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Optical characterization of black water blooms in eutrophic waters

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HIGHLIGHTS

- Black water blooms have led to major problems in eutrophic waters and water supplies.
- The bio-optical properties of black water blooms were compared to typical lake waters.
- Low reflectance was associated with high CDOM absorption and low SPIM backscattering.
- The black water blooms are favored by macrophyte die back during periods of low wind speed.

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ABSTRACT

In the summer of 2007, blooms of "black" water in Lake Taihu entered into the potable water supply of Wuxi City and left more than 1 million people without water. Attempts to monitor these black water blooms have not been successful due to their irregular nature. In May 2012, two black water blooms were observed in one of the lake's eutrophic bays. The bio-optical analyses of these blooms show that they were dominated by higher concentrations of dissolved organic matter and lower backscattering coefficients with respect to the surrounding lake conditions. We show the contribution of each optically active component to the perceived radiance and demonstrate that elevated absorption due to dissolved organic matter and phytoplankton combined with reduced backscattering led to the perception of these water areas as "black", while the true color was dark green. The present analysis indicates that formation of black water blooms is favored during springtime conditions in the macrophyte dominated areas of the lake's hypereutrophic bays.

1. Introduction

Water color was first used to define water masses by the Swiss limnologist Francoise-Alphonse Forel in the late 1800s in a nonquantitative classification approach (Arnone et al., 2004). The color of water is directly related to the concentrations and optical properties of the dissolved and suspended matter in the water column and their impact on the upward flux of scattered radiance perceived by the observer (IOCCG, 2000, 2008). The most important of these are usually phytoplankton, non-algal particulates, chromophoric dissolved organic matter (CDOM) and the water itself (Morel, 1988). In general, CDOM increases absorption in the short visible wavelengths, reducing upwelling radiance and increasing overall attenuation (Battin, 1998; Berthon and Zibordi, 2010; Zhao et al., 2013). Phytoplankton can also lead to significant changes in water color, with both increase attenuation and increased scattered radiance (Dierssen et al., 2006).

The color of water perceived by the human eye can be numerically described by the color matching functions defined by the Commission Internationale de l'Ěclairage (CIE), which transpose radiometric measurements onto a colorimetric coordinate system (Dierssen et al., 2006; Watanabe et al., 2011). Differences in perceived color imply differences in the underwater optical conditions. However, the underlying relationship between apparent optical properties (AOPs) and water color is still poorly understood in most coastal and inland waters due to the complexity of optical conditions, where absorption and scattering of phytoplankton pigments, non-algal particulates, and CDOM may spectrally overlap (IOCCG, 2000).

Lake Taihu, the third largest freshwater lake in China, provides fundamental services to a large surrounding population, even though it is one of the most severely polluted freshwater reservoirs in China (Duan et al., 2009; Hu et al., 2010). Agricultural activities are the major source of non-point pollution while the growing urban communities within the basin and the limited treatment of urban wastewater represent the most important point pollution source (Qin et al., 2007). In the summer of 2007, water quality problems, initially associated with algal blooms, left more than 1 million people in the city of Wuxi without drinking water (Guo, 2007). Further studies indicated that the apparent cause was the intrusion of a black water bloom of unknown origin into the main water intake of the city (Yang et al., 2008). While

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black water blooms had been previously reported (Lu and Ma, 2010), it was only after the 2007 occurrence that academic and government authorities began to treat black water blooms as an environmental priority.

Black water blooms, black water agglomerates, black spots or dead zones have been characterized as hypoxic and malodorous areas of freshwater and marine ecosystems (Diaz and Rosenberg, 2008; Feng et al., 2014; Pucciarelli et al., 2008). They often have elevated sulfide concentrations, principally metal sulfides and hydrogen sulfide (Duval and Ludlam, 2001; Lu and Ma, 2010; Stahl, 1979) associated with the presence of sulfate-reducing bacteria and degrading organic matter from algal blooms or sediment (Feng et al., 2014; He et al., 2013). They present significant threats to drinking water safety. Black blooms have occurred in many inland lakes and continental seas, such as Lake Kasumigaura (Japan) (Sugiura and Nakano, 2000), Lower Mystic Lake (USA) (Duval and Ludlam, 2001), Lake Garda (Italy) (Pucciarelli et al., 2008), Florida Keys (USA) (Hu et al., 2004), Baltic (Europe) (Berthon and Zibordi, 2010), and East China Sea (Bai et al., 2009).

In May 2012, black water blooms were observed during regular *in-situ* algal bloom monitoring activities. Field measurements were made immediately to characterize the bio-optical properties of two of these black water masses. These data provided an opportunity to explore the possible causes of their occurrence and potential methods for their monitoring. To the best of our knowledge, this is the first study to optically address the occurrence of black water blooms in waters destined for human consumption.

