PHYSICAL PROCESSES IN NATURAL WATERS: PPNW 2017

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EXTENDED ABSTRACTS

Typical seasonal transport patterns in Lake Garda

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KEYWORDS
Lake Garda; atmosphere-lake interaction; numerical modelling; transport processes; lake circulations;

Introduction

Atmospheric forcing strongly affects circulation and transport processes in lakes as wind is the major driver of water flow. It is widely recognized that disposing of a reliable representation of the wind forcing is necessary to achieve a good simulation of lake circulation patterns [e.g. Lemmin and D'Adamo, 1997]. However, the combination of complex surrounding orography and lake bathymetry may hamper the simulation of both wind field and water motion. In this respect, Lake Garda (Italy) is an extraordinary example of both aspects and represents a relevant, yet almost entirely unexplored, case study.
In this work, a link between the typical wind-driven circulation patterns in the lake and the complementary water mass transport is pursued through the analysis of the correlation between wind intensity, thermal stratification, and transport, in order to provide a first attempt towards a systematic description of the thermo-hydrodynamics of Lake Garda.

Materials and methods

Numerical experiments are performed through an off-line coupling of the hydrodynamic model Delft3D [Lesser et al., 2004] and the atmospheric model WRF [Skamarock et al., 2008]. The output from WRF simulations is given at 15 minutes intervals and at a spatial resolution of 1 km over a region containing Lake Garda. Five-day hydrodynamic simulations are run under 6 different lake and atmosphere conditions, replicating one-day wind and air pressure fields, which are interpolated over the lake grid as space and time varying boundary conditions. The hydrodynamic grid has a resolution varying from 130 m in the northern narrow part to 400 m in the southern wider part. Fixed layers are built along the vertical with increasing thickness from the top layer (1 m) to the bottom layer (50 m), and initial condition are set using a horizontally uniform temperature profile obtained from measurements.
The analysis is carried out evaluating residual circulations defined as an average over the time of the daily velocity field after a spin up time of 2 days, and quantifying the transport as the volume of water passing through reference vertical cross sections. The effects of wind forcing, stratification conditions, and Earth rotation on the development of transport processes in the different parts of the lake and in time are investigated through a correlation analysis.

Results and discussion

Results obtained by numerical simulations show that space and time variability of the wind field has a key role in the development of transport processes in Lake Garda. In nearly unstratified thermal conditions and under the forcing of a synoptic uniform and constant Fohen wind (winter), surface water is channelled between the steep shores in the northern narrow part towards the southern wider part (Fig. 1a). Earth rotation causes a deviation of the flow to the right relative to the wind direction and downwelling along the western shore.

Under an alternating wind field (typical of the summer season) surface currents produce residual gyre patterns (Fig. 1b and c). In the northern part of the lake the Peler morning breeze moves water northward, while the Ora del Garda afternoon wind blows southward: such a regular and uniformly distributed alternation of wind fields combines to the acceleration of the right-hand side surface flows induced by Coriolis force to produce a cyclonic gyre as a residual outcome.

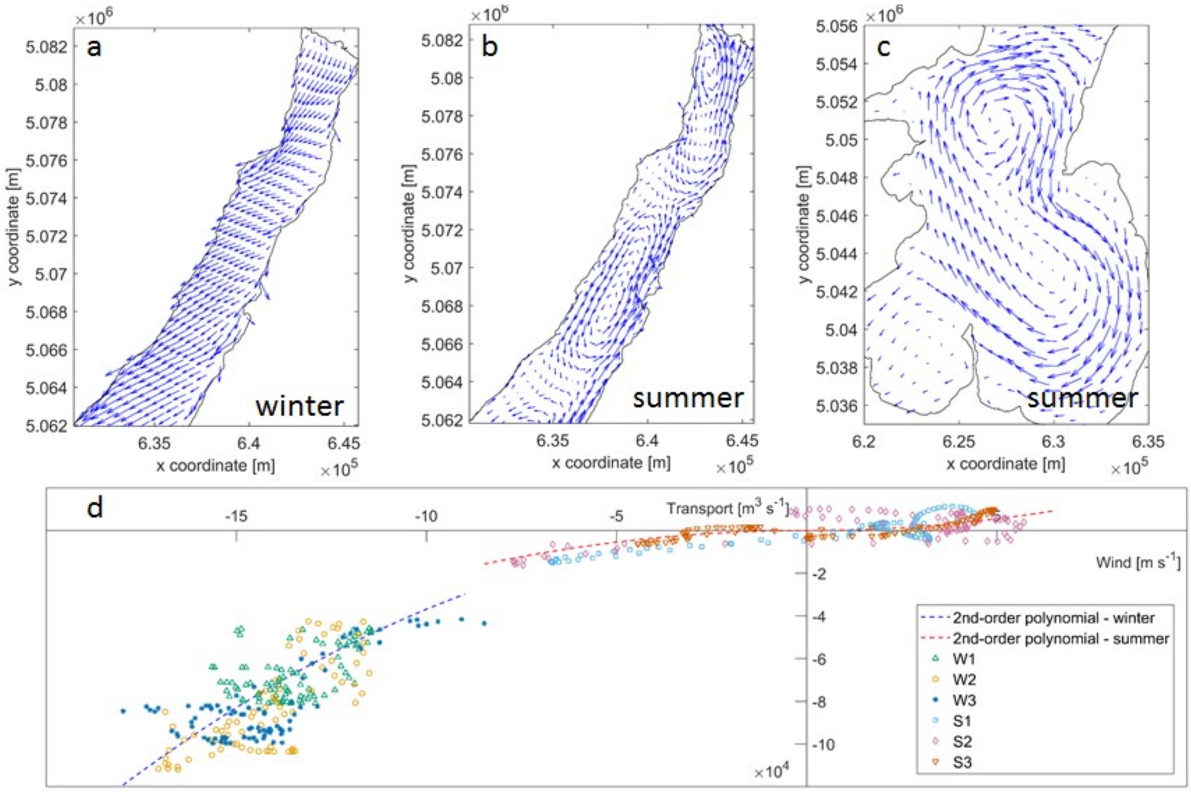

Figure 1 Residual surface circulations in Lake Garda in a winter (a) and summer case (b and c); (d) relationship between wind intensity and total lateral transport for all seasonal simulations.

Hence, both in winter and summer cases, Earth rotation strongly affects transport deviating the surface water current to the right with respect to the along-axis wind direction.
A quadratic dependence of lateral transport as a function of wind speed holds both for winter and summer simulations (Fig. 1d), with different proportionality coefficient, due to the effects of thermal stratification on the thickness of the well mixed layer and on the magnitude of eddy viscosity. Maximum cross-correlation shows that the inertia of the lake delays water transport behind the wind forcing. Such a delay is more relevant in winter when the thickness of the surface layer is larger due to the lower stratification, whereas hysteretic paths are drawn in summer because of the alternating direction of wind.

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Impact of bubble plume aeration system on manganese cycling in Blagdon Reservoir, South West, UK

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KEYWORDS
Water quality; Manganese; drinking water reservoir; bubble plumes.

EXTENDED ABSTRACT

Introduction

Within the UK, millions of £ are spent annually by drinking water utilities to address customer complaints with taste and odor problems stemming from excess manganese, Mn, (e.g., brownish-colored, metallic-tasting drinking water). In the South West UK, Mn is geologic and sedimentary and its transport within drinking water supply reservoir is largely controlled by levels of oxygen concentrations (O_2). Removal of Mn for meeting the UK drinking water limit (50 μg/L) is often difficult and costly using conventional water treatment processes due to complexity of Mn redox kinetics that can create challenges for water utilities. Thus, in the UK, many water utilities are using bubble plumes to destratify the water column and replenish O_2 in the hypolimnion to improve the source water quality prior to treatment plant intake, which ideally minimizes the level of the required treatment in the plant. O_2 concentration plays an important role to oxidize the soluble Mn in the water column to insoluble particulate manganese dioxide (MnO_2) that precipitate to the sediment, thereby removing the Mn from the water column and treatment plant influent.

Materials and methods

This study was performed on Blagdon Lake, which is a man-made drinking water reservoir of 1.78 km^2 in surface area, created by Bristol Water utility with the maximum depth of 12 m near the dam and average depth of 4.3 m. To tackle the high Mn and algae concentrations in the reservoir, seven bubble plums were installed which are in operation throughout the summer stratification period (April- October). Field work including Mn and O_2 concentration measurements in the water column and sediment covering the spatial distribution of Mn throughout the reservoir were performed (April- October 2017) to investigate the efficiency of the aeration system. Sampling strategy involved YSI castaway CTD and YSI EXO1 water-column profiling. Water column sampling in 2 meter increments were done using Von Dorn water sampler for (1) subsequent O_2 concentration measurements via Winkler titration method and (2) total and soluble Mn concentration measurements at the same day via inductively coupled plasma spectroscopy; ICP-MS. Sediment samples were taken using Uwitec sediment corer and sent to the laboratory to determine total manganese and total organic carbon TOC (indicative of precipitated algal biomass) via inductively coupled plasma; ICP and acid digestion.

Results and discussion

Despite the aeration systems, the problem with high concentrations of Mn still persist, average of total Mn concentration near the dam was 139 μg/L and farther away at the back of the reservoir was 36 μg/L. Results will be presented from summer 2016 and 2017. Preliminary data suggest that while O_2 remains high throughout the reservoir, increased mixing actually results in increased levels of Mn near the aeration systems, contrary to management goals.

Assessments of lake indices through a comparison between tropical and subtropical shallow lakes

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KEYWORDS
Lakes; lakes indices, high frequency measurements; lake's hydrodynamic.

EXTENDED ABSTRACT

Introduction

Lake indices such as Lake number, Schimidt Stability, Wedderburn number and others has been frequently used to evaluate and predict waterbody's stratification behavior due to meteorological and climate conditions. Small and shallow lakes are particularly affected in terms of their water quality by onset and mixing episodes related to energy incidence and winds. High resolution measurements of water column temperature and atmospheric variables like air temperature, radiation, precipitation and wind components can be employed to characterize and predict dangerous events that affect aquatic life, water supply systems operations, recreation and others water uses. The aim of this article is to assess computed lake indices along onset and mixing events in shallow lakes and correlate them with main atmospheric driving forces.

Materials and methods

Two size comparable lakes in two different climate regions were considered: Lake Créteil, situated in Paris surroundings, France (Soulignac *et al*., 2017), and Hedberg Reservoir, located 10 km from the City of Sorocaba, Sao Paulo State , Brazil (Smith *et al*., 2013). Both water bodies were monitored along the year 2016 using high time resolution meteorological variables and water temperature instruments.

Lake indices (Lake number (Ln), Schimidt Stability (St), and Wedderburn number (W) were computed for the year of 2016 using Lake Analyzer (Read *et al*., 2011), an numerical application based on indices formulations as follow (Hutchinson, 1957; Thompson e Imberger, 1980):

$$S_T = \frac{g}{A_s}\int_0^{z_D}(z - z_v)\rho_z A_z \partial_z \,;\, L_N = \frac{S_T(z_e+z_h)}{2\rho_h u_*^2 {A_s}^{1/2} Z_v} \,;\, W = \frac{g' z_e^2}{u_*^2 L_s} \,,$$

where g'= g . $\Delta\rho/\rho_h$, ρ_h is the hypolimnion density and g is the gravity acceleration, z_e is the depth of the mixed layer, L_s is the lake fetch length, u_* is the water friction velocity due the wind stress, A_s is the lake area at surface, A_z is the area at depth z, z_D is the maximum depth of the lake, z_v is the centre volume depth, computed as the volume weighted depth, z_e and z_h are the depths to the top and bottom of the metalimnion.

The resulting indices were correlated with the radiation and wind speed driving forces considering stratified and mixed conditions. A filter was applied to consider only 10% higher values to prevent biases due to errors in the indices determinations.

Results and discussion

With the proposed correlations, wind mixing forces are crossed with the warming energy provide by the solar radiation, both considered in the lake indices and the mixing status. The use of those indexes is limited when a comparison between different lakes is aimed because each one has a specific range for the indexes values during mixed and stratified situations. Thus, combining wind and radiation to specific mixing behaviour in similar lakes makes possible to draw a forecast chart of lake type thermal behaviour.

The assessments show that for Lake Number and Wedderburn Number there's a significant correlation between the indices and the driving forces. Plots on Figure 1 show a stratified band with low wind speed (0-1,7 $m.s^{-1}$), a transitional band with the wind speed between 1,8 and 3,5 $m.s^{-1}$, and a mixed band with wind speed higher than 3,5 $m.s^{-1}$ are identified. For Schmidt Stability number the correlations are not so significant.

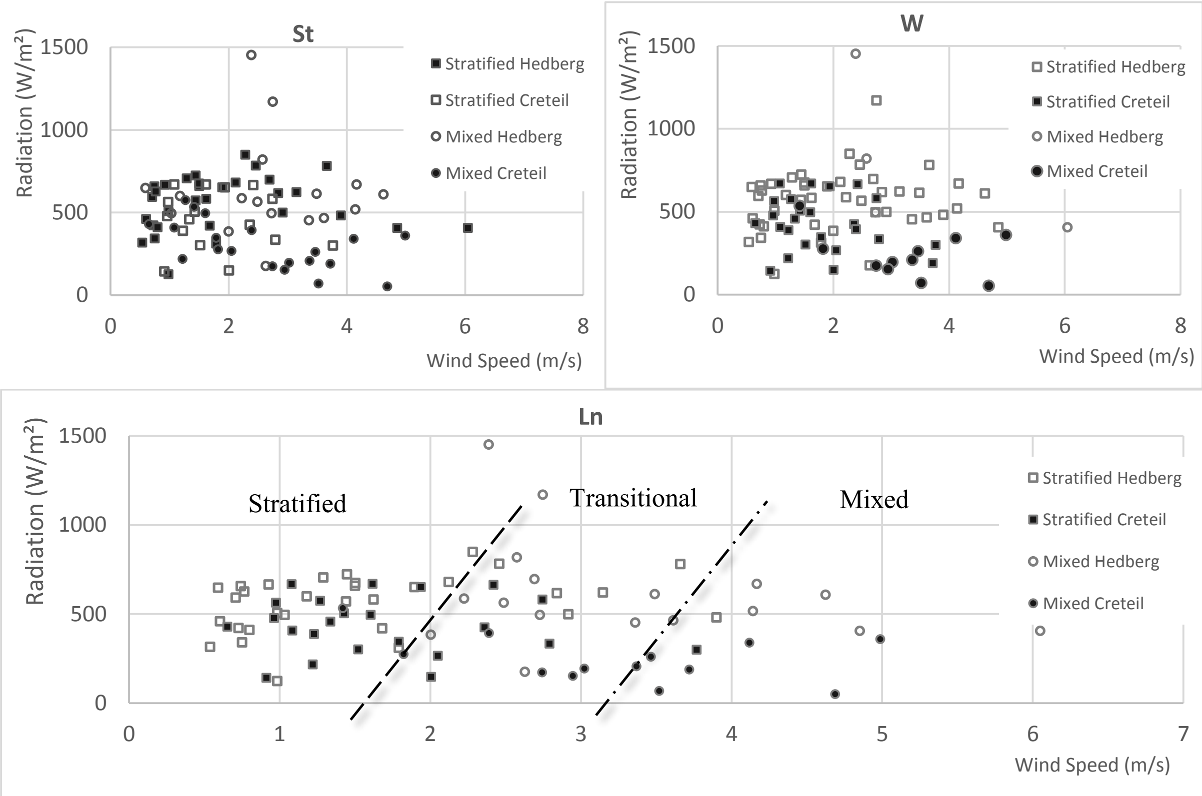

Figure 1. Correlation between the indices (Schmidt Stability – St; Wedderburn Number – W; Lake Number - Ln), and the proposed band division for small lakes.

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Methane storage and ebullition from monimolimnetic waters of polluted mine pit lake Vollert-Sued in Germany

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KEYWORDS
Dissolved gas, gas pressure, meromixis, ebullition

EXTENDED ABSTRACT

Text

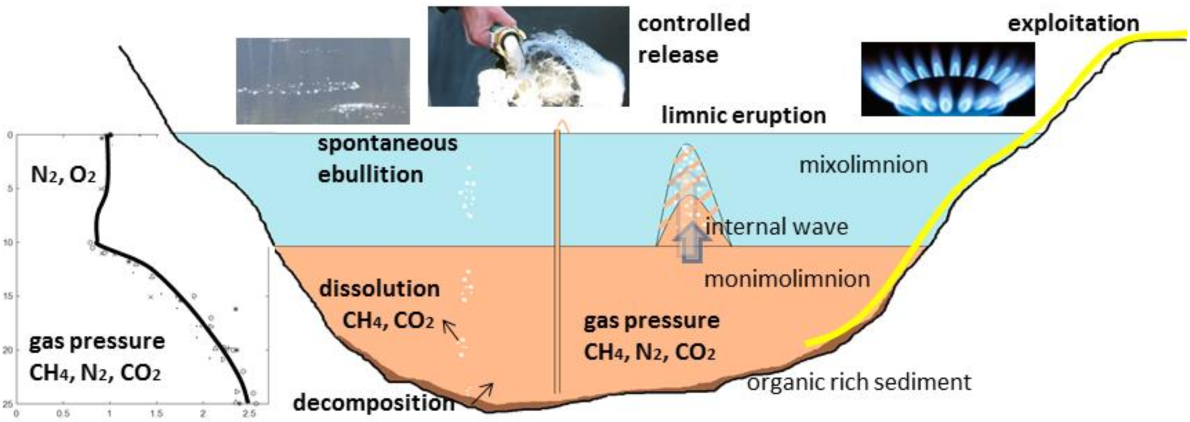

Fig. 1. Possible pathways for the loss of dissolved gas from the deep waters of a meromictic lake (from [2])

Reliable gas measurements from supersaturated deep waters still remain a challenge. However, good information is mandatory to investigate the limnic carbon cycle, assess the endangerment through limnic eruptions and evaluate a potential source of exploitable energy. We addressed these three points in a heavily polluted mine pit lake in Germany [2]. We quantified the ebullition of methane from deep waters and the sediment below. Exposed to continuous percolation of gas bubbles, the deep (monimolimnetic) water had accumulated high concentrations of gas: directly measured gas pressures indicated the proximity to spontaneous ebullition [1]. Consequently, the possibility of a limnic eruption was assessed by initiating a self-sustained flow through a vertical pipe. Despite the high gas pressures, the flow was slow and the endangerment was considered low. A sampling strategy with bags was developed to achieve a reliable measurement of gas content and gas composition in the monimolimnion. As a result, directly measured gas pressures could be confirmed and were nearly exclusively attributed to methane and nitrogen. Contrary to lakes that had shown limnic eruptions, carbon dioxide played a much subordinate role, and hence the driving force for a violent outburst of gases was missing. Nevertheless the amount of dissolved methane was remarkably high. This presentation closes with some estimates of the commercial value of the deposit and limiting conditions for a possible exploitation.

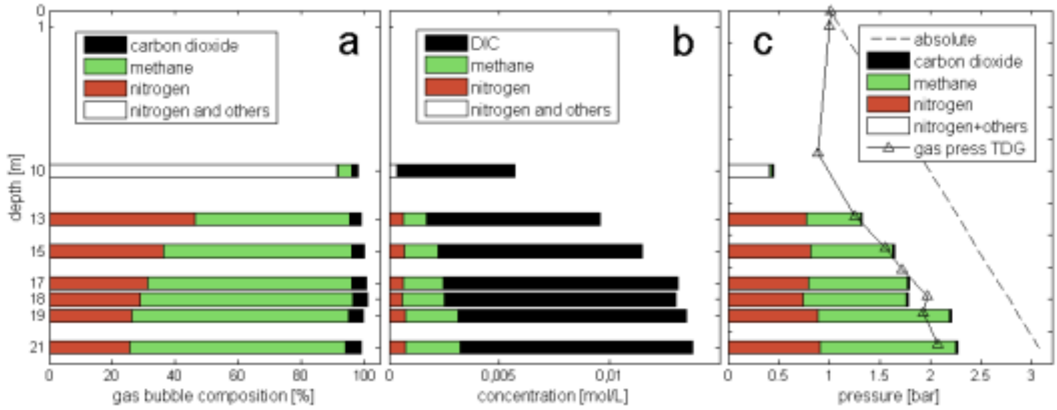

Fig. 1. (a) Measured gas concentration in the gas bubble of samples versus depth (b) calculated gas concentration in the lake (c) gas pressures based on gas concentration compared with direct gas pressure measurements (from [2]).

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Structural and dynamical parameters of the convectively-mixed layer in a shallow ice-covered lake

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KEYWORDS
Ice-covered lakes; convection; convective layer structure; convective cells dynamic.

Introduction

The onset and development of radiatively-driven convection in a shallow ice-covered lake play an essential role in the winter genesis of boreal lake ecosystems. The theoretical aspects of the problem remain also challenging as conjugated with some fundamental properties of fully developed turbulence. A number of papers devoted to this phenomenon is rather restricted (see [Mironov et al., 2002] for references), and available experimental data are rather limited. In particular, nor the detailed description of the structure, neither the common vision of its driving mechanisms is not yet finally established.

Materials and methods

We present the attempt to reconstruct the qualitative picture of the convective layer, based on analysis of data on velocity fields. The experiment was carried out during 8-13 April 2016 on boreal Lake Vendyurskoe, Russia. The Aquadopp HR-profiler was used for measuring all three velocity components in the 2-m under-ice layer.

Results and discussion

The key experimental findings are listed below.

- The progressive-vector diagram (Fig. 1) strongly indicates the presence of large scale circulation with velocities of order 1 mm/c and rather stable direction. One cannot exclude that this large-scale motion is the relict of marginal heating – induced circulation as was discussed in [Huttula et al., 2010; Kirillin et al., 2015].

- The intensities of pulsations oscillate with a period close to 3-5 hours, but the shape of oscillations are far from sinusoidal and resemble relaxation ones with piecewise-linear fragments.

- Horizontal velocity probability density distribution on azimuthal direction clearly reveals the distinguishable peaks with angular distance between them close to $\pi/2$.

- The radiation does not affect crucially the dynamics of horizontal velocities, while the vertical component is suppressed by 1-2 orders in the night.

- The system trajectories on Lumley triangle (Reynolds stress invariant map) reveal the 2D character of structures by night. During daytime, as shown in the Figure 2, the trajectory point moves toward prolate axisymmetric limiting curve and later, in the evening – to oblate axisymmetric one.

To explain these features we suppose that the convectively-mixed layer constitutes the system of eddies rotating in horizontal plane with imposed large-scale circulation. The radiation flux makes the system more complicated due to the onset of additional circulation in a vertical plane. At night the cells survive mostly due to their 2D structure. Besides, their turnover time is comparable with a radiation-free interval.

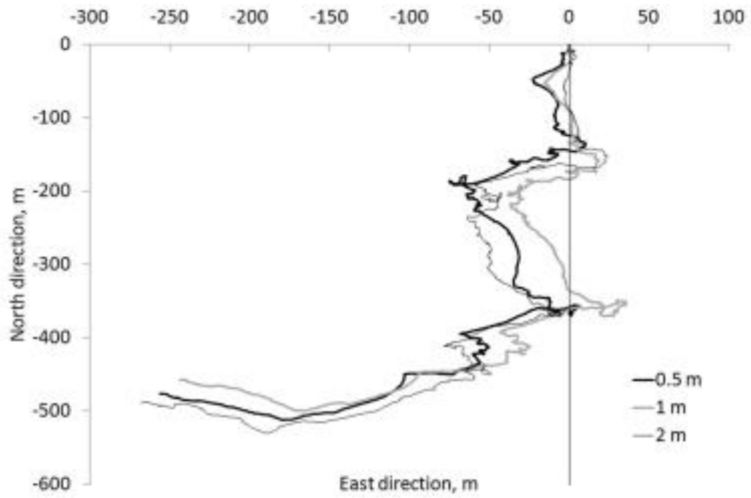

Fig. 1. Progressive-vector diagram for different depths; 8-13 April 2016.

As for velocity jumps and piecewise-linear character of dynamical curves, they both find the simple explanation as a result of passing cyclone-anticyclone cells sequence across the sensor.

Taking this qualitative picture as the basis it becomes possible to estimate such important parameters as cells size and rotation velocities. More sophisticated statistical analysis can shed a light on the time dependence of these parameters and some details of cells geometry.

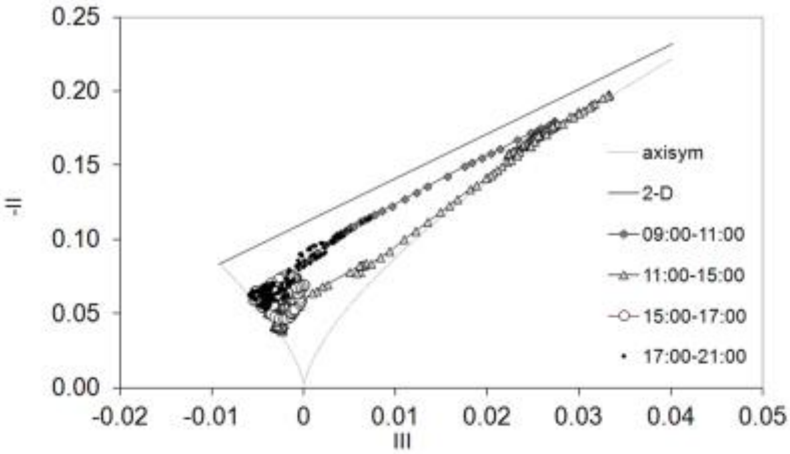

Fig. 2. Vizualization of turbulence evolution during daytime with Reynolds stress invariant map. April 10 2016. Depth - 1 m.

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Boundary layer under an ice-covered lake

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KEYWORDS
Ice-covered lakes; boundary layer; winter limnology.

Introduction

In late winter, the increase in daytime duration and solar radiation can set thermal conditions for driving a convective mixed layer under ice-covered lakes (Kirillin et al. 2012). This convective layer has been widely studied (Mironov et al. 2002; Jonas et al. 2003; Bouffard et al. 2016), and the associated enhanced turbulence is thought to allow early life growth in this layer by balancing the sinking rate of non-motile phytoplankton (Kelley 1997). The boundary layer that separates the ice from the mixed layer is also the place where biological activity has been observed (Hampton et al. 2015). The physical properties of this type of boundary layer remain largely unexplored and strongly differ from the ocean environment case where salinity plays a significant role. This study aims at investigating the dynamic of the under-ice boundary layer at diurnal scale.

Materials and methods

Two field campaigns of measurements were conducted in March 2016 and 2017 in Lake Onego (Russia) with the goal, among others, to measure the temporal evolution of the under-ice boundary layer. A set of 20 TR-1060 RBR temperature loggers were deployed just below the ice with a vertical spacing of 1.5 cm (30 cm long mooring). In order to avoid contamination, the mooring was displaced away from the drilled hole in the ice cover, and the hole was carefully closed with ice. The loggers were recording at 1Hz during one week. A downward looking 600 kHz RDI-Teledyne ADCP was deployed 20 m away. The ADCP recorded in pulse coherent mode (Mode 11) with 5 cm bin size resolution from 25 cm below the ice to 8 m deep. Additionally, the same instrument setup used by Bouffard et al. (2016) was deployed in the observational site, including a meteorological station, long thermistor chains, hourly CTD, and a PAR sensor chain.

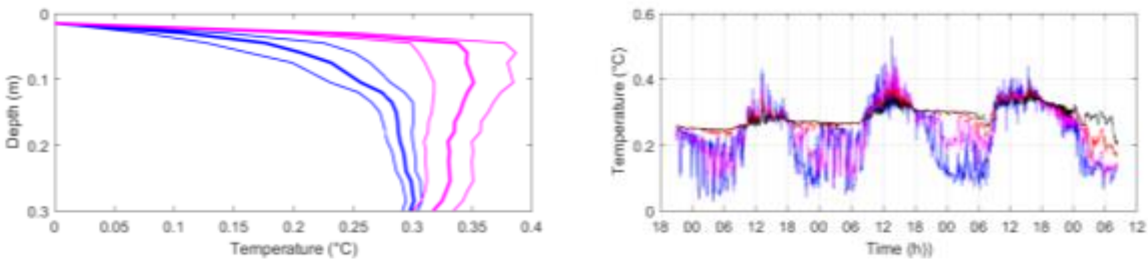

Figure 1: a) Mean and standard deviation temperature profile during day (pink color) and night time (blue color). b) 3 days time series of temperature in the under-ice boundary layer recorded at 3 (blue), 7.5 (pink), 16.5 (red)

and 30 (black) cm under the ice. Note (i) daily fluctuations, (ii) high-frequency fluctuations, and (iii) day time unstable profiles.

