Methane Emissions Offset Net Carbon Dioxide Uptake From an Alpine Peatland on the Eastern Qinghai-Tibetan Plateau

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Abstract Peatlands store large amounts of carbon (C) and actively exchange greenhouse gases (GHGs) with the atmosphere, thus significantly affecting global C cycle and climate. Large uncertainty exists in C and GHG estimates of the alpine peatlands on Qinghai-Tibetan Plateau (QTP), as direct measurements of CO2 and CH4 fluxes are scarce in this region. In this study, we provided 32-month CO2 and CH4 fluxes measured using the eddy covariance (EC) technique in a typical alpine peatland on the eastern QTP to estimate the net C and CO2 equivalent (CO2-eq) fluxes and investigate their environmental controls. Our results showed that the mean annual CO2 and CH4 fluxes were −68 ± 8 g CO2-C m⁻² yr⁻¹ and 35 ± 0.3 g CH4-C m⁻² yr⁻¹, respectively. While considering the traditional and sustained global warming potentials of CH4 over the 100-year timescale, the peatland acted as a net CO2-eq source (1,059 ± 30 and 1,853 ± 31 g CO2-eq m⁻² yr⁻¹, respectively). The net CO2-eq emissions during the non-growing seasons contributed to over 40% of the annual CO2-eq budgets. We further found that net CO2-eq flux was primarily influenced by global radiation and soil temperature variations. This study was the first assessment to quantify the net CO2-eq flux of the alpine peatland in the QTP region using EC measurements. Our study highlights that CH4 emissions from the alpine peatlands can largely offset the net cooling effect of CO2 uptake and future climate changes such as global warming might further enhance their potential warming effect.

1. Introduction

Carbon dioxide (CO2) and methane (CH4) are the two most important long-lived greenhouse gases (LL-GHGs) and together contribute to over 80% of the radiative forcing caused by LLGHGs (WMO, 2018). Peatlands cover only about 3% of the Earth’s land surface area but store over 614 ± 80 Pg (10¹² g) of carbon (C), accounting for one-third of the global soil C pool and about 70% of the atmospheric C pool (Loisel et al., 2017; Xu et al., 2018; Yu, 2011; Yu et al., 2010). It has been widely acknowledged that peatlands have played an important role in regulating the global C and GHG cycles and climate change (Friedlingstein et al., 2019; Froliking et al., 2011; Hopple et al., 2020). Peatland ecosystems have the potential to mitigate climate change by sequestering CO2 from the atmosphere into biomass and soils (Baldocchi & Penuelas, 2019; Nugent et al., 2019; Stocker et al., 2017); meanwhile, peatlands emit large amounts of CH4 to the atmosphere during the peatland forming and growing processes (Dommain et al., 2018; Kirschke et al., 2013), thus resulting in contrasting effects on radiative forcing. Both pathways are sensitive to climate change and anthropogenic activities (Chen et al., 2013; Froliking et al., 2011); for example, drought caused by both peatland drainage and low precipitation (Fenner & Freeman, 2011; Swindles et al., 2019), peatland wildfires and burning (Turetsky et al., 2015), and conversion for agricultural uses (Carlson et al., 2013; Dommain et al., 2018) can shift the peatlands from net GHG sinks to sources. However, it should be noted that the historical, current, and future contributions of peatlands to the global C budget and radiative forcing are still uncertain due to limited knowledge of the synergistic feedbacks of CO2 and CH4 to climatic perturbation and anthropogenic activities (Luan et al., 2018; Petrescu et al., 2015; Stocker et al., 2017).
The uncertainty in CO$_2$ and CH$_4$ stoichiometry of peatlands could be attributed to a variety of sources, such as the lack of reliable global peatland area estimates (Chaudhary et al., 2017; Xu et al., 2018; Yu et al., 2010), difficulties in quantifying terrestrial anaerobic or oxidative sources and sinks (Bridgham et al., 2013; Loisel et al., 2017; Poulter et al., 2017), and the scarcity of both CO$_2$ and CH$_4$ flux measurements, especially from low-latitude and high-altitude peatlands (Bridgham et al., 2013; Kirschke et al., 2013; Schaefer et al., 2016; Yu et al., 2010). To date, most of the peatland C fluxes have been measured in the northern high-latitude (45°–70°N; Loisel et al., 2017; Turetsky et al., 2014). Recent studies show that wetland ecosystems in the subtropical and tropical regions have acted as C sinks, but their CH$_4$ emissions can offset net CO$_2$ uptake under warm scenarios, thus contributing to a positive radiative forcing (Dalmagro et al., 2019; Dommain et al., 2018; J. Liu et al., 2020). Considering peatlands in the low-latitude regions have a sizable amount of C stocks and higher CH$_4$ emissions and CO$_2$ uptake rates compared to the northern peatlands (Loisel et al., 2017; Nilsson et al., 2008; Yu et al., 2010), the lack of C flux measurements from these areas could lead to large uncertainty in the global peatland C and GHG budget estimations (X. Liu et al., 2019; Schaefer et al., 2016; Turetsky et al., 2015). Therefore, more monitoring is needed to reveal the dynamics in peat-land-atmosphere C exchanges and dynamics.

