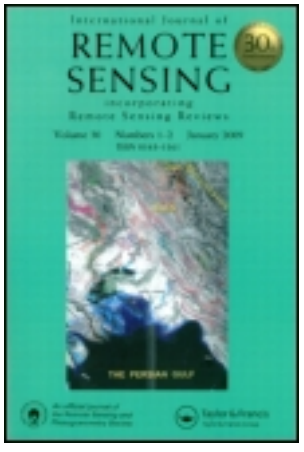

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Absorption and scattering properties of water body in Taihu Lake, China: absorption

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Absorption and scattering properties of water body in Taihu Lake, China: absorption

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In order to acquire inherent optical properties to serve the lake water colour/quality remote sensing in Taihu Lake 67 samples were distributed almost all over the lake. Surface water samples were collected and returned to the laboratory for the subsequent processing and analysis. In the laboratory, the absorptions due to the total particulate matter, non-algal particulate matter, phytoplankton pigment, and CDOM, together with their concentrations were measured and/or calculated, respectively. Then their absorption properties were analysed and compared with those of other lake waters and/or coastal/open waters. Some different and similar characteristics were uncovered. On the one hand, it provides not only a solid basement for the Taihu Lake water colour/quality remote sensing with semi-analytical/analytical approach but also a typical case for inherent optical properties of case two water especially for inland freshwater lakes. On the other, it is very helpful to improve the practical and intensive application and development of remote sensing in monitoring lake water quality.

1. Introduction

Amongst the three approaches for water colour remote sensing, i.e. theory approach, empirical approach and semi-empirical or semi-analytical approach, the semi-analytical approach has been paid more and more attention with optical field equipments becoming available, resulting in a bio-optical model. Inherent optical properties (IOPs), including absorption and scattering of optically active substances, play a vital role in the bio-optical model for the semi-analytical approach. The parameters of IOPs, together with bio-optical models, have a little difference in different water bodies, even in different areas of the same water body (Cao and Huang 2004). Care must be taken to calibrate the model to the water body of interest, and attention must be paid to the accuracy and variability in model parameterization (Pierson and Strömbeck 2001). Accordingly, with more and more embedded applications of bio-optical models and development of a semi-analytical approach, more and more attention should be paid firstly on regional parameterized IOPs and bio-optical models, and the obvious way to increase the precision of

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bio-optical models is to increase measurements of IOPs (Strömbeck 2001), which additionally is one of the important procedures to parameterize the regional pattern. In case one waters, the optically active substances are mainly phytoplankton pigment, or chlorophyll, and there are about 15 sensors mainly for case one water colour remote sensing, such as Coastal Zone Color Scanner (CZCS, 1978–1986), Sea-viewing Wide Field-of-view (SeaWiFS, 1997–present), MODerate-resolution Imaging Spectroradiometer (MODIS, 1999–present), Chinese Ocean Colour and Temperature Scanner (COCTS, 2002–present), Medium Resolution Imaging Spectrometer (MERIS, 2002–present), which are superior in some aspects such as repeat cycle, narrow spectral bands and greater radiometric resolution but smaller spatial resolution. Actually, the area of the lake is greatly less than that of the sea. Smaller spatial resolution means smaller spatial precision of lake water constituents, and some details less than the spatial resolution are covered entirely. Consequently, some change of lake water quality could not be precisely monitored using sensors for case one water colour remote sensing, especially at some specially appointed sites. However, it is a pity that no specially designed satellite sensors for lake water colour/quality remote sensing are available up to now. Most of early the studies were performed using some sensors primarily designed for terrestrial applications (Strömbeck 2001), such as Landsat MSS/TM/ETM+, SPOT, which have higher spatial resolution, generally meeting one of the needs of lake water quality/colour remote sensing, but lower spectral resolution, not corresponding with spectral features of water constituents, and lower sensitivity, such as Landsat ETM+ is 4–5 times less sensitive than MODIS (Hu *et al.* 2004). Also, they mainly employed the empirical approach, whose disadvantages become more and more evident with more and more in-depth applications. Concurrently, the semi-analytical algorithm, widely used in case one water remote sensing, is being paid more and more attention. Up to now, several great projects for case two waters, especially for natural lakes such as European project SALMON (Strömbeck 2001) have been implemented. Absorptions and/or backscattering of all or some of the optically active substances, and/or together with a semi-analytical approach in some lakes such as Lake Ontario in US (Bukata *et al.* 1981, 1991), Chilko Lake in British Columbia (Gallie and Murtha 1992), Finnish and Estonian lakes (Mäekivi and Arst 1996, Kallio 1999, Reinart 2000), Albano Lake in Italy (Lai *et al.* 2000), Swedish lakes especially including Lake Erken, Lake Vättern, Lake Vänern and Lake Mälaren (Pierson and Strömbeck 2001, Strömbeck 2001, Strömbeck and Pierson 2001, Ammenberg *et al.* 2002), Lake Baikal in Russia (Balkanov *et al.* 2003) and so on, have been measured in the lab and/or in the field. But in Taihu Lake with typical case two water, IOPs and Apparent Optical Properties (AOPs) of the whole water body, vitally affecting Taihu Lake water colour/quality remote sensing with semi-analytical approach, have not been well known. The details about Taihu Lake can be seen from Ma and Dai (2005) and Ma *et al*. (2006). Its optically active substances includes suspended particulate matter (SPM) composed of suspended particulate inorganic matter (SPIM) and suspended particulate organic matter (SPOM), phytoplankton pigment mainly composed of chlorophyll-a (CHL), and Coloured Dissolved Organic Matter (CDOM), being an optically active component of dissolved organic carbon (DOC). Here, we call the three components of SPM, CHL and DOC or CDOM together by three-component.

This paper lays emphasis on absorption, including non-algal particulate absorption, phytoplankton pigment absorption, CDOM absorption and the total

absorption, and the objective is mainly to describe absorption properties of the optically active substances and their spatial variations.

2. Methods

The details about the campaign on 18–29 October, the alternant season from autumn to winter, 2004, including locations of all the 67 sampling, together with the measurements of concentrations and absorptions, can be seen from Ma *et al.* (2006). Here some supplemental details about bleaching in the non-algal particulate absorption are introduced. The filtered paper was dipped in 90% hot ethanol at 80°C with a volume of 5–20 ml, determined by the pigment magnitude. Then we rinsed the filters with distilled water and filtrated again.

The comparison method was used mainly between the measured data and their derivates, and the corresponding data from literatures so that the absorption properties of water body in Taihu Lake can be shown clearly. Additionally, linear or non-linear regression analysis was used widely in order to simulate regional absorption spectra/coefficients in the corresponding range or at some wavelength and to compare their parameters with the literature to discover the properties of Taihu Lake that differ from others. In internal aquatic ecosystems (as lakes), the analysis of the inherent and apparent optical properties can be represented with low uncertainty in the estimated points, using interpolation such as the kriging method when spatial resolution of the sampling stations is high (Bracchini 2005). However, the kriging method cannot make full use of the barrier polylines such as islands in the lake and the borders of lake, the interpolation with inverse distance weighted (IDW) in ESRI ArcGIS 9.0 was used in the range of the lake but the islands excluded, and then the ESRI grid file was transformed into coverage polygons, finally the polygons with area less than 10 km^2 were merged into their neighbours and all the polygons were re-edited to divide into different areas to show the spatial variation and distribution.

In order to uncover the spatial variation of contribution of individual component, the mean of contribution of individual component of each sample, r, in the range 400–700 nm is calculated by equation (1). Then, r of each component of each sample is summed, and then averaged to acquire the mean of each component in the whole waters, ra, by equation (2), for showing the general situation of contribution of each component. Additionally, ra' is calculated by equation (3) to show the variation of the mean contribution of each component as a function of wavelength in the whole waters.

$$r_{in} = \sum_{j=400}^{700} \left\{ \left[a_{in}(\lambda_j) / a_{tn}(\lambda_j) \right] / M \right\} \times 100\% \tag{1}$$

$$ra_i = \left(\sum_{n=1}^{67} r_{in} / N \right) \times 100\% \tag{2}$$

$$ra'_i(\lambda_j) = \left\{ \sum_{n=1}^{67} \left[a_{in}(\lambda_j) \right] \Big/ \sum_{n=1}^{67} \left[a_{tn}(\lambda_j) \right] \right\} \times 100\% \tag{3}$$

