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Absorption properties of in-water constituents and their variation among various lake types in the boreal region

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ABSTRACT

We studied the absorption properties of in-water constituents among 15 boreal lakes belonging to various lake types. One of the lakes was also monitored frequently during its growth season to reveal the seasonal variation of absorption properties. Within the studied lakes, CDOM absorption $a_{CDOM}(442)$ varied from 0.4 to 15 m^{-1}. CDOM was clearly dominating the absorption signal at low wavelengths, but even at the red-end of the spectra its contribution to total absorption was notable, varying from 48 to 99% of total absorption (excl. water) at 442 nm and from 5 to 86% at 665 nm. Slope of the CDOM absorption spectra $S_{CDOM}(400–700)$ varied from 12.9 to 19.3 μm^{-1}. Higher slopes were obtained when the wavelength range was extended to the UV-range (350–700 and 300–700 nm). Non-linear relationships were noted between a_{CDOM} and S_{CDOM} calculated over various wavelength ranges. Despite the significant relationship between DOC concentration and a_{CDOM}, almost five-fold variation was noted in DOC-specific CDOM absorption at 442 nm. This variation was clearly associated with concurrent changes in S_{CDOM}. Non-algal particulate absorption varied from 0.037 to 1.8 m^{-1} at 442 nm, contributing <1 to 34% of total absorption at 442 nm and <1 to 27% at 442 nm. Slope of the NAP absorption spectra $S_{NAP}(380–700)$ varied from 7.6 to 12.8 μm^{-1}. Despite of the apparent covariation between weight of suspended particulate matter (SPM) and a_{NAP}, six-fold variation was observed in SPM-specific NAP absorption at 442 nm, which was mostly associated with organic content of the particle pool. Contribution of phytoplankton pigments ranged from 1 to 28% of total absorption at 442 nm, and 13 to 86% at 665 nm, respectively. Chlorophyll a (Chl*a*) specific absorption of phytoplankton pigments varied from 0.012 to 0.038 m^2 (mg Chl*a*)$^{-1}$ at blue peak, and from 0.008 to 0.020 m^2 (mg Chl*a*)$^{-1}$ at red peak. Observed values cluster around the low-end of the previously reported range, indicating a high package effect of phytoplankton cells in lakes. Observed variation was modeled as function of Chl*a* (ranging from 1.8 to 95 mg m^{-3}). Parameters and relationships presented in this study provide useful information for remote sensing of lakes, as well as for various ecological and geochemical applications.

1. Introduction

Remote sensing can provide concurrent and nearly real time information across the various lake ecosystems and thus serve as a valuable tool for their integrated management if interpreted correctly (Bresciani, Stroppiana, Odermatt, Morabito, & Giardino, 2011; Koponen, Kallio, Pulliainen, Vepsäläinen, Pyhälahti & Hallikainen, 2004). However, for the time being there are no universally applicable algorithms for retrieving concentrations of water constituents for optically complex coastal and lake waters (formerly classified as Case 2 waters, Mobley, Stramski, Bissett, & Boss, 2004), but rather a variety of methods, each of them optimized only for specific water types (Odermatt, Gitelson, Brado, & Schaepman, 2012).

Remote sensing data have often been interpreted using empirical algorithms, based on regressions relating the concentration of an optically active substance (OAS) to the remote sensing signal of either one spectral band, or an arithmetic combination of several bands. These simple algorithms are sensitive to seasonal and regional variations of inherent optical properties (IOPs) of in-water constituents (IOCCG, 2000; Odermatt et al., 2012), thus requiring simultaneous ground-based measurements for their validation. Remote sensing of water constituents could become independent from additional ground-based measurements only if more complex, inversion based algorithms, leaning on valid IOPs are used. An advantage of these models over conventional band arithmetic algorithms is that multiple properties can be retrieved simultaneously (Tilstone, Peters, van der Woerd, Eleveld, Ruddick, Schoenfeld et al., 2012). On the other hand, inaccuracies in assumed optical properties of any OAS, e.g. the shape of chromophoric dissolved organic matter (CDOM) absorption, might propagate errors also in estimates of other constituents (Attila, Koponen, Kallio, Lindfors, Kaitala & Ylöstalo, 2013; Odermatt et al., 2012). In bio-optical models, however, these are often assumed as constants (based on any literature values available), although existing data show large

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variability, both seasonally and regionally (e.g. Babin, Stramski, Ferrari, Claustre, Bricaud, Obolensky et al., 2003; Strömbeck & Pierson, 2001; Tilstone et al., 2012). For the further improvement of the models, more information regarding the variability of optical properties of all important in-water constituents is needed.

