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Enhanced nighttime gas emissions from a lake

E Podgrajsek, E Sahlée and A Rutgersson

Department of Earth Sciences, Air, Water, and Landscape Sciences, Uppsala University, Uppsala, Sweden

E-mail: erik.sahlee@met.uu.se

Abstract. Methane (CH₄) and carbon dioxide (CO₂) are two important greenhouse gases. Previous studies have shown that lakes can be important natural sources of atmospheric CH₄ and CO₂. It is therefore important to monitor the fluxes of these gases between lakes and the atmosphere in order to understand the processes that govern the exchange. Most previous lake flux studies are based on chamber measurements, by using the eddy covariance method, the resolution in time and in space of the fluxes is increased, which gives more information on the governing processes. Eddy covariance measurements at a Swedish lake show that both methane fluxes (FCH_4) and carbon dioxide fluxes (FCO_2) experience high nighttime fluxes for a large part of the data set (largest median $FCH_{4night} \approx 13 \text{ nmol m}^{-2} \text{ s}^{-1}$ and smallest median $FCH_{4day} \approx 4.0 \text{ nmol m}^{-2} \text{ s}^{-1}$, largest median $FCO_{2night} \approx 0.2 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$ and smallest median $FCO_{2day} \approx 0.02 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$, with larger variability during night). For the diel cycle of the CH₄ fluxes it is suggested that water side convection could enhance the transfer velocity, transport CH₄ rich water to the surface, as well as trigger ebullition. The high nighttime CO₂ fluxes could to a large extent be explained with enhanced transfer velocities due to water side convection. If gas fluxes are not measured during nighttime, when water side convection normally is generated, periods of potential high gas flux might be missed and estimations of the total amount of gas released from lakes to the atmosphere will be biased.

1. Introduction

Gas fluxes of carbon dioxide (CO₂) and methane (CH₄) are important parts in the global carbon cycle. The global carbon cycle describes how carbon is stored, processed, and transported between different domains such as the ocean, fossil fuel reservoirs, land, and atmosphere. Freshwater systems, including lakes and rivers, have long been seen as only a funnel transporting carbon from the land domain to the ocean, without processing the carbon. Today it is well known that this is not the case [1, 2]. According to Bastviken *et al.* [2] lakes can outweigh the land sink by 25% taking into account CH₄ release only.

To obtain knowledge on processes affecting the gas fluxes of CO₂ and CH₄ over the lake surface, scientists have started to use the eddy covariance (EC) technique for lake gas flux studies. The EC technique, which is frequently used for land and ocean studies, measures the fluxes continuously without much labor. Instruments measuring the turbulent fluctuations of three different wind components and the turbulent fluctuations of the gas concentration are needed when using the EC technique.

Here we present EC measurements of both CO₂ and CH₄ fluxes from one Swedish lake.



2. Methods and site

2.1. Site

The measurement site, Lake Tämnaaren, is located in central Sweden, 60°09'N, 17°20'E (figure 1). Tämnaaren is a shallow lake with a mean depth of only 1.3 m (maximum depth 2 m) and an area of 38 km². The EC tower at Lake Tämnaaren was 6 m high with three levels, 1.4, 2.7, and 6 m above ground, equipped with propeller anemometers for wind speed and wind direction (Young, MI, USA) and radiation shielded and ventilated thermocouples for measurements of air temperature. The EC instrumentation was mounted 4.7 m above ground and the instruments used were a sonic anemometer (WindMaster, Gill Instruments, Lymington, UK) to measure the three-dimensional wind components and virtual (sonic) temperature, a LI-7700 open gas analyzer for CH₄ measurements (LI-COR Inc., Lincoln, NE, USA) and an LI-7500 open-path gas analyzer for CO₂ and H₂O measurements (LI-COR Inc., Lincoln, NE, USA). The tower was positioned on a very small island in the middle of the lake with the closest shore 1 km to the southeast (figure 1). The height of the tower base is approximately 20 cm above lake surface. The entire data set used here is for the open water seasons from September 2010 to August 2012.