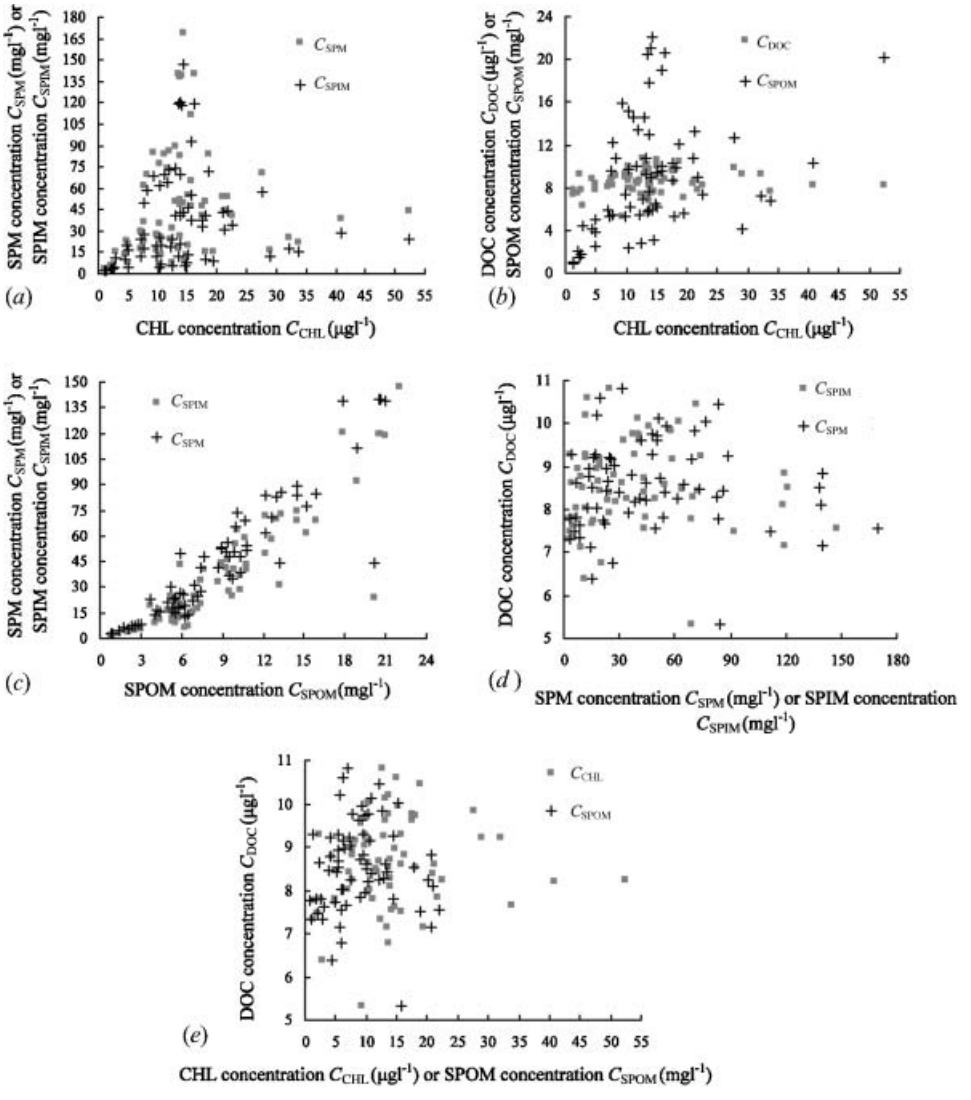

Figure 1. Scatter plots of pairs of: (*a*) C_{CHL} vs. C_{SPM} and C_{CHL} vs. C_{SPIM}, (*b*) C_{CHL} vs. C_{DOC} and C_{CHL} vs. C_{SPOM}, (*c*) C_{SPOM} vs. C_{SPIM} and C_{SPOM} vs. C_{SPM}, (*d*) C_{SPIM} vs. C_{DOC} and C_{SPM} vs. C_{DOC}, (*e*) C_{CHL} vs. C_{DOC} and C_{SPOM} vs. C_{DOC}.

where a is the absorption coefficient. i=1, 2, 3, and 4, respectively, represents pure water (index w), CDOM (index g), phytoplankton pigment (index ph), and non-algal particulate matter (index d). j is the band serial number from 400 to 700. n is the sample serial number from 1 to 67. N (=67) is the total samples. M (=301) is the total bands. r_{in} is the contribution due to a_i of the nst sample. ra_i is the mean of r_i. And ra_i' is ra_i as a function of wavelength.

3. Results

Figure 1 illustrates the scatter plots of pairs of C_{CHL} vs. C_{SPM}, C_{CHL} vs. C_{SPIM}, C_{CHL} vs. C_{SPOM}, C_{CHL} vs. C_{DOC}, C_{SPOM} vs. C_{SPM}, C_{SPOM} vs. C_{SPIM}, C_{SPM} vs.

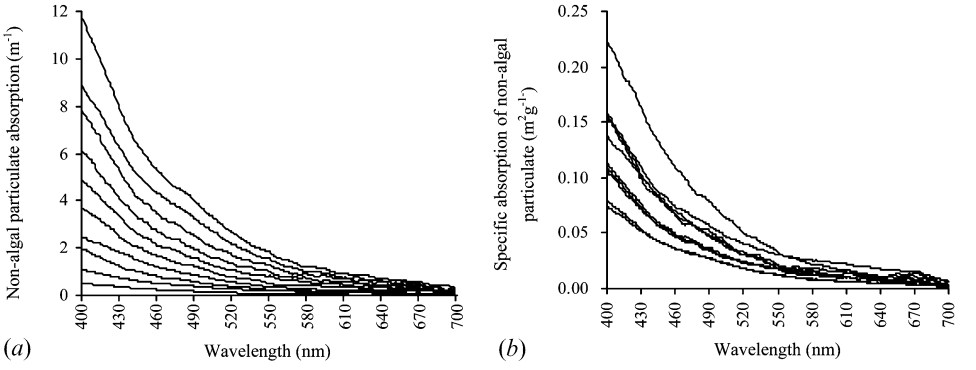

Figure 2. (*a*) Some non-algal particulate absorption spectra $a_d(\lambda)$, and (*b*) the corresponding specific absorption spectra $a_d^*(\lambda)$.

C_{DOC}, C_{SPIM} vs. C_{DOC}, C_{CHL} vs. C_{DOC}, C_{SPOM} vs. C_{DOC}, to show the general situation about the concentrations of constituents in Taihu Lake.

3.1 *Non-algal particulate absorption*

All the 67 spectra due to non-algal particulate (index d), $a_d(\lambda)$, are similar in shape (figure 2(*a*)), which is different from the 'U' shape in Lake Ontario by Bukata *et al.* (1981, 1991) and in Chilko Lake by Gallie and Murtha (1992), but similar to the shape in coastal waters of Japan by Kishino *et al.* (1985), some lakes by Davies-Colley *et al.* (1988), around the San Juan Islands by Roesler *et al.* (1989), the Peru upwelling area and the Sargasso Sea by Bricaud and Stramski (1990), the Rhode River and Chesapeake Bay by Gallegos *et al.* (1990), and the Pearl River estuary by Cao *et al.* (2003), being a negative exponential function with wavelength as the following equation (4). The spectra can also be modeled with many other functions (Twardowski *et al.* 2004), such as a double exponential function, a hyperbolic function. In this paper, we aim not to find out the best model for fitting their spectra but to discover their properties differing from others. So we still used the single exponential function as equation (4) for convenient comparison with other literatures.

$$a(\lambda) = a(\lambda_0)e^{-s(\lambda-\lambda_0)} \tag{4}$$

where λ_0 is the reference wavelength, to $a_d(\lambda)$, generally 440 nm (Bricaud *et al.* 1995, IOCCG 2003), sometimes 400 nm (Roesler *et al.* 1989, Gallegos *et al.* 1990, Kirk 1994, Pierson and Strömbeck 2001, Strömbeck and Pierson 2001) or 420 nm (Ammenberg *et al.* 2002). Also, S (marked by S_d for $a_d(\lambda)$, S_g for $a_g(\lambda)$ and S_t' for the three-component absorption) is a shape factor calculated by linear regression between the wavelength and the natural logarithm of $a(\lambda)$. Here 440 nm was used. We calculated S_d for each spectrum in the different wavelength ranges by linear regression, forced zero intercept, between the wavelength and the natural logarithm of $a_d(\lambda)$ for each individual measured absorption spectrum. The absolute and relative errors between the measured and the simulated spectra with the calculated S_d values in the different wavelength ranges show that it is practical and more precise to simulate $a_d(\lambda)$ with different S_d values calculated respectively in the ranges of 400–440, 440–540 and 540–650 nm. Table 1 gives the values of S_d in the three ranges, together with the range of 400–650 nm, all of which are located in the range

Table 1. Shape factor S_d of non-algal particulate absorption spectra from some literatures, as well as from this study.

Site	Range (nm)	Reference wavelength (nm)	Range of S_d (nm^{-1})	Mean of S_d (nm^{-1})	Reference
Pearl River estuary	400–700	400	0.0101–0.0171	0.0120 ($\pm$0.0020)	Cao *et al.* (2003)
Lake Mälaren	400–750	400	0.0090–0.0130	0.0113 ($\pm$0.0015)*	Pierson and Strömbeck (2001)
Rhode River and Chesapeake Bay	–	400	–	0.0104	Gallegos *et al.* (1990)
Sargasso Sea	380–750	440	0.0080–0.0150	0.0109 ($\pm$0.0019)	Bricaud and Stramski (1990)
Peruvian upwelling waters	380–750	440	0.0024–0.0170	0.0099 ($\pm$0.0036)	Bricaud and Stramski (1990)
San Juan Islands	400–750	400	0.0070–0.0150	0.0110 ($\pm$0.0020)	Roesler *et al.* (1989)
the coastal waters of Japan	–	–	0.0004–0.0007	–	Kishino *et al.* (1985)
Taihu Lake (October)	400–650	440	0.0090–0.0129	0.0117 ($\pm$0.0006)	This study
Taihu Lake (October)	400–440	440	0.0115–0.0178	0.0147 ($\pm$0.0013)	This study
Taihu Lake (October)	440–540	440	0.0103–0.0133	0.0120 ($\pm$0.0005)	This study
Taihu Lake (October)	540–650	440	0.0088–0.0129	0.0116 ($\pm$0.0006)	This study

* Calculated directly with table 1 from Pierson and Strömbeck (2001).

