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Uncertainty analysis of remote sensing of colored dissolved organic matter: Evaluations and comparisons for three rivers in North America

Weining Zhu [a,b,*], Qian Yu [c], Yong Q. Tian [a,b]

[a] Institute for Great Lakes Research, Central Michigan University, United States
[b] Department of Geography, Central Michigan University, United States
[c] Department of Geosciences, University of Massachusetts Amherst, United States

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ABSTRACT

The uncertainties involved in remote sensing inversion of CDOM (Colored Dissolved Organic Matter) were analyzed in estuarine and coastal regions of three North American rivers: Mississippi, Hudson, and Neponset. Water optical and biogeochemical properties, including CDOM absorption and above-surface spectra, were collected in very high resolution. CDOM's concentrations ($a_g(440)$, absorption coefficient at 440 nm) were inverted from EO-1 Hyperion images, using a quasi-analytical algorithm for CDOM (QAA-CDOM). Uncertainties are classified to five levels, in which the underwater measurement uncertainty (level 1), image preprocessing uncertainty (level 4) and inverse model uncertainty (level 5) were evaluated. Results indicate that at level 1, in situ CDOM measurement is significant with 0.1 in the unit of QSU and 0.01 in the unit of $a_g(440)$ (m^{-1}). At level 4, surface wave is a potential uncertainty source for high-resolution images in estuarine and coastal regions. The remote sensing reflectance of wavy water is about 10 times of the truth. At level 5, the overall uncertainty of QAA-CDOM inversion is 0.006 m^{-1}, with accuracy $R^2 = 0.77$, $k = 1.1$ and $RMSE_{\log} = 0.33$ m^{-1}. The correlations between uncertainties and other water properties indicate that the large uncertainty in some rivers, such as the Neponset and Atchafalaya, might be caused by high-concentration chlorophyll or sediments. The relationships among the three level uncertainties show that the level 1 uncertainty generally does not propagate into level 4 and 5, but the large uncertainty at level 4 usually introduce large uncertainty at level 5.

1. Introduction

Colored dissolved organic matter (CDOM) is the optically measurable component of dissolved organic matter in water. CDOM in nature mostly come from decaying vegetation detritus and also sometimes related to anthropogenic releasing (Bukata et al., 1995; Nelson and Siegel, 2002). Knowing CDOM concentration and distribution in riverine, estuarine and coastal regions has important implications to both terrestrial and aquatic ecosystems, such as tracing dissolved organic carbon (DOC) (Chen et al., 2004; Ferrari et al., 1996; Stedmon et al., 2006; Vodacek et al., 1997), monitoring water quality and aquatic photosynthesis (Bukata et al., 1995; Kirk, 1994), and assessing terrestrial carbon transportation to coastal water (Blough et al., 1993; Del Castillo et al., 1999; Nelson et al., 2010).

Remote sensing provides a feasible approach to assess CDOM at large spatial scale. However, compared with the other two major ocean-color components, chlorophyll (CHL) and non-algal particles (NAPs), the remote sensing inversion of CDOM is not fully investigated. Large uncertainties are remained in many aspects of CDOM inversion, especially for complex waters in estuarine and coastal regions. (1) The uncertainty of field CDOM measurement. Small sampling size and narrow CDOM range usually limit algorithm validations and uncertainty assessments. Several recent published studies have used a few to a dozen in situ discrete samples to validate the inversion results without uncertainty analysis (Brando and Dekker, 2003; Ortega-Retuerta et al., 2010). In addition, most of previous estuarine and coastal CDOM studies and their validations were carried out in the sites where the spatial variation of CDOM is limited. Therefore the algorithms, parameters, coefficients, as well as the uncertainty assessment concluded from one site could be inappropriate and hence produce large uncertainties when transferring to other sites. (2) The uncertainty of satellite imagery. High spatial resolution images in estuarine and coastal regions contain more spatial variation and uncertainties than those coarse images for open sea ocean color studies (e.g., 1 km for SeaWiFS and MODIS) (Carder et al., 1999; Garver and Siegel, 1997; O'Reilly et al., 1998; Siegel et al., 2002). Because of

* Corresponding author at: Department of Geography, Central Michigan University, United States. Tel.: +1 989 774 7697.
E-mail address: zhu3w@cmich.edu (W. Zhu).

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complicated freshwater and marine mixing environment, the possible uncertainty sources include the wind-driven glints, boat-driven whitecaps, and anthropogenic release, etc., which arise more often in estuarine and coastal regions than in open sea. These uncertainties usually vary in relatively small space and hence are unseen from low resolution images due to mixed pixels, but they will be revealed by high-resolution images and hence bring interferences and new challenges for ocean-color remote sensing inversion. (3) The uncertainty of CDOM algorithm. Inversion algorithms have not been well developed for CDOM, particularly for complex riverine and coastal waters. Most of previous algorithms are in empirical or oriented to simple CDOM-poor waters in open sea, where CDOM is often taken as the by-products of phytoplankton and sediments are generally in low concentration (O'Reilly et al., 1998; Sathyendranath et al., 1994). When these simple algorithms are applied to complex CDOM-rich waters in estuaries and coasts, where CDOM, CHL and sediments are all independent and likely in high concentration, they tend to bring considerable uncertainties (Yu et al., 2010; Zhu et al., 2011). Therefore it is really necessary to design new algorithms and evaluate their uncertainty for complex waters.

