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APPLIED WETLAND SCIENCE

Methane Emission from a Small Lake after Artificially Created Ebullition

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Abstract

The total amount of methane (CH_4) that is emitted from wetlands worldwide is still uncertain. A major factor contributing to this uncertainty is ebullition, which is the emission of virtually pure methane gas bubbles from water bodies; these short, high-flux pulses are highly variable in space and time. Small, shallow lakes have been found to be prone to high CH_4 emissions related to ebullition, and the fluxes from these ecosystems have been quantified using the eddy covariance (EC) method. However, this method was found to cause systematic biases during high-flux events. In this study, the EC method was used to quantify the CH_4 flux from a small, shallow lake in which an artificial ebullition event was conducted to analyze the EC method's performance under such conditions. Results showed that the flux quality was not necessarily subject to flux biases during the ebullition event but was of sufficient quality to quantify the CH_4 emissions. The total emission flux of CH_4 from the small lake during the artificial ebullition event was of the same magnitude as the respective CH_4 flux over 2.7 days during regular conditions.

Keywords Eddy covariance · Methane · Flux quality · Small lake · Shallow lake · Ebullition

Introduction

As the second strongest driver of radiative-induced global warming after carbon dioxide (CO_2), methane (CH_4) has a huge impact on the global climate. Its atmospheric mixing ratio has increased since the preindustrial time by a factor of about 2.6 to 1857 ppb in 2018, and human activity accounts for about 60% of these emissions (Saunois et al. 2020). According to Saunois et al. (2020), global CH_4 emission estimates from bottom-up approaches suggest a yearly emission of 737 Tg CH_4 yr^{-1} (range 594–881), whereas top-down approaches suggest 576 Tg CH_4 yr^{-1} (range 550–594). This difference arises because bottom-up approaches give higher predicted emissions from wetlands, inland waters and other natural CH_4 sources compared to top-down approaches, likely due to overestimations from individual sources that contribute to the bottom-up estimates (Saunois et al. 2016, 2020). Since inland waters still provide an uncertainty in global CH_4 budget estimations, Saunois et al. (2020) indicated that detailed research should be done on emission factors. This study focusses on one of the key mechanisms driving CH_4 emissions from wetlands.

In inland freshwater bodies, CH_4 is formed primarily in carbon-rich sediments under low oxygen or under anoxic conditions (Rudd and Hamilton 1978). The emission of CH_4 from such lakes to the atmosphere happens through four main mechanisms: diffusion of CH_4 from the depth at which CH_4 is formed through the water body, ebullition, which is the ascent of pure CH_4 bubbles, storage flux, and plant-mediated transport (Bastviken et al. 2004). Small, shallow lakes have been shown to be a greater source of water-derived CH_4 than larger and deeper lakes due to, among others, their high perimeter-to-surface area ratio, which leads to an increased carbon content relative to their water volume (Holgerson and Raymond 2016). Further, (anoxic) sediment respiration can even affect the whole water column under well-mixed conditions in shallow lakes (Kortelainen et al. 2006), while in deep lakes, the oxidation of CH_4 in a still-oxygenated epilimnion will lead to a decrease of CH_4 emissions (Bastviken et al. 2002).

A previous study employing miniature flux chambers stated that ebullition at lake Heideweiher in NW Germany accounted for 65% of the lake's CH_4 emissions in 2017 and

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for 37% in 2018 (Schmiedeskamp et al. 2021). The eddy covariance (EC) method has been recommended for studies of the CH_4 release from inland waters, since it provides the ability to detect CH_4 from diffusive and ebullition fluxes (Schubert et al. 2012). However, uncertainty still exists about a potential underestimation of the flux by EC. Especially during high-flux events, systematic biases in EC data have been expected due to non-stationary conditions or an unfulfilled steady-state assumption, which have caused data losses that needed to be gap-filled in subsequent processing steps (Göckede et al. 2019; Schaller et al. 2019). In their approach, Schaller et al. (2019) used the wavelet technique to account for such losses, stating that the wavelet technique is an appropriate tool for flux correction when the steady-state assumption is not fulfilled. However, this still needs to be systematically evaluated under real-world conditions in which the occurrence of ebullition can be confirmed.

Therefore, to address the uncertainty of CH_4 emission measurement from inland waters during ebullition events, we installed an EC tower at lake Heideweiher. At one point in time with perfect boundary conditions (see section *Artificially created ebullition* in the *Material & Methods* section below), an ebullition event was artificially created (hereafter referred to as “event”) to obtain high CH_4 emission fluxes. In further steps, the data was analyzed to identify factors that impact flux quality. Therefore, the eddy covariance intervals (ECI) were calculated for integration time periods of 5 (ECI5), 10 (ECI10), 15 (ECI15) and 30 (ECI30) minutes. The computed methane emission fluxes and the respective quality flags of the EC routine were quantified.

Material & Methods

Lake Heideweiher is a dystrophic mid-latitude lake (Barth and Pott 2000; Pott 2000) located in the nature reserve *Heiliges Meer*, NW Germany (52° 20′ 46.633" N, 7° 37′ 17.580" E) at 45 m AMSL. It covers an area of 15,470 m^2 with a maximum depth of 83 cm (Schmiedeskamp et al. 2021). According to Holgerson and Raymond (2016), lake Heideweiher can, therefore, be classified as a very small and shallow lake.