Results and discussion

The under-ice boundary layer (UIBL) exhibits a clear diurnal variability as shown in Figure 1. The night time-averaged UIBL profile is simply described by a diffusive thermal layer subjects to a top ice-temperature boundary condition, $T_i = 0$ °C, and a lower limit temperature boundary condition, $T_m \approx 0.3$ °C, set in the upper convective mixed layer during the day before. The layer shows significant variability, and we could correlate the squeezing of the layer to an increase in the horizontal current. The day time-averaged UIBL is characterized by a stable very thin diffusive layer (~10 mm) that separates the ice from a maximum temperature, and is followed by an unstable ~10-20 cm thick layer. Then, the vertical temperature gradient flattens defining the classical mixed convective layer (Figure 1). This diurnal thermal structure can be explained as a balance between vertical diffusion and the buoyancy flux with an exponential decay,

$$\kappa \frac{d^2T}{dz^2} \sim \frac{dI}{dz}, \qquad (1)$$

where $I(z) = (E_0^-/\rho_0 c_p)e^{\gamma z}$ is the kinematic radiation flux, E_0^- is the under-ice incident solar irradiance, $\rho_0 = 1000$ kg m^{-3} the reference density, $c_p = 4.2 \times 10^3$ J kg^{-1} K^{-1} the specific heat of water at constant temperature, γ the extinction coefficient of radiation flux through the water column, and κ, the molecular diffusivity
Assuming (1) in the energy equation, we can solve the thermal structure, $T(z)$, in the diffusive region, by constraining the differential equation to two boundary conditions, $T = 0$ °C at $z = 0$, while the lower boundary condition is characterized by a fixed temperature, $T = T_m > T_i$ at certain $z = \delta$. By setting this second boundary condition, we allow the thermal structure to generate changes in stability through the diffusive region.

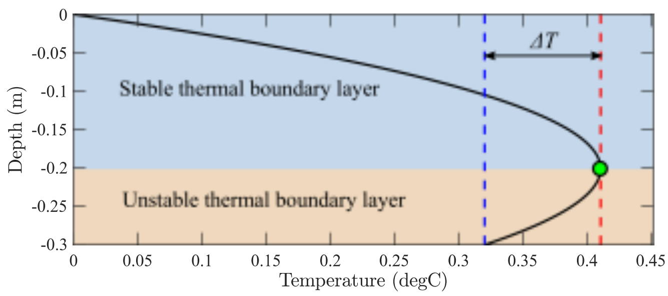

Figure 2: theoretical thermal profile during daytime under ice-covered water and forced by a kinetic radiation flux, $I_0 = (E_0^-/C_p\rho_0) \approx 5 \times 10^{-6}$ K m s^{-1}, and an extension coefficient, $\gamma \approx 1$ m^{-1}. The boundary conditions are $T_i(z = 0) = 0$ °C and $T_m(z_m = 0.3\ m) = 0.32$ °C.

Figure 2 shows the theoretical thermal profile under the ice cover obtained by adopting reference values for the kinematic radiation flux, $I_0 = 5 \times 10^{-6}$ K m s^{-1}, the extinction coefficient, $\gamma \approx 1$ m^{-1}, and temperature boundary conditions $T_i(z = 0) = 0$ °C and $T_m(z_m = 0.3\text{ m}) = 0.32$ °C. The profile is characterized by a upper stable thermal layer $\delta_s \approx 20$ cm and a lower unstable layer, $\delta_u \approx 10$ cm. The theoretical profile predicts a maximum unstable vertical temperature difference of $\Delta T = T_{max} - T_m \approx 0.09$ °C, over a vertical distance $h_{\Delta T} \approx 0.1$ m. If we define the Rayleigh number as $Ra = \alpha g \Delta T h^3/\kappa\nu$, with α the thermal expansion coefficient, κ the thermal diffusivity coefficient, and ν the kinematic viscosity, we obtain a value of $Ra \approx 4.3 \times 10^5$, which is much higher than the canonical critical value for free boundary conditions (stress-free rather than no-slip at the walls), $Ra_C = 675$ (Rayleigh 1916). This theoretical result shows that the unstable thermal layer leads to free convection and it should be an active source of convective induced turbulence and mixing. Vertical mixing should reduce ΔT ($\Delta T_{obs} \approx 0.01$ °C) but also it should reduce/squeeze the thickness of the upper stable layer as a consequence of buoyancy flux.

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Decoupling the combined effects of trophic state recovery and climate change on Lake Hallwil water column structure

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KEYWORDS
Lake restoration; climate change; thermal stability; Secchi depth

EXTENDED ABSTRACT

Introduction

The effects and feedbacks of climate change on lake physics and ecological functioning are still largely uncertain. Recently, Schmid et al. (2014) predicted anomalies in lake surface equilibrium temperature in the range of 2–5°C by the end of the 21st century, as a response to climate change. Warming of surface waters strengthens thermal stratification (Rempfer et al., 2010), which leads to reduced mixing. Since a small light penetration has the effect of shoaling and strengthening the thermocline, numerous authors suggests that global warming leads to a eutrophication effect on lake ecosystems (e.g. Johnk et al., 2008). However, interpreting these effects from long temporal meta-analysis is complicated by the lakes changing trophic state over the evaluated timeframe (Flaim et al., 2016).

After the drastic reduction in phosphorous load in the past 30 years, many lakes (mainly in North America and central Europe) are going through the process of re-oligotrophication (Jeppensen et al., 2005). In most cases, this has led to improved water transparency with possibly major effects on the mixing regime by 1) deepening the thermocline depth and 2) weakening the water column stability that would both counteract the eutrophication due to warmer temperatures.

Since becoming highly eutrophic in the 1970's, Lake Hallwil has undergone intensive restoration measures. Because of these measures, the light regime has dramatically improved since around 2000. During this time, summer Secchi depths have increased from about 2 m in 1999 to 6 meters today. In this work, we will investigate the effects of changing light regime to the lake hydrodynamics, and compare these in context of a warming climate.

Materials and methods

We analysed the response of the hydrodynamic model CE-QUAL-W2 (Cole and Wells, 2000) to a range of Secchi depths (SD) applied to Lake Hallwil (Switzerland, 10.2 km^2, maximum depth of 46.5 m) for the period April-December 2001. Climate forcing is resolved from 1-hr resolution data from Aarau/Buch meteo station. The applied SD of 1, 2, 4, 6 m correspond to decreasing light extinctions coefficients γ of 1.7, 0.85, 0.45, 0.28 m^{-1} respectively estimated by $\gamma \approx 1.7/SD$ (Wetzel 1983). These Secchi depths were in the reported ranges in Lake Hallwil during the re-oligrotrophication process from 1987 to 2016. To test the different responses to eutrophic and oligotrophic lake scenarios to climate change, we run the same simulations with an increase of 2 °C on the air temperature over the analysed period.

Results and discussion

Our results on the effect of light extinction on thermocline depth and surface temperatures are consistent with earlier studies (Rinke et al., 2010, Flaim et al., 2016). We found that increasing the SD in Lake Hallwil leads to an increased mixing depth (Fig 1a). Surprisingly, both higher and lower surface temperatures are observed at higher SD, depending on the heating/cooling phase of the lake. During stable stratification, surface temperatures decrease with increasing SD, while during the onset of fall turnover, surfaces temperatures tend to be warmer with increasing SD. This is because decreased SDs are associated with a reduced overall heat transport into the waterbody (Tanentzap et al., 2008).

We tested the stability of the thermocline at a given SD, and the effect of an air temperature increase by 2°C. By far, the SD had the largest influence on the lake thermal structure. Increasing the SD depth produced a significantly weaker N^2, and a deeper N^2 maximum. The effect of increasing SD can actually then compensate for atmospheric warming. Assuming the Secchi as a proxy for trophic state, we can infer that under such a scenario (plus 2°C), a meso-oligotrophic lake (SD = 6 m) would not experience any heat driven shoaling of thermocline nor a significant increase in thermal stability (Fig.1b). However, even at SD of 6 m, eutrophication effects as a response to increased air temperatures may be due to phytoplankton blooms triggered by the warmer lake surface temperature. While mixing depth and density gradient (N^2) exert important controls on phytoplankton, feedbacks are complex to predict, as they are depending on site-specific algal functional traits (light inhibition, buoyancy capacities). In Lake Hallwil, the thermocline location and stability have a critical influence on the habitat of the toxic cyanobacteria *P. rubescens* (See abstract Ahnlund-McElgunn et al., this issue).

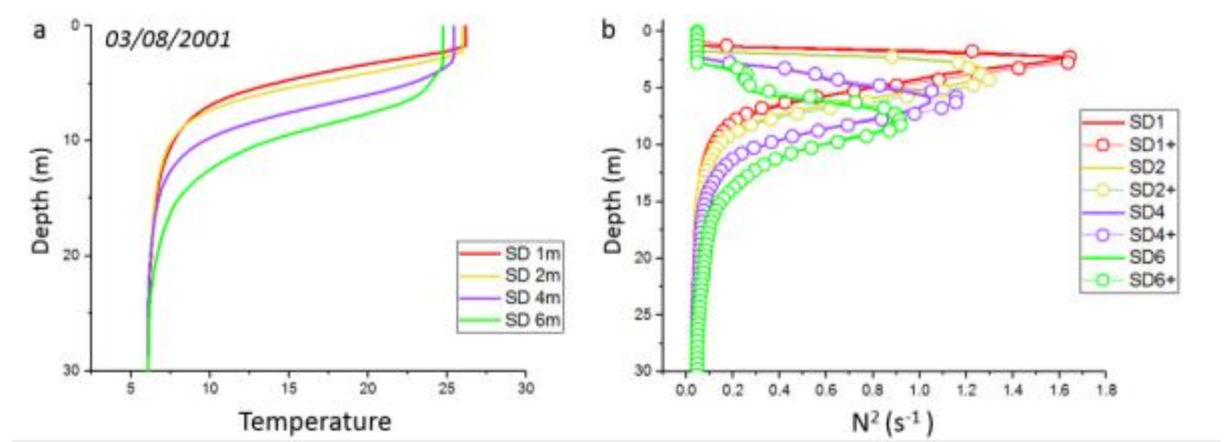

Fig. 1 Lake Hallwil top 30 meters on 3 August 2001. a) Temperature profiles at increasing water transparency. b) N^2 profiles for increasing water transparencies (solid line) and for the same at an air temperature increased by 2°C over the analysed period (April-December 2001).

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Where does methane come from and where does it go? New insights in aquatic methane research

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KEYWORDS
Methane; lakes; headwater streams; terrestrial-aquatic coupling; DOC quality.

EXTENDED ABSTRACT

Overview

Realizing the effect of methane (CH_4) on climate change pushed scientific studies about CH_4 in aquatic water bodies forward and publications tripled from about 100 to 300 per year during the past 10 years. CH_4 is a potent greenhouse gas and is about 34x stronger than CO_2 on a 100 year basis [*IPCC*, 2013]. Methane production is mostly dependent on the amount and the freshness of organic matter available for degradation [*Flury et al.*, 2016] and it is produced at the end of the redox chain during organic matter degradation. In aquatic systems it is known to be produced mainly in sediments under anoxic conditions from either acetate or carbon dioxide (CO_2) as the final electron acceptors. Once, enough CH_4 has accumulated and the total gas pressure exceeds the hydrostatic pressure it may accumulate as free gas in the sediment. Besides diffusing out of the sediment (Fig. 1), pressure drops and shear stress can result in massive bubble release from the sediment [*Joyce and Jewell*, 2003; *Maeck et al.*, 2014] [up to 240 mmol m-2 d-1 in an impounded river - *Maeck et al.*, 2014] and transform aquatic waterbodies into strong greenhouse gas sources. Another effective CH_4 release pathway from sediments in shallow areas is through advective transport of CH_4 gas in aquatic vascular plants (Fig. 1). This pathway can account for a substantial fraction of CH_4 emissions from aquatic systems [*Flury et al.*, 2010; *Sorrell and Boon*, 1994]. However the relative importance of the emission pathways, strongly depends on the biomass and density of the macrophytes [e.g. *Cheng et al.*, 2007; *Grünfeld and Brix*, 1999] and on the physical properties (e.g. lake size, depth, pressure fluctuations) of the system [*Bastviken et al.*, 2004; *Maeck et al.*, 2014; *McGinnis et al.*, 2006]. Diffusive emissions from the water column into the atmosphere have been suggested to be exacerbated by microbubbles [*McGinnis et al.*, 2015; *Prairie and del Giorgio*, 2013] (Fig. 1). Furthermore, very recent studies suggest a considerable contribution to diffusive CH_4 emissions into the atmosphere from CH_4 that is apparently produced in lake surface layers under oxic conditions [*Bogard et al.*, 2014; *Grossart et al.*, 2011; *Tang et al.*, 2016] (Fig. 1). There are a few theories how the presence of rather high CH_4 concentrations under oxic conditions could be explained: a) CH_4 is produced in anoxic micro-niches [*Grossart et al.*, 2011; *Oremland*, 1979], from algal metabolites [*Lenhart et al.*, 2016] or as a by-product of methylphosphonate decomposition by P-starved bacteria [*Karl et al.*, 2008; *Yao et al.*, 2016] or its oxidation is inhibited by light [*Murase and Sugimoto*, 2005]. Although no clear answer could yet be provided to that paradox, the oxic methane occurrence was recognized as an additional potential CH_4 source from lakes placed close to the water-atmosphere interface [*Tang et al.*, 2016].

While knowledge about the methane cycling is rather advanced for lentic systems it is still in its infancy for rivers and especially in headwater streams. In larger lakes organic carbon originates mainly from internal aquatic primary production, while the terrestrial-aquatic coupling is much more pronounced in streams [*Brett et al.*, 2017]. Thus stream metabolism is heavily subsidized by the organic carbon from the adjacent terrestrial areas. The quantity and quality of organic matter transported to the streams largely depends on the land-use [*Brett et al.*, 2017]. For example it is well known that soil compaction by animal trampling reduces soil percolation, but increases surface run-off [*Alderfer and Robinson*, 1947; *Pietola et al.*, 2005]. The latter is additionally affected by the vegetation [*Russell and Bisinger*, 2015].

In a recent study we investigated the controlling factors for CH_4 cycling in headwater streams under the influence of different cattle grazing intensities in the Swiss Alps. In contrary to our expectations we observed reduced yields of dissolved organic carbon and dissolved inorganic nitrogen with increased grazing intensities. Furthermore, grazing intensities also affected some of the DOC quality indices towards more fresh/autochthonous produced organic matter (BIX and Coble peak ratio C:T). PCA analysis suggests that CH_4 loads are partly controlled by delivery of organic carbon and nutrients to the streams and by DOC qualities; however the lower the quality the higher the CH_4 load seemed to be (Fig. 2). CH_4 concentrations in these alpine streams were high and in the range of surface water concentrations in lakes (0.1-11 umol L^{-1}) despite oxygen saturation. A back on the envelope estimate suggests that CH_4 outgassing from headwater streams can be in the order of hydropower dams from lowland rivers and lakes, thus revealing their potential as strong greenhouse gas emitters. Furthermore, the occurrence of high CH_4 concentrations in headwater streams under oxic conditions reveals a similar methane paradox as is currently under heavy debate for lakes.

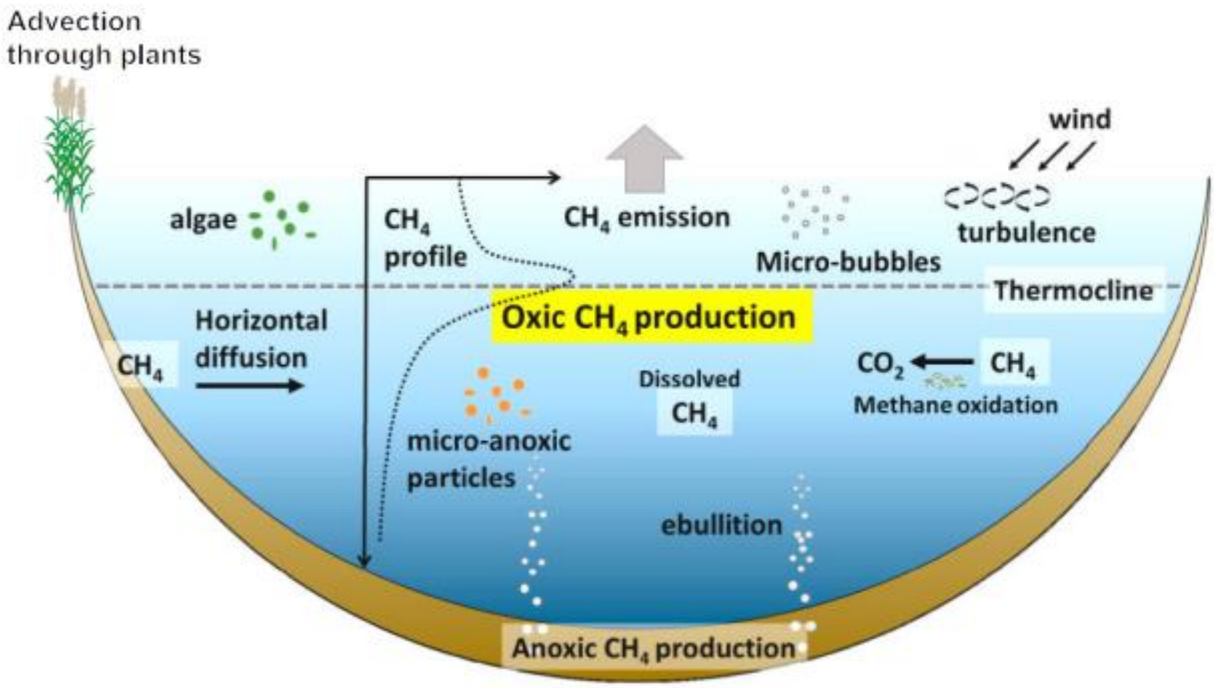

Fig. 1. Schematics of emission pathways including the oxic methane production paradox (figure taken from Tang et al. 2016).

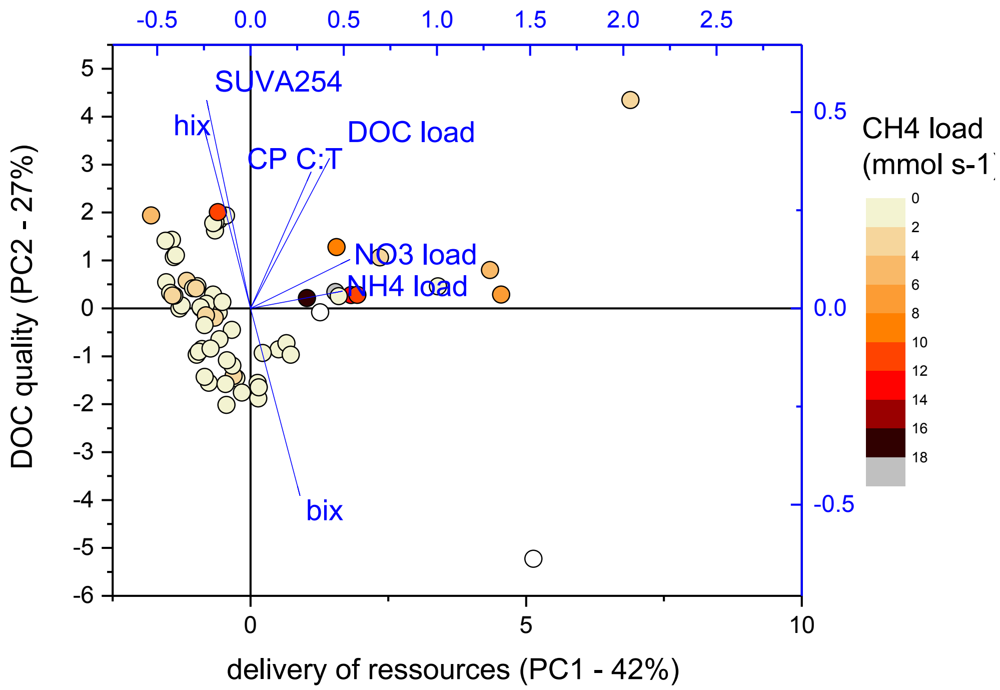

Fig. 2. PCA analysis of driving factors for methane occurrence in 16 headwater streams in the Swiss Alps (own data).

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Analysis of the layer structure of thermal microstructure profiles of stratified lakes: new insights into vertical fluxes?

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KEYWORDS
Lakes; stratification; mixing; thermal microstructure; turbulence

EXTENDED ABSTRACT

Introduction

Thermal microstructure profiling has been an established technique for investigating mixing and stratification in lakes and oceans for many years (e.g. Wuest and Lorke, 2003). Most commonly, data from these instruments are analysed in the frequency domain to extract measures of vertical turbulent diffusivity (K_Z). These may then be used to quantify the rate of vertical turbulent mixing in models of lake heat budgets, nutrient cycling, plankton population dynamics etc. Here, I explore a different approach to these data, focussing on their spatial domain characteristics. In particular, I analyse the multi-scale layered structure of their temperature profiles. I also propose a novel, simple approach to segmentation of the profiles into self-contained mixing layers, and compare values of Thorpe-scaled-derived turbulent diffusivity with those derived from classical curve-fitting methods in the frequency domain.

Materials and methods

The analysed profiles were all recorded with a SCAMP (Self-Contained Automatic Micro-Profiler) (PME Inc., San Diego, USA) in Esthwaite Water, NW England (surface area $1km^2$; maximum depth ~15.5m). Raw profiles were pre-processed by (i) trimming at top and bottom; (ii) interpolating to 1mm resolution; and (iii) removing noise, following Gargett and Garner (2008) using a temperature threshold of 3.5×10^{-3}°C.

Segmentation was carried out by identifying "self-contained" depth sections of the profile i.e. sections where all the data points in the Thorpe-ordered profile also appeared in the original profile, implying no mixing between different sections due to overturns in the profile.

Thorpe-scale-derived turbulent diffusivity was calculated as $K_Z = 1.6\nu^{1/2}L_T N^{1/2}$ (Shih et al., 2005) for every point in the profile (Thorpe scale, L_T, and buoyancy frequency, N, being calculated using centred 0.5m windows). K_Z was also calculated using the Batchelor curve-fitting method (Luketina and Imberger, 2001), and the results of the two methods compared.

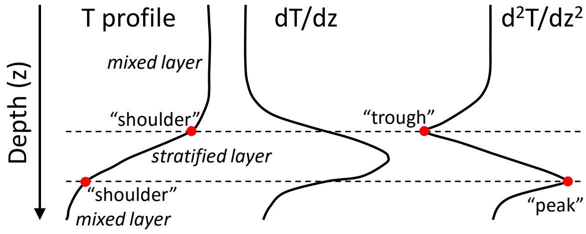

Figure 1: Layer-identification process (repeated at multiple scales)

The multi-scale layering of the (Thorpe-ordered) profiles was carried out using "rulers" (straight best fit lines) of lengths from 3mm to the full profile length. The gradient (dT/dz) of the ruler centred at each point in the profile was recorded, giving a full dT/dz profile for each ruler length. Second derivative (d^2T/dz^2) profiles were then calculated, using the same spatial scale in each case.

At depths where d^2T/dz^2 peaks, the temperature profile is changing most rapidly from a low-gradient (well-mixed) section to a high-gradient (highly-stratified) section; where there are troughs in d^2T/dz^2, the temperature profile is changing most rapidly the other way. Thus, these points identify "shoulders" in the temperature profile that distinguish relatively-mixed layers from relatively-stratified ones (Figure 1). The total number of these shoulders was calculated for each ruler-length, and a pseudo-spectrum (ruler length vs. number of shoulders/layers) then plotted for each main section (active mixing layer; mixed layer; metalimnion, hypolimnion, benthic boundary layer) of each profile.

Results and discussion

Typically, the segmentation identified - as a single segment - a relatively large section at the top of each profile. This is the actively-mixing surface layer, and is distinguished from the surface mixed layer (Gregg and Brainerd, 1995). Beneath this, the segments are typically very small (<10mm), and interspersed with occasional overturns (Figure 2).

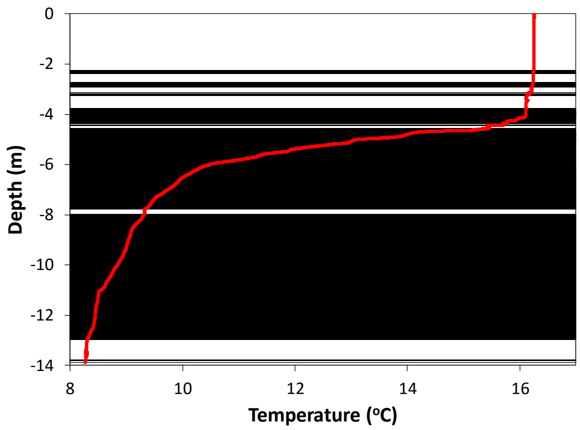

Figure 2: Example temperature profile with segmentation

The Thorpe-scale-derived K_Z was found to fall within the range of variation of the Batchelor curve-fitting K_Z in the strongly-stratified metalimnion, but to underestimate it in less-stratified regions.

The pseudo-spectra of the layered structure of the profile have an approximately fractal form, in that they fit well a constant power law relationship between the ruler scale and the number of layers, where the index of the power law, D, is identified as the fractal dimension (Figure 3). The fractal dimensions of the profile sections vary consistently with respect to N, L_T and K_Z. Deviations of the pseudo-spectra from perfect fractality (i.e. deviations of the plotted pseudo-spectra from best-fit power law lines) are observed and interpreted as indicating more- and less-commonly occurring spatial scales within the layering structure, and therefore preferential mixing scales and differing degrees of completeness of mixing. This suggests that estimates of vertical mixing rates in lakes should consider the effects of differences in small-scale stratification structure, as they may indicate barriers to (or facilitations of) vertical fluxes not picked up by larger-scale estimates of diffusivity.

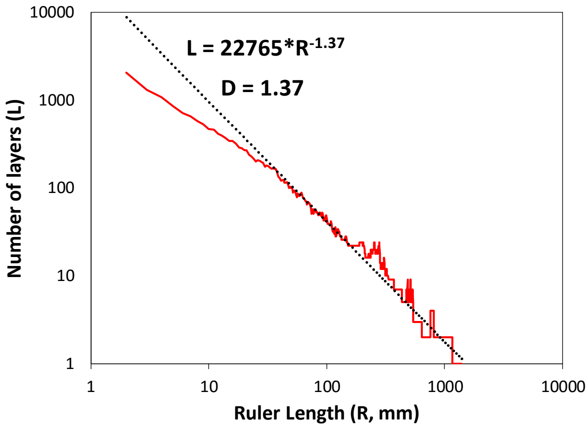

Figure 3: Example of a profile pseudo-spectrum, showing increase in number of layers (L) in profile with decrease in resolution scale (ruler length, R) and best fit power law line with fractal dimension D

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Lake-atmosphere exchange of CO_2 and CH_4 in arctic Siberia

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KEYWORDS
Arctic; thermokarst lake; CO_2 and CH_4 flux, eddy covariance, spring peak.

EXTENDED ABSTRACT

Introduction

Increased carbon release due to permafrost thaw and degradation is considered as intensive positive feedback mechanism of climate change (Schuur et al. 2015). Thermokarst lakes, representing a typical component of circum-Arctic permafrost landscapes, are effective processors of organic carbon and emitters of CH_4, especially in Yedoma permafrost which is rich in ice and organic carbon (Walter et al. 2006). However, in general, arctic lakes are particularly underrepresented in observational studies on lake-atmosphere greenhouse gas (GHG) exchange, as they are most often remote and challenging measurement sites. This is particularly true for the period of ice break-up, which is assumed to result in a spring emission peak especially of CH_4 that could contribute considerably to the annual GHG emissions. In order to prove the existence of such an emission burst and increase the knowledge on arctic lake-atmosphere exchange we applied eddy covariance (EC) flux measurements on a Siberian thermokarst lake. Our specific research questions are: How relevant is the spring ice break-up with regard to the greenhouse gas (GHG) balance of the Siberian thermokarst lake? How do the carbon fluxes differ between ice-covered and open-water conditions?

Materials and methods

The studied lake is located in the Yedoma landscape of Kurungnakh Island in the southern-central part of the Lena River Delta (72° 17.9' N, 126° 10.4' E), which belongs to the zone of continuous permafrost. As common for the Arctic, lakes and ponds capture a considerable proportion of land surface in the delta. The thermokarst origin of lakes is common in the lowland tundra permafrost areas of Northeast Siberia, which have a high to moderate ground ice content and thick sediment cover, similar to the arctic lowlands in central and eastern Siberia, interior and northern Alaska and northwest Canada (Boike et al. 2015). The studied lake has an area of approximately 1.25 km and a mean depth of about 3.1 m. The lake is ice-covered for 8-9 months each year and characterized as floating-ice (Arp et al. 2012) and polymictic lake with only a few days of summer stratification (Boike et al. 2015).

