Effects of summer heat wave on mixing, oxygen dynamics, nutrients and GHG in a small lake

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Introduction

Estimations of GHG emitted from inland waters become more accurate with the improvements in gas transfer coefficient modelling[1] and the more extensive data on dissolved gas concentrations[2]. Further improvement requires a better understanding on how weather and its effects on stratification, turbulence, oxygen and nutrients affect the production, storage and emissions of GHG in lakes of different morphometry. The extreme summer weather recorded in 2012 was an opportunity to investigate the effects of predicted warmer climate on shallow lakes, that are overlooked but abundant aquatic ecosystems.

The aims of this study are (1) to test the effects of recent North American summer heat-wave[3] on the thermal structure and turbulence in a small, shallow lake, and (2) to account for the effects of extreme weather on shallow lake nutrients, primary production, oxygen and GHG dynamics.

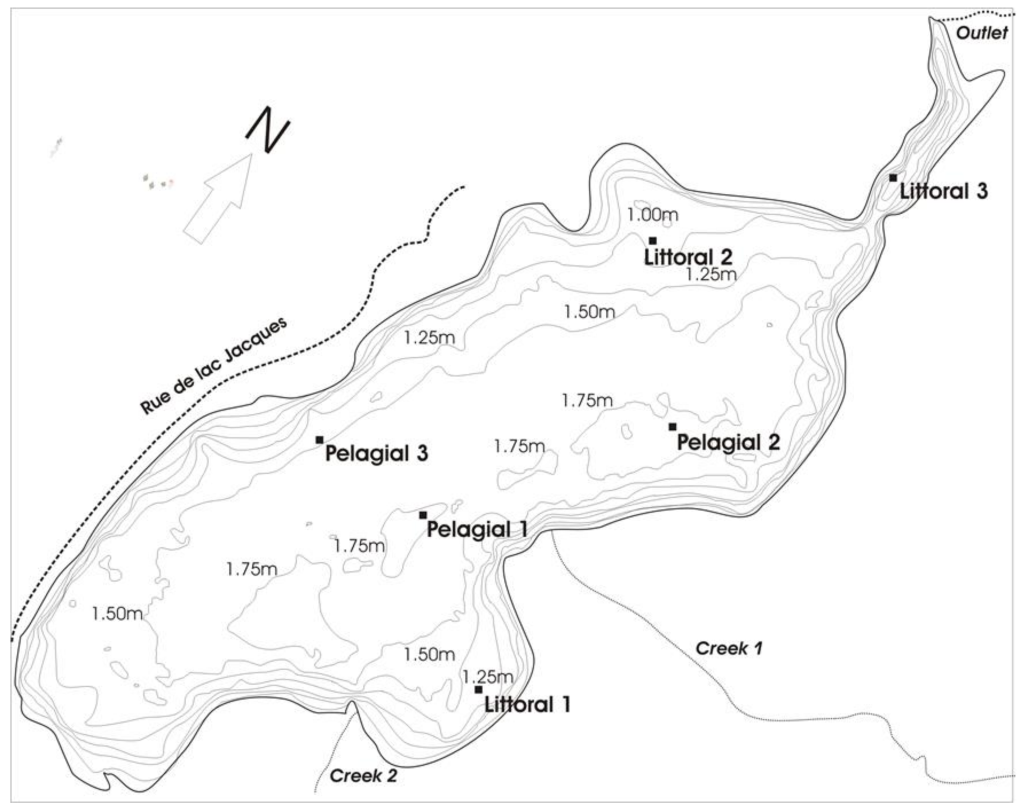

Fig. 1. Lake Jacques bathymetry and sampling stations

Methods

Study site

Lake Jacques is a small (0.18 km^2) and shallow lake (maximum depth = 1.9 m, mean depth = 0.75 m) with a catchment of 5.92 km^2 (Fig. 1). The lake is located 30 km north of Quebec City (QC, Canada) and is supplied with water from two creeks in the eastern side of the lake, as well as from a ground water spring in its southern part.

Lake mixing and gas flux estimations

The surface energy budget and dissipation rate of turbulent kinetic energy used in gas transfer coefficient (k) calculations were computed with surface renewal model[1] (hereafter SR). Gas transfer coefficient was also calculated using wind-based model of Cole and Caraco (1998, hereafter CC).

