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Optical scattering properties of organic-rich and inorganic-rich particles in inland waters

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ABSTRACT

We present the results from a study of the particulate scattering properties of three bodies of water that represent a wide range of optical properties found in inland waters. We found a positive linear relationship ($R^2 = 0.45$, $P < 0.005$) between the mass-specific scattering coefficient at 532 nm ($b_p^*(532)$) and the ratio of the inorganic suspended material (ISM) to the total suspended material (TSM) in our study areas. In contrast to earlier studies in which $b_p^*(532)$ was lower for inorganic particles than for organic particles, we found that the value of $b_p^*(532)$ for ISM ($b_p^*(532)_{ISM} = 0.71\ m^2/g$) was approximately 1.6 times greater than the value found for organic suspended materials (OSM) ($b_p^*(532)_{OSM} = 0.45\ m^2/g$). We found that the dependence of the particle scattering coefficient (b_p) on wavelength (λ) could be described accurately by a power law (with mean average percent error (MAPE) < 0.07) in waters dominated by inorganic particles. The model errors in waters dominated by organic particles, however, were much larger (MAPE > 0.1), especially in the spectral region associated with strong phytoplankton absorption. The errors could be reduced over this wavelength range by adding a term to the model to account for particle absorption, but the additional term tended to increase the error outside of this range. We conclude that information about the nature of the scattering particles in lake waters is necessary for the selection of an appropriate model for particle absorption and that a hybrid model that includes absorption over some wavelength ranges may be necessary.

Introduction

Inherent optical properties (IOPs) of water are solely dependent on the water contents, such as the concentrations of dissolved water constituents and particulate composition, but independent of the distribution of ambient light (Morel, 1988). Light scattering is generally considered one of the most fundamental parameters of IOPs and can reflect the composition and shape characteristics of the total suspended materials (Loisel et al., 2006). Therefore, particulate scattering and a detailed understanding of its variability in natural waters are important for aquatic ecosystem sciences related to the knowledge of total suspended materials. The scattering properties of a water body can determine the way light propagates through water, and this information can be used for inferring water contents from data observed using remote sensing systems (Snyder et al., 2008). In turbid inland waters, scattering is very important in the remote sensing of water contents because the radiometric signal recorded by a sensor onboard a satellite or an aircraft is directly proportional to its intensity (Twardowski et al., 2001).

The majority of scattering is composed of total suspended material (TSM), including organic suspended material (OSM) and inorganic suspended material (ISM). Particulate scattering has been found to be directly associated with the TSM concentration, but the relationship between them varies with the composition of TSM. Large differences in TSM compositions are found in different water types which results in significant variation in the specific scattering coefficient. As theoretically expected, the relationship between the scattering, $b_p(\lambda)$, and the concentration of suspended particles was observed to change significantly with the particle size distribution and refractive index (Babin et al., 2003). Babin et al. (2003) argued that the mass-specific coefficient in Case 2 waters with a high inorganic content would be smaller than in Case 1 waters with a high organic content. Baker and Lavelle (1984) also suggested that a systematic decrease in the mass-specific scattering coefficient could occur from offshore to inshore waters. The influence of the mass-specific scattering coefficient would also be reduced by algal absorption in areas with a high chlorophyll-*a* concentration (*Chl-a*).

On the basis of theoretical considerations, Morel (1988) showed that spectral variations of the scattering coefficient caused by non-absorbing

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particles follow an inverse power law. This dependency has been used in models of the inherent properties of seawater and inland lake waters (Babin et al., 2003; Morel et al., 2006; Roesler and Boss, 2003; Song and Tang, 2006; Sun et al., 2009). Based on the observations made in a number of estuaries, Doxaran et al. (2009) confirmed that, in the near-IR spectral region, where light absorption by particles is low, a power law function does fit the spectral variations in a scattering coefficient with a variable slope. However, this power law function is inappropriate for the visible region of the spectrum where particles absorb more light (Doxaran et al., 2007). Numerous measurements of spectral scattering coefficients have documented significant departures from the power law function in spectral bands associated with strong particulate absorption (Babin et al., 2003; Barnard et al., 1998; Doxaran et al., 2007; Stramski et al., 2001). In Lake Taihu, due to the low OSM to ISM ratio, a power law function is suitable for the spectral variations in a scattering coefficient with variable slope. Therefore, the impact of OSM absorption on the scattering coefficient is negligible in Lake Taihu (Sun et al., 2009). When the TSM has a high OSM ratio, the model can fit spectral variations in the scattering coefficients with variable slopes in wave bands associated with strong particulate absorption by taking into account the particulate absorption effects (Doxaran et al., 2009).

For waters with high inorganic particle contents, numerous studies have been conducted to develop models that simulate the variations in spectral scattering coefficients and to investigate the variations in the relationship between scattering coefficients and TSM and ISM (Boss et al., 2004; Kirk, 1981; Loisel and Stramski, 2000; Loisel et al., 2006; Whitmire et al., 2007). However, little work has been performed on productive inland waters with high organic particle contents.