The Ruoergai peatland in the eastern margin of the Qinghai-Tibetan Plateau (QTP) is the largest consecutive alpine peatland in the world, covering a total area of 4,600 km$^2$ at an average elevation of 3,400 m above sea level (Chen et al., 2014; Xiang et al., 2009; L. Yao et al., 2011). The climate of the eastern QTP is influenced by the Asian monsoons and characterized by short, warm, and wet summer with high solar irradiation and long, cold, and dry winter, which promotes the growth of herbaceous plants and preserving of peat or organic material rich soils (Hong et al., 2005; Peng et al., 2015). The mean annual temperature in the QTP region has been rapidly increasing at a rate of 0.27°C per decade during 1961–2005, which is four times higher than the increasing rate of global mean temperature (Tang et al., 2018; You et al., 2016). Due to the rapid warming, glacier melting and retreats have provided more water for peatland formation despite precipitation in the QTP region has not changed dramatically (T. Yao et al., 2012). As the biogeochemical processes regulating the CO$_2$ and CH$_4$ flux magnitudes are temperature-dependent and sensitive to water availability (Hopple et al., 2020; Peichl et al., 2014; Yuan et al., 2011; Yvon-Durocher et al., 2014), both fluxes can be significantly altered due to climate change in the QTP region (Chen et al., 2013; Yang et al., 2014).

The C balance and radiative forcing of peatlands from decadal to millennial timescales have been well understood in some regions of the globe (Frolking & Roulet, 2007; Johansson et al., 2006; Mathijssen et al., 2017; Minkkinen et al., 2002). Yet, studies into seasonal, annual, and between-years variabilities of wetland net CO$_2$ equivalent flux (net CO$_2$-eq flux, i.e., summing up CO$_2$ and CH$_4$ fluxes weighted by different global warming potential [GWP] metrics of CH$_4$) and its overall environmental controls are still rare (Dalmagro et al., 2019; Dommain et al., 2018; J. Liu et al., 2020), even entirely lacking in the QTP alpine peatlands. In this study, we compiled 32 months of continuous eddy covariance (EC) measurements of CO$_2$ and CH$_4$ fluxes at a typical alpine peatland on the eastern QTP to (a) characterize the temporal variations of net ecosystem exchanges of CO$_2$, CH$_4$, and their CO$_2$ equivalents between the alpine peatland and the atmosphere; (b) investigate the biophysical drivers of the net CO$_2$-eq fluxes at different temporal scales; and (c) assess the overall net radiative forcing arising from sustained CH$_4$ emissions and concurrent net CO$_2$ uptake from the alpine peatland on the eastern QTP. To our knowledge, this study was the first to present a multi-year continuous data set of ecosystem-scale net CO$_2$-eq flux over alpine peatlands on QTP, providing key information for understanding the role of alpine peatlands in the global C balance and net radiative forcing.

2. Methods
2.1. Site Description

The study site is located at the Hongyuan Peatland Carbon Flux Monitoring and Research Station (32°46′ N, 102°30′E, 3,510 m.a.s.l.) and operated by the Institute of Geochemistry, Chinese Academy of Sciences. The site is located in a valley on the eastern side of the Bai River in Hongyuan County, Sichuan Province, China (Figure 1). The Hongyuan peatland extends across an area of 1.1 km$^2$ and the deepest peat deposition is around 6.5 m. It is a part of the Ruoergai wetland, which covers 15% of the Ruoergai Basin area on the eastern QTP (Peng et al., 2019; L. Yao et al., 2011) and stores approximately 0.48 Pg C, some of which have
been formed since 15,000 years ago (Chen et al., 2014). The long-term (1981–2010) meteorological data from the National Benchmark Climate Station in Hongyuan (http://data.cma.cn) showed the regional climate pattern that the mean annual temperature and precipitation are 1.8°C and 746 mm, respectively. The highest monthly mean air temperature is typically observed in July (11.2°C on average) in this region, whereas the lowest is in January with a 30-year mean of −9.4°C. Over 75% of the annual precipitation usually occurs during the growing season from May to September each year. The dominant plant species in Hongyuan peatland are *Carex mulieensis* and *Kobresia tibetica*, and other abundant plant species include *Caltha palustris*, *Gentiana formosa*, and *Trollius farreri*.

### 2.2. Eddy Covariance and Ancillary Measurements

The EC and ancillary data were continuously measured from December 2013 to July 2016. The EC tower was installed in the center of Hongyuan peatland, where the terrain is flat and the average peat depth is 3.3 m. The flat area has a diameter of >300 m, which provides a homogeneous upwind fetch for the EC flux measurements (Figure 1c). The EC sensors were mounted at 2.5 m above the ground, consisting of a 3-D ultrasonic anemometer (WindMaster Pro, Gill Instruments Limited) for measuring wind components, an open-path infrared gas analyzer (LI-7500A, LI-COR Biosciences) for measuring carbon dioxide and water vapor densities, and an open-path gas analyzer (LI-7700, LI-COR Biosciences) for measuring CH₄ concentrations. The LI-7500A was tilted 10° in the main wind direction to avoid water accumulation on the lens. The raw EC data were recorded at 10 Hz using the LI-7550 data logger (LI-COR Biosciences). Other
ancillary environmental measurements, including global radiation ($R_\text{g}$), air temperature ($T_\text{air}$), and relative humidity (RH), precipitation (PPT), soil temperature ($T_{\text{soil}}$) at three depths (10, 25, and 40 cm below the ground), and soil water content (SWC) at a depth of 10 cm, were recorded by a HOBO U30 weather station installed near the EC tower (Figure 1d). Vapor pressure deficit (VPD) was calculated using the $T_{\text{air}}$ and RH measurements. The EC tower was powered by solar panels during daytime and lead-acid batteries during nighttime or when solar radiation was low. A more detailed description of instrumentation is presented in Peng et al. (2019).