In April 2014 we positioned a floatable measurement platform on the 1.7 m thick ice-cover in the centre of the lake. We equipped the platform with eddy covariance instrumentation and measured turbulent fluxes of momentum, heat, H_2O, CO_2 and CH_4. We chose the LICOR enclosed- (LI7200) and open-path analysers (LI-7700) due to the limitations of power, which was supplied by four solar panels. Furthermore, data on basic atmospheric variables (air temperature, relative humidity, radiation), snow depth, water temperatures and platform position as well as time lapse pictures were collected onboard the raft. Continuous EC flux and additional measurements cover four months including late winter 'frozen' ice-cover conditions, the ice-cover melt (starting 21 May 2014) and ice break-up, as well as about two-thirds of the annual open-water season (24 June until mid of August 2014). Half-hourly fluxes were computed with EddyPro 6.1.0 (LI-COR, Nebraska, US) following common procedures.

Results and discussion

Our measurements do not support the hypothesis of a spring CH_4 emission burst associated with ice break-up. Instead, the break-up and associated full water-column mixing yielded an immediate shift in CH_4 and CO_2 exchange behaviour of the lake. The ice-cover period was characterized by small net CH_4 emission with occasional peaks and very variable CO_2 flux rates around zero with a tendency towards emission and uptake during 'frozen' and 'melting' conditions, respectively. The daytime uptake of CO_2 with increasing temperatures in spring was already observed for sea ice (Heinesch et al. 2009, see also Sørensen et al. 2014), and related to brine volume and associated brine *p*CO2 (surface partial pressure of CO_2). Wavelet coherence analysis indicated correlations between CO_2 flux and heat fluxes during ice-covered conditions. For sea ice Sørensen et al. (2014) observed heat fluxes to be aligned with the surface resistance controlling the vertical transport of CO_2 between the atmosphere and the surface. In comparison to ice-covered conditions, the lake was a clear source of CO_2 and CH_4 during the open-water period.

We expect three processes causing the missing CH_4 burst: a) consistent emissions from already ice-free areas (e.g. close to the shore) during melting, indicated by occasional higher emission rates during that period, b) the progressive release of CH_4 trapped in frozen bubbles during ice-cover melt (see e.g. Walter et al. 2006), and c) continuous methane oxidation below the ice-cover (see Denfeld et al. 2016). Supporting the latter, we recognized clear and slightly increased CO_2 emissions for the first ice-free week, when the water column was mixed completely for the first time after winter. During this time CO_2 and CH_4 release showed a similar temporal pattern (wave length > 1 day), especially pronounced in case of CO_2.

Wavelet analysis and coherence illustrated changes of CO_2 flux behaviour during a three-weeks period in summer, when the drifting platform was located close to the eastern shore of the lake. The diurnal cycle was more pronounced (with nighttime peak CO_2 emissions and daytime uptake) than during times when the platform was further away from the shore. CO_2 correlated with short-wave incoming radiation on a daily scale indicating photosynthesis and thus the inclusion of the tundra within the EC source area. During this period we further observed stronger CH_4 emissions throughout the day, potentially highlighting the impact of shallow water areas in the EC footprint. Thermokarst lakes are characterised by continuous erosion of the lake shores and thus refill of organic material into the shallow lake areas during the open-water period. As soon as the raft was brought back closer to the centre of the lake, the flux dynamics switched back to the 'lake flux behaviour', i.e. clear net release of CO_2 and lower CH_4 release rates, indicating in sum a clear source of carbon GHGs. However, CH_4 release in August was much stronger than in June when the lake became ice-free, probably due to higher water and sediment temperatures.

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Harp Lake model intercomparison experiment: focus on vertical gas transfer

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KEYWORDS
LakeMIP; numerical simulation; lakes; gas transfer; diffusivity.

EXTENDED ABSTRACT

Introduction

Over the last decade the field of lake modeling has attracted much attention in weather and climate modelling community. Several lake models of diverse complexity have been developed and incorporated in the numerical weather forecast systems and climate models. Hence, the comparison of lake models and their verification are essentially relevant. Especially it applies to simulation of biogeochemical processes and gas transfer in lakes. One of the projects, accumulating knowledge on the lake models' "behavior" is LakeMIP (Lake Model Intercomparison Project), launched in 2008 [Perroud et al., 2009; Stepanenko et al., 2010; Thiery et al., 2014, etc.]. Previous studies investigated the ability of the different lake models to represent the thermodynamic state of the water bodies in different latitudes. This research focuses on the simulation of key factors of greenhouse gas dynamics in lakes, such as the lake stratification, the diffusion of gases, and the ice cover.

Materials and methods

The study site is a large (71.4 ha), deep (h_{max} = 37.5 m; h_{mean} = 13.32 m) oligotrophic Harp Lake, located in south-central Ontario, Canada (45° 23' N, 79° 07' W). It is enclosed by forest catchment [Cox, 1978; Dillon et al., 1978]. Harp Lake has six inflows and one outflow [Yao et al., 2014]. The observation dataset contains the time series (14.07.2010 – 19.10.2015) of meteorological variables such as: temperature, pressure, precipitation, wind speed, shortwave and longwave downward radiation. In addition, it includes the evolution of temperature profile (up to 27.1 m), oxygen profile (up to 35 m, without winter time period, time step – 1 day) , oxygen (at depths 1 m, 18 m, time step – 1 hour) and carbon dioxide (at a depth 0.39 m, time period: 12.03.2012 – 19.10.2015). The meteorological forcing is used as an identical input for all models.

Among the participating models there are those using Henderson-Sellers-based diffusivity [Henderson-Sellers, 1985] such as: bLake4Me [Tan et al., 2015], FAQ-DNDC [Wang et al., 2016], MTCR-1 [Polli and Bleninger, 2015] ; and k-ε turbulence closure models - LAKE [Stepanenko et al., 2011; Stepanenko et al., 2016], LAKEoneD [Jöhnk and Umlauf, 2001 ; Jöhnk et al., 2008] and the lake model FLake employing a concept of self-similarity of the temperature profile [Mironov, 2003; Mironov, 2008]. The set of numerical experiments includes a baseline experiment and other experiments testing the sensitivity of models to variation of the extinction coefficient, the lake depth, and the initial conditions. Additionally, in order to understand the role of eddy diffusivity for the gases, an experiment solving the vertical transport of passive tracer governed by eddy diffusivities from lake models was conducted.

Results and discussion

Comparing the simulation results allows to select features of models, affecting the vertical distribution of gases in the lake.

The thermodynamic state of Harp Lake (Fig.1), its seasonal variation, sensitivity to the extinction coefficient was adequately represented by all models described above, excepting the Flake model. It produces (as in previous LakeMIP studies) an underestimated temperature gradient in the thermocline, extended to the deep layers, not revealed in observation data. It can be a source of errors in reproducing the distribution of gases by this model in future.

The simulation of the ice-cover period was challenging for all models. Only bLake4Me, FAQ-DNDC, LAKE with more sophisticated approaches of the ice formation and degradation could perform satisfactorily in simulating the onset of ice-cover and ice-off dates.

It has been suggested that temperature in water column largely depend on turbulent diffusivity [Stepanenko et al., 2014]. It possibly also has a crucial role for the transfer of gases. In order to identify “clear” effect (without any biogeochemical influence) of the diffusivity on the vertical distribution of a passive tracer the diffusion equation has been solved considering the vertical turbulent coefficient from the models’ output. The results of the modelling (bLake4Me, MTCR-1, LAKEoneD, LAKE) demonstrate (Fig.2), that the one order difference of the eddy diffusivity can impact the distribution of substance in a lake. The events of the autumn and spring emissions connected to seasonal overturning are very sensitive to the details of a turbulence parameterization. Reducing the depth of lake approximately by half, the mean integral concentration of the tracer in water column decreases from 24 % to 76 %, in different models. Meanwhile, the mean flux, calculated as:

$\frac{F_{surf}}{F_{bottom}} = K \cdot \left(\frac{C_w - C_{eq}}{\Delta z} \right) / F_{bottom}$, where F_{surf} – the flux at the air-water interface; F_{bottom} – the constant flux at the bottom of a lake; K – the eddy diffusivity coefficient from lake models, C_{eq} - the concentration at the surface of a lake ; C_w – the concentration in the underlying water, Δz - the thickness of the finite difference grid layer –

increases from 4 % to 54 %, primarily because of eddy diffusivity variability during summer stratification.

The most sophisticated lake models with biogeochemical modules such as bLake4Me and LAKE demonstrate well representation of the production and dynamics of oxygen. The mean concentration of carbon dioxide in model bLake4Me is greater than in LAKE, probably due to involving the transport from catchment by inflows and less intensive vertical mixing. However, in both models correlation to the observation data (C_{CO_2}) is small: 0.2-0.3.

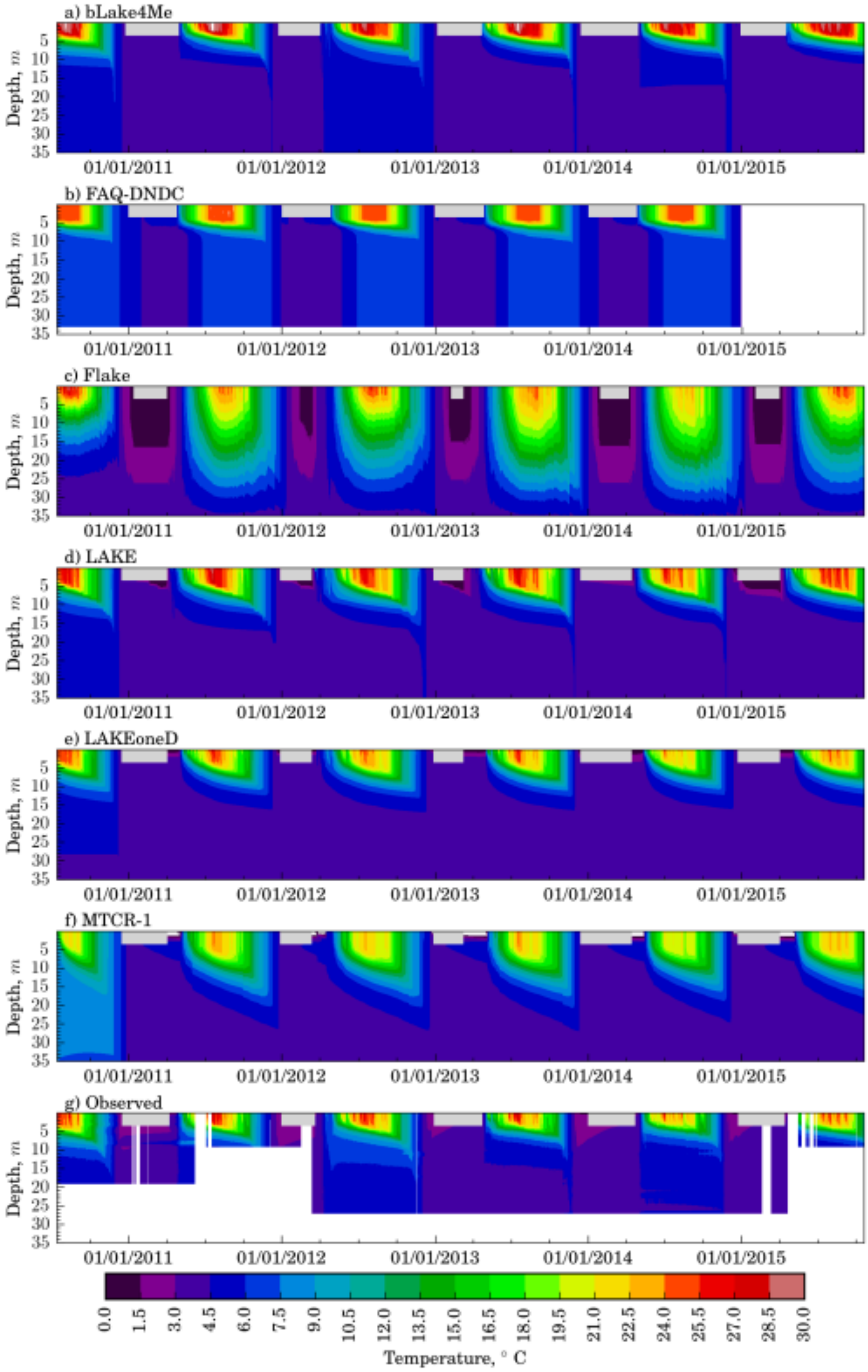

Fig.1. Time-depth profiles of temperature in Harp Lake, reference model run and observation data. The grey boxes indicate duration of the ice-cover period, the white patterns - a lack of data

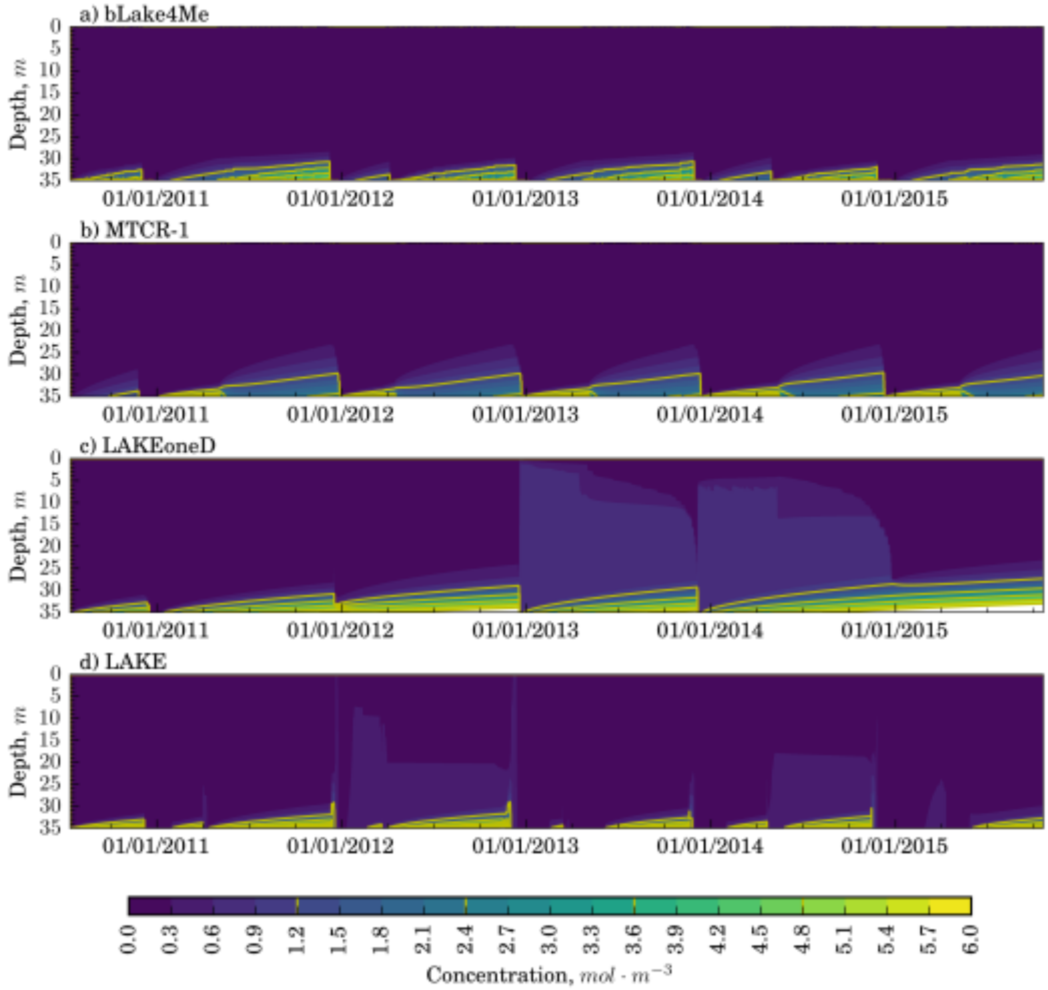

Fig.2. Time-depth profiles of a passive tracer in a lake, reference model run

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Evaluation of methane emission from a mid-latitude lake with the eddy covariance technique

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KEYWORDS
Dissolved CH_4 concentration; ebullition; flux partitioning; stable isotope; wavelet analysis.

EXTENDED ABSTRACT

Introduction

Lake ecosystems are one of the major methane (CH_4) sources. CH_4 emission from lakes to the atmosphere occurs as diffusion through the water column, ebullition, and plant-mediated transport. It was reported that CH_4 emission via ebullition contributed up to 80 % of the total (Bastviken et al., 2004), thus it can be the major emission pathway in some lake. However, such evaluations have been based on discontinuous observations such as the floating chamber technique, and it may have resulted in an underestimation of the ebullition emission (Podgrajsek et al., 2014a) due to the sporadic nature of ebullition both in time and space. For an accurate estimation of CH_4 emission, the eddy covariance technique has an advantage in that it can cover footprint of 10^4 m^2. The application of the eddy covariance technique for CH_4 emission in lakes so far has been limited to a few studies (e.g., Eugster et al., 2011; Podgrajsek et al., 2014b). Thus, more eddy covariance studies are needed to understand the detail of environmental controls on CH_4 emission from lakes.

This study reports CH_4 emission from a shallow lake in Japan observed with the eddy covariance technique along with periodic measurements of dissolved CH_4 concentration.

Materials and methods

Observations were conducted in Lake Suwa, a eutrophic lake, which has an area of 12.8 km^2 and maximum depth of 7.6 m. Eddy covariance instruments were installed on a mast at a pier located on the southeast coast. The instruments include a three-dimensional ultrasonic anemothermometer (CSAT3, Campbell Scientific, USA) and an open-path CH_4 analyzer (LI-7700, Li-Cor, USA). Relevant observations of atmospheric and lake environment were also conducted. The observation started in June, 2016 and still ongoing. Lake water was sampled approximately once a month to analyse for dissolved CH_4 concentration profile. Flux data used in this study were corrected for the high-frequency loss, air density fluctuation, and spectroscopic effect. Only data with wind direction from the lake were used.

Results and discussion

In Lake Suwa large CH_4 emission occurred in specific wind directions, with the maximum emission up to approximately 2.0 μmol m^{-2} s^{-1} in July. We confirmed that steady ebullition occurred in this direction. The trapped bubble was analysed for the CH_4 concentration and stable isotope ratio, and we found the concentration was 91 % and $\delta^{13}C$-CH_4 was -62.8 ‰. The $\delta^{13}C$-CH_4 value suggests that the emitted CH_4 through the steady ebullition had the origin of microbial decomposition.

When data with wind direction from the steady ebullition area were excluded from the analysis, CH_4 emission had a clear seasonal variation, typically with 0.3 μmol m^{-2} s^{-1} in summer and 0.1 μmol m^{-2} s^{-1} in winter, similar to a variation in the temperature near the lake bottom. However, still large CH_4 emissions up to approximately 1.0 μmol m^{-2} s^{-1} were observed sporadically in these directions.

Dissolved CH_4 concentration showed the highest concentration in July, with higher concentration in deeper layer. The maximum concentration was 8.7 μmol L^{-1} near the lake bottom. Subsequently, dissolved CH_4 concentration decreased, but still higher concentration in deeper layer. After October, concentration was nearly constant through the profile, which was the results of complete lake water mixing.

In analysing the response of CH_4 emission to environmental variables, it is desirable to partition the net flux into emissions through diffusion and ebullition processes. Here, we have developed such a flux partitioning technique for CH_4 flux. The 10 Hz turbulence data showed that the scalar similarity between air temperature (or water vapor concentration) and CH_4 concentration held when CH_4 emission was low, whereas the similarity did not hold when CH_4 emission was high due to abrupt large positive deviations of CH_4 signal from the time average. Ebullition occurs sporadically both in time and space and emits bubbles of high CH_4 concentration, thus it can lead to such abrupt large positive deviations, resulting in the scalar dissimilarity. We hypothesized that similar fluctuation components reflect diffusion emission and dissimilar fluctuation components reflect ebullition emission, and the actual turbulent fluctuations are the superposition of both. By separating the similar and dissimilar components based on wavelet coefficients, we partitioned CH_4 flux into emission due to diffusion and ebullition. We found that diffusion emission was controlled by wind speed on a short time scale, rather than temperature near the lake bottom. This suggests that transport efficiency in the water column, rather than CH_4 production in the sediment, has stronger influence on the diffusion emission in this lake.

In summary, the one-year observation of CH_4 flux revealed that both steady and sporadic ebullition emission occurred in Lake Suwa. When these ebullition emissions were excluded, the seasonal variation in CH_4 emission was controlled by CH_4 production in the lake sediment layer. On the shorter time scale, CH_4 emission was influenced by the transport efficiency in the water column. The proposed flux partitioning technique needs further validation, but it can readily be applied to other data sets, since it only requires high-frequency turbulence data with a few empirical parameters.

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Methane oxidation in Lake Kuivajärvi

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KEYWORDS
Boreal lakes; methane; methane oxidation; anoxia.

EXTENDED ABSTRACT

Introduction

Atmospheric methane (CH_4) is a global greenhouse gas that is emitted to the atmosphere by both natural and anthropogenic sources (Dlugokencky et al., 2011). One of most significant natural sources of CH_4 in the boreal region are lakes that mineralize carbon produced within the lake and its catchment. Majority of the CH_4 in lakes is formed in the anoxic lake sediment layers, although CH_4 can also enter lakes from the catchment by surface runoff (Miettinen et al., 2015). While sediments produce substantial amounts of CH_4, very small portion of it enters the water column because CH_4 is oxidized to carbon dioxide (CO_2) in the oxic sediment surface. However, the oxic layer can disappear in late summer when mineralization of organic matter consumes all oxygen from the sediment surface. Consequently, CH_4 is released from the sediment to the water column. CH_4 oxidation can also take place in the water column (Kankaala et al., 2006), but the rates and the rate controlling factors are still poorly known. To gain better understanding of the effect of bottom water anoxia on the CH_4 emissions from boreal lakes, we measured the CH_4 and CO_2 gas concentrations and their $\delta^{13}C$ values from seasonally anoxic Lake Kuivajärvi near Hyytiälä Forest Research Station during open water season 2016. In addition, we measured the potential CH_4 oxidation rates in the water column after it had changed anoxic.

Materials and methods

Water sampling was done 4 times between May and September in 2016 at the deepest point of the lake (~12 m) (Table 1). In addition to nutrients and CH_4 and CO_2 gas concentrations, we also measured the stable isotopic signatures of CH_4 and dissolved inorganic carbon (DIC). The stable isotopic signature of CH_4 ($\delta^{13}C$) can be used as an indicator for CH_4 production and consumption because newly formed CH_4 has a distinctly light isotopic signature ($\delta^{13}C$ = -100 – -45 ‰) (Grey 2016). When CH_4 is oxidized, ^{12}C is preferred over ^{13}C, hence the $\delta^{13}C$- value of the remaining CH_4 increases. Because the $\delta^{13}C$-value does not indicate how fast CH_4 is oxidized, we also measured the potential CH_4 oxidation rate by adding ^{13}C-labelled CH_4 (99% ^{13}C-label) to the samples and following the transfer of ^{13}C label from CH_4 to DIC pool.

Table 1. The sampling dates and parameters analyzed in each sampling time.

Date	**Analyses**
25.5.2016	T, pH, O_2, CH_4, CO_2
18.7.2016	T, pH, O_2, NO_3^-, NH_4^+, SO_4^{2-}, CH_4, CO_2, $\delta^{13}CH_4$, $\delta^{13}DIC$
15.8.2016	T, pH, O_2, NO_3^-, NH_4^+, SO_4^{2-}, CH_4, CO_2, $\delta^{13}CH_4$, $\delta^{13}DIC$, CH_4 oxidation rate
5.9.2016	T, pH, O_2, NO_3^-, NH_4^+, SO_4^{2-}, DOC, Fe, CH_4, CO_2, $\delta^{13}CH_4$, $\delta^{13}DIC$, CH_4 oxidation rate

Results and discussion

The stratification and bottom anoxia had developed by September and the CH_4 concentrations in the hypolimnion peaked simultaneously, indicating that during anoxia the CH_4 was not oxidized in the sediment but instead released to the water column (Figure 1a, 1c). The changes in $\delta^{13}C\text{-}CH_4$ also confirmed the transition of CH_4 oxidation zone from the sediment to the deep water column (Figure 1b).

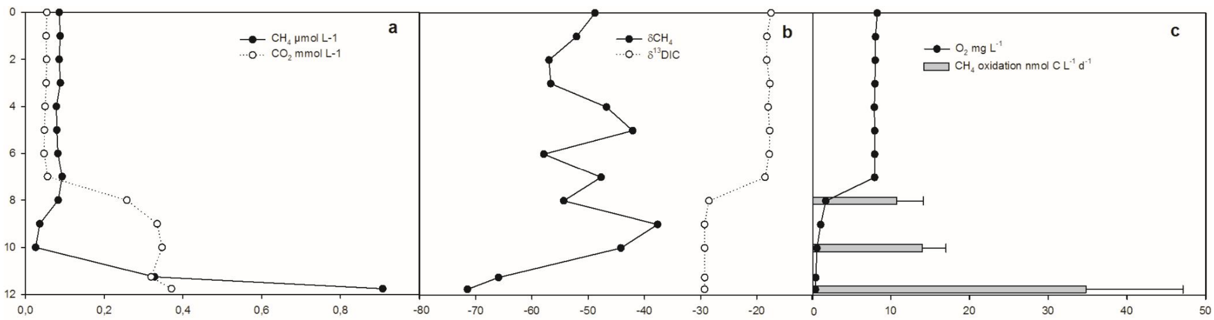

Figure 1. The CH_4 and CO_2 concentrations (a), $\delta^{13}CH_4$, $\delta^{13}DIC$ (b), O_2 concentration, and methane oxidation rates (c) in Lake Kuivajärvi in September 2016.

The potential CH_4 oxidation rates remained below detection limit until September when strong anoxia had developed in the hypolimnion (Figure 1c). Interestingly, the highest potential rates were measured right above the sediment where the O_2 concentration was the lowest (Figure 1c). Since anaerobic CH_4 oxidation taking place in Lake Kuivajärvi seems unlikely, this phenomenon could be explained by temporal micro-oxic zones allowing aerobic CH_4 oxidation in otherwise anoxic environment.

We estimated, based on the changes in the stable isotopic signature of CH_4, that in September, approximately 60 % of produced CH_4 was oxidized in the water column and 40% entered the surface water layers. Even though lakes act as a source of CH_4 especially during the hypolimnetic anoxia, methane-oxidizing bacteria can still significantly reduce CH_4 emissions from lakes to the atmosphere.

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Chemical enhancement of CO_2 at the air-water interface in eutrophic lakes of Quebec

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KEYWORDS
Air-water gas exchange; Chemical enhancement; Lakes; Gas exchange coefficient; CO_2 hydration.

EXTENDED ABSTRACT

Introduction

A precise knowledge of gas exchange processes across the air-water interface of lakes is necessary for properly assessing carbon budgets at regional and global scales. In contrast with chemically non-reactive gases such as methane (CH_4) and nitrous oxide (N_2O), diffusive carbon dioxide (CO_2) exchange can be enhanced by chemical reactions of CO_2 with hydroxyl ions (OH^-), especially at high pH. In eutrophic lakes where pH is relatively high, chemical enhancement is believed to be an important factor in driving CO_2 fluxes [*Bolin*, 1960]. However, there is still considerable disagreement between observed chemical enhancement rates (α) and those predicted from theoretical models [*Wanninkhof and Knox*, 1996; *Bade and Cole*, 2006]. To address this issue, we quantified the actual contributions of chemical enhancement to CO_2 fluxes between the air and water. In addition, we examined any discrepancies that might exist between the observed α in the field and that predicted from the calculation of Hoover and Berkshire (1969) to verify the general applicability of the model.

Materials and methods

We sampled 21 lakes in Quebec, Canada during the summer of 2015 and 2016, selected to cover a wide range of chemical and physical conditions. Diffusive gas exchange of CO_2 and that of CH_4, which does not react with hydroxyl ions in water, were measured using floating chambers. Then, α was obtained in two ways: 1) as the ratio of measured gas exchange coefficients derived from CO_2 ($k_{600\text{-}CO2}$) and from CH_4 ($k_{600\text{-}CH4}$), and 2) from the theoretical model of Hoover and Berkshire (H&B).

Results and discussion

The sampled lakes covered a broad range of trophic status, pH, water temperatures and wind speeds, all of which are considered as important regulators for chemical enhancement. We found that 58% of sites were undersaturated in CO_2 with respect to the atmosphere, leading to a net influx of CO_2 into the lakes. In most lakes, $k_{600\text{-}CO2}$ and $k_{600\text{-}CH4}$ were similar (on average 2.46 and 2.54 m d^{-1}, respectively), suggesting that chemical enhancement of CO_2 was very low even under high pH conditions (8.5 to 9.5) (Figure 1). In addition, observed α values were considerably lower than model predictions (Figure 2). Our results indicate that the often-used theoretical model of H&B overestimates chemical enhancement of CO_2. Our data instead suggest that chemical enhancement is not a very significant contributor to air-water CO_2 flux in lakes of Quebec.

