Journal of Great Lakes Research 37 (2011) 18–25

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

Approximate bottom contribution to remote sensing reflectance in Taihu Lake, China

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ARTICLE INFO

Article history:
Received 16 October 2009
Accepted 29 June 2010
Available online 19 January 2011

Communicated by Schwab

Index words:
Optically shallow water
Bottom effects
Remote sensing
Taihu Lake

ABSTRACT

Remote sensing is a fundamental tool for the analysis of spatial and temporal trends in lake ecosystems. A major challenge in using these approaches is determining the possible influence of reflectance from submerged vegetation or the lake bottom. In the present study, we examine the water leaving radiance measured in a large number of sites in Taihu Lake, a large shallow lake in southeast China. Due to the high concentrations of suspended sediment and phytoplankton biomass, a majority of the lake can be considered optically deep (i.e. bottom reflectance could be ignored). However, optically shallow waters were present in the shallow bays on the eastern side of the lake. In these areas, submerged vegetation was present. To explore the contribution of the lake bottom and submerged vegetation on remotely sensed reflectance, we compared two modeling approaches (Hydrolight and the LEE). The results show that differences in optical and physical characteristics of the lake bottom strongly influence the spectral characteristics of the measured reflectance. The resulting impact on the estimate of chlorophyll-a concentrations was tested using datasets with and without sites where bottom effects may occur. A significant improvement in the predictive capacity of the reflectance based estimated of phytoplankton biomass was made when areas with bottom influences were removed from the calibration procedure.

Introduction

In recent decades, remote sensing has emerged as an important branch of oceanography with many developments in estimating ocean color and the concentration of optically active constituents (e.g. suspended sediments, chlorophyll, etc.,) (Mueller et al., 2003; Bricaud et al., 1999; Gordon, 1995; Carder et al., 1991; Viollier et al., 1980; Dekker, 1993). In more recent years, increased attention has been directed towards remote sensing applications in limnology, especially for lakes strongly impacted by human activities. There are many challenges to developing these retrieval algorithms, including the accurate measurement of irradiance reflectance.

Irradiance reflectance is the sum of upward reflected irradiance from the water itself and the bottom. In optically deep waters, e.g., oceans, the influence of the bottom can be ignored. However, in optically shallow waters, reflected irradiance from the lake floor can be significant. The contribution of bottom reflectance to water leaving radiance (measured by a remote sensor) depends on the water depth, the optical properties of the water column and the optical properties of the bottom (Lodhi and Rundquist, 2001).

Several studies have investigated bottom reflectance properties and effects. Voss et al. (2003) showed that the upwelling radiance distribution over turtlegrass was near-Lambertian at a wavelength of 440 nm. Hojerslev (1977) determined that lake bottom effects on the upwelling spectral signal can be considered insignificant when water depth is three times Secchi disk depth. Mueller and Austin (1995) assumed that the bottom influence may be ignored when water depth is 2.5 times greater than the attenuation length.

For flat and homogenous bottoms with Lambertain reflectance properties, irradiance reflectance (R) can be estimated from the Bidirectional Reflectance Distribution Function (BRDF) (Gordon and Brown, 1974; Mobley and Sundman, 2003). Maritorena et al. (1994) derived a simple expression of irradiance reflectance using the radiative transfer equation. Lee et al. (1994) included Raman scattering of water in their equation of reflectance. Later, Lee et al. (1998) developed an equation for the subsurface upwelling signal which included contributions due to the water and the bottom; Albert and Mobely (2003) gave a more general, but more complex expression that considers a viewing angle just below the water surface. Lee et al. (1999) then developed a semianalytical model to estimate the subsurface reflectance in shallow waters which accounted for solar zenith angle; this was then refined by using Hydrolight simulations (Becker et al., 2009).

Taihu Lake, a large (2427.8 km^2) shallow (mean depth 1.9 m; maximum depth max. 2.6 m) lake, is the third largest fresh-water lake

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doi:10.1016/j.jglr.2010.12.002

in China. It is located in the Yangtze Delta, in eastern China and has a watershed with a high population density (Fig. 1). Eutrophication has intensified in recent years and algal blooms increased, covering large areas of the lake since the 1980s (Duan et al., 2009). The inherent optical properties (IOPs) of Taihu Lake are determined by phytoplankton (chlorophyll-a, CHL), suspended particulate matter (SPM), and chromophoric dissolved organic matter (CDOM). Therefore, absorption and backscattering are controlled by the concentrations and optical properties of phytoplankton (index *ph*), non-algal particulate matter (index *d*), pure water (index *w*), and absorption due to CDOM (index *g*). The total absorption *a* is the sum of absorption of each of these components (Jerlov, 1976; Prieur and Sathyendranath, 1981).

In some areas of Taihu Lake, e.g. the southeast, waters can be relatively clear and optical properties of both the lake bottom and water column may influence the upwelling irradiance. Although numerous studies using remote sensing have been conducted in Taihu Lake (Ma et al., 2006a, 2006b; Sun et al., 2009; Zhang et al., 2009), none have measured the bottom contribution to remote sensing reflectance. Such information is necessary to improve the algorithms used to monitor changes in Taihu Lake waters.

In the present study, we explore the contribution of bottom reflectance on the surface upwelling irradiance of Taihu Lake. We used measurements and observations obtained in an extensive lake survey conducted in October 2004. We examine the results of both the Hydrolight radiative transfer model and the LEE model and compare them to measured reflectance to explore the contribution of reflected bottom irradiance to remote sensing reflectance. We compare the estimation of chlorophyll-a from reflectance measurements by excluding areas where bottom effects may be important to using the full lake dataset, to examine how an improved understanding of these impact influences our ability to observe spatial trends in this important lake.