The SR model yields higher flux estimates than the CC model, with k_{600SR} and k_{600CC} averaging respectively 2.6 and 2 cm hr^{-1} at low wind speed (1 m s^{-1}) or 10 and 6 cm hr^{-1} at high wind speed (6 m s^{-1}). For a neutral atmospheric stability, k_{600SR} and k_{600CC} provide an envelope for anticipated gas transfer coefficient.

GHG diffusive fluxes were estimated as Flux = k (C_w – αC_{air}), where C_w and C_{air} are the concentrations of gas across the air-water interface corrected according to Henry's Law, α is the Ostwald solubility coefficient, and k is either k_{CC} or k_{SR} corrected for Schmidt number. A floating chamber device was used to evaluate the accuracy of the modelled fluxes (hereafter FC).

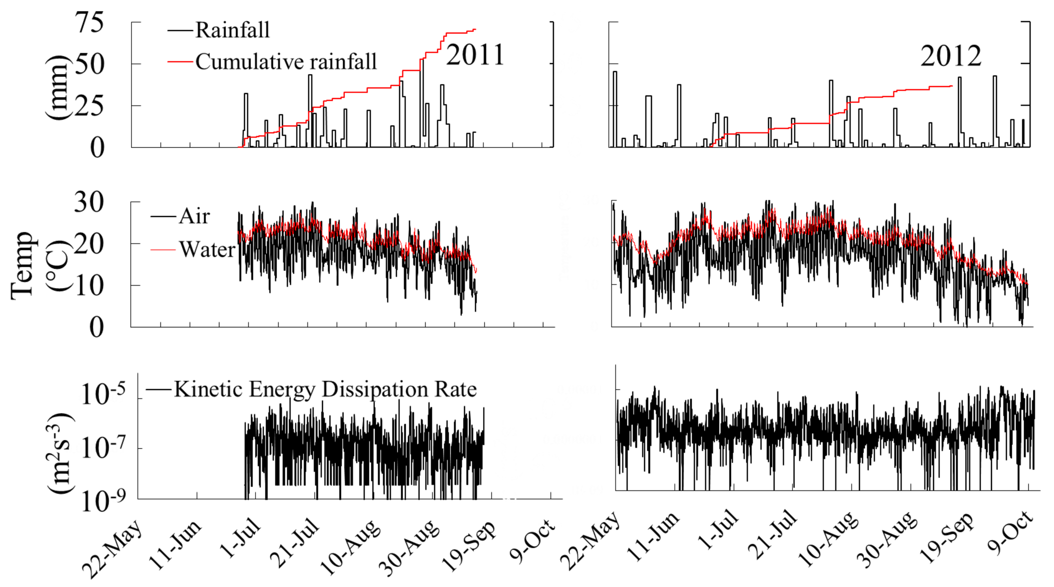

Fig. 2 Meteorological conditions and turbulence following Tedford et al. (2014) in 2011 and during summer heat-wave in 2012.

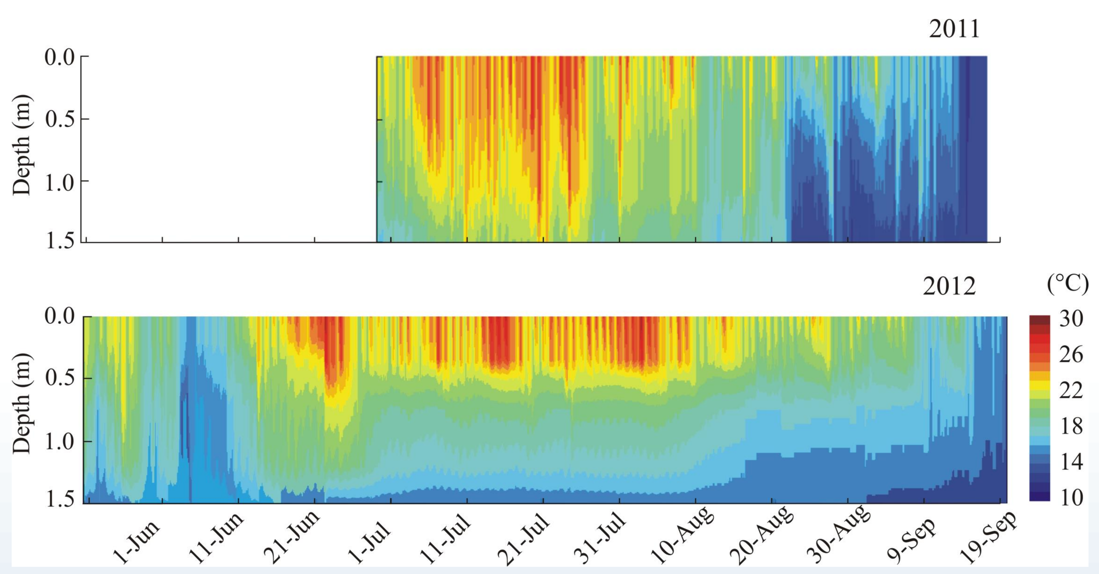

Fig. 3. Thermal structure of the lake during summer 2011 and 2012.