Lake Heideweiher’s sediment was formed in the Weichsel glaciation and consists of glacial sands as well as drift sands and peat. The lake’s center sediment contains a 40-cm-thick iron-hydroxide layer that decreases in thickness toward the shore. This layer attenuates the infiltration of rainwater, by which the lake is predominantly fed (Weinert et al. 2000). Contact with the groundwater occurs at high water levels, while at low water levels, the lake feeds the aquifer (Schmiedeskamp et al. 2021). Following the observations of Schmiedeskamp et al. (2021) and according to our own observations, the lake’s surface is widely covered by *Nymphaea alba (L.)* in summer, which provides a natural supply of organic matter to the sediment and is an indicator of the natural succession to a fen (Hagemann et al. 2000). During dry summers in 2018 and 2019, a shift from aquatic to terrestrial vegetation was reported from episodic observations. Terrestrial plant residues also covered the bottom of the lake in the beginning of this study, in March 2021.

The immediate surroundings of the lake consist of a forested area in eastern, northern, and western directions as well as heathland and grassland areas in the southern direction. The further surroundings are influenced by various agricultural land use. During the warm and dry summers in 2018 and 2019, the lake eventually dried out completely in late summer. Large emissions of CH_4 were reported from sporadic measurements during these periods.

In summer 2021, lake Heideweiher was continuously monitored by a micrometeorological station that was installed in the eastern riparian zone. The study period spanned from the 24th of March 2021, until the 11th of October, 2021. During the meteorological summer (JJA), the mean air temperature was 18.4 °C, while the water temperature reached its maximum of 26.4 °C on the 19th of June. By the middle of October, the water level of lake Heideweiher had decreased by a total of 75 cm from the water level in the beginning of the study (Fig. 1a), which corresponds to a decrease of 35 cm beyond its long-term average of 40 cm (Schmiedeskamp et al. 2021). As a result, the shore areas, including the tower area, dried out, while about a third of the lake area remained underwater.

Experimental Setup

An eddy covariance (EC) tower was equipped with an omnidirectional (R3-50) ultrasonic anemometer (Gill Instruments Ltd., Lymington, Hampshire, UK) at a height of 2.8 m above the ground, which corresponded to a height of 2.2 m above the lake’s surface at the beginning of the study. An LI-7700 open-path CH_4 gas analyzer and an LI-7200 enclosed CO_2/H_2O gas analyzer (LI-COR Biosciences, Lincoln, Nebraska, USA) were installed, using an intake tube with a 0.5 m length and 5.3 mm diameter for the enclosed measurement. All EC data was logged by an LI-7550 analyzer interface unit (LI-COR Biosciences, Lincoln, Nebraska, USA) at a frequency of 10 Hz.

A Levellogger Junior Edge (Solinst Canada Ltd., Georgetown, Ontario, CA) was installed at a depth of 23 cm in the sediment to monitor changes in the water level as well as the water temperature. Air temperature, air pressure, soil temperature and downwelling short-wave radiation data were obtained from the meteorological station at Münster-Osnabrück, which is operated by the *Deutscher Wetterdienst* (DWD), about 24 km south of the study site.

