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Optically active substances and their contributions to the underwater light climate in Lake Taihu, a large shallow lake in China

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With 4 figures and 1 table

Abstract: There are few data sets on optically active substances and optical conditions to partition the relative contribution of every substance on light attenuation in a lake. To address this need, underwater photosynthetically active radiation (PAR), optical parameters and concentrations of three optically active substances, tripton (non-phytoplankton particulate matter), chlorophyll-*a* (Chl-*a*), chromophoric dissolved organic matter (CDOM) were measured at 67 sites in Lake Taihu, a large shallow lake in China in October 2004. The spatial variation of optically active substances and their relative contributions to the underwater light climate were determined. The PAR diffuse attenuation coefficient K_d(PAR) at different sites varied between 0.87 and 12.43 m^{-1}, with a mean of 4.42 m^{-1}. Significant spatial differences were found for optically active substances and PAR attenuation, with low concentrations and weak light attenuation in macrophyte-dominated bays such as East Lake Taihu, Xukou Bay and Gongshan Bay, and high concentrations and strong light attenuation in the open water and algae-dominated areas such as the center of the lake, southwestern region, and Meiliang Bay. The mean relative contributions of tripton, Chl-*a*, and CDOM to light attenuation were 82.6 %, 9.7 %, and 6.8 % of K_d(PAR), respectively. Tripton was the dominant constituent of K_d(PAR), and mean of 97.5 % of the variation in K_d(PAR) could be explained by tripton. In autumn, the relative contribution of CDOM to light attenuation was lower than that of phytoplankton. We conclude that suspended particulate matter, rather than dissolved organic matter, is the dominant factor for PAR attenuation in Lake Taihu.

Key words: tripton; chlorophyll-*a*; CDOM; diffuse attenuation coefficient; Lake Taihu.

Introduction

The optical properties of a water body and the concentrations of optically active substances determine the underwater light climate, which is important for submersed aquatic vegetation (SAV) as well as the appearance of the water. The light availability affects both biomass and community structure of phytoplankton and SAV. Attenuation of the underwater light is controlled by four substances, namely tripton (non-phytoplankton particulate matter calculated from total suspended matter and chlorophyll-*a*, phaeophytin), phytoplankton, chromophoric dissolved organic matter (CDOM) and pure water (Kirk 1994). There are marked differences in the concentrations of optically active substance and their relative contributions to light attenuation for different waters and seasons (Phlips et al. 1995, Christian & Sheng 2003, Lund-Hansen

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2004). Understanding the individual contributions of these different constituents to attenuation of photosynthetically active radiation (PAR) is important for the prediction of the underwater light climate from the constituent concentrations. Therefore, many studies have succeeded to partition their relative contributions to attenuation of PAR (Phlips et al. 1995, Christian & Sheng 2003, Lund-Hansen 2004). However, most of these studies were focused on estuaries and lagoons, and little information is available for lakes.

Lake Taihu is a subtropical, large, shallow lake, with a water area of 2,338 km^2 located in the economically developed Yangtze River Delta in China. Any variations in river input, phytoplankton blooms, and sediment resuspension will result in changes in the underwater light climate. For example, a previous study in summer based on the successive observation demonstrated that sediment resuspension in this shallow lake could significantly affect the underwater light climate (Zhang et al. 2006). Since approximately 1985, much of the submersed aquatic vegetation has been lost, which in many cases has been attributed to increased light attenuation in the water column, due to input of pollutants from rivers, lake eutrophication, and sediment resuspension driven by waves (Qin et al. 2004).

In order to take management action and restore an underwater light climate that permits the growth of SAV, it is necessary to know how the PAR diffuse attenuation coefficient [K_d(PAR)] depends on the constituent concentrations and the individual contribution of these different constituents in different lake regions and seasons. Furthermore, the accuracy of the remote sensing retrieval algorithm for total suspended matter (TSM) and chlorophyll-*a* (Chl-*a*) in Lake Taihu is also affected by the apparent optical properties of water (including the diffuse attenuation coefficient, euphotic depth [Z_{eu}(PAR)] and Secchi disc (SD) depth), and their dependence on the relative contribution of tripton, phytoplankton and CDOM.

The aims of this study were to determine (i) the spatial variability of three optically active substances (tripton, Chl-*a* and CDOM) and three apparent optical properties (K_d(PAR), Z_{eu}(PAR), SD) in Lake Taihu in autumn, 2004, (ii) the relationship between the constituent concentrations and apparent optical properties, (iii) the relative contribution of tripton, Chl-*a* and CDOM to K_d(PAR), and (iv) the potential effect of the underwater light climate on SAV.

Material and methods

Samples were collected from 67 sites during a cruise between October 20 and October 29, 2004 (Fig. 1). Surface water (0.5 m) for CDOM absorption, Chl-*a* analysis and suspended particles, was collected in 1500 ml bottles and was held on ice while in the field. The water samples were usually sent, in the afternoon, to the Taihu Laboratory for Lake Ecosystem Research (TLLER), Chinese Academy of Sciences, located in the littoral of Meiliang Bay, and subsequently kept at 4 °C until analysis. The other samples that were not sent in the afternoon were frozen in the refrigerator at 0 °C.

