

Referee#1

Comments on

‘Continuous In Situ Measurement of Dissolved Methane in Lake Kivu Using a Membrane Inlet Laser Spectrometer’ by Grilli et al., GI-2019-29

Revised submission

I thank the authors for re-submitting their paper considering our comments as well as answering our questions. Most of my comments were addressed, especially the ‘results and discussion’ section, which is now much easier to read.

I still think this paper is worth a publication as it brings a new in situ technique for the measurements of an important greenhouse gas in aquatic environments. The scarcity of data from these specific systems is clearly a limitation for constraining the budgets and therefore the models, so any advance in the field of sensor development must be encouraged.

However, I have noticed many typos that make the MS difficult to read, which should not happen with a re-submission. Also, some re-phrasing would make the text clearer. I suggest a careful review from the authors to avoid these mistakes.

We thank the referee for the critical review. We addressed all the comments below and we carefully checked the manuscripts for other typo and grammatical errors. We also rearranged some sentences for making the manuscript easier to read.

Here are my detailed comments:

Line 26: ‘Methane (CH₄)’... putting (CH₄) there would avoid to do it line 43

Corrected

Line 35: costal -> coastal

Corrected

Line 35-37: ‘a better understanding of the processes... are is needed required’. But I’d rephrase as follows ‘Only fast response instrument for in situ dissolved gas measurements and dynamic profiling can provide the data for a better understanding of the processes...’

Corrected accordingly

Line 40: ‘water’ is too many times used, so I’d suggest: ‘... makes deep water strongly decoupled from the surface layer because...’

Modified as suggested

Line 41: delete ‘and therefore very different in composition’

We changed but we kept to word composition in the sentence: “because of their difference in density and composition”.

Line 43: delete methane ‘... dissolved carbon dioxide (CO₂) and CH₄...’

Corrected

Line 45-46: check the brackets ‘... present in the lake, e.g. Degens et al. (1973), Pasche et al. (2011)...’ Please be careful to the way the references are cited. This should be homogenized

throughout the MS.

Line 47: same comment about the citations

Regarding citations we used the Mendeley citation style for GI journal where the year should not be under brackets. We therefore leave the citation format as it is.

Line 53: ‘Regarding the stability of the lake, Schmid et al. (2005) raised...’

We decided to write “in 2005 Schmid and co-workers raised” and move the citations to the end of the sentence.

Line 59: content -> concentration

Corrected

Line 70: ‘highlighted in the discussion section, in comparison with other methods deployed during the same campaign: water sampling followed...’

Corrected

Line 74-77: Presented this way, this should not be in the introduction but in the discussion section. If the authors want to follow the 2nd reviewer’s comments, then this should be higher in the introduction, but I still think this should be given as comparison in the discussion.

We agreed with the referee that this part would better fit in the discussion session. And it has been moved accordingly.

Line 85: PDMS is for polydimethylsiloxane. It should read ‘using a PolyDiMethylSiloxane (PDMS) membrane...’

Corrected

Line 92: check the brackets ‘...can be found in Grilli et al. (2018).’

Corrected

Line 99: delete polydimethylsiloxane as the acronym is already clarified line 85

Corrected

Line 102: again, check the brackets for the reference ‘... Grilli et al. (2018)’

Corrected

Line 119: dot missing -> ‘speed of ~6m.min-1’

Corrected

Line 120: space missing ‘after resolution of 1m.’

Corrected

Line 126: HydroC is a registered trademark so this should be noted as ‘... underwater sensor, the CONTROS HydroC® HP sensor’. This should be modified throughout the MS.

Corrected

Line 129: same remark as above regarding the registered trademark. Also, another problem with the brackets, which should be ‘in Fietzek et al. (2014), ...’.

Line 181: Sander 2015 cited twice... this should read ‘... equation 19 from Sander (2015) using...’. Delete (Sander, 2015) at the end.

Citations have been revised

Line 197: reference cited twice!

Corrected

Line 203: same remark

Corrected

Line 219: but not at the same depths!

Now mentioned "and over specific discrete depths."

Line 239: delete (Schmid et al. 2015) at the end (already in the sentence).

Corrected

Line 241: 'Nitrogen (N₂) mixing ratio...'

Corrected

Line 251-252: Brackets missing

Line 253: the headspace technique is an extraction technique. The analysis is done using Gas Chromatography.

Modified accordingly

Line 256: Brackets missing

Line 260: greater instead of larger

Corrected

Line 265: are the unpublished data from Roland et al.?

Yes. This is now clearly mentioned

Line 266: brackets missing

We could not see the missing brackets highlighted by the referee.

Line 275: 'O₂ supplied at these depths during the previous dry season was completely vanished'

No clear: this is the phrase as appear in the manuscript. What should be changed here?

Line 282: brackets missing

Line 288: I think the amount of CH₄ in the surface layer mainly depends on the biogeochemical processes, especially in presence of oxygen. To name one: bacterial oxidation of methane. Yes there is a dilution of CH₄ from the anoxic layer to the oxic one but methanotrophy is the main process that control the concentration in any kind of aquatic environments.

We now added the sentence: "Finally, CH₄ concentration in the surface layer may depend on the biogeochemical processes such as for instance the methanotrophy."

Line 328: replace 'discrete sampling' by 'discrete measurements' to avoid confusion between the water sampling done with the Niskin bottles and the discrete in situ measurement performed with the sensor. Closing a Niskin bottle takes less than 1 second, so a 410m profile can be done in less than 10 min...

Changed.

Referee#2

The manuscript has improved by the revision, the necessary context is now included, the new structure is in somewhat better shape, and the technical details are presented in sufficient depths. Still, I find that the authors didn't show a satisfactory effort in condensing the manuscript, which is therefore quite long, presents a range of unrelated information bits, and both aspects make it difficult to read. For a manuscript like this, lacking a testable biogeochemical hypothesis, to warrant publication it is necessary that all elements are clearly structured and the (necessary) information is complete and easily accessible. In my opinion, the combination of results and discussion section is not ideal, and I cannot recommend the manuscript in its present form for publication if the scale is clarity. If Geoscientific Instrumentation .. is happy with the presented kind of report it would be acceptable, though, after some specific points were addressed.

We are sorry to hear that the referee found the manuscript not easy to read. We think that the information provided are complete and easy to access. We think that some generic information about the lake and the methane extraction are important to understand the motivation for comparing different techniques and for a more accurate estimation of the methane budget of the lake. We made further efforts in order to improve the English and more in general the form of the manuscript. We hope that the current version of the manuscript is clear enough and considered acceptable for publication. We thanks again the referee for the very profitable and pertinent remarks that helped us to improve the manuscript.

Specific points.

L26-30 Usually such statements would be accompanied by one or more references.
added

L33 replace "incomes" with "fluxes"
replaced

L42 There is of course also "life" in the anoxic zone (bacteria, archaea,...)
removed from the sentence

L69-70 omit this sentence
Changed according to referee #1

L287 While there is some relation between water depth and methane concentration, the critical point I wanted the authors to make is the horizontal distribution, which is dependent on the distance from the LITTORAL sediments. The title of the reference I was suggesting says it all "No Longer a Paradox: The Interaction Between Physical Transport and Biological Processes Explains the Spatial Distribution of Surface Water Methane Within and Across Lakes", del Sontro 2018. Revise accordingly.

Changed accordingly. "The amount of CH₄ at the surface may strongly depend on the water depth, i.e. on the distance of the sediment to the surface, as well as to the horizontal distance from the shore and littoral sediments (DelSontro et al., 2018b)"

If the journal's copy editing isn't very strong, the manuscript will require thorough checking by a native speaker. Some examples

L46 constitutes

Corrected

L49 lake not Lake

Corrected

L55 hypothesis excluded? temporal variability slower?

This seems to be correct for us.

L97 a word seems missing

adjusted with "is no longer strong enough..."