Remote sensing data are needed for various ecological and geophysical applications; thus desired products by end-users are often concentrations of different in-water constituents e.g. chlorophyll a (Chl*a*), rather than just optical coefficient of OASs, which are primary products of inversion based algorithms. To convert optical coefficients to these more meaningful quantities, specific inherent optical properties (SIOPs) of OAS and their spatial and temporal variations must be known (IOCCG, 2000; Oubelkheir, Claustre, Sciandra, & Babin, 2005). Thus far, most of the efforts have been focused on retrieving Chl*a* concentrations. However, there is growing interest in linking remote sensing reflectance also to other constituents of the carbon pool, like suspended particulate matter (SPM) or particulate organic matter (POC), and dissolved organic matter (DOC) (Schwarz, 2005; Siegel, Maritorena, Nelson, Hansell, & Lorenzi-Kayser, 2002; Stramski, Reynolds, Babin, Kaczmarek, Lewis, Röttgers et al., 2008; Stumpf & Pennock, 1989), due to the essential role of the carbon cycle e.g. energy balance of water ecosystems and climate.

Absorption properties of different in-water constituents are key components of various bio-optical models. Total absorption of natural waters $a_{tot}(\lambda)$ (in units of m^{-1}), is classically expressed as the sum of its four main components: absorption of pure water $a_w(\lambda)$, CDOM $a_{CDOM}(\lambda)$, phytoplankton pigments $a_{ph}(\lambda)$, and non-algal particles $a_{NAP}(\lambda)$, from which $a_w(\lambda)$ is generally considered as constant, with some variation associated to salinity and temperature at specific wavelengths. Some general trends have been observed that allow parameterizations for these individual absorption components, to be utilized in various ecological, bio-optical, and remote sensing applications (e.g. Babin et al., 2003; Bricaud, Babin, Morel, & Claustre, 1995; Bricaud & Stramski, 1990; Kowalczuk, Stedmon, & Markager, 2006; Stedmon & Markager, 2003; Tilstone et al., 2012), but most of these trends are based on observations from oceanic, or less frequently from estuaries and coastal waters, and there is no reason to assume a priori that these are appropriate for lake waters as well.

Absorption of CDOM in boreal lake waters is generally very high, dominating the optical variability of these waters, especially at low wavelengths (Kallio, 2012; Kutser, Pierson, Kallio, Reinart & Sobek, 2005; Kutser, Pierson, Tranvik, Reinart, Sobek & Kallio, 2005). The decline of a_{CDOM} with increasing wavelength is commonly modeled with an exponential function (Jerlov, 1976), although other models have also been proposed (Twardowski, Boss, Sullivan, & Donaghay, 2004). Slope parameter is often used as a proxy of e.g. fulvic to humic acid ratio, molecular size, or degree of photochemical degradation of CDOM as a bulk (Carder, Steward, Harvey, & Ortner, 1989; Fichot & Benner, 2012; Helms, Stubbins, Ritchie, Minor, Kieber and Mopper, 2008). Combined with the salinity, optical properties of CDOM are also often used as quasi-conservative tracers of mixing end-members or as a tool to define relative importance of conservative and non-conservative processes on CDOM distribution (Kowalczuk et al., 2006; Stedmon & Markager, 2003; Stedmon, Osburn, & Kragh, 2010). A significant part of the reported overall variability of S_{CDOM} may, however, originate from different fitting methods and spectral ranges used (e.g. Schwarz, Kowalczuk, Kaczmarek, Cota, Mitchell, Kahru et al., 2002; Stedmon, Markager, & Kaas, 2000; Twardowski et al., 2004; Warnock, Gieskes, & van Laar, 1999), making it difficult to compare and combine results of separate studies (Babin et al., 2003; Twardowski et al., 2004). Although CDOM represents only a portion of the entire DOC pool (Thurman, 1985), significant positive correlations between DOC concentration and CDOM absorption have been observed (e.g. Ferrari, Dowell, Grossi & Targa, 1996; Kallio, 1999; Kutser, Pierson, Tranvik, et al., 2005; Warnock et al., 1999; Yacobi, Alberts, Takács, & McElvaine, 2003). Due to the chemical complexity of DOM, these published relationships are generally valid only for a specific geographical region and season (Siegel et al., 2002).

