Journal of Great Lakes Research Supplement 39 (2013) 161–172

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Resolution of optical gradients and pursuit of optical closure for Green Bay, Lake Michigan

David M. O'Donnell [a,*], Steven W. Effler [a], MaryGail Perkins [a], Christopher Strait [a], Zhongping Lee [b], Steven Greb [c]

[a] Upstate Freshwater Institute, P.O. Box 506, Syracuse, NY 13214, USA
[b] Univ. of Mass. Boston, EEOS Dept., 100 Morrissey Blvd., Boston, MA 02125, USA
[c] Wisconsin Dept. of Natural Resources, 2801 Progress Rd., Madison, WI 53716, USA

ARTICLE INFO

Article history:
Received 16 February 2012
Accepted 23 January 2013
Available online 23 May 2013

Communicated by Robert Shuchman

Keywords:
Green Bay
Apparent optical properties
Inherent optical properties
Secchi depth
Light attenuation

ABSTRACT

Optical properties have fundamental importance to water quality, ecology, and remote sensing initiatives. Paired measurements of optically active constituents (OACs), and inherent optical properties (IOPs) and apparent optical properties (AOPs), were made in September 2010 across the optical gradients of Green Bay, extending from the Fox River to Sturgeon Bay (8 sites), and for three near-shore locations in the main basin of Lake Michigan. The array of laboratory and in situ measurements provided a robust characterization of the underwater and emergent light fields of these waters with respect to magnitudes and spectral features of the OACs, IOPs and AOPs. These measurements resolved the character and possible origins of the major gradients within the bay (5 to 10-fold differences) and the substantial differences between the bay and the main basin. The credibility of the characterizations was supported through closure analyses which demonstrated: (1) the approach to equivalence between various field and laboratory measurements, and (2) good matches of AOP observations by values predicted from measured IOPs using accepted radiative transfer expressions. The bay was demonstrated to be an optically complex case 2 system, with uncoupled variations along the spatial gradient(s) in OACs of phytoplankton biomass, colored dissolved organic material, and non-algal particulates. The documented spatial differences in optical properties rival those reported in much larger marine surveys. Radiative transfer expressions are used to predict changes in AOPs of the downwelling (underwater) attenuation coefficient and remote sensing signal in response to scenarios of changes in levels of OACs of potential ecological and management interest.

Introduction

Optical properties of the near-surface waters of lakes are fundamental attributes that are of interest with respect to water quality and esthetics, ecology, and remote sensing initiatives (Davies-Colley et al., 2003; Kirk, 1994). These properties are determined by the concentrations and compositions of light attenuating optically active constituents (OACs; acronyms and symbols listed in Table 1), including phytoplankton, colored dissolved organic material (CDOM), and non-algal (minerogenic and detrital) particles (NAP). These materials regulate the propagation of light through water, as mediated through their effects on the attenuating processes of absorption and scattering (Kirk, 1994). These processes are quantified by the magnitudes and spectral features of the absorption [$a(\lambda)$, m^{-1}], and particulate scattering [$b_p(\lambda)$, m^{-1}] and backscattering [$b_{bp}(\lambda)$, m^{-1}] coefficients (Kirk, 1994; Mobley et al., 2004). These coefficients are described as inherent optical properties (IOPs), as their values are independent of the geometry of the light field (e.g., direct sun light or diffuse sky light; Kirk, 1994; Mobley, 1994). The IOPs determine an array of more commonly measured optical metrics such as Secchi depth (SD, m), the attenuation coefficient for downwelling irradiance [$K_d(\lambda)$, m^{-1}], and remote sensing reflectance [$R_{rs}(\lambda)$, sr^{-1}] (Gordon et al., 1988; Kirk, 1994). These measurements are described as apparent optical properties (AOPs), as they depend on the geometry of the light field.