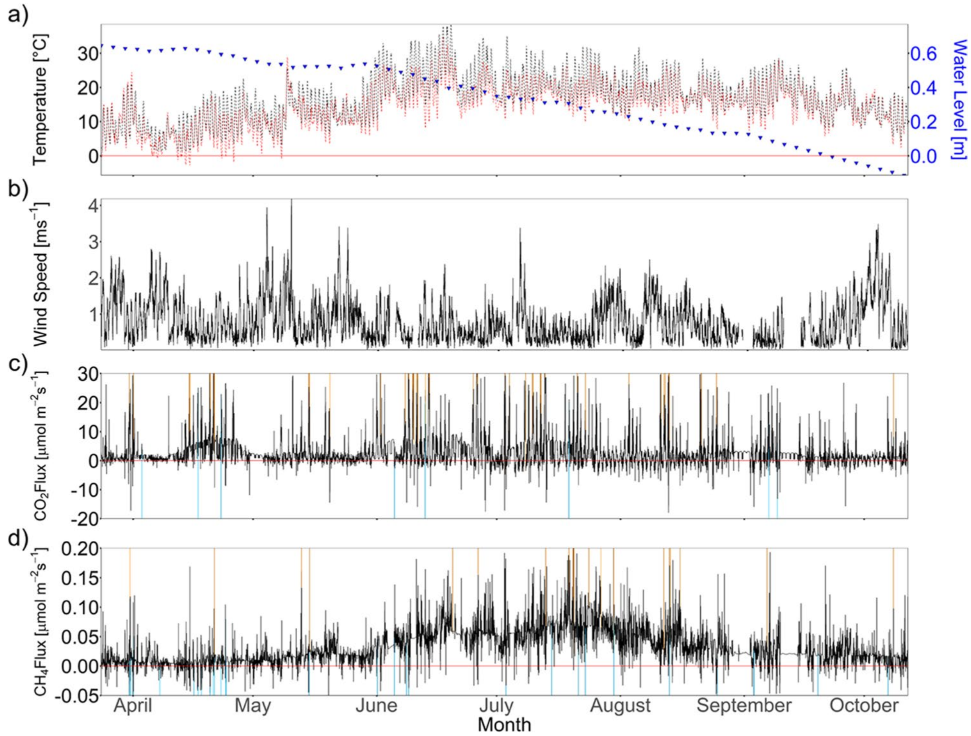

Fig. 1 Time series of lake Heideweiher from the 24th of March until the 11th of October, 2021. Panel **a**: air temperature (red dashed lines), soil temperature at a 5-cm depth (black dashed lines) on a shared y-axis (soil temperature is used as an orientation for sediment temperature), water level (blue triangles); Panel **b**: wind speed; Panel **c**: carbon dioxide flux (black, with positive values exceeding the range marked orange and negative outliers marked blue, after gap-filling); Panel **d**: methane flux (after gap-filling, color coding like panel c)

Data Processing

The turbulent, vertical gas fluxes were computed using the EddyPro software v7.0.6 (LI-COR Biosciences, Lincoln, Nebraska, USA). Several correction procedures were carried out to obtain high-quality flux data. Following Fratini and Mauder (2014), the EddyPro processing routine included despiking (Vickers and Mahrt 1997), double coordinate rotation (Kaimal and Finnigan 1994), Reynolds decomposition by block averaging, maximation of co-variances by cross-correlation, and spectral corrections for losses in the low (Moncrieff et al. 2004) and high (Fratini et al. 2012) frequency ranges.

Also, thresholds for the signal strength of LI-7200 (70%) and LI-7700 (15%) were set to exclude all data that might have been associated with instrument failures. Changes in the water level were accounted for by adjusting the measuring height using a dynamic metadata file in EddyPro. The flux quality was flagged using the procedures proposed by Foken et al. (2004) with classes from "1" (best) to "9" (worst). The footprint was calculated using Tovi v2.8.1 (LI-COR Biosciences, Lincoln, Nebraska, USA) following Kljun et al. (2004). Also, Tovi was used to sort out CH_4 and CO_2 fluxes in the complete time series that derived from footprints with a share of less than 80% within the lake area. Any gaps that remained or arose in the CH_4 data during this step were completed by gap-filling in R, using the REddyProc package (Wutzler et al. 2018), while CO_2 data were processed in Tovi using the quality screening tool and the MDS gap-filling tool.

All other data analysis was conducted using R v4.0.0 (R Core Team 2020). For the analysis of annual CH_4 fluxes, the missing data were filled based on the monthly mean values from the year 2018 by Schmiedeskamp et al. (2021). The CH_4 flux of the time series was calculated for 30-min eddy covariance intervals, while sets of the event data were calculated for 5-, 10-, 15- and 30-min EC averaging intervals, to figure out differences in computed flux quantity and quality.

Artificially Created Ebullition

An experiment was conducted to test the influence of high CH_4 fluxes on the EC method. For this purpose, a group of eight participants coerced an "outburst" event by walking through the lake, triggering the release of the CH_4 bubbles from the sediment (Fig. 2). This was mainly expected to violate the steady-state assumption while possibly also affecting turbulence development through participants' disturbances in the wind field. The event was conducted over 30 min on the 30th of July, 2021, from 07:00 to 07:30 CET and included a live monitoring of the wind direction, wind speed and CH_4 concentration to ensure that the intentional triggering of CH_4 release from the lake occurred within the current footprint area of the eddy covariance station (Fig. 3). Note, that the shore zone of lake Heideweiher had fallen dry by approximately 1 m of the lake's perimeter.

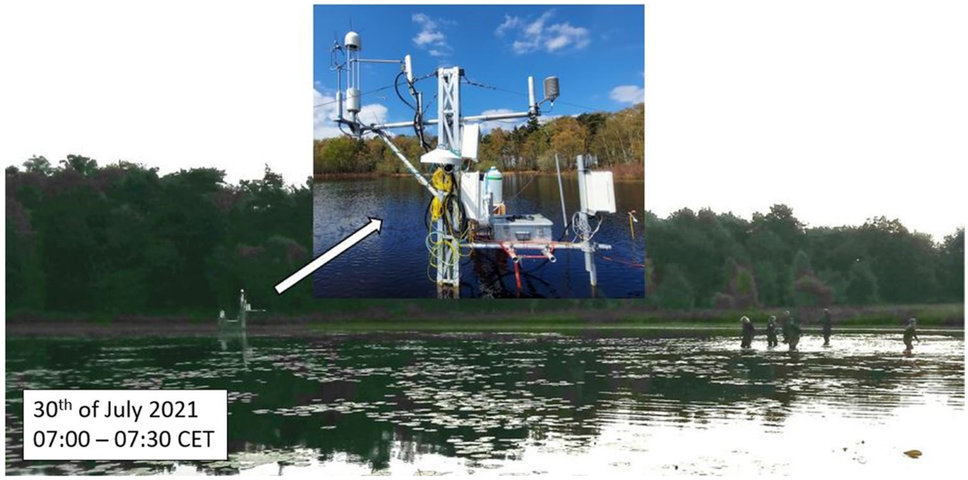

Fig. 2 Artificially created ebullition. The participants triggered the high release event (right side), while the EC tower (left side and upscaled picture) collected the data. Large photo by H. Becker