Results

Weather forcing and lake thermal structure

Although stronger air T forcing and lower rainfall during 2012 heatwave led to between year differences in mixing and turbulence (Fig. 2), thermal stratification was pronounced in both years despite the shallow depth (Fig. 3).

In both summers, diurnal thermoclines formed in the upper 20 cm to 60 cm. In 2011, the afternoon winds caused episodes of apparent mixed layer deepening. Similar events occurred in 2012, but the penetration of warm water was restricted to shallower depths and the amplitude of internal waves following wind events was only 20 cm.

In both years, transports could be associated with rainfall, with large T decrease in the lower water column in 2011 co-occurring with rain events. The transports could also be associated with differential cooling. For example, T cooled between 40 and 80 cm but not at 1 m from 20 to 22 July 2012. As inflows from rain were low at that time, this mid-water column cooling, with T similar to inshore site, is indicative of offshore flows from differential cooling. These patterns were prevalent with each 2012 cold front.

Oxygen, nutrients and chlorophyll

There was less DO in the hypolimnion during the summer heat wave than during the previous summer (Fig. 3). DO stratification started earlier and was more stable in 2012 than in 2011. Surface concentrations, however, were higher in 2012 than in 2011, with maxima in the pelagial of ~13 mg L^{-1}. In 2012, DO was in general higher in the pelagial than in the littoral of the lake where macrophytes were abundant.

During the stratification period both TP and TN were significantly higher in 2012 than in 2011 (Fig. 4), and in 2012, TP was higher in the littoral than in the pelagial zone of the lake. There was also significantly less SRP and NO_3^- in surface waters during 2012 than 2011.

The *Chla* concentrations in surface waters were higher in 2012 than in 2011, and slightly higher in the littoral than in the pelagial.