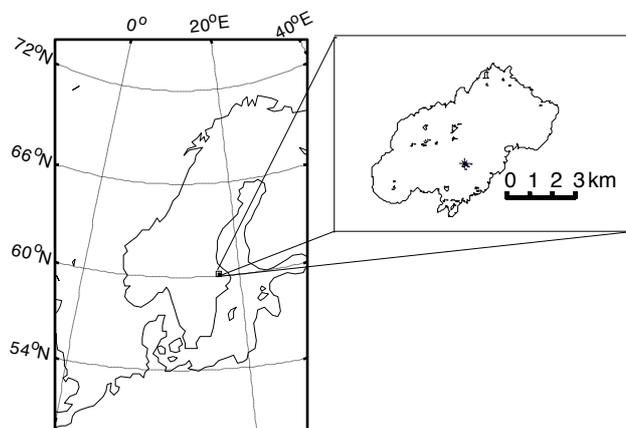


Figure 1. Left: Scandinavia and the location of the lake. Upper right: Lake Tämnaaren (60°09'N, 17°20'E) with the tower location marked with a star.

2.2. EC data treatment

The high-frequency EC data were linearly de-trended and de-spiked over 30-min periods. Prior to flux calculations the sonic data were rotated using the double rotation technique. The time lag between the gas analyzers and the sonic was typically between 0.1 and 0.2 s and was calculated with the same procedure as in Sahlée *et al.* [3]. The gas analyzers measure the molar density fluctuations of the gas. The molar density of the gas can change either if the amount of molecules is changed or if the volume changes due to pressure, temperature, and humidity variations. To take into account concentration changes that are not real changes in the gas concentration the data were corrected according to Webb *et al.* [4] with some modifications for the LI-7700 analyzer [5]. For a more detailed description of the data analysis and quality we refer to previous studies using data from the same site [6, 7, 8].

3. Results

Analyses of the daily changes of CH₄ and CO₂ fluxes (F_{CH_4} and F_{CO_2}) from Lake Tämnaaren revealed that both F_{CH_4} and F_{CO_2} were substantially higher during nighttime compared to during daytime on average. This pattern was representative for a large part of the dataset (figure 2).

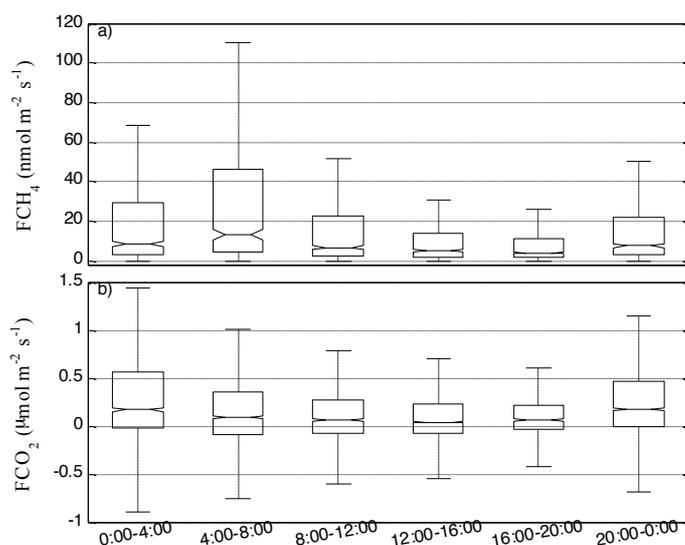


Figure 2. (a) FCH_4 and (b) FCO_2 as a function of time of day. The centerline of the notches in the boxes represent the median values, the edges of the boxes are the 25th (Q1) and 75th (Q3) percentiles, and the upper and lower whiskers represent $Q3 + 1.5(Q3 - Q1)$ and $Q1 - 1.5(Q3 - Q1)$, respectively.