Downwelling PAR was measured on the sunny side of the boat, just below the water surface (0 m), and at five depths (0.2, 0.5, 0.75, 1.0, 1.5 m), using a Li-Cor 192SA sensor connected to a Li-Cor1400 datalogger. Diffuse attenuation coefficients for downward irradiance K_d(PAR) were obtained from the nonlinear regression of the underwater irradiance profile (Kirk 1994). Only K_d(PAR) values from regression fits of $r^2 \geq 0.95$ were accepted. The number of depths used in these fits was never less than three, depending on the penetration depth (Huovinen et al. 2003).

Biologically, the euphotic zone is defined as the upper layer of water that is irradiated with sufficient light to support photosynthesis. Its lower boundary is often roughly defined as a depth at which PAR falls to 1 % of its value just under the surface. Therefore, euphotic depth [Z_{eu}(PAR)] was calculated as: $Z_{eu}(PAR) = 4.605/K_d(PAR)$ where K_d(PAR) is PAR diffuse attenuation coefficient. A widely used apparent optical parameter, transparency (SD) was measured with a 30 cm diameter black and white quadrant (Secchi) disk.

The CDOM samples were gently filtered through precombusted 0.7 µm pore Whatman GF/F fiberglass filters (Rochelle-Newall & Fisher 2002, Frenette et al. 2003, Callahan et al. 2004) and collected into glass bottles, pre-combusted in an oven at 550 °C for 6 h. Although in many other studies CDOM was obtained through 0.22 µm pore Millipore filters, in this study we defined the organic matter that remained in solution through our 0.7 µm pore GF/F filters as dissolved organic matter (DOM). We used glass fiber GF/F filters instead of 0.22 µm nltrocellulose Millipore filters because they could be precombusted to avoid contamination (Laurion et al. 2000, Yoro et al. 1999). In fact, we compared 0.22 and 0.7 µm pore size filters for differences in CDOM absorption, and found that the differences were almost negligible because the pores will be blocked quickly due to the high concentration of TSM in shallow lake when water sampling is gently filtered.

Absorption spectra of the filtrate were obtained between 240 and 800 nm at 1-nm intervals, using a Shimadzu UV-2401-PC UV-Vis recording spectrophotometer equipped with matching 4-cm quartz cells. Milli-Q water was used in the reference cell. The absorption coefficients were obtained by:

$$a(\lambda') = 2.303D(\lambda)/r \quad (1)$$

where $a(\lambda')$ was uncorrected CDOM absorption coefficient at wavelength λ, $D(\lambda)$ was the optical density at wavelength λ, and r was the cuvette path length in m.

Absorption coefficients were corrected for backscattering of small particles and colloids which pass through filters using Equation (2) (Bricaud et al. 1981).