L279 indicate neither...nor

Corrected

L297 "for a correctly determine"

Corrected

Further improvements have been done for making the manuscript clearer and easier to read. We hope that this work can now be accepted for publication.

Continuous In Situ Measurement of Dissolved Methane in Lake Kivu Using a Membrane Inlet Laser Spectrometer

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10 **Abstract.** We report the first high resolution continuous profile of dissolved methane in the shallow water of Lake Kivu, Rwanda. The measurements were performed using an in situ dissolved gas sensor, called Sub-Ocean, based on a patented membrane-based extraction technique coupled with a highly sensitive optical spectrometer. The sensor was originally designed for ocean settings, but both the spectrometer and the extraction system were modified to extend the dynamical range up to six orders of magnitude with respect to the original prototype (from nmol L⁻¹ to mmol L⁻¹ detection) to fit the range of

15 concentrations at Lake Kivu. The accuracy of the instrument was estimated to ±22% (2σ) from the standard deviation of eight profiles at 80 m of depth, corresponding to ±0.112 μmBar of CH₄ in water or ±160 nmol L⁻¹ at 25°C and 1 atm. The instrument was able to continuously profile the top 150 m of the water column within only 25 min. The maximum observed mixing ratio of CH₄ in the gas phase concentration was 77% ~~at 150 m depth~~, which at 150 m of this depth and thermal condition of the lake, corresponds to 3.5 mmol L⁻¹. Deeper down, dissolved CH₄ concentrations were too large for the methane absorption spectrum

20 to be correctly retrieved. Results are in good agreement with discrete in situ measurements conducted with the commercial HydroC@ sensor. This fast profiling feature is highly profitable to study the transport, production and consumption of CH₄ and other dissolved gases in aquatic systems. While the sensor is well adapted for investigating most of environments with concentration of CH₄ up to few mmol L⁻¹, ~~in the future~~ the spectrometer could be replaced with a less sensitive analytical technique possibly including simultaneous detection of dissolved CO₂ and total dissolved gas pressure, for exploring settings

25 with very high concentrations of CH₄, such as the bottom waters of Lake Kivu.

1 Introduction

Methane (CH₄) is the second most important greenhouse gas contributing to the anthropogenic radiative forcing of the atmosphere and its atmospheric content raised by 2.5 times since the Industrial age. During the last decades, significant efforts have been made to better estimate methane contributions of natural and anthropogenic sources to the global atmospheric budget

30 (Kirschke et al., 2013; Saunois et al., 2019). The development of more advanced techniques allowed the recognition of a larger

number of sources which, coupled with the improvements in the modelling, led to continuous rectifications of this budget (Hamdan and Wickland, 2016). In the last three decades, natural sources contribute for ~35-50% of the total global methane emissions, and freshwater constitutes one of the largest ~~incomes-fluxes~~ after natural wetland and together with geological sources (including seafloor). This highlights the importance and urgency for a better inventory of the sources of CH₄, and to reduce the uncertainties of the contributions of aquatic systems (lakes, rivers, estuaries, coastal seas and open ocean) (Ciais et al., 2013). Fast response instruments for in situ dissolved gas measurements and dynamic profiling can provide the data for ~~For this, a better understanding of the undergoing processes of production, transport, and transformation are needed and fast response instruments for in situ dissolved gases measurements and dynamic profiling are key tools.~~

In this work, a fast response prototype instrument was deployed for the first time at Llake Kivu, located in East Africa at the border between Rwanda and the Democratic Republic of the Congo. The meromictic character of this lake, defined by a strong stratification of the water, makes deep water strongly decoupled from surface ~~water-layer~~ because of their difference in density (~~Schmid and Wüest, 2012~~) and ~~therefore very different in~~ composition (Schmid and Wüest, 2012). The upper tens of meters (ranging from 65 to 25 m depending on seasons) correspond to the oxic zone, ~~with life (fishes, algae and bacteria)~~ while deeper waters are anoxic and contain large amount of dissolved carbon dioxide (CO₂) and ~~methane (CH₄)~~, with the strongest chemocline situated at 250 m of depth (Schmid et al., 2005). Since 1935, several measurement campaigns have been carried out, aiming at quantifying the amount of dissolved CH₄ and CO₂ present in the lake (e.g. ~~Degens et al., 1973; Pasche et al., 2011; Schmitz and Kufferath, 1955; Tassi et al., 2009; Tietze et al., 1980~~). On the one hand, the presence of those gases constitutes a risk of catastrophic event such as a gas eruption, which in the past already occurred in other gas-rich lakes (e.g. in 1984 at Llake Monoun and in 1986 at Llake Nyos in Cameroon (Kling et al., 1987; Kusakabe, 2017; Sigurdsson et al., 1987)). On the other hand, dissolved CH₄ represents a potentially important energy resource. Methane extraction would allow to compensate further accumulation of gas at the bottom of the Llake and therefore preventing the possibility of a gas eruption. From this field campaign, the maximum total dissolved gas pressure (TDGP) was estimated to be 50±7 % of the hydrostatic pressure at 320 m of depth (Bärenbold et al., 2019; Schmid et al., 2019). Meanwhile, extraction has to be performed without destabilizing the stratification of the lake or altering its ecosystem. Regarding the stability of the lake, in 2005 Schmid and co-workers et al. (~~Schmid et al., 2005~~) raised the possibility that dissolved CH₄ in the lake was increasing with a rate of ~0.5 % per year, with consistent repercussion on the safety of the surrounding population (Schmid et al., 2005). However, from the work of Pasche et al. (2011) as well as the results from this recent field campaign, the hypothesis of a fast increase is today excluded, and the temporal variability appears to be slower than previously expected (Bärenbold et al., 2019; Boehrer et al., 2019; Schmid et al., 2019). In the future, regular monitoring of the lake is required to estimate the CH₄ and CO₂ budgets as well as their temporal variability, using reliable, fast and easy to use techniques. For a more precise estimation of the dissolved gas ~~content~~concentration, inter-comparison between different sensors and methods is required, as conducted and presented in this work and in the even more comprehensive results from the entire inter-comparison campaign (Bärenbold et al., 2019; Boehrer et al., 2019; Schmid et al., 2019). A fast response sensor as the one proposed in this work here could also be highly profitable for estimating ~~the~~ methane fluxes from the water surface and their spatial and seasonal variabilities.

The development of the Sub-Ocean sensor grew out of a project for measuring the composition of air bubbles in-situ in ice sheets (Alemany et al., 2014; Grilli et al., 2014). After a first test in the Mediterranean Sea in 2014 with a different prototype but based on the same principle (Grilli et al., 2018), the sensor described and deployed here was developed. In October 2015 it was deployed over a hydrate degassing zone west of Svalbard, highlighting for the first time high variability of dissolved CH_4 near the seabed together with a strong diffusivity most probably induced by the di-phasic medium generated by the gas flares (Jansson et al., 2019). In this work we report a successful deployment of the Sub-Ocean sensor in a very different setting, highlighting the reliability and adaptability of the technique to different aquatic environments. Advantages and drawbacks of the technique are highlighted in the discussion section in comparison with other methods deployed during the same campaign. Two other research groups participated to the inter-comparison campaign using different methods: water sampling followed by laboratory gas chromatography analysis (Boehrer et al., 2019) and on-line water pumping followed by on-site mass spectrometry analysis (Brennwald et al., 2016). These results are not reported here as they focused on the concentrations in the deep waters (Bärenbold et al., 2019; Schmid et al., 2019).

