Remote Sensing of Environment 134 (2013) 342–354

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Using Hyperion imagery to monitor the spatial and temporal distribution of colored dissolved organic matter in estuarine and coastal regions

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ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form 13 March 2013
Accepted 14 March 2013
Available online 12 April 2013

Keywords:
CDOM
Hyperspectral remote sensing
Estuaries
EO-1 hyperion
QAA-CDOM
Climate impacts
Land-surface processes

ABSTRACT

Establishing a link between the optical and biogeochemical properties of near-shore waters continues to be a challenge for both riverine and estuarine areas worldwide due to terrestrial influences. This study aimed to evaluate the effectiveness of an inversion algorithm for the extraction of riverine and estuarine CDOM properties at global scales. Our CDOM evaluation focused on five aspects: 1) the range of worldwide CDOM levels, 2) spatial distribution patterns, (3) climatic influences, (4) influences of land cover change, and (5) seasonal effects. The study locations consisted of the estuarine and coastal regions of 10 major rivers spread across five continents. Our approach was to examine the QAA-CDOM algorithm by extracting CDOM properties from hundreds of EO-1 Hyperion images acquired during the last decade (2001–2011). Preliminary results showed that CDOM absorption coefficients at 440 nm within the 10 selected rivers exhibited a broad range (0.02–7.2 m^{-1}). Spatial CDOM distribution patterns showed many plumes dispersing from source areas (e.g. adjacent terrestrial vegetated areas) along the direction of flow. Seasonal variations in CDOM levels are also evident (i.e. 0.5–4.0 m^{-1}) as illustrated by the January, April, August and October images of the Volga River. CDOM levels also appeared to trend upward with the increase in forest coverage (i.e. terrestrial influence) within the watersheds studied over the last decade. Our results strongly suggest that the algorithm is effective in distinguishing riverine and estuarine CDOM levels affected by factors such as global biogeography, climate conditions and regional land surface processes.

1. Introduction

Colored dissolved organic matter (CDOM) is often used as an effective tracer for evaluating relative levels and the spatial distribution of dissolved organic carbon (DOC) in aquatic environments. CDOM is the photoactive portion of dissolved organic matter (DOM) (Ferrari et al., 1996; Mannino et al., 2008; Vodacek et al., 1997). CDOM $a_g(440)$, (absorption coefficient at 440 nm) is detectable from above the water surface remotely (i.e. in-situ, airborne or space-borne), since its chromophore property displays absorbance of light decreasing quasi-exponentially with increasing wavelength across the entire UV and visible spectrum (Kutser et al., 2005). Therefore, the quantification of relative CDOM levels via remote sensing technologies could be a valuable tool for studying ecological/environmental changes as well as carbon cycling at global scales (Tranvik et al., 2009). Remote estimation of CDOM is also relevant to aquatic ecological/limnological research in that it is a significant factor in overall light penetration, which is a critical factor of chlorophyll photosynthesis carried out by phytoplankton and other aquatic vegetation (Kirk, 1994).

Remote sensing of CDOM has been well studied in Case 1, open sea environments where CDOM concentrations are generally in low concentration and spatially homogeneous (Yu et al., 2010). CDOM in these waters is mainly autochthonous, formed from exudates and partial decomposition products of phytoplankton (Nelson & Siegel, 2001). Contrarily, relative CDOM levels in coastal waters (e.g. Case 2 waters) are usually much higher than that in open-sea environments because of influences from terrestrial biological and geochemical sources (i.e. allochthonous). The humic and fulvic acid released from the decay of detritus represents the most significant component of terrestrial/soil CDOM in riverine and near-shore environments (Coble, 1996; De Souza Sierra et al., 1994). Geochemical source means the amount of DOC in deep soils deposited thousands years ago and moved to rivers through weathering processes (Petsch et al., 2003). In addition, both chlorophyll concentrations and turbidity are typically much higher in riverine systems, when compared to open sea environments. The algorithms developed for case 1 waters may not be accurate for riverine and estuarine environments because of potential interference from solutes and suspended matter found in such waters that are not typically found in open oceans.

A remote sensing algorithm for extracting CDOM for estuarine and coastal regions (QAA-CDOM) recently was developed by Zhu and Yu (2013) and Zhu et al. (2011). The key innovation of the algorithm is

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http://dx.doi.org/10.1016/j.rse.2013.03.009

the capability of estimating CDOM and sediment absorption coefficients separately instead of a single combined parameter. Although the algorithm was based on both field and synthetic data worldwide, it has only been validated across 12 riverine, estuarine, and coastal sites that exhibit a limited range of climatic and geographic variation (Zhu, 2011; Yu et al., 2010; Zhu and Yu, 2013; Zhu et al., 2011). The relatively limited geographic and climatic areas to which the algorithm was applied may indeed limit its reliability across global scales that typically exhibit a much wider range of CDOM levels It is also known that temperature and precipitation are highly correlated to both riverine DOC and relative CDOM levels due to the influence of terrestrial gross primary production (GPP) and metabolic processes within the surrounding watershed (Huang & Chen, 2009; Raymond & Bauer, 2001; Tian et al., 2013). Land surface characteristics, such as vegetation types, soil carbon sinks, and hydrologic characteristics (e.g. surface runoff rates, groundwater discharge) determine CDOM sources and transport processes (Coble, 1996; De Souza Sierra et al., 1994; Tian et al., 2013). Therefore, in order to confirm the suitability of QAA-CDOM at global scales, it is necessary to examine its applicability across more varied scenarios.

