Remote Sensing of Environment 114 (2010) 781–791

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Optimized extraction of daily bio-optical time series derived from MODIS/Aqua imagery for Lake Tanganyika, Africa

S. Horion [a,*], N. Bergamino [b], S. Stenuite [c], J.-P. Descy [c], P.-D. Plisnier [d], S.A. Loiselle [b], Y. Cornet [a]

[a] Unit of Geomatics, University of Liège, Allée du 6 Août 17, B-4000 Liège, Belgium
[b] Environmental Spectroscopy Group, Department of Applied and Medicinal Chemistry, CSGI, University of Siena, Via A. Moro 2, 53100 Siena, Italy
[c] Laboratory of Freshwater Ecology, Research Unit in Biology of Organisms, Department of Biology, University of Namur, Rue de Bruxelles 61, B-5000 Namur, Belgium
[d] Royal Museum for Central Africa, Leuvensesteenweg, 13, B-3080 Tervuren, Belgium

ARTICLE INFO

Article history:
Received 15 November 2007
Received in revised form 21 July 2009
Accepted 21 November 2009

Keywords:
Phytoplankton dynamics
Bio-optical algorithms
SeaDAS process optimization
MODIS Aqua
Lake Tanganyika

ABSTRACT

Lake Tanganyika is one of the world's great freshwater ecosystems. In recent decades its hydrodynamic characteristics have undergone important changes that have had consequences on the lake's primary productivity. The establishment of a long-term Ocean Color dataset for Lake Tanganyika is a fundamental tool for understanding and monitoring these changes. We developed an approach to create a regionally calibrated dataset of chlorophyll-*a* concentrations (CHL) and attenuation coefficients at 490 nm (K490) for the period from July 2002 to December 2006 using daily calibrated radiances retrieved from the MODIS-Aqua sensor. Standard MODIS Aqua Ocean Color products were found to not provide a suitable calibration for high altitude lakes such as the Lake Tanganyika. An optimization of the extraction process and the validation of the dataset were performed with independent sets of in situ measurements. Our results show that for the geographical, atmospheric and optical conditions of Lake Tanganyika: (i) a coastal aerosol model set with high relative humidity (90%) provides a suitable atmospheric correction; (ii) a significant correlation between in situ data and CHL estimates using the MODIS specific OC3 algorithm is possible; and (iii) K490 estimates provide a good level of significance. The resulting validated time series of bio-optical properties provides a fundamental information base for the study of phytoplankton and primary production dynamics and interannual trends. A comparison between surface chlorophyll-*a* concentrations estimated from field monitoring and from the MODIS based dataset shows that remote sensing allows improved detection of surface blooms in Lake Tanganyika.

1. Introduction

Lake Tanganyika is one of the world's most important freshwater ecosystems, providing fundamental resources for 10 million people living in its catchment's area as well as a unique reservoir of biodiversity (Mölsä et al., 1999). The lake, situated in the East-African rift, approximately at 773 m above sea level, covers a large transnational area of 32,900 km^2 with borders in Tanzania, Democratic Republic of Congo, Burundi and Zambia (Fig. 1). It is the second deepest freshwater lake in the world (after Lake Baïkal), and is characterized by deep basins in the north (max. depth of 1310 m) and south (max. depth of 1470 m) separated by a sill at 600 m deep.

The lake is oligotrophic and permanently stratified with an anoxic hypolimnion. During the dry season (from May to September), strong southerly winds induce upwelling of nutrient-rich deep waters in the southern part of the Lake, and a tilting of the thermocline. In addition to this major hydrodynamic phenomenon, the depth of the mixed layer varies seasonally in all lake basins as a result of change in the temperature–density gradients and of variation of wind velocity (Naithani et al., 2003). Along with internal waves which enhance diffusion through the thermocline, these events are key drivers of phytoplankton growth and dynamics, as they determine nutrient availability in the euphotic zone. (Hecky et al., 1991; Plisnier et al., 1999; Naithani et al., 2007).

The plankton assemblages of Lake Tanganyika also show seasonal and spatial variations, with a chlorophytes–cyanobacteria (Chroococcales) assemblage in the wet season (October–April), when high light is combined with poor nutrient availability in the shallow epiliminion (Hecky and Kling, 1981). In the dry season (May to September), when deep mixing occurs, an increase of diatoms is observed, favoured by lower light levels and higher nutrient availability. Surface blooms of filamentous cyanobacteria (*Anabaena* sp.) develop frequently at the end of the dry season, when the water column re-stratifies. More recently, both algal pigment (Descy et al., 2005) and microscopy (Cocquyt and Vyverman, 2005) surveys updated the data on algal biomass, composition and dynamics in the pelagic waters of Lake Tanganyika, and underlined the cyanobacteria–chlorophyte dominance in the most part of the year cycle, with particular prominence of

* Corresponding author.
E-mail address: stephanie.horion@jrc.ec.europa.eu (S. Horion).

