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The significant contribution of lake depth in regulating global lake diffusive methane emissions

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ABSTRACT

Global lakes have been identified as an important component of natural methane (CH_4) sources. Given that lake CH_4 emissions involve multiple, complex processes influenced by various environmental factors, estimates of global lake CH_4 emissions are largely uncertain. In this study, we compiled global CH_4 emission data on 744 lakes from published studies, and found a significantly negative correlation ($R^2 = 0.50$, $p < 0.01$) between diffusive CH_4 flux and lake maximum depth. Further analysis indicated that no significant differences in global sediment CH_4 production were found for the different maximum depths investigated. Owing to the longer oxidation pathway, presence of oxycline layer, and the lower nutrient environment, deeper lakes yield less diffusive CH_4 efflux compared to shallower lakes. Additionally, we also found that lake area was negatively correlated ($R^2 = 0.13$, $p < 0.01$) to diffusive CH_4 flux. Therefore, based on empirical correlations between lake morphometry (maximum depth and area) and diffusive CH_4 emission, as well as the combination of two lake databases, we estimated that the annual diffusive CH_4 emission from global lakes is approximately 11.2 (6.2–19.5) Tg CH_4/yr, and greater than 84% is emitted from lakes with a mean depth of less than 5 m. Furthermore, two regions, 40–70° N (30.4%) and 20° S~10° N (37.4%), were found to be the dominant contributors of global lake diffusive CH_4 emissions, resulting from the considerable total lake area and the extensive shallow lakes in these regions. This study highlights the significance of the 'depth-effect' which controls the spatial distribution of lake diffusive CH_4 flux and allows for the quantification of global lake diffusive CH_4 emissions.

1. Introduction

Recent studies have raised considerable concern on the rapid increase in global atmospheric methane (CH_4) levels since 1750 (Myhre et al., 2013; Saunois et al., 2016), while also motivating fields of research targeted at investigating the magnitude and spatiotemporal dynamics of dominant sinks and sources (Kirschke et al., 2013; Deemer et al., 2016). Of late years, global lake ecosystems (including ponds) have been identified as important natural CH_4 sources (Bastviken et al., 2011; Kirschke et al., 2013), contributing 20.6%–32.8% to global natural CH_4 emission despite the fact that such water bodies only cover from approximately 1.8%–3.6% of the total land area (Verpoorter et al., 2014; Messager et al., 2016). Abundant organic carbon (C) storage and anoxic conditions in lake sediment stimulate high CH_4 production by methanogenic bacteria (Bastviken et al., 2008; Tranvik et al., 2009; DelSontro et al., 2016), resulting in CH_4 supersaturation in the many lakes (Kankaala et al., 2013; Beaulieu et al., 2016). To date, there have been many field investigations into the magnitude and regulation of lake CH_4

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emission, as well as its spatio-temporal dynamics (Juutinen et al., 2009; Bastviken et al., 2010; Sepulveda-Jauregui et al., 2015; Rasilo et al., 2015; Northington and Saros, 2016).

With the increasing number of field measurements and improvements in geographic mapping technology, some studies set out to estimate the global lake CH_4 emissions via compiling the lake CH_4 observations around the world (Bastviken et al., 2004, 2011; Walter et al., 2007; Juutinen et al., 2009; Holgerson and Raymond, 2016; DelSontro et al., 2018). A first systematic study of global lake CH_4 emission estimation was presented by Bastviken et al. (2011). They reported that global lakes emit approximately 71.6 Tg CH_4 into atmosphere every year via four pathways: diffusive flux, ebullitive flux, storage flux and plant-mediated flux. Recently, Holgerson & Raymond (2016) found a significantly negative correlation between the CH_4 concentration and the lake surface area. Thus, based on the mean diffusive flux and the corresponding lake area of each area class (e.g., <0.001 km^2, 0.001–0.01 km^2, etc.), they estimated that global lakes (including ponds) release about 16 Tg CH_4/yr through diffusion pathway. Besides lake area, DelSontro et al. (2018) demonstrated that lake CH_4 emissions also are related with trophic status (chlorophyll *a* and total phosphorus) at global scale. Subsequently, they combined the lake area databases and a global chlorophyll *a* distribution map (Sayers et al., 2015), to estimate a global lake CH_4 emissions of 78–139 Tg CH_4/yr. Overall, these works revealed the important role of lake ecosystems in global CH_4 budget, and gave us some enlightenment about quantifying the magnitude and dynamics of lake CH_4 emission.