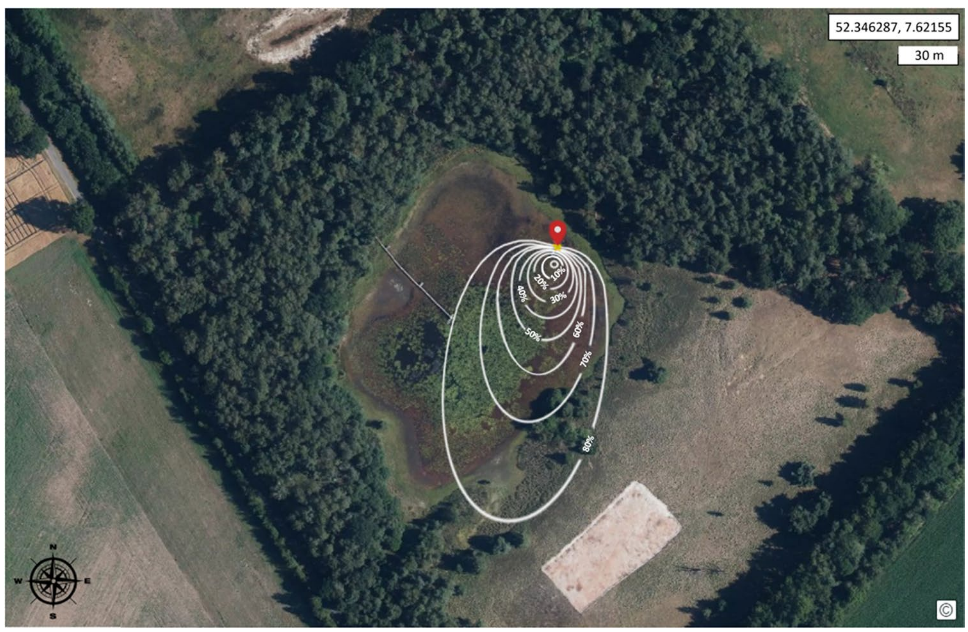

Fig. 3 The footprint area during the event (07:00—08:00 CET). The percentages show the flux contributions from their associated areas. Sources: Mapdata from OpenStreetMap (CC-BY-SA); Satellite Imagery from Mapbox; modified

Results & Discussion

The Time Series

Methane Fluxes

During the study period, the predominant wind direction was SW (28%) and the median of the wind speed was 0.62 m s^{-1} (Fig. 1b). The highest CH_4 emission flux occurred in July (median 0.06 µmol m^{-2} s^{-1}, disregarding the event), while the lowest monthly median was found in April (0.01 µmol m^{-2} s^{-1}, Fig. 1d). For CO_2, the highest emissions were found in June (median of 2.56 µmol m^{-2} s^{-1}), while the lowest monthly median fluxes occurred in May (1.09 µmol m^{-2} s^{-1}, Fig. 1c). Note, that the months from October through March were not used for monthly calculations, because our data for these months are incomplete. Concerning the study period, the CH_4 flux had a median of 84.8 ± 1.56 ($\pm$ S. E.) µmol m^{-2} h^{-1}, while the CO_2 flux had a median of 5.58 ± 0.28 ($\pm$ S. E.) mmol m^{-2} h^{-1}.

Daytime and Nighttime Fluxes

The CH_4 fluxes were predominantly positive (emissions). Negative CH_4 fluxes were observed mainly at night. Between 20:00 and 08:00 h, 73% of negative CH_4 and 20% of negative CO_2 fluxes occurred. Negative fluxes were also flagged worse by the software than positive fluxes, with 31% of the quality flags ≥ 7 for CH_4 and 34% of the quality flags ≥ 7 for CO_2.

The violation of the steady-state condition was the main reason for bad quality flagging in this regard, accounting for 99% of all flags ≥ 7 for CH_4 and 96% of all flags ≥ 7 for CO_2. At daytime, the integral turbulence characteristic (ITC) value showed a slightly higher impact on flux quality than at night, accounting for 7% of the CH_4 fluxes and 6% of the CO_2 fluxes flagged ≥ 7. Still, the non-fulfillment of the steady-state condition remained the predominant cause for poor flux qualities. The CO_2 fluxes showed a typical diurnal pattern, while no daytime-dependent pattern was observed for CH_4.

Data Losses

During the study, 17.8% of the CH_4 data and 9.3% of the CO_2 data were lost or had to be omitted from the analysis. Thereof, 5.8% were lost due to electricity failure. In addition, 3.6% of the CH_4 data were excluded for insufficient signal quality and 1.0% were flagged as 9. For CO_2, 1.8% of the data were excluded for insufficient signal quality and 1.7% were flagged as 9. Remaining percentages were sorted out during the data processing in EddyPro or manually in clearly unrealistic cases.