$$a(\lambda) = a(\lambda') - a(700')\,\lambda/700 \quad (2)$$

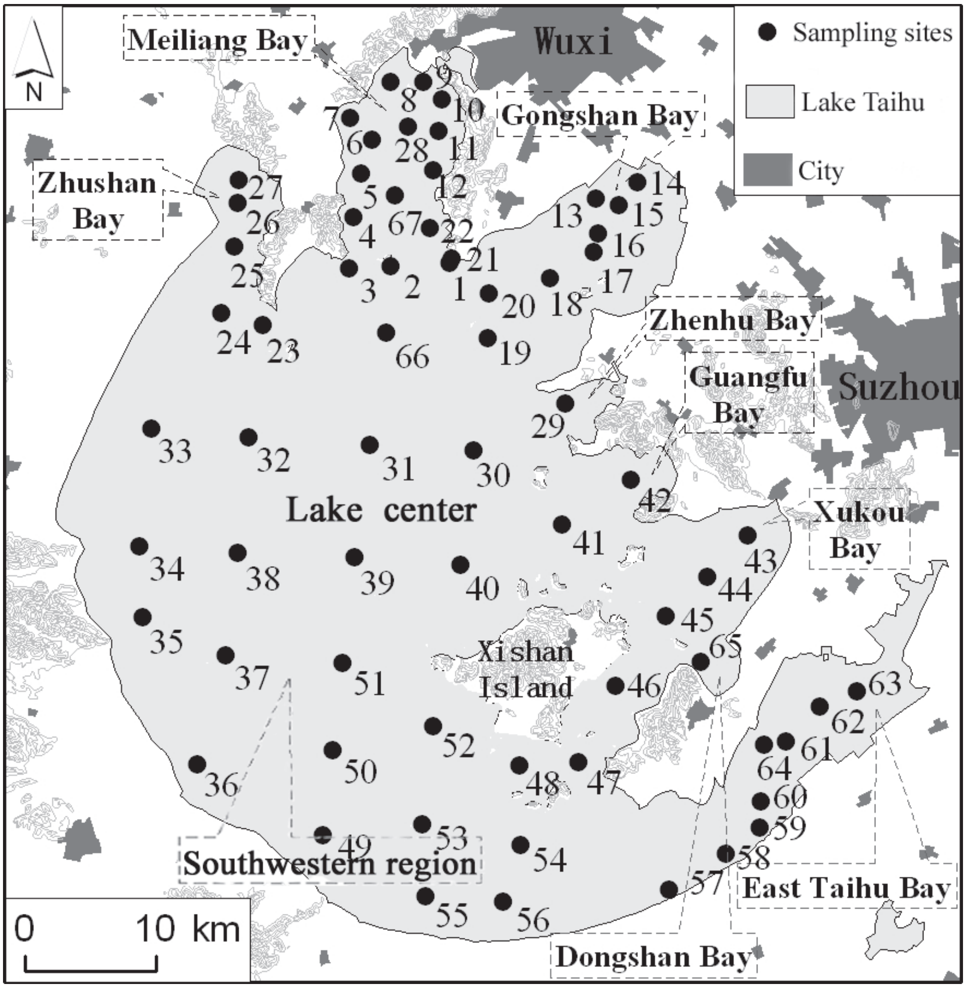

Fig. 1. Location of sampling sites in Lake Taihu October 20 to October 29, 2004.

where $a(\lambda)$ = absorption coefficient at a given wavelength (λ) corrected for scattering, $a(\lambda')$ = measured absorption coefficient at a given λ, $a(700')$ = measured absorption coefficient at 700 nm corrected for scattering.

Samples for Chl-*a* were filtered on Whatman GF/C fiberglass filters. The Chl-*a* and phaeophytin-*a* (P-*a*) were extracted with ethanol (90 %) at 80 °C and analyzed spectrophotometrically at 750 and 665 nm with correction for phaeophytin-*a*.

To obtain TSM, water samples were filtered through precombusted Whatman GF/C fiberglass filters (450 °C for 4 h) to remove suspended organic matter, dried (105 °C for 4 h), and weighed.

For the separation of the dry weight of tripton from the dry weight of total particles, the following algorithm was used by Hoogenboom & Dekker (1997) (for Dutch inland waters):

$$\text{Tripton} = \text{TSM} - 0.07\,(\text{Chl-}a + \text{P-}a) \quad (3)$$

where Tripton is tripton concentration; TSM is total suspended matter concentration; Chl-*a* and P-*a* are chlorophyll-*a* and phaeophytin-*a* concentrations, respectively. In the present study we assumed that the relationship between the dry weight of total particles in Lake Taihu was comparable to that in Dutch inland waters considering that Lake Taihu was close to the eutrophic shallow lakes in the Netherlands, and thus we used the same algorithm.

For the partitioning of K_d(PAR) into components, we assumed that K_d(PAR) is the sum attenuation of pure water K_w(PAR), CDOM K_{CDOM}(PAR), phytoplankton K_{PH}(PAR) and tripton K_{TR}(PAR) (Kirk 1994, Phlips et al. 1995). Light attenuation by pure water K_w(PAR) is taken as a constant of 0.027 m^{-1} (Smith & Baker 1978). The K_{CDOM}(PAR) is estimated using Pfannkuche's (2002) relation: $K_{CDOM}(\text{PAR}) = 0.221a(440)$ where $a(440)$ is the CDOM absorption coefficient measured at 440 nm. The mean PAR specific attenuation coefficient in Lake Taihu is known to be 0.246 (determined from *Microcystis* experiments) (Wu et al. 2005). A long term monthly monitoring study (1995–2003) by the Taihu Lake Laboratory Ecosystem Research station, the Chinese Academy of Sciences, showed that *Microsystis* spp. was the dominant phytoplankton species in autumn. Therefore, K_{PH}(PAR) was estimated from the mean PAR specific attenuation coefficient and Chl-*a* concentration. Light attenuation of tripton K_{TR}(PAR) was calculated as

$$K_d(\text{PAR}) - (K_w(\text{PAR}) + K_{CDOM}(\text{PAR}) + K_{PH}(\text{PAR})).$$

Arcgis software was used to obtain the spatial patterns of optically active substances and optical properties within the lake.

Results

Spatial distribution of tripton, Chl-*a* and CDOM

In Lake Taihu, the optically active substance concentrations and the optical properties were all very variable (Table 1). There were marked spatial variations in the three optically active substances: tripton, Chl-*a* and CDOM (Fig. 2 a–c). Tripton concentration ranged from 2.95–167.81 mg l^{-1}, with a mean of 45.02 mg l^{-1}. It was highest in the southwestern open lake region, with the highest value of 167.81 mg l^{-1} at site 49, which was 57 times that of the lowest value of 2.95 mg l^{-1} at site 57 located in the southeastern littoral macrophyte-dominated zone. Chl-*a* ranged from 1.21 to 53.59 μg l^{-1} with a mean of 14.39 μg l^{-1}. It was generally highest in the northern lake regions, with the highest value at site 22 in Meiliang Bay (Fig. 2b). The lowest value was found at site 57 located in the southeastern littoral macrophyte-dominated zone. The CDOM displayed a similar spatial trend as Chl-*a,* with higher CDOM absorption in the northern lake regions than in other lake regions (Fig. 2c). Generally, the lowest values for tripton, Chl-*a* and CDOM were recorded in macrophyte-dominated lake bays such as East Taihu Bay.