~~Methane concentrations at Lake Kivu spans from few tens of nmol L^{-1} at the surface up to 18 mmol L^{-1} at the bottom. Other lakes of the same kind have different concentration ranges. For instance, Lake Pavin in France and Lake Völert-Sued in Germany both reach concentrations up to few mmol L^{-1} (Horn et al., 2017; Lopes et al., 2011) making our probe in its current status well suitable for acquiring continuous full vertical profiles in these lakes.~~

2 Materials and Methods

2.1 The Sub-Ocean Instrument

The optical instrument used in this study is based on the OFCEAS technique (optical feedback cavity enhanced absorption spectroscopy) (Morville et al., 2003, 2014) developed for trace gas sensing. The dissolved air from the extraction unit (Figure 1) is continuously pumped toward the optical cavity of the spectrometer. The internal volume of the cell is less than 20 cm^3 and provides sample residence times $< 30 \text{ sec}$ for optimal running conditions (compromise between the cell pressure and the total gas flow).

Extraction of dissolved gases from water is performed using a silicon PpolyDdimethylSiloxane-silicone (PDMS) membrane. The extraction technique does not rely on gas equilibration across the membrane but, in order to achieve fast response, the dry side of the membrane is maintained at low pressure while continuously flushing it with dry zero air (Triest et al., 2017). The pressure at the ~~membrane~~-dry side controls the total flow of dry and wet air through the membrane, and the system is designed to keep this pressure constant. While the spectrometer operates at about 20 mbar, the pressure at the dry side of the membrane is maintained at about 30 mbar.

A full description of the in situ membrane inlet laser spectrometer instrument (Sub-Ocean), together with the experimental setup used for laboratory calibrations can be found in (Grilli et al., 2018). In order to adapt the instrument to the high concentrations of dissolved CH_4 expected in Lake Kivu, the absorption spectrum of the optical spectrometer was set away

from the strong CH₄ rotational-vibrational transitions, more precisely at 2238.5 nm, where concentrations inside the optical cavity may reach up to 1.5 - 2 % of CH₄ in air before optical saturation (equivalent to an absorption 10⁻⁵ - 10⁻⁶ cm⁻¹). Above this absorption, the transmission signal at the maximum of the peak of absorption becomes too weak and the optical feedback to the laser, required ~~with by the OFCEAS-optical technique method, is not longer~~ strong enough to lock the laser frequency for a period of time close to the cavity free spectral range. This leads to narrower cavity modes and to a failure in ~~correctly~~ retrieving the absorption features ~~s-correctly~~. A stainless-steel membrane block (MB) was equipped with two 10 µm thick ~~polydimethylsiloxane (PDMS)~~ membranes of 56 mm diameter mounted face-to-face. The thin-film membranes were mounted on porous bronze frits of 3 mm of thickness (Poral, grade 20), providing mechanical strength for the membrane under high hydrostatic pressure. A schematic of the membrane block can be found in the supplementary information of Grilli et al., 2018. For this campaign, in order to increase the dynamic range of the measurements, one of the two membranes was replaced with a gas-tight Teflon film. This increased the dilution factor by decreasing the flow of the permeating gas with respect to water vapor and carrier gas flow, but degrades the precision of the measurements due to the low dry gas flow through the membrane. A picture of the instrument and the assembly taken during the campaign is shown in ~~Figure 2~~ Figure 2. The main (central) pressure tube (140-cm long, 28-cm diameter) is mounted on a metal frame. The membrane block ~~-at the bottom~~ is connected with a submersible water pump (Sea-Bird Electronics, SBE 5T) providing a flow of 0.8 L min⁻¹ along the membrane. A 1 L carrier gas (CG) tank containing dry zero air at a pressure between 2 and 40 bar, depending on the suitable autonomy, is attached on the frame and connected to the instrument via a 1/8" stainless-steel tube. A subsea battery (Seacell, STR) was mounted on the metal frame, providing up to 12 hours of continuous operation. An independent CTD (Sea & Sun Marine Tech, CTD-60) was also attached to the frame for depth, temperature, conductivity and dissolved oxygen measurements. For an operation where the instrument is powered through an electromechanical cable the autonomy will be limited by the storage of the dry gas inside the instrument housing. For fast response measurements, at maximum carrier gas flow of 6 ml min⁻¹ ~~is required this will~~ corresponding to ~~an 24-h~~ an 24h autonomy of 24h, whereas without the use of carrier gas the autonomy will stretch to 90 days since most of the gas flow will be composed of water vapor that is trapped before the vacuum pump by the silica gel dryer (however, the long-term deployment may be limited by the capability of the silica gel).

The embedded spectrometer is continuously measuring the gas composition at 10 Hz, while the response time of the sensor during the campaign, expressed as τ_{90} , was ~10 sec. At a lowering speed of ~6 m min⁻¹, ~~this corresponds to a the~~ vertical resolution ~~of is~~ 1 m. From the composition of the dissolved gas the instrument can ~~give an indirectly~~ estimate of the amount of N₂. This requires to know: TDGP, pCO₂ and pO₂ which were not measured by the Sub-Ocean probe and ~~relies~~ on other sensors. The partial pressure of N₂ can then be estimated as $p_{N_2} = TDGP - p_{CH_4} - p_{CO_2} - p_{O_2}$.

2.2 The HydroC-CH₄ commercial instrument

In situ discrete measurements of dissolved CH₄ at five different depths along the upper 150 m of the water column were performed using a commercial equilibrium-based underwater sensor, the Contros HydroC® HP ~~system sensor (Contros)~~. The

195 dissolved gas diffuses from the liquid through a thin film composite membrane into an internal gas cell. Therein, the total dissolved gas pressure and the partial pressure of CH₄ gas are measured by a pressure sensor and a non-dispersive infrared spectrometer, respectively. The HydroC® CH₄ HP sensor is similar to the HydroC® CO₂ sensor presented in (Fietzek et al., 2014), except for the absence of an internal zeroing system and a CH₄-specific fixed narrow-band spectral filter from 3.3-3.4 μm. The sensor was calibrated in October 2012 and November 2015 by the manufacturer. The calibrations were made using a
 200 specially designed pressure chamber with fresh water brought to pressure using compressed target gas. Three standard gas mixtures of CO₂, CH₄ and N₂ (100 % pressure N₂; 50 % pressure CH₄ and 50 % pressure CO₂; 100 % pressure CH₄) were used to equilibrate the water volume along a gas pressure gradient (5-6 points) from 1 up to 30 bars and partial pressures of CH₄ from 0.5 to 18 bars. The calibration results showed the absence of a significant drift of the sensor (< 3 % within the Lake Kivu gas concentration range) between the October 2012 and November 2015 calibrations. Also, several CH₄ profiles were carried
 205 out in Lake Kivu from 2016 to 2018 using the HydroC® CH₄ HP sensor and the repeatability of the observed CH₄ partial pressures was 3.8 % (2σ) below the main density gradient. However, the calibration curve as a function of the methane concentration was determined by using three points (0, 50 and 100% CH₄), and because of the nonlinear behavior of the detection system, a systematic error could be present, but it should not exceed 10 % (manufacturer personal comm.).

The HydroC®-CH₄ HP system was mounted on a SeaBird 19plus V2 SeaCAT CTD profiler equipped with a SBE 43
 210 Dissolved Oxygen sensor and a SBE 18 pH sensor. Calibrations of the SeaBird sensors were performed following manufacturer instructions. Water circulation in front of the HydroC®-membrane was provided by a SeaBird 5T pump, ensuring a continuous and homogeneous water flow to-at the membrane. A zero calibration of the HydroC®-CH₄-HP-system was made daily before each deployment using surface waters. The sampling rate was 1 Hz. The steady-state of the sensor was generally reached within 40 minutes and real-time data communication using an electromechanical cable allowed to adjust the waiting time at
 215 each depth accordingly. In all cases, the waiting time for each depth never exceeded 1 hour. The retained partial pressure of CH₄ is the average for the last 5 min of the equilibration curve.