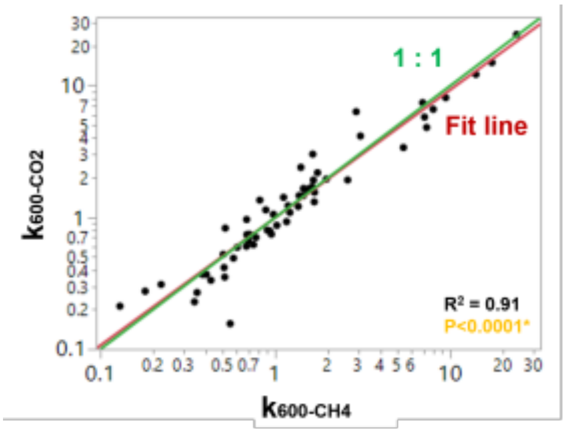

Figure 1. The relationship between the gas exchange velocity (k_{600}, m d^{-1}) estimated from CO_2 and CH_4. Green line and red line represent line of equality and regression fit, respectively.

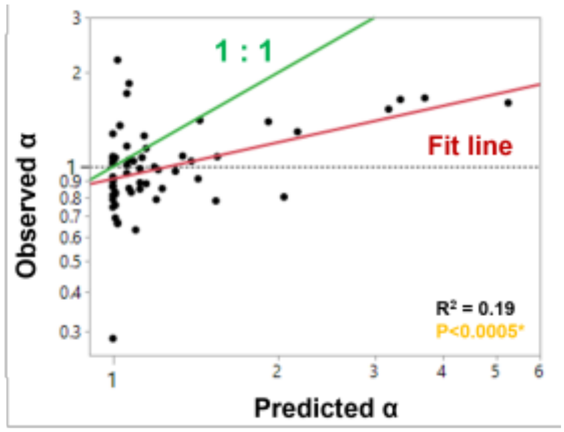

Figure 2. Observed chemical enhancement factor (α, dimensionless) versus that predicted from the theoretical model of Hoover and Berkshire (1969). If the model fits well, the dots should be close to the green line.

Likely reasons for the discrepancy between calculated and observed values of α are: 1) high alkalinity of the sampling lakes, 2) errors associated with the assumption of H&B model that pH within the surface boundary layer and 3) enhanced $k_{600\text{-}CH4}$ resulting from microbubble-mediated fluxes. H&B conducted tank experiments with distilled water when they developed and first tested their model. We propose that these tank experiments are a poor approximation of conditions in actual lake systems. Higher alkalinity means more bicarbonate (HCO_3^-) in the water, and a lower probability of CO_2 chemical reactions. The alkalinity of our study lakes ranges from 400 to 1900 μeq/L. In addition, H&B utilized the stagnant boundary layer model [*Lewis and Whitman*, 1924]. For the stagnant boundary layer model, it is assumed that the CO_2 concentration is in non-equilibrium within the layer while the concentration of CO_2 and carbon species are in thermodynamic equilibrium in the turbulent water body. However, H&B assumed that the pH inside the boundary layer would be roughly same as that of turbulent water body. Contrary to their assumption, if the pH of the boundary layer is lower than that of turbulent water body resulting from atmospheric CO_2 absorption, the actual chemical enhancement can be lower than what we might expect from the model. Also, recent studies have shown the potential influence of microbubble-mediated CH_4 fluxes [*Prairie and del Giorgio*, 2013; *Rosentreter et al.*, 2016]. While microbubble-mediated enhanced $k_{600\text{-}CH4}$ would partially decrease the observed α, there is little to believe that it is pH driven. In addition, the observed k600-CH4 is entirely consistent with wind based models suggesting that microbubbles are not very important in these systems.

We expect these results can improve the estimation of gas exchange in eutrophic systems, and have important consequences for the assessment of regional carbon budgets.

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Modelling the effect of changes in air temperature and carbon loading on CO_2 in a boreal lake

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KEYWORDS
Lakes; carbon dioxide; modelling; biogeochemistry; climate change.

EXTENDED ABSTRACT

Introduction

The importance of freshwater lakes in carbon cycling is pronounced in the boreal zone as the lakes ventilate carbon originally fixed by the surrounding terrestrial system. The effect of climate change on lake ecosystems is most evident in high latitudes. Higher air temperature (T_a) shortens the duration of the ice-covered period and accelerates organic matter degradation. Increase of precipitation and alteration of the seasonal distribution of stream flow may elevate terrestrial carbon loading. Modelling is an efficient tool for estimating the effects of climate change, but the number of mechanistic models simulating carbon in boreal lakes is low. Recent advances in long-term high-frequency measurement of lake carbon dioxide (CO_2) concentration and air-water flux (Mammarella et al., 2015) facilitate model development. The purpose of our study was to estimate the possible implications of higher T_a and increased carbon loading on lacustrine carbon cycle and to give insight on in-lake mechanisms behind the potential impacts of climate change on CO_2 in a boreal lake.

Materials and methods

We used a one-dimensional process-based model for simulation of lake CO_2 dynamics (Kiuru et al., 2016). The model is an extension of a lake model MyLake (Saloranta and Andersen, 2007), and it simulates lake thermodynamics, phosphorus, phytoplankton, dissolved oxygen, and inorganic and organic carbon species. We calibrated the model for Lake Kuivajärvi, a small, humic boreal lake, which is a constant source of CO_2 to the atmosphere in the present climate, using the comprehensive data available on carbon inflow and the concentrations of CO_2 and dissolved organic carbon (DOC) in the lake.

We studied the potential effects of climate chance induced warming on the CO_2 dynamics of the lake between the control period 1980–2009 and the scenario period 2070–2099 using downscaled air temperature data from three recent-generation global climate models (see Lehtonen et al., 2016). The climate models were forced with representative concentration pathway (RCP) scenarios representing intermediate (RCP4.5) and high change (RCP8.5) in radiative forcing. Literature estimates were used for climate change impacts on lake inflow volume. In addition, we compared the effects of 40 % increases in the concentrations of inflow DOC and CO_2 under the RCP4.5 scenario.

Results and discussion

The near-surface CO_2 concentrations were substantially higher in the scenario period (Figure 1a, b), especially under the high forcing scenario RCP8.5. Higher wintertime inflow accumulated more CO_2-rich water in the surface layers under ice in the scenario period, but the maximum water-column average CO_2 concentration under ice was smaller and the spring peak in CO_2 air-water flux was lower because of shorter ice-covered period (Figure 1e) when only changes in T_a and discharge volume were considered. The increase of annual CO_2 flux to the atmosphere due to higher T_a and altered seasonal distribution of inflow was 17–20 % in the RCP4.5 scenario and 33–38 % in the RCP8.5 scenario. The projected annual mean temperature increases of 2.8–3.6 °C and 5.3–5.8 °C resulted in shortening of the ice-covered period by 44–49 and 69–88 days in RCP4.5 and RCP8.5, respectively.

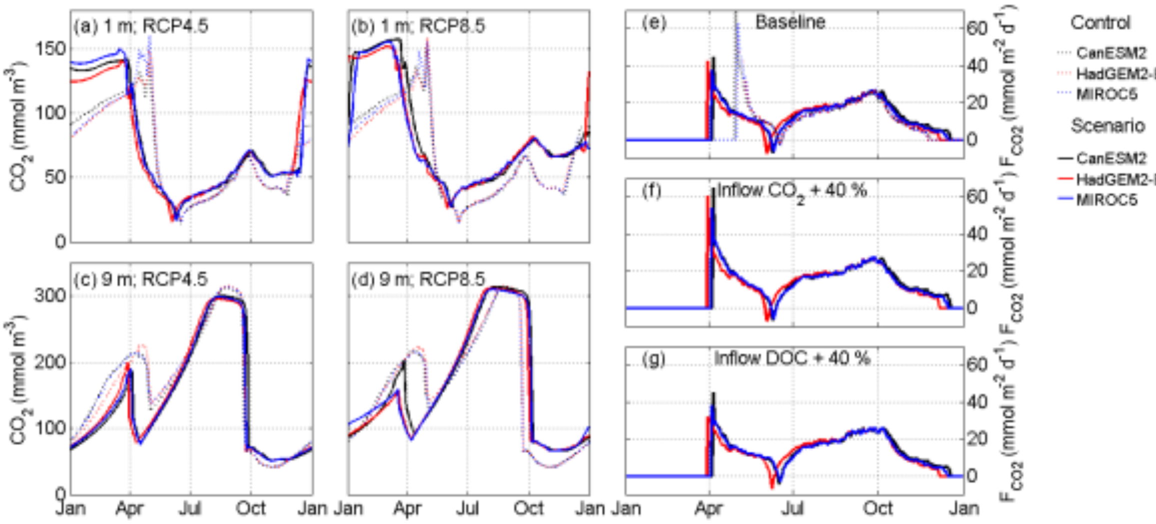

Figure 1. Simulated CO_2 concentrations (mmol m-3) in Lake Kuivajärvi in the control period 1980–2009 (dashed lines) and the scenario period 2070–2099 (solid lines) at the depths of 1 m (a, b) and 9 m (c, d) using RCP4.5 (a, c) and RCP8.5 (b, d) as climate forcing, and CO_2 air-water fluxes in the control period and without changes in the inflow carbon concentrations (baseline) in the RCP4.5 scenario period (e), with a 40 % increase in the inflow CO_2 concentration (f), and with a 40 % increase in the inflow DOC concentration (g).

The increase in direct CO_2 loading raised the simulated air-water flux of CO_2 more than a similar increase in DOC loading (Figure 1f, g). The impact of increased DOC loading on CO_2 concentration was moderate because of the supposed rather refractory nature of inflow DOC although we used a loading scenario with a substantial concentration increase. However, the uncertainties in the climate scenarios and in the simple estimate of changes in inflow used in this study as well as the sources of uncertainty in the biochemical model due to lack of knowledge of lacustrine carbon system functioning need to be recognized.

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Designing Very Shallow Water Bodies for Disinfection: Impact of Daily Stratification/Destratification

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KEYWORDS
Shallow water bodies; stratification; turbulent modelling; disinfection.

EXTENDED ABSTRACT

Introduction

Very shallow fresh water bodies are very common throughout the world. They occur as both natural and constructed systems, with the latter being used extensively in waste water treatment systems in the form of maturation ponds. These ponds, which are normally 0.9 to 1.5 m deep are used primarily for pathogen inactivation/removal by various mechanisms, including naturally supplied sunlight that results in ultraviolet disinfection, predation and high pH levels (Stratton et al., 2015). The treatment efficiency, with regard to pathogen removal is, however, extremely variable between maturation ponds, which in part is due to a lack in the understanding of the flow and mixing dynamics in these ponds.

While sunlight disinfection is an important component of the treatment, the vertical movement of the pathogens is also critical. This movement is affected by the diurnal stratification cycle, which is prevalent in these common, very shallow water systems. Turbulent and thermal convection play a major role in transporting pathogens into the near-surface region to be affected by the ultraviolet component of sunlight. This study analyses a slice of a maturation pond and simulates *E. coli* moving within the slice and being affected by the stratification, sunlight attenuation and mixing driven by wind shear and natural convection. Importantly, the results found here are readily applicable to our understanding of how pathogens can decay in natural shallow water systems.

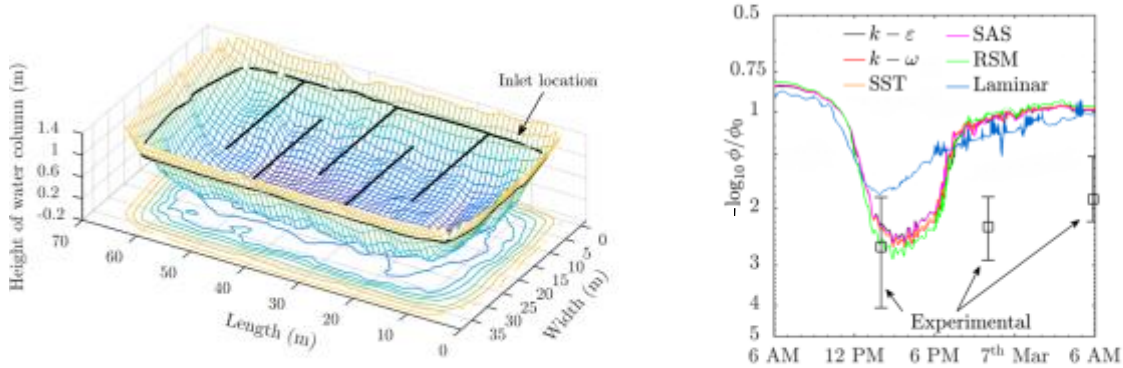
Materials and methods

Measurements of various parameters, including temperature at various depths, solar radiation and light attenuation within the water column, wind speed and direction and pathogen levels, were taken in an operational maturation pond, fitted with baffles, located in South-East Queensland (SEQ). Fig. 1a shows the pond layout with five baffles at approximately 80% length. The average depth of the pond is 0.8 m with an average inflow of $10^{-3} m^3 s^{-1}$ making the theoretical residence time ~16 days (Stratton et al., 2015).

The pond was modelled using the computational fluid dynamics (CFD) package ANSYS FLUENT. A two-dimensional simulation in the vertical-horizontal plane of the first baffled area was considered to be representative of the flow dynamics of the pond. Five different turbulence models were considered for closure of the momentum conservation equations Buoyancy effects were included in each turbulence model. Scalar transport, representative of

E. coli, was simulated within the geometry. UV disinfection (Nguyen et al., 2015) of *E. coli* was accounted for via the source term in the model equations.

Boundary conditions at the air-water surface included the shear stress from the wind, shortwave and longwave radiation, and sensible and evaporative heat fluxes. Generation of thermal energy from the attenuation of shortwave radiation in the water column was also modelled. Unsteady simulations were done over a diurnal cycle with boundary conditions and internal sources being applied from measured data.



a) Measured pond geometry

b) Pond outlet log-reduction of *E. coli*

Fig. 1. a) Measured geometry of the maturation pond - the water-level and baffle placement are shown by dark solid lines. Note that the depth scale is exaggerated; b) Measured and predicted outlet surface concentrations of *E. coli* for 6/7th March 2015.

Results and discussion

A key conclusion from this work is that the choice of turbulence model for CFD simulations is less significant than the inclusion of the buoyancy production term in the turbulent closure model. It has a major influence on thermal distributions, velocity distributions and on the die-off of *E. coli* resulting from sunlight disinfection. As shown in Fig. 1b, reasonable agreement is found between experimental and modelled die-off at midday. Differences in the late afternoon can be explained by the neglect of other types of die-off mechanisms (e.g. predation and starvation) and secondary effects (e.g. temperature, pH, ROS, 3D mixing). Improvements to modelling of shallow water systems, including maturation ponds, could be made through further development and refinement of the turbulent buoyancy production term (due to its pronounced influence on diurnal stratification/destratification) and through greater elucidation of the various and complex mechanisms for die-off.

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Comparison of ice drift characteristics derived from Eulerian and Lagrangian measurements in the Gulf of Finland, the Baltic Sea

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KEYWORDS
Gulf of Finland; ice drift measurements; ice dynamics; ice drift velocity spectra.

EXTENDED ABSTRACT

Introduction

The Gulf of Finland is of an elongated form – 330 km long and 80–100 km wide with the main waterways extending along the Gulf for cargo vessels and across the Gulf for the passenger ship traffic. The presence of ice cover sets specific navigation limits for as in many cases cargo vessels need icebreaker assistance. Operating simultaneously several vessels in the abovementioned circumstances requires the knowledge of local ice dynamics and therefore we focused our study on this issue in the frame of EU project SAFEWIN. The study aims to describe the high resolution sea ice dynamics at three different locations of the cross transect of Gulf of Finland in relation to wind forcing using both ice drift Eulerian and Lagrangian measurements supported by satellite remote sensing ice coverage maps. This kind of measurements are unique in the Baltic Sea in general as well as in the Gulf of Finland in particular.

Materials and methods

The winter 2010 was colder than normal and the whole Gulf of Finland froze over. In the southern coast the ice conditions were quite variable due to south–westerly winds occasionally producing large open water areas. The main study area was selected as the section between Kotka, Finland and Kunda, Estonia, almost north–south in the longitude section 26–27°E. MODIS (Moderate resolution imaging spectrometer of Aqua/Terra satellite of NASA) images of the ice conditions at the study area were collected. Ice drift velocities were measured by bottom-mounted ADCP and drifting buoys. The ADCP was deployed in the central zone of the Gulf of Finland on 12 January 2010 and recovered on 27 April 2010. The site (59°42.09'N, 26°24.23'E; depth 63 m) was located in the deep basin extending south–east toward Kunda Bay, at around 15 km from the coast. A 307.2 kHz broadband ADCP (Workhorse Sentinel, RD Instruments) deployed on the bottom was used. In the present ice dynamics study, the bottom-track (BT) option of the ADCP with a sampling interval of 10 minutes (an average of five high-frequency pings) was utilized to trace from below the sea surface/ice bottom. Thus the data include the ice drift velocity (its BT velocity), the BT error velocity and the vertical profiles of current velocity with vertical resolution of 2 m (from 6 to 58 m). The drifters were launched on the 8th of March in two groups: #5 and #6 in the middle of the gulf at about 15 nautical miles to the north of the ADCP station, with a maximum distance between buoys of about two nautical miles. Drifters #8 and #10 were launched even further to the north at around 32 nautical miles from the ADCP station (figure 1). The drifters are compact devices with the length of about 1 m, the diameter of 11 cm and the mass of 10 kg. Their measurement interval can be controlled remotely between 15 minutes and 2 hours during field experiments. The ice drifter experiments lasted for total of 66 days until the 14th of May. However, for this paper only the measurements performed until the end of March were analysed as in April at the ADCP location the sea was free of ice.

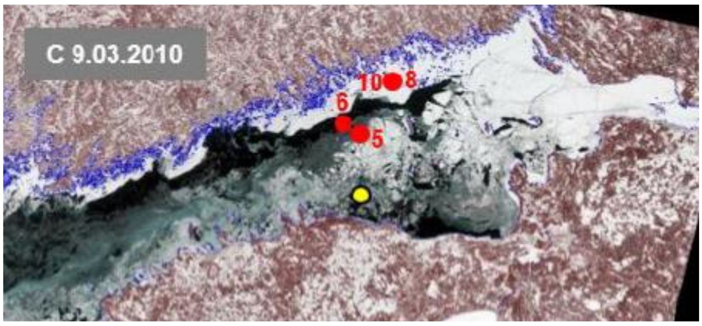

Figure 1. MODIS image of the ice conditions in the Gulf of Finland on 9 March 2010, one day after to the installation of the drifter buoys. Image corresponds to the ADCP ice-covered period C (origin of the image is NASA, processed by Dr. Liis Sipelgas). The drifters are numbered as 5, 6, 8 and 10 and their positions are marked with red dots, the ADCP location is marked with a yellow dot.

Results and discussion

The analysis of the experiment data revealed frequent alternation of ice cover periods with open water periods in the Gulf of Finland. Leads were present on the north and south coasts due to repeated changes in wind direction. A total of five ice periods with a duration of 6–12 days were obtained at the ADCP measurement site (site of Eulerian measurements) until the end of March (periods A (Jan.), B (Feb.), C, D and E (all in Mar.). The ice drifting speed at the ADCP site was well correlated with the wind data measured nearby. The sub-periods mean asymptotic wind factor and deviation angle at large wind speeds were 0.034 and 9°, respectively, in the oceanic boundary layer, corresponding to the ratio of 0.92 of the air–ice and water–ice drag coefficients. The latter probably was affected by the geometry of the Gulf of Finland. The asymptotic wind factor was higher than it is usually estimated but still in accordance with other ice studies in the Baltic Sea (Björk *et al.*, 2008; Leppäranta, 2005).

In period C three instruments (buoy 5, buoy 6 and the ADCP) showed a coinciding ice drift direction, indicating homogenous ice drift in the middle of the Gulf of Finland. Still closer to the south coast (ADCP site) for all 3 sub-periods C, D and E the mean ice drift speed was substantially higher than in the central region measured by drifters (Lagrangian measurements).

The clockwise (CW) spectra of fluctuating part of ice velocity (ice velocity minus mean ice velocity) showed a wide peak at the inertial frequency and a power law with the exponent of -1.9 for the higher frequencies. Eulerian CW spectra showed a higher level than the Lagrangian spectra in the frequency range of 0.04–0.2 cph (the corresponding time periods 5 to 25 hours). Eulerian and Lagrangian counter-clockwise spectra had roughly the same energy density values. Spatial correlations were significant in the range from 3 to 60 km, with the best-fit falling power of -0.18. The correlation level approached 1 at about 1 km distance (i.e., at the scale of the size of ice floes, although the scatter of the correlation *vs*. length scale was large). The estimated integral correlation length scale was 48 km.

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An integrated process-based minimal model to account for the feedbacks between ecological and physical processes in lakes

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KEYWORDS
Lake ecosystems; integrated model; process-based model; minimal model; feedbacks.

EXTENDED ABSTRACT

Introduction

Since their introduction in the 1960s, the development of ecosystem models has been driven by the wide spectrum of potential applications they offer us to better reconstruct and interpret experimental results, improve our understanding of the real world and allow us to test hypotheses and predict future environmental changes under different scenarios such as climate change. These models often fall into one of two types: overly simplistic representations of isolated processes with limited potential to explain real-world observations; or overly complex models that can hardly improve scientific understanding of the represented system due to their results being too difficult to analyse in terms of fundamental processes and controls. Over-parameterisation is also an issue in the latter case. Moreover, most models are designed for very specific purposes and the usual way to cope with the limitations of a single model is to partially couple it to another one, i.e., to feed the output of the one to the other. This strategy hinders the consideration of the feedbacks that processes modelled by the latter may give to processes modelled by the former, which is normally the case when a hydrodynamic model is partially coupled to an ecosystem model.

However, ecological processes are now known to have the potential to significantly alter the physical behaviour of aquatic ecosystems. For example, a higher light attenuation due to increasing concentrations of dissolved organic carbon in natural waters, one of many alterations associated to climate change, results in different physical responses of such systems to solar radiation (Persson & Jones, 2008; Rinke et al., 2010). Through a similar mechanism, planktonic events can alter the duration of the stratified period, thermal structure and mixing regime of medium-depth temperate lakes (Shatwell et al., 2016). Yet feedbacks are related not only to an altered underwater light climate, but to changes in other physical properties as well. In this respect, studies have shown that exopolymeric substances secreted by phytoplankton can modify the rheological properties of water to the extent of altering, for instance, the thickness of a pycnocline (Jenkinson & Sun, 2011).

An integrated process-based minimal model to account for the feedbacks

With the aim of addressing the limitation of partially-coupled models to account for the feedbacks between ecological and physical processes in lake ecosystems in general, we further develop the model reported by Jäger et al. (2010). State variables are described by a set of partial differential equations (PDEs) that are simultaneously solved while keeping model complexity to a minimum so that the relative importance of the different processes can still be assessed, as well as that of the feedbacks between them.

Coefficients in these PDEs are dynamically calculated via another set of process-based algebraic equations that depend on parameters whose values are calibrated within ranges reported in the scientific literature, and on the state variables. Thus, all processes are fully coupled and all known feedbacks are considered. External forcing can also be dynamically simulated so that the response of the system can be assessed not only under steady state conditions, but also under different scenarios involving the variation at different time scales of solar radiation, air temperature, wind speed, precipitation, nutrient loading and brownification, among others. The model also allows for the implementation of different boundary conditions such as lake-groundwater exchanges.

Physical processes include light attenuation as a function of water colour and turbidity, thermal stratification (and the associated density stratification) resulting from the absorption of shortwave solar radiation, heat exchanges with the atmosphere and the lakebed, and the turbulent diffusion of heat that is due to wind shear on the surface, accounting for the reduction of the mixing under stratified conditions by an empirical relationship based on the Richardson number.

Ecological processes include light- and nutrient-limited primary production and nutrient cycling. Modelled primary producers can potentially comprise multiple taxonomic groups of phytoplankton, periphyton and macrophytes, making it possible to analyse how community structure may change, for example, under climate change scenarios (as in Vasconcelos et al., 2016), where the temperature dependence of growth, metabolic and other biological rates plays an important role. Nutrients are cycled between the water column, the sediments, where remineralisation of organic nutrients occurs, and the biotic components of the system. For the latter, nutrient uptake rates are modelled as a function of the concentration of dissolved nutrients, the corresponding nutrient quotas, which can be either fixed or dynamically simulated, and potentially water temperature. Finally, predation pressure exerted on primary producers can also be incorporated as a fixed or variable component of the loss rates.

Expected impact

Relatively few modelling studies consider these feedbacks, and those that do usually focus on the very specific lake types for which enough data is available. Therefore, their actual importance for a more accurate representation of lake ecosystems in general is still unknown. By applying the proposed model to a wider spectrum of lake types, particularly to those for which high-frequency data is now being produced (e.g. shallow subtropical lakes), we expect to gain new insights on the fundamental processes driving the overall functioning of these ecosystems and the potential effects of changing environmental factors.

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Hydrodynamic characteristics of the Xiangxi Bay in the Three Gorges Reservoir, China

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ABSTRACT:
Based on continuous monitoring in 2010, this paper analysed the hydrodynamic processes of the Xiangxi Bay(XXB), a tributary of Three Gorges Reservoir (TGR). It showed that the hydrodynamics of the XXB could be generalized as a density-stratified flow, and could not be simply simulated by one-dimension model. The upstream water mainly flowed out of the bay in a process of downslope-bottom density current, meanwhile, the TGR mainstream water entered into the XXB as a reverse density current. The density current of the XXB was mainly caused by the water temperature difference and turbidity difference between the TGR mainstream and the bay, and the former played a dominant role.

KEYWORDS
Three Gorges Reservoir; Xiangxi Bay; hydrodynamics; density current; water temperature difference.

EXTENDED ABSTRACT

Introduction

The reservoir behind the controversial Three Gorges Dam (TGD) — the world's largest hydropower station(Stone, 2008), located on the Yangtze River in Hubei Province, China — has been regulated with the top water level at 175 m above sea level since October 26, 2010. The changed hydrological conditions caused serious impacts on the environment and ecosystem (Fu et al., 2010; Shen and Xie, 2004; Stone, 2008). One of the most severe challenges, algal blooms impairing the aquatic ecosystem, and threatened drinking water quality and human health (Liu et al., 2012), has become a serious social and environmental problem for the TGR(Wu, 2008.).

As no blooms happened before the construction of TGD, the inducement for blooms could certainly be attributed to the TGD (Fu et al., 2010). Undoubtedly, the dam can only directly change the hydrology, then indirectly influence the eco-environmental parameters condition and cause some problem such as algal blooms. In practice, the hydrodynamic in the TGR present not a simple one-dimensional flow from upstream to downstream, especially, in some tributary bays, complex bidirectional currents dominate(Holbach et al., 2014; Ji et al., 2010), which are different from some other reservoirs in the world. Thermal stratification(Yi et al., 2009)and vertical mixing(Liu et al., 2012) caused by those currents might having great effect on the presence or absence of algal blooms. In this present study，we used a special method to investigate of hydrodynamic, in order to study the mechanism of the algal bloom in the tributary bays of TGR.

Materials and methods

Sampling sites

The Xiangxi River (XXR) is the largest tributary close to the TGD in Hubei Province (Fig. 1 b), which is approximately 94 kilometers long and located in a subtropical continental monsoon climate. The average annual temperature is 16.6 °C, and annual rainfall and river discharge are 1015.6 mm and 40.18 m^3/s, respectively. When the TGR operated at a water level of 175 m, a 40 km reach covered by the backwater from the estuary, called as Xiangxi Bay (XXB). Since the initiation of storage in 2003, different phytoplankton species dominate XXB during different seasons(Liu et al., 2012; Wang et al., 2011).

In order to monitor the temporal and spatial variation of the eco-environmental parameters, we set eleven sampling sites (at intervals of approximately 3 km) in the XXB, indicated as XX00-XX10 (Fig. 1 c) in succession from the estuary to the end of the backwater. Another site was located at the mainstream of the Yangtze River to represent the mainstream of the reservoir, indicated as "GJB" (Fig. 2). A site was also located in the inflow river of the XXB, indicated as "Inflow" (Fig. 2).