Absorption properties of non-algal particles (NAPs) are probably the least known of all OASs (Robinson, Antoine, Darecki, Gorringe, Pettersson, Ruddick et al., 2008), and thus far relatively few studies have been carried out in optically complex waters, in which $a_{NAP}(\lambda)$ has been actually measured (e.g. Babin et al., 2003; Tilstone et al., 2012). Also, the dependency of S_{NAP} on different fitting methods and the wavelength ranges used is far less studied than for S_{CDOM} (Seppälä, Ylöstalo, & Kuosa, 2005). NAP pool is composed of variable proportions of inorganic and organic particles. In open oceans, it is generally assumed to be dominated by organic particles, although mineral particles carried out by atmospheric transport or produced by local biological activity could also contribute significantly to the particle pool of oceans (Babin & Stramski, 2004; IOCCG, 2000). In coastal and estuarine waters, mineral particles introduced by river discharge or resuspension of bottom sediments obviously contribute more significantly to the particulate assemblage than in oceans (Babin & Stramski, 2004; Duarte, Agustí, Satta, & Vaqué, 1998; IOCCG, 2000). The particulate assemblage of lake waters is also expected to vary significantly. Loading of inorganic materials to lakes is largely governed by basin morphometry, characteristics of the drainage basin, and climatic factors, while the particulate organic matter in lakes is more dependent on its autochthonous production by phytoplankton and littoral flora (Ward, Ward, Dahm, & Aumen, 1994; Wetzel, 1983).

Chl*a* specific phytoplankton absorption $a_{ph}^*(\lambda)$, defined as $a_{ph}(\lambda)$/Chl*a*, is one of the fundamental parameters of bio-optical models aimed to retrieving Chl*a* concentrations or primary production (Campbell, Antoine, Armstrong, Arrigo, Balch, Barber et al., 2002; Gordon & Morel, 1983; Johnsen, Bricaud, Nelson, Prézelin, & Bidigare, 2011; Morel & André, 1991). Variability of $a_{ph}^*(\lambda)$ is generally related to changes in pigment packaging and pigment composition of phytoplankton cells, either via short-term physiological acclimation of the prevailing phytoplankton populations, or long-term adaptation leading to taxonomic changes within the community structure, driven by alternating growth conditions e.g. availability of light and nutrients (Bricaud, Claustre, Ras, & Oubelkheir, 2004; Fujiki & Taguchi, 2002). Nutrient enrichment leads generally to higher phytoplankton biomass and increased light attenuation, which favors large sized phytoplankton species, having higher photosynthetic pigment content, and consequently higher package effect (e.g. Bricaud et al., 1995; Bricaud et al., 2004; Johnsen et al., 2011; Stæhr & Markager, 2004). Taking these trends into account, $a_{ph}^*(\lambda)$ has been modeled as a function of Chl*a* (e.g. Bricaud et al., 1995; Stæhr & Markager, 2004). The most widely used model by Bricaud et al. (1995), based on samples from oceanic waters, is parameterized over a rather limited range of Chl*a* concentrations (from 0.02 to 25 mg m^{-3}). The model by Stæhr and Markager (2004), instead, is based on samples representing oceanic, coastal and estuarine waters, thus covering a wider Chl*a* range (from 0.01 to 100 mg m^{-3}). However, due to known differences between optical regimes and phytoplankton community composition between marine and lake waters, there is no basis to assume that either of these models is valid for lakes as such. Furthermore, both models are mainly based on a_{ph} spectra derived by numerical decomposition methods (Bricaud & Stramski, 1990). As far as we are aware, only one lake-specific model for $a_{ph}^*(\lambda)$ has been presented previously (Strömbeck & Pierson, 2001). This model was based on data collected from a single lake and its explanatory power was rather low.

The main aim of this study was to characterize variations of different absorption components between different lake types and seasons, and to derive parameterizations for these components that are applicable for remote sensing, but also for other ecological and geophysical applications. Useful information is also provided regarding the selection of optimum channel configuration for next generation spectrometers.