2.3 Calculation of dissolved CH₄

Both the Sub-Ocean and the HydroC® HP sensors measure CH₄ in the gas phase, and raw data are expressed as the
 220 concentration of CH₄ with respect to the total amount of dry gas permeating the membrane. For the MHS-Sub-Ocean system, the concentration of CH₄ in the dry gas downstream from the membrane [CH₄]_g' can be expressed with respect to the expected concentration of the gas in the headspace which would be in equilibrium with the water sample, [CH₄]_g. In eq. 1, Pr are the membrane permeability coefficients for CH₄ and X (N₂, O₂ and CO₂) reported in Robb (1968), but corrected for their temperature and salinity dependency.

$$[CH_4]_g' = \frac{Pr_{CH_4} \cdot [CH_4]_g}{\sum Pr_X \cdot [X]_g} \quad (1)$$

Concentrations, $[CH_4]$, $[X]$ are expressed as mixing ratios. Measuring the concentration of water vapor $[H_2O]_g$ is required in order to retrieve the dissolved CH_4 concentration, $[CH_4]_{dissolved}$, since water vapor flow will cause dilution of the measured dry gas mixture (as well as the carrier gas flow). This measurement is performed by the OFCEAS spectrometer embedded in the Sub-Ocean probe, simultaneously with the CH_4 measurement. Precision on the water vapor concentration was $\pm 0.6 \%$ (2σ). $[CH_4]_{dissolved}$ is then calculated from the following equation:

$$[CH_4]'_{dissolved} = \frac{[CH_4]'_g \times f_t}{f_t - f_{CG} - (f_t \times [H_2O]_g)} \times \frac{1}{m_{eff}}, \quad (2)$$

where $[CH_4]'_g$ represents the methane mixing ratio measured by the optical spectrometer, f_t and f_{CG} are the total- and carrier-gas flow ($ml \text{ min}^{-1}$), respectively, and $[H_2O]_g$ corresponds to the mixing ratio of water permeating through the membrane. The denominator term $(f_t - f_{CG} - (f_t \times [H_2O]_g))$ corresponds to the dry flow permeating the membrane. m_{eff} represents the enrichment factor due to the membrane and corresponds to the quantity $\frac{Pr_{CH_4}}{\sum Pr_X \cdot [X]_g}$ in eq. 1. Its dependency with temperature and salinity is calculated by running calibrations under various conditions (Grilli et al., 2018). From our calibration, a m_{eff} of 2.84 ± 0.11 for fresh water at 25°C and 1.2 bar was calculated. This is in agreement with an expected value of 2.76 calculated from the permeation coefficients reported by Robb (1968).

As reported in eq. 1 above, this technique requires to know the main composition of the dissolved gas, in order to account for the different permeation coefficients of the species through the silicon-PDMS membrane. This does not represent a problem for most of the ocean and lake settings, where the gas mixture is mainly composed of nitrogen and oxygen, but it requires a more complex analysis for a setting such as Lake Kivu. For the data analysis we assumed a bulk gas mainly composed of N_2 , O_2 , CO_2 and CH_4 . H_2S is only present in bottom water and in lower amount with respect to CO_2 and CH_4 , and was therefore neglected here. Oxygen concentrations were calculated from the CTD measurements and converted into partial pressures using equation 19 from Sander 2015 (using H^{cp} of $1.25 \times 10^{-5} \text{ mol m}^{-3} \text{ Pa}^{-1}$ and $d\ln(H^{cp})/d(1/T)$ of 1500 K) ~~(Sander, 2015)~~.

As mentioned above, concentrations reported so far are expressed in mixing ratio with respect to the total dissolved gas pressure TDGP. Therefore, by knowing the TDGP, a value of partial pressure, pCH_4 , can be retrieved which is then converted into dissolved methane concentrations, C_{CH_4} , expressed in mol per liter of water. This conversion is performed by ~~taking into account~~ considering the solubility of the gas in water under given physical conditions as well as its fugacity. The procedure has been previously described in a scientific report (Schmid et al., 2019). C_{CH_4} is related to the pCH_4 through the following equation:

$$C_{CH_4} = K(T, S, P) pCH_4 \phi_{CH_4}(T, P), \quad (3)$$

where φ_{CH_4} is the fugacity coefficient, i.e. the ratio between the fugacity of a gas and its partial pressure, which is a function of temperature T , pressure P and gas composition, and K is the solubility coefficient, i.e. the ratio between the dissolved concentration of a gas and its fugacity. The solubility coefficient K ($\text{mol L}^{-1} \text{ atm}^{-1}$) of CH_4 as a function of temperature T (K) and salinity S (g/kg) is calculated using the following equation:

$$\ln(K) = A_1 + A_2(100/T) + A_3 \ln(T/100) + S[B_1 + B_2(T/100) + B_3(T/100)^2] , \quad (4)$$

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The parameters in eq. 4 are from ~~Wiesenburg and Guinasso (1979)~~ (Wiesenburg and Guinasso, 1979).

The solubility coefficients need to be corrected for the local pressure P (bar) at the sampling depth (sum of hydrostatic pressure plus atmospheric pressure), using the following equation (Weiss, 1974):

$$K(P) = K e^{\left[\frac{(1-P) v_{CH_4}}{RT} \right]} , \quad (5)$$

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where $R = 83.1446 \text{ cm}^3 \text{ bar K}^{-1} \text{ mol}^{-1}$ is the gas constant, and v_{CH_4} is the partial molar volume ($\text{cm}^3 \text{ mol}^{-1}$) of CH_4 calculated from ~~Rettich et al., 1981~~ (Rettich et al., 1981).

The fugacity coefficients were calculated using the methods described ~~by in Ziabakhsh-Ganji and Kooi~~ (Ziabakhsh-Ganji and Kooi, 2012). A Maple script was provided by Z. Ziabakhsh-Ganji, which was transcribed to Matlab code by M. Schmid (Schmid et al., 2019). The script calculates, among other things, the fugacity coefficients for CO_2 and CH_4 , including the interactions between both gases.

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2.4 The Lake and the field campaign

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Lake Kivu [2.50°S - 1.59°S ; 29.37°E - 28.83°E] located at 1460 m above sea level, has a surface of 2 700 km^2 (of which 2385 km^2 represents the water covering) and a maximum depth of ~485 m. The measurement campaign took place from 9th to 13th March 2018 at ~6 km from Goma and ~5 km from Gisenyi/Rubavu at the Northern shore of the lake (1.74087°S - 29.22602°E) and nearby a permanent platform with water depth of 410 m. During the campaign other types of measurements of dissolved methane and carbon dioxide were performed. The research team from Eawag (Switzerland) analyzed pumped water on the platform using a field mass spectrometer instrument (Brennwald et al., 2016), while a second team from UFZ (Germany) sampled water from a boat and measured the samples by head-space equilibration and gas chromatography (GC) analysis at the Lake Kivu Monitoring Program (LKMP) laboratory in Rubavu (Boehrer et al., 2019). The Sub-Ocean sensor was deployed from a research boat during three days of the campaign: 10th, 12th and 13th of March, with a total of eight continuous profiles. Measurements with the commercial HydroC® HP sensor were conducted during the campaign and on May 8th -11th at the same location as the Sub-Ocean measurements and over specific discrete depths.

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3 Results and Discussions

In ~~Figure 4~~ Figure 4 an example of a consecutive downward and upward profile of dissolved CH₄ measured by the Sub-Ocean sensor is reported. CH₄ concentrations are expressed as mixing ratio with respect to the total dissolved gas. The sensor was lowered at a speed of ~6 m/min, reaching 100 m depth in only 18 min. The response time of the sensor during the campaign expressed as τ_{90} was ~10 sec, which corresponds to a vertical resolution of 1 m. On the right-hand side, dissolved CH₄ is plotted against depth, showing the reproducibility of the sensor during descent and ascent.

