028$), for 320 nm (DTR = 1.78, $R^2 = 0.84$, $p = 0.002$), and for 380 nm (DTR = 2.89, $R^2 = 0.788$, $p = 0.003$), but not for PAR ($R^2 = 0.03$, $p = 0.680$). During other sample dates, however, there was no significant relationship.

[17] The least squares linear regression of chlorophyll *a* concentration versus transparency over time revealed that at the Index site, UVB, UVA, and PAR transparency were inversely related to chlorophyll *a* while Secchi depth showed no significant relationship with chlorophyll *a* (Figure 2 and Table 2). Particulate analysis showed that the density of particulates increased over an order of magnitude between the dates of highest transparency and those of lowest transparency at the Index site (Figure 3). Seasonal changes in chlorophyll *a* concentration were not significantly related to changes in particulates. The date with the lowest transparency for UVB and UVA was 2 January 2007 (ordinal day 2) and for PAR was 23 March 2007 (ordinal day 82). The date with the highest transparency for all wavelengths was 24 July 2007 (ordinal day 205). There was a significant increase in particle concentration with depth within each particle size class on the date with the highest transparency (24 July, $p < 0.001$ for all size classes, R^2 = 0.97, 0.95, 0.91, 0.82 for the size classes 0.5–1.0, 1.0–2.01, 2.0–3.0, and 4.0–20.0 μm). There was no relationship between particle concentration and depth for any particle class on either of the two dates with lowest transparency. Smaller-sized particles (<4 μm) were found in much greater concentrations than larger-sized particles on all sampling dates. There was a moderate but significant relationship between vertical changes in particulates and chlorophyll *a* on 24 July ($R^2 = 0.35$, $p = 0.035$), but not on 2 January ($p = 0.91$) or 23 March ($p = 0.861$). There were somewhat stronger and significant relationships between temperature at 2 m and the transparency ratio for all UV wavelength (305 nm $R^2 = 0.45$, $p = 0.003$; 320 nm $R^2 = 0.51$, $p = 0.001$; 380 nm $R^2 = 0.61$, $p < 0.001$) at the Index site. At the Midlake site, 320 nm and 380 nm UV were significantly related to temperature (320 nm $R^2 = 0.53$, $p = 0.027$; 380 nm

Table 2. Linear Regressions Relating Secchi Depth and Diffuse Attenuation Coefficients K_d for UVB, UVA, and PAR to Chlorophyll *a* Concentration Through Time at the Index Site

Optical Measurement	R^2	p Value	Slope	Intercept
UVB (320 nm)	0.712	0.008	0.084	0.137
UVA (380 nm)	0.718	0.009	0.061	0.063
PAR (400–700 nm)	0.644	0.017	0.025	0.069
Secchi depth (m)	0.001	0.970	0.219	20.387

