Variability of light absorption properties in optically complex inland waters of Lake Chaohu, China

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A B S T R A C T

Absorption coefficients of phytoplankton, colored detrital matter (CDM), non-algal particles (NAP), colored dissolved organic matter (CDOM), and their relative contributions to total non-water absorption (αw−λ)w are essential variables for bio-optical and radiative transfer models. Light absorption properties showed large range and variability sampled at 194 stations throughout Lake Chaohu between May 2013 and April 2015. The αw−λw was dominated by phytoplankton absorption (αph) and NAP absorption (αn). The contribution of CDOM absorption to αw−λw was lower than 30%. Phytoplankton and NAP were the primary sources of spatial and vertical variability in absorption properties. Light absorption by CDOM, though significant in magnitude, was relatively constant. CDM absorption (αCDM) was dominated by NAP. The spatial variation of the absorption coefficients from each of the optically active constituents were driven by several main inflow rivers in the western and middle part of Lake Chaohu. Algal blooms and bottom resuspension contributed to vertical variability as observed by phytoplankton and NAP profiles. Specific absorption of phytoplankton had significant spatial and seasonal variations without vertical variation. The spectral slope of absorption showed no significant spatial variability (p > 0.05). Variations of absorption affected different ranges of remote sensing reflectance (Rr) spectrum, thereby increasing the difficulty of applying the remote sensing algorithm in optically complex waters. Parameters and relationships presented in this study provide useful information for bio-optical models and remote sensing of lakes similar to Lake Chaohu in terms of optical properties.

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Introduction

Inherent optical properties (IOPs, Table 1) of a water column depend on the concentration, composition, and size of optically active constituents (OACs), including phytoplankton, non-algal particulates (NAP), and colored dissolved organic matter (CDOM) (Aurin et al., 2010; Bricaud et al., 2010; Mckee et al., 2003; Ylöstalo et al., 2014). The light absorption coefficients of various OACs are important parameters in determining the optical variability of natural waters and their apparent optical properties (AOPs) (Bricaud et al., 2010). Absorption of colored detrital matter (CDM) plays an essential role in the carbon cycle and in the control of the penetration of UV and blue radiation in the surface ocean layers (Bricaud et al., 2012). The absorption coefficients have been related to important biogeochemical properties, such as phytoplankton biomass, chlorophyll-α concentration (Chl α) (Bricaud et al., 1998), phycocyanin concentration (Li et al., 2015), total suspended material (TSM) (Cui et al., 2013), dissolved organic carbon (DOC) (Hestir et al., 2015; Jiang et al., 2012), and particle size distribution (PSD) (Bricaud et al., 2012; Devred et al., 2011; Roy et al., 2013). Furthermore, absorption coefficients can also be related to the diffuse attenuation coefficients of downwelling irradiance (Lee, 2005).

Many previous studies focus on light absorption properties and their variability of oceanic waters (Bricaud et al., 2010; Morel and Maritorena, 2001; Naik et al., 2013) and coastal waters (Babin et al., 2003; Mckee et al., 2003). Inland lakes are more optically complex than oceanic and coastal waters (Binding et al., 2008; Shi et al., 2014). In Case I waters, OACs usually co-vary with Chl α, and their optical properties are controlled by phytoplankton and associated constituents (Babin et al., 2003). Complex source and composition of OACs enhance the variability of optical properties of Case II waters (Wu et al., 2011). Inland lakes usually have a relatively high OAC content and diverse optical properties (Ficek et al., 2012). Riddick et al. (2015) found that the relative contributions to the absorption budget in an optically complex lake varied more widely than oceans with a greater contribution from NAP (up to 30%).

Variability of absorption coefficients could be affected by the specific absorption coefficients and spectral slope of absorption coefficients. Chl α-specific absorption of phytoplankton (αph(λ)) is an essential component for many forward radiative transfer models and remote sensing interpretation schemes (Mckee et al., 2014). The observed variability in αph(λ) indicates change in pigment composition or package effect. Most of the seasonal changes observed in αph(λ) were driven by

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The aims of this study are (1) to describe the characteristics of the OACs (phytoplankton, NAP, CDOM, CDM) and their absorption coefficients in Lake Chaohu, China; (2) to explore the spatial, seasonal, and vertical variations of light absorption properties; and (3) to describe the impact of absorption variations on remote sensing reflectance modeling. The present study contributes to bio-optics and remote sensing of inland waters, through extensive documentation on light absorption properties of different lake regions and seasons of Lake Chaohu.

Methods

Study area

Lake Chaohu, the fifth largest freshwater lake in China, is a eutrophic shallow lake in the lower reaches of Yangtze watershed, with an area of 770 km² (31°25′–31°43′N, 117°17′–117°51′E, Fig. 1) and a mean depth of 3.0 m (Chen et al., 2013; Tang et al., 2015). The area of the lake is characterized by a subtropical monsoon climate with an annual mean temperature of 15 °C–16 °C and an annual mean rainfall of 1100 mm (Chen et al., 2013). The eight major inflowing rivers of Lake Chaohu (Fig. 1), namely, Zhanghe River (ZGR), Nanfei River (NFR), Shiwuli River (SWLR), Pai River (PR), Fengle River (FLR), Hangbu River (HBR), Baishitian River (BSTR), Zhao River (ZR), account for >80% of the total inflows of the lake basin. Yuxi River is the only outflowing river as well as an influent to the Yangtze River (Fig. 1).

Lake Chaohu is the primary source of drinking water for the provincial capital Hefei City and for the medium-sized Chaohu City of Anhui province (Qin et al., 2013) (Fig. 1). >9.1 million people live in the lake watershed, where agricultural runoff, industrial pollution, and municipal sewage are the three major pollution sources (Qin et al., 2013; Yang et al., 2013). In Lake Chaohu, water quality is poor, and algal blooms frequently occur because of severe eutrophication and pollution. Temporal and spatial changes of total nitrogen (TN), total phosphorus (TP) and Chl a showed no substantial improvement from 2001 to 2011 (Yang et al., 2013). The eutrophication of the western part of Lake Chaohu (WCH) is more serious than that of the middle (MCH) and eastern part (ECH) primarily because the riverine runoff is considered an important route for the transport of contaminants to Lake Chaohu (Jiang et al., 2014; Tang et al., 2015). The TN and TP content showed clear spatial variability and were significantly higher in WCH and MCH than ECH (Gao et al., 2015; Yang et al., 2013).

Data collection

Seven cruise surveys and one vertical survey, with 185 surface samples and 76 vertical samples, were performed from May 2013 to April 2015 to measure OACs and IOPs in Lake Chaohu (Fig. 1, Table 2). Water samples were collected and analyzed for the OACs and corresponding absorption coefficients. The field measurements, laboratory analysis, and data processing are briefly summarized below.

Water samples of each station were stored in the dark at a low temperature (4 °C) before laboratory analysis of chlorophyll-a (Chl a, μg/L), suspended particulate inorganic matter (SPIM, mg/L), dissolved organic carbon concentration (DOC, mg/L), and absorption coefficients (m⁻¹). Water samples of the vertical survey were obtained from nine depths (surface, 0.1, 0.2, 0.4, 0.7, 1.0, 1.5, 2.0, and 3.0 m) and collected in separate 1 L Niskin bottles using an ad hoc vertical collection device, which comprises a 3.5 m perforated tube, a small vacuum pump (0.1 m diameter), connective tubes, and a scale bar. The depth of the water inlet was controlled and determined by a scale bar (Xue et al., 2015). Wind speed were measured at each station using a FR-HW handheld anemometer (Wuhan, China).

Table 1
Acronyms, abbreviations, symbols and units as applied in this study.