Spatial distribution of K_d(PAR), Z_{eu}(PAR) and SD

The spatial distributions of K_d(PAR), Z_{eu}(PAR) and SD are shown in Fig. 2d–f. The K_d(PAR) ranged from 0.87 m^{-1} at site 57, to 12.43 m^{-1} at site 49 (Table 1). The highest value was about 14.3 times of the lowest value. The coefficient of determination (r^2) for the fit of K_d(PAR) was consistently higher than 0.99, with a mean value of 0.9964, suggesting that the water column was vertically homogeneous. Lower light penetration was generally observed in eastern bays such Gongshan Bay and East Taihu Bay, and higher K_d(PAR) was generally recorded in the open water region including the lake center and the southwestern lake region (Fig. 2d). In contrast, Z_{eu}(PAR) displayed the opposite spatial trend to K_d(PAR), with higher values in the eastern bays and lower values in the open water of the lake center and the southwestern lake regions (Fig. 2e). The spatial distribution of SD was similar to that of K_d(PAR) (Fig. 2f).

A highly significant power correlation was recorded between K_d(PAR) and SD ($K_d(PAR) = 193.44\ SD^{-1.050}$, $R^2 = 0.94$, $P < 0.0001$), which demonstrated PAR attenuation could be approximated by SD for those cases where underwater PAR was not measured.

Correlation between K_d(PAR) and tripton, Chl-*a* and CDOM

The major variables related to light attenuation included in this study were tripton (non-phytoplankton particulate matter), Chl-*a* (an estimator of living phytoplankton in the water column), and CDOM. For the pooled data set of all samples, K_d(PAR) was most strongly correlated to tripton (Fig. 3a), and some 97.5 % of the variation in K_d(PAR) could be explained by tripton. In contrast, K_d(PAR) was not significantly correlated to Chl-*a* or to the CDOM absorption coefficient. This was not surprising, considering the generally low Chl-*a* and CDOM values observed in autumn, but the comparatively high tripton in shallow lake due to sediment resuspension caused by wind action. Furthermore, a stepwise multiple linear regression of K_d(PAR) versus tripton, Chl-*a* and CDOM (using *a*(440) as the concentration of CDOM) for all sites, only resulted in an additional increase of 0.4 % in explaining the variation of K_d(PAR) compared with tripton only. Similarly, a significant positive correlation was found between transparency and tripton concentration (Fig. 3b).

The PAR attenuation due to tripton could be expressed as the specific-diffuse attenuation coefficient K_{TR}*(PAR) and tripton concentration: $K_{TR}(PAR) = K_{TR}^*(PAR)Tripton$. In many water color and water quality algorithms, the values of K_{TR}^*(PAR) are considered constantly and this is the important input parameter of models. The linear correlation between K_{TR}(PAR) and

Table 1. Summary of optically active substances and optical properties in Lake Taihu for October, 2004.

	TSM (mg l^{-1})	Tripton (mg l^{-1})	Chl-*a* (μg l^{-1})	*a*(440) (m^{-1})	K_d(PAR) (m^{-1})	Z_{eu}(PAR) (m)	SD (cm)	Depth (m)
Minimum	3.10	2.95	1.21	0.33	0.87	0.37	15	1.3
Maximum	169.47	167.81	53.59	2.05	12.43	5.27	180	3.0
Mean	46.54	45.02	14.39	1.03	4.42	1.51	52	2.2
Standard deviation	38.34	38.14	9.13	0.39	2.64	1.06	36	0.4