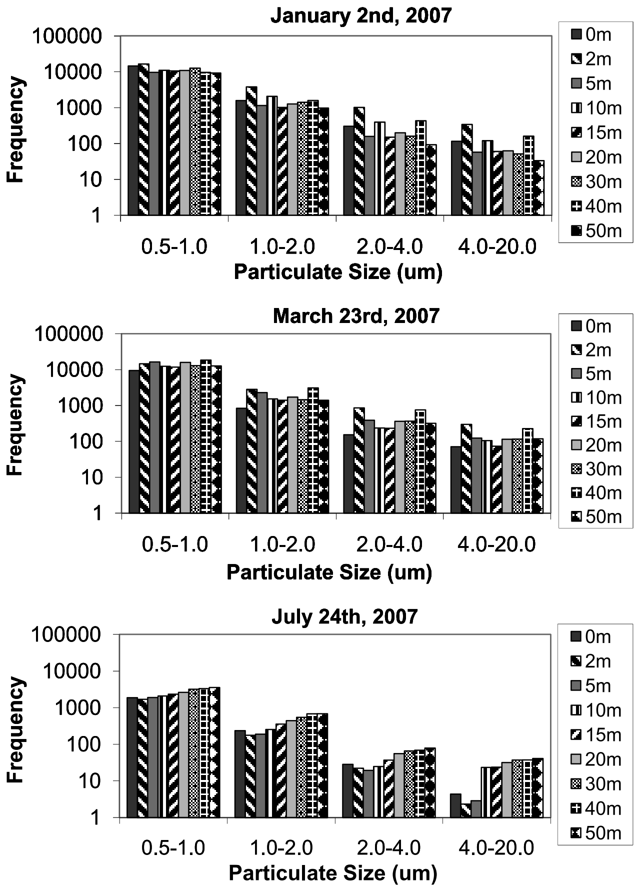

Figure 3. Particulate size frequency distribution at different depths for the Index site in Lake Tahoe in 2007. Dates for the lowest transparency (2 January for UVB and UVA, 23 March for PAR, ordinal days 2 and 82) and greatest transparency (24 July, ordinal day 175 for all wavelengths) are shown. Note that particulate concentrations varied by over an order of magnitude among dates, and that particle frequency increased with depth on 24 July but not on 2 January or 23 March.

$R^2 = 0.76$, $p = 0.002$), but 305 nm UV was not (305 nm $R^2 = 0.37$, $p = 0.080$).

[18] Horizontal (inshore to offshore) transects conducted in May and July 2006 showed that transparency inshore near the mouth of the Truckee River was much lower than at offshore sites (Figure 4). As with the seasonal patterns of variation, UVA wavelengths varied the most along the transect, followed by UVB and PAR. For example, in May 2006 UVA increased up to 45% from inshore to offshore, while PAR only increased 8%.

[19] Seasonal changes along the inshore-offshore gradient showed that nearshore sites (near the Truckee River mouth) increased in transparency from May to July while offshore sites decreased in transparency (Figure 5). Again, UVA changed the most and PAR changed the least and the change in UVB was similar to, but slightly less than changes in UVA. Inshore, UVA increased in transparency 90% while PAR increased only 68%. The opposite patterns of change were observed offshore where both UVA and PAR decreased in transparency seasonally, though UVA decreased again more than PAR (100% versus 25%, respectively).

5. Discussion

[20] Lake Tahoe showed pronounced patterns of variation in water transparency seasonally, horizontally (inshore to offshore), and vertically within the water column. In almost all cases the changes in UV transparency were much more pronounced than those for PAR and Secchi depth. Furthermore, the seasonal and inshore-offshore variability showed that UV, PAR, and Secchi depth were responding to different substances and processes within the lake. More pronounced changes in UV relative to PAR and Secchi transparency suggest that UV is a more sensitive indicator of environmental change than the more conventionally used longer radiation wavelengths. The very low K_d values (as low as 0.047 m^{-1} for 380 nm) and optical patterns observed from Lake Tahoe are comparable to some of the most transparent water bodies in the world [*Morel et al.*, 2007].

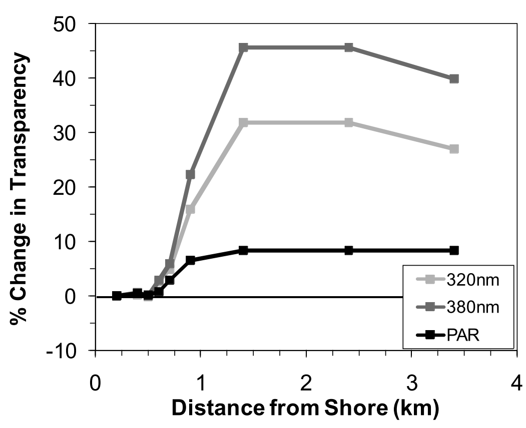

Figure 4. Inshore-offshore changes in transparency relative to the nearshore site (Truckee River) in Lake Tahoe on 4 May 2006. Note that UVA showed the strongest signals of change.

