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Optical characterization of Lake Champlain: Spatial heterogeneity and closure

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ABSTRACT

A robust optical characterization of the underwater and emergent light fields of Lake Champlain was conducted for sites ($n = 11$) throughout the lake in August 2011, based on *in situ* measurements with modern instrumentation and laboratory measurements of optically active constituents (OACs) and components (a_x) of the absorption coefficient (a). Inherent optical property (IOP) measurements included a, a_x, and the particulate scattering and backscattering coefficients. Metrics of apparent optical properties (AOPs) included Secchi depth, the diffuse attenuation coefficients for downwelling [$K_d(\lambda)$] and scalar (K_0) irradiance and remote sensing reflectance [$R_{rs}(\lambda)$]. The credibility of the measurements is demonstrated through: (1) consistency of relationships between OACs and IOPs and AOPs, (2) the approach toward equivalence of laboratory and field measurements, and (3) the extent of closure of predictions of $K_d(\lambda)$ and $R_{rs}(\lambda)$, based on IOP measurements and radiative transfer expressions, with paired observations of these AOPs (average differences of 9.4 and 19.3%). Wide spatial differences in OACs, and the resulting IOPs and AOPs, are documented throughout the bounds of the lake and are the result of its morphologic complexity and differing external loading. The lake is a complex case 2 system, with uncoupled variations in OACs and a_x over the bounds of the lake. Both empirical and radiative transfer expressions are used to predict changes in AOPs in response to hypothetical changes in OACs.

Introduction

Optical attributes are important with respect to the ecology and water quality of the upper waters of lacustrine systems and to related remote sensing initiatives (Davies-Colley et al., 2003; Kirk, 2011). These attributes are determined by the concentrations and compositions of a diverse array of light attenuating substances, described as optically active constituents (OACs; acronyms and symbols listed in Table 1). Contemporary studies generally partition these substances into three groups: (1) phytoplankton, (2) non-algal particulates (NAP), that include both organic detritus and minerogenic particles (Babin et al., 2003b; Peng and Effler, 2010), and (3) colored dissolved organic material (CDOM; "gelbstoff" in earlier literature). These materials have both autochthonous and allochthonous origins, but external inputs are the primary drivers (e.g., nutrient loading for phytoplankton growth) for lacustrine systems (Kirk, 2011).

The effects of the OACs are mediated through the light attenuating processes of absorption and scattering, as quantified by coefficients that include, the absorption [$a(\lambda)$; wavelength, λ)], scattering [$b(\lambda)$], and backscattering [$b_b(\lambda)$] coefficients. These coefficients have a range of spectral dependencies (Babin et al., 2003a; Kirk, 2011; Snyder et al., 2008), and are described as inherent optical properties (IOPs; Kirk, 2011), in that they are independent of the geometry of the light field. The capability for routine direct measurement of IOPs has emerged over the last 20 years in marine studies (Dickey et al., 2006); but in comparison, such measurements remain uncommon in lake studies. In sharp contrast, the optical metrics of Secchi depth (SD) and the attenuation coefficients for downwelling (K_d) and scalar (K_0) irradiance for photosynthetically active radiation [PAR; K_d(PAR) and K_0(PAR)] have a long history in limnological studies (Kirk, 2011). These are apparent optical properties (AOPs) that depend on the geometry of the light field. Measurements of remote sensing reflectance [$R_{rs}(\lambda)$, sr^{-1}], another AOP, have more recently been implemented in large lakes to support remote sensing initiatives (O'Donnell et al., 2010). The values of AOPs are determined by IOPs (and, in turn the OACs); these dependencies are represented by radiative transfer expressions (Kirk, 2011).

Modern optical instrumentation (Dickey et al., 2006) offers the opportunity to advance the characterization and understanding of the underwater light field, as well as its relationship with the emergent flux signal available for remote sensing, through improved quantification of OACs, IOPs and AOPs. Algorithms and models can be developed and tested based on such characterizations that have management value for predicting responses to changes in OACs associated with anthropogenic influences (O'Donnell et al., 2010), such as nutrient loading, land use practices, and climate change. It is important to establish the credibility of the optical characterizations through consistency checks and closure analyses (Gallegos et al., 2008; O'Donnell et al., 2010; Pegau and Zaneveld, 1995). Consistency

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Table 1
Acronyms, abbreviations, and symbols.