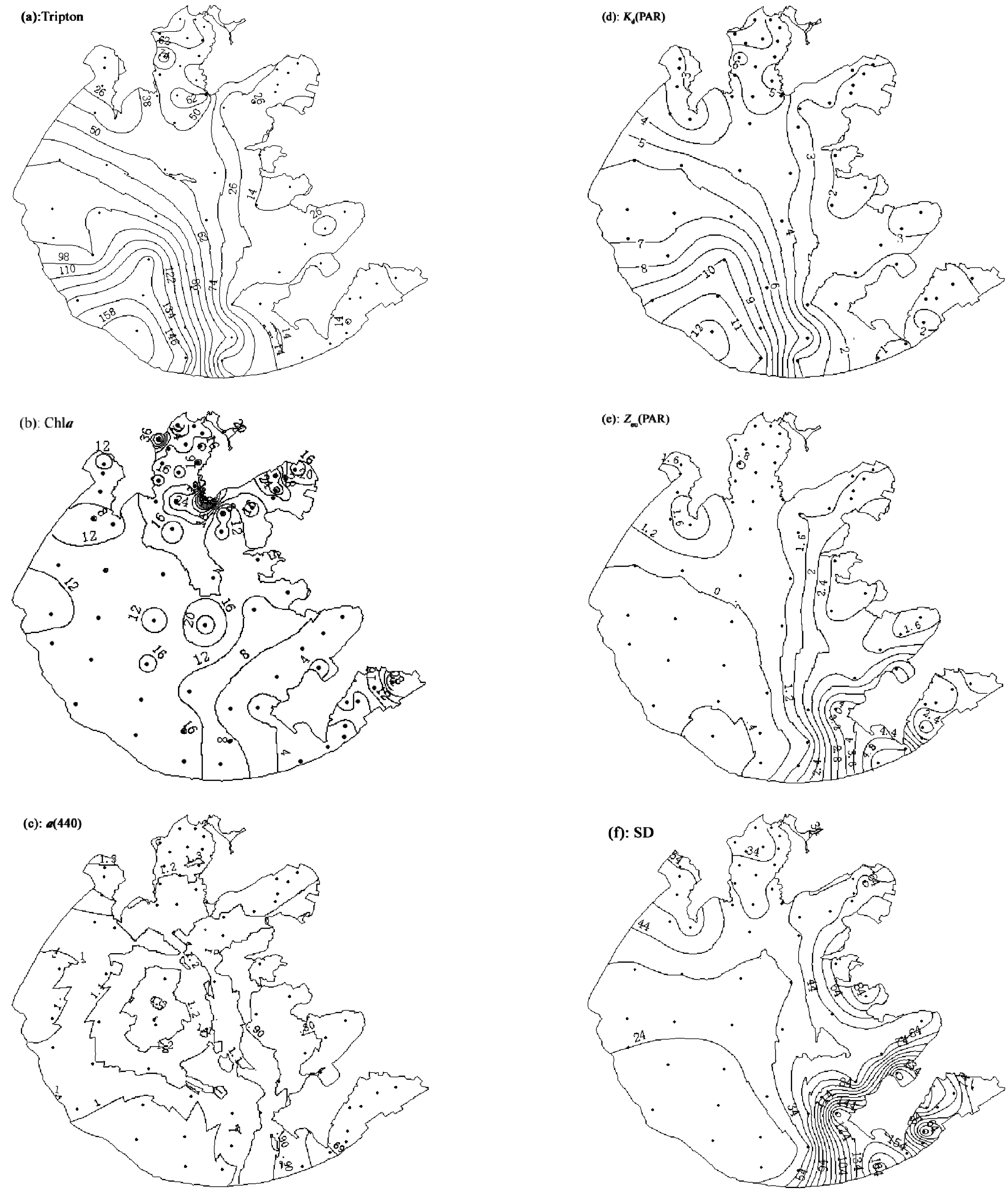

Fig. 2. Spatial pattern of optically active substances and apparent optical properties in Lake Taihu in October 2004. **(a):** Tripton concentration (mg l^{-1}); **(b):** Chl-*a* concentration (μg l^{-1}); **(c):** CDOM absorption coefficient $a(440)$ (m^{-1}); **(d):** PAR diffuse attenuation coefficient (m^{-1}); **(e):** PAR euphotic depth (m); **(f):** transparency (cm).

tripton concentration without intercept is as follows: $K_{TR}(PAR) = 0.0775Tripton$ ($R^2 = 0.94$, $P < 0.0001$), which showed that the specific-diffuse attenuation coefficient $K_{TR}^*(PAR)$ of tripton was 0.0775 m^{-1}. If the intercept of the regression is estimated as well, the correlation coefficient becomes only marginally better ($R^2 = 0.98$, $P < 0.0001$), yielding: $K_{TR}(PAR) = 0.0673Tripton + 0.7862$ ($R^2 = 0.98$, $P < 0.0001$).

Relative contribution of tripton, Chl-*a*, CDOM and pure water to K_d(PAR)

The percentage of K_d(PAR) due to tripton, Chl-*a*, CDOM and pure water is each plotted against K_d(PAR) in Fig. 4a–d. The relative contributions of tripton, Chl-*a*, CDOM and pure water to K_d(PAR) were 58.1–95.9 %, 2.8–34.6 %, 0.8–22.8 %, and 0.2–3.1 %, respectively. The mean contributions of tripton, Chl-*a*, CDOM and pure water were 82.6, 9.7, 6.8, and 0.9 %, respectively. Tripton plays a dominant role in PAR attenuation. A division K_d(PAR) is carried out at K_d(PAR) = 2.0 m^{-1}. Below K_d(PAR) = 2.0 m^{-1}, Chl-*a*, CDOM and pure water have a greater influence on K_d(PAR) (11.3, 11.0 and 2.0 %, respectively), than at higher K_d(PAR), (9.4, 6.0 and 0.7 %, respectively). At K_d(PAR) values be-