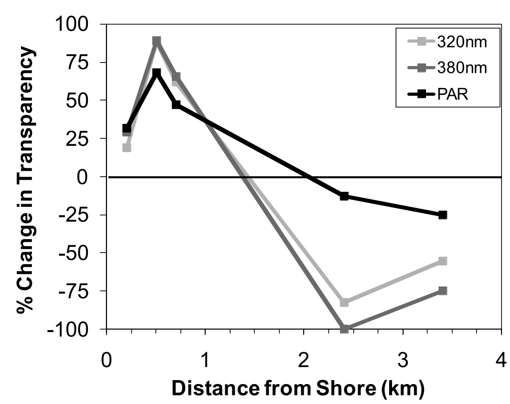

Figure 5. Seasonal changes along the nearshore to offshore transect in Lake Tahoe from 4 May to 24 July 2006 (ordinal days 124 and 175). Note that inshore sites became more transparent while offshore sites (>2 km) became less transparent, and that UV transparency showed a stronger pattern than PAR at both locations.

[21] While our primary intention here was to characterize variations in UV versus PAR/visible transparency in Lake Tahoe, our data do permit some inference about the factors controlling attenuation and thus contributing to the observed spatial and temporal variations in transparency. Chlorophyll *a*, a proxy for phytoplankton densities, was significantly related to UV transparency but not to Secchi depth. This indicates that variations in phytoplankton concentration control seasonal changes in UV and PAR transparency but not Secchi depth. The mechanisms of this control in this extremely oligotrophic system may be either through particulate control over UV or release of autochthonous DOM which absorbs UV. While DOC is usually the dominate factor controlling transparency in most lakes [*Morris et al.*, 1995], in low-DOC alpine and subalpine systems such as Tahoe, phytoplankton tend to be more important in controlling variation in UV transparency [*Laurion et al.*, 2000; *Tartarotti and Sommaruga*, 2006]. Similar large spatial differences in transparency have been observed in another large lake, Lake Biwa in Japan [*Vincent et al.*, 2001]. There, DOC varied very little, while scattering and absorption by autochthonous particulate matter reduced both UV and PAR transparency. In other very transparent inland waters as well as many oceanic studies researchers have found that transparency is often strongly related to chlorophyll *a* concentration [*Hargreaves et al.*, 2007; *Vincent et al.*, 1998; *Morel et al.*, 2007]. Lake Tahoe, during many times of the year, behaves like a Case I water body, where transparency is regulated by autochthonous primary production [*Morel and Prieur*, 1977].

[22] Variation in wavelength-dependent seasonal transparency suggest that different processes may be altering water transparency both in the spring versus the summer and inshore versus offshore. While PAR transparency and Secchi depth decreased more than UV from winter to early spring (around day 82) at the Index site, both UVA and UVB transparency increased more than PAR during the summer. The greater summertime increase in UV transparency in comparison to PAR and Secchi depth are consistent with a photobleaching hypothesis, where under natural solar radiation UVA tends to have the greatest photobleaching effect, followed by UVB and finally PAR [*Osburn et al.*, 2001].

[23] At nearshore locations, transparency increased from spring to summer while offshore the reverse was true. In addition, UV wavelengths varied more than PAR in both the nearshore and offshore sites. Nearshore transparency increased from May to July, likely a result of decreased allochthonous inputs from the Truckee River or photobleaching of material at these nearshore sites. Though we do not have simultaneous DOC data for this set of observations, the DOC data that we do have are consistent with a photobleaching hypothesis. At more transparent inshore sites around Lake Tahoe, the DOC concentration was about 0.4–0.5 mg/L and had lower DOC specific absorbance in July of 2007 compared to June of 2007. For example, at Obexer's marina, an inshore site near the Index site, the DOC specific absorbance went down 25% from June to July 2007. At inshore locations around Lake Tahoe, both DOC and chlorophyll *a* were significantly related to UV and PAR transparency (A. J. Tucker et al., Ultraviolet radiation affects invasibility of lake ecosystems by warmwater fish, submitted to *Ecology*, 2009).