However, significant uncertainties remain in lake CH_4 emission estimation. On one hand, among the four types of CH_4 flux components mentioned above, the ebullitive flux, storage flux and plant-mediated flux, in general, only occur in some special circumstances. For instance, previous studies have suggested that lake ebullitive CH_4 emission is highly episodic, and mostly happened in the sites with high sediment carbon storage (Saunois et al., 2016; West et al., 2016). The storage flux and plant-mediated flux usually can be observed during lake overturn and in the mostly vegetated regions, respectively (Bastviken et al., 2004). Therefore, current field measurements of ebullitive flux, storage flux and plant-mediated flux usually are scarce and highly spatiotemporally variable (Saunois et al., 2016). On the other hand, most of lake CH_4 measurements used in previous estimations were sampled from boreal regions (Bastviken et al., 2011; Holgerson and Raymond, 2016). However, more and more evidences revealed that temperate and tropical lakes have higher CH_4 emission rates than lakes located in northern latitude regions (Narvenkar et al., 2013; Rinta et al., 2017). Lacking of substantial data to calculate a representative mean CH_4 emission rate for each classification category (i.e., flux types or regional divisions) could bring large uncertainties during estimating global lake CH_4 emission.

Another source of uncertainty in current estimations is lacking in the fitting drivers used to upscaling emission estimates. In detail, these fitting drivers should have a significant impact on CH_4 emission at global scale, and be easy to access from the current global maps or other databases. Although the significant impact of lake area and chlorophyll *a* on CH_4 emission had been proved in previous studies, and thus had been used to estimate global lake CH_4 emission (West et al., 2016; Beaulieu et al., 2019), it should be noted that the combination of lake area and chlorophyll *a* explained only a minority of variations in lake CH_4 emissions (e.g., $R^2 = 0.29$ in the model of predicting CH_4 diffusion) (DelSontro et al., 2018). Interestingly, a large amount of studies found the significantly reverse dependency of lake depth and diffusive CH_4 flux in the different regions (Natchimuthu et al., 2016; West et al., 2016; Wik et al., 2016). In addition, Messager et al. (2016) developed a new global database, termed HydraLAKES, to simulate surface area and depth of global lakes by employing a geo-statistical model. Therefore, we might simulate the global spatial distribution of diffusive CH_4 emission based on that spatially resolved lake depth database (HydroLAKES), if we can demonstrate the significant correlation between lake depth and diffusive CH_4 flux at global scale.

In this study, we focused on diffusive CH_4 flux from global lakes, to explore the relationship between diffusive CH_4 emission and lake size (i.e., maximum depth and area) on global scale, and we used this relationship to provide a spatial map of diffusive CH_4 emission from global lakes. We compiled global database including in situ CH_4 measurements (CH_4 concentration/diffusive CH_4 flux) and basin morphometry data (maximum depth and surface area) of 744 lakes from published literature updated to 2018. The main objectives of this study were: to explore variation in diffusive CH_4 emissions from global lakes; to analyze and quantify the potential relevance of diffusive CH_4 emissions and lake size; to simulate spatial dynamics of global lake diffusive CH_4 emissions and to obtain a more accurate global lake CH_4 budget.