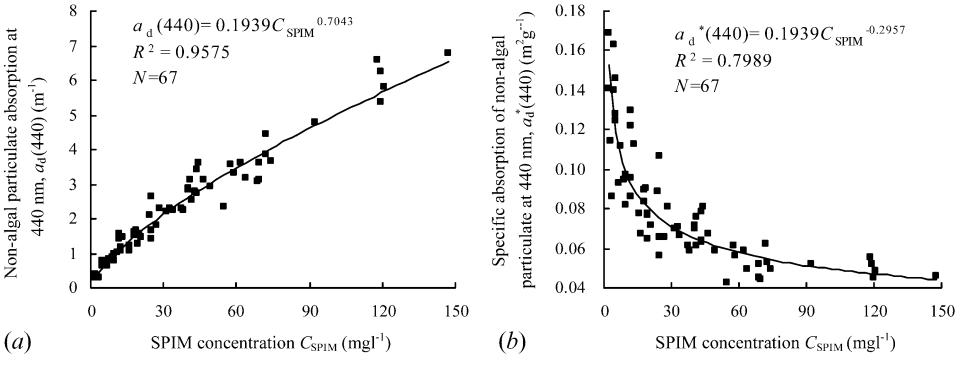

Figure 3. Relationship between SPIM concentration and: (*a*) non-algal particulate absorption coefficient at 440 nm, (*b*) the corresponding specific absorption coefficient at 440 nm.

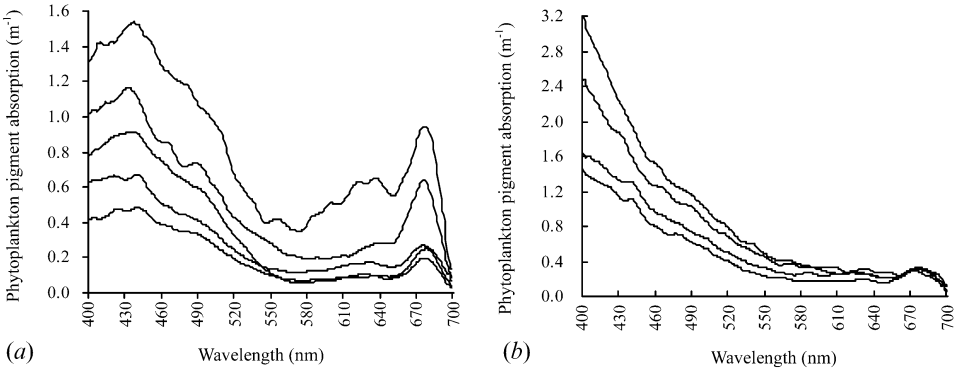

Figure 4. Two types of phytoplankton pigment absorption: (*a*) Type One, (*b*) Type Two.

Figure 5. Spatial distribution of two types of phytoplankton pigment absorption.

of 0.007–0.015 nm^{-1} by Roesler *et al.* (1989) and Babin *et al.* (2003), and shows they are relatively higher than in other lakes and rivers, evidently higher than in the sea, but close to the mean in Pearl River estuary.

$a_d(440)$ is in the range of 0.31–6.77 m^{-1} with a mean of 2.33 m^{-1}, 6.6 times in Lake Mälaren, and greatly more than those around the San Juan Islands with a range of 0.02–0.19 m^{-1} (Roesler *et al.* 1989). The relationship between $a_d(440)$ and C_{SPIM} agrees greatly with a positive exponential function (figure 3(*a*)). Like $a_d(\lambda)$, the specific absorptions $a_d^*(\lambda)$ $(=a_d(\lambda)/C_{SPIM})$ also conform approximately to a negative exponential function of wavelength as equation (4), illustrated by figure 2(*b*), but with different spectral slopes. $a_d^*(400)$ and $a_d^*(440)$, respectively, are in the range of 0.074 to 0.290 m^{2}g^{-1} with a mean of 0.137 m^{2}g^{-1}

Table 2. Description of $a_{ph}^{*}(440)$, $a_{ph}^{*}(676)$, C_{CHL} and C_{SPM} of the tree types of phytoplankton pigment absorption, together with their spatial distributions.

	Samples	Spatial distribution	$a_{ph}^{*}(440)$ (m^2g^{-1})		a_{ph} *(676) (m^2g^{-1})		Mean of C_{CHL} (μgl^{-1})	Mean of C_{SPM}, (mgl^{-1})
			Range	Mean	Range	Mean		
Type One	30	Zhushan Bay, Meiliang Bay, Gongshan Bay, Zhenhu Bay, Guangfu Bay, East Taihu Bay, and their vicinities	18.5–125.5	57.7 ($\pm$ 28.1)	11.4–38.2	20.1 ($\pm$ 5.6)	14.01	26.28
Type Two	37	Lake centre and South Taihu	27.3–203.1	90.9 ($\pm$ 50.7)	10.5–47.0	23.7 ($\pm$ 7.5)	14.14	62.97
Type Three	67	The whole lake	18.5–203.1	76.1 ($\pm$ 45.0)	10.5–47.0	22.2 ($\pm$ 6.9)	14.08	46.54

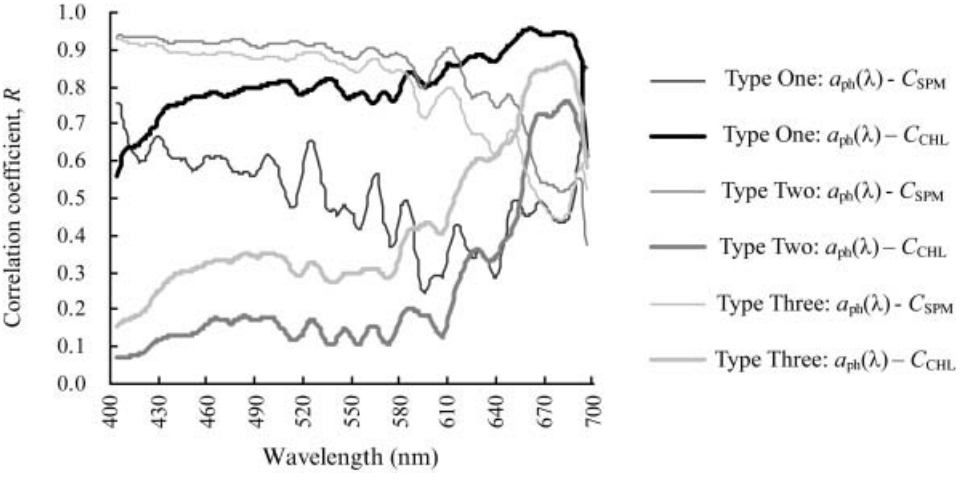

Figure 6. Relationships between the phytoplankton pigment absorption spectra $a_{ph}(\lambda)$, and SPM concentrations C_{SPM} and CHL concentrations C_{CHL}.

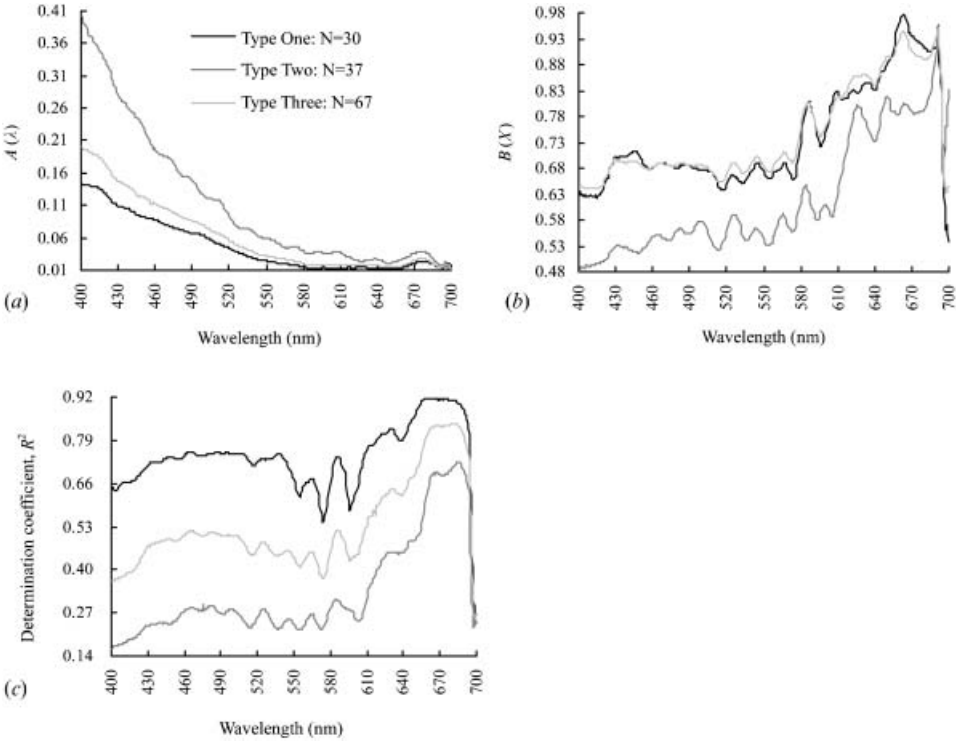

Figure 7. Relationship between phytoplankton pigment absorption and CHL concentration: $a_{ph}(\lambda)=A\ (\lambda)C_{CHL}{}^{B(\lambda)}$, (*a*) $A(\lambda)$, (*b*) $B\ (\lambda)$, (*c*) the determination correlation, R^2.

(SD 0.048 m^2g^{-1}), and of 0.043–0.169 m^2g^{-1} with a mean of 0.080 m^2g^{-1} (SD 0.030 m^2g^{-1}). Their means are, respectively, 3.9 times in Chilko Lake and 0.5 times in Lake Mälaren. A single negative exponential function can be used to fit the

Table 3. The parameters A and B from equation (5) in waters with three types of phytoplankton pigment absorption.