*Acronyms and abbreviations**	
AOPs	Apparent optical properties
CDOM	Colored dissolved organic material
cv	Coefficient of variation
IOPs	Inherent optical properties
LTMP	Long-term monitoring program
MERIS	European Space Agency's Medium Resolution Imaging Spectrometer
NAP	Non-algal particulates
OACs	Optically active constituents
SAX	Scanning electron microscopy compared with automated x-ray analyses
w	Water
*	Site abbreviations given on Fig. 1
Symbols	
$a(\lambda)$	Total absorption coefficient (m^{-1}), at wavelength(λ)
$a_{CDOM}(\lambda)$	Absorption by CDOM (m^{-1}), at wavelength (λ)
$a_{NAP}(\lambda)$	Absorption by NAP (m^{-1}), at wavelength (λ)
$a_p(\lambda)$	Absorption by particles (m^{-1}), at wavelength (λ)
$a_{t\text{-}w}(\lambda)$	Total absorption, with the water (w) component omitted, at wavelength (λ)
$a_w(\lambda)$	Absorption by water (m^{-1}), at wavelength (λ)
$a_x(\lambda)$	Absorption coefficient for component "x", e.g., a_{CDOM}, a_{NAP}, a_φ, and a_w (m^{-1}), at wavelength (λ)
$a_\varphi(\lambda)$	Absorption by phytoplankton (m^{-1}), at wavelength (λ)
$b(\lambda)$	Total scattering coefficient (m^{-1}), at wavelength (λ)
$b_p(\lambda)$	Particulate scattering coefficient (m^{-1}), at wavelength (λ)
$b_{bp}(\lambda)$	Particulate backscattering coefficient (m^{-1}), at wavelength (λ)
$\tilde{b}_{bp}(\lambda)$	Backscattering ratio (dimensionless), of wavelength (λ)
$b_m(\lambda)$	Scattering by minerogenic particles (m^{-1}), at wavelength (λ)
$b_w(\lambda)$	Scattering by water (m^{-1}), at wavelength (λ)
$b_o(\lambda)$	Scattering by organic particles (m^{-1}) at wavelength (λ)
c	Speed of light ($m\ s^{-1}$)
$c(660)$	Attenuation coefficient at 660 nm, (m^{-1})
$CDOM_f$	CDOM (μg/L), measured fluorometrically
$c_{t\text{-}w}(\lambda)$	Total attenuation coefficient with the water component omitted (m^{-1}), at wavelength (λ)
Chl	Chlorophyll *a* (μg/L) concentration, measured in the laboratory
Chl_f	Chlorophyll *a* (μg/L) concentration, in situ fluormetrically
$E_d(\lambda)$	Downwelling irradiance ($\mu W\ cm^{-2}\ nm^{-1}$), at wavelength (λ)
$E_d(PAR)$	Downwelling irradiance ($\mu M\ cm^{-2}\ s^{-1}$), for PAR
$E_{d,\lambda}(PAR)$	Downwelling irradiance ($\mu M\ cm^{-2}\ s^{-1}$), for PAR, calculation from $E_d(\lambda)$
$E_s(\lambda)$	Solar irradiance ($\mu W\ cm^{-2}\ nm^{-1}$), at wavelength (λ)
f	Coefficient in radiative transfer expression for $R_{rs}(\lambda)$
$G(\mu_o)$	Coefficient in radiative transfer expression for $K_d(\lambda)$
h	Planck's constant
ISPM	Inorganic suspended particulate material concentration (mg/L)
$K_d(\lambda)$	Diffuse attenuation coefficient for downwelling irradiance (m^{-1}), at wavelength (λ)
$K_0(PAR)$	Diffuse attenuation coefficient for scalar irradiance (m^{-1}), for photo-synthetically active radiation (PAR)
$K_{d,\lambda}(PAR)$	Diffuse attenuation coefficient for downwelling irradiance (m^{-1}), for PAR, calculation from $E_d(\lambda)$
L_u	Upwelling radiance ($\mu W\ cm^{-2}\ sr^{-1}\ nm^{-1}$)
L_w	Water-leaving radiance ($\mu W\ cm^{-2}\ sr^{-1}\ nm^{-1}$)
OSPM	Organic suspended particulate material concentration (mg/L)
Q	Coefficient in radiative transfer expression for $R_{rs}(\lambda)$ (sr)
$R_{rs}(\lambda)$	Remote sensing reflectance (sr^{-1}), at wavelength(λ)
S_{CDOM}	Slope of $a_{CDOM}(\lambda)$ spectrum (nm^{-1})
SD	Secchi depth (m)
S_{NAP}	Slope of $a_{NAP}(\lambda)$ spectrum (nm^{-1})
SPM	Suspended particulate material concentration (mg/L)
T_n	Turbidity (NTU)
μ_o	Cosine of solar incidence angle after refraction at air-water interface
z	Depth (m)
λ	Wavelength (nm)
λ_r	Reference wavelength