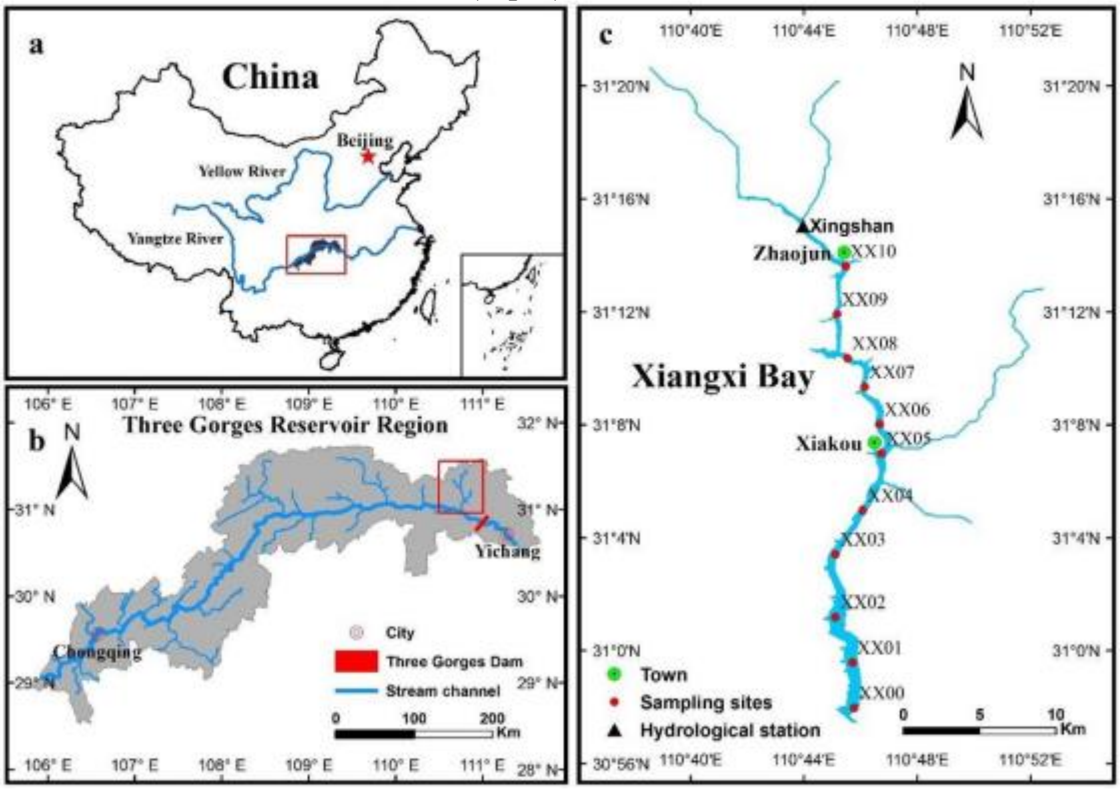

Fig. 1 (a) Location of the Three Gorges Reservoir (TGR) in China; (b) Location of Xiangxi Bay (XXB) in the TGR outlined in red; and (c) Location of the sampling sites in the XXB, where XX00 is near the confluence with the TGR

Measurements of velocity.

Profiles of velocity was measured from a boat equipped with an Acoustic Doppler Vector velocimeter (ADV; Nortek, Norway). Vertical resolution of the measurements was 1 m. Using the method proposed by Ma (Ma et al., 2011), flow velocities in east (Ve), north (Vn) and vertical (Vu) directions were measured at depths of 0.5 and 1 m and then to the bottom at 1 m intervals.

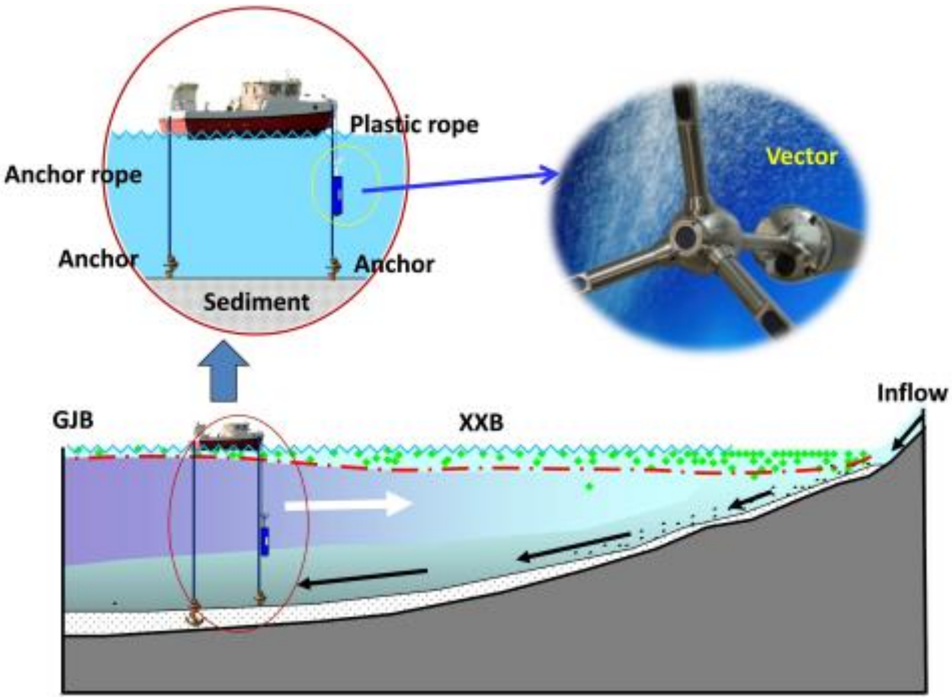

Fig. 2 Schematic diagram of field monitoring of velocity(Ma et al., 2011)

Results and discussion

Hydrodynamic process and characteristics of the Xiangxi Bay (XXB)

Overall, the flow rate of the Xiangxi Bay (XXB) is small and the average flow rate is only centimeter level. The flow direction of the XXB is from north to south, and the direction of the water flow is roughly the same as that of the XXB, and the lateral velocity is small. Therefore, when analyzing flow characteristics of the XXB, the northward divergence velocity vector was used.

Fig. 3 is the dynamic distribution of the longitudinal velocity of the XXB in 2008. It can be seen that the water flow is not a 1-D flow but a stratified flow during the whole year.

In the reservoir water supply, water level drawdown and flood season, the upper reaches water flows to the estuary from the bottom of the XXB. The bottom flow velocity is increasing since May. The maximum upstream velocity reaches 0.46 m/s (Fig. 3 (h)) on June 22nd, which is related to the sudden increase in inflow at the upstream in the flood season.

In the upper reaches of the XXB, water flows to the estuary from the bottom since the middle of February. Meanwhile, there is a "wedge" shaped water flowing into the XXB at the bottom of the XXB estuary from the Yangtze River. The reverse density current travels about 5 km from the estuary and the average flow rate is 0.04 m /s (Fig. 3 (b)). The travel distance gradually expanded to about 7 km from the estuary in March (Fig. 3 (c)).

There is a continuous stratification flow in the XXB since then. Water intrudes from the Yangtze River into the XXB at the middle layer of the estuary range from 5-40 m depth from April to September. The average flow rate is 0.05 m/s and the maximum velocity reaches to 0.16 m/s at 5 m depth on May 10 (Fig. 3 (f)). The travel distance of stratification flow from April to September is significantly further than that of February and March. The reverse density flow can affect the upper reaches of the XXB most of the time from April to September.

During the first stage of reservoir impoundment from the end of September to October 6th, the density current intrudes into the XXB from the surface and immediately affects the entire XXB. The average flow rate was 0.06 m/s (Fig. 3 (k), (l)). But the density current intruded from the middle layer during the second impoundment (Figure 3 (m), (n)). At the same time, the upper reaches water of the XXB still flows out to the estuary. There is still density current intruding from the bottom or middle layer after impoundment in November and December. But the intruding distance is less than 10 km (Figure 3 (o), (p)).

Thus, the hydrodynamics of the XXB are difficult to be generalized as one-dimensional characteristics, but in the long-term, there are complex stratified density flows in the vertical direction. In the whole year, there is always the underflow which flows to the estuary at the bottom of the XXB, and density current intrusion will occur at the estuary most of the time. The plunging point and travel distance of intruding density current will vary with the physical properties of the water, inflow of the XXB, water level and water level daily fluctuation in different seasons.

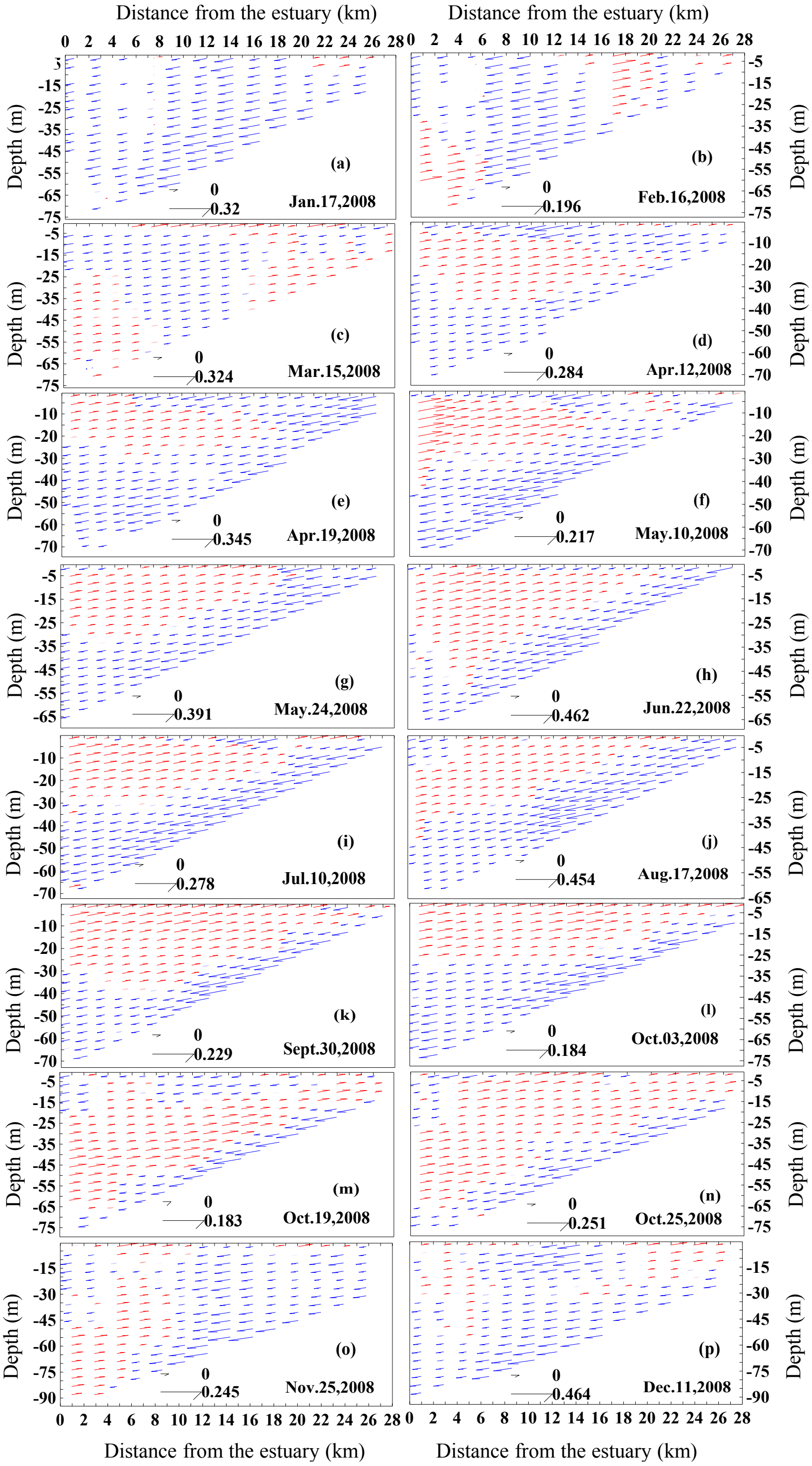

Fig. 3 Longitudinal-vertical velocity profile of the Xiangxi Bay in 2008 (Unit: m/s)

Note: The red vector indicates the water flows into the XXB, the blue vector indicates the water flows out of the XXB. The vector length indicates the magnitude of flow velocity.

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The Role of Water Level Fluctuation on GHG Dynamics in a Temperate UK Reservoir

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KEYWORDS
Reservoir drawdown; sediment fluxes; aquatic carbon; biogeochemistry; inland waters.

EXTENDED ABSTRACT

Introduction

Inland waters play an important role in the transport, transformation, loss and storage of carbon (C) in the pathway between terrestrial and marine systems. Reservoirs in particular are likely to represent biogeochemical cycling hotspots, and a potential source of greenhouse gases (GHGs) to the atmosphere due to large inputs of terrestrial carbon alongside operational and mixing processes. Although all aquatic systems experience natural fluctuations in water level, this is often more extreme in reservoir environments due to seasonal demands or operational maintenance. Drawdown emissions occur when fluctuating water levels cause changes in hydrostatic pressure and create sediments that are periodically inundated with water and then exposed to aerobic conditions. During drawdown events, ebullition becomes more intense and bubbles bypass methane consumption in the sediment and water column leading to a larger atmospheric methane flux. Vegetation which re-colonises this zone may also provide a significant labile C input on rewetting. As these processes can act to convert atmospheric CO_2 to the more potent GHG CH_4, this zone may contribute disproportionately to emissions from the system as a whole. Recent drawdown studies have found exposed reservoir sediments to produce pulses of CH_4 (Harrison *et al.,* 2017) and CO_2 (Jin *et al.,* 2016) emissions. Whilst many studies focus on the magnitude of reservoir emissions, we still lack a clear picture of the internal controls on GHG production within the complex reservoir system.

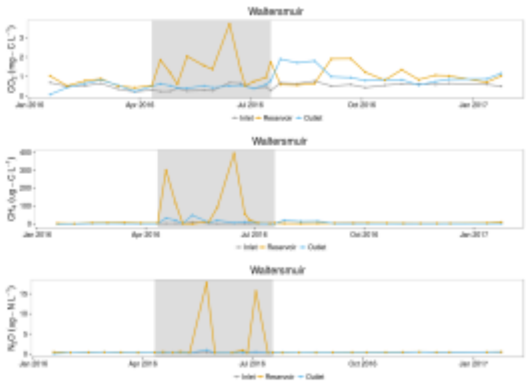
Materials and methods

Bi-weekly samples were taken from Waltersmuir Reservoir over a one year period, January 2016 to January 2017. During the 11-week drawdown event from April to July, sampling frequency increased to weekly. Waltersmuir Reservoir is located in central Scotland and has a surface area of 3 ha, mean depth of 4.4 m and catchment area of 1169 ha. Duplicate water samples were collected at five sampling locations using a 60 ml syringe and filtered in the field. Dissolved oxygen (DO), pH, temperature and electrical conductivity (EC) were also measured in-situ. Water samples were analysed for DOC and DIC on a LabTOC instrument (PPM Solutions), and ammonia, nitrate and nitrite using an AQ2 discrete analyser (Seal

Analytical). Dissolved CO_2, CH_4 and N_2O gas samples were collected using the headspace technique which is fully described by Kling *et al.,* (1991) and Billett *et al.,* (2013). A 40 ml water sample, collected from ~10 cm water depth, was equilibrated with 20 ml headspace of ambient air in a 60 ml syringe by shaking vigorously underwater for one minute. The headspace was then injected into a 12 ml Exetainer® and analysed on a 7890B gas chromatograph (Agilent Technologies) for CH_4, CO_2 and N_2O. During the 11-week drawdown and rewetting period, fluxes at the sediment-water interface were measured weekly in a transect using nine static and soil respiration chambers covering areas of different slope and sediment moisture. To investigate the drivers of measured fluxes, water-table, water chemistry and sediment nutrient concentrations were also analysed. A UAV survey also took place during maximum drawdown to help quantify sediment evasion and upscale emissions.

Results and discussion

Dissolved GHG concentrations (Fig. 1), particularly CH_4 (median = 0.62 µg C L^{-1}; max = 393.3 µg C L^{-1}) and N_2O (median = 0.38 µg C L^{-1}; max = 17.6 µg C L^{-1}) show increased concentrations during the drawdown period. Two CH_4 peaks coincide with two partial refilling events during periods of heavy rainfall. Similar but delayed peaks are also seen in N_2O concentrations, likely linked to a reduction in anaerobic activity as water levels fall. DOC and DIC both increase during the drawdown period but with greater peaks in late Summer.



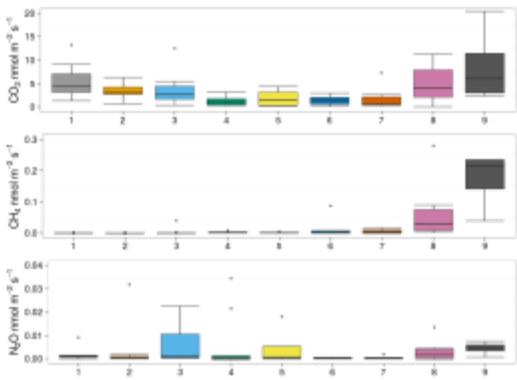


Figure 1 (left). Dissolved GHG concentrations from Waltersmuir reservoir from January 2016-2017 with grey area highlighting 11 week drawdown. Figure 2 (right). Sediment fluxes across all nine chambers, with higher fluxes in wetter areas.

Sediment fluxes (Fig. 2) were low across chambers 1-7, with increased fluxes observed at chambers 8 and 9 which were consistently saturated with water. A PCA was performed to examine the covariances and correlations between variables, where 56% of total variation was explained with the top three principal components. At the 95% confidence level, a statistically significant relationship was found between CO_2 and soil moisture ($p=0.0001$); CO_2 and pH ($p=0.0244$); CH_4 and pH ($p=0.00601$), and CH_4 and soil moisture ($p=0.006$). The results highlight that pulses of aquatic CH_4 concentrations occur during rewetting, with sediment fluxes linked to moisture and pH. Further studies are required to further understand spatial and temporal variability of drawdown events on total reservoir C budgets.

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Light and hydrodynamics as key drivers behind the recent decline of *Planktothrix rubescens* in a mesotrophic lake (Lake Hallwil)

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KEYWORDS
Planktothrix rubescens; environment; water quality; modelling; internal waves.

EXTENDED ABSTRACT

Introduction

After the onset of eutrophication in the mid-1900's, substantial efforts were implemented at Lake Hallwil (Canton Aargau, Switzerland) to reduce nutrient loading (Fig. 1). The aggressive restoration program was extremely successful, and resulted in returning Lake Hallwil from nearly hypereutrophic to now meso-/oligotrophic conditions. With the phosphorus reduction and improvement, the nuisance cyanobacteria *Planktothrix rubescens* began to reappear around 1985. The species had previously lived in Lake Hallwil at turn of the 20th century, but had disappeared with the onset of eutrophication in the mid-1900s.

The cyanobacteria *Planktothrix rubescens* have been the dominant algal species in Lake Hallwil since about 1999 and peaked in concentration in 2002. This red filamentous nuisance species resides in the metalimnion and utilizes gas vesicles to achieve neutral density at optimal light and nutrient levels. These restoration efforts have led to a decrease in most phytoplankton species (Fig. 1) since 2000, resulting in increased Secchi disk depth and allowing light to access the metalimnion where the *P. rubescens* thrive. Consequently, an increase in biomass of the species was observed as the trophic state improved from 1985 - 2002. Since 2002, however, the *P. rubescens* populations have continued to decline. In this paper, we explore the relationship between their sustainability in relationship to local hydrodynamics.

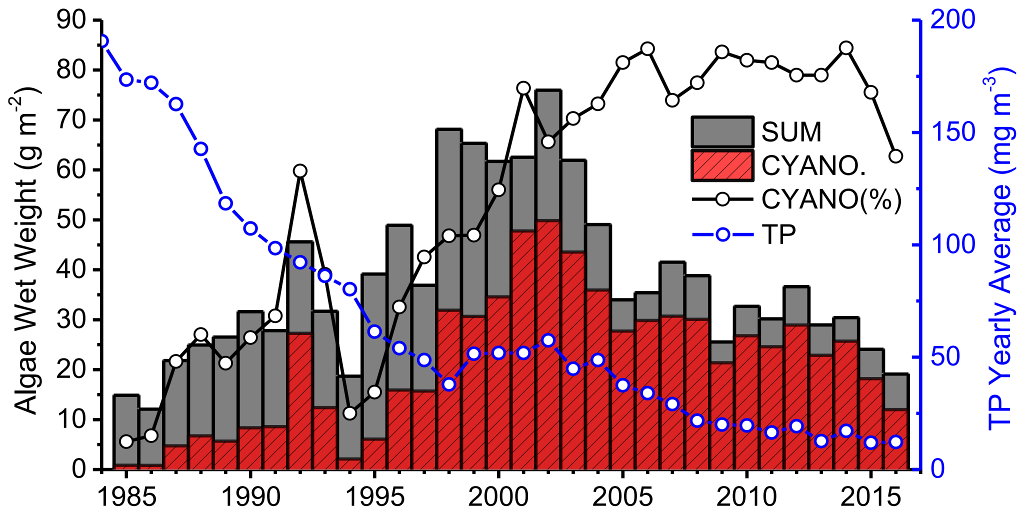

Fig. 1. *P. rubescens* (CYANO) compared to total algae (SUM). Black open symbols: % of *P. rubescens* compared to total biomass. Blue open symbols: yearly average total P (*The Department of Bau, Verkehr und Umwelt, Abteilung für Umwelt, Canton Aargau*).

Methods

Lake Hallwil is glacially formed, with a mean depth of 28 m. Located in the central Swiss plateau, the lake has undergone artificial aeration since 1985 (McGinnis *et al.*, 2004). Biogeochemical data were provided by the Department of Bau, Verkehr und Umwelt, Abteilung für Umwelt, of the Canton Aargau. A temperature mooring was installed to resolve the basin-scale diffusivities (K_z) with the heat budget method (Wüest *et al.*, 2000). The water column stability is calculated as $N^2 = g\rho^{-1}\partial\rho/\partial z$ (s^{-2}), while the Osmidov Length Scale is $L_o^2 = K_z/(0.15N)$ (m^2).

Results and discussion

Secchi depths increased from ~2 m in 1999 to 6 m in 2015/2016. Though decreasing since their peak in 2002, in 2015 *P. rubescens* began a more dramatic decline in concentration. Our results show that *P. rubescens* follow the depth where light penetration is ~0.1 - 1% of surface irradiance, and now reside at the base of the metalimnion (Fig. 2). As Lake Hallwil experiences regular basin-scale motions (seiche) (McGinnis *et al.*, 2004), the lower boundary of the metalimnion is characterized by increased turbulent mixing length scales and decreasing water column stability (Fig. 2, right). Therefore, when *P. rubescens* become deeper (Fig. 2 center), they experience increasingly larger eddy length scales which exceed their daily migration rate and thus transport *P. rubescens* into the hypolimnion at an unsustainable rate (Fig. 2).

As their migration (buoyancy compensation) rate is 1 m d^{-1}, the combination of light penetration and hydrodynamics in Lake Hallwil therefore suggest that *P. rubescens* can only inhabit the metalimnion (~ 5 – 14 meters), with their position determined by the light availability. Above or below this layer, the turbulent length scales become too large and stability too low, overcoming their buoyancy compensation ability. The results of this study therefore provide important insights into management strategies to mitigate *P. rubescens* in lakes and suggest in the case of Lake Hallwil, a further improvement in Secchi depth will force *P. rubescens* into an unsustainable habitat.

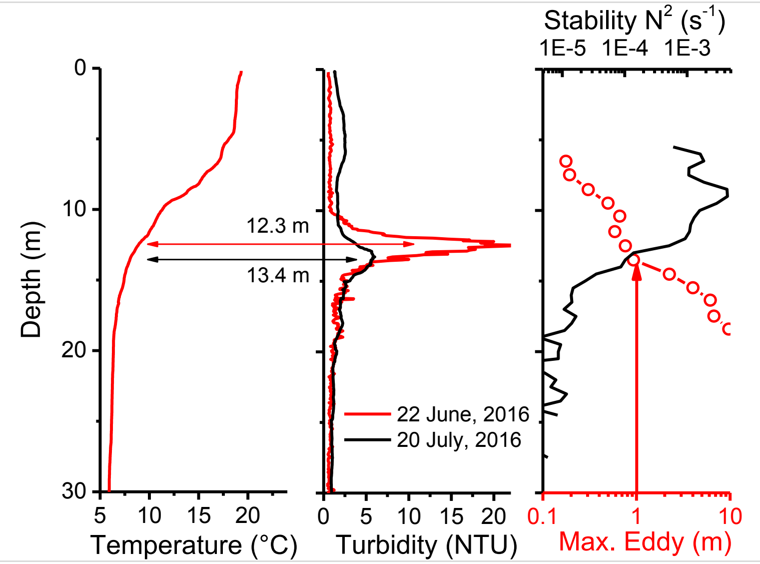

Fig. 2. Left: Temperature profile from summer 2016. Center: *P. rubescens* distribution in June and July. Right: Mean N^2 and L_o (estimated from basin-scale diffusivities).

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Effect of density currents on the seasonal evolution of basin-scale internal waves in a Tropical Andean reservoir

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KEYWORDS
Tropical Andean reservoir, internal waves, density currents, seasonal evolution.

EXTENDED ABSTRACT

Introduction

Existing literature about basin-scale internal waves in temperate lakes and reservoirs is prolific. However, there are few investigations about tropical Andean lakes, where thermal stratification is typically weak, unlike the strong thermal gradients observed during summer in temperate systems. Similarly, the interaction between different processes commonly observed in stratified flows has been little addressed, such as is the case of the interaction between density currents and basin-scale internal waves. Recent investigations have shown that density currents are a prominent feature for the seasonal evolution of the thermal structure in tropical Andean reservoirs (Román-Botero et al., 2013), which in turn should rule basin-scale internal waves behaviour. Motivated by the lack in this topic, we investigated, at a seasonal scale, the effect of the inflow hydrological regime on the internal wave field in a tropical Andean reservoir.

Materials and methods

The study site was Porce II reservoir, located at 06°47'00"N in Colombia. Porce II is an elongated canyon reservoir, 9.8 km long, with a mean width of 1 km and maximum depth of 92 m. The reservoir was continuously monitored for 170 days during wet and dry seasons with two thermistor chains and a meteorological station. Inflow and outflow discharges were provided by the reservoir managing company, Empresas Públicas de Medellín, and inflow temperatures were recorded during most part of the survey. Wavelet analysis was conducted on thermistor data to determine periodicity and vertical structure of the internal wave field. Theoretical natural modes were calculated every ten days through the survey by solving the 2D eigenmodel proposed by Fricker and Nepf (2000). Intrusion depth of inflows was estimated by solving the inflow mixing model described in Fischer et al. (1979).

Results and discussion

Significant differences in the basin-scale internal wave field were observed during the different hydrological stages (Fig. 1). Transitional and dry stages were dominated by V1H1 and V2H2 natural modes, respectively (Fig. 1d,e); both excited by resonance with the diurnal wind forcing (Fig. 1c). By contrast, despite the fact that during the wet season theoretical V1H1 natural period matches the diurnal frequency of the wind (Fig. 1d), the internal wave signature in the temperature records disappears below 20 to 30 meters depth, as is shown by the continuous wavelet analysis of coherence and phase around the 24-h period band conducted between temperature signals recorded at the different depths (Fig. 1e). This behaviour is a consequence of the inflows density currents, whose intrusion depth is highly variable during this season (Fig. 1f) hence destroying coherent motions in the water column. The high variability in the intrusion depth is associated to the small temperature gradient of the water column during the wet season (Fig. 1f) with a top to bottom temperature difference of 2°C (Fig. 1b), close to the amplitude of the diurnal cycle of temperature of the inflow (Fig. 1b). During the transition and dry seasons, natural modes can be excited by the wind given that inflow discharges are low and confined above the first 20 m (Fig. 1f).