	Range of A	Mean of A	Range of B	Mean of B	Range of C_{CHL} (μgl^{-1})	Range of C_{SPM} (mgl^{-1})
Type One	0.0117–0.1423	0.0474 ($\pm$ 0.0402)	0.5382–0.9758	0.7404 ($\pm$ 0.1005)	1.18–52.44	3.10–84.00
Type Two	0.0090–0.4044	0.1122 ($\pm$ 0.1059)	0.4802–0.9532	0.6209 ($\pm$ 0.1135)	2.28–40.79	4.46–169.47
Type Three	0.0126–0.1997	0.0622 ($\pm$ 0.0547)	0.6320–0.9524	0.7466 ($\pm$ 0.0929)	1.18–52.44	3.10–169.47

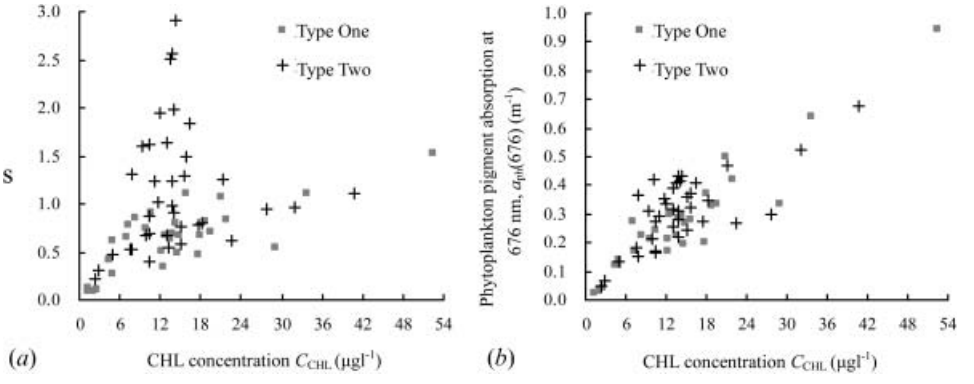

Figure 8. Scatter plots of pairs of: (*a*) phytoplankton pigment absorption at 440 nm, i.e. $a_{ph}(440)$ vs. C_{CHL}, and (*b*) phytoplankton pigment absorption at 676 nm, i.e. $a_{ph}(676)$ vs. C_{CHL}.

relationship between a_d*(440) and C_{SPIM} (figure 3(*b*)). The specific absorptions vary in a wide range and have a great difference in magnitude in the whole lake but only little difference in some lake area.

3.2 *Phytoplankton pigment absorption*

Generally, the absorption spectra due to phytoplankton pigment (index ph) have two typical diagnostic characteristics: one locating at about 440 nm in the blue range of 430–500 nm, and the other at about 670 nm in the red range of 650–680 nm. Maybe some differences exist in magnitude and shape because of package effect and pigment composition of phytoplankton cells, mainly depending on individual species, cell size, pigment content and the physiological state of phytoplankton caused by temperature, nutrients and light availability (Hoepffner and Sathyendranath 1991, Kirk 1994, Bricaud *et al.* 1995, Suzuki *et al.* 1998). Thereinto, package effect is wavelength-dependent (Suzuki *et al.* 1998). In this

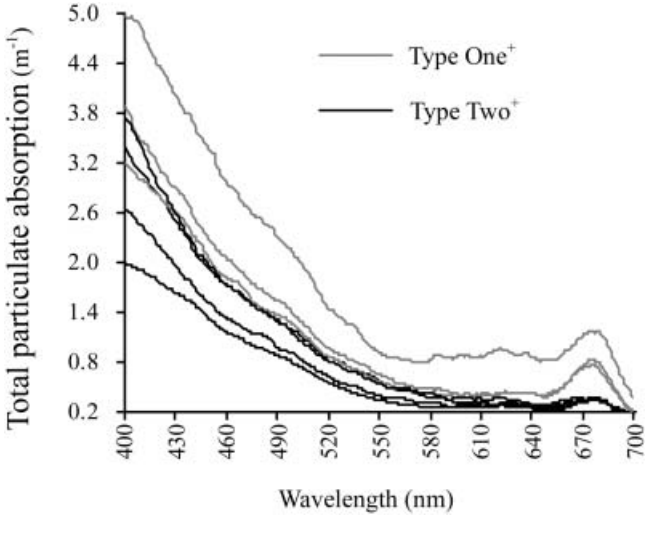

Figure 9. Two types of total particulate absorption.

Figure 10. Spatial distribution of two types of total particulate absorption.

measurement, there exist two types of phytoplankton pigment absorption, Type One and Type Two (figures 4 and 5). Additionally, we might as well mark the whole lake waters as Type Three, sum of Type One and Type Two. Type One, mainly distributed in several lake bays (figure 5), has obvious and diagnostic peaks like shoulder or pinnacle near 440 and 676 nm (figure 4), similar with almost all the reported, however only near 676 nm exists the peak in Type Two, similar with ones of Stn.14 and Stn.21 in the northwestern North Pacific by Suzuki *et al.* (1998). Table 2 shows that: (a) the mean of C_{CHL} in Type One is very close to that in Type Two, but the means of C_{SPM} of two types have great difference and Type Two is about 2.5 times Type One; (b) the mean of a_{ph}*(440) in Type Two is about 1.6 times

Table 4. General information about three types of the total particulate absorption.

	Samples	Spatial distribution	Mean of the contribution due to phytoplankton pigment to total particulate absorption (%)	Mean of ratio of C_{SPOM} to C_{SPM} (%)	Range of ratio of C_{SPOM} to C_{SPM} (%)	Mean of C_{SPIM} (mgl^{-1})
Type One$^+$	8	Gongshan Bay, Zhenhu Bay, Guangfu Bay and their vicinities	45	38	29–48	12.06
Type Two$^+$	59	Almost all the lake waters	28	22	12–37	41.08
Type Three$^+$	67	The whole lake	31	24	12–48	37.61

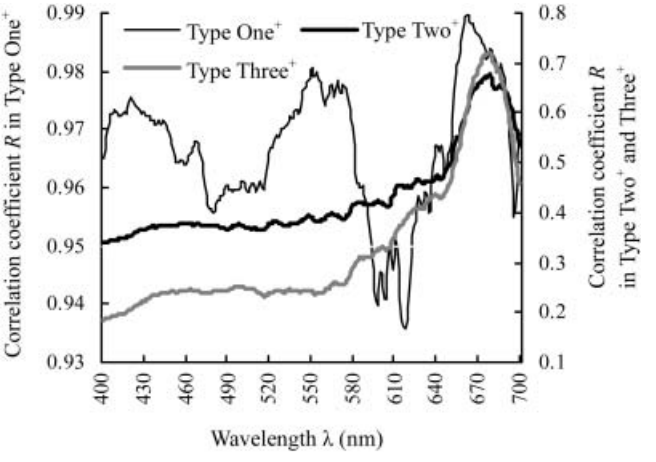

Figure 11. Relationships between the three types of total particulate absorption and their CHL concentrations C_{CHL}.

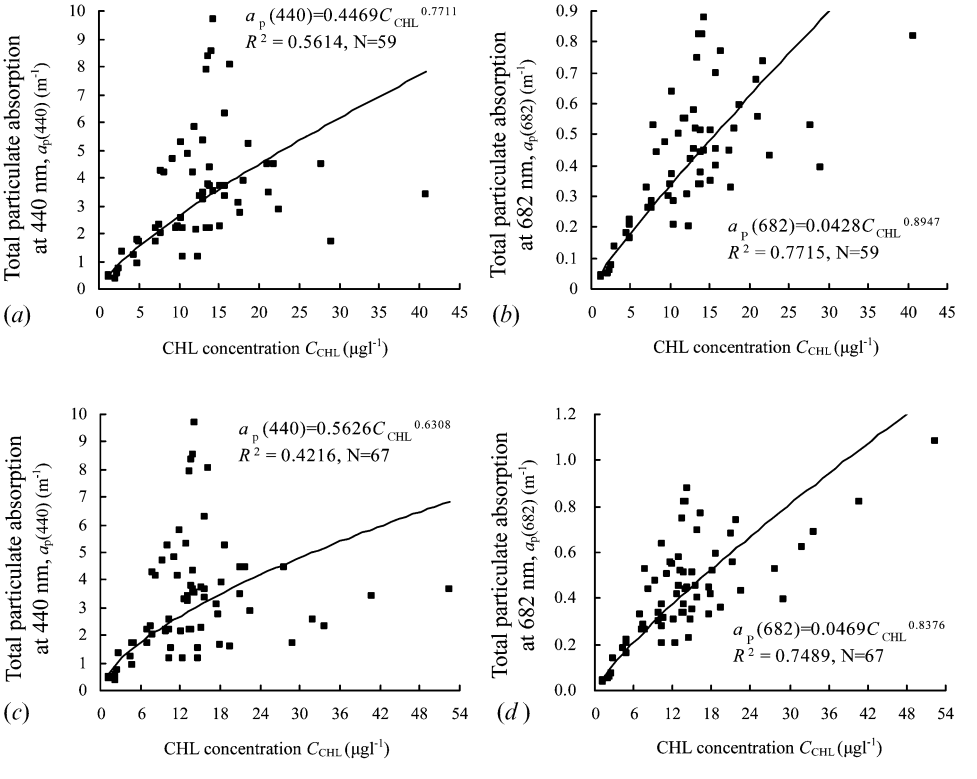

Figure 12. Relationships between CHL concentrations C_{CHL} and the second type of total particulate absorption coefficients in: (*a*) Type Two$^+$ at 440 nm, (*b*) Type Two$^+$ at 682 nm, (*c*) Type Three$^+$ at 440 nm, (*b*) Type Three$^+$ at 682 nm.

that of Type One and 4.8 times that of Stn.14 and Stn.21 by Suzuki *et al.* (1998), however, the mean of a_{ph}*(676) in Type Two is very close to that in Type One. Figure 6 illustrates the variational relationships as a function of wavelength between

pairs of $a_{ph}(\lambda)$ vs. C_{CHL}, and $a_{ph}(\lambda)$ vs. C_{SPM} for the three types, which shows that: (a) the common effect of package effect and pigment composition decreases gradually with wavelength increasing, maybe the package effect and pigment composition of phytoplankton cells have much difference between waters with two types of phytoplankton pigment absorption; (b) the specific absorption at 440 nm is more accessible than at 676 nm to be affected by suspended particulate matter. As a whole, namely in Type Three, the means of $a_{ph}^*(440)$ and $a_{ph}^*(676)$, respectively, are 0.8 and 21 times those of Chilko Lake by Gallie and Murtha (1992), indicating more obvious absorption property in the red range in Taihu Lake.