In fact, remote sensing inversion of CDOM in estuarine and coastal regions is extremely complicated. Uncertainties will be generated, propagated, and accumulated in the processes of in situ measurement, acquisition and preprocessing of satellite images, and all steps of inverse algorithms. The former uncertainty analyses of remote sensing inversion of ocean color components often focused on one level (Antoine et al., 2008; Lee et al., 2010; Melin, 2010; Wang et al., 2005). For example, Antoine et al. (2008) discussed the uncertainties introduced by satellite sensors, and Lee et al. (2010) discussed the uncertainties induced by QAA algorithm. In our study, we suggest classifying CDOM inversion uncertainty to five levels according to their order, including underwater measurement uncertainty (level 1), above-surface measurement uncertainty (level 2), satellite measurement uncertainty (level 3), image preprocessing uncertainty (level 4), and inverse model uncertainty (level 5) (Fig. 1). The level 1 is the uncertainty of measured CDOM concentration via conventional underwater optical instruments, such as a fluorometer or spectrophotometer. Actually any instrumental measurement will introduce uncertainties depending on random noise, instrumental calibration errors, and instrumental accuracy, etc. As far as we know, there are no studies on the uncertainty analysis of in situ CDOM measurements. Both level 2 and 3 uncertainties are related to spectral measurements. Level 2 is the uncertainty of above-surface spectral measurement of water. All in-water components, CDOM, chlorophyll, non-algal particles, and water conditions, such as surface wave and white caps, will contribute the above-surface spectrum uncertainties. Level 3 is the uncertainty of satellite spectral response, similar to the level 2 but adding the atmospheric effect. Level 4 and 5 are model uncertainties. Level 4 is the uncertainty contained in the input data to inverse models, e.g., remote sensing reflectance. This uncertainty is generated by satellite images preprocessing, such as atmospheric correction and water surface reflectance removal. The uncertainty in level 5 is generated by the inversion model itself. Level 4 and 5 uncertainties are often known as the errors between the model-derived estimates and the ground truth. Moreover, these 5-level uncertainties are not fully independent of each other – uncertainties at low levels may propagate to high levels.

The objective of this study is to evaluate the uncertainties involved in the whole process of remote sensing inversion of CDOM for estuarine and coastal waters, using our best solutions (high-resolution field measurements, high-resolution images, and high accuracy algorithm). We focused on the evaluation of uncertainties on the level 1, 4 and 5. These evaluations were based on recent data acquired from three rivers: the Mississippi, Hudson and Neponset, as well as their adjacent sites. We will evaluate level 1 uncertainties by analyzing the in situ data, the level 4 uncertainties by comparing satellite acquired (after atmospheric corrections) and the field measured spectra, and level 5 uncertainties by comparing the model derived and field measured CDOM concentrations. The impacts of low level uncertainties on the high levels will be discussed in the last section.

2. Data collections and processing

2.1. Study sites

Our study sites locate in estuarine regions of three river systems in U.S. – the Mississippi site (including Atchafalaya River, Mississippi River and their plumes, and the Northern Gulf of Mexico), the Hudson site (including the Hackensack River, Passaic River, Newark Bay, Upper/Lower New York Bay, Raritan River, Raritan Bay, and Hudson River), and the Neponset Site (including the Neponset River and Dorchester Bay), see Fig. 2. The Mississippi River, with length 3730 km, is the longest river and has the largest drainage basin in the North America, and the length of the Hudson River and Neponset River are 507 km and 47 km, respectively. Due to the large discharge and massive sediment transportation, the Mississippi and Atchafalaya estuaries show large sediment plumes. The estuaries of Hudson and Neponset are adjacent to highly urbanized areas, New York City and Boston, respectively. In this study we use the three rivers as the representatives of river systems at different scale – large, medium, and small. They locate in different climate zones: the Mississippi and Atchafalaya estuaries are in sub-tropical region and the Hudson and Neponset are in temperate region with high seasonal variations.

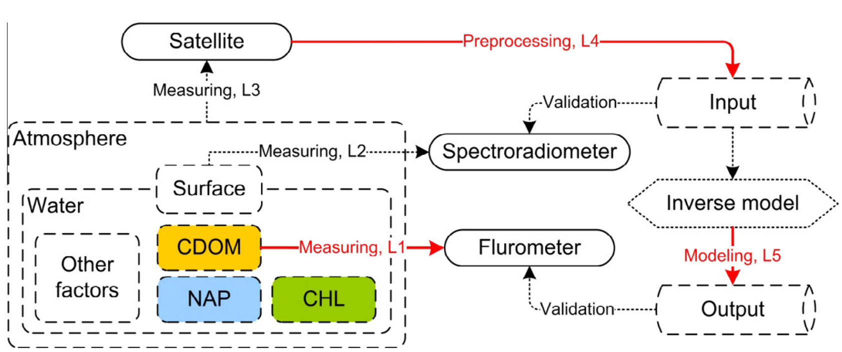

Fig. 1. Uncertainties and their levels remote sensing inversion of CDOM. The first 3 levels are related to the field measurements of CDOM, reflectance above water surface and at the top of atmosphere. Each factor contained in the dashed box contributes the major uncertainties measured by the corresponding instrument.