### 2.3. Flux Data Processing and Radiative Forcing Calculation

The 10 Hz EC raw data were processed using the EddyPro® software (Version 7.0.6, LI-COR Biosciences) to obtain the half-hourly averaged fluxes of CO$_2$ and CH$_4$. In brief, double rotation (Wilczak et al., 2001), block average (Gash & Culf, 1996), and covariance maximization (Fan et al., 1990) were applied in the EddyPro settings. Flux data were corrected for spectral attenuations (Moncrieff et al., 1997, 2004) and density fluctuations (Webb et al., 1980). The self-heating correction (Burba et al., 2008) for the LI-7500A open-path analyzer was not applied at this site, as it had negligible effects on our CO$_2$ and CH$_4$ fluxes (Figure S1). The 30-min CO$_2$ and CH$_4$ flux data were filtered according to the “0-1-2” quality check flagging policy (Mauder & Foken, 2004) that data with a flag of “2” were discarded. As spikes still occurred in the time series data, half-hourly CO$_2$ and CH$_4$ fluxes were further filtered if they were outside the range of mean ± 3 × standard deviation over a moving window of 10 days. Moreover, the half-hourly CO$_2$ flux data measured during the calm and stable atmospheric conditions, indicated by low friction velocity ($u_*$) were discarded via the REdddyProc online tool (Wutzler et al., 2018) following the procedures described in Papale et al. (2006). The average $u_*$ threshold was 0.084 m s$^{-1}$ with a range of 0.079–0.099 m s$^{-1}$ at our site. The effects of $u_*$ threshold selection on cumulative gap-filled CO$_2$ flux data were shown in Figure S2. The same $u_*$ thresholds estimated for CO$_2$ flux were also applied to filter CH$_4$ flux data. During the measurement period, 21% of CO$_2$ and 14% of CH$_4$ flux data were lost due to sensor malfunctioning, 14% of CO$_2$ and 11% of CH$_4$ flux data were filtered due to the steady state and developed turbulent condition tests (Mauder & Foken, 2004), 7% of CO$_2$ and 8% of CH$_4$ flux data were discarded due to this $u_*$-filtering approach, and another 2% of CO$_2$ and 9% of CH$_4$ flux data were filtered due to the statistical outliers. Overall, 56% of CO$_2$ and 51% of CH$_4$ flux data were retained as good quality data. The monthly gap fractions were shown in a greater detail in Figure S3.

Gaps in CO$_2$ flux were filled using the marginal distribution sampling (MDS) method (Reichstein et al., 2005) implemented in the REdddyProc online tool. The MDS look-up table variables include global radiation, air temperature, and VPD. As CH$_4$ emissions are widely found to be controlled by soil temperature and water table level (e.g., Chen et al., 2021; Rinne et al., 2018; Ueyama et al., 2020), the CH$_4$ flux data were gap-filled by the regression fitting approach using soil temperature and SWC as environmental drivers. More details are provided in our previous study (Peng et al., 2019). The micrometeorological sign convention was used in this study that positive and negative fluxes indicated emission from and uptake by the peatland ecosystem, respectively.

The net radiative forcing of Hongyuan peatland was computed as the sum of the vertical CO$_2$ and CH$_4$ fluxes in CO$_2$ equivalents (defined as net CO$_2$-eq flux) weighted by GWP of CH$_4$. We applied both the traditional and sustained GWP (SGWP) metrics, the latter of which has been recently used to determine the net radiative forcing of several ecosystems by considering their persistent GHG emissions rather than the isolated pulse emissions (e.g., Hemes et al., 2018, 2019; J. Liu et al., 2020). In this study, we chose the CH$_4$ GWP of 28 CO$_2$-eq (GWP-28) without the inclusion of climate-carbon feedbacks (Myhre et al., 2013) and the SGWP of 45 CO$_2$-eq (SGWP-45) (Neubauer & Megonigal, 2015) over the 100-year time horizon. A positive net CO$_2$-eq value indicates an overall climatic warming effect and vice versa.

### 2.4. Flux Uncertainty, Statistical, and Footprint Analyses

Flux uncertainties due to the random measurement errors and gap-filling methods were estimated for CO$_2$ and CH$_4$ fluxes, respectively. The random measurement errors ($\sigma_{\text{rm}}$) in half-hourly CO$_2$ and CH$_4$ fluxes were obtained from the EddyPro output using the approach described in Finkelstein and Sims (2001). The half-hourly CO$_2$ and CH$_4$ flux uncertainties due to gap-filling ($\sigma_{\text{gf}}$) were estimated separately due to the
different gap-filling methods. We applied the Monte Carlo simulation (100 repetitions) approach following the procedures from Richardson and Hollinger (2007) to estimate the $\sigma_{gf}$ in CO$_2$ flux by calculating the standard deviations of the 100 half-hourly CO$_2$ flux data sets. The half-hourly $\sigma_{gf}$ in CH$_4$ flux was estimated using the bias errors (i.e., the difference between the modeled and measured CH$_4$ fluxes). The half-hourly total flux uncertainty was calculated by error propagation of $\sigma_{rm}$ and $\sigma_{gf}$. The half-hourly errors were further summed by squares to obtain the daily, monthly, and yearly cumulative errors.