Bricaud *et al.* (1995) found an averaged dependence of the specific absorption coefficient of phytoplankton on C_{CHL} (0.02–25 μgl^{-1}) as shown by equation (5) or (5′), taking into account the properties of phytoplankton and the package effect.

$$a_{ph}(\lambda) = A(\lambda) C_{CHL}^{B(\lambda)} \tag{5}$$

$$a_{ph}^*(\lambda) = A(\lambda) C_{CHL}^{B'(\lambda)} \tag{5'}$$

where $B'(\lambda) = B(\lambda) - 1$. In Taihu Lake, the relationship between $a_{ph}(\lambda)$ and C_{CHL} (1.18–52.44 μgl^{-1}) also approximately agrees with equation (5) or (5′) (figure 7), as in the Pearl River estuary by Cao *et al.* (2003) and in Lake Mälaren by Pierson and Strömbeck (2001). So, with C_{CHL} increasing, the phytoplankton pigment absorption increases exponentially but the specific absorption decreases exponentially. In Taihu Lake, no matter which type of phytoplankton pigment absorption, there are similar tendencies of approximately positive-exponential decreasing for the parameter A, and of increasing gradually up to a maximum at about 660–690 nm for the parameter B (figure 7(*a*) and 7(*b*)) but different in magnitude (table 3), which are different from the shape and magnitude in Lake Mälaren by Pierson and Strömbeck (2001). Additionally, there is a great difference between determination coefficients R^2 (figure 7(*c*)), amongst which Type One with a mean of R^2 0.74 (SD 0.10), is much better than Type Three with a mean of 0.53 (SD 0.14) and Type Two with a mean of 0.34 (SD 0.15). The maximum R^2 in the three types are, respectively, 0.92, 0.74 and 0.84 and all appear in the range 670–690 nm. Concretely, figure 8 gives the scatter plots of pairs of $a_{ph}(440)$ vs. C_{CHL}, and $a_{ph}(676)$ vs. C_{CHL} in order to show more clearly the variability of phytoplankton pigment absorption as a function of CHL concentration.

3.3 *The total particulate absorption*

The total particulate absorption equals non-algal particulate absorption plus phytoplankton pigment absorption. The mean of ratio of C_{SPIM} to C_{SPM} of all the 67 samples is 76%. And the ratio of the mean of non-algal particulate absorption to the mean of total particulate absorption in the range of 400–700 nm is 69%. As a whole, we can divide the total particulate absorption into two types in this measurement (figures 9 and 10), named by Type One$^+$ and Type Two$^+$; similarly, Type one$^+$ plus Type Two$^+$ is named by Type Three$^+$, namely the whole lake waters. General information about the three types can be seen in table 4. The absorption property of phytoplankton pigment protrudes from Type One$^+$, similar with Type Two phytoplankton pigment absorption, only distributed in Gongshan Bay, Zhenhu Bay, Guangfu Bay and their vicinities (figure 9). Type Two$^+$ is dominated by non-algal particulate absorption. The ratio of C_{SPIM} to C_{SPM} in Type

Table 5. Shape factor S_g of CDOM absorption spectra from some literatures, as well as from this study.

Site	Range (nm)	Reference wavelength (nm)	Absorption coefficient at reference wavelength (m^{-1})		S_d (nm^{-1})		Reference
			Range	Mean	Range	Mean	
Yellow Sea	250–550	440	0.03–0.18	–	0.0116–0.0234	0.0175 (±0.0024)	Zhu and Li (2003)
12 inland freshwater lakes	280–460	440	0.09–4.87	–	0.0151–0.0205	0.0187	Davies–Colley and Vant (1987)
6 rivers in Georgia	300–450	440	1.61–10.19	–	0.0150–0.0160		Yacobi *et al.* (2003)
Lake Mälaren	–	400	1.77–4.72	2.64	–	0.0151 (±0.0016)	Pierson and Strömbeck (2001)
Taihu Lake	280–650	400	0.84–3.20	1.83 (±0.55)	–		This study
San Juan Islands	400–750	400	0.20–0.39	–	–	0.0170 (±0.0030)	Roesler *et al.* (1989)
Mauritanian upwelling region, Indian-Antarctic Ocean, Gulf of Guinea, Billefranche Bay, Mouth of River Var, Baltic Sea, Gulf of Fos-sur-Mer, Near discharge of Marseilles drains	375–500	375	0.06–4.2		0.0100–0.0200	0.0140 (±0.0032)	Bricaud *et al.* (1981)
Pearl River Estuary	300–500	355	0.24–1.93	–	0.0138–0.0184	–	Hong *et al.* (2005)
Taihu Lake	280–650	440	0.35–2.01	1.04 (±0.38)	0.0099–0.0241	0.0141 (±0.0030)	This study
Taihu Lake	280–320	440	0.35–2.01	1.04 (±0.38)	0.0135–0.0215	0.0162 (±0.0020)	This study
Taihu Lake	320–500	440	0.35–2.01	1.04 (±0.38)	0.0116–0.0231	0.0151 (±0.0026)	This study
Taihu Lake	500–650	440	0.35–2.01	1.04 (±0.38)	0.0085–0.0362	0.0135 (±0.0046)	This study

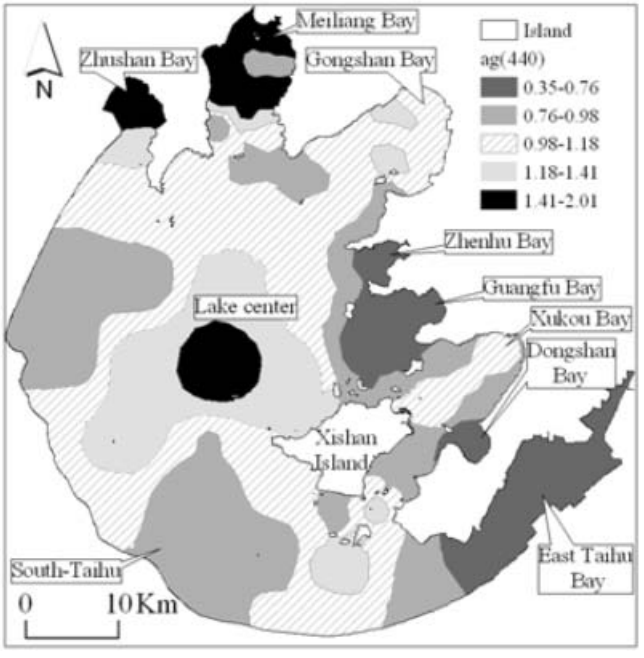

Figure 13. Spatial variation of CDOM absorption coefficients at 440 nm.

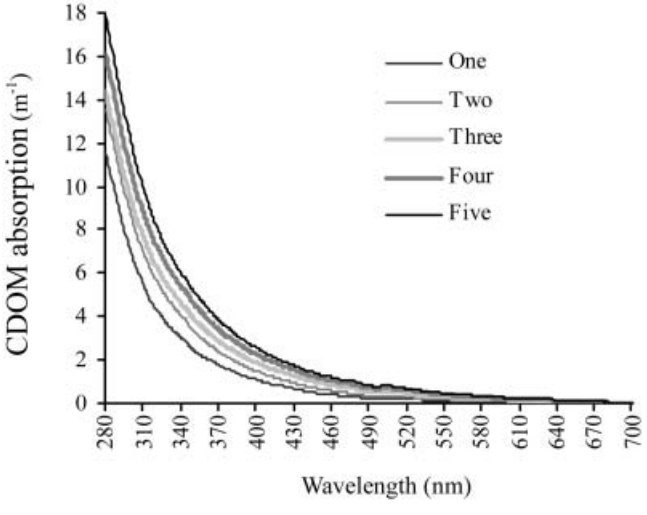

Figure 14. The mean spectra of CDOM absorption; One, Two, Three, Four and Five denote those whose absorption coefficients at 440 nm are in the ranges 0.35–0.76, 0.76–0.98, 0.98–1.18, 1.18–1.41, 1.41–2.01 m^{-1}, respectively.