A total of eight continuous profiles (downward and upward) were obtained with the Sub-ocean instrument during the campaign. They are reported in ~~Figure 5~~ Figure 5 together with dissolved CO₂, CTD data (temperature, conductivity and dissolved oxygen) and total dissolved gas pressure (TDGP). For the measurement of CH₄ only one of the eight profiles reached 150 m, while the others are shallower, only covering the upper 100 m of depth. The accuracy of the measurement was estimated at 80 m depth, where water mass is well stratified. At this depth, an average concentration of $35.5 \pm 7.8\%$, corresponding to 508.3 ± 112 mbar of partial pressure and 0.71 ± 0.16 mmol L⁻¹ of CH₄ was calculated, leading to a repeatability of $\pm 22\%$ (2σ). This relatively large standard deviation can be explained by the large uncertainty in determining the total flow of dry gas permeating the membrane. The value is in agreement with previously observed performances, where an error propagation of $\pm 12\%$ (2σ) was calculated using two semipermeable membranes (Grilli et al., 2018). The use of only one membrane allowed to further increase the dynamic range of the sensor by diluting the dry gas permeating the membrane. However, in this condition, a dry gas flow of only ~0.065 cm³ STP/min is delivered by the extraction system. The large uncertainty on this dry flow measurement directly affects the accuracy on the retrieved concentration. The uncertainty represented by the grey lines in ~~Figure 6~~ Figure 6 represents the measured variability over the eight vertical profiles from 0 to 80 m, and was fixed to $\pm 22\%$ at larger depths. The CO₂ data are from Schmid et al. (2005) and are calculated from alkalinity and pH measurements (Schmid et al., 2005). TDGP are discrete measurements at seven different depths measured with the HydroC@ HP sensor which have been interpolated to match the depth resolution of the Sub-ocean data. Nitrogen (N_2) mixing ratio was retrieved assuming that the main gas is composed by N₂, CO₂, CH₄, and O₂ ($pN_2 = TDGP - pCH_4 - pCO_2 - pO_2$).

The molar concentrations as a function of depth for the average continuous profile recorded by the Sub-Ocean sensor and for the discrete measurements obtained with the HydroC@ HP sensor are reported in ~~Figure 6~~ Figure 6. A good agreement between the two independent measurements is observed. The measurements were obtained during the same field campaign at the measurement site location near Goma (the two vessels were a few hundred meters away from each other). However, the measurements were not performed simultaneously. In the graph, results from previous campaigns are also reported. Data from the University of Liege obtained during a ~~long-long~~ term monitoring of the lake are reported in orange. Data were collected from June 2011 to August 2014 at different periods of the year (both dry and rainy seasons) and at different locations (northern and south basin) (Roland et al., 2017, 2018). The large variability of these ~~data-measurements~~ is reported by the orange lines (~~Figure 6~~ Figure 6) defining the 3σ distribution of the data. Data from the works of Pasche et al. 2011 and Schmid et al. 2005 are also reported in green and blue, respectively. ~~Data~~ The measurements from ULiege and Pasche 2011 were obtained by

sampling the water using Niskin bottles and analyzing the dissolved gas in the laboratory by head-space technique followed by GC analysis. The others (this work and Schmid 2005) are from in situ measurements. From the data, one can see that below 80 m depth, where the TDGP becomes larger than atmospheric pressure (1.4 bar at 80 m, Figure 5), a problem due to degassing of the sample collected on the Niskin bottles was observed, leading to an under-estimation of the dissolved CH₄. Data from Schmid 2005, which are from a commercial Capsum Met sensor (Franatech) and data from the Contros sensor are a bit lower than the measurements with the Sub-Ocean probe at higher concentrations (and depths), but they still lie within the measurement uncertainties. During the campaign the HydroC@ HP sensor also showed a good agreement with the other discrete techniques (on site mass spectroscopy and discrete sampling followed by GC analysis) between 150 and 250 m, while at larger greater depths, the HydroC@ HP values were lower by ~12% (Schmid et al., 2019). This may be due to a problem of calibration of the sensor at high hydrostatic pressures, but it requires further investigations to be confirmed. Regarding the Capsum Met sensor, no information about the calibration of the sensor were found, therefore no further discussion can be carried out.

Surface measurements performed by the Sub-Ocean instrument lead to average concentrations of $0.59 \pm 0.03 \mu\text{mol L}^{-1}$ and $0.72 \pm 0.14 \mu\text{mol L}^{-1}$ over the upper 10 and 30 m, respectively. Those values sit at the higher edge of the observed average seasonal concentrations, which span from 0.008 to $11 \mu\text{mol L}^{-1}$ (Roland et al., 2017, 2018, and more recent unpublished data from the same authors). Despite the large seasonal and spatial variability, our results are in good agreement with the one from Pasche et al 2011 which were obtained at a similar time of the year but at different locations (May 2006 and 2007 in Kibuye, Gisenyi and Ishungu). A stronger similarity can be found with the dataset from the same location (Gisenyi 2007) in the northern basin. CTD measurements (temperature, conductivity and dissolved oxygen, Sea & Sun Marine Tech, CTD-90M) performed a few months prior to the campaign at the research platform (Figure 7) confirmed a typical behavior of the lake stratigraphy while going from a dry into a rainy season (Roland et al., 2017) and justified therefore the high concentrations measured in this work. The lake was mixed down to at least 50 m depth during the previous dry season, and started to stratify in mid-December, leading to a 25-m depth seasonal thermocline. Below the thermocline, O₂ was rapidly consumed by mineralization of organic matter and oxidation of reduced compounds (e.g. methane, ammonium) diffusing upward. By the end of February, O₂ supplied at these depths during the previous dry season was completely vanished. Then, on the first-half of March, a mixing event occurred down to about 35 m depth, favoring the mixing between anoxic water (35-25 m depth), enriched in dissolved CH₄, and surface water. From the top 10 m layer temperature profiles reported in Figure 7 one can see that by March 22nd the temperature slope disappeared, supporting the occurrence of the water mixing-event.

Unfortunately, the reasons for this mixing event are still unknown. Meteorological records from December 2017 to March 2018 do not indicate neither high wind speed, low temperature, nor low relative humidity events that could clearly support our observations. Comparing the second-half of February to the first-half of March, average temperatures decreased by 1°C (from 21.2 to 22.2°C) and average precipitations increased by a factor of two, with peaks up to 7.6 mm of rainfall on March 6th. As reported by Rooney et al., 2018, rain may have a cooling effect on the lake surface by lowering the near-surface air temperature and inducing a convective mixing of the lake surface layer. Finally, CH₄ concentration in the surface layer may depend on the

biogeochemical processes such as for instance the methanotrophy. Further investigations are therefore required to better understand the dynamic of the surface layer of the lake at this period of the year.

This type of fast response sensors could be used to better investigate the fluxes of CH₄ (or other greenhouse gases) from lakes, oceans, rivers and other water reservoirs. In this campaign, only a specific location at 5 km from the coast with 410 m of water depth was investigated. The amount of CH₄ at the surface may strongly depend on the water depth, i.e. on the distance of the sediment to the surface, as well as to the horizontal distance from the shore and littoral sediments (DelSontro et al., 2018b). A fast sensor ~~w~~ould allow to follow the spatial distribution of dissolved gases at the surface ~~layer for different depths~~, as well as its variability over the seasons. This would help to better constraint the greenhouse gas emissions in the face of global change. (DelSontro et al., 2018a).