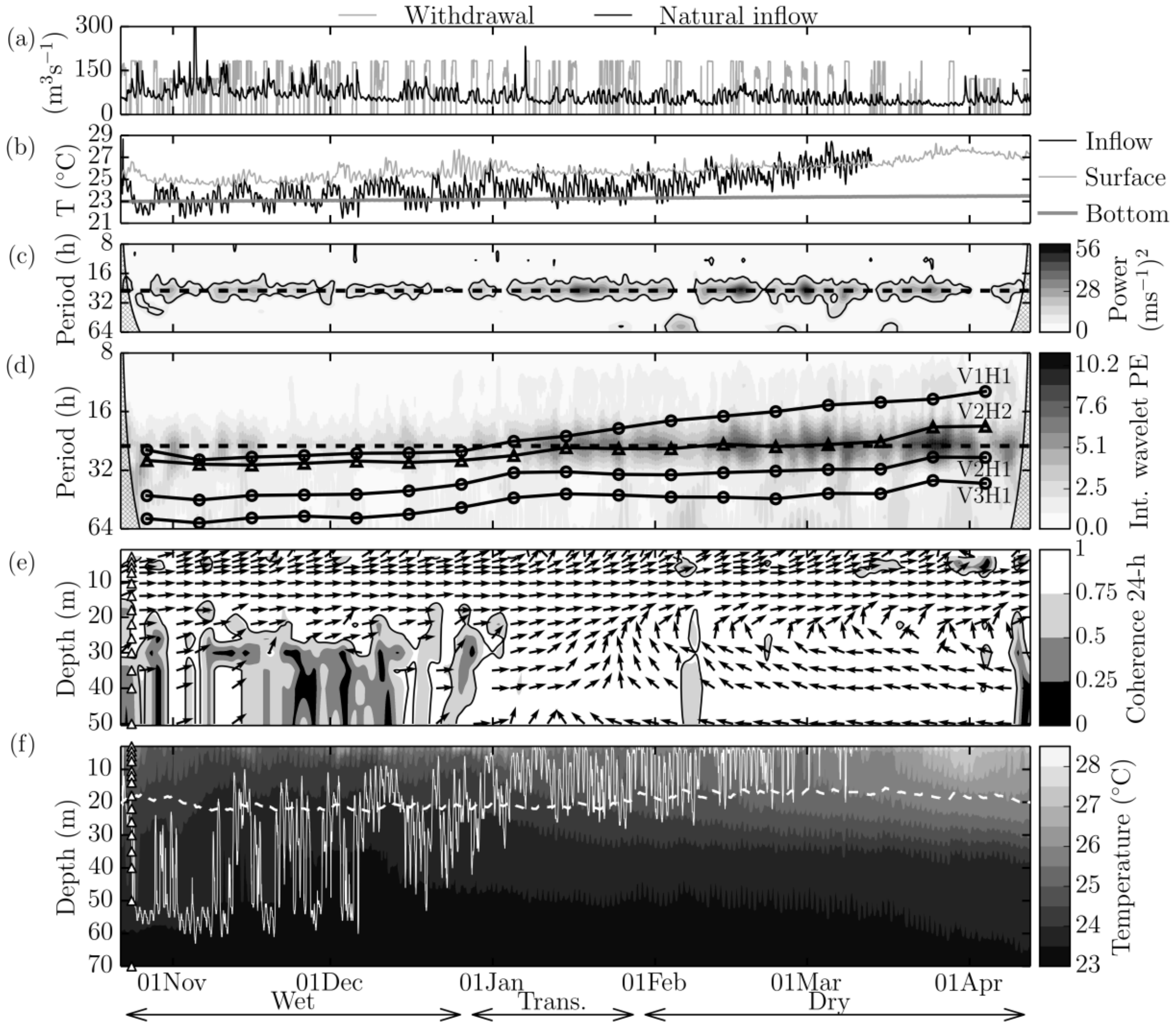

Figure 1. Seasonal evolution of external forcings and internal waves. (a) Flow, (b) inflow, surface and bottom temperature, (c) wavelet power spectrum of wind speed, (d) vertically integrated wavelet transform of discretized potential energy (PE) signal (contours) and natural periods evolution (black lines), (e) 24-h period wavelet coherence (contours) and phase difference (arrows) between temperature recorded at every thermistor against temperature at 12-m depth; right-pointing arrows (→) indicate in-phase fluctuations and left-pointing arrows (←) anti-phase fluctuations. (f) Thermal structure (contours), intrusion depth of inflows (white continuous line) and outtake depth (white dotted line).

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FVCOM modelling study of physical processes in a Scottish fjordic system

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KEYWORDS
Modelling; fjords; estuarine circulation; FVCOM; Scottish sea loch.

EXTENDED ABSTRACT

Introduction

Scottish coastal waters are characterized by an intricate coastline and complex bathymetry. The Scottish west coast consists of over 100 fjordic systems (sea lochs) with different characteristics often separated into two or more basins by sills (Edwards and Sharples 1986). A newly developed hydrodynamic model of the Scottish shelf, an FVCOM implementation (Chen *et al*. 2003, Wolf *et al*. 2016), is used to evaluate and interpret circulation patterns within one of Scotland's largest sea lochs, Loch Linnhe. The circulation in this system is forced by buoyancy gradients, winds, tides, and the Earth's rotation. Loch Linnhe has been extensively studied in the past with both models and observations because it is an economically valuable system including a variety of ecosystem services.

Materials and methods

In addition to the wider Scottish shelf model, four smaller-scale case studies have been implemented. These include higher resolution grids, especially in regions of interest, and the case studies have been run for certain time periods in addition to the climatology run. One of the case studies focuses on the wider Loch Linnhe system. We investigate a climatological run as well as a run from May to October for the year 2011 as an example. This time period was chosen because extensive field data from Loch Linnhe exists for that year along with previous model runs by a different model (i.e. POLCOMS, Holt and James 2001).

Two comparisons are performed between the unstructured grid FVCOM model and the previously run structured grid POLCOMS model. One focus is on differences in freshwater input (leading to differences in vertical salinity structure) and grid differences, when each model was forced with the best available forcing at the time the model was run. The other focus is on using the same (or as similar as possible) forcing and boundary data and then investigate differences between the two model outputs. A comparison against available observational data will also reveal goodness of fit of the two different models.

Results and discussion

Comparisons of model differences independent of forcing and boundary data leads to the following preliminary results:

- Freshwater input: Freshwater has a strong influence on sea lochs and coastal areas and is represented in the FVCOM model through a daily freshwater input derived from a distributed rainfall-runoff and routing model (Robson *et al*. 2010). In the POLCOMS model freshwater was introduced as distributed sources. These represented contributions from only a few side lochs and might therefore be cruder.

- Model grid: The FVCOM model resolves islands, sills, and the open boundary much better due to its flexible grid structure and smaller mesh size (tens of meters) in areas of interest/importance (Fig. 1). The POLCOMS model has a fixed 100x100m horizontal grid, and side lochs were not resolved. The vertical grids are different as well (sigma layers versus an s-grid configuration).

An investigation of the circulation within this sea loch with the help of the two different models (when using similar forcing and boundary data) looks at, for example, processes caused by wind forcing. Physical processes, such as deep water renewal over the 12m deep sill between the upper and the lower basins, is represented in the FVCOM model but not the POLCOMS model. An estuarine circulation develops in the system, which causes for example halocline differences in time and space, which in turn are of importance for ecological processes.

Due to an increasing interest in the extension of existing ecosystem services of the Loch Linnhe area and also new forms of development a good understanding of the underlying physical processes of the system and its connectivity to other areas are required.

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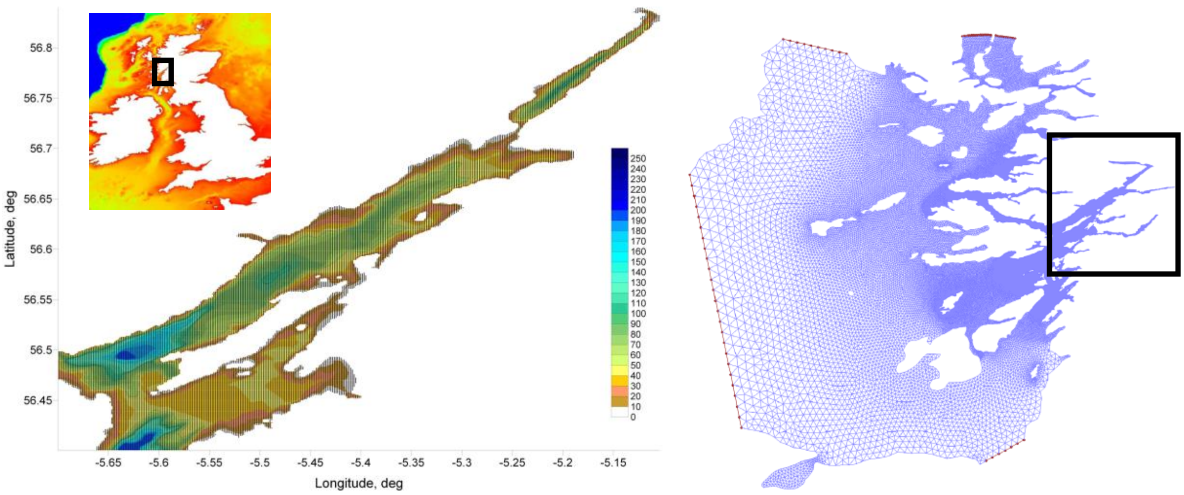

Figure 1: Left: POLCOMS Loch Linnhe model bathymetry (no side lochs resolved). Small map shows location of Loch Linnhe. Right: FVCOM model grid showing the larger extent of this case study and Loch Linnhe (including side lochs) in the black box.

Vertical mixing in a tropical Andean Reservoir, Porce II

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KEYWORDS
Tropical Andean reservoir, internal waves, density currents, vertical mixing.

EXTENDED ABSTRACT

Introduction

Observations have revealed density currents are the main precursor of seasonal water column temperature changes in tropical Andean reservoirs. In turn, the water column changes modify the mean and turbulent characteristics of the density currents and basin-scale internal waves. An understanding of turbulence mechanisms is crucial for a good comprehension of water quality in lakes and reservoirs. The influence of density currents and basin-scale internal waves on mixing at different time scales has not been investigated in tropical Andean reservoirs. Motivated by this, we investigated the vertical mixing in Porce II reservoir, an elongated Colombian reservoir located at 06°47'00"N. Porce II is 9.8 km long with a maximum depth of 92 m and it is fed by Porce River.

Materials and methods

Microstructure profiles of temperature and turbidity (~1mm resolution) and velocity (0.8 m bin-size) were measured in four short field campaigns carried out during dry and wet seasons between 2015 and 2016, when a marked difference was found in the vertical temperature stratification between seasons (Figure 1). The measurements were done in periods of different external forcing: before and after flood events and in weak and strong winds (Figure 1). We estimated different mixing indicators such as Reb (Buoyancy Reynolds number) and Kz (vertical eddy diffusivity) following Bouffard and Boegman (2013) (hereafter BB), L_T (Thorpe scale) and the F_{rT}-R_{eT} diagram (turbulent Froude-Reynolds numbers) proposed by Ivey and Imberger (1991) (hereafter I&I). The location where the data collection was done is not directly influenced by selective withdrawal, neither by differential cooling. During the measurement, negative atmospheric heat fluxes were not observed, so there was no convective mixing in the surface layer.

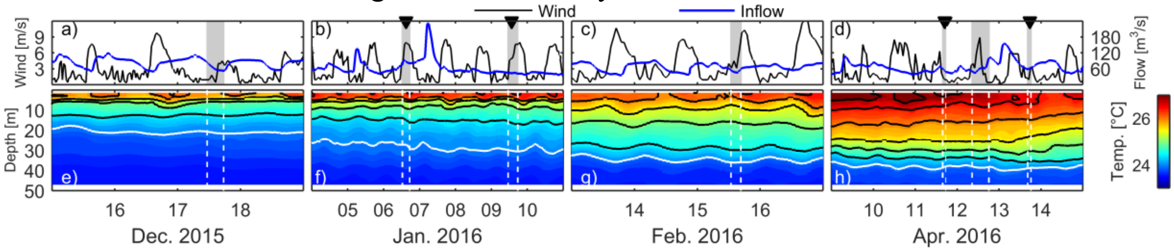

Figure 1. Evolution of wind, Porce inflow (a-d) and temperature in 48 m depth, at the measurement station (e-h). Gray rectangles (a-d) and white dashed-rectangles (e-h) show the times of measurements. Black countours are each 0.5°C. The white contour marks 24°C. Triangles mark the period of profiles in Figure 2.

Results and discussion

The observations revealed distinctive transport processes, being the basin-scale internal waves and density currents the most predominant. The amplitude of internal oscillations was larger during the dry periods, when the reservoir was more stratified but also the winds were the strongest (Figure 1a-d). The internal wave field had different structure according to the season, with V1H1 and V2H2 modes in transition and dry seasons respectively, but an indistinct mode in the wet season (Posada-Bedoya et al, 2017). Density currents behaved always as intrusive plumes, being shallower and less turbid in the dry season (Figure 2a-b), although in a flood event during the dry season (13/Apr) the plume was deeper, and changed the vertical temperature structure (Figure 1h). During basin-scale internal waves the generated turbulence was strongly stratified turbulence (Figure 3a, most points near the limits of Reb and $F_{R\Upsilon}$ around 8 and 3.9 respectively, with $F_{rT} < 1$), a characteristic of high stratification, low dissipation with anisotropic, and possibly youthful, turbulence (the ratio L_T/L_O, with L_O the Osmidov scale, increases above 1 as the non-dimensional parameter $L_{T\nu} = L_T(N/\nu)^{0.5}$ is large (Mater et al, 2015), Figure 3b). There was even no turbulence, as the regime for some patches was laminar (Reb ($F_{R\Upsilon}$) < 8 (3.9), $R_{eT} < 15$ and $Kz \sim 10^{-7} m^2/s$). The flood events generated, in general, isotropic-high turbulence (Reb~400 and higher, $F_{rT} \sim 1$ for large R_{eT} and $L_T/L_O \sim 1$ as $L_{T\nu}$ increases) with larger Thorpe scales (Figure 3c). As expected, the turbulence in the surface layer was also high and isotropic while the winds were strong, common behaviour in the dry season.

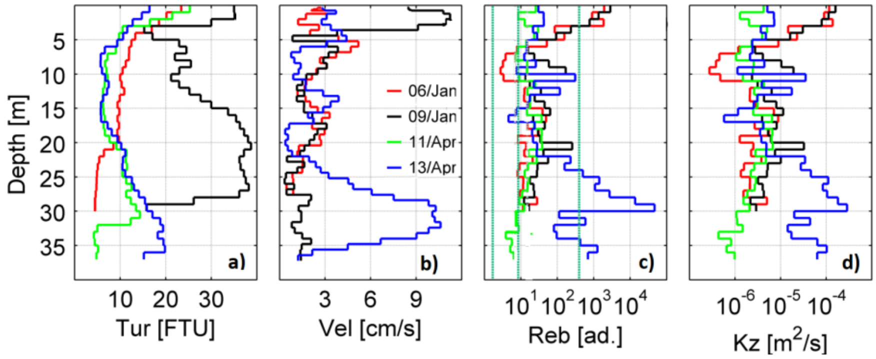

Figure 2. Bin and time averaged profiles (1 m bin per day) of a) turbidity, c) velocity (no velocity April 11), d) Reb (green vertical lines define turbulent regimes according to BB) and e) vertical eddy diffusivity.

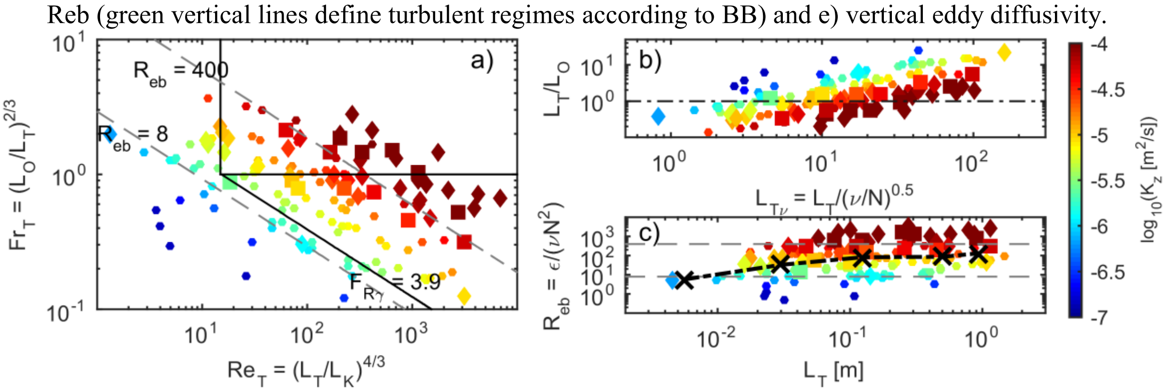

Figure 3. a) FrT-ReT diagram and limits by following I&I, b) The ratio L_T/L_O as a function of $L_{T\nu}$ (Mater et al, 2015) and c) Reb as function of L_T. Gray dashed lines in a) and c) mark the Reb regimes and in b) the ratio L_T/L_O =1. In the figures the rectangles mark the plume zone in April 13 (below of 23m), diamonds the mixing zone (above of 4m) and the circles the remaining data. Black cross-dashed line in c) is a running mean of Reb.

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Distribution of sea water natural constituents on shelves of Black Sea and Brazilian coast obtained remotely from board a ship

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KEYWORDS
Ecology of coastal waters, passive optical remote sensing, natural water constituents concentration.

EXTENDED ABSTRACT

Introduction

For studying of the ecological state of shelf waters it is often necessary to obtain data from a shipborne or an airborne measuring complex operating remotely [Mouw, 2015]. We used a three-channel passive optical spectrophotometer that enables us to get the sea reflectance coefficient spectra from board a moving ship. The data of the measurements were processed then according to our original method, which is based on the intrinsic properties of the pure water absorption spectrum – water absorption step method (WASM) [Rostovtseva, 2016]. It gives us the possibility to obtain estimates of the absorption spectra of the sea waters under exploration. The retrieved spectra in its turn were the source of information about water constituents concentration.

Materials and methods

The measurements were carried out with a semiautomatic measurement complex EMMA (Ecological Monitoring of Marine Aquatories) operating from board a ship at 1 Hz frequency. It includes three hyperspectral photometers, the data from which are processed by special algorithm on base of WASM. In natural waters we can get estimates of phytoplankton pigments, "yellow substance" and suspended matter concentrations. An example of EMMA operating from board a small ship and its main characteristics are given in Fig. 1.

EMMA: 3 STS-VIS
+ 2 fiber with lenses
+ 1 fiber with cosine corrector
STS-VIS:
Dimensions: 40mm*42mm*24mm
Weight: 60g
Detector: ELIS1024
Wavelength range: 350-800 nm
Integration time: 10µs – 10s
Signal-to-noise ratio: >1500:1 (maximal signal)
Dark noise: < 3counts rms
Slit: 50 µm
Optical resolution: 3 nm
Stray light: <0.25% at 590 nm
Fiber optic connector: SMA905

Figure 1. Monitoring of the sea water from board a moving ship with a semiautomatic measurement complex EMMA

Results and discussion

The data from the new semiautomatic complex EMMA obtained during the operative monitoring of coastal waters from board a moving vessel are given for two shelf regions with different types of sea waters: for the Black Sea coastal waters of oligotrophic and mesotrophic types as well as for Brazilian coastal waters at the Rio-Grande river mouth of eutrophic type. From every three measured at the same time spectra for the sea, the sky and the overall water surface illumination we calculated the sea reflectance coefficient spectra (this value being dimensionless is proportional to dimensional reflectance). Some typical sea reflectance coefficient spectra for both regions under investigation are given in Fig. 2.

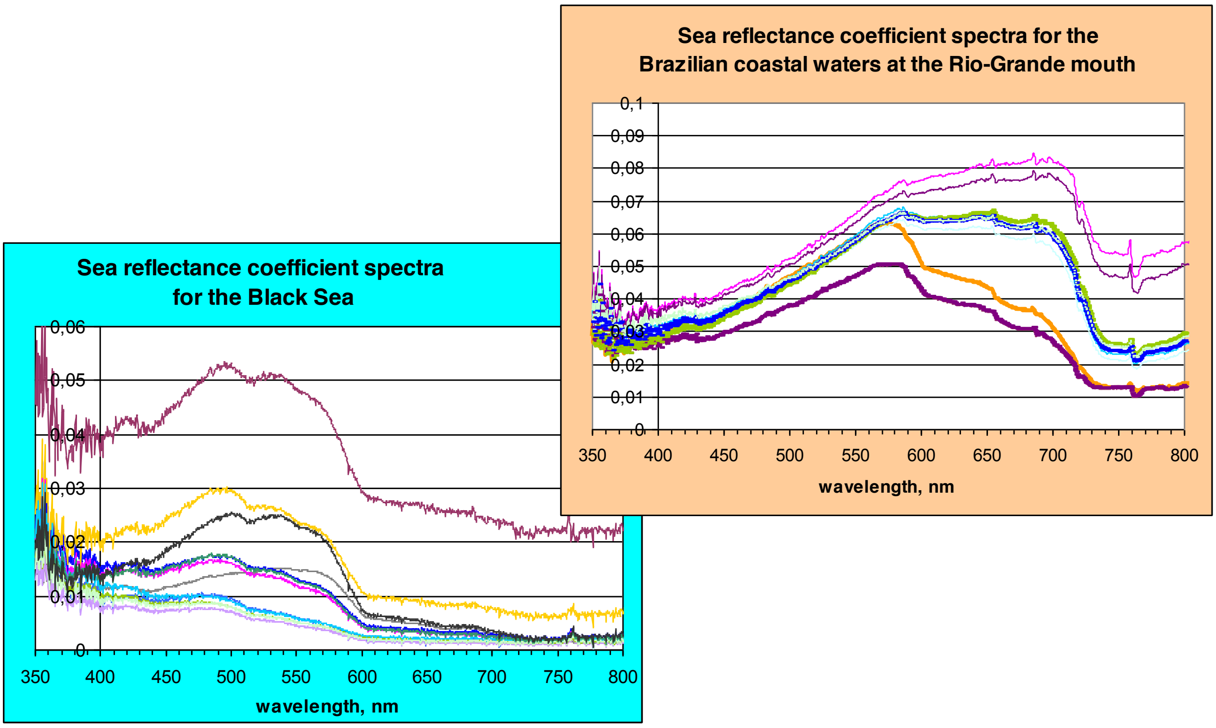

Figure 2. Sea reflectance coefficient spectra measured in oligotrophic, mesotrophic (the Black Sea) and eutrophic (the Brazilian coast) water types

The average difference in magnitude between the spectra from these regions (2 – 5 times) is not as big as the difference in constituents concentration (about 2 orders of magnitude). So we considered mostly the difference in shapes. Using such spectra with the help of WASM we estimated first the water absorption and then the concentrations of the sea water natural constituents such as suspended matter and coloured organic matter. Distributions of these sea water natural constituents over the shelves of the Black Sea and Brazilian coast were mapped. The obtained distributions are in good coincidence with the results of measurements in water samples and with the satellite data.

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On the feasibility of kinetic energy production by *Daphnia* diel vertical migration

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KEYWORDS
Biomixing; *Daphnia*; turbulence; eddy diffusivity; zooplankton.

EXTENDED ABSTRACT

Introduction

Biomixing refers to the contribution of living organisms towards the mixing of waters in oceans and lakes. Our project focuses on the stirring generated by *Daphnia spp.* in a small lake. This very common zooplankton species is engaged in a vertical migration (DVM) at sunset, with many organisms crossing the thermocline despite the density stratification. During the ascent, they may create hydrodynamic disturbances in the lake interior where the stratification usually suppresses the vertical diffusion.

Experimental measurements in an unstratified tank by Wilhelmus & Dabiri (2014) show that zooplankton can impart kinetic energy at length scales bigger than organism's size of few mm through collective motions. Noss & Lorke (2014) measured instead the eddy diffusivity K_V from *Daphnia* induced migration in a stratified water tank, suggesting that the zooplankton species generates no mixing, with $K_V=10^{-9}$ m^2 s^{-1}. Very recently, DNS by Wang & Ardekani (2015) showed instead a maximum diffusivity of $K_V=10^{-6}$ m^2 s^{-1} for millimetre-sized swimming organisms, therefore supporting the idea of zooplankton-generated mixing.

Materials and methods

Measurements were conducted on three different days (21 July, 28 July and 18 August 2016), during the summer stratification, in Vobster Quay, a small and deep (40m) quarry with small wind fetch and steep sides, located in the south-west UK. Zooplankton vertical concentration was evaluated using a zooplankton 100-µm mesh net, by collecting and analysing samples in 8 layers of the lake. A bottom-mounted ADCP was also employed to track their concentration and migration with the measured backscatter strength. Turbulence and mixing were measured before and during the DVM with the SCAMP, a microstructure temperature profiler. Dissipation rates of turbulent kinetic energy (TKE) were determined by fitting the Batchelor spectrum of temperature fluctuations and removing invalid spectra with statistical criteria by Ruddick et al. (2000).

Results and discussion

Figure 1 shows the time series of TKE dissipation rates ε in the foreground (top colour-bar) overlapped with the estimated *Daphnia*'s concentration (bottom grey colour-bar). Data with $\varepsilon < 10^{-9}$ W kg^{-1} are not shown because they represent undisturbed water with background turbulence conditions. Our data do not show evidence of intensified turbulence during the vertical ascent of *Daphnia*: turbulent patches do not increase either in frequency or in dissipation magnitude on any of the three different sampling dates, despite high *Daphnia* concentrations up to 90 org. L^{-1} during the DVM in the migrating layer. We observed no correlation between the zooplankton concentration and turbulence. Moreover, turbulent patches were too sporadic to create mixing, even if they were generated by the migrating zooplankton. Part of the observed dissipations might have been associated with penetrative convection or wind-driven motions but in any case, turbulence was not effectively enhanced enough to prevail over other shear-generated instabilities.

This seems to suggest that migrating *Daphnia* do not globally affect the mixing regime. However, microstructure profilers based on temperature fluctuations measurements may not be suitable for turbulence sampling if the generated eddy diffusivity is less than 10^{-7} $m^2 s^{-1}$.

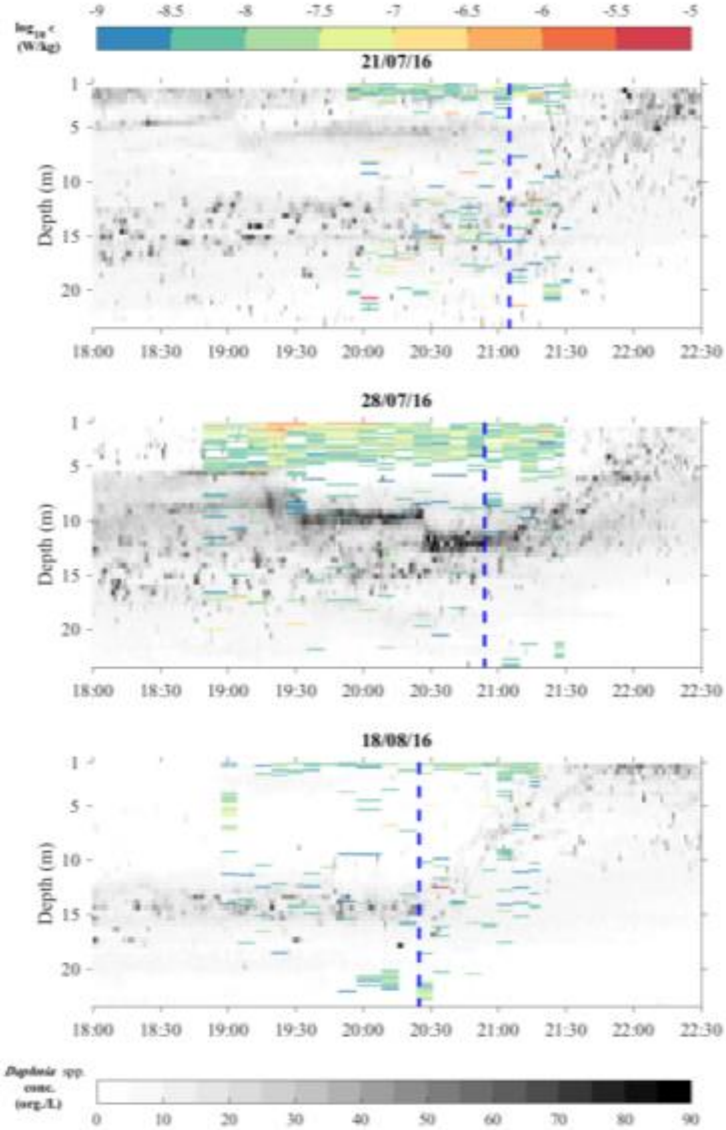

Figure 1: TKE dissipation rates ε in the foreground (top colour-bar) overlapped with the estimated *Daphnia*'s concentration (bottom grey colour-bar). Blue dashed line shows the sunset time when DVM begins.

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Measurement of Greenhouse Gas Emissions from Reservoirs

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KEYWORDS
Eddy covariance; methane and carbon dioxide emissions; ebullition; temporal and spatial variability; meteorological impact.

EXTENDED ABSTRACT

Introduction

The emissions of carbon dioxide (CO_2) and methane (CH_4) from inland waters are an important source in the global greenhouse gas (GHG) balance (Bastviken et al., 2011; Raymond et al., 2013). Reservoirs are particular hot spots of GHG emissions (Deemer et al. 2016). The GHG emissions are temporally and spatially highly variable (Zhao et al., 2013). Currently, there is not much known about the actual flux rates from temperate reservoirs, and the processes involved are not completely understood. In our recently started project TregaTa, we aim to quantify the GHG emissions from two German reservoirs. The central topic is the understanding of the regulation of CO_2 and CH_4 emissions and, especially, to comprehend effects of altering water levels, trophic state and meteorological drivers. We would like to test three major hypotheses:

(1) Short term events contribute significantly to the overall balance.

