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Q1 Effects of turbulence on carbon emission in shallow lakes

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ABSTRACT

Turbulent mixing is enhanced in shallow lakes. As a result, exchanges across the air–water and sediment–water interfaces are increased, causing these systems to be large sources of greenhouse gases. This study investigated the effects of turbulence on carbon dioxide (CO_2) and methane (CH_4) emissions in shallow lakes using simulated mesocosm experiments. Results demonstrated that turbulence increased CO_2 emissions, while simultaneously decreasing CH_4 emissions by altering microbial processes. Under turbulent conditions, a greater fraction of organic carbon was recycled as CO_2 instead of CH_4, potentially reducing the net global warming effect because of the lower global warming potential of CO_2 relative to CH_4. The CH_4/CO_2 flux ratio was approximately 0.006 under turbulent conditions, but reached 0.078 in the control. The real-time quantitative PCR analysis indicated that methanogen abundance decreased and methanotroph abundance increased under turbulent conditions, inhibiting CH_4 production and favoring the oxidation of CH_4 to CO_2. These findings suggest that turbulence may play an important role in the global carbon cycle by limiting CH_4 emissions, thereby reducing the net global warming effect of shallow lakes.

Introduction

Global warming has intensified extreme weather events, such as hurricanes, droughts, heat waves, and floods (Fedorov et al., 2010; Min et al., 2011; Tollefson, 2012). The greenhouse gases carbon dioxide (CO_2) and methane (CH_4) are two main drivers of global warming, contributing 63% and 18%, respectively (Hu et al., 2017; Smith et al., 2013; Tu and Li, 2017). Current atmospheric CH_4 and CO_2 concentrations are approximately 2.5 and 2 times, respectively, pre-industrial levels (Kirschke et al., 2013; Hartmann et al., 2013). Inland waters are considered to be hotspots of CH_4 and CO_2 emissions, which are estimated at 0.65 Pg C/year (CO_2 eq) and 1.2–2.1 Pg C/year, respectively (Bastviken et al., 2011; Raymond et al., 2013). Thus, CH_4 and CO_2 emissions from inland waters have received considerable research attention.

In aquatic systems, CH_4 and CO_2 have different production pathways. CH_4 is primarily produced in surface sediment by microbial communities as part of anaerobic respiration, usually within the first few centimeters of the sediment layer (Conrad et al., 2007). CO_2 is produced by aerobic respiration and acetoclastic methanogenesis throughout the lake and lake sediment (Casper et al., 2000). Microbial CH_4 production (methanogenesis) is achieved by specific groups of Archaea in anoxic environments, where anaerobic degradation of organic matter occurs as a result of fermentation (Nazaries et al., 2013).

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CO_2 production is driven largely by the aerobic decomposition of organic matter (Jung et al., 2014; Sobek et al., 2005). Under aerobic conditions, CH_4 can be oxidized to CO_2 by methanotrophic Proteobacteria (Bastviken et al., 2008; Xiao et al., 2013). Thus, environmental conditions strongly influence organic matter mineralization and CH_4 and CO_2 emissions from inland waters.

The hydrodynamics of waves created by the wind play an important role in aquatic ecosystems, and turbulence is a ubiquitous hydrodynamic feature of all inland waters, especially shallow lakes (Margalef, 1997). Waves are generated by wind passing over a water surface. As long as the waves propagate more slowly than the wind speed just above the waves, there is an energy transfer from the wind to the waves; however, there is little space for wave energy to dissipate in shallow lakes, enhancing turbulent kinetic-energy and turbulent shear forces (G-Tóth et al., 2011). Lake Taihu is a shallow eutrophic lake in China, with an average depth of 1.9 m. The lake's turbulence is mainly determined by wind velocity, wind direction, and prevailing wind (Qin et al., 2007). Physical turbulence can strongly affect the stability of lake water and sediment. Specifically, wind-induced turbulence controls the exchange of material across both air–water and sediment–water interfaces. Previous studies have shown that disturbance can accelerate the rate at which oxygen diffuses from the atmosphere into the water column (Chatelain and Guizien, 2010; You et al., 2007). By changing the dissolved oxygen (DO) concentration of water, turbulent mixing can shift the mineralization pathways of organic matter, altering CO_2 and CH_4 emissions to the atmosphere (Li et al., 2012; Stoliker et al., 2016), particularly in small or shallow lakes (Holgerson and Raymond, 2016). These studies have focused on the impacts of turbulence and mixing on physical and chemical properties of aquatic ecosystems; however, the fundamental relationship between turbulence and greenhouse gas emissions from lakes has not been fully addressed.