Quantification of the interplay between OACs, IOPs and AOPs is important to advance the understanding of the underwater light field, as well as its interplay with the character of the emergent (water leaving) flux signal. In more practical terms, such initiatives can support algorithms and models to predict changes in optical features of water quality from management interventions that target the reduction of an OAC. Similarly, insights concerning the feasibility of resolving patterns of OACs in time and space, or systematic changes from interventions, through remote sensing can be obtained through rigorous optical characterizations. Advancements in field instrumentation for in situ measurements of IOPs and $R_{rs}(\lambda)$ (Dickey et al., 2006), and

* Corresponding author. Tel.: +1 315 431 4962x119.
E-mail address: daveod@ourlake.org (D.M. O'Donnell).

0380-1330/$ – see front matter © 2013 International Association for Great Lakes Research. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jglr.2013.04.002

Table 1
Acronyms, abbreviations, and symbols as applied here.

Acronyms and abbreviations	
AOPs	Apparent optical properties
AVHRR	Advanced Very High Resolution Radiometer
CDOM	Colored dissolved organic material
G1, G2, etc.	Green Gay monitored sites, Fig. 1
IOPs	Inherent optical properties
LM1	Lake Michigan monitored sites, Fig. 1
MERIS	European Space Agency's Medium Resolution Imaging Spectrometer
NAP	Non-algal particulates
NOAA	National Oceanic and Atmospheric Administration
OACs	Optically active constituents
TM	Land Thematic Mapper
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)
$a_{t-w}(\lambda)$	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)
$b_{b,NAP}$	Backscattering by NAP (m^{-1}), at wavelength (λ)
$b_{b,\varphi}$	Backscattering by phytoplankton (m^{-1}), at wavelength (λ)
$b_{NAP}(\lambda)$	Scattering by NAP (m^{-1}), at wavelength (λ)
$b_w(\lambda)$	Scattering by water (m^{-1}), at wavelength (λ)
$b_{\varphi}(\lambda)$	Scattering by phytoplankton (m^{-1}) at wavelength (λ)
$c(660)$	Attenuation coefficient at 660 nm (m^{-1})
$CDOM_f$	CDOM (μg/L), measured fluorometrically (in situ)
$c_{t-w}(\lambda)$	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, measured fluorometrically (in situ)
CY_f	Phycocyanin (μg/L) concentration, measured fluorometrically (in situ)
$E_d(\lambda)$	Downwelling irradiance ($\mu W \cdot cm^{-2} \cdot nm^{-1}$), at wavelength ($\lambda$)
$E_d(PAR)$	Downwelling irradiance ($\mu M \cdot cm^{-2} \cdot s^{-1}$), for PAR
$E_{d,\lambda}(PAR)$	Downwelling irradiance ($\mu M \cdot cm^{-2} \cdot s^{-1}$), for PAR, calculation from $E_d(\lambda)$
$E_s(\lambda)$	Solar irradiance ($\mu W \cdot cm^{-2} \cdot nm^{-1}$), at wavelength ($\lambda$)
f	Coefficient in radiative transfer expression for $R_{rs}(\lambda)$
$G(\mu_o)$	Coefficient in radiative transfer expression for $K_d(\lambda)$
ISPM	Inorganic suspended particulate material concentration (mg/L)
$K_d(\lambda)$	Attenuation coefficient for downwelling irradiance (m^{-1}), at wavelength (λ)
$K_d(PAR)$	Attenuation coefficient for downwelling 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 ($\mu W \cdot cm^{-2} \cdot sr^{-1} \cdot nm^{-1}$)
L_w	Water-leaving radiance ($\mu W \cdot cm^{-2} \cdot sr^{-1} \cdot nm^{-1}$)
OSPM	Organic suspended particulate material concentration (mg/L)
Q	Coefficient in radiative transfer expression for $R_{rs}(\lambda)$
$R_{rs}(\lambda)$	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)
μ_o	Cosine of solar incidence angle after refraction at air–water interface