(2) Temporal patterns of CO_2 and CH_4 emissions depend on the trophic state of the reservoir and are complexly overlaid by atmospheric effects.

(3) The spatial distribution of the CO_2 and CH_4 fluxes depends differently on internal (e.g., hydro-chemical parameters and water depth) and external interacting factors (e.g., wind, air pressure, radiation and energy balance).

Our project is placed in the nexus between limnology, hydrology and boundary layer meteorology. We will investigate two different reservoirs – the mesotrophic Rappbode reservoir in the Harz Mountains and the eutrophic reservoir Bautzen in Lusatia. Temporal patterns of CO_2 and CH_4 emissions will be quantified by a combination of micro-meteorological and water-side measurements. Central to the project is a floating Eddy Covariance (EC) measurement system. The conflation of EC flux measurements, in situ concentration measurements of the water body, and meteorological basic data allows the determination of the physical gas transfer coefficient. Additionally, the spatial variability of GHG emissions will be analysed by floating chamber measurements and ebullition funnels (bubble traps). The measurements of emission rates are accompanied by the analysis of sediment and hydro-chemical parameters, e.g., pH and concentrations of O_2, CO_2 and CH_4 as well as by continuous measurements of energy balance, radiation budget and classical meteorological variables. Proper modelling approaches will be used for generalisation and regionalisation of measurements and project results.

Materials and methods

A floating measurement station has been established on Rappbode reservoir in March 2017 to measure greenhouse gas (GHG) emissions and energy exchange between water surface and atmosphere via eddy covariance (EC) technique. EC measurement are the state-of-the-art method to monitor carbon dioxide flux exchange (F_{CO2}) and methane emissions (F_{CH4}) as well as sensible (H) and latent heat fluxes (LE). However, EC measurements on floating platforms are not a standard task but imply several technical and scientific challenges. Notwithstanding that the concept of a floating platform is an elegant opportunity for EC measurements which are largely unaffected by surrounding land surfaces. Our prototype of a floating platform is easy to assemble and provides a proper basis for 'offshore' observations.

The EC measurement system device consists of an ultrasonic anemometer (Campbell CSAT3, Campbell Scientific Ltd., UK) for measurements of 3-dimensonal wind velocity, a closed-path gas analysers, LI-COR LI-7000 (LI-COR Biosciences, USA) for high frequency concentration measurements of carbon dioxide and water vapour in air, an open-path gas analyser, LI-COR LI-7700 (LI-COR Biosciences, USA) for high frequency measurements of methane concentration in air, a logger unit (Campbell CR6, Campbell Scientific Ltd., UK) and a high frequency inclinometer (SCA114, a.b.jödden GmbH, Germany) to monitor platform movement. The EC system is operated with 10 Hz, i.e., data of 3-dimensonal wind speed, air temperature, platform's roll and pitch angle as well as air concentrations of methane, carbon dioxide and water vapour are measured and logged 10-times per second.

Based on high frequency raw data, exchange rates, i.e., H, LE, F_{CO2} and F_{CH4}, are processed according to standards of EUROFLUX community (Aubinet et al., 2012) and usage of the software package EdiRe (The University of Edinburgh, 2007) in half-hourly resolution. Outliers and data beyond absolute limits are eliminated, covariances and raw fluxes are calculated based on half-hourly block averages, and time lags between wind speed and gas concentration measurements are removed applying covariance maximisation. The axis rotation for tilt correction is applied using double rotation method as described by (Wilczak et al., 2001). However, standard proceeding of tilt correction is extended by algorisms correcting actual roll and pitch angles of the platform measured by the attached inclinometer. Furthermore, flux processing includes algorisms for spectral attenuation (Spank and Bernhofer, 2008), sonic temperature correction (Schotanus et al., 1983) and density fluctuations (Webb, 1982). The quality of processed fluxes is assessed according to Foken and Wichura (1996)

Besides turbulent fluxes, radiation balance, i.e., all four components of radiation balance (Campbell CNR1, Campbell Scientific Ltd., UK; installed 1m above water surface) and water temperature in different depths are measured for assessment of energy balance and energy exchange of water body. Sensors (LI-COR LI-190SZ, LI-COR Biosciences, USA) to monitor incoming and reflected photosynthetic active radiation are installed 1 m above the water surface. Photosynthetic active radiation is also measured in water depths of 0.25 and 4.0 m (LI-COR LI-193, LI-COR Biosciences, USA) to estimate penetration depth of solar radiation. In addition, air temperature and air humidity (HMP 45, Vaisala, Finland) are logged.

The micro-meteorological and hydro-physical measurements are supplemented by continuous hydro-chemical observations of oxygen (O_2), carbon dioxide and methane as well as special measurement campaigns (executed twice per month) investigating spatial variability of CO_2 and CH_4 emissions via chamber measurements. Bubble traps are installed at several points in the reservoir to investigate ebullition. The oxygen sensors (D-Opto, Zebra-Tech Ltd, New Zealand) are installed in a depth of 0.25 m and 4 m. The sensors for continuous measurements of dissolved CO_2 (CONTROS HydroC CO2, Kongsberg Maritime Contros GmbH, Germany) and CH_4 (METS methane sensor, Franatech GmbH, Germany) are installed shallowly below the water surface in a depth of 25 cm. Thus, fluxes of CO_2 and CH_4, derived from EC measurement, can be cross checked with fluxes that are classically estimated from concentration differences between water and air as well as with floating chamber measurements

Results and discussion

At the workshop, we will present a complete data set of greenhouse gas emissions and energy exchange form the transition of spring mixing to summer stagnation. Special focus of the presentation will be on the effect of meteorological 'extremes' such as storm events on emissions of CO_2 and CH_4. At the same time, we want to provide an honest report on specific technical challenges and hurdles as well as an initial assessment of the feasibility of 'offshore' EC measurements. Figures 1 and 2 show the complete instrumented station and the position of the station (51° 44.2726'N, 10° 53.4270'E) on the Rappbode reservoir. It should be noted that the distance to the nearest bank is more than 150m and to the dam 270m.

Figure 1: Floating micro-meteorological and hydro-chemical measurement station on Rappbode reservoir in Harz Mountains. The poles and wires are for lighning protection.

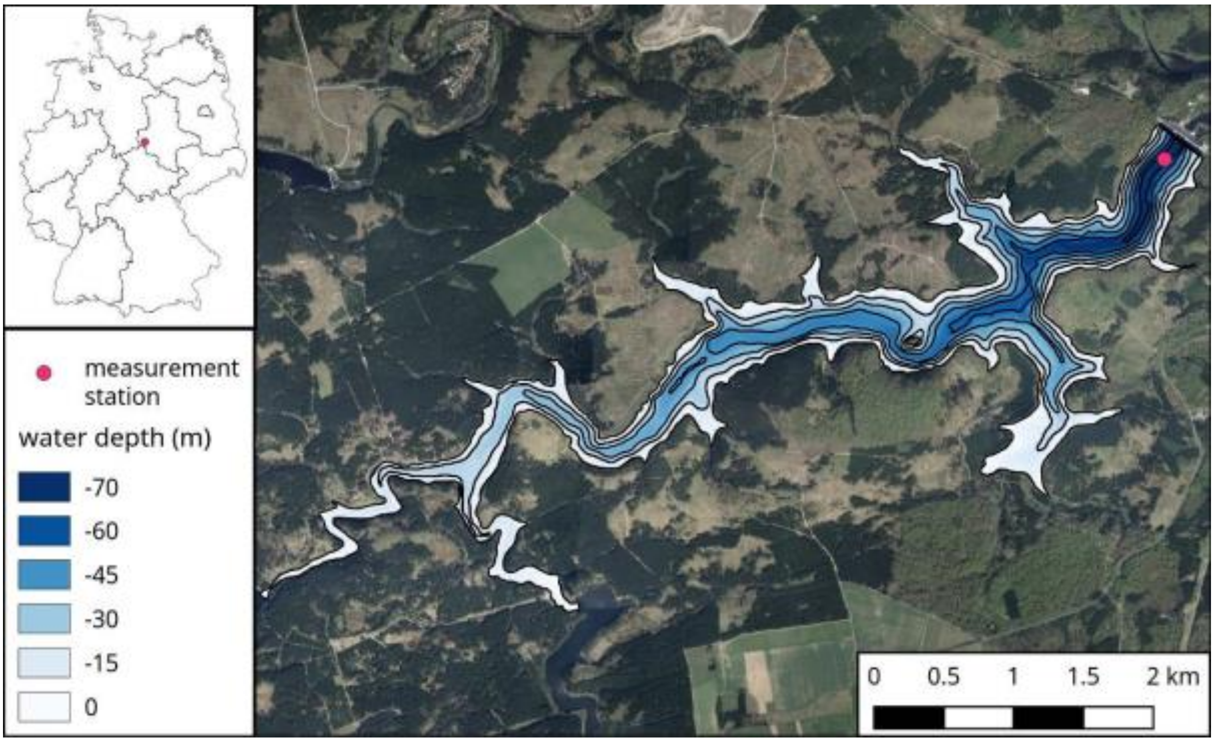

Figure 2: Location of Rappbode reservoir in Germany (upper left) and position of the measurement station on the Rappbode reservoir (right). Also shown bathymetric characteristic of reservoir

Acknowledgements

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Earth rotation vs. seiching in lakes: implications for one-dimensional modelling

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Keywords
Lakes; seiches; Coriolis force; modelling; mixed-layer dynamics.

EXTENDED Abstract

Introduction

Most 1D lake models developed so far are based on equations for heat and momenutm of boundary-layer theory taking into account Coriolis force, where horizontal lake sizes are not involved. More sophisticated 1D models incorporate area-depth dependence introducing exchange of scalars and momentum between water body and sloping bottom and explicitly specifying the water volume over which momentum, heat and gases are distributed. These models, however, still lack the gross features of lake dynamics, such as 3D mass distribution, surface level variations and related horizontal pressured gradients altogether caused by presence of impermeable boundaries. In lakes, all these features are interconnected by mechanism of gravitational barotropic and baroclinic waves (seiches), affected by Earth rotation. The linear wave theory tells us that Coriolis force becomes negligible compared to pressure gradient when the lake is much smaller than the internal Rossby deformation radius, which is several kilometers in summer in midlatitudes. Thus, for such lakes, models may neglect rotation but should necessarily account for barotropic and baroclinic horizontal pressure gradient. However, conventional 1D lake models include Coriolis acceleration, but not horizontal pressure gradient. Moreover, numerous applications of such models to small lakes demonstrate they are still capable of realistically reproduce the vertical mixing. This poses the questions, addressed in current study:

– what is the reason for apparent realistic vertical mixing in conventional 1D lake models, whereas the simulated lake dynamics is far from that in enclosed water bodies?

– what are the ways to parameterize lake seiching motions in 1D models?

Materials and methods

We propose a mathematical approach to include seiche motions into 1D lake model. It combines traditional 1D equations for simulating continuous vertical profiles of momentum, temperature and tracers, with multilayer model of seiche dynamics, operating with step-wise density profile schematization (e.g. Münnich et al., 1992). The key hypothesis making it possible is that only 1-st horizontal seiche mode is considered, justified by a bulk of empirical evidence indicating that this mode contains a major part of internal wave energy (e.g., Horn et al., 1986; Kirillin et al., 2015).

Consider a stratified basin of uniform depth H with horizontal dimensions L_x and L_y. Assume, that the vertical density profile may be approximated by N homogeneous layers, of mean thicknesses and densities H_i and ρ_i, respectively. Then, under moderate wind forcing the mean velocity components and thickness deviations h_i' for all layers of the frictionless fluid are governed by a linearised multi-layer set of shallow water equations, linked by hydrostatic approximation. On the other hand, the momentum equations for these layers may be derived from the momentum equations of 1D model as well by vertical averaging, providing the same equations but with extra inter-layer friction terms. As friction reduces h_i', linearised equation for h_i' (continuity equation) from multi-layer system holds when 1D momentum equations are used to describe average velocities in discrete layers. This enables to involve h_i'-equation to close the horizontal pressure gradient terms in 1D momentum equations, keeping this gradient constant in each i-th layer. The continuity equation is 2D in horizontal, so the predefined horizontal structure for h_i' and velocities has to be assumed in order to fit the 1D framework. Hence, we assume 1-st horizontal mode in both horizontal directions for these variables. The resulting momentum equations of 1D model take the form:

$$\frac{\partial u}{\partial t} - \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z} - lv = -\frac{\pi g}{2L_x\rho_j}\sum_{k=1}^{N}\rho_{\min(j,k)}\Delta_x\overline{h'_k},\ j: z \in [z_j, z_{j+1}),$$

$$\frac{\partial v}{\partial t} - \frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z} + lu = -\frac{\pi g}{2L_y\rho_j}\sum_{k=1}^{N}\rho_{\min(j,k)}\Delta_y\overline{h'_k},\ j: z \in [z_j, z_{j+1})$$

$$\frac{d\Delta_x\overline{h'_j}}{dt} = \frac{2\pi H_j}{L_x}\overline{u_j},\ j = \overline{1,N},$$

$$\frac{d\Delta_y\overline{h'_j}}{dt} = \frac{2\pi H_j}{L_y}\overline{v_j},\ j = \overline{1,N}.$$

where z_j, z_{j+1} are the boundaries of j-th layer, u and v in last two equations (that are derived from continuity equation) are averaged over j-th layer. The left-hand sides of first two equations represent the traditional 1D momentum equation terms, while the right-hand sides stand for the pressure gradient force. Hence, the pressure gradient force is represented as piecewise-constant with depth. The seiche parameterization described above has been introduced into the 1D LAKE model (Stepanenko et al., 2016).

Results and discussion

The model described above was run in the idealized Kato-Phillips experiment setup, where the wind-driven mixed layer deepens into the stratified water basin. It is shown that for the small horizontal size of a lake, seiches are the main contributor to hampering the mixed-layer deepening, while for the lake size much exceeding the Rossby deformation radius, Coriolis force effect dominates. The side effect of seiches in a small basin is production of shear-driven turbulence near the bottom, that cannot be reproduced by conventional 1D models.

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Coupled methane and oxygen dynamics during distinct periods of thermal stability in a small Swiss lake (Soppensee)

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KEYWORDS
eutrophic lake; methane dynamics; greenhouse gases emission; thermal stratification; methane bubbling.

EXTENDED ABSTRACT

Introduction

Methane (CH_4) is a potent greenhouse gas and its emissions from lakes are significant at the global scale. Lake CH_4 emissions to the atmosphere are the net results of production and removal processes. Unless CH_4 is directly emitted through ebullition (McGinnis et al. 2006), it is often assumed that most CH_4 is oxidized before reaching the atmosphere (Bastviken et al. 2008). Physical transport is thus the key to link CH_4 production/removal and efflux, as it will dictate if produced CH_4 will be oxidized or emitted. Understanding the complex interaction between CH_4 production/removal and lake hydrodynamics is central quantify CH_4 dynamics under future environmental changes.

Here we resolve the vertical fluxes of CH_4 during different stratification periods using profiles and vertical diffusivities (K_z). We then evaluate the production and consumption rates by a mass balance approach and compare with laboratory incubations.

Materials and methods

Soppensee, a small (26 ha and maximum depth of 27 m) eutrophic kettle lake situated in the Canton Lucerne, Switzerland, was sampled monthly from April to October 2016 for CH_4 diffusive fluxes and profiles. A temperature chain was deployed at the deepest point of the lake to calculate vertical diffusivity (K_z) using the heat budget method.

Monthly water column CTD/O_2 and dissolved CH_4 (with stable isotopes) profiles were performed at the deepest point of the lake. Diffusive flux with the atmosphere was measured using a floating chamber connected in a closed loop with a portable greenhouse gas analyser. Bubble-mediated CH_4 fluxes were estimated using inverted funnels. Vertical diffusive gas (CH_4 and O_2) fluxes at depth between epilimnion/metalimnion and metalimnion/hypolimnion were estimated using Fick's first law of diffusion. We calculated the CH_4 mass budget for each layer of the lake (epi-, meta- and hypolimnion) for each stratification periods (warming, stable and cooling). Sediments cores were taken to evaluate CH_4 production and diffusive flux. Methane oxidation was assessed using lake water in situ incubations.

Results and discussion

In Soppensee, O_2 saturation varied in the surface layer from 80%, in spring to 230% in July-August during the strongest stratification period. Bottom waters (10-25m) remained anoxic until November (Figure 1a). In the epilimnion, dissolved CH_4 concentrations were always oversaturated, often around 200-300 times the atmosphere saturation, but ranging from 3 to up to 1000 times) (Figure 1b).

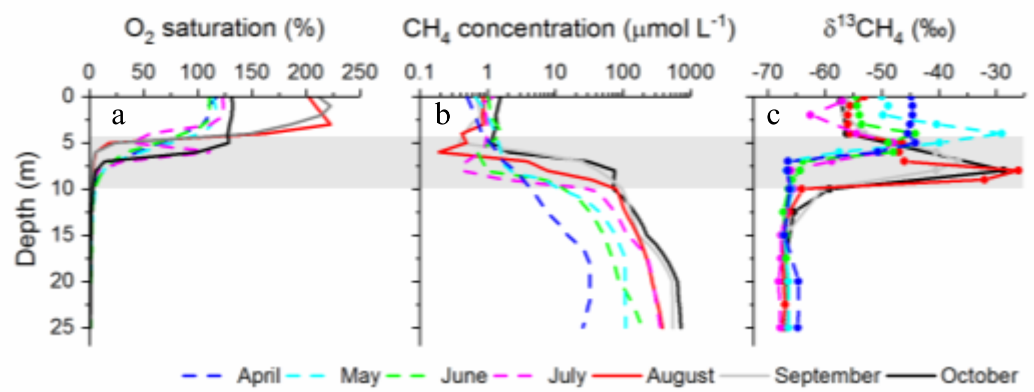

Figure 1. Water column profiles of O_2 saturation (%), CH_4 concentration (µmol L^{-1}) and CH_4 isotopic signature $\delta^{13}C$-CH_4 (‰). Grey area represent the metalimnion.

As CH_4 diffusion at the epi-/metalimnion interface was nearly zero until fall mixing, surface fluxes were almost completely independent of processes occurring in the deeper layers. The net CH_4 production rates derived from the mass balance were constant during the stratified period (~0.34 mmol m^{-3} d^{-1}). This suggests that summer diffusive fluxes were entirely sustained by local processes, either coming from the littoral environments (Bastviken et al. 2008), from bottom water via non-diffusive processes like CH_4 bubble re-dissolution (McGinnis et al. 2006), zooplankton-mediated transport (McGinnis et al. 2017) or by in situ production (Donis et al. in review).

The metalimnion acts as a "CH_4 trap", where it is actively oxidized. Between June and October, a CH_4 minimum peak concentration remained ~0.3 µmol L^{-1}. Most of the oxidation activity occurred at the base of the metalimnion, as indicated by enriched ^{13}C-CH_4 values (Figure 1c). Rates of oxidation derived from the mass balance agreed well with incubation rates (~ -0.3 µmol L^{-1} d^{-1}). We calculated that CH_4 oxidation accounted for about 30% and 18% of the net O_2 consumption in the metalimnion during the warming and stable periods, respectively.

In the hypolimnion, dissolved CH_4 accumulated due to strong water column stability to almost 1000 µmol L^{-1} (Fig 1). The rate of CH_4 accumulation (below 10 m) was an order of magnitude higher than what Bastviken et al. (2008) found in two oligotrophic lakes, even though sediment fluxes were comparable. We estimated from the mass balance sediment CH_4 production rates of 9.7-13.7 mmol m^{-2} d^{-1}, in good agreement with the CH_4 diffusion and production rates from incubations.

Our results show that in this small eutrophic lake, summer emissions are sustained and independent of deep-water methane. The vertical diffusivity strongly modulates O_2 and CH_4 vertical fluxes and accumulation, which in turns drives the CH_4 fate and emission. Implementing robust lake hydrodynamics is necessary to refine constituent budgets leading to robust insights on their fates.

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Radiatively-driven convection in a small ice-covered lake: Dynamics of velocities and energy dissipation

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KEYWORDS
Ice-covered lakes; convection; energy dissipation; convective cells dynamic.

Introduction

Radiatively driven convection in ice-covered lakes is a unique natural phenomenon suitable for studying the fundamentals of turbulence onset and development in a stratified fluid. The convective mixing during late spring, being the most energetic event during the ice season, governs the dynamics of important chemical and biological processes. A number of papers are devoted to studying the mixed layer properties and penetrative convection dynamics, but some topics still remain challenging, including in particular 2D-3D interplay, turbulent transport specifics, intermittency effects. These challenges are only stressed by some LES and direct numerical simulations. More detailed experimental data is necessary for further progress.

Materials and methods

For Lake Vendyurskoe, a typical shallow (max depth 13 m) boreal lake, located at southern part of Russian Karelia, the first observations of convection under the ice were taken in spring 1994 and 1995. During 2000's seasons the structure and dynamics of water temperature have been studied in detail by analyzing the observational data [Mironov et al., 2002]. A new stage of the research began in April 2016, when the Aquadopp HR-profiler was used for measuring all three velocity components. The scanned region included the 2-m thick layer under the ice. Spatial (vertical) resolution of 5 cm was chosen with records one minute apart taking into account the values of $r_d = (\eta^3/\varepsilon)^{1/4} \sim 3$ mm and $t_d = (\eta/\varepsilon)^{1/2} \sim (10\text{-}30)$ s of Kolmogorov scales.

Results and discussion

The prior attention is paid to mean velocity and pulsations profiles and its diurnal dynamics, along with the energy dissipation rate ε. The Temperature Microstructure Method based on fitting the experimental series with Batchelor spectra was explored in [Jonas et. al., 2003] for evaluating ε. One of the alternative ways to derive the value of ε is based on the analysis of 2-point structure functions. With available experimental data only the following types of longitudinal and transverse structure functions are available

$$D_{NN}(z) = \left\langle (u(z_0 + \Delta z) - u(z_0))^2 \right\rangle$$

$$D_{LL}(z) = \left\langle (w(z_0 + \Delta z) - w(z_0))^2 \right\rangle$$

Here z_0 is the reference point; u and w are horizontal and vertical velocity fluctuations, respectively; < > denotes the averaging with time.

Both functions are calculated for different time intervals and depths z_0. In most cases the presence of the so-called inertial interval was proved. Namely, the classical asymptotic dependence $D = C\, \varepsilon^{2/3} r^{2/3}$ valid for $L \gg \Delta z \gg r_d$, is detected (L is the thickness of the layer). For both structure functions the $r^{2/3}$ – interval is clearly manifested in daytime within one decade and even more: 0.05 m < Δz < (0.5-1) m as presented in the Figure. This result can be regarded as clear evidence of the fully developed turbulence regime.

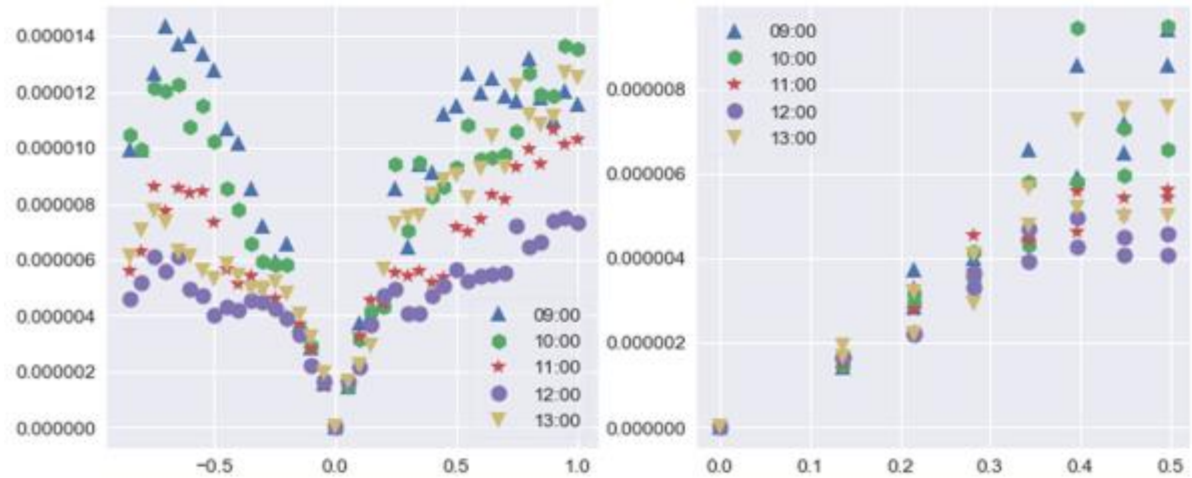

Figure 1: Transverse structure function evolution during daytime. Apr 10 2016. Left – $D_{NN}(\Delta z)$, right – $D_{NN}(\Delta z^{2/3})$, reference point – 1 m.

As for estimation of ε, it was straightforward, through identification of inertial interval and applying least squares method for analyzing linear correlation between D and $r^{2/3}$. The typical values vary within few units of 10^{-8} Wt/kg during daytime with mean value close to $4*10^{-8}$. The mean error was about 5 %. It must be stressed that calculated values for vertical and horizontal rates of energy dissipation are sufficiently different. This finding strongly indicates the anisotropy of pulsations even in the inertial interval. In night series, the inertial interval is rather hidden, and ε estimations are not fully accurate. However, the rough correlation of ε(t) with radiation dynamics is obtained.

Last but not least, the question concerning the direction of energy transfer arises. Taking into account both the existence of inertial interval and the dynamics of Reynolds stress tensor components, we can conclude that the transfer is direct (large to small scales) during daytime.

As for further activity, we plan to concentrate on

- More detailed analysis of correlation between dynamics of solar radiation and ε, in particular: do there exist time lags, radiation thresholds etc.

- The study of the mechanisms of energy supply and anisotropy survival.

- The thorough analysis of high-order (at least – cubic) 2-point structure function in order to shed an additional light on the specifics of direct energy transfer.

The study was supported by the Russian Foundation for Basic Research (project 16-05-00436_a).

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Combining downstream river demands with a sustainable raw water supply from a drinking water reservoir

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KEYWORDS
Reservoir management; reservoir modelling; selective withdrawal; thermal stratification; hypolimnetic dissolved oxygen.

EXTENDED ABSTRACT

Introduction

Dams and reservoirs interrupt the river continuum and affect water temperature, discharge, sediment transport and nutrient availability downstream. Freshwater resources like rivers and drinking water reservoirs must be specially protected in times of global change and population growth. Therefore, the demands of a safe raw water supply and a good ecological status of the downstream river should be balanced.

Selective withdrawal is a common practice in reservoir management to control downstream discharge and in-reservoir water quality. While selective epi-/metalimnetic withdrawal allows to reconstruct the natural downstream temperature, hypolimnetic withdrawal through the bottom outlet controls the dissolved oxygen (DO) content in the deep reservoir layers. In this study, we aim at improving the current withdrawal strategy focussing on three goals:

- restoring the natural temperature and flow discharge downstream,
- securing raw water quality by maximizing hypolimnetic oxygen,
- minimizing the loss of hypolimnetic water.

Because all three goals are inter-linked and could not be altered without a feedback on the others, we use a numerical reservoir model to link water quantity management with water quality.

Materials and methods

We set-up the numerical model for the second largest drinking water reservoir in Germany, the oligotrophic and monomictic Grosse Dhuenn Reservoir (max. volume 81 million m). For a realistic withdrawal management, we included reservoir management parameters and operational rules into the source code of the model. Now, the model is able to determine the best height for selective epi-/metalimnetic withdrawal based on stratification and the interaction with the bottom outlet withdrawal during runtime. First, we identified the practicability of a new withdrawal strategy that focuses on the temperature and flow requirements of the downstream river. Second, we searched in scenario simulations for the ideal balance of both withdrawal types to avoid low-oxygen conditions in the deep hypolimnion while keeping discharge temperature natural.

The reservoir model and its source code are freely available for download from GitHub (https://github.com/AquaticEcoDynamics).

Results and discussion

We found that a predominant withdrawal from the epi-/metalimnion severely affected stratification and decreased hypolimnetic DO concentrations. Using a parallel withdrawal through the bottom outlet kept DO concentrations sufficiently high enough (3-4 mg/L) to guarantee a safe raw water supply (Fig. 1c). Scenario simulations showed that a smart mixing of cold hypolimnetic water with warm epi-/metalimnetic water to follow a target downstream temperature and flow discharge can be achieved without jeopardizing raw water quality.

The model was able to restore the natural temperature downstream as closely as possible (Fig. 1b, RMSE 1.7 °C for summer period). The average water temperature of the withdrawn water was 11.7 °C and approximately 6.3 °C higher than with a withdrawal strategy using the bottom outlet withdrawal only. Our new withdrawal strategy with only four parameters can be easily integrated into the operational use.