[24] *Swift et al.* [2006] found that suspended particulate matter was the dominant cause of clarity loss for Secchi depth readings at the Index site and that the period of late spring exhibited the greatest increase in inorganic particulates while autumnal deep mixing increased the role of organic particulate scattering and absorption in altering Secchi transparency. In our analysis at both sites, we found that chlorophyll *a* was related to seasonal changes in UV and PAR transparency, but not Secchi transparency. The decrease in transparency and high degree of log linearity (low DTR value) in May of 2007 (ordinal day 130) was not coupled with high chlorophyll *a*. In contrast, the December transparency minimum (ordinal day 347) was coupled with high chlorophyll *a*. Our particulate analysis showed that particulate density varied over an order of magnitude between the least and most transparent sample dates at the Index sites, suggesting that particulates played an important role in regulating both UV and PAR transparency. We found no significant relationship between seasonal changes in chlorophyll *a* and particulates, but the weak relationship may have been caused by weak statistical power; we had only five dates where we sampled both chlorophyll *a* and particulates at all depths. In similarly large Lake Taupo in New Zealand, *Belzile et al.* [2004] found that a combination of phytoplankton, chromophoric dissolved organic matter (CDOM), and nonalgal particles were responsible for controlling transparency and color at blue wavelengths.

[25] The smooth and consistent decrease in transparency with depth that characterizes many sampling time points could result from several different processes including the settling of light absorbing particulates, phytoplankton absorption and scattering, and/or photobleaching of surface waters. The significant relationship between temperature and the transparency ratio indicates that reduced mixing probably played an important role in the development of non-log linear transparency with depth. As the lake warmed, stratification probably reduced mixing, thereby facilitating increasing photobleaching and particulate settling. The transparency estimates for the 320 and 380 nm DTR integrated over water above and below the thermocline, thus processes that occurred in both the epilimnion and hypolimnion are taken into account, while the 305 DTR only included water in the epilimnion, however.

[26] The significant positive relationship between chlorophyll *a* and K_d on 24 July suggests that chlorophyll *a* at least partially controlled vertical changes in transparency. The significant relationship between the DTR and the chlorophyll ratio further supports this argument. This suggests that the DTR may also be a useful indicator of the seasonal development of the deep chlorophyll maximum. In Lake Vanda, an optically similar lake in Antarctica, *Vincent et al.* 1998 also found non-ln-linear changes with depth in transparency and chlorophyll *a* was an important factor regulating transparency. In Lake Tahoe, vertical changes in K_d were also significantly related to vertical changes in particulate concentrations; however, the significant relationship between vertical changes in both chlorophyll *a* and particulates suggests that the transparency relationship is driven by autochthonous particulate matter. The lack of a relationship between chlorophyll *a* and vertical changes in

K_d on other dates, even when the DTR was large, may be partially due to shadow effects and wave focusing as the K_d estimates over 1 m intervals varied greatly near the surface.

[27] Photobleaching is known to increase UV transparency [*Morris and Hargreaves*, 1997], and photobleaching of CDOM may have contributed to the observed seasonal changes in transparency and to changes in the DTR in particular. In Crater Lake, Oregon, *Boss et al.* [2007] found that CDOM increased with depth during the summer. As photobleaching may increase surface transparency more than transparency deeper in the water column, the DTR would increase seasonally, with the peak near or soon after summer solstice (21 June, day 172). While we do not have concurrent CDOM or DOC-specific absorbance measurements with our study, we sampled the vertical water column at the midlake site in early September 2008 and found that dissolved absorbance increased with depth, 86% from 3 m to 50 m at 380 nm, for example. Tahoe's seasonal increase in UV transparency fits well with a photobleaching model that predicts highest transparency near summer solstice [*Osburn et al.*, 2001]. The transparency ratio may be responding to a mixture of particulates, chlorophyll *a*, and photobleaching processes and thus results in a smooth and consistent increase of attenuation with depth.