2. Materials and methods

2.1. Data collection

We compiled lake diffusive CH_4 flux and concentration data from published literature by searching keywords that include “methane”, “CH_4”, “GHG”, and “greenhouse gases” along with “lake” and “pond” from the Web of Science, Google Scholar and CNKI (China national knowledge infrastructure, http://www.cnki.net/) database until March 2018. Given that there is only limited CH_4 data from temperate and tropical lakes in previous global estimations, we contented to compile lake CH_4 measurements from temperate and tropical regions ($n = 265$ from 102 articles, where n is the number of lakes compiled) as much as possible. In Total, our database comprised of 744 lakes wherein diffusive CH_4 flux ($n = 554$) and concentration ($n = 407$) data were recorded from a total of 171 published studies. In order to reduce potential methodological bias or other restrictive reasons, we directly adopted the CH_4 flux data (including diffusive flux, ebullitive flux and sediment CH_4 flux) reported in the original studies, rather than calculating these fluxes by ourselves. Besides, this study used three criteria for CH_4 data collection: 1) We directly adopted diffusive CH_4 flux data that was measured using floating chamber method or have already been calculated from dissolved CH_4 concentrations (i.e., the boundary layer method) by the authors. We did not include CH_4 flux measured by eddy covariance flux towers in this study because it was not possible to distinguish between diffusion and ebullition flux (Paranaíba et al., 2018). 2) All CH_4 flux observations from littoral zones were excluded, which could potentially represent a mixture of diffusive flux and plant-mediated flux (CH_4 flux emitted through aquatic vegetation) (Juutinen et al., 2003). Although littoral zones have a large contribution to total CH_4 emission from the whole lake ecosystem, it is very difficult to distinguish between diffusion and plant-mediated flux in each study, because of the limited information about the presence/absence of plants during data compilation. 3) We only included diffusive CH_4 flux and concentration data measured on/in the surface water layer, which represents CH_4 diffusion from lakes into the atmosphere and dissolved CH_4 concentration in the surface water layer, respectively.

Furthermore, we also recorded maximum depth, surface area, and geographic location (longitude/latitude) information of each lake from corresponding literature, or from relevant documents which contained such information. Although we have made great effort to collect maximum depth and area data, we ultimately obtained limited records about maximum depth ($n = 355$) and surface area ($n = 534$) from the 774 lakes we compiled. Therefore, some

lakes compiled in our database may still lack maximum depth or lake area data or both. In other words, the actual numbers of lakes used in our statistical analysis could be less than 744. To avoid inaccurate or misleading results, we recorded the number of lakes used in each statistical analysis (e.g., lake number n in Eq. (2), see Fig. 1). Additionally, it is important to mention that mean depth could be a more effective index of morphometric basin characteristics than maximum depth. However, in our database, we found (1) that there was only limited information on mean depth in the literature, and its relevance to CH_4 flux was relatively limited compared to maximum depth (Fig. S4 in Appendix A) (2) that most of CH_4 measurements were sampled from (or in the vicinity of) the pelagic zone; and (3) that the correlation between maximum depth and mean depth was highly significant ($R^2 = 0.97$, $n = 152$, Fig. S5 in Appendix A). Taken this into account, we used maximum depth as a proxy of mean depth in this study.

2.2. Estimating the annual diffusive CH_4 flux and average CH_4 concentration of each lake

Before conducing statistical analysis, we needed to estimate the annual diffusive CH_4 flux and concentration of each lake. In our database, CH_4 measurements from most lakes (n = 560) were sampled multiple times over a one year period. For these lakes, we directly adopted annual diffusive CH_4 flux and concentrations reported in the original studies. Moreover, approximately 23% of lakes only reported CH_4 measurements during the summer or winter seasons, or during ice free periods. For these lakes, we calculated the average seasonal CH_4 measurement as the annual diffusive CH_4 values. For lakes that had multiple sampled locations, we first excluded the CH_4 measurements from littoral habitats (vegetated zones) and then calculated the mean flux and concentration sampled from the remaining locations. Moreover, for the same lake were recorded in multiple studies, we calculated the mean diffusive CH_4 flux and concentration, separately. Finally, we converted units of all CH_4 flux and concentration data into mg CH_4/m^2 h and mg CH_4/L, respectively, to simplify database management.

2.3. Statistical analysis

We adopted regression analysis to evaluate the relationship between diffusive CH_4 flux and concentration with lake morphometric characteristics (maximum depth and lake area), respectively. Due to the high spatiotemporal variability in the original data, we log-transferred data (CH_4 flux and concentration) prior to regression analysis.