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Abbreviations</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>OAPs</td>
<td>Apparent optical properties</td>
<td>a(λ)</td>
</tr>
<tr>
<td>CDOM</td>
<td>Colored dissolved organic matter</td>
<td>a(λ)</td>
</tr>
<tr>
<td>CDM</td>
<td>Colored detrital matter</td>
<td>b(λ)</td>
</tr>
<tr>
<td>IOPs</td>
<td>Inherent optical properties</td>
<td>d(λ)</td>
</tr>
<tr>
<td>N</td>
<td>Number of samples</td>
<td>s(λ)</td>
</tr>
<tr>
<td>NAP</td>
<td>Non-algal particulates</td>
<td>a - b(λ)</td>
</tr>
<tr>
<td>OACs</td>
<td>Optically active constituents</td>
<td></td>
</tr>
<tr>
<td>WCH</td>
<td>West Lake Chaohu</td>
<td></td>
</tr>
<tr>
<td>MCH</td>
<td>Middle Lake Chaohu</td>
<td></td>
</tr>
<tr>
<td>ECH</td>
<td>East Lake Chaohu</td>
<td></td>
</tr>
<tr>
<td>Symbols</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Total absorption coefficient (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption by CDOM (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption by NAP (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption by CDM (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption by phytoplankton (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a - b(λ)</td>
<td>Total absorption, with pure water component omitted, at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption by pure water (m⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>a(λ)</td>
<td>Absorption coefficient for component “k”, such as aₙ, aₙₐ, aₙₕ, and aₙₑ, at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>aₑ(λ)</td>
<td>Chl a-specific absorption by phytoplankton (m² μg⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>aₑ(λ)</td>
<td>SPIM-specific absorption by phytoplankton (m² g⁻¹) at wavelength (λ)</td>
<td></td>
</tr>
<tr>
<td>Chl a</td>
<td>Chlorophyll-a concentration (μg/L)</td>
<td></td>
</tr>
<tr>
<td>Chl a(λ)</td>
<td>Vertical profile of chlorophyll-a concentration (μg/L)</td>
<td></td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved organic carbon concentration (mg/L)</td>
<td></td>
</tr>
<tr>
<td>Qₑ(765)</td>
<td>Package effect index (dimensionless)</td>
<td></td>
</tr>
<tr>
<td>Sₚ</td>
<td>Slope of aₙₑ spectrum (nm⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Sₚₑ</td>
<td>Slope of aₙₑ spectrum (nm⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Sₘₑ</td>
<td>Slope of aₙₑ spectrum (nm⁻¹)</td>
<td></td>
</tr>
<tr>
<td>SPIM</td>
<td>Suspended particulate inorganic matter (mg/L)</td>
<td></td>
</tr>
</tbody>
</table>

The complex optical properties of Case II waters present distinct challenges to bio-optical modeling and water color remote sensing algorithm parameterization and performance (Li et al., 2013; Mitchell and Cunningham, 2015; Organelli et al., 2016; Shi et al., 2013). Overcoming these challenges requires optical properties to be well understood in the context of driving physical and biological dynamics of a region (Aurin et al., 2010). In addition, remote sensing data are often directly interpreted using empirical algorithms based on regressions that relate the concentration of OACs to the remote sensing signal of either one spectral band or an arithmetic combination of several bands (Ylöstalo et al., 2014). These empirical algorithms do not consider spatial and seasonal variations in IOPs (Odermart et al., 2012; Sathyendranath, 2000). The vertical distribution of OACs has an important effect on the underwater light field and remote sensing reflectance (Gordon and Clark, 1980; Kutser et al., 2008; Stramska and Stramski, 2005). Absorption coefficients may exhibit corresponding vertical variation owing to the internal relations of OACs and IOPs. Accurate descriptions of the scales of variability in IOPs and specific IOPs are needed for an accurate inversion of the remote sensing signal into biogeochemical quantities and simulation of underwater light field (Campbell et al., 2010; Oubelkheir et al., 2006).
acetone as reference. The Chl $a$ value was calculated using absorbance at 630, 645, 663, and 750 nm measured with a Shimadzu UV-2600 spectrophotometer (Werdell et al., 2013). For SPIM, 47 mm Whatman GF/F glass filters were pre-combusted at 450 °C for 6 h and pre-weighted. Water samples were filtered, and filters were dried at 105 °C for 4–6 h. SPIM was derived gravimetrically by burning organic matter from the filters at 450 °C for 6 h and weighing the filters again (Jiang et al., 2012). The filtered water obtained by filtering onto pre-combusted GF/F glass fiber filters was used to determine the concentration of DOC using a Shimadzu TOC-5000A analyzer (Chen et al., 2004; Jiang et al., 2012).

**Absorption coefficient**

Determination of the spectral absorption coefficients of water constituents essentially involved direct measurements of three quantities, namely, absorption coefficient of phytoplankton, $a_{\text{ph}}(\lambda)$, absorption coefficient of non-algal particulates (also referred to as the detritus), $a_d(\lambda)$, and absorption coefficient of CDOM, $a_c(\lambda)$, and absorption coefficient of pure water, $a_w(\lambda)$.

$$a(\lambda) = a_{\text{ph}}(\lambda) + a_d(\lambda) + a_c(\lambda) + a_w(\lambda)$$  \hspace{1cm} (1)

The absorption coefficients of pure water were obtained from Pope and Fry (1997). The methods for measurement of absorption coefficients of phytoplankton, NAP, and CDOM are described below.

Absorption coefficients of the total particulate matter, phytoplankton pigments, and NAP were determined using the quantitative filter technique (Mitchell, 1990) with 47 mm GF/F filters and a Shimadzu UV2600 spectrophotometer with 1 nm interval in the range 350 to 800 nm. Absorbance spectra of non-algal particles were measured after the pigments were bleached with sodium hypochlorite (Ferrari and Tassan, 1999). The baseline was corrected using a blank filter wetted with filtered water (Ma et al., 2006). Absorbance spectra were corrected for backscatter by subtracting the average absorbance at 750 nm from the entire spectra (Ma et al., 2006; Zhang et al., 2007) and pathlength amplification (Cleveland and Weidemann, 1993; Ylöstalo et al., 2014). The increase in pathlength caused by multiple scattering was corrected using Eq. (2) from Cleveland and Weidemann (1993).

$$A = 0.378OD_f + 0.523OD_f^2; OD_f \leq 0.4$$  \hspace{1cm} (2)

where $A(\lambda)$ is the absorbance at wavelength $\lambda$ and $OD_f$ is optical density of total particulate matter on the filter. After these corrections, the

### Table 2

Summary of Lake Chaohu bio-optical measurements from May 2013 (201305) to April 2015 (201504). WCH, MCH, and ECH stand for West Lake Chaohu, Middle Lake Chaohu, East Lake Chaohu, respectively. In each cruise, “S” indicates samples of water surface at 0–0.4 m; and “V” indicates vertical measurements (0, 0.1, 0.2, 0.4, 0.7, 1.0, 1.5, 2.0, 3.0 m).

<table>
<thead>
<tr>
<th>Cruises</th>
<th>Date</th>
<th>N</th>
<th>Wind speed (m/s)</th>
<th>Location</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>201305-S</td>
<td>May 11–14, 2013</td>
<td>47</td>
<td>1.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>201305-V</td>
<td>May 28, 2013</td>
<td>76</td>
<td>1.09</td>
<td></td>
<td>Spring</td>
</tr>
<tr>
<td>201306-S</td>
<td>June 14–15, 2013</td>
<td>24</td>
<td>2.34</td>
<td>WCH, MCH, ECH</td>
<td>Summer</td>
</tr>
<tr>
<td>201309-S</td>
<td>September 4, 6 and 17, 2013</td>
<td>31</td>
<td>2.47</td>
<td>WCH, MCH, ECH</td>
<td>Autumn</td>
</tr>
<tr>
<td>201406-S</td>
<td>June 12, 2014</td>
<td>15</td>
<td>1.69</td>
<td>WCH, MCH, ECH</td>
<td>Summer</td>
</tr>
<tr>
<td>201409-S</td>
<td>September 20–21, 2014</td>
<td>24</td>
<td>1.66</td>
<td>WCH, MCH, ECH</td>
<td>Autumn</td>
</tr>
<tr>
<td>201501-S</td>
<td>January 16–17, 2015</td>
<td>30</td>
<td>2.6</td>
<td>WCH, MCH, ECH</td>
<td>Winter</td>
</tr>
<tr>
<td>201504-S</td>
<td>April 14, 2015</td>
<td>14</td>
<td>1.86</td>
<td>WCH, MCH, ECH</td>
<td>Spring</td>
</tr>
</tbody>
</table>

* Represents that wind speed of May 11–14 2013 was collected from historic data of nearby weather station.
absorption values were converted to absorption coefficients of total particles \( q_0(\lambda) \) and NAP \( q_a(\lambda) \) \((\text{m}^{-1})\) as follows (Cleveland and Weidemann, 1993):

\[
a_i(\lambda) = 2.303 \times A(\lambda) \times A_f/V
\]

where \( i \) represents the phytoplankton pigment or NAP, \( A_f \) is the effective filtration area, and \( V \) is the filtration volume. Absorption of phytoplankton \( q_0(\lambda) \) was obtained by subtracting \( a_i(\lambda) \) from \( q_0(\lambda) \).