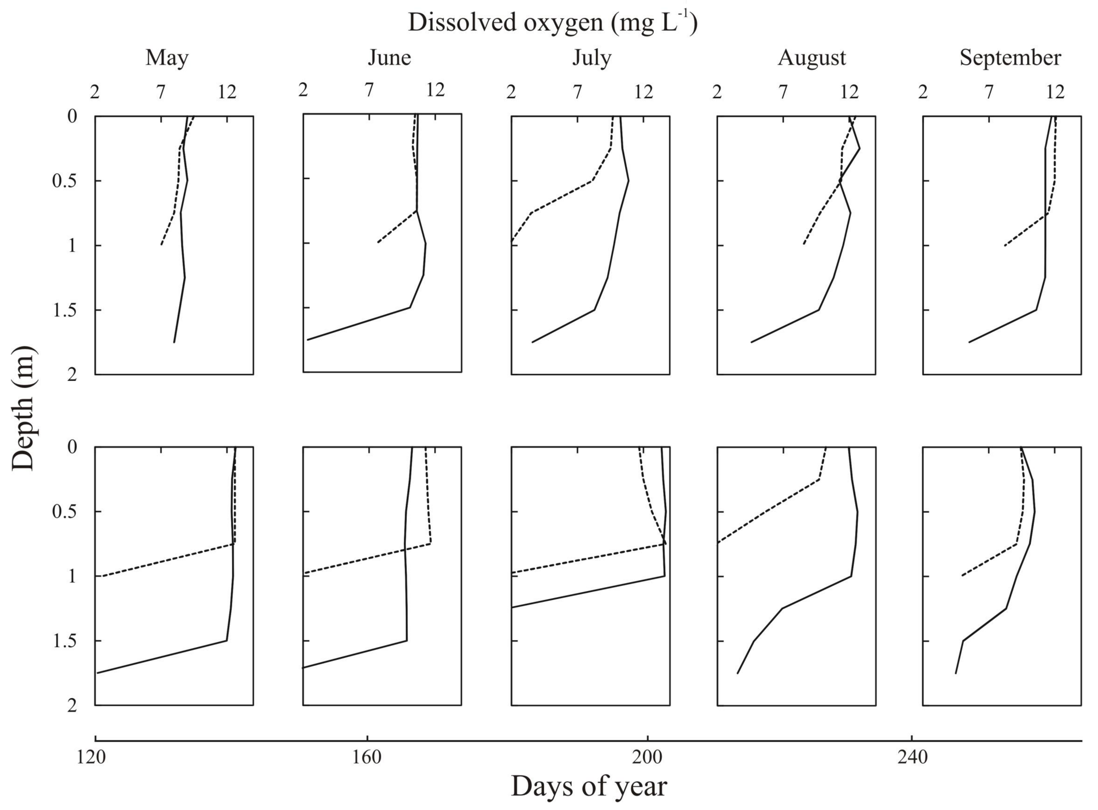

Fig. 4. The oxygen stratification in the littoral (dotted lines) and pelagial (solid lines) in 2011 (upper panels) and during heat-wave in 2012 (lower panels).

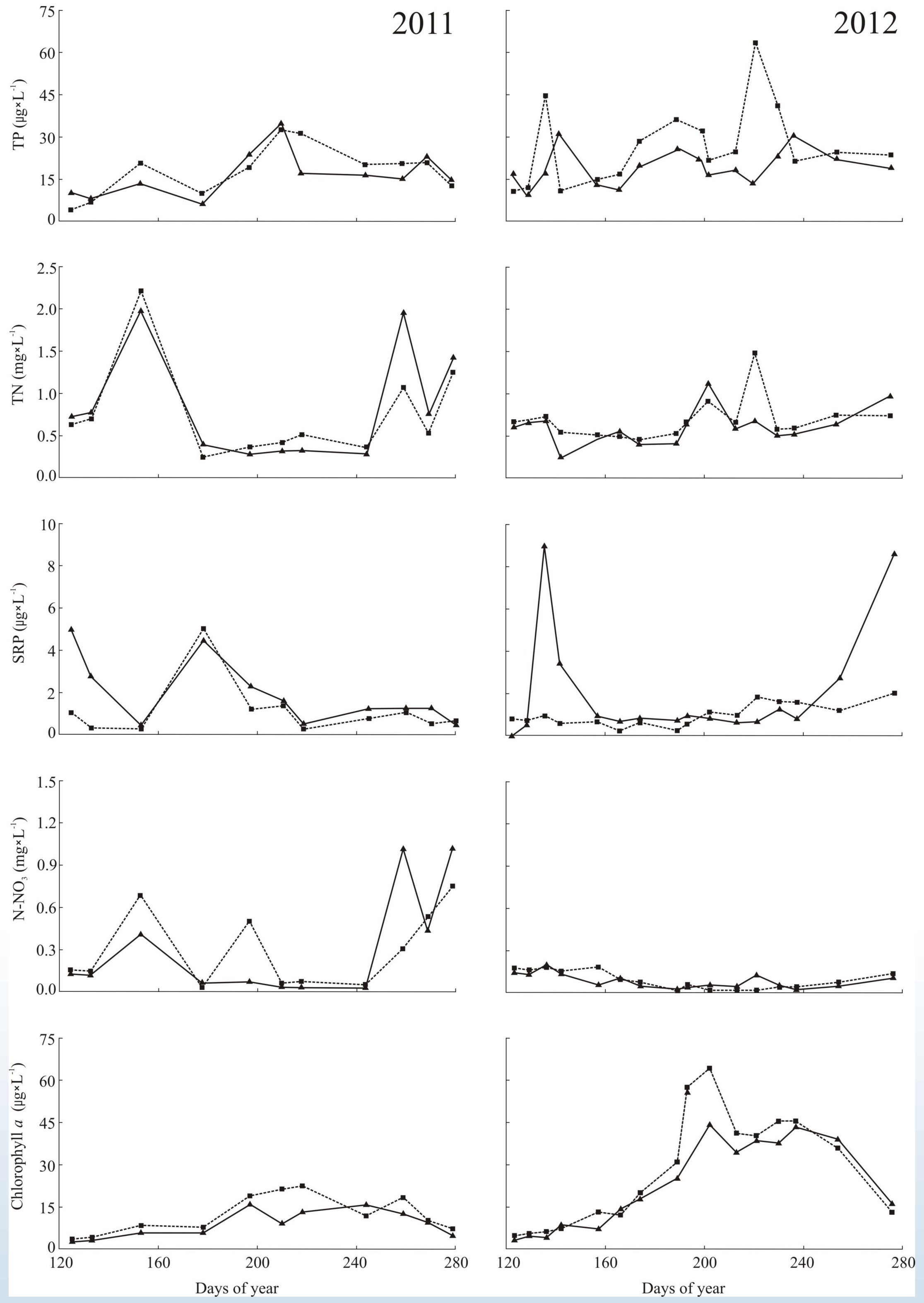

Fig. 5. The dynamics of nutrients and *Chla* in the littoral (dotted lines) and pelagial (solid lines) in 2011 and during heat-wave in 2012.