[28] Light profiles in Lake Tahoe revealed unusual transparency and light attenuation compared to other inland water bodies. For example, the estimated UVA transparency was greater than that for PAR at the surface at both sites for several light profiles, particularly during the summer. This only occurred when PAR or UVA transparency were estimated over a shallow (generally less than 20 m deep) profile where PAR attenuation was non-log linear. This pattern of transparency has been observed in other clear water bodies [*Vincent et al.*, 1998; *Morel et al.*, 2007; *Hargreaves et al.*, 2007] and results from selective absorption and scattering of longer PAR wavelengths. This phenomenon will only occur when concentrations of light absorbing matter are very low such that the absorption of water becomes an important regulator of transparency.

[29] Transparency generally increased throughout the summer months at both the Index and MLTP sites, except for a short-term in late June and early July (ordinal days 173–191). This drop occurred soon after a forest fire broke out within Tahoe's watershed. The forest fire, which began in late June 2007 (around ordinal day 175), may be responsible for reducing transparency immediately after this time. The drop in transparency occurs at the Index site, but not at the Midlake site which is further offshore and about 10 km further from the site of the forest fire. The observed decrease is more pronounced in UV wavelengths than in PAR, suggesting that the forest fire reduced UV transparency more than it reduced PAR transparency. This has important ecological implications. *Goldman* [1988] related lake productivity to forest fire conditions where fire activity decreases light inhibition and greatly increases phytoplankton productivity and efficiency. We also noted an increase in chlorophyll *a* at day 191 at the Index site. He also speculated that forest fire activity could be responsible for some debris found in the water column. Research further suggests that forest fires in Northern California and throughout the Rockies have increased over the last several decades likely due to both climate and land use changes [*Westerling et al.*, 2006]. Because UV transparency was suddenly reduced at the same time the forest fire spread through Lake Tahoe's watershed, UV transparency may be a sensitive tool to understand and measure the impact of climate and land use changes such as forest fire activity, on aquatic ecosystem processes. Because of the immediate change in transparency, the transparency change was likely induced by allochthonous deposition of material rather than stimulation of autochthonous productivity; however, the increase in chlorophyll *a* at day 191 could have impacted transparency on this date, and the fact that we have data on only a single event makes these relationships speculative at this point.

[30] Collection of UV as well as PAR/visible/Secchi data clearly has the potential to provide more insight into how lake ecosystems respond to environmental change than Secchi transparency or visual/PAR measurements alone. Whereas we found significant relationships between transparency and chlorophyll *a*, transparency may be responsive to more than just changes in chlorophyll *a* [*Edmondson*, 1980; *Megard et al.*, 1980; *Lorenzen*, 1980]. UVR provides a stronger signal of change than do either PAR or Secchi depth and responds somewhat differently to common environmental drivers. Secchi transparency is a universally accepted, inexpensive, and easy-to-use metric. Secchi depths also provide a single value, integrating transparency over the entire Secchi depth. UV profiles, on the other hand, integrate over a much smaller depth range. While *Morris et al.* [1995] found "little evidence of vertical heterogeneity of Kd" across 65 sites from 59 lakes in Alaska, Colorado, the northeastern United States, and the Bariloche region of Argentina, we found that in Lake Tahoe, with its extremely high transparency and large size, transparency often decreased with increasing depth. This indicates that light absorption varies within the water column and that deeper depth profiles are more accurate to determine UVR penetration in clear lakes.

[31] Beyond the ecological and biological implications of variations in UV transparency such as those we observed in Lake Tahoe, research on attenuation characteristics has potentially important resource management implications. UV transparency provides a much stronger signal of environmental change across spatial and temporal gradients than does PAR transparency or Secchi depth. Therefore, measuring and monitoring UV transparency may provide an important advanced indicator of how ecosystems are changing in response to a suite of factors including anthropogenically induced changes in climate and land use. By understanding how UV attenuation is altered seasonally and spatially, the factors controlling transparency shifts can be better related to either shorter-term processes or longer-term changes that require different types of management strategies.

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