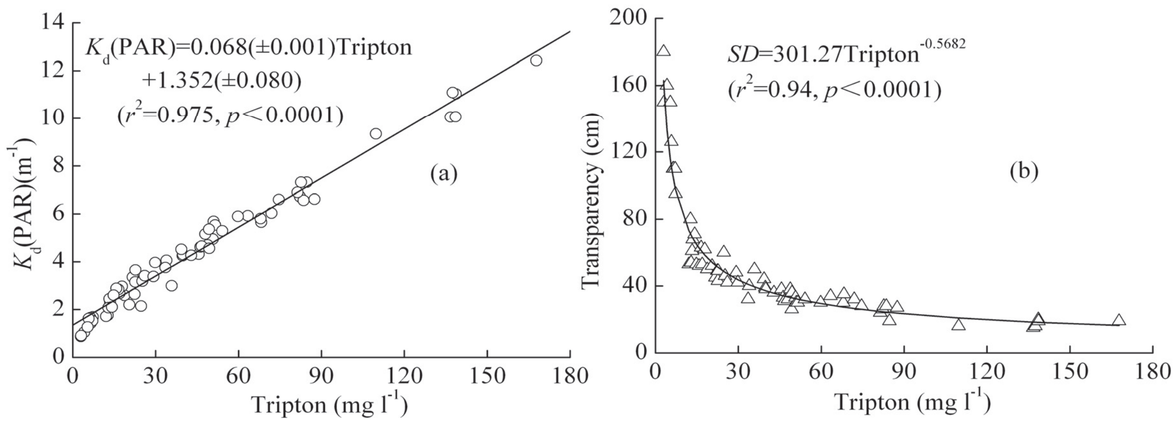

Fig. 3. Correlations between K_d(PAR) **(a)**, transparency **(b)** and tripton concentration.

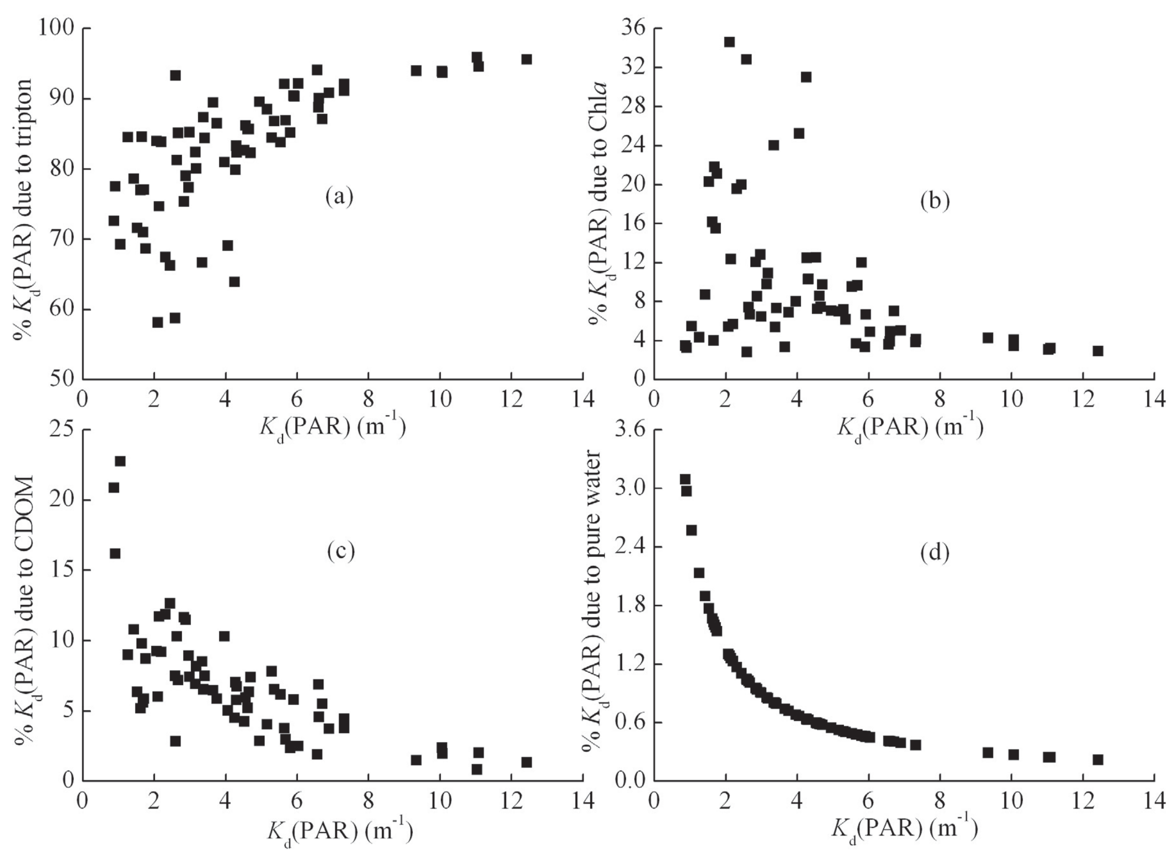

Fig. 4. The relative contributions of tripton **(a)**, Chl-*a* **(b)**, CDOM **(c)** and pure water **(d)** to K_d(PAR).