GHG saturation and fluxes

The ΔN_2O and ΔCH_4 were higher during summer heat-wave than previous summer, and higher in the littoral than pelagial of the lake (Fig. 6). The ΔCO_2 was lower in 2012 than in 2011, at least during the stratified period.

In 2012, ΔCO_2 was negatively correlated with water T and *Chla* (R<-0.6, p<0.05), ΔCH_4 was positively correlated to water T, TP, *Chla* and hypolimnetic DO depletion (R>0.4, p<0.05), and ΔN_2O was correlated with NO_3 (R=0.34, p=0.04).

In 2012, the lake was a sink for CO_2 in the stratified period, but diffusive flux exceeded 90 mmol m^{-2} day^{-1} during fall overturn, when stratification was eroded. At this time, the CH_4 fluxes also reached maximal value of 15 mmol m^{-2} day^{-1} (Fig. 7).

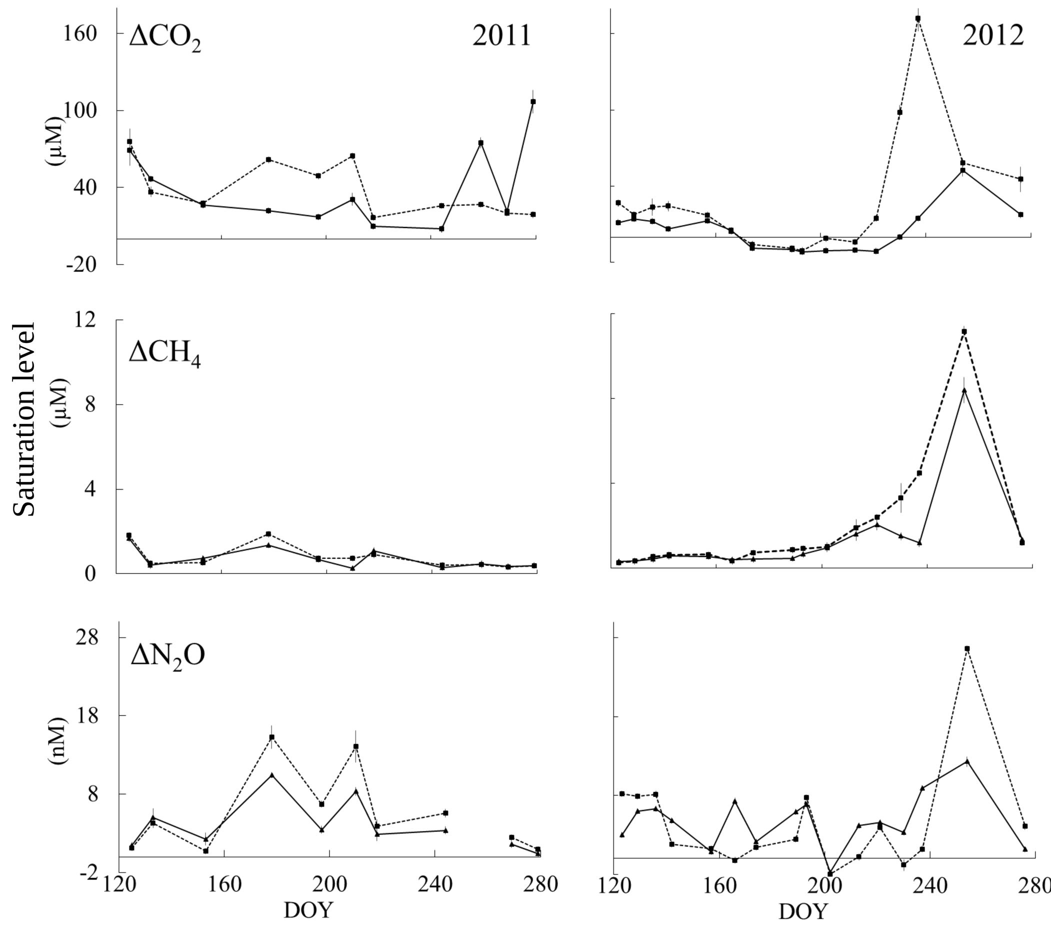

Fig. 6. The GHG saturation level in the littoral (dotted lines) and pelagial (solid lines) in 2011 and during heat-wave in 2012.

