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Climate- and human-induced changes in suspended particulate matter over Lake Hongze on short and long timescales

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ABSTRACT

Changes in global climate drivers have multiple impacts on lake ecosystems, as rain and wind conditions control catchment surface runoff and lake mixing regimes. However, human activities in lakes and their watersheds may have direct and indirect impacts on aquatic optical properties. Therefore, identifying key drivers that can be controlled (human) from those that cannot (climate) represents an important objective. In the present study, we develop an algorithm to estimate the concentrations of suspended particulate matter (SPM) in Lake Hongze (the fourth largest freshwater lake in China) using MODIS/Aqua images with concurrent data collected from six cruise surveys. The algorithm resulted in root mean square errors (RMSEs) of 7.64–7.86 mg/L for SPM ranging from 10 to 80 mg/L. The algorithm was applied to 1602 cloud-free MODIS/Aqua images from 2002 to 2015. Our results show: (1) inter-annual and seasonal variations of SPM concentrations in Lake Hongze are divided into two distinct periods between 2002 and 2011 and 2012–2015, with the transition associated to intensive dredging activities that were initiated in 2012. (2) SPM concentrations exhibit four typical patterns of spatial distribution which depend on local meteorological (wind speed and wind direction) and hydrological conditions (catchment rainfall and Huai River flowrate). Based on these results, a new spatial zoning of the lake is derived to support government and agency monitoring. The study shows additive and synergistic effects of climate change and human activities on SPM concentrations over short and long timescales and the possibility to monitor these changes by remote sensing in shallow optically complex lakes.

1. Introduction

Lakes are extensively distributed on Earth's surface and constitute a large network of ecological systems (Downing et al., 2006). Lakes not only provide fresh water and food for humans but can also act as sentinels of climate change (Adrian et al., 2009). One of the main manifestations of global climate change on a regional lake-basin scale is a significant increase or decrease in rainfall (Arnell and Reynard, 1996; Onyutha et al., 2016). Under the influence of strong rainfall levels, a basin transfers large volumes of suspended particles into a lake through runoff, resulting in a rapid increase in the suspended particulate matter (SPM) concentrations at the corresponding inlet and causing a turbid plume region that expands significantly (Saldías et al., 2012; Zhang et al., 2016). The increase in SPM concentrations reduces light propagation and limits the growth of plankton and submerged vegetation in lakes, thereby affecting primary production (Moore et al., 1997; Ondrusek et al., 2012).

Lakes are also significantly affected by human activities in both direct and indirect ways (Pham et al., 2008; Williamson et al., 2008). For example, humans can directly change lake shapes, water levels, and SPM concentrations by reclaiming farmland from lakes, by constructing water locks and dams, or through heavy dredging activities (Feng et al., 2012b; Hamm et al., 2002). Further, human-induced land use changes associated with soil erosion and exogenous input materials can modulate the water turbidity of inland waters (Fraterrigo and Downing, 2008; Jones et al., 2005). In fact, human activities and global climate change often change the concentrations and compositions of substances in lake water. Therefore, it is critical to understand the SPM variations in lakes that result from global climate change and human activities.

The SPM concentrations of coastal and inland waters are often inhomogeneous at both space and time scales, which makes it extremely difficult for traditional field sampling methods to fully capture their changing characteristics. Through frequent and synoptic observations, satellite remote sensing has been widely used to estimate SPM concentrations since 1970 (Holyer, 1978; Ritchie et al., 1976). In recent decades, satellite remote sensing data such as SeaWiFS, MODIS, MERIS, Landsat, and VIIRS data have been extensively used to estimate SPM

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concentrations in various water bodies around the world (Loisel et al., 2014; Miller and McKee, 2004; Volpe et al., 2011). Remote sensing algorithms for SPM concentrations can be generally classified into two types. The first type is composed of empirical algorithms established based on the relationship between either a single band or combinations of several bands and SPM concentrations (Ondrusek et al., 2012; Shi et al., 2015). The general principle of this method is that the signals of certain spectral bands can increase significantly due to the strong backscattering (b_b) effect of suspended materials in water (Doxaran et al., 2002; He et al., 2013). The second type involves semi-analytical algorithms based on radiative transfer theory (Neil et al., 2011; Volpe et al., 2011) in which the SPM concentrations are estimated from satellite-retrieved Inherent Optical Properties (IOPs) such as absorption (a) and b_b coefficients. Unfortunately, the optical properties in inland waters are often complex, which makes it rather challenging for semi-analytical algorithms to derive a and b_b directly from the remote sensing reflectance (R_{rs}). Therefore, various localized empirical algorithms have been developed to determine the SPM concentrations in optically complex waters.

Lake Hongze is the main water supply source and passage route of the eastern line of China's South-North Water Transfer Project (Yin et al., 2013; Zuo et al., 2012). It is the fourth largest freshwater lake in China and the largest in the Huai River Basin (Wang and Dou, 1998). The Huai River (one of the seven major rivers in China) flows directly into the middle reaches of Lake Hongze, making the lake important for regulating incoming water from the upper and middle reaches. Situated in a climatic transition zone between northern and southern China, rainfall occurs primarily during the flood season, and alternating floods and droughts occur frequently (Zuo et al., 2012). Uneven spatial and temporal distribution of water resources and deteriorating water quality due to a loss of sediments flowing into the lake have considerably affected both people's lives and industrial and agricultural production in the region (Gao et al., 2008). However, the understanding of how weather and hydrological conditions may affect SPM patterns in this lake remains limited. Additionally, sand dredging activities have triggered rapid water turbidity increases due to the large number of dredge vessels used since 2012, which damage bottom structures and threaten wildlife habitats. Unfortunately, the relationships between sand dredging activities and turbidity dynamics and their associated effects on regional ecological environments remain generally unknown (Yan, 2015).

