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Will enhanced turbulence in inland waters result in elevated production of autochthonous dissolved organic matter?☆

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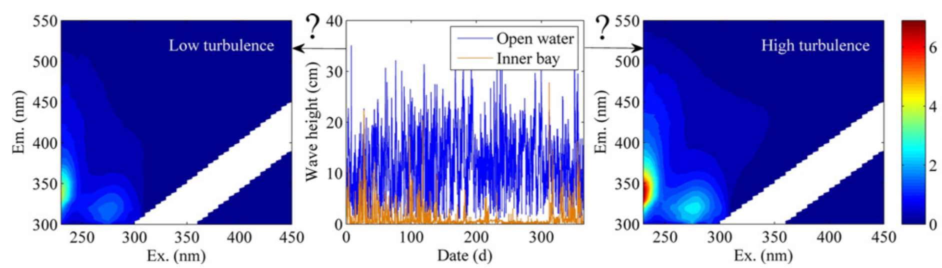
HIGHLIGHTS

- Parallel factor analysis decomposed EEMs into seven components.
- Elevated endogenous CDOM was produced under enhanced turbulence in the field.
- Enhanced turbulence resulted in higher autochthonous CDOM and DOC in the mesocosms.
- Enhanced turbulence led to increased Chl-*a* and phytoplanktonic APA in the mesocosms.

GRAPHICAL ABSTRACT



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ABSTRACT

Biological activity in lakes is strongly influenced by hydrodynamic conditions, not least turbulence intensity; which increases the encounter rate between plankter and nutrient patches. To investigate whether enhanced turbulence in shallow and eutrophic lakes may result in elevated biological production of autochthonous chromophoric dissolved organic matter (CDOM), a combination of field campaigns and mesocosm experiments was used. Parallel factor analysis identified seven components: four protein-like, one microbial humic-like and two terrestrial humic-like components. During our field campaigns, elevated production of autochthonous CDOM was recorded in open water with higher wind speed and wave height than in inner bays, implying that elevated turbulence resulted in increased production of autochthonous CDOM. Confirming the field campaign results, in the mesocosm experiment enhanced turbulence resulted in a remarkably higher microbial humic-like C1 and tryptophan-like C3 ($p < 0.01$), indicating that higher turbulence may have elevated the production of autochthonous CDOM. This is consistent with the significantly higher mean concentrations of chlorophyll-*a* (Chl-*a*) and dissolved organic carbon (DOC) and the enhanced phytoplanktonic alkaline phosphatase activity (PAPA) recorded in the experimental turbulence groups than in the control group ($p < 0.05$). The C:N ratio (from 3.34 to 25.72 with a mean of 13.13 $\pm$ 4.08) for the mesocosm CDOM samples further suggested their probable autochthonous origin. Our results have implications for the understanding of CDOM cycling in shallow aquatic ecosystems influenced by wind-induced waves, in which the enhanced turbulence associated with extreme weather conditions may be further stimulated by the predicted global climate change.

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1. Introduction

Dissolved organic matter (DOM) is ubiquitous in all natural aquatic ecosystems and originates from a variety of sources (Coble, 2007; Coble et al., 1990; Stedmon and Markager, 2005a). In coastal and inland waters, terrestrial organic carbon dominates the organic carbon pool (Coble, 2007; Guo et al., 2014; Stedmon and Markager, 2005a; Yamashita et al., 2008; Yang et al., 2013). However, the accumulation of high concentrations of protein-like substances in hypereutrophic waters is typically closely associated with biological activity, including extracellular release by phytoplankton and viral lysis of plankton (Stedmon and Markager, 2005b; Zhang et al., 2009). Biological activity in inland waters, especially shallow aquatic ecosystems, is strongly influenced by hydrodynamic conditions, especially turbulence intensity (Kristensen et al., 1992; Liu et al., 2013; Zhang et al., 2014a). Previous studies have indicated that mixing events in inland waters may create a large increase in algal production and shifts in algal community composition (Carrick et al., 1993; Zhu et al., 2014). The accumulation of autochthonous DOM associated with biological processes is mediated by the rate at which the individual plankters encounter other organisms or patches of resources (Visser et al., 2009). For example, moderate turbulence in inland waters is beneficial for the growth of phytoplankton, zooplankton and microbes as it increases the encounter rate of producers–consumers as well as the contact between phytoplankton and the nutrient patches (Alcaraz et al., 2002; Cardoso and Marques, 2009; Carrick et al., 1993; G.-Tóth et al., 2011; Vincent, 1992). Furthermore, enhanced turbulence may accelerate the release of extracellular polymeric substances derived from algae (Donaghay and Osborn, 1997) and thus potentially lead to elevated production of autochthonous DOM. The influences of turbulence on the concentration and fluxes of DOM are especially notable during extreme weather events (Grinsted et al., 2013; Guo et al., 2014), and both the intensity and frequency of turbulence in inland aquatic ecosystems are expected to increase in the future due to the ongoing climate change (Schindler, 2009; Zhang et al., 2015). The direct physical effect of turbulence on the production and transformation of DOM is, however, poorly elucidated.