Besides, to explore how the relationships (e.g., lake diffusive flux vs. maximum depth) varied in different biomes, we classified the lakes into different biomes and conducted regression analysis of each biome zones, separately. In this study, we determined the biomes zone of each lakes based on Köppen-Geiger climate classification map (Kottek et al., 2006). Considering the limited the number of lakes in our database, we simplified the categories of Köppen-Geiger map and classified the 744 lakes into 5 biome classes: tropical, temperate, boreal, tundra, and other biome types (i.e., desert, ice, mangroves, etc.). All statistical analyses were performed using R software (version 3.5.0).

2.4. Upscaling to global diffusive CH_4 emissions

We estimated diffusive CH_4 flux for global lakes based on Eq. (1) which integrates the maximum depth and surface area of lake to predict potential CH_4 diffusion rates. First of all, we need a global high-resolution lake database to provide the morphometric parameters (surface area and maximum depth) and the geographic location of global lakes. A satellite imagery-based lakes database (GLOWABO, Global Water Bodies database) consists of 117 million lakes with an area greater than 0.002 km^2, and its combined total lake area is approximately 5.4×10^6 km^2, which has a higher resolution and covers a greater total area than previous global lake

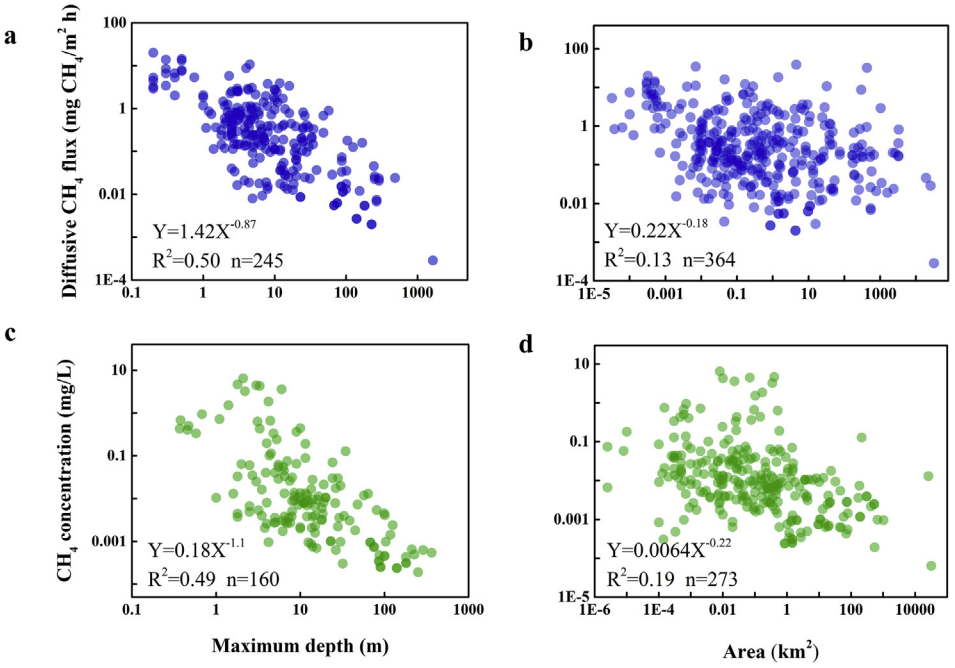

Fig. 1. Variation in diffusive CH_4 flux (mg CH_4/m^2 h) and dissolved CH_4 concentration (mg CH_4/L) with an increase in maximum depth (m) and surface area (km^2). **a** and **b**: Diffusive CH_4 flux versus maximum depth ($y = 1.42x^{-0.87}$; $R^2 = 0.50$; $p < 0.001$; $n = 245$; Eq. (2)) and surface area ($y = 0.22x^{-0.18}$; $R^2 = 0.13$; $p < 0.001$; $n = 364$; Eq. (3)) of global lakes. **c** and **d**: Dissolved CH_4 concentration versus maximum depth ($y = 0.18x^{-1.1}$; $R^2 = 0.49$; $p < 0.001$; $n = 160$; Eq. (4)) and surface area ($y = 0.0064x^{-0.22}$; $R^2 = 0.19$; $p < 0.001$; $n = 273$; Eq. (5)) of global lakes. Each axis was generated on a logarithmic scale.