In this paper, we used MODIS/Aqua data for 2002–2015 to study the spatio-temporal distribution of SPM concentrations in Lake Hongze to determine the effects of climate change and human activities. The main objectives were: (1) to develop a practical algorithm to estimate SPM concentrations using satellite data that is suitable in Lake Hongze; (2) to retrieve the spatio-temporal variation patterns of SPM concentrations in Lake Hongze; (3) to analyze the effects of hydrological and climatic factors (runoff, rainfall, and wind) on the formation and transformation of SPM spatial patterns in Lake Hongze; and (4) to explore the influence of human dredging activities on inter-annual changes in SPM concentrations in Lake Hongze. To our knowledge, this is the first study to employ an extended time series of MODIS data to study the driving mechanisms of the spatial and temporal variations in SPM concentrations in Lake Hongze, China.

2. Materials and methods

2.1. Study area

Lake Hongze (33°06′-33°40′N, 118°10′-118°52′N, Fig. 1) is a shallow lake. The area covered by Lake Hongze varies with water levels. At the water level of 12.5 m, the lake's area is 1597 km^2, and its volume is 3.04 billion m^3. The lake's average water depth is 1.9 m, and its maximum water depth is 4.5 m (Cai et al., 2016; Cao et al., 2016; Zhu and Dou, 1993). Lake Hongze is located in a warm temperate zone that belongs to the semi-humid monsoon climate region (Zuo et al., 2012). In the winter and spring, the Huai River Basin experiences drought with minimal rainfall; in the summer and fall, the area is hot and rainy. Beyond atmospheric precipitation, lake replenishment is primarily dependent on incoming river water, and its water body is relatively turbid. The rivers that flow into Lake Hongze are concentrated west of the lake, including the Huai, Sui, Bian, Xinbian and An Rivers. Runoff from the Huai River accounts for >70% of all river water runoff into the lake. The San River and Subei General Irrigation Canal are the primary outlets through which Lake Hongze flows into the Yangtze River and into the sea, respectively. Approximately 60–70% of the lake water flows into the Yangtze River through the San River Sluice.

The bottom of the lake is higher than the eastern North Jiangsu Plain by 4 to 8 m. A man-made dam (67.25 km) on the eastern coast was built in the Eastern Han Dynasty (CE 200) to protect the North Jiangsu Plain, rendering Lake Hongze a "suspended lake" on the plain. However, since 2012, dredging activities have significantly threatened the security of the eastern dam of Lake Hongze. Note that Lake Hongze is divided into three segments (Z1, Z2 and Z3) in this study for the reasons discussed below.

2.2. Field and satellite data

2.2.1. Field data

Six field trips to Lake Hongze were completed, and 157 datasets were collected from 30 stations between April 2014 and February 2016 (Fig. 1 and Table 1). Surface water (depth ~30 cm) were collected using a standard two-liter polyethylene water-sampling instrument. Environmental parameters such as surface wind speed were measured using a handheld anemometer, and the cloud conditions were recorded simultaneously. Samples were stored in the dark and kept cool with ice bags before the SPM concentrations were measured in a laboratory.

The SPM concentrations were gravimetrically determined from samples collected on pre-combusted and pre-weighed GF/F filters with a diameter of 47 mm that were dried at 105 °C overnight. SPM was differentiated into suspended particular inorganic matter (SPIM) and suspended particular organic matter (SPOM) by burning the organic matter from the filters at 450 °C for 4 h and then re-weighing the filters. The correlation between the SPM concentrations and SPIM was 0.95 ($p < 0.001$), whereas the correlation with SPOM was only 0.48 ($p < 0.001$). We can thus state that SPM in Lake Hongze primarily consists of inorganic matter (Table 1).

2.2.2. Satellite data and preprocessing

We primarily used MODIS data at 250 m and 500 m resolutions to study the SPM variability. Less frequent Landsat TM, ETM+ and OLI data at a resolution of 30 m were used to identify and monitor dredging vessels.

2.2.2.1. MODIS data. The MODIS/Aqua Level-1A data for Lake Hongze between July 2002 and December 2015 were downloaded from NASA's archive (https://oceandata.sci.gsfc.nasa.gov/). Level-1A data were first processed using SeaDAS 7.3 to generate Level-1B. Then, a partial atmospheric correction was applied to the Level-1B data to correct for the gaseous absorption (mainly by ozone) and Rayleigh scattering (molecular) effects, because a full atmospheric correction (such as the Management Unit of the North Sea Mathematical Models (MUMM) and shortwave infrared (SWIR) algorithm through SeaDAS) often resulted in data loss due to incorrect data masking and high uncertainties in the retrieved remote sensing reflectance (R_{rs}, sr^{-1}). Such failures generally resulted from: (1) the fixed thresholds used for mask-building in SeaDAS for land, clouds, high light levels and stray light are subject to significant errors in highly turbid waters (Aurin et al., 2013; Wang and Shi, 2006), which can easily be mistakenly identified as clouds or land; (2) the NIR black-pixel assumption in the MUMM algorithm is ineffective in inland waters due to their high turbidity (Zhang et al., 2014); (3) the signal to noise ratio (SNR) of shortwave-bands is very low, which leads to large uncertainties in the SWIR algorithm (Aurin et al.,