Two$^+$ is greatly more than in Type One$^+$ (table 4). Concomitantly, the contribution due to non-algal particulate absorption in Type Two$^+$ is greatly more than in Type One$^+$. There is a good agreement between $a_p(\lambda)$ and C_{CHL} in Type One$^+$, much better than in Type Two$^+$ and Type Three$^+$ (figure 11), and the linear relationship is better than the exponential, showed by equations (6) and (6′). However, the exponential relationship is better in Type Two$^+$ and Type Three$^+$ (figure 12). The

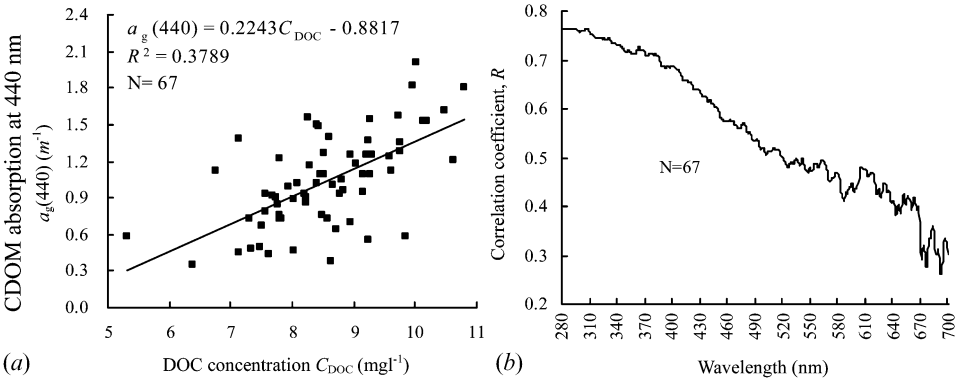

Figure 15. Relationship between CDOM absorption and DOC concentration: (*a*) an agreement between absorption coefficient at 440 nm and DOC concentration; (*b*) correlation coefficient decreasing almost linearly with wavelength increasing.

fitting functions is not very stable, which has a little difference with those in case one waters (Rosler 1998, Bricaud *et al.* 1995, Cleveland 1995) and in coastal case two waters (Cao *et al.* 2003), where exists a relatively stable exponential function. In Type Two$^+$, there are good agreements between $a_p(\lambda)$ and, C_{TSM}, C_{SPIM} and C_{SPOM}, the correlation coefficients R more than 0.90 in the range of 400–600 nm and more than 0.84 in the range of 600–700 nm. Figures 6 and 11 show that there are similar variation tendencies of relationships between a_p and C_{CHL} and between a_{ph} and C_{CHL} as a function of wavelength.

$$a_p(440) = 0.2080(SD\ 0.0591) \times C_{CHL}^{0.7157(SD\ 0.0818)},\ R^2 = 0.9249,\ N = 8\ \left(\text{in m}^{-1}\right) \quad (6)$$

$$a_p(440) = 0.0565(SD\ 0.0056) \times C_{CHL} + 0.6213(SD\ 0.1562),$$
$$R^2 = 0.9438,\ N = 8\ \left(\text{in m}^{-1}\right) \quad (6')$$

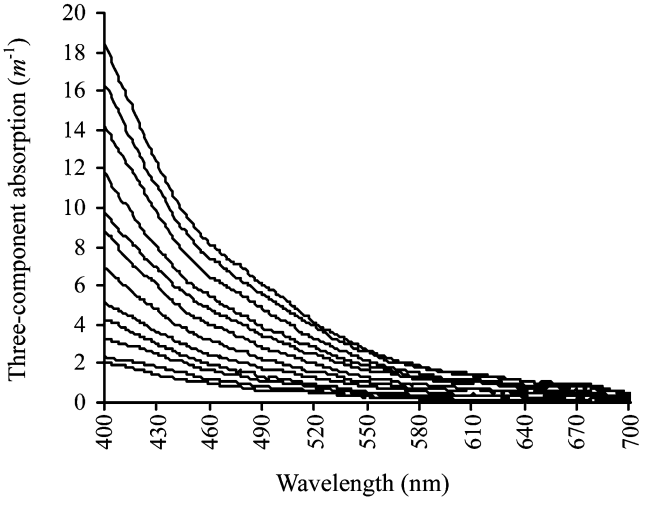

Figure 16. Some three-component absorption spectra, $a_t'(\lambda)$.

3.4 *CDOM absorption*

CDOM is an optically active matter of DOC. The spectra, like $a_d(\lambda)$, decreases exponentially with increasing wavelength (Bricaud *et al.* 1981), almost entirely uniform in different water environments (Bricaud *et al.* 1981, Prieur and Sathyendranath 1981, Carder *et al.* 1989), shown by equation (4). In equation (4) for $a_g(\lambda)$, 440 nm is considered as the better reference wavelength λ_0 (Kirk 1994, Zhu and Li 2003), but 400 nm (Gallegos *et al.* 1990, Pierson and Strömbeck 2001, Strömbeck and Pierson 2001), 375 nm (Bricaud *et al.* 1981) or 355 nm (Hong *et al.* 2005) was also used sometimes. In this study, 440 nm is selected. Table 5 shows that CDOM absorption at 440 nm in Taihu Lake is more than in Yellow Sea and in Pearl River Estuary, greatly less than those of 6 rivers in Georgia by, but located in the range of 12 inland freshwater lakes. Figure 13 illustrates the spatial variation of $a_g(440)$ and figure 14 shows the corresponding CDOM absorption spectra: (a) in the region with non-phytoplankton, such as Lake Center and Meiliang Bay, is more than in the region with phytoplankton, such as East Taihu Bay, Dongshan Bay, Guangfu Bay, Zhenhu Bay; (b) in the main inflow regions, such as Meiliang Bay and Zhushan Bay, is greatly more than in the main outflow, East Taihu Bay. Compared with $a_g(400)$ in Lake Mälaren by Pierson and Strömbeck (2001), the value in Taihu Lake is evidently lower but still much more than that around San Juan Islands by Roesler *et al.* (1989). In Taihu Lake, there is a little difference between DOC concentrations of 67 samples, a mean of 8.55 mg l^{-1} (SD 1.04 mg l^{-1}), whose spatial variation is almost identical to that of $a_g(440)$. $a_g(440)$ is lowly correlated with C_{DOC} (figure 15 (*a*)), which is different from the high correlation in 6 rivers by Yacobi *et al.*

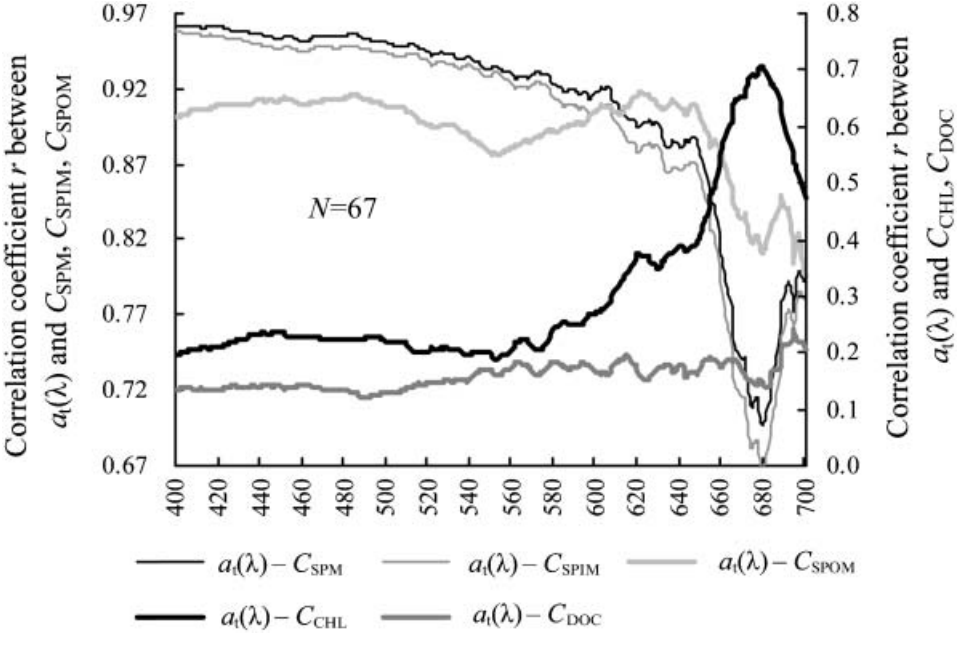

Figure 17. Relationship between the total absorption $a_t(\lambda)$ of 67 samples and their concentrations of SPM, SPIM, SPOM, CHL, DOC.

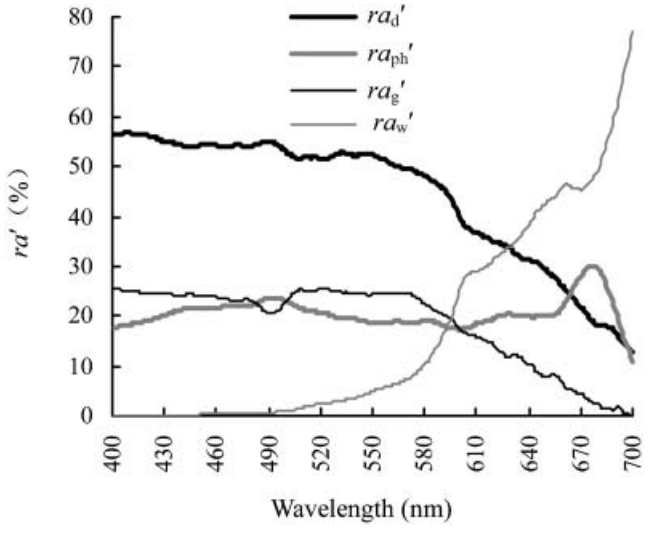

Figure 18. The variational contributions due to pure water, CDOM, phytoplankton pigment and non-algal particulate to the total absorption as a function of wavelength.

(2003). In the whole wavelength, the correlation between a_g and C_{DOC} decreases almost linearly with wavelength increasing (figure 15(*b*)), which is identical to the result by Rochelle-Newall and Fisher (2002). Additionally, a_g is lowly correlated with C_{CHL} in the whole wavelength (R^2 less than 0.4). All the mentioned above shows that in Taihu Lake: (a) the spatial variation and difference may be caused mainly by variability of the constituents and the molecule size distribution of DOC rather than mainly by DOC concentration; (b) as a whole, the self-decomposition of phytoplankton is not the main source of CDOM, maybe in different areas or in the same area but in different seasons exist differences.