Tracing of the dynamics of DOM in natural aquatic environments using traditional chemical measurements has proved difficult due to its complex composition. Chromophoric DOM (CDOM) is the coloured fraction of DOM, and fluorescence measurements of CDOM can be used as a proxy for tracing CDOM dynamics as a fraction of CDOM fluoresces rapidly and sensitively (Coble, 1996; Murphy et al., 2008; Osburn et al., 2012; Stedmon and Markager, 2005a; Yamashita et al., 2008). A combination of excitation–emission matrices (EEMs) and parallel factor (PARAFAC) analysis has been shown to have considerable advantages in tracing the dynamics of CDOM compared to traditional chemical measurements (Fellman et al., 2010; Murphy et al., 2013; Stedmon et al., 2003). Furthermore, the presence of high concentrations of CDOM is responsible for the formation of carcinogenic substances and unpleasant odours in natural waters (Baghoth et al., 2011; Zhang et al., 2011) and may compromise the safety of drinking water sources. Thus, numerous studies have been dedicated to unravelling the dynamics of CDOM in natural aquatic ecosystems (Markager et al., 2011; Osburn et al., 2011; Singh et al., 2010; Stedmon et al., 2007; Toming et al., 2013; Yamashita and Tanoue, 2008).

Harmful blooms of autotrophic cyanobacteria (CyanoHABs) may constitute a large potential labile CDOM pool upon cell death (Paerl and Otten, 2013). In large, shallow and eutrophic lakes, such as Lake Taihu in China, nuisance algal blooms have occurred nearly every year over the last decade (Paerl and Otten, 2013; Paerl and Paul, 2012; Qin et al., 2015). The high concentrations of autochthonous CDOM in this lake are closely associated with turbulence during algal blooms, with strongly adverse effects on the local economic development (Paerl and Paul, 2012; Qin et al., 2010). A study conducted in the lake further indicated that enhanced turbulence induced by tropical cyclones may stimulate CyanoHABs (Zhu et al., 2014). However, other studies suggest that a continuously very high turbulence may disorientate the movement of the algae block mass and lead to uncontrolled vertical drifting (G.-Tóth et al., 2011; Visser et al., 2009), possibly reducing the growth rate of algae and the production of autochthonous CDOM. However, whether and, if so, when enhanced turbulence in inland waters will result in elevated or decreased production of autochthonous CDOM remains unknown.

The objective of this study was to provide a first attempt at unravelling the influence of turbulence on the dynamics of autochthonous CDOM by a combination of field campaigns and mesocosm experiment. By investigating the variations of autochthonous CDOM fractions under different turbulence intensities in the field and in controlled experiments, we sought to elucidate the production and depletion processes of biological CDOM fuelled by enhanced turbulence. We hypothesised that enhanced turbulence can result in elevated production of autochthonous CDOM in shallow and eutrophic aquatic ecosystems.

2. Materials and methods

2.1. Sampling sites and sampling collection

Lake Taihu is an important drinking water source in the Yangtze River Delta for a population of at least 10 million people living within its watershed (Qin et al., 2010). The eutrophic lake has a surface water area of 2338.1 km^2, a mean depth of ~1.9 m (maximum depth < 3.0 m) and a water retention time of ~300 d (Tang et al., 2010). Due to its location in the most developed region in China, Lake Taihu receives excessive nutrient input from the upstream watershed, and CyanoHABs blooms have appeared persistently in the summer period for the last three decades. The accumulation and subsequent decay of massive algal blooms may result in the outbreak of black water events (Zhou et al., 2015b; Zhu et al., 2013), with frequently high concentrations of CDOM. Disturbance, especially wind-induced waves, is directly associated with euphotic depth and growth of the algal and microbial communities, affecting the production and depletion processes of autochthonous CDOM in Lake Taihu (Qin et al., 2007; Zhang et al., 2014a). This is especially true for the dynamics of microbial CDOM fractions in the open water of the lake where the daily maximum wind speed can be up to >10 m/s (Liu et al., 2013).

Two extensive sampling campaigns were conducted at the same sites ($n = 116$) in Lake Taihu in January and July 2014 (Fig. 1), and a total of 232 (116 × 2) surface water samples (0–0.5 m) were collected. The samples were kept on ice in the field and filtered immediately upon arrival at the laboratory. The samples were first filtered through precombusted (450 °C for 4 h) Whatman GF/F filters (0.7 μm porosity) and then through pre-rinsed Millipore membrane cellulose filters (0.22 μm porosity) to determine CDOM absorption and fluorescence. The filtered samples were stored in the dark at 4 °C and CDOM spectral measurements were finished within 3 days.

2.2. Mesocosm experiment

The experiment was carried out in 12 acid-cleaned transparent glass mesocosms with 60 cm length, 30 cm width and 70 cm depth from July 7th–July 22th 2014. Surface lake water (0–0.5 m, ~96 L) was pumped directly into each mesocosm from the nearshore of Meiliang Bay, Lake Taihu, to introduce algal cells from the lake to the mesocosms and to conduct the mesocosm experiment under near-natural field conditions. No noticeable plant detritus was found in the water pumped to the mesocosms. Submerged wave-maker pumps (WP, Jiebao, China) were fixed under the water surface with magnets in each mesocosm to create hydrodynamic turbulence similar to wind-induced waves (Härkönen et al., 2014; Zhou et al., 2015a). The mesocosms were placed in the vicinity of the Taihu Laboratory for Lake Ecosystem Research (TLLER), located at the shore side of Meiliang Bay (Fig. 1). The mesocosms were

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