The Artificially Created Ebullition Event

Methane Fluxes

The CH_4 flux data indicate a clear impact of the event throughout the 30 min it was conducted, while the corresponding footprint during this hour shows a flux contribution of 90% from the lake area (Fig. 3). Above-average fluxes appeared during the hour from 07:00 to 08:00 CET (Fig. 4). The emissions were thus enhanced until about 30 min after termination of the active triggering of ebullition by walking through the lake. Likely, ebullition from the deepest section of the lake was activated toward the end of the event, leading to the largest release of gas bubbles. In the further analysis, we defined four intervals of EC averaging, namely ECI5, ECI10, ECI15 and ECI30, describing the EC interval (ECI) with the attached digits (5, 10, 15, 30) indicating the averaging time in minutes. The highest flux value in ECI5 was 17.7 µmol m^{-2} s^{-1} at 07:35 CET. The last above-average CH_4 flux value during the event found in ECI5 was 0.16 µmol m^{-2} s^{-1} at 07:45 CET, which was followed by an average-ranged value of 0.07 µmol m^{-2} s^{-1} at 07:50 CET. In total, during the event and the following 30 min, an amount of 15.1 mmol m^{-2} h^{-1} of CH_4 (ECI30) was emitted, which corresponds to 2.7 days of natural CH_4 release from the lake in July or 24.1 days in April.

In contrast, the total CH_4 flux emitted during the event calculated for ECI5 was 15.9 mmol m^{-2} h^{-1}, which corresponds to 2.8 days of natural CH_4 release in July or 25.4 days in April. Even though the event resulted in a massive ebullition, there was no phase of "CH_4 renewal" detected in the aftermath, in which low fluxes would have indicated a "depletion" of the stored gas.

Methane Flux Quality

According to Foken et al. (2004), the quality flags were clustered into three quality flag classes, ranging from 1–3 (usable for fundamental research), 4–6 (general use), and 7–8 (orientational use only), while a quality flag of 9 (unreliable

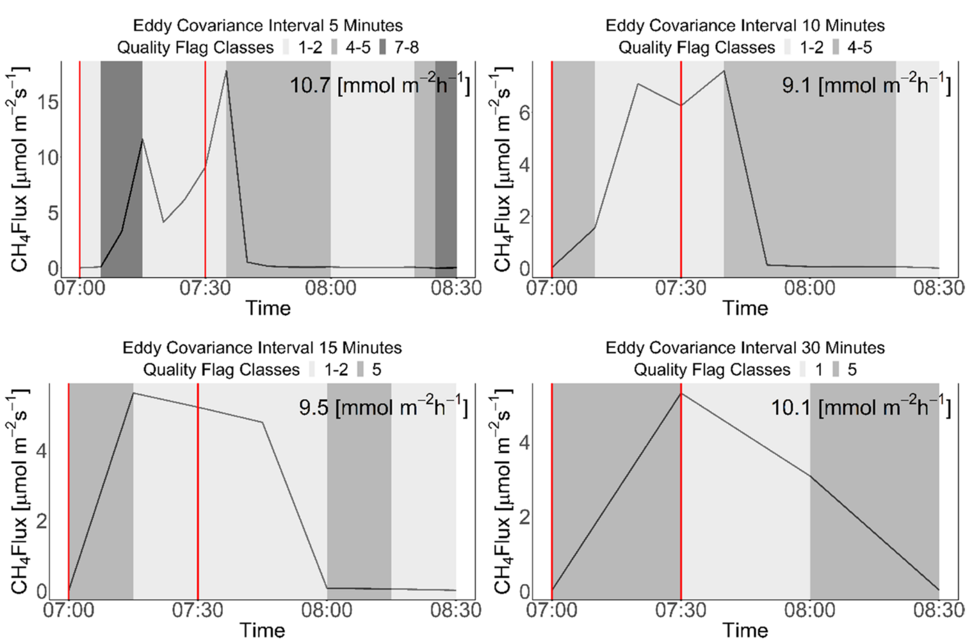

Fig. 4 Eddy covariance fluxes for the 30th of July, 2021, as calculated for the averaging intervals of 5, 10, 15, and 30 min, including quality flags. The quality flag classes are only displayed in the ranges for which they occurred. The red vertical lines indicate the half hour in which the event was conducted. In the top-right corners of the graphs, the peak integral of the respective graph is given. Note that the y-axis changes in scale between certain ECIs and the calculation of the hourly CH_4 fluxes refers to the entire 90-min interval displayed

data) was never reached during the event. The worst quality flags were found in ECI5 at 07:05 (8), 07:10 (7) and 08:25 (7) CET. Note that the last of these flags occurred outside of the event's time span. The quality flags at 07:05 and 08:25 CET were the result of bad steady-state conditions, while the flag at 07:10 CET derived from a bad ITC value. Apart from these three, the highest quality flag value found in all intervals was 5; in these cases, the quality flag values were not better than 5 due to the ITC value. Regarding the average of the quality flags, ECI30 showed the best quality of 2.1, followed by ECI15 with 2.2 and ECI10 and ECI5 with 3.1 each. Noticeably, the ITC value appeared to cause higher quality flag values during the event than in the usual daytime. The steady-state conditions were violated in at least in two 5-min time steps in ECI5 that showed a high discrepancy between the previous and the following flux values. Still, it can be stated, that the EC method performed well during the event, and no biases related to high fluxes occurred.