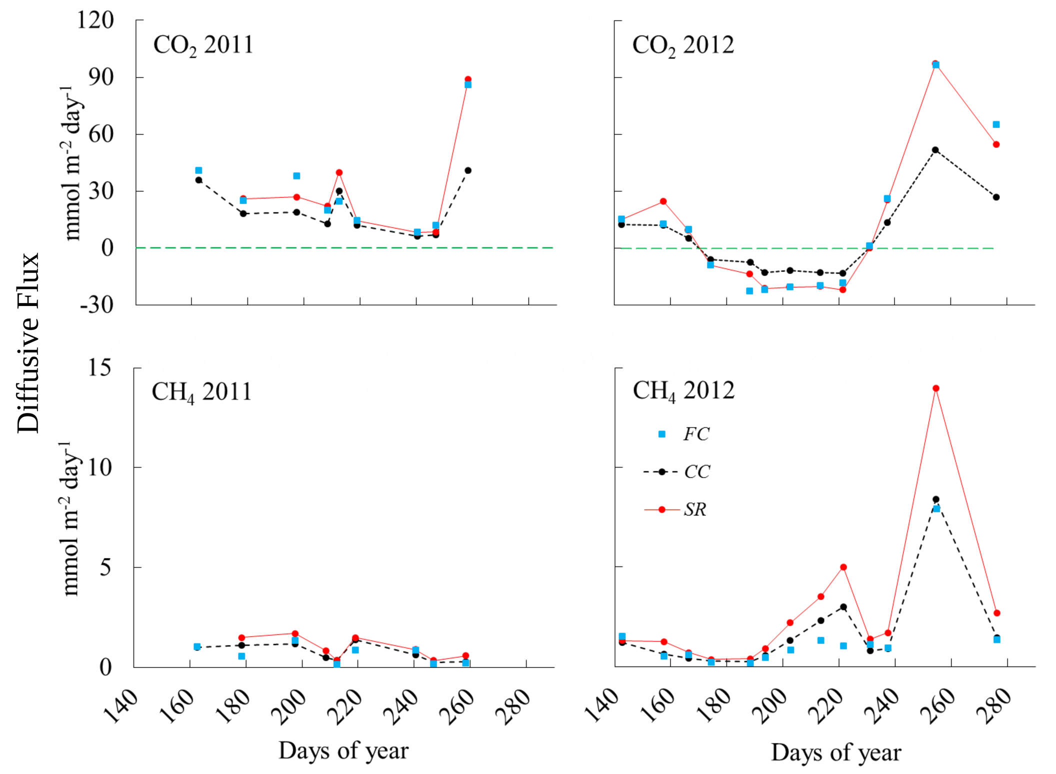

Fig. 7. The GHG diffusive fluxes in 2011 and 2012 estimated using wind-based (CC, black line) and surface renewal model (SR, red line) or measured directly using floating chamber (FC, blue squares).

Conclusions

The response of small, shallow lake to weather conditions during a heat wave may be used to assess the effect of climate change in such systems

Stronger stratification during summer heat-wave lead to hypolimnetic anoxia probably linked to nutrient release from the sediment

As climate warms, the water quality of shallow lakes is likely to deteriorate since increase nutrients will stimulate phytoplankton growth

The macrophyte-colonized zones may be particularly susceptible to the effect of hot, dry weather and become hot spots for GHG emissions

More of the potent GHG such as CH_4 and N_2O will diffuse from shallow lakes as a result of decreased oxygen in the hypolimnion and increased deposition of OM to the sediments

References, acknowledgments and funding

1) Tedford et al. 2014. JGR:Oceans, *in press;* 2) Raymond et al., 2013. Nature: 503; 3) Mills et al. 2013. Oceanography:26(2).

We would like to express our gratitude to V. Sauter, X. Egler, P. Michaud, A. Przytulska, K. Hudelson and K. Negandhi for their help in the field. The study was supported by a NSERC Discovery Grant to IL, GRIL Grant to IL and RM, and GRIL scholarship to MB.