CDM absorption spectra \( a_0(\lambda) \) ranged from 280 to 700 nm with 1 nm interval and was determined from filtered water (Millipore filter with 0.22 μm pore size) using a spectrophotometer (Shimadzu UV2600) with Milli-Q water as the reference. A quartz cuvette with a light path of 1 cm was used for measurements. Absorbance at each wavelength were baseline corrected by subtracting the absorbance at 700 nm according to Eq. (5) (Bricaud et al., 1981; Ma et al., 2006; Zhou et al., 2015). The measured absorbance values were converted to absorption coefficients \( a_0(\lambda) \) \((\text{m}^{-1})\) using the following equations:

\[
a_i(\lambda) = 2.303 \times A(\lambda)/l
\]

\[
a_0(\lambda) = a_0(\lambda) - a_i(700) \times \lambda/700
\]

where \( a_i(\lambda) \) and \( a_0(\lambda) \) are the pre-corrected and corrected absorption coefficient, respectively. \( A(\lambda) \) is the absorbance at wavelength \( \lambda \) (nm), and \( l \) is the path length of the quartz cell (m).

**Remote sensing reflectance**

Following NASA protocols (Mueller et al., 2003), an ASD field spectrometer (FieldSpec Pro Dual VNIR, Analytical Spectra Devices, Inc.) was used to measure downwelling radiance and upwelling total radiance above water surface. This instrument had a spectral range of 350–1050 nm with two probes and a viewing field of 25°. The total water leaving radiance \( L_w(\lambda) \), radiance of gray panel \( L_d(\lambda) \), and sky radiance \( L_{sky}(\lambda) \) were measured.

Each water spectrum was sampled at 90° azimuth with respect to the sun and with a nadir viewing angle of 45°. \( L_w(\lambda) \) was measured using the target probe at approximately 0.5 m above the water surface, whereas another probe measured \( L_{sky}(\lambda) \). The \( L_d(\lambda) \) with reflectance \( R_d(\lambda) \) was used to determine the incident downwelling radiantance \( [E_d(\lambda, 0^\circ)] \) (Eq. (6)).

\[
E_d(\lambda, 0^\circ) = L_d(\lambda) \times P/P_d
\]

\[
L_w(\lambda) \text{ consisted of the desired water leaving radiance } L_w(\lambda) \text{ and } L_{sky}(\lambda), \text{ and was corrected by:}
\]

\[
L_w(\lambda) = L_{sw}(\lambda) - p L_{sky}(\lambda)
\]

The water surface reflectance factor \( p \) depended on sky conditions, wind speed, and solar zenith angle (Mobley, 1999). Considering the average wind speed (< 5 m/s) and sky conditions (under clear sky or low cloud), it was assumed to be 0.028 based on the look up table for \( p \) coefficient in the article of Mobley (1999). \( R_{ai}(\lambda) \) was then derived by the ratio of \( L_w(\lambda) \) to incident downwelling spectral plane irradiance \( E_d(\lambda, 0^\circ) \).

\[
R_{ai}(\lambda) = L_w(\lambda) / E_d(\lambda, 0^\circ)
\]

**Data analysis**

**Absorption coefficient**

Bio-optical models generally combine CDOM and detrital particles into colored detrital matter (CDM) because of their similar spectral signatures. CDM absorption \( (a_{0g}) \) is the sum of NAP and CDM absorption:

\[
a_{0g}(\lambda) = a_g(\lambda) + a_e(\lambda)
\]

Chl \( a \)-specific absorption coefficient of phytoplankton \( (a_{ph}(\lambda)) \) was calculated by normalizing \( a_{ph}(\lambda) \) to Chl \( a \). SPIM-specific absorption coefficient of NAP \( (a_{NAP}(\lambda)) \) was calculated by normalizing \( a_{NAP}(\lambda) \) to SPIM.

The slope coefficient of CDM absorption \( S_p \) \((\text{nm}^{-1})\) was obtained by fitting an exponential equation over the 400–700 nm wavelength range to the data via nonlinear least squares curve fitting (Ylöstalo et al., 2014) using the lsqcurvefit routine in MATLAB (R2012b) software. The \( a_{0g}(\lambda) \) spectra were similar to those of CDM. The following expressions were fit to the spectra:

\[
a_g(\lambda) = a_g(\lambda_0) \exp[S_g(\lambda_0 - \lambda)]
\]

\[
a_e(\lambda) = a_e(\lambda_0) \exp[S_e(\lambda_0 - \lambda)]
\]

\[
a_{0g}(\lambda) = a_{0g}(\lambda_0) \exp[S_{0g}(\lambda_0 - \lambda)]
\]

where \( \lambda_0 \) (nm) was the reference wavelength (commonly 440 nm), \( a_{0g}(\lambda) \), \( a_g(\lambda) \), and \( a_{0g}(\lambda) \) was the absorption coefficient of CDM, NAP and CDM at \( \lambda \) nm, and \( S_p, S_g, S_{0g} \) was the spectral slope of the \( a_g(\lambda) \), \( a_e(\lambda) \), and \( a_{0g}(\lambda) \) spectrum, respectively.

**Absorption budget**

The absorption budget was presented to analyze the dominant constituent/s in the total light absorption across the visible spectrum (Naik et al., 2011), which was made by phytoplankton pigments, NAP and CDM to the total non-water absorption coefficient \( (a_i - w) \). It was derived at any wavelength by:

\[
a_i(\lambda) = a_i(\lambda)/a_i - w(\lambda) \times 100\%
\]

where \( a_i(\lambda) \) was a relative contribution of \( a_i \) to the total non-water absorption at \( \lambda \) nm, \( \lambda \) was the wavelength, \( i \) represented phytoplankton, NAP, or CDM, and \( a_i - w(\lambda) \) was the sum of \( a_{ph}(\lambda), a_g(\lambda) \) and \( a_{0g}(\lambda) \). The sample can then be optically characterized by a single point on a triangular plot, in which the axes were the fractional contributions due to each of the three components (Sathyendranath, 2000). To examine the relative contributions of phytoplankton, NAP, and CDM absorption coefficients to the total non-water absorption, the coefficients were displayed on a normalized ternary plot at three wavebands (443, 555, and 675 nm).

According to the classification scheme of IIOCCG Report 3 (Sathyendranath, 2000), seven distinct dominant types of water were identified, such as cases where only one component dominates \( (a_{ph}, a_g, a_{0g}) \), cases where two substances dominate, and third component plays a minor role \( (a_{ph} - d_p, a_{ph} - d_p, a_g - d_p) \), and case where all the three components play important roles \( (a_{ph} - a_g - d_g) \).

**Statistical analyses**

The variability of each optical parameter was examined by calculating the mean, maximum, and minimum values with the standard deviations (SDs) and variation coefficients \( (CV = SD/\text{mean}) \). The relational equations between optical parameters and \( r^2 \) value of the regressions were shown in their respective figure panels. When one variable between different regions or seasons was compared, ANOVA (analysis of variance) \( p \) value was given to show whether the difference was significant or not. The F-value was used for comparing the factors of the total deviation. The number of degrees of freedom (DF) was the number of values in the calculation of a statistic that are free to vary.
Modeling of remote sensing reflectance

\[ R_\text{es}(\lambda) = \frac{f b_\text{h}(\lambda)}{a(\lambda) + b_\text{h}(\lambda)}, \]  

(14)

where \( f = f / Q \) and \( Q \) varied with the illumination conditions. \( f \) was usually set as 0.0945 (Gordon et al., 1988) and 0.0922 (Lee et al., 1998; Morel and Gentili, 1991); \( a(\lambda) \) was the total absorption coefficient, calculated from Eq. (1); \( b_\text{h}(\lambda) \) was the backscattering coefficient. Given the lack of available field measured backscattering coefficients, an optimization method was used to calculate the backscattering coefficient spectrum and \( f \) of each sample based on the above bio-optical model (Ma et al., 2008).