2. Materials and methods

2.1. Fieldwork

Water samples and optical data were collected at 12 stations from three areas of Gonghu Bay, Lake Taihu on 17th May, 2012 (Fig. 1). Two areas (Zones 1 and 2) were identified as "black" water areas with samples taken from an area of typical lake water (Zone 3) in the center. At each station, remote sensing reflectance (R_{rs}) was measured with an ASD hand-held spectrometer, following the NASA Ocean Optics protocols (Mueller and Fargion, 2003). The viewing angle of the measurement was ~40° from nadir, and the relative azimuth angle to the sun was ~135°. Data from several stations (Nos. 1–3, 5–6) were removed due to low signal to noise ratio. Water samples were collected just below the surface with a standard 2-liter polyethylene water-sampler

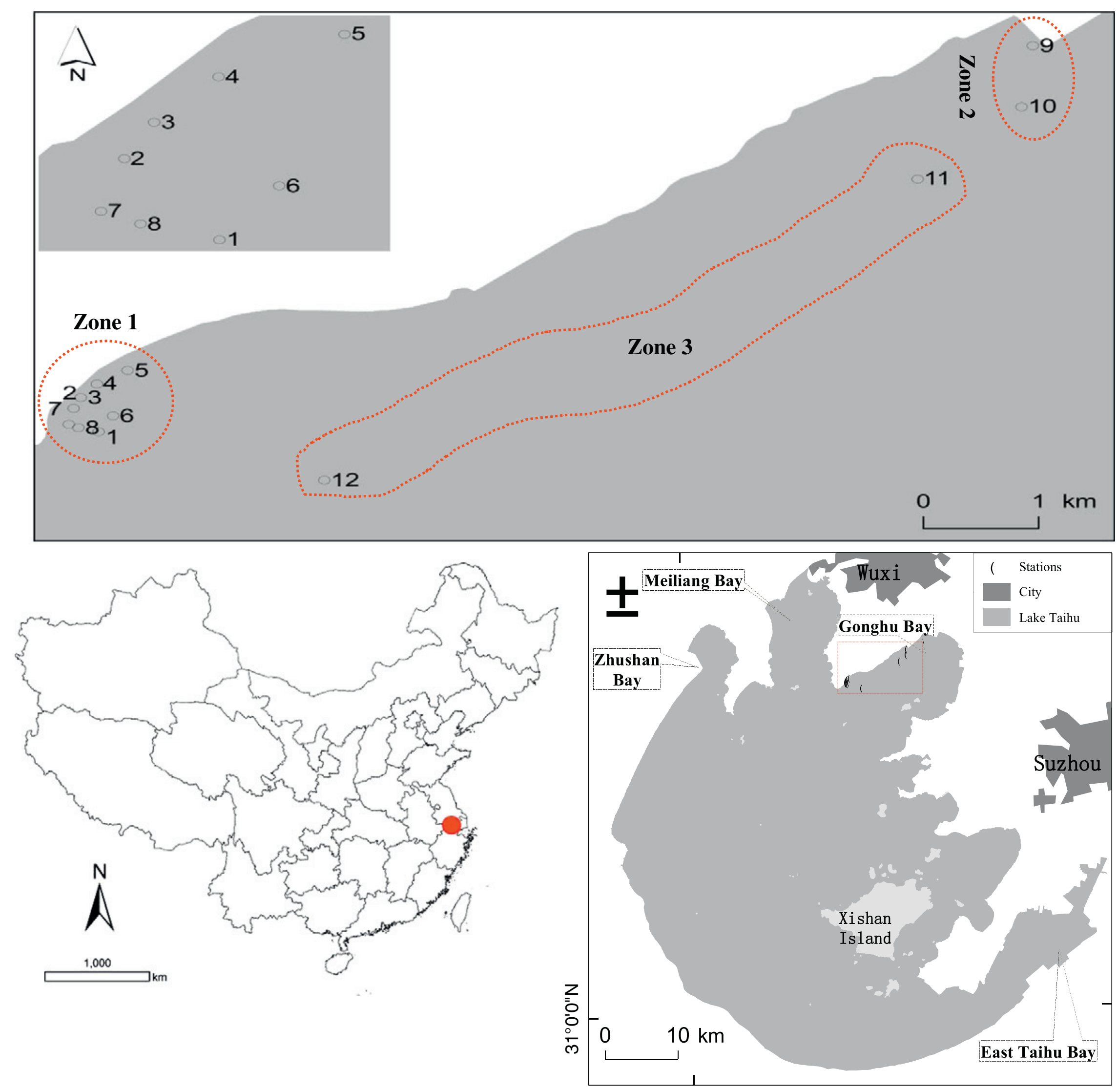

Fig. 1. Sampling sites in Gonghu Bay, Lake Taihu (China) near the potable water source for Wuxi City. Black water masses were present in Zone 1 (stations 1–8) and Zone 2 (stations 9–10) with typical lake waters characterizing Zone 3 (stations 11–12).