Principle component analysis (PCA) was performed on the time-series data at the temporal resolutions of 30-min (non-gapfilled), daily, and monthly to investigate the correlation structures of the CO$_2$, CH$_4$, and net CO$_2$-eq fluxes with the environmental variables. Flux measurement footprint was estimated using the two-dimensional footprint parametrization (Kljun et al., 2015). Roughness length ($z_0$) and zero-plane displacement height ($d$) were estimated as 1/10 and 2/3 of the canopy height (0.1 m), respectively. Besides, other footprint model input includes wind direction, standard deviation of lateral wind component fluctuations, friction velocity, Monin-Obukhov length, and atmospheric boundary layer height, that is, 800 and 200 m for daytime-condition and nighttime-condition, respectively, for the eastern QTP region (Slättberg & Chen, 2020).

2.5. Evaluation Periods

During the study period from December 2013 to July 2016, the annual period is defined as the calendar year, which is further divided into four seasons based on the approaches described in Aurela et al. (2002) and Lund et al. (2010). The first and last dates of growing season (GS) were the first day with daily mean $T_{air}$ > 5 and <5°C for 7 consecutive days, respectively. The start and end of winter (W) were defined as the first day with daily mean $T_{soil}$ at the depth of 10 cm was below and above 0°C for 2 consecutive days, respectively. Soil thawing (ST) incorporated the time period between winter and growing season and soil freezing (SF) extended from the end of the growing season to the beginning of the winter. The starting and ending dates and length for each season during the study period were listed in the Supporting Information (Table S1).

3. Results

3.1. Environmental Conditions

The environmental conditions showed distinct characteristics between the two full annual periods (Figure 2). As shown in Figure 2a, $T_{air}$ did not differ much between the 2 years ($p > 0.05$), but the mean $R_{se}$ during 2015 was significantly higher than in 2014 ($p < 0.05$), especially during the growing season. Compared to 2014, the year of 2015 was identified as a dry year, with 182 mm less PPT occurring during the growing season. However, the cumulative PPT during the first half of the growing season (May–July) was similar in 2014 and 2015 (316 vs. 334 mm), and thus the largely reduced PPT mainly occurred from August 2015 (Figure 2b). During the first half of the growing season, $T_{soil}$ at the depth of 10 cm decreased by 1.0°C from 2014 to 2015, forming a cooler and wetter soil condition over that period due to a slight increase in PPT. In contrast to the growing season, $T_{soil}$ at 10 cm deep was on average 0.53°C warmer during the non-growing season in 2015 (1.21°C) compared to 2014 (0.68°C). As expected, SWC mainly varied with PPT throughout the study period (Figure 2c).

3.2. Temporal Patterns of CO$_2$ and CH$_4$ Fluxes

The peatland was a net CO$_2$ sink from May or June to September each year but a net source of CH$_4$ throughout the entire study period (Figure 3). Combining both CO$_2$ and CH$_4$ fluxes into CO$_2$-eq equivalents using the GWP-28 metric, the peatland acted as a net source of CO$_2$-eq fluxes for 10 and 11 months during 2014 and 2015, respectively. The lowest net CO$_2$-eq flux concurred with the highest CO$_2$ uptake in July each year, around which the highest monthly CH$_4$ fluxes were also observed, that is, in August 2014, July 2015, and July 2016. The peak net CO$_2$-eq emission was observed at the end of the growing season each year, that is, September 2014 and October 2015. While applying the SGWP-45 metric, the monthly net CO$_2$-eq fluxes
Figure 2. Monthly means (or sums) of environmental variables during the study period from December 2013 to July 2016 at Hongyuan peatland. (a) Monthly mean global radiation ($R_g$, red bars) and air temperature ($T_{air}$, red dots); (b) monthly precipitation sums (PPT, cyan bars) and monthly mean vapor pressure deficit (VPD, blue dots); and (c) monthly mean soil water content at a depth of 10 cm (SWC, green bars) and soil temperature ($T_{soil}$) at the depths of 10 cm (green dots), 25 cm (gray dots), and 40 cm (black dots).

Figure 3. Monthly sums of CO$_2$, CH$_4$, and net CO$_2$-eq (GWP-28) fluxes over the study period from December 2013 to July 2016 at Hongyuan peatland. All flux components are in g CO$_2$-eq m$^{-2}$ month$^{-1}$ using CH$_4$ traditional global warming potential of 28 (GWP-28). The error bars represent the flux uncertainties due to random measurement errors and gap-filling methods.
were positive for 31 out of the 32 months, illustrating that the peatland was mostly a net source of net CO\textsubscript{2}-eq over the monthly scale (Figure S4).

3.3. Seasonal, Annual, and Between-Year Variability of CO\textsubscript{2}-eq Fluxes

The net CO\textsubscript{2}-eq flux (GWP-28) during the SF period accounted for 33% of the annual net CO\textsubscript{2}-eq value (GWP-28), comparable to the contribution from the growing season (Table 1). Moreover, the net CO\textsubscript{2}-eq (GWP-28) emission during the wintertime was 14% and 18% of the annual CO\textsubscript{2}-eq sums during 2014 and 2015, respectively. In both years, the net CO\textsubscript{2}-eq flux contribution from the short ST periods (Table S1) was similar to the long winter seasons, thus showing a twice higher daily net CO\textsubscript{2}-eq emission rate on average (Table 1). In contrast, the SGWP-45 metric showed the most significant net CO\textsubscript{2}-eq emissions occurring during the growing seasons, 57% and 48% during 2014 and 2015, respectively (Table 1).