Differences between the Eddy Covariance Intervals

In ECI5 and ECI10, the maximum value was reached after the 30-min event, while ECI15 and ECI30 show the maximum value within the event time. This is a consequence of the chosen averaging intervals and illustrates how single ebullition "outbursts" are hardly visible in common 30-min EC intervals but are, nevertheless, accounted for within the computed flux data. Since the graphs of the different ECIs differ from each other in shape and scale, the peak integrals were used to test the impact of the interval length on the magnitude of the flux.

To ensure that the peak integral is comparable among the intervals, it was calculated for the time from 07:00 to 08:30 CET. As Fig. 4 shows, the peak integral result over the displayed 90 min was 10.7 mmol m^{-2} h^{-1} for ECI5, while it was 9.1 mmol m^{-2} h^{-1} for ECI10, 9.5 mmol m^{-2} h^{-1} for ECI15, and 10.1 mmol m^{-2} h^{-1} for ECI30.

Note that the actual CH_4 flux of the hour between 07:00 to 08:00 CET, in which the impact of the event was clearly visible, was 15.1 mmol m^{-2} h^{-1} of CH_4 (ECI30), while the values displayed in Fig. 4 show the average hourly flux of the 90-min interval to account for the comparability of the EC intervals calculated using the peak integral approach.

Along with Heidbach (2019), who observed negligible divergences in CH_4 fluxes under non-outburst conditions between 10- and 30-min EC intervals in her study, we found no significant impact of the interval length on the CH_4 flux during the event. In contrast to the study by Göckede et al. (2019), the high fluxes during the event were neither flagged 9, nor did they drop out during the data processing in EddyPro. This observation means that high fluxes within an EC interval of 30 min and shorter do not necessarily lead to flux biases even when the steady-state assumption is affected.

Comparison of the Annual CH_4 Flux

Holgerson and Raymond (2016) calculated the annual average CH_4 flux of lakes with a similar size to lake Heideweiher as 2.28 ± 0.51 (± S. E.) mmol C m^{-2} d^{-1} with a sample size of 50 lakes in the corresponding category. In comparison, lake Heideweiher's median daily CH_4 flux was quantified as 0.93 ± 0.12 (± S. E.) mmol C m^{-2} d^{-1}, meaning that it is at the lower end of the expected pattern of the lake's size class. This is likely linked to the oxidation of CH_4 in the lake's sediment in dried-out zones during seasonal changes in the water level. Winter fluxes are expected to be even much smaller, given the lower temperatures and potential ice coverage. Still, lake Heideweiher has a high emission potential regarding methanogenesis. Its rich organic sediment is refilled by terrestrial vegetation and by remains of macrophytes providing the source of CH_4 production. Moreover, its small size and its shallow depth of < 1 m allow a high carbon content relative to the water content at a high perimeter-to-surface area ratio (Holgerson and Raymond 2016) and facilitate the occurrence of well-mixed conditions at high water temperatures (Jacobs et al. 2008). In summer, the effect of the rising temperature on the CH_4 emissions described in Schmiedeskamp et al. (2021) were also observed in this study.

Performance of the Eddy Covariance Method

The EC method was found to be capable of quantifying emissions from a lake and could be executed automatically with reasonable maintenance effort for long-term continuous monitoring. In this study, an artificial ebullition event was conducted under stationary atmospheric conditions, forcing high ebullition CH_4 fluxes over a 30 min to 60 min time interval. This differs from intermittent natural ebullition events that may occur on shorter time scales. Whenever EC is applied under natural conditions which may or may not include ebullition events, a quality screening of raw data needs to be performed. We show in this study that high flux events are not necessarily excluded from the data due to systematic biases even when the fluxes vary strongly in their magnitude during these events (Fig. 4), and that the standardized averaging interval of 30 min performed best regarding flux quality. Note that data losses may still occur e. g. through mesoscale meteorological effects or under less well-developed turbulence conditions. Lately, wavelet-based approaches from Schaller et al. (2019) enabled a precise gap-filling of EC flux biases due to mesoscale meteorological effects, while Iwata et al. (2018) described methods to partition fluxes into ebullitive and diffusive fluxes, making ebullition events discernible in EC approaches. Difficulties in applying the EC method can yet be caused by the location of the measuring tower if it cannot be placed in the main wind direction or if the wind field is massively affected by environmental obstacles in the surrounding area.