Beside the advantages of the Sub-Ocean probe to provide in situ, continuous and fast measurements, some drawbacks of the technique can be identified: **i)** the instrument was designed for measuring background concentrations in the oceans (sub-nmol L⁻¹) while ~~L~~lake Kivu reaches ~18 mmol L⁻¹ in bottom waters, thus with eight orders of magnitude difference. Despite the efforts to make the sensor less sensitive, the Sub-Ocean could not measure below 150 m depth, corresponding to a maximum measurable concentration of 3.5 mmol L⁻¹, where absorption becomes too strong for the optical spectrometer at the selected laser frequency. **ii)** In such environment, a good knowledge of the total dissolved gas pressure and of the concentration of dissolved CO₂ are required ~~for a~~ correctly determine the concentration of CH₄. Those parameters were measured during the field campaign, but they are not currently integrated in the sensor. This could be performed in the future by detecting simultaneously CO₂ and CH₄ using the same gas analyzer and by integrating the TDGP measurement or deploying the sensor with an independent TDGP device. It should be noticed that TDGP sensors have response times of a few minutes (e.g. $\tau_{63} = 2$ min for the Mini-TDGP from Pro-Oceanus) which could be a limiting factor with respect to the faster response time of the Sub-Ocean sensor. **iii)** Because a small dry gas flow through the membrane was required (in order to increase the dilution factor), the precision of the measurement was degraded by a factor of two with respect to previous deployments, leading to a $\pm 22\%$ precision. By using a less sensitive gas analyzer, the above drawbacks could be avoided, or at least minimized, making the technique fully suitable for monitoring meromictic lakes with a large range of dissolved CH₄ concentrations.

It should be noticed that different lakes have different dissolved CH₄ concentration ranges. Lake Kivu represents a very high range (with ~18 mmol L⁻¹ at the bottom) while for instance lake Pavin in France or lake Vollert-Sued in Germany both reach concentrations up to few mmol L⁻¹ (Horn et al., 2017; Lopes et al., 2011) making the Sub-Ocean probe in its current status well suitable for acquiring continuous full vertical profiles at those sites.

4 Conclusions

The comparison between different types of measurements confirms the reliability of the fast response membrane extraction system of the Sub-Ocean sensor under more extreme conditions (in terms of dissolved gas content) than ocean

settings. Lake Kivu is particularly challenging because of the high amount of dissolved CH₄ and CO₂ as well as their large variability. The gas composition strongly varies across the oxic-anoxic boundary and further down across the different chemoclines, going from a background composed by N₂ and O₂, to another one which sees CH₄ and CO₂ as the main dissolved gases. The Sub-Ocean sensor allowed fast vertical profiles of CH₄ which are in good agreement with the discrete in situ measurements made with the commercial HydroC® HP sensor at five different depths. During the campaign the HydroC® HP sensor also showed good agreement with the other discrete techniques (on site mass spectroscopy and discrete sampling followed by GC analysis) between 150 and 250 m. At 80 m of depth, ~~where,~~ no spatial variability of the dissolved gas is expected, ~~and we therefore estimate the~~ accuracy of ~~the SubOcean sensor to~~ $\pm 22\%$ (2σ) was estimated for the Sub-Ocean probe by comparing the eight independent profiles at this depth. The maximum measurable concentration of dissolved CH₄ was 3.5 mmol L⁻¹ at 24°C, 150 m of depth, and TDGP of 2.62 bar, which corresponds to a mixing ratio of 77% with respect to the total dissolved gas.

An average concentration of $0.59 \pm 0.03 \mu\text{mol L}^{-1}$ of CH₄ was found in the 10-m surface layer, which sits at the higher edge of the observed average seasonal concentrations of the lake. The variability of the physical parameters during a period of three months prior the campaign suggests a mixing event of the top 35 m, which can explain the high values measured at the surface. The causes of this mixing event are however not clear and further investigations will be required to better understand the behavior of the lake while going from the dry into the rainy season.

Such a campaign highlights the advantages of using the Sub-Ocean technology for measuring the dissolved gas content in meromictic lake settings. The technology allows in situ, continuous and fast profiling, important for a long-term monitoring of water resources. The in situ deployment prevents any possible contamination and artefact of the measurement due to water and/or gas sampling and subsequent laboratory analyses. The fast response of the instrument would allow to complete a full vertical profile over 470 m of depth with 1 m resolution within ~1h 20min, while current techniques of in situ discrete ~~sampling~~ measurements would take more than 1h per measured depth. The measurement by this technique has now been proven over a very large dynamic range of seven orders of magnitude, spanning from sub-nmol L⁻¹ in open ocean waters to mmol L⁻¹ concentrations of dissolved CH₄ and in a context of very different dissolved gas composition and TDGP. The instrument is therefore well suitable for fast profiling on different water reservoirs, and could be further adapted to the entire vertical column of Llake Kivu by using a less sensitive gas analyzer.

Author Contributions: RG, JT and JC are the inventors of the Sub-Ocean instrument. JC, AM and AU initiated the collaboration leading to the field campaign. AM and AU organized the field campaign and took care of the project administration. RG optimized the instrument for the measurements at Llake Kivu and ran the laboratory calibrations. RG prepared the instrument for the field and was in charge of the field campaign with the Sub-Ocean instrument. FD handled the measurements with the HydroC® HP sensor and its data analysis. JT contributed to the analysis of the HydroC® HP sensor and TDGP data. RG analyzed the Sub-Ocean data. All authors contributed to the manuscript.

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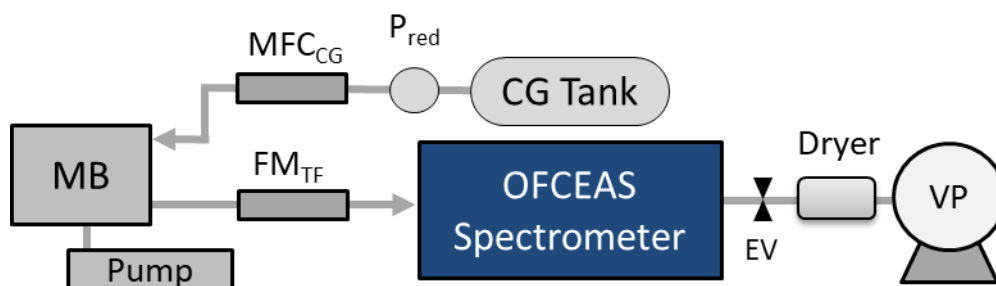


Figure 1. A schematic of the Sub-Ocean sensor. MB is the membrane block where the gas extraction occurs. Water circulates at the membrane using a submersible pump. The carrier gas (CG) flow is controlled by a mass flow controller (MFC_{CG}) and the flowmeter FM_{TF} is used for monitoring the total gas flow. The low pressure on the optical spectrometer is provided by a vacuum pump (VP) and an electronic valve (EV). P_{red} is a pressure reducer. A silica gel dryer is placed before the VP for trapping water vapor.

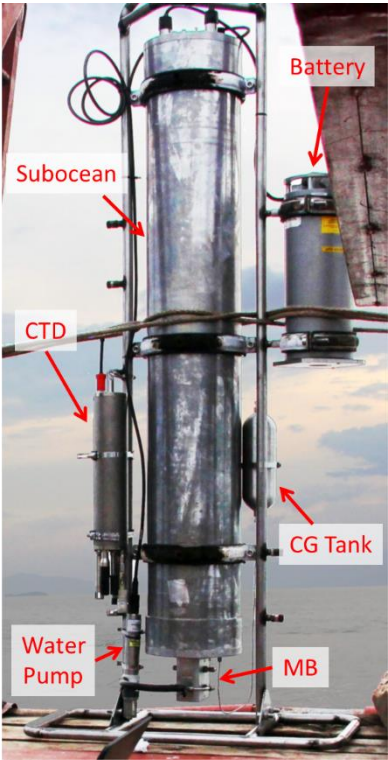


Figure 2. A picture of the Sub-Ocean instrument and the full assembly. The sensor is mounted on a metal frame. The main tube at the center is 150-cm long and 28-cm diameter. The membrane block (MB) at its bottom is connected to the water pump to ensure a constant flow of water against the membrane. The carrier gas (CG) tank is attached to the metal frame and connected with a 1/8” stainless-steel tube at the instrument. An STR battery pack and a CTD sensor were also attached to the metal structure. The total weight of the assembly is 120 kg with about -50 kg of buoyancy.