For each annual period, Hongyuan peatland acted as a sink for atmospheric CO\textsubscript{2} but a source of CH\textsubscript{4} to the atmosphere (Table 1). While considering the GWP-28 of CH\textsubscript{4}, the annual CO\textsubscript{2}-eq flux will be 1,047 and 1,071 g CO\textsubscript{2}-eq m\textsuperscript{-2} yr\textsuperscript{-1} during 2014 and 2015, respectively, which was almost doubled when applying the SGWP-45 metric (Table 1). The slightly increased annual net CO\textsubscript{2}-eq emission during 2015 corresponded with the reduced CO\textsubscript{2} uptake and slightly lower CH\textsubscript{4} emission, compared to the year of 2014. Moreover, the small between-year annual CO\textsubscript{2}-eq flux difference (24 g CO\textsubscript{2}-eq m\textsuperscript{-2} yr\textsuperscript{-1}) originated from the comparable between-year variabilities during the growing season (−100 g CO\textsubscript{2}-eq m\textsuperscript{-2}) and the non-growing seasons (124 g CO\textsubscript{2}-eq m\textsuperscript{-2}).

| Year | CO\textsubscript{2} flux | CH\textsubscript{4} flux | Net C or CO\textsubscript{2}-eq flux |
|------|------------------|-----------------|-------------------|
|      | g C m\textsuperscript{-2} (d\textsuperscript{-1}) | g CO\textsubscript{2} m\textsuperscript{-2} (d\textsuperscript{-1}) | g C m\textsuperscript{-2} (d\textsuperscript{-1}) (GWP-28) | g CO\textsubscript{2}-eq m\textsuperscript{-2} (d\textsuperscript{-1}) (SGWP-45) |
|      |      |      |      |      |
| A\textsubscript{sum} 2014  | −91 (5) | −334 (19) | 37 (0.2) | 1,381 (6) | 2,220 (10) | −54 (5) | 1,047 (20) | 1,886 (21) |
| A\textsubscript{mean} 2015  | −44 (6) | −161 (21) | 33 (0.2) | 1,232 (6) | 1,980 (10) | −11 (6) | 1,071 (22) | 1,819 (23) |
| A\textsubscript{mean} 2014  | −0.25 (0.01) | −0.92 (0.05) | 0.10 (0.001) | 3.78 (0.02) | 6.08 (0.03) | −0.15 (0.01) | 2.87 (0.05) | 5.17 (0.06) |
| A\textsubscript{mean} 2015  | −0.12 (0.02) | −0.44 (0.06) | 0.09 (0.001) | 3.38 (0.02) | 5.42 (0.03) | −0.03 (0.02) | 2.93 (0.06) | 4.98 (0.06) |
| ST\textsubscript{sum} 2014  | 28 (1) | 103 (2) | 0.9 (0.02) | 34 (1) | 54 (1) | 29 (1) | 137 (2) | 157 (2) |
| ST\textsubscript{mean} 2015  | 36 (2) | 132 (7) | 1.3 (0.04) | 49 (1) | 78 (2) | 37 (2) | 181 (7) | 210 (7) |
| ST\textsubscript{mean} 2014  | 0.74 (0.03) | 2.71 (0.05) | 0.02 (0.001) | 0.89 (0.03) | 1.42 (0.03) | 0.76 (0.03) | 3.61 (0.06) | 4.13 (0.06) |
| ST\textsubscript{mean} 2015  | 0.61 (0.03) | 2.24 (0.12) | 0.02 (0.001) | 0.83 (0.02) | 1.32 (0.03) | 0.63 (0.03) | 3.07 (0.12) | 3.56 (0.12) |
| GS\textsubscript{sum} 2014  | −167 (5) | −613 (17) | 28 (0.1) | 1,045 (4) | 1,680 (7) | −139 (5) | 432 (17) | 1,067 (18) |
| GS\textsubscript{mean} 2015  | −154 (5) | −564 (19) | 24 (0.1) | 896 (4) | 1,440 (7) | −130 (5) | 332 (19) | 876 (20) |
| GS\textsubscript{mean} 2014  | −0.97 (0.03) | −3.56 (0.10) | 0.16 (0.001) | 6.08 (0.02) | 9.77 (0.04) | −0.81 (0.03) | 2.51 (0.10) | 6.20 (0.11) |
| GS\textsubscript{mean} 2015  | −1.03 (0.03) | −3.79 (0.13) | 0.16 (0.001) | 6.01 (0.03) | 9.66 (0.05) | −0.87 (0.03) | 2.23 (0.13) | 5.88 (0.14) |
| SF\textsubscript{sum} 2014  | 36 (2) | 152 (6) | 5.3 (0.1) | 198 (3) | 318 (5) | 41 (2) | 330 (7) | 450 (8) |
| SF\textsubscript{mean} 2015  | 51 (2) | 187 (6) | 4.9 (0.1) | 183 (3) | 294 (5) | 56 (2) | 370 (7) | 481 (8) |
| SF\textsubscript{mean} 2014  | 0.58 (0.03) | 2.13 (0.10) | 0.09 (0.002) | 3.19 (0.05) | 5.13 (0.08) | 0.67 (0.03) | 5.32 (0.11) | 7.26 (0.13) |
| SF\textsubscript{mean} 2015  | 0.73 (0.03) | 2.67 (0.09) | 0.07 (0.001) | 2.61 (0.04) | 4.20 (0.07) | 0.80 (0.03) | 5.29 (0.10) | 6.87 (0.11) |
| W\textsubscript{sum} 2014  | 12 (1) | 44 (5) | 2.8 (0.1) | 104 (3) | 168 (4) | 15 (1) | 148 (6) | 212 (6) |
| W\textsubscript{mean} 2015  | 23 (1) | 84 (5) | 2.8 (0.1) | 104 (2) | 168 (4) | 26 (1) | 188 (5) | 252 (6) |
| W\textsubscript{mean} 2014  | 0.13 (0.01) | 0.47 (0.05) | 0.03 (0.001) | 1.12 (0.03) | 1.81 (0.04) | 0.16 (0.01) | 1.59 (0.06) | 2.28 (0.07) |
| W\textsubscript{mean} 2015  | 0.26 (0.01) | 0.97 (0.06) | 0.03 (0.001) | 1.20 (0.02) | 1.93 (0.05) | 0.30 (0.01) | 2.16 (0.06) | 2.90 (0.07) |