databases (Lehner and Döll, 2004; Verpoorter et al., 2014; Messager et al., 2016). Additionally, the GLOWABO database has previously been used to estimate regional or global CH_4 emissions from lakes (Holgerson and Raymond, 2016; Wik et al., 2016). In this study, we also adopted the GLOWABO database to estimate global diffusive CH_4 emissions. However, it is important to note that maximum depth had not been reported in most current global lake databases, including GLOWABO database. Fortunately, HydroLAKES, another global lake database, has successfully simulated lake mean depth by employing a multiple variable geo-statistical model, although both its total area (2.7×10^6 km^2) and lake number (1.42 million) are smaller than the GLOWABO database (Verpoorter et al., 2014; Messager et al., 2016). One of important works is how to obtain the maximum depth of each lake in the GLOWABO database. Firstly, we found a strong correlation between maximum depth and mean depth for global lakes ($R^2 = 0.97$, Fig. S5 in Appendix A). Based on this correlation, we calculated the maximum depth of each lake in HydroLAKES database. Secondly, we used the inverse distance weighting (IDW) method to interpolate a global grid map of lake maximum depth (grid cell area = 0.002 km^2). Thirdly, for 117 million lakes in GLOWABO database, we extracted maximum depth value of each lake (based on their geographic location) from the interpolated global map mentioned above. And then, we simulated the diffusive CH_4 flux (mg CH_4/m^2 h) of individual lakes ($n \approx 117$ million) with the corresponding maximum depth and area data, according to Eq. (1). Finally, we calculated annual diffusive CH_4 emissions (Tg CH_4/yr) by multiplying diffusive flux by the surface area of each lake. All spatial analyses (e.g., IDW analysis) were performed using ArcGIS software (Esri, version 10.1).

3. Results and discussion

3.1. Effect of morphometric characteristics on methane lake dynamics

CH_4 lake emissions and concentrations were typically highest in shallow lakes (or ponds) and decreased with an increase in maximum depth (Fig. 1 a, c), where maximum depth explained 50% ($p < 0.001$; $n = 245$) and 49% ($p < 0.001$; $n = 160$) of variation in lake CH_4 flux and concentration, respectively. Additionally, lake area was negatively correlated to CH_4 lake flux ($R^2 = 0.13$; $p < 0.001$; $n = 364$) and concentration ($R^2 = 0.19$; $p < 0.001$; $n = 273$), respectively (Fig. 1 b, d). The maximum depth and area combined explained 61% of variation in CH_4 lake emissions:

$$\mathrm{Log}_{10}F_{CH_4} = 0.42(\pm 0.085) + 0.097(\pm 0.028) * Log_{10}Area - 1.08(\pm 0.072) * Log_{10}D_{max} \quad (1)$$

where numbers in parentheses represent standard deviations of regression coefficients.

In contrast to maximum depth, the impact of area size on CH_4 lake emissions was relatively minor, which differed somewhat from previous assessments (Holgerson and Raymond, 2016; Wik et al., 2016). In fact, this finding can be explained by our updated database. For instance, high CH_4 flux has been measured in some shallow lakes with relatively large areas, such as Lake Dong (10.77 mg CH_4/m^2 h, surface area = 32 km^2), Chilika Lake (2.92 mg CH_4/m^2 h, surface area = 1032.5 km^2), and Lake Poyang (0.36 mg CH_4/m^2 h, surface area = 3210 km^2) (Ray, 2013; Xiao et al., 2013; Liu et al., 2017), compared to mean values from lakes around the world (0.10 mg CH_4/m^2 h). Additionally, we further classified measurements into four biome types (tundra, boreal, temperate, and tropical), and explored the impact of maximum depth and area on CH_4 lake emissions within specific biomes. Results suggested that lake CH_4 flux exhibited a significantly decreasing trend with an increase in maximum depth for the different biome types (Fig. 2, left), which further demonstrates that shallow lakes are "hot spots" of diffusive CH_4 emissions in different biomes. On the contrary, only CH_4 flux from tundra and boreal lakes were significantly correlated to lake area, and no correlation was found between lake area and CH_4 flux of temperate and tropical lakes (Fig. 2, right). Similar findings were also reported in Rinta et al. (2017). The weaker correlation between CH_4 flux and lake area in temperate and tropical lakes could be the result of their larger range of lake surface area cover, compared to tundra and boreal lakes. More specifically, most tundra and boreal lakes are glacial origin (Wik et al., 2016), and could therefore characterized by less variable morphometry compared to lakes of tectonic and volcanic origin in temperate and tropical regions.