Different S_g values can be in response to variability of the constituents of DOC to a certain extent (Carder *et al.* 1989). The straight-line portions of the spectra extended to red wavelengths (>600 nm), but in some spectra, fluctuations at these wavelengths artifacts of the measurement of absorption coefficients of low magnitude with low relative precision or of the application of the scattering correction. In order to avoid these fluctuations, we calculated S_g by fitting linear regression, acquired by a logarithmic transformation, in the region 280–650 nm rather than throughout the near-UV to visible regions. Kopelevich *et al.* (1989) reported that they were wavelength-dependent to a certain extent and the dividing position was at 500 nm. In this study, comparison of the absolute and relative errors between the measured and the calculated spectra shows that it is the most appropriate to divide the whole range of 280–650 nm into three successive ranges of 280–320 nm, 320–500 nm and 500–650 nm, and their S_g values can be listed in table 5. The mean in the whole range of 280–650 nm is slightly lower than in Lake Mälaren, and also lower than in 6 rivers in Georgia, however greatly less than in 12 inland freshwater lakes, but in the typical range around 0.014–0.015 nm^{-1} from historical precedence (Twardowski *et al.* 2004), which all are located in the range 0.0010–0.0250 nm^{-1} with a mean of 0.0177 nm^{-1} (SD 0.0008 nm^{-1}) for the freshwater lakes by Markager and Vincent (2000).

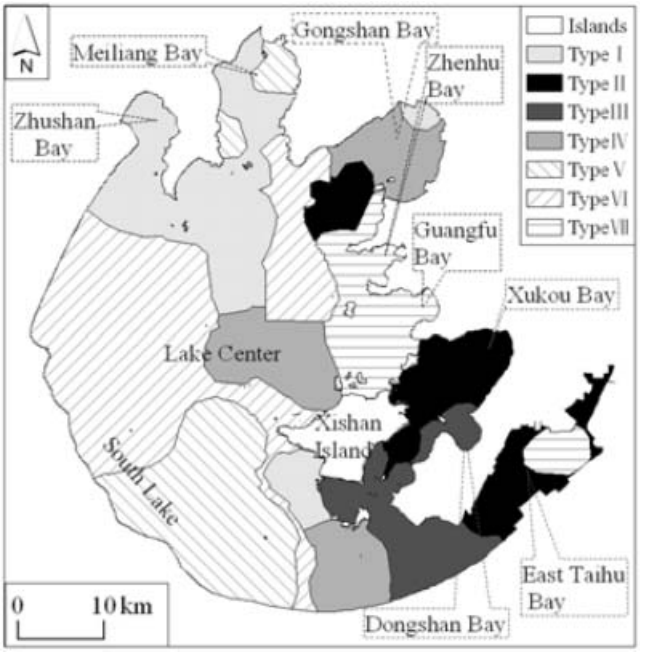

Figure 19. Spatial distribution of 9 types of the total absorption of water body in Lake Taihu.

3.5 *The total absorption*

The total absorption of the waters, $a(\lambda)$, is the sums of all contributions of each water component and pure water (index w) (Jerlov 1976, Prieur and Sathyendranath 1981). So

$$a_t(\lambda) = a_w(\lambda) + a_g(\lambda) + a_{ph}(\lambda) + a_d(\lambda) \quad (7)$$

where λ is limited in the range of 400–700 nm. $a_w(\lambda)$ was determined by Pope and Fry (1997). Thereinto, we call the sum of contributions due to $a_g(\lambda)$, $a_{ph}(\lambda)$ and $a_d(\lambda)$ as the three-component absorption, $a_t'(\lambda)$. Like $a_g(\lambda)$ and $a_d(\lambda)$, $a_t'(\lambda)$ also approximately conforms to the minus-exponential curve as a function of wavelength shown by equation (4) (figure 16). Similarly, it is necessary and appropriate for the three-component absorption spectral slope, S_t', to divide the whole wavelength into the ranges of 400–440, 440–600 and 600–700 nm. The mean values of S_t' are $0.0132\,nm^{-1}$ (SD $0.0011\,nm^{-1}$), $0.0121\,nm^{-1}$ (SD $0.0007\,nm^{-1}$) in the first two ranges, respectively. However, in the last range does not exist highly fitted S_t'.

Figure 17 shows that: (a) in the range of 400–600 nm, the contribution due to SPM to the total absorption is greatly more than those due to CHL and DOC. Thereinto, the contribution due to SPIM is more than due to SPOM. The contribution due to CHL is very low; (b) in the range of 600–700 nm, the contribution due to SPM decreases sharply. The contribution due to SPOM is more than due to SPIM. Noticeably, the contribution due to CHL begins to increase sharply and the maximum appears at 680 nm; (c) in the whole range 400–700 nm, there is a poor agreement between $a_t(\lambda)$ and C_{DOC}; accordingly, to the whole waters in Taihu Lake,

Table 6. Description about 7 types of the total absorption of water body in Taihu Lake.

Type number	Named by prominent characteristic	Covering area (about %)	Main spatial distribution
I	Dominated commonly by CDOM and non-algal particulate	16.4	A great portion of Meiliang Bay, a small portion of Zhushan Bay, and Southwest of Xishan Island
II	Dominated commonly by CDOM, non-algal particulate and pure water	10.7	Xukou Bay, a great portion of East Taihu Bay, and mouth of Gongshan Bay
III	Dominated commonly by CDOM and pure water	7.2	Dongshan Bay, Southeast of Xishan Island and mouth of East Taihu Bay, where all exist numerous hydrophytes and waters are vary clear
IV	Dominated commonly CDOM, phytoplankton pigment and non-algal particulate	12.8	A great portion of Gongshan Bay, and a portion of Lake Center located at Northwest of Xishan Island
V	Dominated by non-algal particulate	15.7	A small portion of Meiliang Bay, a great portion of South Lake
VI	Dominated commonly by phytoplankton pigment and non-algal particulate	28.5	West of Taihu Lake, a portion off Gongshan Bay and Meiliang Bay
VII	Dominated commonly by phytoplankton pigment, non-algal particulate and pure water	8.7	Zhenhu Bay, Guangfu Bay and a small portion of East Taihu Bay

the contribution due to DOC is low, which is a general situation; however, there are great differences between different lake areas. Especially in East Taihu Lake and Dongshan Bay, also in Zhushan Bay and Meiliang Bay, the contributions due to DOC to the total absorption are much more than in other lake areas.

The ra_i calculated by equation (2) shows that to the whole water body, the non-algal particulate absorption dominates the total absorption to a certain extent (ra_d=41%) and the contributions due to the other three components are relatively low but almost equal (ra_w=21%, ra_g=20%, ra_{ph}=18%), which validates the correlation analysis mentioned above. Figure 18 by equation (3) shows that to the whole water body: (a) in the blue and green wavelengths, the non-algal particulate absorption dominates the total absorption to a certain extent and the contributions due to phytoplankton pigment and CDOM are almost equal, the contribution due to pure water can be entirely neglected, (b) in the red wavelength, the pure water dominates almost entirely the total absorption but the contribution due to phytoplankton pigment is suddenly given prominence at the red-peak wavelength and the contributions due to CDOM and the non-algal particulate decrease gradually linearly.

In order to have a sketch of the spatial variation of the total absorption in Taihu Lake, we divide the whole waters into 7 types of absorption areas according to r value by equation (1) as the following: (a) values of r of each component, i.e. r^1, r^2, r^3, and r^4, at 67 sampling points are interpolated into the whole lake with IDW method to create files with grid format in ArcGIS 9.0 environment; (b) the data with grid format are transformed into the data with coverage format and with a class attribute, evaluated zero if $0 < r$ (i.e. r^1, r^2, r^3, r^4, the following is the same) $\leqslant 10\%$, one if $10 < r \leqslant 20\%$, two if $20 < r \leqslant 30\%$, three if $30 < r \leqslant 40\%$, four if $40 < r \leqslant 50\%$, the others by analogy with that mentioned above, and then overlaid and reclassified sequentially as the following rules: (a) if the class attribute value of a component is more than five, or more than four but those of the other three components all are less than or equal to two, then we consider them as a type dominated by the component, (b) if the sum of the class attribute values of any two components is more than seven and any one of the two components is more than any one of the other two components, then we consider them as a type dominated commonly by the two components, (c) if any one of the class attribute values of any three components is equal and the sum is more than seven, or any two of them is equal and the third is more than the fourth, then they are clustered into a type dominated commonly by the three components; (d) all the re-classified polygons are aggregated based on the class attribute values, and the polygons with area less than 10 km^2 are merged into their neighbours and then re-edited. The spatial distribution of the seven types of absorption can be seen in figure 19 and their details can be seen in table 6.

4. Discussions and conclusions

Taihu Lake is a typical case two water, different from open sea water and also coastal case two water. The absorptions, together with the contents of matter components, have great spatial difference. If we divide the whole lake into several areas with different absorption properties as well and truly as possible, we can estimate approximately the total absorption coefficient as simply and conveniently as possible. For instance, in the area dominated commonly by phytoplankton pigment and non-algal particulate, we can consider that the total absorption equals approximately the sum of absorption due to phytoplankton pigment and non-algal particulate, i.e. the total particulate absorption, closely correlated with CHL concentration especially at some wavelengths. So the sections *the total particulate absorption* and *the total absorption* are very important for us to estimate approximately and quickly the remote sensing reflectance by IOPs, and/or to retrieve approximately and quickly the contents of constituents from remote sensing image data by remote sensing reflectance. Absorptions due to optically active matter have effects on one anther to a certain extent. Maybe the effect modes are different in different lake areas and/or in different seasons. It is necessary to consider the mutual effect for reference when determining absorption of a single component.