Note: A, annual; ST, soil thawing; GS, growing season; SF, soil freezing; W, winter. Numbers in parentheses represent flux uncertainties due to random measurement errors and gap-filling methods.
Controlling Factors of Net CO\textsubscript{2}-eq Flux

During the study period, the net CO\textsubscript{2}-eq flux dominantly varied with the CO\textsubscript{2} flux component at half-hourly (\(r = 0.98, p < 0.001\)), daily (\(r = 0.87, p < 0.001\)), and monthly (\(r = 0.83, p < 0.001\)) timescales, whereas little correlation existed between net CO\textsubscript{2}-eq and CH\textsubscript{4} flux at all three temporal scales (Figure 4). The positive correlation between CO\textsubscript{2} uptake and CH\textsubscript{4} emissions increased from half-hourly to monthly scales (Figures 4d–4f). At the half-hourly scale, the cross-correlation showed that the highest correlation (\(r = -0.33\)) between CO\textsubscript{2} and CH\textsubscript{4} fluxes was achieved when a time lag of 4.5 h (CH\textsubscript{4} flux in +4.5 h) was considered.

Among the six investigated environmental variables, \(R\text{\textsubscript{g}}\) was the strongest controlling factor of the half-hourly CO\textsubscript{2} flux and \(T\text{\textsubscript{soil}}\) was the most influencing parameter of the half-hourly CH\textsubscript{4} flux at all three temporal scales (Figure 4). The positive correlation between CO\textsubscript{2} uptake and CH\textsubscript{4} emissions increased from half-hourly to monthly scales (Figures 4d–4f). At the half-hourly scale, the cross-correlation showed that the highest correlation (\(r = -0.33\)) between CO\textsubscript{2} and CH\textsubscript{4} fluxes was achieved when a time lag of 4.5 h (CH\textsubscript{4} flux in +4.5 h) was considered.

During the growing season, bin-averaged responses of net CO\textsubscript{2}-eq fluxes to different \(R\text{\textsubscript{g}}\) classes illustrated that the net CO\textsubscript{2}-eq uptake (negative CO\textsubscript{2}-eq flux) was significantly enhanced by the increasing \(R\text{\textsubscript{g}}\) before reaching light saturation where \(R\text{\textsubscript{g}}\) was around 500 W m\(^{-2}\) (Figure 5a). Meanwhile, \(T\text{\textsubscript{air}}\) (5–15°C) and intermediate PPT (15–25 mm d\(^{-1}\)) positively affected the net CO\textsubscript{2}-eq uptake and emission rates, respectively (Figures 5b and 5c). The relationship between net CO\textsubscript{2}-eq flux and VPD showed that the net CO\textsubscript{2}-eq uptake quickly increased with VPD up to a threshold of \(\sim 0.66\) kPa, beyond which the net CO\textsubscript{2}-eq uptake started to decrease (Figure 5d). Additionally, the net CO\textsubscript{2}-eq flux during the growing season showed similar responses...
to $T_{\text{soil}} (>5^\circ \text{C})$ and SWC (>0.44 m$^3$ m$^{-3}$) as to $T_{\text{air}}$ and PPT, respectively (Figures 5e and 5f). During the non-growing seasons, net CO$_2$-eq generally increased with the rising $T_{\text{soil}}$ and with the increasing SWC at the lower range (e.g., 0.16–0.26) (Figures 5e and 5f).

As the CO$_2$ flux component was dominantly driving the variations in net CO$_2$-eq fluxes, its sensitivity to the environmental parameters was similar to the responses of net CO$_2$-eq flux (Figure S6). Whereas for CH$_4$ flux, we observed that CH$_4$ emissions during the growing season were linearly increasing with $T_{\text{soil}}$ and exponentially increasing with $T_{\text{air}}$, which were also inhibited at the high VPD range (>1.7 kPa; Figure S7). Moreover, CH$_4$ emission sensitivities to $R_g$, $T_{\text{soil}}$, and SWC were noted only during the SF period. The environmental responses of net CO$_2$-eq fluxes for the SGWP-45 metric did not differ much from the GWP-28 metric (Figure S8).