Convective mixing in the water could be a possible mechanism enhancing the nighttime gas fluxes. Podgrajsek *et al.* [6] report that convection in the water might enhance FCH_4 through different mechanisms: enhancing the diffusive transport over the air-water interface, transporting CH_4 -rich water from the bottom to the surface, and triggering ebullition events (bubbles with high concentration of methane).

The diffusive gas flux of CO_2 over the air-water surface is driven by the difference of partial pressure between the water and air (ΔpCO_2), and the efficiency of the gas transfer, the transfer velocity (k): $FCO_2 = K_o \cdot k \cdot \Delta pCO_2$, where K_o is a gas specific solubility constant. During one year the water CO_2 concentration was measured continuously (every 30 min) with a Submersible Autonomous Moored Instrument (SAMI) sensor (Sunburst Sensors, MT, USA). With these water measurements and air measurements of the CO_2 concentration and FCO_2 , k_{meas} could be calculated. Normally k is parameterized with solely wind speed at 10 m. A commonly used parameterization of k for lakes is: $k_u = 2.07 + 0.215 \cdot u^{1.7}$ [9]. Podgrajsek *et al.* [8] observed that a vast amount of relatively large k_{meas} compared to k_u occurred when the water side velocity scale was large. Water side convection has previously been shown to increase the transfer velocity in marine environments [10]. Water side velocity scale is defined as $w_{w*} = (B \cdot h)^{1/3}$, where h is the mixed layer depth and B is the water side buoyancy flux defined as $B = \frac{gaQ_{eff}}{c_{pw}\rho_w}$, where g is the acceleration of gravity, a is the thermal expansion coefficient, Q_{eff} is the effective surface heat flux defined as the sum of the total heat flux, longwave radiation, and shortwave radiation, c_{pw} is the specific heat of water, and ρ_w is the density of the water [11, 12] (figure 3).

It was concluded that the high nighttime FCO_2 fluxes could to a large degree be explained with enhanced diffusive transport over the air-water interface due to water side convection [8].

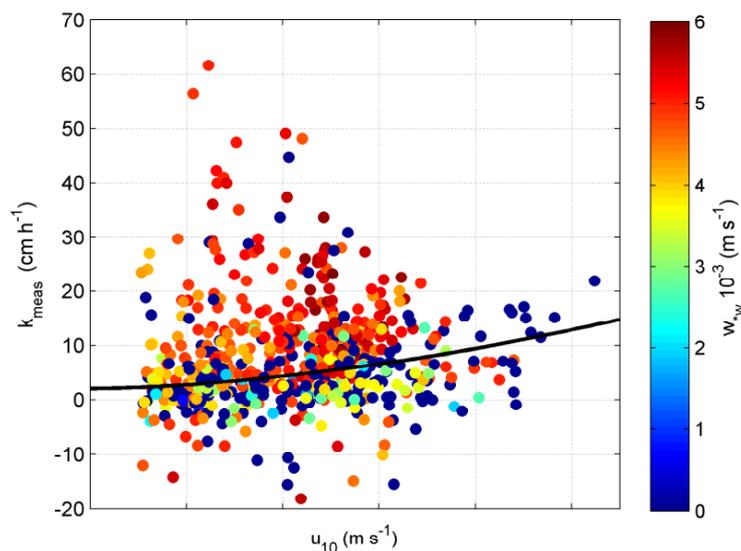


Figure 3. Transfer velocities for different wind speeds. The black line shows the parameterization from Cole and Caraco [9], k_u , and the color scale shows increasing water side velocity.

4. Summary and discussion

EC flux measurements of F_{CH_4} and F_{CO_2} from a lake in Sweden show that both gases have a diel cycle with higher values during nighttime compared to during daytime. The results show that water side convection can to a large extent explain the elevated fluxes during nighttime for both CH_4 and CO_2 . This large variability in the fluxes measured during night and day and also between weeks and seasons, emphasizes the importance of making long-term continuous measurements when estimating total CH_4 and CO_2 fluxes from lakes. If gas flux measurements are not conducted during nighttime, potential high gas flux periods might be missed and estimations of the total amount of gas released from lakes to the atmosphere will be biased.

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