low 2 m^{-1}, tripton accounts for a mean of 75.7 % of K_d(PAR). Above K_d(PAR) = 2.0 m^{-1}, however, tripton accounts for a mean of 83.9 % of K_d(PAR). Therefore, the relative influence of Chl-*a*, CDOM and pure water increases when K_d(PAR) decreases, while the influence of tripton decreases but it still remains the most important optically active substance contributing to PAR attenuation.

Discussion

In Lake Taihu, the optically active substances were highly inhomogeneous spatially, which was attributed not only to differences among the lake regions, but also to the distribution of sampling sites. The large dimensions of the lake meant that it was not feasible to have extensive sampling throughout the lake, and samples could be collected most easily in the bays. Therefore, the distribution of the sampling sites in some of the bays and the central part was uneven. Additionally, in this study we only had one sampling campaign, conducted in autumn. The spatial distribution pattern of the optically active substances and their relative contributions to PAR attenuation may be different in other seasons.

In Lake Taihu as a whole, light attenuation was most strongly affected by tripton. This optically active substance accounted for 58.1–95.9 % of PAR attenuation, with a mean of 82.4 %. As a result, Tripton showed the highest correlation to K_d(PAR). This large effect of tripton is mainly caused by strong sediment resuspension, which is particularly important in shallow polymictic aquatic ecosystems, such as Lake Taihu (Blom et al. 1994, James et al. 1997, 2004, Phlips et al. 1995).

In different areas of Lake Taihu, there were marked regional differences in the relative roles of tripton, Chl-*a* and CDOM to PAR attenuation. In the eastern regions of the lake such as Gongshan Bay, Zhenhu Bay, Guangfu Bay, Xukou Bay, Dongshan Bay, and East Taihu Bay, the relative contribution of tripton to K_d(PAR) was lower compared to the northern and open lake regions. These eastern bays are characterized by abundant SAV communities, and small waves, which suppress sediment resuspension. In the northern regions, including Meiliang Bay and Zhushan Bay, high concentrations of Chl-*a* from frequent algal blooms, indicated a relatively high contribution of phytoplankton to K_d(PAR) especially in summer. For example, the interannual monthly mean Chl-*a* concentration in Meiliang Bay was 50.1 μg l^{-1} in summer (June–August), but only 28.6 μg l^{-1} in autumn (September–November), from 1995 to 2003 based on the monthly monitoring data of the Taihu Lake Laboratory Ecosystem Research station of the Chinese Academy of Sciences. In those situations with small waves and algal blooms present, the relative contribution of Chl-*a* to PAR attenuation often exceeded that of tripton. The southwestern and central open water regions (sites 30–40 and 49–55) are characterized by strong wind waves and sediment resuspension, and few algal blooms, therefore the high K_d(PAR) observed in these regions is the result of high tripton concentration.

In shallow lakes, sediment resuspension driven by waves has a great effect on tripton concentration and light attenuation (Zhang et al. 2006). Lake Taihu is such a typical large shallow lake, having a mean water depth of 1.9 m and water surface area of 2,338 km^2. In order to assess the sediment resuspension, we calculated the dynamic ratio, (the square root of the surface area divided by mean depth (Hakanson 1982)), and derived the value of 25.6 km m^{-1}. A previous study by Bachmann et al. (2000) found that sediment resuspension would be driven by wave disturbance when the dynamic ratio was larger than 0.8 km m^{-1}. Therefore, since the dynamic ratio in Lake Taihu considerably exceeds this, we consider that 100 % of the lake bottom is subject to sediment resuspension.

Our previous successive observations at a fixed sampling site showed a significant positive correlation between wind speed (range 3.5–7.0 m s^{-1}) and K_d(PAR) in Lake Taihu (Zhang et al. 2006). Due to malfunction of the anemoscope at some sites, wind speed was available only for sites 1–17 of the 67 sites to evaluate the effect of sediment resuspension on the underwater light climate. Wind speed (range 1.0 – 4.8 m s^{-1}, mean 3.33 m s^{-1}) was significantly and positively correlated with K_d(PAR) in the present study ($r^2 = 0.31$, $p < 0.05$, $n = 17$); however, this correlation is much lower than the correlation from the fixed sampling site ($r^2 = 0.89$, $p < 0.0001$, $n = 16$) because of the confounding effects of many factors including wind speed and direction, fetch length, time scale, sediment, and SAV. Nevertheless, we still were able to conclude that sediment resuspension had a marked effect on PAR attenuation. In addition, boat traffic often leads to increased light attenuation by disturbing the sediment and increasing tripton due to the shallow water depth. Distinct TSM belts marking the main boat-routes can be seen in remote sensing images.