4. Discussion

4.1. CH$_4$ Emissions Offset the Net Cooling Effect of CO$_2$ Uptake

On an annual basis, our CO$_2$ and CH$_4$ flux measurements demonstrated that Hongyuan peatland was a net sink for atmospheric CO$_2$, a source of atmospheric CH$_4$, and an overall net C sink. The mean annual net C sink strength (33 g C m$^{-2}$ yr$^{-1}$) during the study period was close to the range of C accumulation rates (35–171 g C m$^{-2}$ yr$^{-1}$) during the recent decades for the alpine peatlands in the Ruoergai Basin (e.g., Hao et al., 2011; X. Liu et al., 2019; Wang et al., 2015), which further confirms that the recent C accumulation rates of peatlands in this region are higher than their Holocene averaged values (Wang et al., 2015; Y. Zhao et al., 2014). Within the C balance, C loss via CH$_4$ emissions was relatively lower compared to the magnitude of net CO$_2$ uptake.

While considering the GWP and SGWP of CH$_4$ over the 100-year timescale, CH$_4$ emissions have exceeded the net cooling effect of CO$_2$ uptake by 4.1 and 7.7 times (GWP-28) and 6.6 and 12 times (SGWP-45) for
2014 and 2015, respectively, resulting in the net positive radiative forcing and a potential warming effect of Hongyuan peatland. Considering the warming potential of CH$_4$ over the 20-year time horizon (GWP and SGWP were 84 and 96, respectively) is ~4 times stronger than that over a 100-year timescale, the GHG emissions from Hongyuan peatland would have a more substantial warming effect over a shorter timescale (e.g., decades). It is thus expected that the alpine peatlands are accelerators of global warming despite they are net C sinks in the meantime. Future studies assessing the peatland radiative forcing should account for the land-atmosphere exchanges of both CO$_2$ and CH$_4$.

A large portion (~49% and 38% for GWP-28 and SGWP-45) of the annual net CO$_2$-eq flux was observed during the SF and winter periods when the environmental conditions were unfavorable for plant growth. During these cold periods, soil respiration was expected to be the dominant process that released CO$_2$ into the atmosphere (X. Liu et al., 2019), and meanwhile, the peatland was still emitting CH$_4$ via anaerobic decomposition of soil organic matters (Peng et al., 2019). Moreover, winter was not dormant in terms of CO$_2$ and CH$_4$ production, even though $T_{\text{soil}}$ at 10 cm depth and $T_{\text{air}}$ dropped below zero for 98% and 76% of the wintertime of 2014 and 2015, respectively. During the wintertime, CO$_2$ and CH$_4$ emissions from peatlands can still occur through the frozen or snow-covered soils via diffusion and transportation through the chimney effect led by dead plant tissues and ice cracks and also through the burst emissions caused by rapid ST and freezing (Alm et al., 1999; Mastepanov et al., 2008; C. Song et al., 2020). The large amounts of CO$_2$-eq emissions during the non-growing season were in accordance with previous studies, which have recently highlighted that the overall C and GHG budgets may be underestimated without an accurate assessment for the non-growing season emissions (Aurela et al., 2002; Commane et al., 2017; Natali et al., 2019; W. Song et al., 2015).

4.2. Abiotic Controls of Net CO$_2$-eq Flux

Compared to 2014, the comparable annual CO$_2$-eq source strength during 2015 was attributed to the elevated CO$_2$-eq emissions during the non-growing seasons and slightly reduced net CO$_2$ uptake during the growing season. Our PCA and sensitivity analyses revealed that global radiation and soil temperature were the primary influencing factors of net CO$_2$-eq flux variabilities. More specifically, we found that clouds (indicated by low $R_g$) strongly reduced the net CO$_2$-eq uptake by blocking the incoming solar radiation and thus primarily reducing photosynthesis (Alton, 2008; Nijpp et al., 2015). Meanwhile, precipitation could also stimulate soil respiration during the drier years (e.g., 2015 in this study) due to the increased soil moisture (e.g., Bubier et al., 2003; Juszczak et al., 2013) and thus contributed to the overall reduced net CO$_2$ uptake (Figure S6f). Additionally, the higher SWC associated with a higher water table level during the ST and winter periods in 2015 could maintain anaerobic conditions and thus have primarily stimulated CH$_4$ emissions from the peatland compared to the other two years (Figures S7, S9, and S10).

Low soil temperature was expected to slow down the processes of photosynthesis, ecosystem respiration, and CH$_4$ production simultaneously in peatland ecosystems (Figures S6 and S7). However, the positive correlation between $T_{\text{soil}}$ and net CO$_2$-eq uptake during the growing season indicated its primary role in enhancing photosynthesis relative to CO$_2$ and CH$_4$ emissions at the alpine peatlands in the QTP region (Hao et al., 2011). This also explained the between-year variability of net CO$_2$-eq uptake (Figures S9–S12). Indeed, the observed positive effect of $T_{\text{soil}}$ on CH$_4$ emissions (Figure S7), which has been widely found in this region (e.g., Chen et al., 2008; W. Song et al., 2015) and worldwide (e.g., Dalmagro et al., 2019; Drollinger et al., 2019; Treat et al., 2014; J. Zhao et al., 2016), amplified the sensitivity of net CO$_2$-eq emission to $T_{\text{soil}}$ during the non-growing season but did not switch the overall relationship between net CO$_2$-eq and $T_{\text{soil}}$ during the growing season.