The impact of absorption coefficients on remote sensing reflectance modeling was assessed by changing the absorption coefficient of each OAC and keeping \( b_\text{h}(\lambda) \) and \( f \) fixed. The influence of absorption variation of phytoplankton, NAP, and CDOM on \( R_\text{es}(\lambda) \) was estimated using Eq. (15):

\[ R_{\text{es-M}}(\lambda) = \frac{f b_\text{h}(\lambda)}{a(\lambda) + x \cdot a(\lambda) + b_\text{h}(\lambda)}, \]  

(15)

\( x \) was set as ± 30% or ± 50% and \( a(\lambda) \) represented \( a_{\text{phy}}(\lambda) \), \( a_{\text{d}}(\lambda) \), or \( a_{\text{g}}(\lambda) \). The relative change between \( R_\text{es} \) and modeled \( R_{\text{es-M}} \) was calculated by:

\[ \Delta R_{\text{es}}(\lambda) = \left( \frac{R_{\text{es-M}}(\lambda) - R_\text{es}(\lambda)}{R_\text{es}(\lambda)} \right) \times 100\% \]  

(16)

Results

Optically active constituents

There was a great variability in concentrations of OACs (\( \text{Chl} a \), SPIM, and DOC), ranging more than one order of magnitude (Tables 3-4). \( \text{Chl} a \) ranged from 6.85 to 138.55 \( \mu \text{g/L} \) with an average of 38.3 (± 29.46, \( N = 185 \)) \( \mu \text{g/L} \). Large dynamic ranges and high variability were also observed for SPIM (2–105, 32.22 ± 21.34 mg/L, \( N = 185 \)) and DOC (0.18–22.49, 9.92 ± 4.43 µg/L, \( N = 185 \)). Shi et al. (2013) reported that the average \( \text{Chl} a \) and SPIM of Lake Chaohu was 58.22 mg/L (23.82–165.76 µg/L) and 30.7 mg/L (8.45–68.4 mg/L), respectively.

Mean concentrations of \( \text{Chl} a \), SPIM, and DOC generally decreased from WCH to MCH and ECH of Lake Chaohu (Table 3). ANOVA tests indicated significant spatial differences in \( \text{Chl} a \) (\( DF = 184, F = 25.68, p < 0.001 \)) for the three segments of Lake Chaohu. Unlike \( \text{Chl} a \), no significant regional variability was observed in SPIM (\( DF = 184, F = 1.07, p = 0.35 \)) and DOC (\( DF = 184, F = 1.32, p = 0.24 \)) for the three segments. Some seasonal differences were found for optically active constituents. In summer and autumn, concentrations of \( \text{Chl} a \) and SPIM were higher than that in spring (Table 4). However, average \( \text{Chl} a \) (54.36 ± 36.89 mg/L) and DOC (14.22 ± 1.88 mg/L) were high, and SPIM (17.27 ± 9.15 mg/L) was low in winter (only one cruise on January 16–17, Table 2). As algal blooms were recorded on January 16–17, 2015, data of one cruise might not represent the general condition of winter. More field data need to be collected to describe the temporal variation of absorption properties effectively.

Light absorption properties

Absorption coefficient of phytoplankton

The absorption spectra of phytoplankton showed that the pigments had two absorption maxima at the blue (~440 nm) and red wavelength (~675 nm) (Figs. 2a-b). Ficek et al. (2013) indicated that the blue part of the spectrum (~440 nm) is due to absorption by almost all of the main pigments contained in phytoplankton cells, and the red part (~675 nm), narrower and smaller, is due primarily to the absorption by chlorophyll-\( a \), and to a lesser extent by chlorophyll-\( b \).

Table 4

<table>
<thead>
<tr>
<th></th>
<th>Spring ( (N = 61) )</th>
<th>Summer ( (N = 39) )</th>
<th>Autumn ( (N = 55) )</th>
<th>Winter ( (N = 30) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Chl} a )</td>
<td>6.85 ± 135.39</td>
<td>11.01 ± 137.72</td>
<td>16.63 ± 137.77</td>
<td>17.86 ± 138.55</td>
</tr>
<tr>
<td>SPIM</td>
<td>25.15 ± 22.64</td>
<td>35.83 ± 20.59</td>
<td>44.11 ± 24.82</td>
<td>54.36 ± 36.89</td>
</tr>
<tr>
<td>DOC</td>
<td>1.54 ± 0.35</td>
<td>0.86 ± 0.32</td>
<td>0.037 ± 0.014</td>
<td>0.028 ± 0.014</td>
</tr>
</tbody>
</table>

Table 3 Statistics for range (first line for each parameter) and mean and standard deviation (second line) for chlorophyll-\( a \) concentration [\( \text{Chl} a, \mu \text{g/L} \)], suspended particulate inorganic matter [SPIM, mg/L], dissolved organic carbon [DOC, µg/L], phytoplankton absorption coefficients at 443 nm \( a_{\text{phy}}(443) \), m\(^{-1}\), and 675 nm \( a_{\text{phy}}(675) \), m\(^{-1}\), detrital, CDOM, and CDOM absorption coefficient at 443 nm \( a_{\text{d}}(443) \), m\(^{-1}\), and 675 nm \( a_{\text{d}}(675) \), m\(^{-1}\), of Lake Chaohu from 7-cruise surveys between 2013 and 2015. WCH, MCH, and ECH stand for West Lake Chaohu, Middle Lake Chaohu, East Lake Chaohu, respectively (Fig. 1). Not shown are the samples with floating algae were deleted in this study, considering that their extremely high \( \text{Chl} a \) concentration may increase the average value dramatically.
8.89 m$^{-1}$ and from 0.16 to 5.39 m$^{-1}$, respectively, corresponding to Chl $a$ range of 6.85–138.55 μg/L (Table 3). The average $a_{ph}(\lambda)$ in WCH was higher than that in MCH and ECH (Fig. 2b) because of the frequent outburst of algal blooms and high concentration of Chl $a$ in WCH. Significant variability of $a_{ph}(443)$ (DF = 184, $F = 10.42$, $p < 0.001$) and $a_{ph}(675)$ (DF = 184, $F = 10.63$, $p < 0.001$) was found among the three lake segments, with average $a_{ph}(443)$ decreasing from WCH ($1.74 \pm 1.56$ m$^{-1}$) to MCH ($1.08 \pm 0.66$ m$^{-1}$) and ECH ($0.96 \pm 0.53$ m$^{-1}$) (Table 3). In spring, $a_{ph}(443)$ ranged from 0.32 to 3.88 m$^{-1}$ and $a_{ph}(675)$ ranged from 0.16 to 2.1 m$^{-1}$, while in autumn $a_{ph}(443)$ ranged from 0.5 to 8.89 m$^{-1}$ and $a_{ph}(675)$ ranged from 0.24 to 5.39 m$^{-1}$. The mean $a_{ph}(443)$ were $0.85 \pm 0.53$ nm$^{-1}$ and $1.32 \pm 1.24$ m$^{-1}$ in spring and autumn, respectively, with significant difference (DF = 184, $F = 16.28$, $p < 0.001$) (Table 4).

The Chl $a$-specific phytoplankton absorption [$a_{ph}^{*}(443)$, $a_{ph}^{*}(675)$] showed large variability in Lake Chaohu (Table 5) and may pose problems when it is assumed to be constant. The variability of $a_{ph}^{*}(443)$ that ranged from 0.008 to 0.102 m$^{2}$ mg$^{-1}$ with average of 0.037 ± 0.017 m$^{2}$ mg$^{-1}$ was greater than $a_{ph}(675)$, ranging from 0.004 to 0.008 to 0.039 m$^{2}$ g$^{-1}$ with average of 0.004 to 0.023 m$^{2}$ g$^{-1}$.