checks demonstrate relationships between the metrics that are consistent with widely reported dependencies or theory. Closure analyses may include: (1) comparisons of measurements with alternate instrumentation or laboratory versus field protocols, and (2) demonstration of the approach to equivalence of AOP predictions, based on IOP measurements using radiative transfer expressions, and observations (Gallegos et al., 2008; O'Donnell et al., 2010; Tzortziou et al., 2006).

Large lacustrine systems with strong spatial differences in water quality and OACs offer opportunities for robust characterization with modern instrumentation. Moreover, survey results can support rigorous closure and consistency analyses. This paper describes a robust optical characterization across spatial differences of water quality and OACs in Lake Champlain. The goals of the paper are to: (1) advance the description and understanding of the underwater and emergent light fields of this large lake, (2) expand the testing of the credibility of such optical measurements through consistency and closure analyses, (3) resolve the origins of the spatial differences in IOPs and AOPs, and (4) project changes in AOPs for this system to be expected from hypothetical changes in OACs.

Methods

Lake Champlain

Lake Champlain is positioned in a continental rift valley between the Green Mountains of Vermont and the Adirondack Mountains of New York (Levine et al., 2012), and is oriented along an approximately north-south axis (Fig. 1). It is a large lake, extending 194 km in length, with a surface area of 1127 km^2, a volume of 26 km^3, with mean and maximum depths of 23 and 122 m. The drainage basin of the lake is about 21,300 km^2. The lake drains to the north through the Richelieu River into the St. Lawrence River; it flushes approximately once every three years.

The lake has been described as morphologically complex (Levine et al., 1997, 2012), with numerous islands, sills, peninsulas, and a number of man-made causeways, that limit transport and promote differences in limnological and water quality conditions (Effler et al., 1991; Henson and Gruendling, 1977; Levine et al., 1997; Smeltzer et al., 2012). Wide differences in land use practices within the drainage basin and tributary loading also contribute to the spatial differences in water quality, including manifestations of cultural eutrophication (Levine et al., 2012). Two shallow embayments in the northeastern part of the lake, Missisquoi Bay and St. Albans Bay (Fig. 1), have elevated phosphorus concentrations, are eutrophic, and experience severe cyanobacterial blooms (Levine et al., 2012; Smeltzer et al., 2012). In contrast, the Main Lake (Fig. 1) demonstrates oligo-mesotrophic conditions (Smeltzer et al., 2012).

Long-term monitoring has established that strong spatial differences in water clarity (SD) prevail in the lake (Effler et al., 2001; Smeltzer et al., 2012), though substantial variability is observed for most areas, as reflected in the generally broad distributions of measurements since 1992 (Fig. 1). The highest SD values are often observed in the Main Lake (median ~5.3 m), while the lowest are from the South Lake area (median ~4 m). Relatively low values have also usually prevailed in the eutrophic bays, with median values of 1.5 and 2.6 in Missisquoi Bay and St. Albans (outer) Bay, respectively. Analyses of paired data sets of SD and chlorophyll *a* (Chl) with a mechanistic SD model indicated that non-phytoplankton particles (tripton) were important in influencing clarity throughout the lake and primarily responsible for the largest spatial differences in SD (Effler et al., 2001). Clay minerals are the dominant form of tripton in most of the lake; an exception is Missisquoi Bay where organic detritus is also important (Effler et al., 1991). Optical characterization of Lake Champlain, beyond SD, has been limited. Effler et al. (1991) reported SD, $K_d(PAR)$, CDOM absorption (a_{CDOM}) spectra and turbidity (T_n) from eleven sites throughout the lake (Fig. 1), based on a survey conducted in early August 1990. Recently some spatially limited optical characterizations of "optical density" of CDOM and inorganic particles relative to total absorption at 620 and 665 nm were made to support an initiative to