most recently for $b_{bp}(\lambda)$ (Loisel et al., 2007; Snyder et al., 2008), have provided critical support for these initiatives, that have mostly targeted marine systems. It is critical to establish the credibility of the various optical measurements that are to be used in characterization and integrated into the development and application of optical models. This is pursued through consistency checks and optical closure analyses (Gallegos et al., 2008; Pegau and Zaneveld, 1995). Consistency here refers to the demonstration of dependencies between the metrics (e.g., OACs, AOPs, or IOPs) that are consistent with theory or widely accepted observations. Closure analyses may include comparisons of laboratory and field measurements, and reasonable matches of AOP observations by values predicted from paired IOP measurements using accepted radiative transfer algorithms or models (Gallegos et al., 2008; O'Donnell et al., 2010; Pegau and Zaneveld, 1995).

Cases of systematic spatial gradients in optical properties offer special opportunities for robust characterizations, and testing of measurements, relationships among the metrics, and performance of radiative transfer models, across a wide range of conditions. Robust optical characterizations in the Laurentian Great Lakes, that include paired measurements of OACs, AOPs, and IOPs [particularly $a(\lambda)$, $b_p(\lambda)$, and $b_{bp}(\lambda)$] have been rare (Bergmann et al., 2004; O'Donnell et al., 2010). This paper describes such a characterization across the distinct optical gradients of lower Green Bay, Lake Michigan (Auer et al., 1986; Lathrop et al., 1990; Qualls et al., 2007), and includes, for comparison, sites in the main body of Lake Michigan. The goals of the paper are to: (1) advance the description and understanding of the underwater and emergent light fields of these waters, (2) test the credibility of the program of measurements through consistency and optical closure analyses, (3) identify and quantify the roles of the OACs responsible for the gradients, and (4) preliminarily project changes in AOPs in response to scenarios of changes in OACs.

Methods

Study area

This study focuses on the southern portion of (or lower) Green Bay, a large gulf located in the northwest corner of Lake Michigan (Fig. 1). The bay is oriented along a northeast–southwest axis. It has a length of 160 km, an average width of 22 km, a mean depth of 15.8 m, and a drainage area of 40,600 km^2 (Martin, 1995). Counterclockwise currents are known to prevail in southern portions of the bay (Qualls et al., 2007) and seiches are common (Miller and Saylor, 1985). The largest tributary (about 45% of the major tributary flow), the Fox River, enters the bay at its southern end. This river delivers high loads of phosphorus (Klump et al., 1997) and OACs, including suspended solids (Lathrop et al., 1990), phytoplankton biomass (Qualls et al., 2007) (from upstream

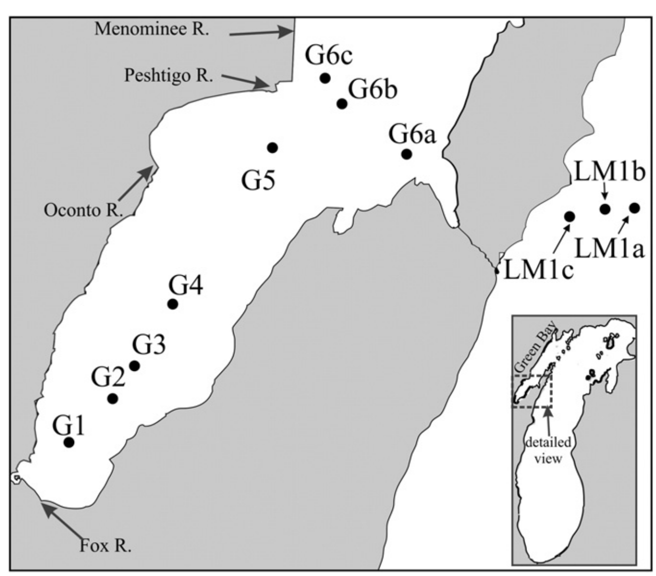

Fig. 1. Inner to mid-bay portions of Green Bay (see inset) with tributary mouths' identified and proximate near-shore area of Lake Michigan, with monitoring sites for this study.