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Research Paper

Using VIIRS/NPP and MODIS/Aqua data to provide a continuous record of suspended particulate matter in a highly turbid inland lake

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ABSTRACT

Inland lakes are generally an important source of drinking water, and information on their water quality needs to be obtained in real time. To date, Moderate-resolution imaging spectroradiometer (MODIS) data have played a critical, effective and long-term role in fulfilling this function. However, the MODIS instruments on board both the Terra and Aqua satellites have operated beyond their designed five-year mission lifespans (Terra was launched in 1999, whereas Aqua was launched in 2002), and these instruments may stop running at any time in the near future. The Visible Infrared Imager Radiometer Suite (VIIRS) on board the Suomi National Polar-Orbiting Partnership (Suomi NPP, which was launched in Oct 2011) is expected to provide a consistent, long-term data record and continue the series of observations initiated by MODIS. To date, few evaluations of the consistency between VIIRS and MODIS have been conducted for turbid inland waters. In this study, we first used synchronous MODIS/Aqua and VIIRS/NPP data (± 1 h) collected during 2012–2015 to evaluate the consistency of Rayleigh-corrected reflectance (R_{rc}) observations over Lake Hongze (the fourth-largest freshwater lake in China), since accurate remote sensing reflectance (R_{rs}) values cannot be acquired over turbid inland waters. Second, we used recently developed algorithms based on R_{rc} in the red band to estimate the concentrations of suspended particulate matter (SPM) from MODIS/Aqua and VIIRS/NPP data. Finally, we assessed the consistency of the SPM products derived from MODIS/Aqua and VIIRS/NPP. The results show the following. (1) The differences in R_{rc} among the green (VIIRS 551 nm and MODIS 555 nm) and red bands (VIIRS 671 nm and MODIS 645 nm) indicate a satisfactory consistency, and the unbiased percentage difference (UPD) is < 12%. Meanwhile, the results for the near infrared (NIR) band (MODIS 859 nm and VIIRS 862 nm) indicate relatively large differences (UPD = 21.84%). (2) The satellite-derived SPM products obtained using MODIS/Aqua and VIIRS/NPP have a satisfactory degree of consistency (0–150 mg/L SPM: R^2 = 0.81, UPD < 16% and 0–80 mg/L SPM: R^2 = 0.85, UPD < 12%, respectively). These results demonstrate that VIIRS/NPP can continue to record the SPM observations initiated by MODIS/Aqua for turbid inland waters and establish environmental datasets over long time periods to support water quality management endeavors.

1. Introduction

Like stars in the sky, lakes are widely distributed over the surface of the Earth, and they collectively represent an immense network of ecological systems. Lakes provide fresh water and food for human sustenance. They also have multiple other functions, including the storage of floodwater, transportation, irrigation and fishery production (Guo, 2007). As an important constituent of terrestrial ecological systems, lakes create strong exchanges of material, energy and information with the terrestrial ecosystem and serve as important gathering places for various types of elements on the terrestrial surface (Pham et al., 2008; Williamson et al., 2008). Due to the combined effects of natural factors with human activities, inland lakes are always turbid, and their optical properties are complex. An increased turbidity in a lake reduces the water clarity and the ability of light to propagate through the water, thereby restricting the growth of plankton and submerged vegetation in the water and eventually leading to an impoverished ecological status (Jeppesen et al., 2009; Moore et al., 1997).

The SPM, including organic and inorganic matter that are held in suspension, is a well-recognized indicator of water turbidity (Bilotta and Brazier, 2008). MODIS data are often used to effectively estimate SPM concentrations and to monitor the dynamics of rapid changes in the spatial-temporal distribution of SPM in large inland lakes (Miller and McKee, 2004; Shi et al., 2015a; Zhang et al., 2010). However, the

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MODIS instruments on board the Terra and Aqua satellites have operated beyond their designed five-year mission lifespans, and they are showing signs of sensor degradation; thus, scientists are faced with the possibility that these instruments may stop running at any time in the near future (Hu and Le, 2014). For example, the Terra spacecraft entered safe mode on 18 Feb, 2016, and although it was successfully recovered on 24 Feb, 2016, no scientific data were collected during the safe-mode period (Ocean color announcement, NASA OBPG). Therefore, it is very urgent to identify a new sensor that can continue to collect the types of observations presently acquired by the MODIS instruments. The more recent VIIRS (2011–), which is located on board the Suomi NPP satellite, is expected to provide a consistent, long-term data record and continue the observational records initiated by its predecessors. As a newer satellite sensor, the VIIRS instrument has demonstrated that it can continue to record MODIS-type observations over the ocean and coastal waters by measuring the remote sensing reflectance (R_{rs}) and optically active constituents (Hlaing et al., 2013; Hu and Le, 2014; Ladner et al., 2014; Wang et al., 2014). However, it is still unclear whether VIIRS ocean color products for inland lakes are consistent with the products of MODIS data due to a lack of available research.

There are several considerable challenges to meeting these expectations, such as the saturation of ocean bands, the failure to conduct atmospheric corrections and the lack of general algorithms for estimating SPM concentrations in inland waters using MODIS and VIIRS. Although the ocean bands are highly sensitive, they have a narrow dynamic range, and thus, they are always saturated in highly turbid waters (Hu et al., 2012). Fortunately, some historical reports have demonstrated that the bands designed for terrestrial applications also have the potential for the remote sensing of ocean colors. In particular, there is a significant correlation between red band reflectance values and SPM concentrations in coastal and inland waters (Miller and McKee, 2004; Ondrusek et al., 2012). In fact, the greatest challenge is the retrieval of accurate R_{rs} estimates from turbid inland waters, because full atmospheric corrections, such as those from the Management Unit of the North Sea Mathematical Models (MUMM) and the shortwave infrared (SWIR) algorithm of the SeaDAS software package, often result in the loss of data due to incorrect data masking and high uncertainties in the retrieved R_{rs} values (Aurin et al., 2013; Cao et al., 2017; Hu et al., 2012; Wang and Shi, 2006). Currently, R_{rc} data, which are derived after correcting for Rayleigh scattering and gaseous absorption effects, are frequently employed for studying inland lakes (Duan et al., 2014a; Oyama et al., 2015; Shi et al., 2015b).