Conclusion

In this study, the median hourly CH_4 flux from lake Heideweiher was quantified as 30.4 ± 1.65 (± S. E.) µmol m^{-2} h^{-1}. During the event, the EC method performed well. Concerning the standardized EC averaging interval of 30 min, the quality flag was 5 in the worst case, and, therefore, the results are of sufficient quality for ecological and biogeochemical interpretation. Regarding flux quality, the steady-state test was the key driver of bad flagging, which was especially observed during nighttime periods for CH_4 measurements. The choice of integration intervals during EC computation (5, 10, 15, 30 min) had a negligible impact on the measured flux, although shorter flux intervals were flagged somewhat worse than longer intervals. Based on our observations under stationary atmospheric conditions and during continuous high CH_4 fluxes, the commonly used 30-min EC interval performed best regarding flux quality. In natural intermittent flux conditions, a quality screening is important to account for data losses due to environmental or meteorological conditions. However, high flux events were not found to cause systematic biases in the CH_4 flux data. Therefore, the results of our study suggest the use of the common 30-min EC interval in future studies. Further research on the performance on the EC method can help to improve the understanding of its sensitivity towards impacting factors. This pilot study was meant to be a step into that direction.

Concerning other studies on CH_4 fluxes from lakes, lake Heideweiher, a small and shallow lake, is a below-average emitter of CH_4. This is likely related to the process of seasonal drying, followed by declining emissions in the winter, that lower the overall CH_4 emissions in an annual context. The magnitude of emitted CH_4 is highest in summer. Although small-scale measurements might not be suitable for flux estimations of all lakes, the techniques are relevant for identifying "hotspots" of gas production and their spatiotemporal variability, helping to understand the environmental and biogeochemical processes within a lake. Future bottom-up studies on CH_4 fluxes from wetlands should be encouraged to use the EC method, since it can be used successfully to quantify fluxes, including ebullition, and because it is straightforward to operate the method over long time periods.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare that there are no competing interests of any kind.

References

Barth E, Pott R (2000) Vegetationsgeschichtliche und paläoökologische Untersuchungen zur Trophie-Entwicklung in Stillgewässern der pleistozänen Sandlandschaft Norddeutschlands. In Abhandlungen aus dem Westfälischen Museum für Naturkunde. Ökosystemanalyse des Naturschutzgebietes „Heiliges Meer" (Kreis Steinfurt). Interaktionen zwischen Still- und Fließgewässern, Grundwasser und Vegetation sowie Landnutzung und Naturschutz. LINDEN Print & Media GmbH. https://www.lwl.org/wmfn-download/Abhandlungen/Abh_62(Beiheft)2000.pdf

Bastviken D, Ejlertsson J, Tranvik L (2002) Measurement of Methane Oxidation in Lakes: A Comparison of Methods. Environ Sci Technol 36(15):3354–3361. https://doi.org/10.1021/es010311p

Bastviken D, Cole J, Pace M, Tranvik L (2004) Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. Global Biogeochemical Cycles 18(4). https://doi.org/10.1029/2004GB002238

Foken T, Göckede M, Mauder M, Mahrt L, Amiro BD, Munger JW (2004) Post-field data quality control. In: Lee X, Massman W, Law B (eds) Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, pp 181–208

Fratini G, Mauder M (2014) Towards a consistent eddy-covariance processing: An intercomparison of EddyPro and TK3. Atmosph Measure Tech 7(7):2273–2281. https://doi.org/10.5194/amt-7-2273-2014

Fratini G, Ibrom A, Arriga N, Burba G, Papale D (2012) Relative humidity effects on water vapour fluxes measured with closed-path eddy-covariance systems with short sampling lines. Agric For Meteorol 165:53–63. https://doi.org/10.1016/j.agrformet.2012.05.018

Göckede M, Kittler F, Schaller C (2019) Quantifying the impact of emission outbursts and non-stationary flow on eddy-covariance CH₄ flux measurements using wavelet techniques. Biogeosciences 16(16):3113–3131. https://doi.org/10.5194/bg-16-3113-2019

Hagemann B, Pott R, Pust J, Recke (2000) Bedeutung der Vegetation für Stillgewässer-Ökosysteme, Trophiedifferenzierung und Trophieentwicklung im Naturschutzgebiet „Heiliges Meer" (Kreis Steinfurt, Nordrhein-Westfalen). In Abhandlungen aus dem Westfälischen Museum für Naturkunde. Ökosystemanalyse des Naturschutzgebietes „Heiliges Meer" (Kreis Steinfurt). Interaktionen zwischen Still- und Fließgewässern, Grundwasser und Vegetation sowie Landnutzung und Naturschutz. LINDEN Print & Media GmbH. https://www.lwl.org/wmfn-download/Abhandlungen/Abh_62(Beiheft)2000.pdf

Heidbach K (2019) Flux Footprint Modeling of Biosphere-Atmosphere Exchange Measurements [Technische Universität München]. https://mediatum.ub.tum.de/doc/1436746/1436746.pdf

Holgerson MA, Raymond PA (2016) Large contribution to inland water CO2 and CH4 emissions from very small ponds. Nat Geosci 9(3):222–226. https://doi.org/10.1038/ngeo2654

Iwata H, Hirata R, Takahashi Y, Miyabara Y, Itoh M, Iizuka K (2018) Partitioning Eddy-Covariance Methane Fluxes from a Shallow Lake into Diffusive and Ebullitive Fluxes. Bound-Layer Meteorol 169(3):413–428. https://doi.org/10.1007/s10546-018-0383-1