Furthermore, the net CO$_2$-eq uptake was inhibited under hot and dry conditions (i.e., high VPD) as a result of the declined CH$_4$ emissions and net CO$_2$ uptake (Figures S6 and S7). As CO$_2$ and CH$_4$ fluxes were tightly coupled at daily and monthly scales due to their strong connection in biogeochemical processes (Figure S13), we also found that higher CO$_2$ uptake could lead to higher CH$_4$ production in peatland ecosystems, most likely due to the promoted root exudates (Hatala et al., 2012; Shoemaker et al., 2012). Therefore, it is critical to investigate the environmental controls on the net CO$_2$-eq flux that integrated the soil biogeochemical and plant physiological processes.
4.3. C and GHG Budgets of Alpine Peatlands on the QTP Under Global Change

The alpine peatlands on the QTP typically act as net C sinks considering the C gains and losses involved in the biogeochemical and physiological processes in the peatland ecosystem (Chen et al., 2014; X. Liu et al., 2019). However, peatlands can be strong sources of net CO$_2$-eq and thus result in net positive radiative forcing while taking the GWP and SGWP of other GHGs into account. As peatlands in this region could also be significant sources of N$_2$O (e.g., Chen et al., 2013; II. Liu et al., 2019; Marushchak et al., 2011), which has 265 times stronger GWP than CO$_2$, the net positive radiative forcing of alpine peatlands on QTP would be further enhanced if combining N$_2$O flux into the GHG budget. Besides, as the CO$_2$ and CH$_4$ exported through stream discharge could account for ~10% of the land-atmosphere C fluxes (Nilsson et al., 2008), the positive radiative forcing of Ruoergai peatlands would be stronger if these exports are included in the C and radiative balances. One recent model study also showed similar results to this study that the significant CH$_4$ emissions from wetlands even offset the entire regional GHG balance on the QTP (Jin et al., 2015). Therefore, the non-CO$_2$ GHG emissions from peatlands play an important role in the regional GHG budgets by potentially switching the alpine peatlands from a radiative cooling to a warming effect.

The C and GHG balances of the Ruoergai peatland are sensitive to the rapid climate warming on the QTP, which has been widely observed during the last decades (Yang et al., 2014; T. Yao et al., 2012; You et al., 2016). As the warmer temperature has been found to accelerate CH$_4$ emissions from peatlands in the Ruoergai Basin by promoting both anaerobic and aerobic metabolisms (Cui et al., 2015; Yang et al., 2014), it is expected that the Ruoergai peatland will emit more CH$_4$ to the atmosphere and result in more offsetting to both the radiative cooling effect and the carbon sink strength of peatland ecosystems in a projected future warming scenario of the QTP region (L. Zhao et al., 2010) if other influencing factors (e.g., management practices, water balance, etc.) remain similar. In addition, glacier melting and permafrost thawing in response to the rising temperature could lead to more peatland formations in this region (Luan et al., 2018; T. Yao et al., 2012), which will create more CH$_4$ emission hotspots in the future.

Due to the intensified human disturbance in the QTP region, many peatlands have been drained for animal husbandry or mined for fuels (Chen et al., 2014; L. Yao et al., 2011). Rapid increases in runoff have caused many river diversions and thus incised extensive amounts of peatlands, leading to enhanced regional peatland drainage (Li et al., 2015). Drainage can further alter the GHG and C balances by affecting hydrology, soil, and vegetation composition in the degraded peatland ecosystems (Gyimah et al., 2020). It has been observed that the increased soil temperature and decreased SWC altered by peatland drainage could reduce CH$_4$ emissions and net CO$_2$ uptake in the QTP region (Yang et al., 2014, 2017; Zhou et al., 2017), which would further strengthen the positive radiative forcing of these alpine peatlands. Therefore, investigations on the effects of peatland drainage and restoration are greatly needed to identify the role of alpine peatlands in regional and global C and GHG cycles under the circumstances of climate change and anthropogenic disturbances in the future.

5. Conclusions

During the study period, our 32-month EC flux measurements showed that the typical alpine peatland on the eastern QTP acted as a net sink for atmospheric CO$_2$, a net CH$_4$ source, and an overall net C sink. When considering their potential influence on radiative forcing, the CH$_4$ emissions considerably offset the radiative cooling effect of the peatland net CO$_2$ uptake, thus switching the peatland to a net CO$_2$-eq source and causing a potentially warming effect. Our analysis further demonstrates that global radiation and soil temperature were the main environmental drivers that influenced the alpine peatland net CO$_2$-eq flux variabilities from half-hourly to annual timescales. Besides, we found that both CH$_4$ and CO$_2$ emissions during the SF and winter periods have contributed significantly to the annual net CO$_2$-eq fluxes, suggesting that the non-growing season C emissions are extremely important for assessing the overall C and GHG budgets of the alpine peatlands in the QTP region, particularly in a warming climate. The extended long-term continuous GHG monitoring is advocated to further investigate the feedback between the alpine peatlands and global change.
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