It is important to note that CH_4 flux in our study only represents diffusive flux, even though ebullitive flux was regarded as the dominant pathway in previous studies (Bastviken et al., 2004, 2011). Previous studies found that ebullitive flux could also be correlated to the mean depth or surface area of lakes (Juutinen et al., 2009; Holgerson and Raymond, 2016). In this study, we specifically collected ebullitive CH_4 flux data from 153 global lakes to analyze the correlation between ebullitive flux with maximum depth and area (Fig. 3 and Fig. S6 in Appendix A), but the correlation was not significant, which means that ebullitive flux is not significantly different in lakes of variable depth or area. Additionally, when we incorporated ebullitive flux into our estimate, we found that the correlation between the sum of CH_4 flux (diffusive + ebullitive) and morphometric characteristics (maximum depth and area) was relatively low compared to diffusive flux only (Fig. S7 in Appendix A). In fact, ebullitive CH_4 flux could be directly released into the atmosphere, and only limited CH_4 transported by this means would oxidize along the water column (Walter et al., 2007). Therefore, CH_4 ebullition flux could potentially be determined by net CH_4 production in sediment (DelSontro et al., 2016). Additionally, CH_4 transported through ebullitive flux is most often observed in carbon-rich and shallow lakes (Bastviken et al., 2004; Juutinen et al., 2009), where dissolved CH_4 is generally supersaturated, being rarely found in deeper lakes. In addition to the high randomness of ebullitive flux, more data and better knowledge of ebullitive CH_4 dynamics is required before we can begin to assess global ebullitive CH_4 emissions.

3.2. Global estimation of diffusive methane emissions from lakes

By combining our updated global lake database and Eq. (1) (see the Methods and Materials section), we were able to simulate the global diffusive CH_4 flux (mg CH_4/m^2 h) and the annual diffusive CH_4 emission (Tg CH_4/yr) for global lakes (Fig. 4). We obtained an average of 0.10 mg CH_4/m^2 h (0.077–0.14 mg CH_4/m^2 h, where the range was calculated with Eq. (1)), which is slightly less than the global estimation obtained by Bastviken et al. (2011) using 365 lakes (0.30 mg CH_4/m^2), but it is close to a previous estimation of boreal lakes (0.075 mg CH_4/m^2 h) (Juutinen et al., 2009). High diffusive CH_4 flux is found in the lakes from two regions: high