This study used simulated mesocosms to investigate the effects of turbulence on lake CH_4 and CO_2 emissions. CH_4 and CO_2 fluxes were measured using a static chamber method throughout the experiment. Methanogen and methanotroph abundances were also analyzed using real-time quantitative PCR (qPCR), to illustrate the associated molecular mechanism. We hypothesized that under turbulent conditions, (1) water column oxygenation is enhanced; (2) the heterotrophic microbial community shifts towards taxa tolerant of this oxygenation; and (3) the degradation of organic carbon is changed, decreasing CH_4 and increasing CO_2 emissions.

1. Material and methods

1.1. Experimental design

The experiments were conducted in simulated trapezoidal tanks with a upper plane (67 × 30 cm), a bottom plane (53 × 30 cm), and a height of 70 cm (Zhou et al., 2016). An energy dissipation plate was placed in the tank to prevent wave rebound, which was fixed by a groove on the side wall and kept parallel to the slope wall at a distance of 2 cm. The detailed description is presented in Appendix A Fig. S1 in the Supporting Materials. Each tank was filled with 0.5 cm thick sediment and 96 L lake water, collected from the center of Meiliang Bay (31°26′07″N, 120°11′18″E), Taihu Lake. Sediment was acquired from the lake bed using a Petersen grab sampler. The collected sediment was placed onto the tank bottom, and then lake water was gently drained into the tanks with a rubber tube. At this location, sediment often suffers wind-induced resuspension, and is homogeneous in the upper 10 cm. The main properties of the sediment are presented in Appendix A Table S1 in the Supporting Materials. The simulated systems were allowed to stand for 3 days before starting the experiment. To be close to field conditions (temperature, light, *etc*.), these tanks were placed and floated in an outside artificial pond (10 × 10 × 2 m) on the shores of Taihu Lake.

This experiment included twelve tanks with 4 different treatments: a control without turbulence, low turbulence (LT), medium turbulence (MT), and high turbulence (HT). Each treatment was conducted in triplicate. The LT, MT, and HT tanks were each equipped with one wave-maker pump (WP, Jebao, China), which can produce flow with shear and induce turbulence in the water (Härkönen et al., 2014; Zhou et al., 2016). The pump was fixed below the surface of the water when starting the experiment using strong magnets. Prior to the experiment, the pump speed was set by measuring the energy dissipation rate using an acoustic Doppler velocimeter (ADV, 10 MHz ADVField, Sontek/YSI, USA), based on the turbulence conditions observed in Lake Taihu.

The turbulence was measured from the middle of the tank with a 25 Hz measurement for a period of 2 min. The measurements were started after the turbulent motion in the tank had reached a steady state (approximately 10 min). To define the characteristic speed of the turbulence, the root mean square velocity (U, cm/sec) was calculated by using the following formula:

$$U = \sqrt{{\mu_{\mathrm{RMS}_x}}^2 + {\mu_{\mathrm{RMS}_y}}^2 + {\mu_{\mathrm{RMS}_z}}^2} \qquad (1)$$

where

$$\mu_{\mathrm{RMS}_x} = \sqrt{\left(\sum {\mu_x}^2 - \left(\sum \mu_x\right)^2 / n\right) \Big/ (n-1)} \qquad (2)$$

μ_{RMSx} is the fluctuation of the flow for Cartesian vector X (which is similarly calculated for the Y and Z vectors). μ_x is the instantaneous flow velocity measured by the acoustic Doppler velocimeter and n is the number of samples per measurement. *U* is root mean square turbulent velocity, which was expressed as the average for the whole tank in this study. The energy dissipation rate (m^2/sec^3), which describes the rate at which the turbulent energy decays over time, was deduced from the *U* (m/sec) following the formula described by Sanford (1997):

$$\text{Energy dissipation rate} = \left(A_1 U^3\right) \Big/ l_1 \qquad (3)$$

In this expression, A_1 is a dimensional constant of order 1 (Kundu and Cohen, 2010), and *l* (m) is the water depth associated with the largest vortices.

According to the energy dissipation rates in the range of 6.01×10^{-8}–2.39×10^{-4} m^2/sec^3 in Taihu, the root mean square turbulent velocity (*U*) values applied in LT, MT and HT were

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