### Table 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CH ($N = 185$)</th>
<th>WCH ($N = 59$)</th>
<th>MCH ($N = 67$)</th>
<th>ECH ($N = 59$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{ph}^{*}(443)$</td>
<td>0.008-0.102</td>
<td>0.008-0.102</td>
<td>0.015-0.09</td>
<td>0.015-0.072</td>
</tr>
<tr>
<td>$a_{ph}^{*}(675)$</td>
<td>0.004-0.039</td>
<td>0.004-0.039</td>
<td>0.008-0.038</td>
<td>0.009-0.034</td>
</tr>
<tr>
<td>$a_{d}^{*}(443)$</td>
<td>0.023-0.923</td>
<td>0.039-0.521</td>
<td>0.037-0.923</td>
<td>0.025-0.456</td>
</tr>
<tr>
<td>$S_d$</td>
<td>0.11 ± 0.098</td>
<td>0.104 ± 0.072</td>
<td>0.119 ± 0.129</td>
<td>0.106 ± 0.075</td>
</tr>
<tr>
<td>$S_g$</td>
<td>0.011-0.016</td>
<td>0.012-0.015</td>
<td>0.011-0.014</td>
<td>0.012-0.016</td>
</tr>
<tr>
<td>$S_{dg}$</td>
<td>0.004-0.001</td>
<td>0.013 ± 0.001</td>
<td>0.013 ± 0.001</td>
<td>0.013 ± 0.001</td>
</tr>
</tbody>
</table>

Fig. 2. Absorption spectra of (a) phytoplankton pigments ($N = 185$), (c) detrital particles ($N = 185$), (e) colored dissolved organic matter [CDOM] ($N = 185$), and (b, d, f) their mean and standard deviation of the west (WCH, $N = 59$, blue lines), middle (MCH, $N = 67$, red lines), and east (ECH, $N = 59$, green lines) parts of Lake Chaohu.
Table 6
Bio-optical parameters (Min–Max, first line for each location, Mean ± SD, second line for each location) of several lakes or coastal waters.

<table>
<thead>
<tr>
<th>Area</th>
<th>Chl a (μg/L)</th>
<th>SPIM (mg/L)</th>
<th>a_{ph}(440) (m⁻¹)</th>
<th>a_{ph}(675) (m⁻¹)</th>
<th>a_{g}(440) (m⁻¹)</th>
<th>a_{g}⁎ (675) (m² mg⁻¹)</th>
<th>S_{a}(400–700) (nm⁻¹)</th>
<th>S_{g}(400–700) (nm⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Chaohu</td>
<td>23.82–165.76</td>
<td>8.45–68.4</td>
<td>0.38–5.32</td>
<td>0.34–2.58</td>
<td>0.9–12.6</td>
<td>0.472–1.094</td>
<td>0.005–0.03</td>
<td>0.01–0.012</td>
<td>(Shi et al., 2013)</td>
</tr>
<tr>
<td>China</td>
<td>58.22 ± 36.61</td>
<td>30.7 ± 14.12</td>
<td>1.69 ± 0.37</td>
<td>0.90 ± 0.50</td>
<td>3.96 ± 2.14</td>
<td>0.682 ± 0.033</td>
<td>0.014 ± 0.005</td>
<td>0.011 ± 0.0005</td>
<td>0.016 ± 0.00035</td>
</tr>
<tr>
<td>Lake Taihu</td>
<td>1.26–130.72</td>
<td>2.67–222.5</td>
<td>0.11–0.35</td>
<td>0.02–3.98</td>
<td>0.51–1.15</td>
<td>0.138–1.157</td>
<td>0.002–0.147</td>
<td>0.0088–0.0137</td>
<td>(Shi et al., 2013)</td>
</tr>
<tr>
<td>China</td>
<td>15</td>
<td>45.4</td>
<td>1.14</td>
<td>0.48</td>
<td>3.45</td>
<td>0.467</td>
<td>0.03</td>
<td>0.0112</td>
<td>(Shi et al., 2013)</td>
</tr>
<tr>
<td>Lake Dianchi</td>
<td>38.97–156.7</td>
<td>0–22.8</td>
<td>1.67–5.57</td>
<td>0.74–2.99</td>
<td>0.51–3.15</td>
<td>0.711–2.286</td>
<td>0.012–0.035</td>
<td>0.0082–0.015</td>
<td>(Shi et al., 2013)</td>
</tr>
<tr>
<td>China</td>
<td>96.43 ± 35.76</td>
<td>9.01 ± 4.25</td>
<td>3.75 ± 1.12</td>
<td>2.01 ± 0.58</td>
<td>1.88 ± 0.73</td>
<td>1.657 ± 0.099</td>
<td>0.022 ± 0.006</td>
<td>0.011 ± 0.0017</td>
<td>0.011 ± 0.00039</td>
</tr>
<tr>
<td>Lake Poyang</td>
<td>1.47–24.65</td>
<td>13–148</td>
<td>0.2853–2.0142</td>
<td>–</td>
<td>1.24–10.44</td>
<td>0.3277–1.0067</td>
<td>–</td>
<td>0.0114–0.0175</td>
<td>(Wu et al., 2011)</td>
</tr>
<tr>
<td>China</td>
<td>8.85 ± 6.41</td>
<td>48 ± 28.27</td>
<td>0.8008 ± 0.3057</td>
<td>–</td>
<td>4.55 ± 2.4829</td>
<td>0.5581 ± 0.1552</td>
<td>–</td>
<td>0.0142 ± 0.0015</td>
<td>(Wu et al., 2011)</td>
</tr>
<tr>
<td>Boreal lakes</td>
<td>1.8–94.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.04–1.78</td>
<td>0.43–14.5</td>
<td>0.008–0.020</td>
<td>0.0075–0.0128</td>
<td>(Ylöstalo et al., 2014)</td>
</tr>
<tr>
<td>Finland</td>
<td>20.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.47ème</td>
<td>2.65ème</td>
<td>0.014</td>
<td>0.0101b</td>
<td>(Ylöstalo et al., 2014)</td>
</tr>
<tr>
<td>Tampa Bay</td>
<td>0.37–78.93</td>
<td>–</td>
<td>0.023–1.58ème</td>
<td>–</td>
<td>0.0095–1.05ème</td>
<td>0.065–9.41ème</td>
<td>0.0022–0.072</td>
<td>0.008–0.0193</td>
<td>(Le et al., 2013)</td>
</tr>
<tr>
<td>USA</td>
<td>7.99 ± 7.73</td>
<td>–</td>
<td>0.22 ± 0.16</td>
<td>–</td>
<td>0.19 ± 0.16</td>
<td>0.72 ± 1.00</td>
<td>0.013 ± 0.0027</td>
<td>0.0122 ± 0.002</td>
<td>(Le et al., 2013)</td>
</tr>
<tr>
<td>Long Island Sound</td>
<td>0.7–80.6</td>
<td>–</td>
<td>0.008–0.47ème</td>
<td>–</td>
<td>0.025–0.42ème</td>
<td>0.12–0.75ème</td>
<td>–</td>
<td>0.0075–0.0118</td>
<td>(Aurin et al., 2010)</td>
</tr>
<tr>
<td>USA</td>
<td>7.1 ± 12</td>
<td>–</td>
<td>0.072 ± 0.126</td>
<td>–</td>
<td>0.115 ± 0.107</td>
<td>0.3 ± 0.1</td>
<td>–</td>
<td>0.0089 ± 0.0008</td>
<td>(Aurin et al., 2010)</td>
</tr>
</tbody>
</table>

* Represents the 442 nm wavelength.

b Represents the 380–700 nm.

c Represents the 443 nm wavelength.
0.039 m² mg⁻¹ with average of 0.019 ± 0.007 m² mg⁻¹. The absorption coefficient of the water at 443 nm (aₕ(443)) ranged from 0.0025 to 0.029 m² mg⁻¹ with average of 0.012 ± 0.017 m² mg⁻¹. The absorption coefficient at 675 nm (aₕ(675)) was 0.0138, 0.0123, 0.0109, 0.0117 m² mg⁻¹ from spring to winter (DF = 184, F = 4.27, p = 0.006), and was 0.0104, 0.0126, 0.0139 m² mg⁻¹ from WCH to ECH (DF = 184, F = 9.68, p < 0.001).