Jacobs AFG, Heusinkveld BG, Kraai A, Paaijmans KP (2008) Diurnal temperature fluctuations in an artificial small shallow water body. Int J Biometeorol 52(4):271–280. https://doi.org/10.1007/s00484-007-0121-8

Kaimal JC, Finnigan JJ (1994) Atmospheric boundary layer flows: Their structure and measurement. Oxford University Press

Kljun N, Calanca P, Rotach MW, Schmid HP (2004) A Simple Parameterisation for Flux Footprint Predictions. Bound-Layer Meteorol 112(3):503–523. https://doi.org/10.1023/B:BOUN.0000030653.71031.96

Kortelainen P, Rantakari M, Huttunen JT, Mattsson T, Alm J, Juutinen S, Larmola T, Silvola J, Martikainen PJ (2006) Sediment respiration and lake trophic state are important predictors of large CO_2 evasion from small boreal lakes: LARGE CO_2 EVASION FROM SMALL BOREAL LAKES. Glob Chang Biol 12(8):1554–1567. https://doi.org/10.1111/j.1365-2486.2006.01167.x

Moncrieff J, Clement R, Finnigan J, Meyers T (2004) Averaging, Detrending, and Filtering of Eddy Covariance Time Series. In: Lee X, Massman WJ, Law BE (eds) Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, pp 7–31

Pott R (2000) Vorwort. In R. Pott (Hrsg.), Abhandlungen aus dem Westfälischen Museum für Naturkunde. Ökosystemanalyse des Naturschutzgebietes „Heiliges Meer" (Kreis Steinfurt). Interaktionen zwischen Still- und Fließgewässern, Grundwasser und Vegetation sowie Landnutzung und Naturschutz. LINDEN Print & Media GmbH. https://www.lwl.org/wmfn-download/Abhandlungen/Abh_62(Beiheft)2000.pdf

R Core Team. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/

Rudd JWM, Hamilton RD (1978) Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism 1: Methane cycling in lakes. Limnol Oceanogr 23(2):337–348. https://doi.org/10.4319/lo.1978.23.2.0337

Saunois M, Bousquet P, Poulter B, Peregon A, Ciais P, Canadell JG, Dlugokencky EJ, Etiope G, Bastviken D, Houweling S, Janssens-Maenhout G, Tubiello FN, Castaldi S, Jackson RB, Alexe M, Arora VK, Beerling DJ, Bergamaschi P, Blake DR, … Zhu Q (2016) The global methane budget 2000–2012. Earth Syst Sci Data 8(2): 697–751. https://doi.org/10.5194/essd-8-697-2016

Saunois M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais P, Arora VK, Bastviken D, Bergamaschi P, Blake DR, Brailsford G, Bruhwiler L, Carlson KM, Carrol M, … Zhuang Q (2020) The Global Methane Budget 2000–2017. Earth Syst Sci Data 12(3):1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schaller C, Kittler F, Foken T, Göckede M (2019) Characterisation of short-term extreme methane fluxes related to non-turbulent mixing above an Arctic permafrost ecosystem. Atmos Chem Phys 19(6):4041–4059. https://doi.org/10.5194/acp-19-4041-2019

Schmiedeskamp M, Praetzel LSE, Bastviken D, Knorr K (2021) Whole-lake methane emissions from two temperate shallow lakes with fluctuating water levels: Relevance of spatiotemporal patterns. Limnol Oceanogr 66(6):2455–2469. https://doi.org/10.1002/lno.11764

Schubert CJ, Diem T, Eugster W (2012) Methane Emissions from a Small Wind Shielded Lake Determined by Eddy Covariance, Flux Chambers, Anchored Funnels, and Boundary Model Calculations: A Comparison. Environ Sci Technol 46(8):4515–4522. https://doi.org/10.1021/es203465x

Vickers D, Mahrt L (1997) Quality Control and Flux Sampling Problems for Tower and Aircraft Data. J Atmos Oceanic Tech 14(3):512–526. https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2

Weinert M, Remy D, Löhnert EP (2000) Hydrogeologische Systemanalyse des Naturschutzgebietes „Heiliges Meer" (Kreis Steinfurt, Nordrhein-Westfalen). In R. Pott (Hrsg.), Abhandlungen aus dem Westfälischen Museum für Naturkunde. Ökosystemanalyse des Naturschutzgebietes „Heiliges Meer" (Kreis Steinfurt). Interaktionen zwischen Still- und Fließgewässern, Grundwasser und Vegetation sowie Landnutzung und Naturschutz. LINDEN Print & Media GmbH. https://www.lwl.org/wmfn-download/Abhandlungen/Abh_62(Beiheft)2000.pdf

Wutzler T, Lucas-Moffat A, Migliavacca M, Knauer J, Sickel K, Šigut L, Menzer O, Reichstein M (2018) Basic and extensible post-processing of eddy covariance flux data with REddyProc. Biogeosciences 15(16):5015–5030. https://doi.org/10.5194/bg-15-5015-2018