In the alternant season from autumn to winter in Taihu Lake, the algae floating over the water died in large area and some of the livings were collected together by wind. In this measurement, only number 21 is located in the algae floating area, and its proportion of C_{SPOM} to C_{SPM} is more than 50%. Ratios of C_{SPOM} to C_{SPM} of the other samples all are less than 40%. The means of non-algal particulate absorption in the range of 400–700 nm, having more representative meaning than at a special wavelength, increases approximately positive-exponentially with increasing SPM concentration, SPIM concentration, SPOM concentration and CHL concentration,

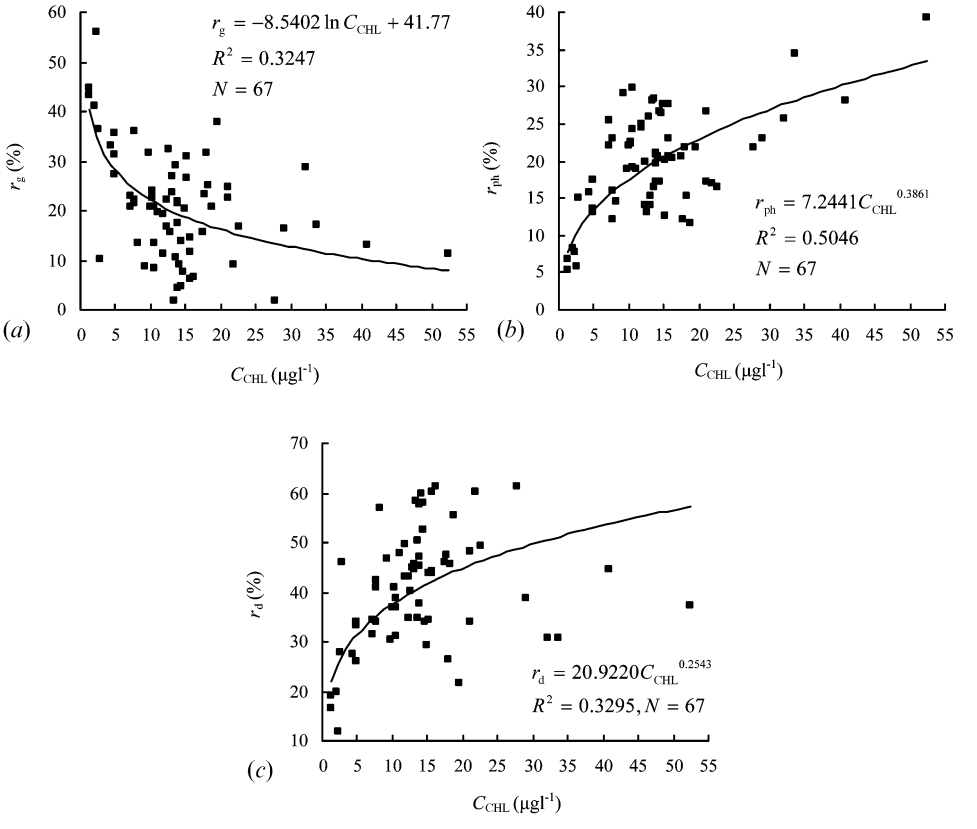

Figure 20. Relationships between CHL concentration C_{CHL} and: (*a*) contribution due to CDOM, r_g, (*b*) contribution due to phytoplankton pigment, r_{ph}, (*c*) contribution due to non-algal particulate, r_d.

respectively, with R^2 0.9592, 0.9596, 0.8511 and 0.3522, which shows that maybe the non-algal particulate absorption is mainly due to non-pigmented cellular material of living phytoplankton and heterotrophic plankton, died algae, plant and animal detritus, and land-driven and re-suspended mineral particles. So in Taihu Lake, the composition of non-algal particulate matter is complex. Generally, land-driven or re-suspended mineral particles occupy a dominant position, which is similar with in coastal case two water such as waters in the Pearl River estuary by Cao *et al.* (2003). Maybe those mineral non-algal particulates are different in different areas because of difference in its composition including size and shape, and nature including internal structure and refractive index (Stramski *et al.* 2004). As a result, they have different absorption properties in different areas. This causality about the non-algal particulates is similar to a certain extent with that about CDOM. The optical characteristics of DOC are an outcome of the additive influence of DOC components (Yacobi *et al.* 2003). The composition (Carder *et al.* 1989) and molecule size (Yacobi *et al.* 2003) have a large effect on the pattern of CDOM absorption and its magnitude, which results in different values of S_g. The logarithmic transformation of the absorption coefficient function of CDOM did not result in a perfectly linear line in this study, maybe the deviation from linearity is caused by variability of the constituents of yellow substance (Yacobi *et al.* 2003). As a whole, CDOM in Taihu Lake is mainly

land-driven and the contribution due to CDOM to the total absorption is relatively low. However, in some areas, such as in Dongshan Bay, the contribution is relatively high and it is mainly phytoplankton-decomposed. And the details about spatial variation of CDOM absorption are worthy of discussion in future. The absorption spectra due to CDOM and non-algal particulate matter are easily mixed because of their similar shapes. It is worthy and important to pay more attention on how to discriminate and decompose them in water colour remote sensing.

The phytoplankton pigment absorption is entirely different from the two mentioned above, which is materialized primarily by the red-peak near 676 nm in the range 670–680 nm. Generally, a peak at about 440 nm is also expected. However, in this measurement, only some samples have obvious peaks near 440 nm. Maybe there are two reasons. One is attributed to different pigment composition of cells and wavelength-dependent package effect, which increases when either the average cell size or the absorption coefficient of the cellular material increases, with the result of depressing absorption at all wavelengths and flattening of the spectrum (Morel and Bricaud 1981). The other is attributed to the bleaching procedure in the phytoplankton pigment extraction, as saying by a referee. Maybe some type of constituent, different from phytoplankton pigment, was also bleached with 90% hot ethanol. Or maybe in this lake there is a particular type of particulate organic matter that is bleached by 90% hot ethanol. The most possible reason will be validated in the next measurement.

The comparison between the two types of non-algal particulate absorption shows that with SPIM concentration increasing, the correlation between a_p and C_{CHL} decreases. In almost all the total particulate absorption spectra, no peak or no obvious peak appears near 440 nm, which does not like those in the open ocean waters. Maybe it is because the high SPOM concentration no including phytoplankton pigment and the high SPIM concentration, causing much stronger non-algal particulate absorption in Taihu Lake than in open ocean waters, cover up the phytoplankton pigment absorption at 440 nm. Whereas, CHL content has also an effect on absorption of the individual component to a certain extent but the effect modes on each component are different in general, indicated by the relationships between r_i, mentioned in section 3.5, and C_{CHL} in figure 20, illustrating that with increasing CHL concentration, the contributions due to non-algal particulate and phytoplankton pigment to the total absorption increase approximately exponentially but due to CDOM decrease approximately logarithmically. Additionally, figure 20 also shows a probable approach to have a sketch of the total absorption by contribution estimation with CHL concentration.

The total absorption is greatly different in spatial and can be divided into seven types according to contribution due to individual component. As a whole, to the water body of Taihu Lake, the absorption due to non-algal particulate dominates the total absorption to a certain extent, and the contributions due to pure water, CDOM and phytoplankton pigment are relatively low but almost even, but in different wavelength ranges exist great differences: (a) in blue and green band, the total absorption is dominated by non-algal particulate absorption, the contributions due to phytoplankton pigment and CDOM are almost equal, and the contribution due to pure water could be neglected; (b) however, in red band, the pure water together with the red-peak of phytoplankton pigment absorption dominates the total absorption, the contributions due to non-algal particulate and CDOM decreases rapidly.

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Nomenclature

List of main symbols

SPM	suspended particulate matter
SPIM	suspended particulate inorganic matter
SPOM	suspended particulate organic matter
CHL	chlorophyll-*a*
DOC	dissolved organic carbon, yellow substance
CDOM	coloured dissolved organic matter
C_{SPM}	concentration of suspended particulate matter
C_{SPIM}	concentration of suspended particulate inorganic matter
C_{SPOM}	concentration of suspended particulate organic matter
C_{CHL}	concentration of chlorophyll-*a*
C_{DOC}	concentration of dissolved organic carbon
$a_t(\lambda)$	total absorption coefficient/spectra
$a_t'(\lambda)$	three-component absorption coefficient/spectra
$a_w(\lambda)$	pure water absorption coefficient/spectra
$a_d(\lambda)$	non-algal particulate absorption coefficient/spectra
$a_g(\lambda)$	coloured dissolved organic matter absorption coefficient/spectra
$a_{ph}(\lambda)$	phytoplankton pigment absorption coefficient/spectra
$a_p(\lambda)$	total particulate coefficient/spectra
$a_d^*(\lambda)$	specific absorption coefficient/spectra of non-algal particulate
$a_{ph}^*(\lambda)$	specific absorption coefficient/spectra of phytoplankton pigment
$A(\lambda)$	empirical constant used to determine $a_{ph}^*(\lambda)$
$B(\lambda)$	empirical constant used to determine $a_{ph}^*(\lambda)$
S_d	shape factor for non-algal particulate absorption
S_g	shape factor for coloured dissolved organic matter absorption
S_t'	shape factor for the three-component absorption
r	total average contribution of individual component of each sample in the range 400–700 nm
ra	mean value of r of 67 samples
$ra'(\lambda)$	variational contribution due to individual component to the total absorption following wavelength

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