Absorption coefficient of NAP and CDOM

The spectral dependencies of aₕ(λ) and aₕ(λ) are both well represented by exponential functions (Eqs. (10)–(11), Fig. 2c, e). The mean aₕ(λ) and aₕ(λ) of different parts of Lake Chaohu showed that the absorption of NAP is about three times that of CDOM in each part (Fig. 2d, f). Variation of aₕ(λ) was large, ranging between 0.76 and 7.33 m⁻¹ at 443 nm, and aₕ(440) ranged more than one order of magnitude, that is, 0.16–4.26 m⁻¹. aₕ(443) ranged from 1.46 to 8.73 m⁻¹ with average value of 3.21 (±1.23) m⁻¹ (Table 3). The three segments of Lake Chaohu had significant spatial variability of aₕ(443). Higher values of aₕ(443) are associated with higher phytoplankton absorption coefficients (Fig. 3).

**Fig. 3.** Relationships between (a) suspended particulate inorganic matter [SPIM] and SPIM-specific detrital particles absorption at 443 nm [aₕ(443)], (b) spectrum slope of non-algal particles absorption [Sₕ] and detrital particles absorption coefficient at 440 nm [aₕ(440)], (c) spectrum slope of CDOM absorption [Sₕ] and CDOM absorption coefficient at 440 nm [aₕ(440)], (d) Sₕ and Sₕ (dashed line indicates the average deviation, and dotted lines are standard deviations). WCH (blue squares, N = 59), MCH (red circles, N = 67), and ECH (green triangles, N = 59) stand for West Lake Chaohu, Middle Lake Chaohu, and East Lake Chaohu, respectively.

**Fig. 4.** Percentage contribution of phytoplankton, detrital particles, and CDOM to total non-water absorption at (a) 443 nm, (b) 555 nm, and (c) 675 nm of the water surface (N = 185). WCH (blue squares, N = 59), MCH (red circles, N = 67), and ECH (green triangles, N = 59) stand for West Lake Chaohu, Middle Lake Chaohu, and East Lake Chaohu, respectively.
a_dg(443) were found in WCH (3.62 ± 1.35 m−1) and MCH (3.25 ± 1.31 m−1), and the lowest average value was recorded at ECH (2.74 ± 0.79 m−1) (Table 3). A significant spatial variability was also found in a_dg(443) (DF = 184, F = 5.61, p = 0.004) and a_dg(443) (DF = 184, F = 5.07, p = 0.007) with spatial trend similar to a_dg(443). The average a_dg(443) were 2.54 ± 1.16 m−1, 2.7 ± 1.07 m−1, and 2.53 ± 0.71 m−1 in spring, summer, and autumn, respectively (Table 4). The average a_dg(443) for all 185 surface sampling sites were 0.66 ± 0.42 m−1 and 1.02 ± 0.54 m−1 in spring and autumn, respectively, with that in autumn being significantly higher than that in spring (DF = 184, F = 6.67, p < 0.001).

The variation of a_d(λ) was large, ranging between 0.023 and 0.923 m2 g−1 at 443 nm (Table 4-5, Fig. 3a). A decreasing trend of a_d(443) is observed with increasing SPIM from 2 to 105 mg/L (Fig. 3a). a_d(443) has no significant spatial (DF = 184, F = 0.39, p = 0.67) and significant seasonal (DF = 184, F = 5.63, p = 0.001) variability. S_d was found to vary in the range of 0.011–0.016 nm−1 (Table 5), with an average of 0.013 ± 0.001 nm−1 without significant spatial variability (DF = 184, F = 0.96, p = 0.38). S_d was found with significant seasonal difference (DF = 184, F = 15.88, p < 0.001). The average S_d of Lake Chaohu in this study was slightly higher than previous reported (Table 6). S_d varied up to fourfold from 0.012–0.043 nm−1, with an overall mean of 0.019 ± 0.004 nm−1 (N = 185, Table 5). In comparison, WCH had much higher slope coefficients. However, no significant difference was found in S_d either spatially for three parts (DF = 184, F = 1.48, p = 0.23) or seasonally for different seasons (DF = 184, F = 0.28, p = 0.83). The average S_d of Lake Chaohu in this study was slightly higher than previous published (Table 6). S_d showed low variation in different segments of Lake Chaohu with average of 0.014 ± 0.001 nm−1, ranging from 0.012 to 0.017 nm−1 (Table 5). The S_d values had less variable compared with S_g (Fig. 3d), consistent with several previous studies (Table 6).
Fig. 3b and c showed that $S_d$ was plotted against $a_d(443)$, and $S_g$ was plotted against $a_g(443)$ for three parts of Lake Chaohu. They exhibited no clear inverse relationships as suggested by previous studies (Blondeau-Patissier et al., 2009; Bricaud et al., 2010). There was no strong relationship between $a_g(443)$ and $S_g$ (Fig. 3c) over all sites.

**Dominant optical types of Lake Chaohu**

The relative contributions of phytoplankton, NAP, and CDOM absorption coefficients to total non-water absorption were analyzed to determine the dominant constituent/s in the light absorption (Fig. 4). At 443 and 555 nm, $a_d(\lambda)$ and $a_{ph}(\lambda)$ dominated the total non-water absorption coefficient, while $a_g(\lambda)$ contributed < 30%. At 443 nm, NAP absorption contributed most to the total non-water absorption. $a_{ph}(443)\%$, $a_d(443)\%$, and $a_g(443)\%$ were 33%, 46%, and 18% for WCH, 27%, 56%, and 17% for MCH, and 26%, 55%, and 19% for ECH, respectively. The total NAP and CDOM contribution to total non-water absorption was approximately 25% in the red region (675 nm), and the average relative contribution of $a_{ph}(675)$ was 75%.

The dominant types of the samples were derived from the classification scheme, and the results showed that type $a_{ph}-a_d-a_g$, which...
indicated optically complex water, played an important part in Lake Chaohu (Fig. 5). In WCH, the dominant types were \( a_{ph} - a_{d} - a_{g} \) (39.67%), \( a_{ph} - a_{d} \) (25%), and \( a_{d} \) (21.7%); type \( a_{ph} \) usually occurred in algal bloom waters. The ECH was also dominated by type of \( a_{ph} - a_{d} - a_{g} \) (55.9%), \( a_{ph} - a_{d} \) (20.33%), and \( a_{d} \) (18.64%). Overall, light absorption was dominated by \( a_{ph} \) and \( a_{d} \), and contribution of \( a_{g} \) was lower than 30% in Lake Chaohu.

A previous study of dominant optical types of Lake Chaohu obtained \( a_{ph} - a_{d} - a_{g} \) (81.82%) and \( a_{d} - a_{g} \) (18.18%) in October 2009 \( (N = 11) \) (Wang et al., 2013).

Vertical profiles of absorption properties

The vertical variation of absorption properties are highly variable and dependent on meteorological, biological and hydrological conditions. On short timescales (one day to several days), algal blooms and sediment resuspension played an important role in affecting the variability of phytoplankton, NAP and CDOM absorption. To assess the vertical variations of absorption coefficients, we focused our analysis on the vertical cruise on May 28, 2013.

Among the nine stations of the cruise to examine vertical structure on May 28, 2013 (Fig. 1), algal blooms occurred at five stations (S1–S3, S7–S8), and their Chl \( \alpha \) vertical distribution belonged to the negative power function with maximum occurred at water surface (see Fig. 2 and Table 2 in Xue et al., 2015). The Chl \( \alpha \) profiles of four other stations (S4–S6, S9) in non-algal bloom waters belong to Gaussian distribution with maximum value at water surface (see Fig. 2 and Table 2 in Xue et al., 2015). Both Chl \( \alpha \) and \( a_{ph}(443) \) had maximum values at the water surface for bloom conditions; these values tended to decrease with depth. This distribution mainly resulted from the vertical movement of algae in the water column and gathered at the water surface. The contour plot of \( a_{ph}(443) \) of the cruise revealed a variation range that covered more than one order of magnitude \( (0.2-8.07 \text{ m}^{-1}) \) (Fig. 6b) throughout the transect. Variation of \( a_{ph}(443) \) was very similar to the variation of Chl \( \alpha \) (Fig. 6a), which suggested covariation between \( a_{ph}(443) \) and Chl \( \alpha \) concentration. However, \( a_{ph}(443) \) was not constant, ranging from 0.012 to 0.051 m\(^2\) mg\(^{-1}\) (Fig. 6c). The average CV of \( a_{ph}(443) \) and \( a_{ph}(675) \) vertical profiles is 28.8% and 24.2%, respectively.