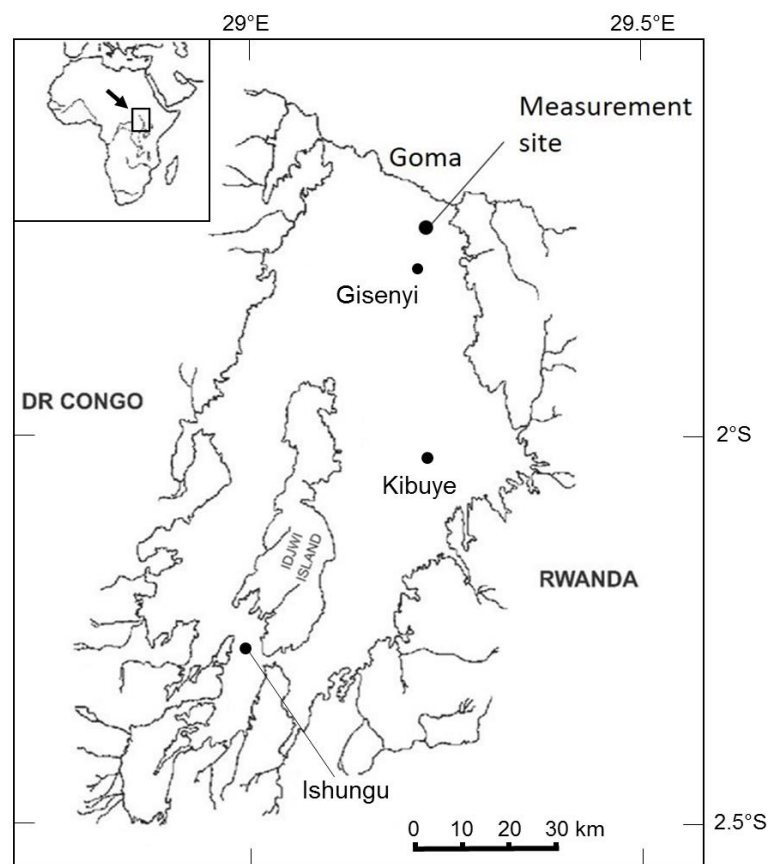
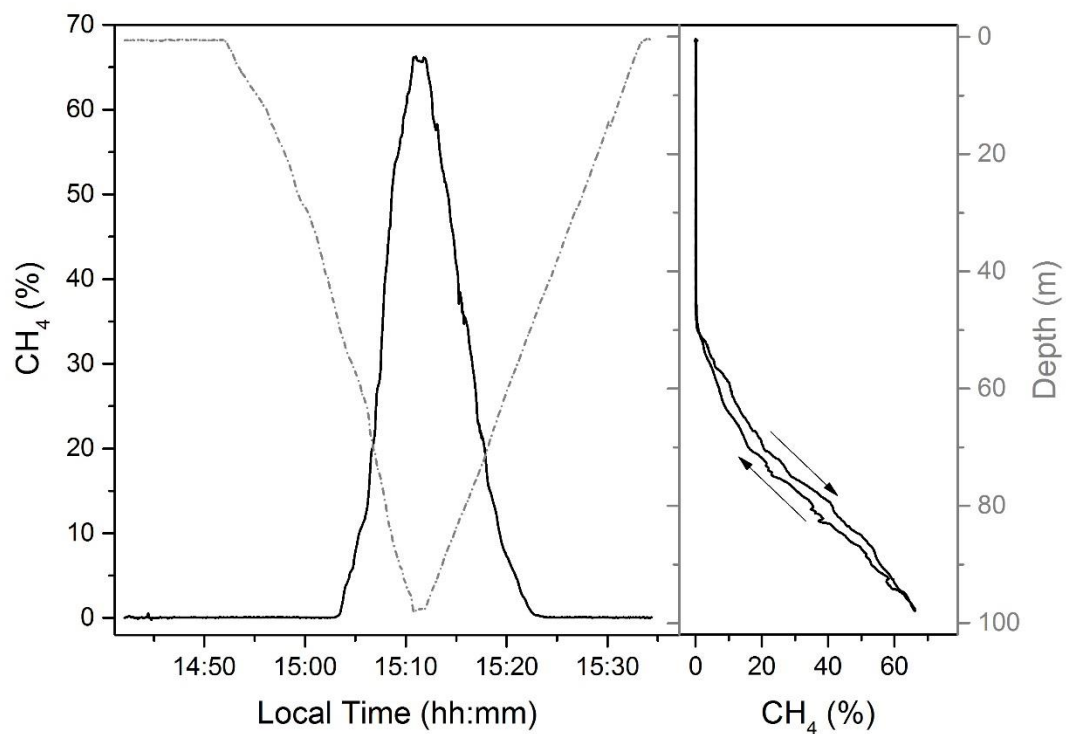


Figure 3. Map of Lake Kivu showing the location of the measurement site. Locations of previous campaigns mentioned in the discussion part are also reported (named Gisenyi, Kibuye and Ishungu).



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Figure 4. One of the methane continuous profiles recorded by the Sub-Ocean on 10th March 2018. The concentration is expressed as a percentage of CH₄ with respect to the total dissolved gas. The 100 m downward and upward profile was recorded in 42 min. On the right panel the two profiles are superposed, highlighting the reproducibility of the measurement between descent and ascent.

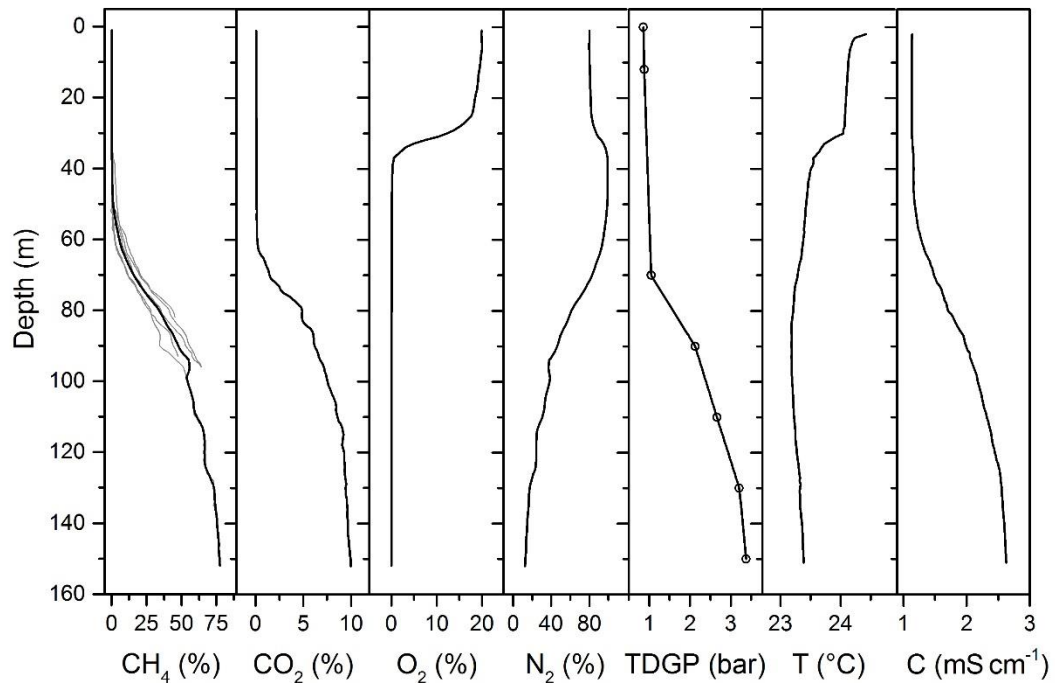


Figure 5. Mixing ratios of individual gas species in the dissolved gas mixture and total dissolved gas pressure. Grey CH₄ lines ~~combine-represent~~ the eight profiles recorded by the Sub-Ocean instrument during the campaign, while the black line is the averaged value. CO₂ data are from (Schmid et al., 2005), O₂, ~~temperature and electrical conductivity comes-are~~ from CTD data during the campaign, and N₂ is a concentration profile deduced from the other measurements (TDGP – pCH₄ – pCO₂ – pO₂). The total dissolve gas pressure, TDGP, was measured using the Contros HydroC® HP sensor (open circles), the black line is an interpolation of the data. ~~Temperature and electrical conductivity were recorded by the CTD during the deployment.~~