This study focuses on the properties of optical scattering in three optically distinct regions in China: Lake Taihu, Lake Chaohu, and Lake Dianchi. The two questions we address in this study are (1) how well does a power-law function describe the shape of the particulate scattering spectra in different inland waters (that is, waters with inorganic-rich or organic-rich particles) and (2) can the mass-specific scattering coefficient be related to the amount of organic and inorganic suspended materials?

Material and methods

Study areas

The study areas, including Lake Taihu, Lake Chaohu, and Lake Dianchi, are located in the Yangtze River drainage area (Fig. 1). Lake Taihu is a large, eutrophic shallow lake with high spatial heterogeneity in the Yangtze Delta plain on the border of the Jiangsu and Zhejiang provinces in China. With an area of 2338 km^2 (Zhang et al., 2007), it is the third largest freshwater lake in China. This lake is a typical large shallow lake with an average depth of 1.9 m, indicating wave-induced sediment resuspension has a significant impact on the water quality of Lake Taihu. Lake Chaohu is located at the juncture of Chaohu and Hefei cities in Anhui Province, China. With a water area of 750 km^2 and an average depth of 3 m, it is the largest lake in Anhui and one of the five largest freshwater lakes in China. Similar to Lake Taihu, the water quality of this lake is also severely affected by wave-induced sediment resuspension. The optical properties of these two lakes (Lake Taihu and Lake Chaohu) are generally dominated by inorganic particles from resuspended bottom materials and a strong influence from gelbstoff (chromophoric dissolved organic matter; CDOM) with a relatively lower contribution from phytoplankton.

Our third study site was Lake Dianchi, located on the Yungui Plateau in China. With a water area of approximately 300 km^2 and an average depth of 5 m, Lake Dianchi is the largest freshwater lake in the Yunnan Province. The optical properties of this lake were typically controlled by phytoplankton with minor influences from inorganic suspended materials (Sun et al., 2012).

These lakes have high concentrations of TSM. However, the TSM composition varied drastically among the three lakes. The waters in Lake Taihu and Lake Chaohu had a high concentration of non-algal particles, i.e., fine sediments with a combination of silts and clays. Conversely, there was a high concentration of algal particles in Lake Dianchi. The measurements at Lake Taihu were performed in November 2008 (56 stations) and April 2009 (31 stations). The measurements at Lakes Chaohu and Dianchi were carried out in June (30 stations) and

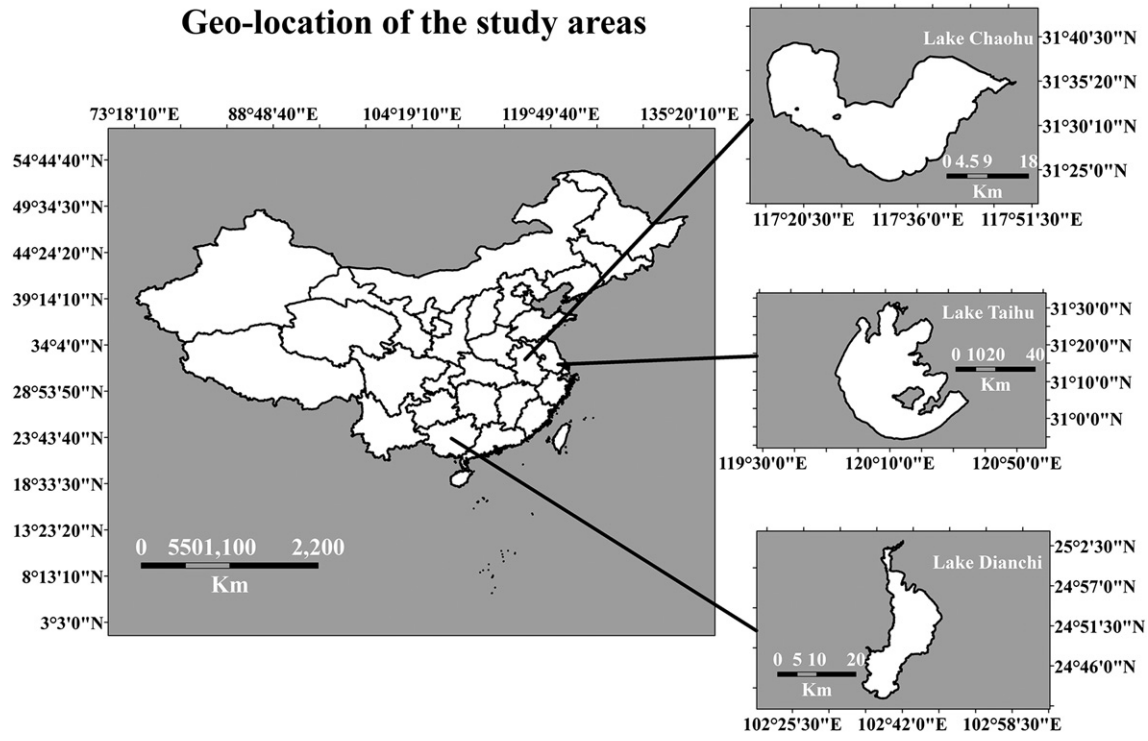

Fig. 1. Geo-location of the three study lakes in China.

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