The vertical profiles of \( a_{d}(443) \) and \( S_d \) were displayed in Fig. 7b and c. S1–S6 exhibited higher concentration of SPIM compared with S7–S9, especially near the bottom of the lake, which possibly resulted from sediment resuspension (Fig. 7a). However, the spatial pattern of \( a_{d}(443) \) showed much less similarity with SPIM concentration, thereby suggesting a large scatter in the \( a_{d}(443) \) versus SPIM. High values of \( a_{d}(443) \) were observed when SPIM was \( >40 \text{ mg/L} \) and low values were observed with SPIM \( <30 \text{ mg/L} \) (Fig. 7b). \( S_d \) showed less variability across the transect with high values in algal bloom waters and low values in high-suspension waters.

Fig. 10. Influence of (a, b) phytoplankton absorption \( [a_{ph}\{\lambda\}] \), (c, d) detrital particles absorption \( [a_{d}\{\lambda\}] \), and (e, f) CDOM absorption \( [a_{g}\{\lambda\}] \) on remote sensing reflectance \( [R_{rs}\{\lambda\}] \) modeling. N1 and N2 are two representative samples. The solid black lines are in situ \( R_{rs}\{\lambda\} \). Sensitivity of \( R_{rs}\{\lambda\} \) on absorption coefficient is determined by changing the \( a_{ph}\{\lambda\}, a_{d}\{\lambda\} \) or \( a_{g}\{\lambda\} \) value by \( \pm 30\% \) or \( \pm 50\% \).
Vertical structure of DOC and $a_b(443)$ of the cruise exhibited different patterns in accordance with the result of surface samples. High DOC concentration was observed at S6–S8 mainly no deeper than 0.5 m, whereas $a_b(443)$ had the highest values at S1–S2 and S6, reaching $>1.5$ m$^{-1}$ in the algal bloom waters and lowest values at S7–S8. CVs of $S_a$ covered 12% to 29.6%, showing a larger variation than $S_a$ without a regular vertical trend.

Relationship of OACs and absorption coefficients

For the entire data range, dependence of $a_{ph}(675)$ on $Chl_a$ can be described using power functions ($a_{ph}(675) = 0.0473$ $Chl_a^{0.72}$, $r^2 = 0.63$) when $Chl_a$ varied from 6.85 to 138.55 µg/L (Fig. 8a). Similar relationships were found if the data were partitioned according to different regions. The function of $a_{ph}(675)$ and $Chl_a$ was slightly lower than that reported in Shi et al. (2013) ($a_{ph}(675) = 0.0358$ $Chl_a^{0.854}$, Fig. 8a). Zhang et al. (2007) provided a linear regression between $a_{ph}(675)$ and $Chl_a$ in Lake Taihu of China ($a_{ph}(675) = 0.0176$ $Chl_a – 0.0723$).

For NAP absorption, $a_{ph}(443)$ increased with increasing SPIM following a linear function ($a_{ph}(443) = 0.032$ SPIM +1.32, $r^2 = 0.51$, with SPIM ranging 2–202 mg/L) (Fig. 8b). No significant correlation was found between $a_{ph}(443)$ and DOC at wavelengths of 400–700 nm at a significance level of 0.05 for the water surface samples. The results also showed no significant correlation between $a_{ph}(443)$ and $Chl_a$ or SPIM, thereby further confirming the complex component of water constituents.

A decreasing trend of $a_{ph}^*(443)$ from 0.102 to 0.008 m$^{-1}$ was observed with increasing $Chl_a$ from 6.85 to 138.55 µg/L (Fig. 9a). As the accessory pigments are known to absorb significantly higher amounts of light in the blue region than in the red, the blue to red ratio of specific absorption coefficient [$a_{ph}^*(443)/a_{ph}^*(675)$] is strongly correlated with the ratio of accessory pigments to $Chl_a$ (Naik, 2010). This ratio varied from 1.02 to 3.84, demonstrating an approximate fourfold decrease as $Chl_a$ increasing (Fig. 9b). $a_{ph}^*(675)$ variability was attributed mainly to package effect (Naik, 2010), and could be quantified by $Q_a^*(\lambda)$, which is the ratio of $a_{ph}^*(\lambda)$ and specific phytoplankton absorption of the same pigmented material in suspension [$a_{ph}^{sol}(\lambda)$]. With $a_{ph}^{sol}(675)$ set equal to 0.0207 m$^{-1}$ (Bricaud et al., 1995; Naik et al., 2011; Naik et al., 2013), $Q_a^*(675)$ was calculated. $Q_a^*(675)$ decreased from 1.89 to 0.17 with increasing $Chl_a$ concentration in Lake Chaohu (Fig. 9c).

Impact of absorption variations on remote sensing reflectance modeling

In order to investigate the effect of light absorption on remote sensing reflectance modeling, absorption coefficients from field measurements and backscattering coefficients derived from the optimization method were used to model remote sensing reflectance at two stations (N1, N2) (Fig. 10). Keeping $b_{ph}(\lambda)$ the same, the effect of $a_{ph}^*(\lambda)$ variation on the green and red wavelengths and to a lesser extent on the blue wavelengths was apparent on $R_n(\lambda)$ spectra for the two samples (Fig. 10a, b). 50% variation of $a_b^*(\lambda)$ led to about 20% relative change of $R_n(\lambda)$ in the red range. The influence of $a_{ph}^*(\lambda)$ variation on $R_n(\lambda)$ spectra focused on the blue and green wavelengths, similar with $a_b(\lambda)$ (Fig. 10c–f). NAP absorption had a more important impact on the reflectance than CDM absorption, about a factor of 2–3 over the blue-green domain. Effect of changing CDM absorption became negligible compared to the effect of variability in particular absorption. Variations of $a_{ph}^*(\lambda)$ and $a_b^*(\lambda)$ affected different ranges of $R_n(\lambda)$ spectrum, thereby adding to the difficulty of remote sensing algorithm application. Those empirical blue-green band–ratio based Chl $a$ algorithms are unlikely to work in Lake Chaohu. Chl $a$ inversion algorithm development in optically complex waters had focused on utilizing longer wavelengths. Alternatively, developing spatial or seasonal semi-analytical algorithms based on the specific absorption properties may also be feasible to avoid the absorption variation.

Discussion

Variations of light absorption coefficients

$Chl_a$-specific absorption of phytoplankton

The observed variability in $a_{ph}^*(\lambda)$ indicated change in pigment composition or package effect. Accessory pigments are known to absorb significantly higher amounts of light in the blue region than in the red. $a_{ph}^*(443)/a_{ph}^*(675)$ showed the ratio of accessory pigments to $Chl_a$ (Naik, 2010). $a_{ph}^*(443)/a_{ph}^*(675)$ can also be used as an indicator of phytoplankton size, with higher values (e.g., $a_{ph}^*(443)/a_{ph}^*(675) > 3$) known to be associated with smaller cells (Naik et al., 2013). Previous studies of other regions showed that the blue to red ratio of small cells were typically $>2.5$ (Naik, 2010). A large part of $a_{ph}^*(443)/a_{ph}^*(675)$ values were $<3$ (mean = 1.92), signifying a relatively larger phytoplankton size in Lake Chaohu. Several values of $a_{ph}^*(443)/a_{ph}^*(675) > 3$ were also obtained. The inverse correlation of $a_{ph}^*(443)/a_{ph}^*(675)$ with $Chl_a$ indicated the dominance of smaller phytoplankton size at low $Chl_a$ and vice versa (Fig. 8b). The significant seasonal and spatial variation of $a_{ph}^*(620)$ also showed the presence of phycocyanin (PC) pigments. PC absorption peaks around 610–620 nm and imparts a blue-green color in combination with $Chl_a$.

Pigment packaging leads to absorption variation as phytoplankton cells accumulate in algal bloom waters. Average value of $a_{ph}^*(675)$ was lower at water surface than in the water below, which might be caused by larger Microcystis colonies accumulated and moved to the water surface (Zhu et al., 2014). For example, it has been reported that Microcystis colonies with diameters <200 µm distributed vertically homogeneously in the water column, and tended to gather in the water surface with diameters between 200 mm and 800 µm (Fan et al., 2013). $a_{ph}^*(675)$ variability was attributed mainly to package effect (Naik, 2010). Decrease of $Q_a^*(675)$ from 1.89 to 0.17 with increasing $Chl_a$ concentration (Fig. 8c) showed the effect of pigment packaging on $a_{ph}^*(\lambda)$ variation in Lake Chaohu.