For shallow lakes, many studies demonstrate that changes in tripton concentration can significantly influence PAR attenuation (Somlyody & Koncsos 1991, Blom et al. 1994, Phlips et al. 1995, James et al. 1997, 2004, Van Duin et al. 2001, Pierson et al. 2003). In contrast, there are no studies for lakes that partition the relative contribution of tripton, Chl-*a* and CDOM to the underwater light climate. In estuaries tripton can also account for a high percentage of the PAR attenuation (Phlips et al. 1995), and the relative contributions of tripton, Chl-*a* and CDOM have been studied. For example, 75 %, 14 %, 7 %, respectively in Florida Bay (Phlips et al. 1995); 73 %, 4 %, 21 %, respectively in Charlotte Harbor (McPherson & Miller, 1987); and 59–78 %, 10–26 %, and 5–25 %, respectively in Indian River Lagoon (Christian & Sheng, 2003). The relative contributions of tripton, Chl-*a* and CDOM in Lake Taihu are 58.1–95.9 %, 2.8–34.6 %, and 0.8–22.8 % in autumn, respectively. A further similarity in the conditions in a lake and in an estuary or lagoon is shown by the specific-diffuse attenuation coefficient K_{TR}^*(PAR) of tripton. In Lake Taihu K_{TR}^*(PAR) was 0.0775 with an intercept of 0 or 0.0673 with an intercept of 0.7862 m^{-1}, and a very close value in the Indian River Lagoon is 0.0669 with an intercept of 0.4999 m^{-1} (Christian & Sheng 2003).

The importance of light availability in controlling the maximum depth of SAV in aquatic ecosystems is well established (Duarte 1991, Gallegos 2001). Several different model relationships between light attenuation and depth maxima for SAV D_m have been presented in the literature including $D_m = 1.36/K_d$(PAR) (Vincente & Rivera 1982), and $D_m = 1.86/K_d$(PAR) (Duarte 1991, Gallegos 2001). If we assume the relationship $D_m = 1.86/K_d$(PAR) is suitable for Lake Taihu, only seven of the 67 sites (sites 47, 57, 58, 61, 62, 64, 65) have the maximal SAV depth D_m greater than the water depth, thus indicating that in the remaining lake regions, light probably limits SAV. The in situ cruise investigation also shows that these 7 sampling sites are characterized by high SAV coverage. However, during our sampling period, SAV was often observed in other sites, particularly in the east, in Gongshan Bay, Xukou Bay and East Taihu Bay. Therefore, we assume that in these sites, the euphotic depth is the maximal depth of SAV distribution. A total of 12 sites, all in the eastern bays, had the ratio of D_m to water depth > 1. In fact, we found SAV was distributed in these regions with the ratio of D_m to water depth > 0.8, including sites 14–17 in Ganshan Bay, 29 in Zhenhu Bay, 41–48 in Xukou Bay, and 57–65 in East Taihu Bay. Havens (2003) reported that in Lake Okeechobee, a large shallow lake in the southeastern United States, dense SAV was found only where water depth was < 2 m and TSM < 20–30 mg l^{-1}. Our study in Lake Taihu confirms the distribution pattern of SAV for the water depth and TSM concentration ranges presented by Havens (2003). It should be also noted that these regions in Lake Taihu with SAV are a sheltered bay, reducing the possibility for resuspension by wind. Furthermore, the presence of SAV reduces resuspension of particulate matter. These combined characteristics (small bay, low wind resuspension, SAV) are consistent with low light attenuation (Fig. 2d). For other lake regions, there is a potential for light limitation of SAV growth because of high light attenuation, and almost no SAV are found.

Summary

Based on analysis of data collected throughout Lake Taihu in autumn, there was a significant spatial difference in the concentration of three optically active substances (tripton, Chl-*a*, and CDOM), which resulted in significant spatial differences in apparent optical properties (K_d(PAR), Z_{eu}(PAR), SD). Of the three optically active substances, tripton had the greatest influence on the light attenuation coefficient. The relative influences of Chl-*a*, CDOM, and pure water increased when K_d(PAR) decreased, while tripton became somewhat less important. Additional sampling in other seasons will provide more accurate temporal-spatial distributions of the optically active substances and their relative contributions to PAR attenuation in future studies.

In most of the lake regions, SAV growth was limited by the underwater light climate. The significant effect of tripton on PAR attenuation, and the limitation of the underwater light climate on SAV have major implications for Lake Taihu restoration planning and management strategy. In order to restore SAV, the tripton concentration must be decreased, and the underwater light climate must be improved. The restoration of SAV is recommended in bay or littoral zones with low wave action and shallow depth. Some strategies for reducing tripton concentration are presented, including artificially reducing waves by use of enclosures, and minimizing boat-induced sediment resuspension.

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