Accordingly, this study aims to evaluate the feasibility of applying the QAA-CDOM model to rivers and their associated coastal environments at global scales. We selected 10 rivers across three different climate zones and five continents in order to include varied levels of land surface and biological processes. Hundreds of EO-1 Hyperion images acquired from 2001 to 2011 were examined for this investigation. The two main research objectives were to: 1) assess the variations in relative CDOM levels in coastal and riverine areas from the ten study sites derived from Hyperion data and the QAA-CDOM algorithm, and 2) investigate the potential of Hyperion imagery and the QAA-CDOM algorithm to detect CDOM seasonal variation at the same 10 locations. The investigation focused on five aspects of CDOM in riverine and estuarine systems: 1) the range of worldwide CDOM levels, 2) spatial distribution patterns, (3) climatic influences, (4) influences of landuse change, and (5) seasonal effects.

Unlike many studies that address global scale phenomena, our use of Hyperion imagery took advantage of the relatively high spectral (i.e. 10 nm wide bands) and spatial (i.e. 30 m) resolution of this platform, while also providing scientific insight of scenarios responsive to global scale climatic and environmental variables. The CDOM dynamics of the near-shore/river interface are applicable to a variety of research topics and to the management of coastal environments. Specifically, CDOM dynamics can help to better understand DOC export processes from terrestrial inputs/carbon sinks to coastal waters as part of the carbon cycle.

2. Methods

2.1. Study sites

The 10 major rivers from five continents selected for this study are the: Mississippi River and Mackenzie River in North America, Amazon River and Plata River (Rio de la Plata) in South America, Yangtze River (Changjiang) and Irrawaddy River in Asia, Nile River and Congo River in Africa, and Rhine River and Volga River in Europe. They are all well-known major rivers with large drainage areas and significant discharge, playing a crucial role in the hydrologic systems of each continent. All are closely linked to the human populations along their shores, serving functions such as water supply, agricultural irrigation and transportation corridors. They drain and traverse varied and diverse ecosystems, such as arid desert (i.e. lower Nile River), humid tropical forests (i.e. upper Nile River), tropical evergreen forest (i.e. Amazon River) and boreal forest (i.e. Mackenzie River). These big rivers typically deposit large alluvial fans (i.e. deltas) where they flow into their estuarine and coastal regions. Often, as in the case of the Nile River and Yangtze River Delta, high human population densities are supported on these deltaic sediments. Due to the amount of discharge and sediment load, many of these rivers form huge sediment plumes at their termination, such as the Amazon River and Mississippi River. Some of the selected rivers periodically freeze, such as the Mackenzie River and Volga River. The general characteristics of each river, including the length, watershed area, annual discharge, outflow, and climate type, are listed in Table 1. The relative locations of the 10 rivers used in this study are shown on a world map (Fig. 1).

Data obtained or collected from ten additional estuarine and coastal locations along with the Mississippi River and Amazon River study sites outlined above were used for algorithm validation. The ten additional sites are; the Atchafalaya River in Louisiana, the Passaic River, Hackensack River, and Newark Bay in New Jersey, the Hudson River along the New Jersey/New York border, the Neponset River and Boston Harbor in Massachusetts, the Saginaw River and Kawkawlin River in Michigan, and the Brisbane/Logan/Pine/Caboulture Rivers flowing into Moreton Bay in Australia (Brando & Dekker, 2003). As outlined in Table 2, the Amazon River and Moreton Bay validation data were extracted from previous studies (Brando & Dekker, 2003; Zhu & Yu, 2013), while data collected in the United States were derived from our in-situ measurements. The in-situ data used to derive relative CDOM levels were measured below water surface at relatively high spatial resolution (i.e. 5 m intervals) with concurrent R_{rs} (remotely sensed reflectance) measured just above the water surface. These in-situ data below and above water surface were collected through our multiple research cruises in rivers in Louisiana, New York, and Massachusetts. Recently, we also conducted several research cruises in freshwater environments and validated the algorithm for the Saginaw River, Kawkawlin River, and the Lake Huron in Michigan. The rivers used for the validation are latitudinally well distributed across the continental U.S. (Table 2).

2.2. Hyperion imagery

In November of 2000, NASA launched the Earth Observing-1 satellite mission as part of their New Millennium Program, with the Hyperion imaging spectrometer being a key component of this mission.

Table 1
Hydrological properties of the ten studied rivers.

River	Rank*	Outflow	Length (km)	Discharge (10^3 m^3/s)	Drainage area (10^3 km^3)	Climate categories
Mississippi	1st, N. Am.	Gulf of Mexico	5971	17.30	3220	Subtropical
Mackenzie	2nd, N. Am.	Beaufort Sea	4241	7.93	1805	Frigid
Amazon	1st, S. Am.	S. Atlantic Ocean	6400	212.38	5778	Tropical
Plata	2nd, S. Am.	Rio de la Plata	4880	14.89	2305	Subtropical
Yangtze	1st, Asia	East China Sea	6300	21.80	1942	Subtropical
Irrawaddy	23rd, Asia	Andaman Sea	1992	13.56	430	Tropical
Nile	1st, Africa	Mediterranean Sea	6650	2.83	2978	Subtropical
Congo	2nd, Africa	S. Atlantic Ocean	4700	39.64	4014	Tropical
Volga	1st, Europe	Caspian Sea	3530	8.06	1380	Temperate
Rhine	15th, Europe	North Sea	1392	2.21	145	Temperate

* The rank is by river's length. The data of length, discharge, and drainage area are from *The Water Encyclopedia*, 3rd Ed., by Pedro Fierro, Jr. and Evan K. Nyer.