Variation of $a_{ph}^*(\lambda)$ is also influenced by associated uncertainties in $Chl_a$ and $a_{ph}^*(\lambda)$ measurements (McKee et al., 2014). For instance, incorporating previously derived uncertainty estimates of 21% and 28% for $a_{ph}^*(\lambda)$ and $Chl_a$, respectively, obtains an uncertainty of 3% for $a_{ph}^*(\lambda)$ (McKee et al., 2014). Incomplete removal of phytoplankton pigments through depigmentation may introduce mismatch between the desired absorption coefficients of $a_b(\lambda)$ and $a_{ph}^*(\lambda)$ and the actual (Binding et al., 2008; Zheng and Stramski, 2013).

CDM absorption

It has been shown that CDM is largely dominated by CDM in global ocean (Bricaud et al., 2012; Nelson et al., 1998), but CDM of Lake Chaohu was largely dominated by NAP, for example, $a_q(443)/a_q(443)$ was 74%, 70% and 78% at 443, 555 and 675 nm, respectively. There is some evidence that $S_{sd}(\lambda)$ (approximately 0.010 to 0.050 nm$^{-1}$) is variable spatially and seasonally, both in the coastal and open ocean (Bricaud et al., 2012). $S_{sd}$ and $S_d$ have no significant spatial, seasonal, and vertical variability with relatively small variation. $S_{sd}$ of Lake Chaohu had weak variation ($0.012–0.017$ nm$^{-1}$) and showed no clear inverse relationship with $a_q(443)$ ($r^2 < 0.1$) ranging from 1.46 to 8.73 nm$^{-1}$. $S_{sd}$ variations were generally considered to reflect variations in the composition of NAP. To a lesser extent, the variable contribution of CDM absorption to the CDM also contributed to the overall variability in $S_{sd}$. $S_d$ and $S_d$ show less vertical variability with average CV of 18.9% and 3.4%, respectively, which is lower than the CV of surface samples.

Average $S_q(0.019$ nm$^{-1}$) in Lake Chaohu was slightly higher than that in Lake Taihu, China (Shi et al., 2013), Lake Poyang, China (Wu et al., 2011), boreal lakes of southern Finland (Ylöstalo et al., 2014), Tampa Bay of the USA (Le et al., 2013), and coastal waters around Europe (Babin et al., 2003). Brezonik et al. (2015) reported that $CV$ of $S_q(440)$ was 30%–50% in lakes and rivers of the U.S. Upper Midwest and lakes in Florida, and $S_d$ in a given water body tended to have
only small variations over time scales up to a decade or more. S2 showed larger variability at smaller $a_d(443)$, which is expected from the experimental random error (Babin et al., 2003). A possible explanation for the lack of correlation between $a_d(443)$ and $S_4$ is that there are multiple sources and processes affecting the composition of the DOM pool (Hestir et al., 2015). $S_4$ can be used as an indicator of the composition and processes acting on CDOM, and has been shown to be related with DOM composition, molecular weight of CDOM, mixing of end members, and photochemical bleaching (Blough and Del Vecchio, 2002). The weak correlation between $a_d(443)$ and Chl $a$ ($r^2 < 0.1$) can be attributed to CDOM processes being out of phase with phytoplankton biomass or production, and it indicated that most CDOM of Lake Chaohu was from river input or terrestrial origin (Naik et al., 2013). The variability of $S_4$ has also been proposed to be related to the relative importance of fulvic and humic acids (Xi et al., 2013). High $S_4$ values measured in Lake Chaohu indicated that fulvic acids dominate the CDOM.

The $S_4$ values were less variable compared with $S_2$ (Fig. 3d), consistent with several previous studies (Table 6). $S_2$ values ($mean = 0.013 \pm 1$) in Lake Chaohu were slightly higher than those in Lake Taihu, China (Shi et al., 2013), Tampa Bay of the USA (Le et al., 2013), boreal lakes of southern Finland (Västolbo et al., 2014), and coastal waters around Europe (Babin et al., 2003), and lower than those in Lake Po- yang, China (Wu et al., 2011) (Table 6). The presence of organic particles of different natures coexisting in variable proportions within the non-algal pool may lead to variations in $S_4$ values (Bricaud et al., 2010). The mean $S_4$ varied minimally over broad geographic regions.

Causes of light absorption variation

OACs and their light absorptions of Lake Chaohu showed large range and significant spatial variability, and the total non-water absorption was dominated by phytoplankton and NAP (~75%). Variation of phytoplankton and NAP accounted for a large part of absorption variation. Frequently occurring algal blooms enhanced the spatial and vertical variation of Chl $a$ concentration. Bottom resuspension caused by wind-driven waves in inland lakes mixed the water constituents across the water column and increased the concentration of suspended particulate matters (SPM) near the bottom. These two processes changed the composition and concentration of OACs, increased the variation of absorption coefficients, and produced a more complex underwater light field.

The occurrence of algal blooms increased the aggregation of algae, and introduced obvious vertical heterogeneity of Chl $a$ and $a_d(443)$. In addition, algal blooms changed the specific absorption of phytoplankton as a result of the package effect. $a_d(443)_{Chl-a}$ had significant spatial variation with the average value increasing from WCH to ECH (Table 5). $a_d(443)_{Chl-a}$ showed relatively lower values near the water surface, but without significant vertical variation. The significant spatial variation of $a_d(443)_{Chl-a}$ indicated that eutrophication and algal blooms affected the composition and size of phytoplankton.

On short time scales (one day to several days), bottom resuspension caused by wind driven waves played a key role in the variation of suspended matter in shallow lake (Giardino et al., 2014). Bottom resuspension affected the vertical profile of optically active constituents, NAP absorption, and contribution of NAP to total non-water absorption in Lake Chaohu. Sediment resuspension increased the variation of $a_d(443)$ and $a_d(443)_{Chl-a}$ of the water column. $S_0$, $S_2$, and $S_4$ showed no significant spatial and vertical variations. That is, bottom resuspension had no significant effect on variations of specific absorption of NAP and spectral slope of $a_d(443)$ and $a_d(443)_{Chl-a}$.

Conclusions

Absorption coefficients of phytoplankton, NAP, and CDOM measured at Lake Chaohu between May 2013 and April 2015 showed a large range and variability in accordance with OACs. OACs and their absorption coefficients had significant spatial variation, especially for phytoplankton. One possible mechanism to explain this variation was serious eutrophication of WCH and increased mixing due to several main inflowing rivers in the WCH and only one outflowing river in the ECH. Algal blooms and bottom resuspension were the main physical processes that affected the vertical variations of phytoplankton and NAP, and further altered the light absorption. The main dominant absorption budget types of Lake Chaohu were $a_d(443)$-$a_d(680)$ ($40\%$), $a_d(443)$-$a_d(860)$ ($25\%$), and $a_d(443)$-$a_d(940)$ ($22\%$). Variation of phytoplankton and NAP introduced a large part of the variation in absorption in Lake Chaohu. CDM absorption of Lake Chaohu was dominated by $a_d(443)$, which differed from the global ocean. Specific absorption of phytoplankton had significant regional and seasonal variations, but no vertical variation. No significant spatial variation of specific absorption and spectral slope was observed in NAP, CDM and CDM. Variation of $a_d(443)$ mainly affected the blue range of $K_4(443)$, and 50% variation of $a_d(443)$ could lead to about 20% relative change of $K_4(443)$ in the red range.

The complex constituents of OACs and large optical absorption variability could explain the unsuitability of the bio-optical models, both empirical and semi-analytical, for Lake Chaohu. With regard to water color remote sensing, our results supported the idea that algorithms may have to be developed at regional scales to perform well in inland lakes, and acquire source, composition, and size data of the OACs may be necessary to explain the variation of IOPs. Ultimately, laboratory studies on the optical properties of a variety of particles (various types of minerals, phytoplankton, heterotrophs, and detritus) combined with information on the type of particles present in situ and coupled with hydrodynamic-biogeochemical models will probably be the best approach for remote sensing of complex coastal systems.

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