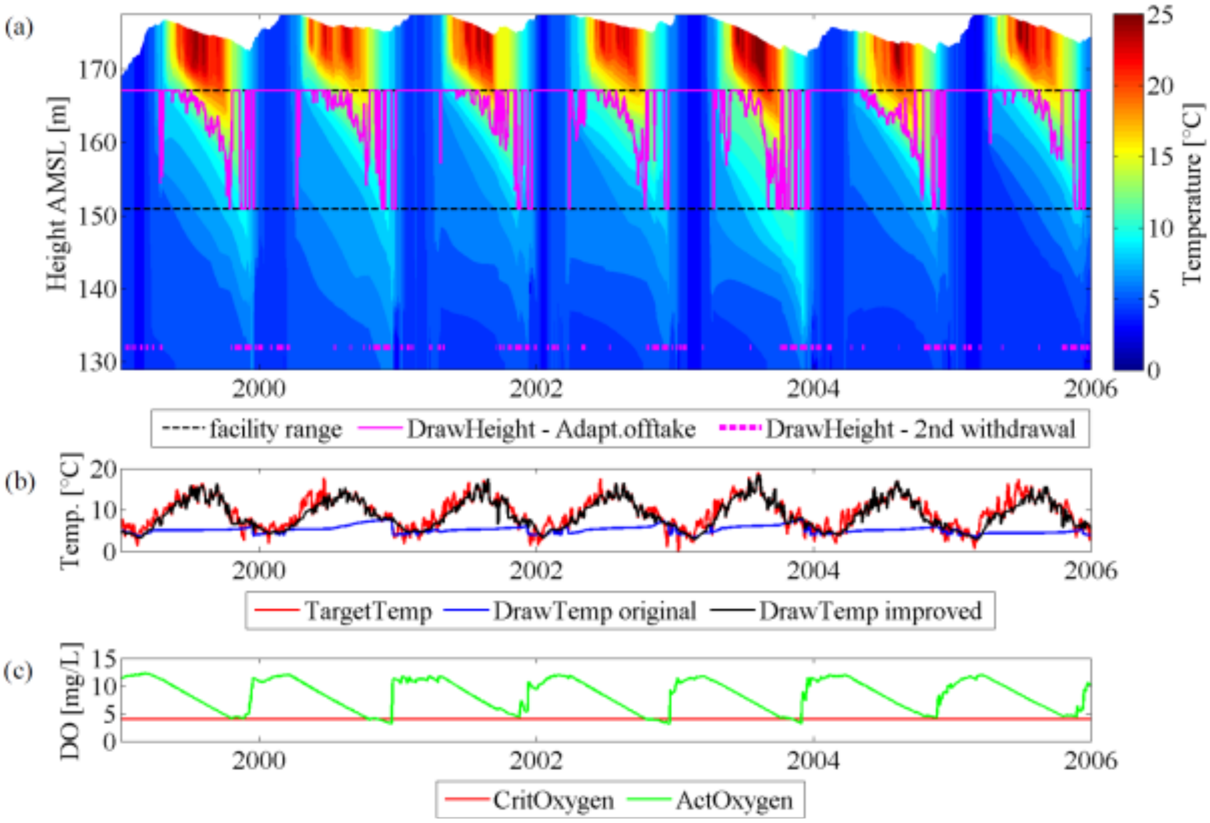

Fig. 1. (a) Contour plot of simulated water temperatures of the Grosse Dhuenn Reservoir assuming improved withdrawal strategy over the period of 1996-2013; the solid magenta line indicates the autonomously determined withdrawal height for the pivoted pipe (selective epi-/metalimnetic withdrawal) on basis of upstream river temperature and flow discharge as a target; the dashed magenta line indicates withdrawal height and time, when the bottom outlet was activated. (b) Upstream river temperature as target discharge temperature (red solid line) versus original operated (only bottom outlet, blue solid line) and improved (both withdrawals, black solid line) discharge water temperature achieved by the model. (c) Simulated dissolved oxygen concentrations in 5 m above bottom (green solid line) of the improved withdrawal strategy versus the threshold for the model of 4 mg/L (red solid line).

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ABSTRACTS

Flowpath and retention of snowmelt in an ice-covered Arctic lake

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ABSTRACT

The extent to which snowmelt flowing into ice-covered lakes spreads horizontally and mixes vertically influences retention of solutes derived from the landscape. To quantify these transport processes and retention, we combine time series temperature and specific conductance measurements in Toolik Lake (Alaska) and its major inflow, with measurements of discharge and meteorology, and profiles of specific conductance, temperature, fluorescence, chlorophyll *a* and dissolved organic carbon (DOC) in spring of 3 years. During early snowmelt, the concentration of DOC in the stream was 750 µM, twice that in the lake. During slow melt (discharge (Q) < 4 m^3 s^{-1}), the incoming solute-rich intrusion spread lakewide below the ice. During melt with Q > 6 m^3 s^{-1}, the incoming water partially flushed the inlet basin and the more dilute water flowed over the original intrusion with a preferential flowpath to the outlet. Penetrative convection was restricted by the increased density gradients from the incoming plume and initially constrained to shallow mixing zones associated with the step changes in density. As ice thickness decreased to less than 1 m, heating caused density instabilities at the base of the intrusions that mixed solutes ~10 m vertically. Near-surface layers enriched with DOC persisted for over 3 weeks when melt was slow but ~10 days during a rapid melt when 15% of the solutes introduced into the lake were retained. Variability in retention additionally depends on the extent of mixing within the plume on the preferential flowpath and on the onset of deep mixing from penetrative convection.

KEYWORDS
Arctic lakes, ice cover, snowmelt inflow, dissolved organic carbon

20th International Physical Processes in Natural Waters (PPNW) workshop

EVALUATING ALGAL-DRIVEN SHIFTS IN COASTAL SEDIMENT-WATER OXYGEN DYNAMICS

Rebecca Ellis, University of Bath/ Plymouth Marine Laboratory

Key biogeochemical processes at the sediment-water interface, including decomposition of precipitated algal matter and bio-irrigation, have been shown via certain studies to have a significant influence on sediment-water oxygen (O_2) uptake. Yet this seasonal component of water-column O_2 dynamics is frequently overlooked in assessments of O_2 budgets. The main objective of this research is to comprehend in situ dissolved O_2 dynamics on seasonal scales. This study focuses on elucidating and quantifying the sediment-water interface O_2 budgets at a coastal site. In essence, this project provides a comprehensive analysis of the water column O_2 budget, with particular focus on the influence of seasonal algal blooms and sedimentary biochemical processes off the coast of Plymouth on sediment O_2 uptake. An eddy covariance system is used to assess turbulence accompanied by supporting laboratory experiments evaluating the influence of bio-irrigation on sediment O_2 uptake. All equipment is deployed over one seasonal cycle at the Western Channel Observatory. L4 is a long-term coastal monitoring site that is easily accessed from Plymouth Marine Laboratory. The L4 study site is an excellent location due to the extensive historical datasets for the water column (> 20 years) and benthos (> 50 years). The novel O_2 data obtained via this project will be combined with the pelagic and benthic datasets to gain important understanding of the O_2 dynamics at L4.

Quantifying Spatial Variability in a Deep, sub-Alpine Lake

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KEYWORDS
Spatial variability; surface mixing; horizontal spectra; autonomous underwater glider

Lakes of all sizes are known to display heterogeneity in both the horizontal and vertical directions. The causes range from interactions with boundaries, distributed wind and radiation patterns and, in larger lakes, rotational effects. This spatial variability in the upper water column was investigated in Lake Tahoe (CA-NV, USA), a deep (maximum depth of 501 m), sub-alpine lake located in the Sierra Nevada using an autonomous underwater glider. The glider was programmed to run repeated dives to 150 m depth at a 26º dive angle along a repeat transect 15 km long across the widest, central region of the basin. A total of 17 transects were run over 11 days, with a typical transect taking 15 hours. As the glider operated continuously, the same parts of the lake were sampled at different times from transect to transect. Key variables being measured included temperature, specific conductivity, dissolved oxygen, chlorophyll fluorescence and optical backscatter in the water column. The sampling period covered a range of different lake forcing, including major wind-driven upwelling events. Aggregating the transects allow estimates of the mean and standard deviation to be made for any location within the single cross-sectional matrix of the lake for the observed time period. In the first instance, such an exercise provides quantitative estimates of the inherent heterogeneity as a function of both depth and position across the lake. Horizontal spatial spectra were also derived for fixed depths of 5 m (in the surface mixed layer), 20 m (at the approximate seasonal thermocline) and 50 m (in the metalimnion) across each transect by assuming a constant interval spacing. The spectra slope of the derived passive tracer spectrum at these three depths allows estimates of the mixing heterogeneity at these three depths to be derived. Understanding this natural variability of the physical processes within this large lake system is critical for interpreting data from ongoing lake monitoring programs and for customizing future experimental designs.

Remobilization and transport of particles in the nearshore zone of Lake Constance

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Oral presentation

ABSTRACT
Many lake shores experience erosion due to modifications in shore morphology, e.g. harbors and piers, long-term changes in water level and storm events. It is of upmost importance to understand the governing processes of erosion, e.g. the interaction between the nearshore hydrodynamics, sediment remobilization, and transport. Sediment dynamics in the nearshore zone of lakes are strongly affected by the characteristics of the surface wave field, the basin-scale background currents, the particle properties of the upper sediment layer and the water level. Nearshore hydrodynamics as well as sediment dynamics and budget were studied by short- and long-term measurements in alpine Lake Constance. These measurements were combined with different numerical experiments using the wave model SWAN, the nearshore model SWASH and DELFT3D. Most of the time wind waves were characterized by small amplitudes, high frequencies and short wave lengths. Only during strong onshore wind events significant remobilization and transport of particles could be observed. The background current field was dominated by alongshore-directed velocities especially in the shallow nearshore zone, where significant net sediment transport occurred. The pattern of the resultant background current field is seasonally varying and is highly affected by the interplay between the direction of the large-scale currents, the direction of the surface wave field, and morphological features in the nearshore zone. The interactions between shore morphology, sediment remobilization, and the background currents are decisive for the horizontal pattern of the net sediment budget.

KEYWORDS
lake hydrodynamics, surface waves, currents, sediment dynamics, numerical modelling

Physics of boreal lakes –reflections on our learning during the last decades

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Abstract

I will summarize the experience and lessons in physical limnology in the boreal zone since 1970's using case studies from Finland, Estonia and Russia and even East Africa as examples. During this period the legislation and administrative frame work in Finland was changed several times. Also global technical development was very intensive as computational resources have grown and some new algorithms have been developed. New innovations also in sensor development have facilitated abundant data collection. The deepening collaboration with hydrochemists, ecologists and physicists in our country has been intensified by administrative solutions as well as by international contacts and projects. Our understanding has grown very much. Chemical pollution and global change are major challenges together with eutrophication. Sensible use of human and material resources are very much needed.

Kimberly Huynh
20th International Physical Processes in Natural Waters (PPNW) Workshop
February 15, 2017

Thermally-driven transport of dissolved methane and carbon dioxide through the water column in a subtropical rice field

Wetlands are the single largest source of methane emissions, but the underlying processes behind this flux are not yet fully understood. Typically, methane fluxes from wetlands have been attributed to ebullition (bubbling) and to transport through vegetation. However, a third major pathway--hydrodynamic transport--has been seen in a temperate wetland in the Sacramento-San Joaquin Delta. We wish to explore whether this additional pathway is also important to a subtropical rice paddy site where the diel thermal cycle is less pronounced than in the temperate site.

Measurements in the surface water of a rice field were collected over two different rice-growing seasons in 2016 and 2017. Specific measurements collected included dissolved and atmospheric methane concentration, surface water velocity, and air and water temperature. These were used to augment a long-term dataset of micrometeorology and gas fluxes. Together, these data demonstrate the role that surface water motions play in the fluxes between soil and atmosphere. Data are analyzed to reveal the fraction of total methane flux that is governed by advective/diffusive transport through surface water, and daily cycles in this behavior. Results will be used to advance predictions of atmospheric methane gas concentrations and could be foundational for developing methane management solutions. Closing this gap in knowledge is key to improving calculations of current global greenhouse gas emissions.

Hydrological controls on spring carbon gas emissions from sub-arctic lakes

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Northern lakes are an important atmospheric source of climate forcing trace gases — methane (CH_4) and carbon dioxide (CO_2) — despite being ice covered for up to seven months of the year. As much as 52% of annual C emissions occur during ice-out in spring. This flux is driven primarily by accumulation of carbon gas in the water column below the ice. Hydrodynamic processes such as under-ice circulation and snowmelt events are important regulators of lake biogeochemistry. In this study we present a detailed carbon gas budget for three subarctic lakes in northern Sweden during winter and spring. We combine continuous eddy covariance and water temperature measurements with monthly observations of the dissolved gas content. CH_4 and CO_2 accumulated at the sediment-water interface following ice-on and at intermediate depths after anoxia set in. This accumulation pattern made the pelagic zone the locus of the spring CH_4 efflux, contrary to summer, when the largest emissions were from the littoral zone. However, the vertical distribution of carbon gas remains somewhat puzzling. Stable water column stratification prohibited vertical transport, with dissolved CH_4, CO_2 and HCO_3^- instead strengthening the thermal density gradient. The process of diffusion was too slow to generate the concentration profiles observed. We therefore hypothesize that dense, carbon-rich water moved laterally from the littoral to the pelagic zone, vertically displacing less dense water to the ice-water interface. Snowmelt may also have displaced under-ice water. In two of the study lakes we found that between 65 and 84% of carbon gas had disappeared several weeks prior to ice-out during periods of heavy snowmelt. Thus, only a small part of the potential ice-out flux was picked up by the eddy covariance system. These observations indicate that catchment hydrology plays an important part in regulating both winter accumulation and the spring efflux of carbon gas in seasonally ice-covered lakes.

Lake classification revisited: scaling of lake seasonal stratification.

By

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Hutchinson and Löffler's (1956) classification of lakes based on the seasonal thermal mixing regime has become a cornerstone of any analysis of lakes as elements of the earth surface. Until now however the lake classification has lacked a physically sound quantitative criterion distinguishing between two fundamental lake types: thermally stratified during a large portion of the year (mono- and dimictic) and predominantly mixed to the bottom (polymictic). Using the mechanistic balance between potential and kinetic energy we derived a generalized scaling for seasonal stratification in a closed lake basin. The scaling parameter is the critical mean basin depth, H_{crit}, that delineates lakes that mix regularly from those that stratify seasonally based on lake water transparency, lake length, and an annual mean estimate for the Monin-Obukhov length. The scaling criterion consistently describes the mixing regime significantly better than either the conventional unbounded basin scaling or a simple depth threshold. Thus, the generalized scaling is universal for freshwater lakes and allows the seasonal mixing regime to be estimated without numerically solving the heat transport equations.

Melting of lake ice: measurements and modelling

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Melting of lake ice is a complex process driven primarily by solar radiation. Ice melts at the boundaries and in the interior, with fractions depending on the solar radiation balance and surface heat balance. Complications arise from large variability of optical properties of ice in the melting season. To gain more understanding of the melting process, field experiments have been performed in Finnish lakes from the boreal zone to Arctic tundra. In particular, an extensive research program has been carried through in Lake Kilpisjärvi in the tundra zone in 2013–2014. The surface area of the lake is 37.1 km^2, and the maximum depth is 57 m. The heat budget in the melting season was dominated by the radiation balance, and turbulent heat fluxes were small except that occasionally sensible heat flux was large. The strong solar radiation leads to internal melting, and under the ice water warms up resulting in convective mixing. The radiation transfer through the ice was measured using photo-synthetically active radiation (PAR). The data obtained will be also used as the reference of mathematical model development.

Methane bubble growth and transport in aquatic sediments observed by micro-scale X-ray computed tomography

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Biogenic methane gas bubble formation and migration in surface aquatic sediments is an important process for global biogeochemistry cycling at sediment-water interface. However, the mechanisms of bubble migration in sediment are still unclear. A long-term (20 d) laboratory incubation was done to study methane bubble growth and migration mechanisms in homogenized natural sediments (clay, sand). During the incubation experiment, X-ray computed microtomography (micro-CT) was employed to track bubble formation dynamics. At the end of bubble growth experiment, two micro-CT column scans were done to track bubble migration patterns in sediment in response to a scheduled water level change. The incubation shows capillary invasion and sediment expansion were both important in bubble growth in the two investigated sediments. Associated with sediment expansion, a significant gas-enriched upper layer (8 cm) was observed in sand. Bubbles were observed to move only in the surface layer of sand, in contrast to the entire depth in clayey sediment. Bubble migration in sediments was primarily determined by the mobility of bubbles, which was determined by the relative size of pores (in sediment) and bubbles. The findings will provide a solid basis for a methane bubble release model in sediments.

Near-surface turbulence and gas exchange velocities in shallow streams

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ABSTRACT

We analyzed the relationships between surface flow type, near-surface flow and turbulence, and the air-water gas exchange velocity (k_{600}) in shallow streams. The surface flow type is an empirical measure of the spatial variation of hydraulic conditions in streams, which is often mapped visually for ecological and morphological surveys. We used freely floating instrumented particles, which were equipped with acceleration sensors to obtain a measurement-based categorization of surface flow types. The spatial and temporal dynamics of near surface flow fields and turbulence were measured using acoustic Doppler velocimeter and particle image velocimetry. Gas exchange velocities were measured for carbon dioxide and methane with flux chambers. All measurements were conducted in natural streams and cover a range of different surface flow types. The data analysis focused on improving the current understanding of the processes and driving forces of local turbulence generation and gas exchange velocities in shallow streams. We further explored the potential of using surface flow type characterization and measurement for estimating gas exchange velocities at the reach scale and beyond.

Circulation and Respiration in Ice-covered Alaskan Arctic Lakes

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Abstract - Arctic lakes are ice-covered 9 months of the year. For some of this time, the sediments heat the overlying water, and respiration in the sediments increases specific conductivity, depletes oxygen, and produces greenhouse gases (GHG). Whether anoxia forms and whether the greenhouse gases are sequestered at depth depends on processes inducing circulation and upward fluxes. Similarly, whether the GHG are released at ice off depends on the extent of vertical mixing at that time. Using time series meteorological data and biogeochemical arrays with temperature, specific conductivity, and optical oxygen sensors in 5 lakes ranging from 1 to 150 ha, we illustrate the connections between meteorological forcing and within lake processes including gravity currents resulting from increased density just above the sediment water interface and internal waves including those induced by winds acting on the surface of the ice and at ice off. CO_2 production was well predicted by the initial rate of oxygen drawdown near the bottom at ice on. Upward density flux depended on lake size, with values initially high in all lakes but near molecular in lakes of a few hectares in size by mid-winter. Both CO_2 production and within lake vertical fluxes were independent of the rate of cooling in fall and subsequent within lake temperatures under the ice. Anoxia formed near the sediments in all 5 lakes with the concentration of CH_4 dependent, in part, on lake size and depth. Considerable internal wave

induced mixing occurred at the time of ice off. Twenty to fifty percent of the greenhouse gases produced under the ice remained in the lakes by the time thermal stratification was established in summer despite the mixing, unless, in the case of the largest of the lakes studied, strong winds occurred while the lake was partially ice covered. These observations and analysis lay a framework for understanding the links between within lake hydrodynamics, within year variability, and the fraction of greenhouse gases produced over the winter which evade at ice off.

Carbon dioxide fluxes in tropical waters: application of a surface renewal model based on near surface turbulence and vertical mixing

Melack, University of California Santa Barbara

Exchange of carbon dioxide between surficial water and overlying atmosphere depends on the concentration gradient and on physical processes at the interface, usually parameterized as a gas exchange coefficient (denoted as k). Near-surface concentrations of the gases depend on concentrations at different depths and physical processes that bring them to the air-water interface. We report results from studies in an Amazonian lake and reservoir in which we used a combination of meteorological data, time series measurements of temperature and oxygen with high resolution moored sensors, carbon dioxide concentrations and chamber-based gas fluxes, and a temperature-gradient microstructure profiler used to compute the rate of dissipation of turbulent kinetic energy through the water column. Surface energy budgets and near-surface dissipation rates derived from the microstructure profiler are used to calculate k values with a surface renewal model; k values are also obtained by inverse procedures from chamber measurements. In contrast to expectations, our results indicate that k values can be high under light winds and heating. For winds less than 3 m s^{-1}, there was no dependence on wind speed under heating, and gas transfer coefficients were about 4 times higher than predicted from established relations with wind speed. By combining these results with measurements of gas concentrations and meteorological variables, we estimate that fluxes of carbon dioxide from Amazon floodplains are likely to be 2 to 3 times greater than previous estimates.

Riverine carbon and nitrogen & Greenhouse gases (GHGs) emissions in rivers of the Tibetan Plateau

Qu, Lappeenranta University of Technology, Finland

The permafrost soils on the Tibetan Plateau represent a carbon store of 12.3 Pg-C ($Pg=10^{15}g$), which is potentially vulnerable to climate warming. It was revealed due to climate change, old carbon from permafrost regions of the Tibetan Plateau is being exported with its melting and degradation, and there will be an increasing export of ancient carbon from the rivers if the temperature constantly increasing on the plateau. Once previously frozen permafrost carbon is released into surface waters, it will likely be rapidly degraded and result in CO_2 evasion to the atmosphere. The pCO_2 in the rivers of the Tibetan Plateau were significant related to DIC. And during the summer half year, the fluxes of CO_2 (3,452 mg-C m^2 d^{-1}) are comparable with most other rivers in the world, despite the low partial pressures of CO_2 in rivers of the plateau. Therefore, with global warming, an increasing exportation of carbon substances (including CO_2 emissions) from rivers of the Tibetan Plateau can be expected in the future, which will potentially add feedback to the regional climate.

Lake CO_2 measurements using UAV

Sahlée, Uppsala University

Abstract

Recent technological advancements of miniaturized sensors, electronics and the development of navigational software now allows for meteorological measurements to be performed on the local (i.e. lake) scale using small unmanned aerial vehicles (UAVs). These platforms are relatively cheap, easy to deploy and maintained in comparison to manned aircraft, and has the potential to revolutionize studies of atmospheric boundary layer processes. Here we present atmospheric CO_2 measurements from a Swedish lake using a recent prototype drone system consisting of a commercially available quadcopter and an electronics hub produced by the Swedish company Sparv Embedded.

PPNW 2017 Workshop Abstract

Verlet-Banide Antonin
Uppsala University

Methane outgassing observation from lake Erken

Uppsala University is involve in a interdisciplinary project focusing on the impact of inland water ecosystems in the global carbon cycle. As part of the meteorology group my aim is to focus on methane outgassing from lake Erken via a field campaign combining Eddy covariant measurements and water methane concentration measurements.

Lake Erken is located in east central Sweden, about 70 km east of Uppsala (59^{o} 51’ 00" N, 18^{o} 34’ 00" E). The water lake surface is 24 km^2 with a mean depth of 9 m
The aim of this field campaign is to asses the variation in methane concentration in the water other a week period. The water measurement will be done continuously overs 12 h observation period. Simultaneously the methane flux outgassing from the lake will be observe using an Eddy covariance method on an island locate close to the southeast of the lake. The measurements are taken on a two level tower. First level at 4.10 m and the second level at 6.17 m height both with measurements of wind speed, wind direction and temperature. CH_4 flux measurement are at the first level with a sonic anemometer for wind measurements and a Li-7700 (LI-COR Inc.,Lincoln,NE,USA) for the methane concentration.
From the result a long-term continuous methane flux observation is attempted. In addition, the methane water concentration variation will be study. I will try to observe the potential concentration variation due to different meteorological process. I will also try to observe if there is a diurnal variation in water methane concentration.
From the the results of the methane concentration and the flux measurement a first attempt to estimate the transfer velocity will de calculated from those continuous measurements. I will try to understand the the impact of different physical process on the estimated transfer velocity.

Contribution of high and low frequency internal waves to boundary turbulence in a lake

Wain, University of Bath

Stratification in lakes restricts vertical mixing and often controls the spatial variability of nutrients and other substances, affecting the distribution of dissolved oxygen in the water column, the availability of nutrients to phytoplankton, and transport of pollutants between the hypolimnion and epilimnion. The interior of lakes is often quiescent and most of the mixing in a lake occurs at the sloping boundaries, where wind-induced internal waves create turbulence (which leads to mixing) through interactions with the lakebed. To predict the occurrence and strength of turbulence in terms of meteorological forcing and stratification, we investigated the dependence of internal wave type, and their contribution to turbulence on the slope, on the Lake number, which compares the stabilizing tendency of stratification to the destabilizing tendency of the wind.

Three thermistor chains and a meteorological station were deployed in West Okoboji Lake (length ~ 9 km, max. depth ~ 40 m) for two weeks. A wavelet analysis was conducted to determine time periods when different wave frequencies were excited, with particular focus on the first vertical mode seiche, the critical frequency with respect to the stratification and slope, and high frequency waves in the band of 1-10 times the buoyancy frequency. We measured the velocities in the bottom boundary layer (BBL) with a high resolution acoustic current profiler (2 MHz Nortek HR Aquadopp) and then computed the turbulent dissipation rate using the structure function method, which uses the spatial correlations of velocity along a beam to estimate the dissipation. This generated a two week time series of turbulent dissipation rate in the BBL which was then compared to the wavelet amplitudes.

During the deployment, a strong daily wind forced near constant internal wave activity. The theoretical period of the first vertical mode seiche was ~17 hours, but the diurnal wind forcing interfered with free oscillation of this mode. Although not an obvious natural frequency of the lake, waves of the critical frequency (which had a period of ~11 hours) were activated throughout the measurement period. High-frequency waves were observed in the thermistor chain near the slope at the lowest Lake number wind events. The turbulence observed on the boundary was highest during these events, implying that the low frequency seiching was less important than higher frequency motions in driving turbulence on the slope.

High spatial variability in stream gas transfer velocity revealed by ADV derived turbulence measurements

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Abstract

Streams are concluded to be major emitters of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere. However, streams are also known to be very variable in their emission rates resulting in large uncertainties connected to scaled emission estimates. One of the largest uncertainties derives from the choice of an appropriate gas transfer velocity (*k*), which describes the physical efficiency for gas exchange across the stream-atmosphere interface. In this study we therefore aimed to determine the variability in *k* and subsequent emission rates within and across streams of different stream order (SO) using direct turbulence measurements by an Acoustic Doppler Velocimeter (ADV). The measured ADV-dissipation rates were converted into gas transfer velocities which were used to calculate CO_2 and CH_4 emissions. The results show that ADV measurements can be used to determine *k* in streams. There was high spatial variability in *k* and corresponding emissions at small scales, both within stream reaches and across SO, and especially during high discharge. There was further no clear relationship between *k* and SO nor specific stream characteristics such as width and depth, which are parameters often used in empirical models of *k*. This suggests that the relationship between physical stream characteristics and *k* are not straightforward, and may introduce uncertainties when used for scaling purposes. Improved understanding of the small-scale variability in the physical properties along streams, especially during periods of high discharge, is therefore an important step to reduce the uncertainty in existing gas transfer models and GHG emissions estimates for stream systems.

Bacteria induced mixing – comparing field observations with DNS

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ABSTRACT

In this presentation we extend earlier reports on this workshop about the ability of purple sulphur bacteria *Chromatium okenii* (*C. okenii*) to convectively mix their natural stratified environment over vertical scales of several dm to m. For this type of bioconvection, the microorganisms induce water movements not by their own propulsion as such, but by their ability to swim upwards and thereby to change the vertical density structure of the water-bacteria mixture. As the *C. okenii* are denser than water (~1.15 g mL^{-1}), their drive to swim towards the light generates a homogenised water layer of macroscopic dimensions. In this particular study in a meromictic alpine lake, a homogeneous bacterial layer develops each summer in ~12 m depth and its vertical thickness ranges from 0.3 to 1 m.

Using Direct Numerical Simulation (DNS), we have been able to model the expansion dynamics of this homogenised layer for realistic environmental conditions, characterized by a narrow transition between oxic (upper half) and anoxic sulfidic (lower half) lake water, and *C. okenii* densities of ~10^4 to ~10^5 cells per mL and upward swimming speeds of ~9 µm s^{-1}. DNS results show that the buoyancy flux generated by the upward swimming bacteria balances well with the change of the potential energy related to the expansion of the mixed layer and the dissipation of turbulent kinetic energy. The dissipation of the convective eddies, measured by using a RSI VMP-500 microstructure profiler operated from a float, showed excellent agreement with DNS predictions. This consistency between field observations and modelling, both from a conceptual as well as from a numerical point of view, strongly suggests that this outstanding, and quite unique, phenomenon in natural waters is adequately interpreted.

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