0034-4257/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2009.11.012

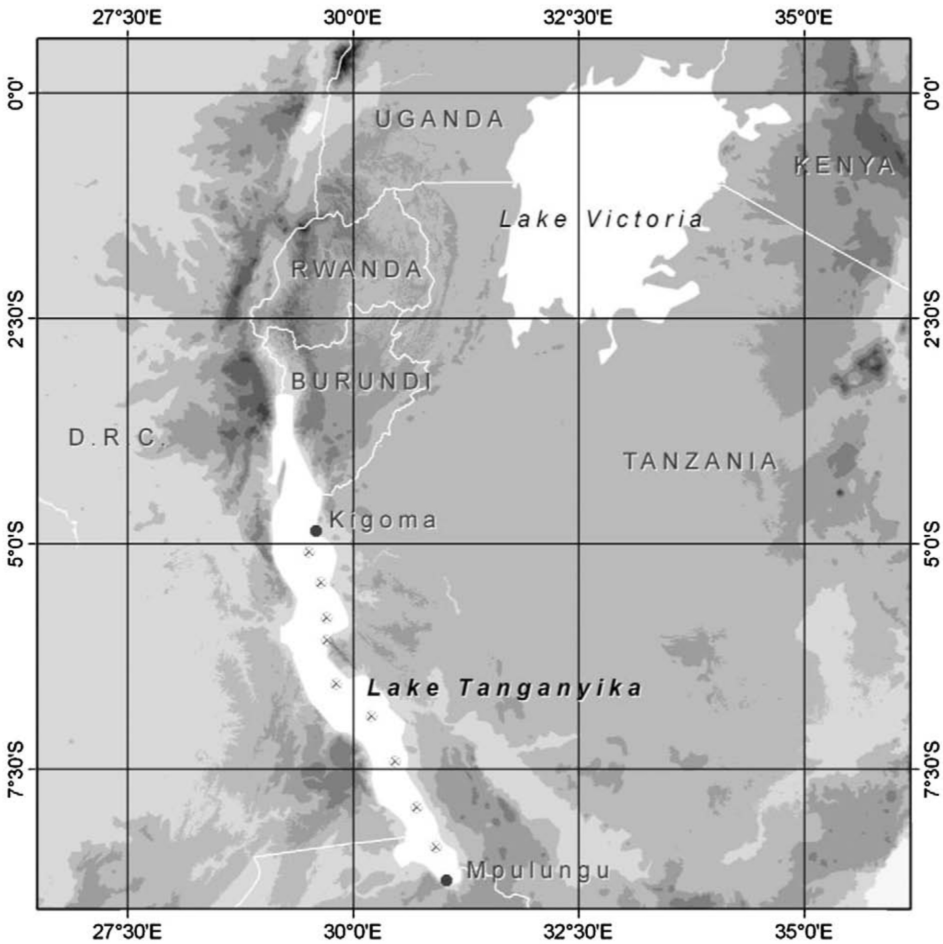

Fig. 1. Lake Tanganyika in East Africa, Black dots are the pelagic permanent stations named by the closest towns (Kigoma and Mpulungu). Crossed points are sampling sites of the lake transects cruises realized between 2002 and 2004.

the picocyanobacteria *Synechococcus* sp. (Vuorio et al., 2003; Descy et al., 2005; Sarmento et al., 2007, Stenuite et al., 2009). There is, however, significant spatial variation in Lake Tanganyika: the dry season diatom peak coinciding with the chlorophyll-*a* maximum in the water column (Cocquyt & Vyverman, 2005), is clearly visible in the northern part of the lake. By contrast, in the southern basin, where the temperature density gradient is usually weaker, diatom maxima has a less pronounced seasonal pattern, and picocyanobacteria tend to dominate at all times (Descy et al., 2005; Stenuite et al., 2009). The same recent investigations (Descy et al., 2005) report that green algae are far more abundant and diverse off Kigoma (northern basin) than off Mpulungu (southern basin).

Several authors have emphasized the risk of a decreasing primary productivity of the lake due to rising surface temperatures and decreasing wind speeds, in the context of global change (O'Reilly et al., 2003; Verburg et al., 2003; Verschuren, 2003). In this regard, Lake Tanganyika's ecosystem and biodiversity, as well as the regional population which depends on lake resources, may face a critical situation in the near future. A better understanding of the lake's mechanisms is essential to managing these resources to ensure their sustainable exploitation. However, the large size of the lake precludes the use of in situ measurements for the creation of a database with sufficient temporal and spatial resolutions (Naithani et al., 2007). In this regard, satellite data have a great potential for the study of the spatio-temporal variability of the Lake.

In the present paper, we describe and validate an approach for the development of a time series of chlorophyll-*a* concentration (CHL) and vertical attenuation coefficient (K490) based on daily MODIS Aqua calibrated radiances. Both bio-optical parameters have been directly linked to primary productivity and fisheries. In situ data from measurements on lake transects carried out in the same period were used to calibrate and validate the algorithms as well as to examine dominating optical components of the water column. Finally, we compare surface chlorophyll-*a* concentrations determined in two sites in the lake with the coincident data from the MODIS based time series. The results show the advantages of using remote sensing to detect surface blooms in Lake Tanganyika.

2. Data and methods

2.1. In situ data

Measurements in two permanent stations situated in the pelagic zone of the lake near Kigoma and Mpulungu were made each fortnight from 2002 to 2006 (Fig. 1). Major optical and physical parameters were measured at the water surface and every 20 m to a depth of 100 m: water temperature, conductivity, pH, dissolved oxygen, transparency, turbidity and chlorophyll-*a*. Water samples were obtained from each sampling depth for phytoplankton pigment analysis by HPLC; all methods were described in Descy et al. (2005). Chlorophyll-*a* concentrations were typically low in both stations (mean CHLsurface = 0.7 mg/m^3, max. CHLsurface = 3.77 mg/m^3 at Mpulungu and max. CHLsurface = 2.00 mg/m^3 at Kigoma) with a higher temporal variability of the chlorophyll-*a* concentration in Mpulungu (Plisnier & Descy, 2005). The highest pigment concentrations were usually found in the 0–40 m layer and decreased sharply downward.

HPLC analysis was also used to estimate the contribution of different phytoplankton groups to total chlorophyll-*a*, using marker pigment