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Intense methane ebullition from open water area of a shallow peatland lake on the eastern Tibetan Plateau

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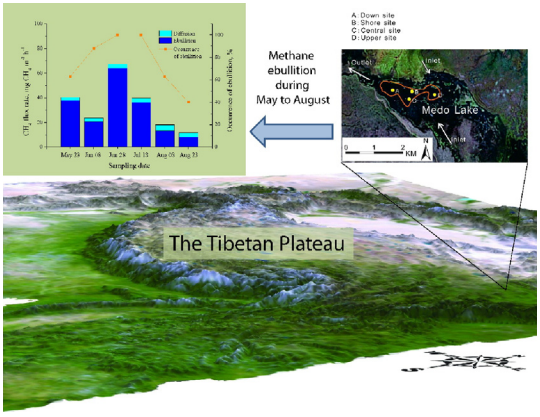
HIGHLIGHTS

- Intense methane ebullition was found in Lake Medo.
- Sediment temperature and water depth were the regulators of ebullition.
- Shallowness of lake water and low atmospheric pressure facilitated ebullition.

GRAPHICAL ABSTRACT



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ABSTRACT

Methane fluxes from a shallow peatland lake (3450 m a.s.l., 1.6 km^2 in area, maximum depth <1 m) on eastern Tibetan Plateau were measured with floating chamber method during May to August, 2009. The overall average of methane emission rate during the study period was 34.71 ± 29.15 mg CH_4 m^{-2} h^{-1}. The occurrence of ebullition among the overall methane flux from Lake Medo was about 74%. The average rate of ebullition was 32.45 ± 28.31 mg CH_4 m^{-2} h^{-1}, which accounted for 93% of the overall average of methane emission. Significant seasonal variation was found for occurrence ($P < 0.05$) and rate ($P < 0.01$) of ebullition, both peaking synchronously in mid-summer. Both the occurrence and rate of ebullition were found positively related to sediment temperature but negatively related to lake water depth. The high methane production in the lake sediment was likely fueled by organic carbon loaded from surrounding peatlands to the lake. The shallowness of the water column could be another important favorable factor for methane-containing bubble formation in the sediment and their transportation to the atmosphere. The methane ebullition must have been enhanced by the low atmospheric pressure (ca. 672 hPa) in the high-altitude environment. For a better understanding on the mechanism of methane emission from alpine lakes, more lakes on the Tibetan Plateau should be studied in the future for their methane ebullition.

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1. Introduction

Methane is an important radiative trace gas, accounting for about 20% of the greenhouse effect (Cicerone, 1988; Wuebbles and Hayhoe, 2002). About 6–16% of total non-anthropogenic methane emission is thought to be contributed by lakes (Bastviken et al., 2004). It is estimated that 33–88% of the total methane in the sediment is in the gas-phase (Tokida et al., 2005a; Strack and Waddington, 2008). Since methane is continuously produced in lake sediment and is relatively insoluble in water, methane-containing bubbles are formed in pore water (Boudreau et al., 2005; Laing et al., 2008). Release of such methane-containing bubbles due to buoyancy presumably occurs when the stored gas volume exceeds some critical value (Beckwith and Baird, 2001). Methane release via bubbles (ebullition) results in direct flux of methane from the sediment to the atmosphere, with limited impact of methane oxidation in the water column, therefore ebullition is often the dominant pathway of methane release from lakes, particularly from the shallow area of lakes (Bastviken et al., 2004, 2008).

Organic matter in sediment, as the source of acetate or CO_2/H_2 for methane production, is the major producer of methane ebullition from lakes (Bastviken et al., 2008; Walter et al., 2008). Besides the major producer, one key factor influencing methane ebullition is temperature, related both to the production and solubility of methane in sediment. Another key factor is hydrostatic pressure, i.e. water depth, which is related to both bubble formation and transportation (Chanton et al., 1989; Keller and Stallard 1994; Chanton and Whiting, 1995; Bazhin, 2010). Moreover, atmospheric pressure is also regarded as an important factor controlling methane ebullition from peatland (FechnerLevy and Hemond, 1996), lakes (Wik et al., 2013), and river (Maeck et al., 2014).

Previous studies focused on methane fluxes from lakes are limited to the low-altitude regions (Bastviken et al., 2004, 2008; Engle and Melack, 2000; Walter et al., 2008), except for diffusive fluxes reported from lakes on the Colorado Rockies (Smith and Lewis, 1992) and littoral zone on the Tibetan Plateau (Chen et al. 2009). The Tibetan Plateau, which is called the "Third Pole" of the earth, encompasses a huge area of 2.5×10^6 km^2 with approximately 50,000 km^2 lake area. There are 1091 lakes larger than 1 km^2 in area, accounting for about 50% of the total lake area in China (Wang and Dou, 1998). The source strength of methane emission from lakes in this region is to date poorly studied, with the few attempts very limited in data sources, either from lakes in other regions of China (Chen et al., 2013) or from littoral zone of lakes within this region (Yang et al., 2011).