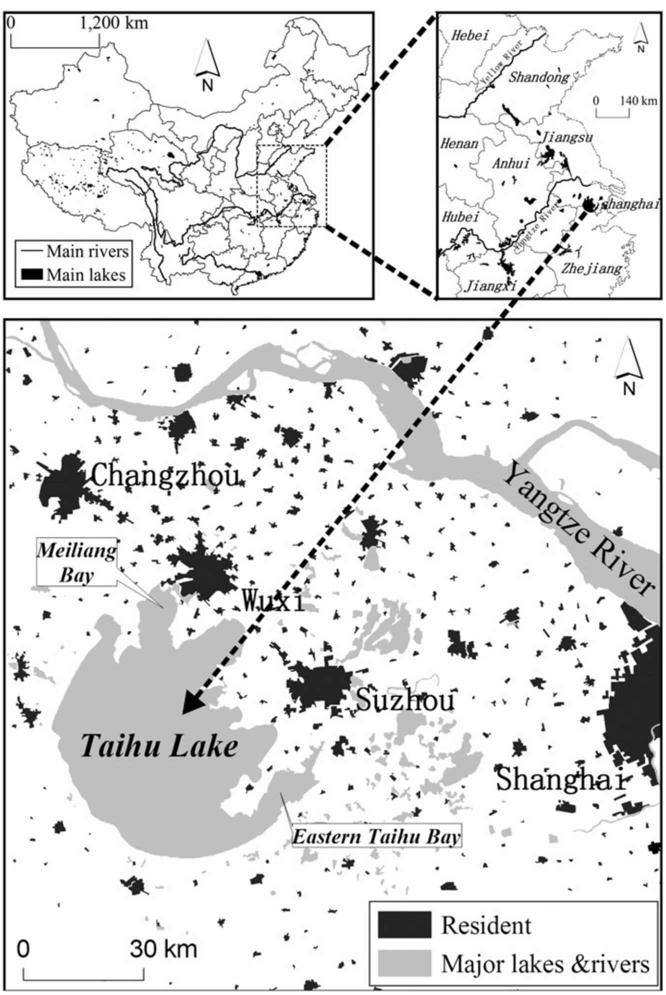

Fig. 1. The location of the Taihu Lake in China.

Methods

Field and laboratory methods

From October 18–29, 2004, we measured IOPs at 67 stations throughout the lake (Fig. 2); two sites (sites 17 and 18) were excluded from subsequent analyses because of faulty measurements of remote sensing reflectance. Field measurements included water depth, Secchi disk transparency, wind speed and direction, water temperature and water-leaving radiance, backscattering and bottom spectra. Water samples were collected in the first 0.30 m of the water column, using a pre-rinsed 2-liter polyethylene water-bottle. These samples were collected in the afternoon and kept in the dark at 4 °C until analyses for estimating the concentrations of chlorophyll-a, SPM, and DOC and their related absorption i.e., phytoplankton pigment absorption, non-algal particulate absorption and CDOM absorption.

Water transparency was measured with a Secchi disk at the shaded side of the boat while water-leaving radiance was measured *in situ* using a dual channel FieldSpec 931 spectrometer (ASD Ltd., USA) following NASA protocols (Mueller et al., 2003). The backscattering coefficient was measured using a HydroScat-6 Spectral Backscattering Sensor (HS-6, HOBI Lab Inc.) at six wavelengths, respectively, centered at 442, 488, 532, 589, 676 and 852 nm, following HOBI-labs Inc. (2003); the instrument was calibrated for the dark offset and gain ratios prior to its use. After the field sampling, a sigma correction was performed to improve the accuracy of backscattering measurements; this was needed because some light was lost due to the water's attenuation resulting in an underestimate of scattering, i.e., when light traveled from the sensor to the scattering site and back. For very clear waters, the correction factor is insignificant, but as turbidity increases so does the underestimate of scattering; therefore an accurate backscattering probability $\tilde{b}_b$ (the ratio of backscattering coefficient to scattering coefficient) was used.

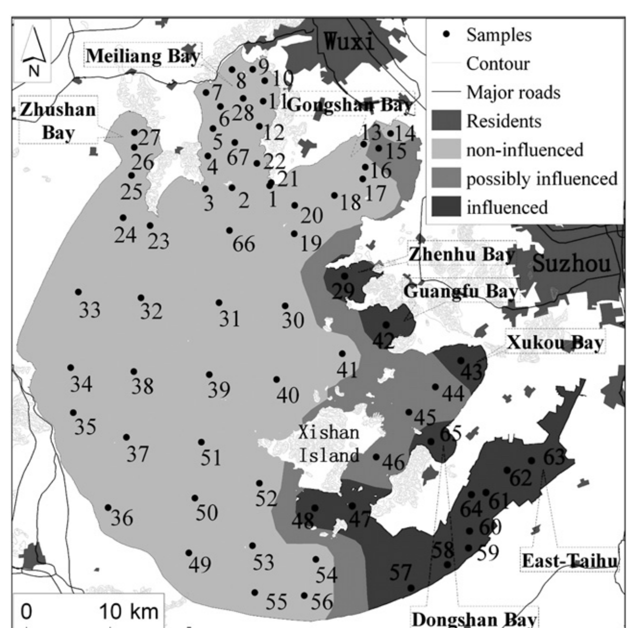

Fig. 2. Locations of study sites and optical regions defined by whether or not water-leaving radiance is affected by the lake bottom.