Lake Hongze, which is the fourth-largest freshwater lake in China, is characterized by highly turbid waters and complex optical properties. In this study, we selected Lake Hongze as a test case in order to (1) quantify the differences between and assess the continuity within the R_{rc} measurements obtained through MODIS/Aqua and VIIRS/NPP data for Lake Hongze, (2) develop effective algorithms for the retrieval of SPM concentrations from MODIS and VIIRS data, and (3) evaluate the continuity between the MODIS and VIIRS SPM products. We believe that this study may be the first in this field to focus on inland waters and that it can both improve upon the applications of VIIRS to inland lakes and help support long-term monitoring activities.

2. Study area

Lake Hongze (33°06′–33°40′N, 118°10′–118°52′N, Fig. 1) is located in southeastern China and has a surface area of 1597 km^2 with an average water depth of 1.9 m. We selected Lake Hongze as a test case to provide an evaluation of the consistency between MODIS and VIIRS data for two reasons. First, Lake Hongze is a typical inland lake with complex optical properties wherein the SPM, chlorophyll-a (Chla) and colored dissolved organic matter (CDOM) concentrations significantly contribute to the total absorption coefficients (Cao et al., 2016), despite the presence of algal blooms during the summer and autumn. Second, Lake Hongze is a shallow lake with a large dynamic ratio of 21.04 km/m (Shi et al., 2014), and thus, all of its optical constituents can substantially vary in both space and time. The SPM ranges from 6.00 to 110.00 mg/L (mean: 37.57 ± 18.64 mg/L), the Chla ranges from 0.1 to 85.69 μg/L (mean: 13.55 ± 9.78 μg/L), and the CDOM absorption coefficient at 440 nm ($a_g(440)$) ranges from 0.23 to 1.95 m^{-1} (mean: 0.94 ± 0.28 m^{-1}). Therefore, the selection of Lake Hongze, which is a typical inland lake, is well suited for an evaluation of the continuity of VIIRS observations for SPM products.

3. Materials and methods

3.1. Field data

Six field trips to Lake Hongze were conducted and 157 datasets were collected between Apr 2014 and Feb 2016 (Fig. 1 and Table 1). At each station, surface water samples were collected at a depth of ~30 cm using a 2-L polyethylene water-fetching instrument. The water samples were stored within ice bags in the dark and then measured in a laboratory. Chlorophyll-a (Chla) was measured spectrophotometrically using a UV2700 spectrophotometer (Shimadzu Corp., Japan), and the CDOM absorption was determined from filtered water (using Whatman Millipore filters with a pore size of 0.22 μm) using the UV2700 spectrophotometer while employing distilled water as a reference (Duan et al., 2012). The SPM concentrations (in mg/L) were gravimetrically determined from samples collected from pre-combusted and pre-weighed Whatman GF/F filters with diameters of 47 mm that were dried at 105 °C for 4 h. The SPM was further differentiated into suspended inorganic matter (SPIM) and suspended organic matter (SPOM) by burning the organic matter from the filters at 450 °C for 4 h and weighing the filters again. The statistics of the water quality variables are summarized in Table 1. Note that the correlation between the SPM and SPIM concentrations is 0.95 ($p < 0.001$), whereas the correlation of SPM with SPOM is only 0.48 ($p < 0.001$), indicating that the SPM is primarily controlled by inorganic matter.

3.2. MODIS/Aqua and VIIRS/NPP data

The MODIS/Aqua and VIIRS/NPP Level-1A (L1A) data spanning the period between January 2012 and December 2015 were downloaded from the NASA Ocean Color Archive (https://oceandata.sci.gsfc.nasa.gov/). Then, Level-1B data were generated from the L1A data using the SeaDAS 7.3.2 software by incorporating the most recent updates within the calibration file (reprocessing version R2014.0; https://oceancolor.gsfc.nasa.gov/cms/reprocessing/r2014/). The R2014.0 file generated by the OBPG is a multi-mission reprocessed dataset incorporating MODIS and VIIRS data that is used to implement updates to the ocean color product suite and existing product algorithms and to incorporate new knowledge from sensor-specific instrument calibrations. The vicarious calibration of both MODIS/Aqua and VIIRS/NPP using the vicarious calibration gains from R2014.0 minimized the radiometric deviations. In addition, as mentioned above, a full atmospheric correction through SeaDAS often results in the loss of data due to (1) invalid assumptions of black water at near-infrared bands in turbid waters, (2) incorrect data masking of clouds and land and (3) large uncertainties in R_{rs} values in the SWIR algorithm due to excessive extrapolation and a low signal noise ratio (SNR) in the SWIR bands (Aurin et al., 2013; Wang and Shi, 2006; Zhang et al., 2014). Consequently, the R_{rc} values were derived after correcting for Rayleigh scattering and gaseous absorption effects (Hu et al., 2004) in the MODIS and VIIRS bands (MODIS: 469 nm, 555 nm, 645 nm and 859 nm; VIIRS: 486 nm, 551 nm, 671 nm and 862 nm). It is worth noting that the ocean bands of MODIS were not used in this study because they were originally designed for oceanic applications, and thus, they are highly sensitive with a narrow dynamic range and are consistently saturated in highly turbid waters (Hu et al., 2012; Qi et al., 2014). R_{rc} data from three MODIS and