In order to understand the methane emission from lakes on the Tibetan Plateau, we chose a shallow lake here to investigate 1) the methane emission rate from the lake and the relative contribution of ebullition; 2) factors influencing methane ebullition from those lakes; and 3) the data gap for estimating the methane budget of lakes in this region.

2. Materials and methods

2.1. Lake description

Lake Medo (also called Lake Huahu), a small, shallow lake (1.6 km^2 in area with maximal depth <1 m) on Zoige Plateau (33°6′N, 102°2′E, 3430 m a.s.l.), was chosen for this study. Zoige Plateau is a basin located on the eastern edge of the Tibetan Plateau, with the lakes here undergoing a continuous water-table drawdown since 50 ka B.P. (Wu et al., 2000). During Holocene, peatlands developed extensively on this plateau, including intensive transition from lakes to peatlands (Cai et al., 1965). The Zoige Wetland was listed in the Ramsar List of Wetlands of International Importance in 2008 [http://www.ramsar.org/wetland/china]. The region is characterized by cold Tibetan climatic conditions with average annual precipitation 650 mm and air temperature 1.7 °C. Average annual atmospheric pressure and wind speed are 672 hPa and 2.4 m s^{-1}, respectively. The growing season is from May to September.

The dominant submerged plants in Lake Medo are mixed and patch-like *Ceratophyllum demersum* and *Potamogeton pectinatus*. The submerged plants fringe the open water area of Lake Medo, occupying approximately 30% of the bottom; the rest of the bottom is soft sediment. The littoral zone covers 12% of the area of Lake Medo (Chen et al., 2009). *Hippuris vulgaris*, *Carex muliensis*, *Glyceria maxima* are dominant plants in the steep littoral zone, while *Kobresia tibetica* and *Polygonum amphibium* are dominant plants in the smooth littoral zone (Fig. 1).

The catchment of Lake Medo is 275 km^2 in area and mainly covered with peatland (30%) and meadow (70%), roughly estimated from a remote sensing imagery of Google Earth. There are two visible inlets entering the Lake Medo in the east and one visible outlet in the west. Chemical characteristics of sediment in Lake Medo are shown in Table 1. More information about the lake is available in Zhu et al. (2012).

2.2. Sampling plots and gas flux measurement

Four sites (upper site, central site, down site and shore site) were chosen to monitor methane fluxes in the open water area of Lake Medo. Four plots (size 2×2 m^2, distance between plots <5 m) were set in each site. Gas fluxes were sampled once every other week or once every 20 days between May 23 and August 23, 2009.

Methane fluxes across the atmospheric-water interface were collected with floating chambers. The chamber method for gas flux monitoring is a widely used cost-efficient method with disadvantages including being instantaneous, local and isolated from the ambient environment. This study used a modified chamber placed on a buoy for floating. The chamber was a clear, close ended polycarbonate one, 40 cm in height and 30 cm in diameter, equipped with a small lateral vent stopped by silicon septum for sampling. A boat was used for transportation. On May 22, 2009 (one day before the first sampling campaign), a stick was inserted into the sediment of each plot as an anchor, which was kept throughout the whole study period. During gas sampling, the anchor and chamber was connected by a 1 m long cord. When our boat approached the chamber, we parked the boat by holding the anchor, avoiding hitting the chamber or touching the sediment in the plot. When gas sampling began, we enclosed the chamber and pulled the cord gently and kept the chamber close enough so that gas in the chamber can be sampled and therefore the disturbance of our presence to gas flux was minimized. For each sampling, four gas samples from the chamber air headspace were taken into 5 ml air tight vacuumed vials by a needle at 0, 5, 10 and 15 min after deployment. The needle inserted into the vial was 0.2 mm in diameter and 2.5 cm in length. The vials were pre-evacuated, and the residual volume in the vial was determined by sampling water instead of air into three random vials every 100 in the field (the equilibrium time was also tested). In addition, the ambient air was also sampled to determine the environmental concentration of methane. All the gas samples were collected during the period of 09:00 to 11:00 Beijing Standard Time (GMT + 8:00). All samples were transported to the laboratory in a cool box.

The methane concentration was determined by a gas chromatography (PE Clarus 500, PerkinElmer, Inc., USA), equipped with a FID (flame ionization detector) operating at 350 °C and a 2 m Porapak 80–100 Q Column. The column oven temperature was 35 °C and the carrier gas was N_2 with a flow rate of 20 cm^3 min^{-1}. The minimum detectable concentration was 1×10^{-3} μl L^{-1} (ppb). Certified methane standard in 4.9 μl L^{-1} (China National Research Center for Certified Reference Materials, Beijing) was used for calibration.

Generally, the methane emission was calculated by the temporal variation of methane concentration of chamber headspace during the sampling period. The emissions were considered as diffusive when the r^2 of linear correlation between methane concentration and the elapsed time was greater than 0.90. For r^2 below 0.90, the emissions were