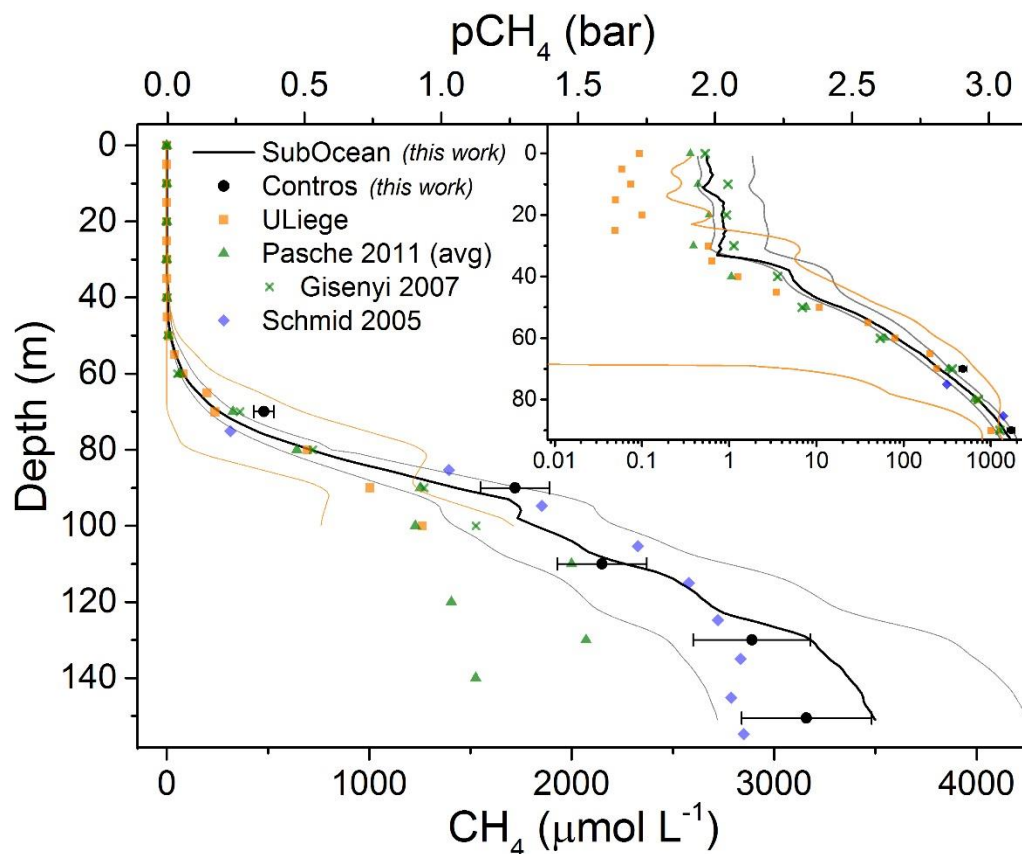


Figure 6. Continuous methane profile of the upper 150 m of water depth in Lake Kivu measured by the Sub-Ocean instrument (black line). Grey lines represent the measured variability over the eight continuous profiles estimated between 0 and 80 m depth and fixed to the estimated uncertainty of $\pm 22\%$ at larger depths. Black dots are discrete measurements made with the Contros HydroC[®] HP sensor at different depths. Error bars corresponds to the estimated uncertainty of $\pm 10\%$. Orange squares are from the long term monitoring from the University of Liege (Roland et al., 2017, 2018) with the corresponding 3σ variability (orange lines). Green triangles are average concentrations from Pasche et al. 2011 (Pasche et al., 2011) from three different campaigns conducted in May 2006 and 2007 at different locations (Kibuye, Ishungu and Gisenyi). Green crosses are data from Gisenyi 2007. Blue rhombus correspond to measurements from Schmid et al. 2005 in the northern basin using a commercial Capsum Met sensor (Schmid et al., 2005). In the insert a zoom on the shallow data is presented with a log-scale on the concentrations allowing a better comparison of the different datasets.

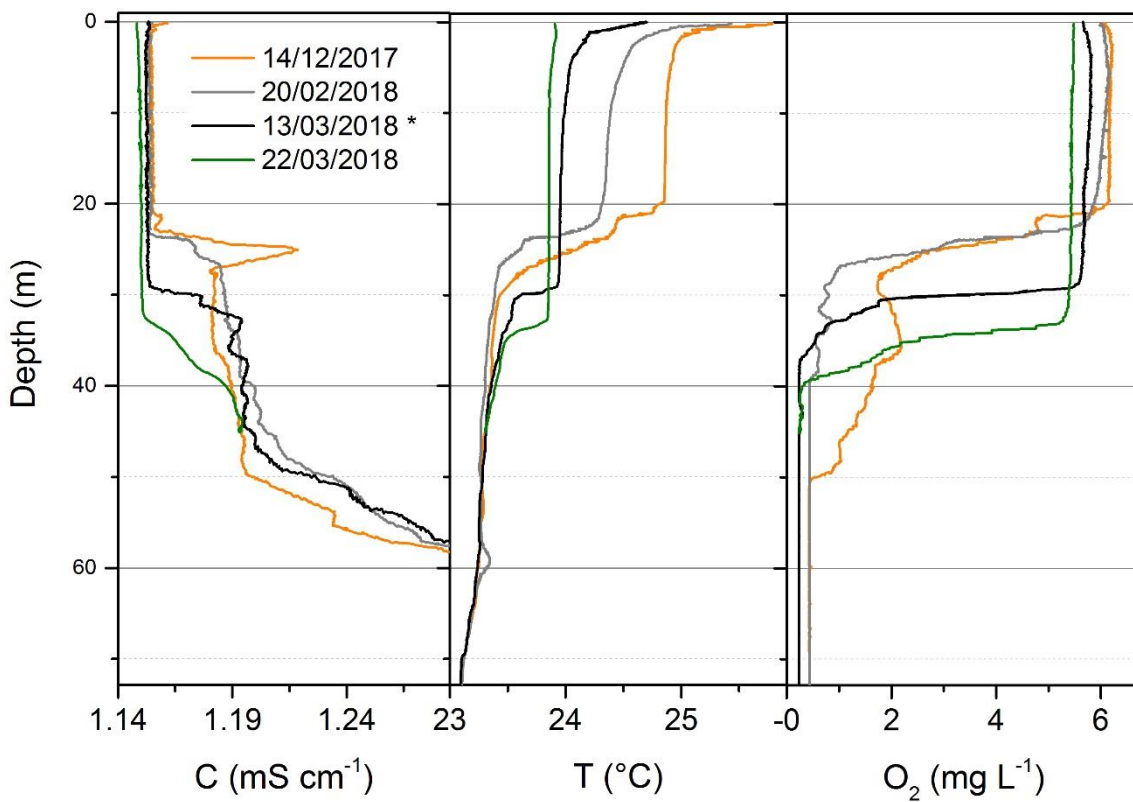


Figure 7. CTD (conductivity at 25°C, temperature and dissolved oxygen) data obtained a few months prior to the campaign. The black lines correspond to the conditions during the field measurements (*). The O₂ profiles highlight how the mixing layer extended down to 50 m depth during the previous dry season. From mid-December, the lake started to stratify at 25 m, while at the beginning of March the oxic layer increased down to 35 m depth.