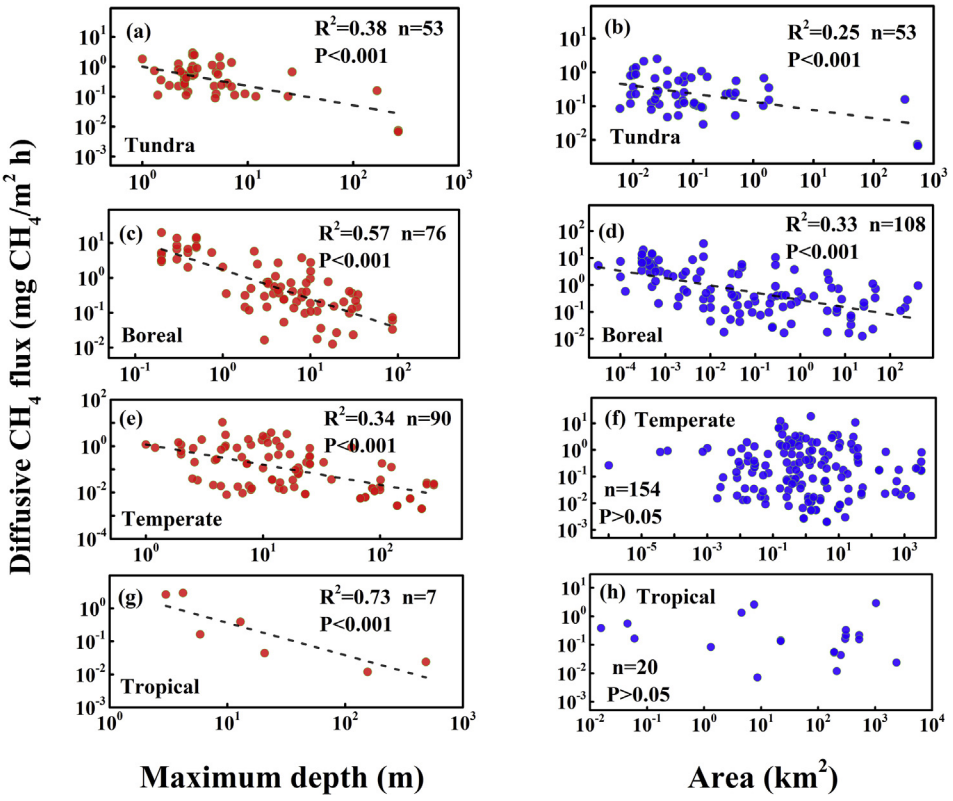

Fig. 2. Variation in diffusive CH_4 flux with an increase in maximum lake depth and area of the four major biome types. (a), (c), (e), and (g) represent variation in diffusive CH_4 flux with an increase in maximum depth in tundra, boreal, temperate, and tropical biomes, respectively. (b), (d), (f), and (h) represent variation with an increase in lake area in tundra, boreal, temperate, and tropical biomes, respectively. Note that '*n*' represents the available number of lakes simultaneously recorded diffusive flux and the corresponding morphological information (i.e., depth or surface area).

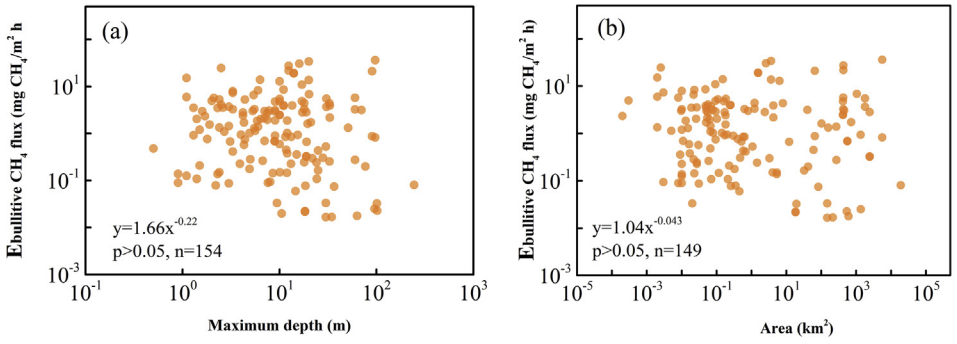

Fig. 3. Variation in ebullitive CH_4 flux along with maximum depth (a) and area (b) gradients. Each axis was generated on a logarithmic scale.

northern latitudes and large tropical river watersheds. One of the links between these two regions is their numerous shallow and small lakes, which could result in high diffusive CH_4 emissions. A great number of shallow and small lakes (or ponds) pervade boreal and northern tundra regions, which have recently been identified as critical hotspots of global CH_4 emissions (Wik et al., 2016; Elder et al., 2018). Moreover, previous studies suggested that shallow lakes (or more precisely forest flood zones) along floodplains and large rivers, such as the Amazon basin, also contribute significantly to CH_4 emissions (Devol et al., 1990; Smith et al., 2000).

In this study, we estimated the annual diffusive CH_4 emission (the total number of lakes: 117 million) at 11.2 Tg CH_4/yr (6.2–19.5 Tg CH_4/yr, where the range was calculated using Eq. (1)) from global lakes (Fig. 4b and Table 1). This estimation is slightly higher than that calculated by (9.7 Tg CH_4/yr) (Bastviken et al., 2011), but lower than a recent estimation (16 Tg CH_4/yr by Holgerson and Raymond (2016)). One of the primary differences between our estimation and previous estimations is total lake area that we adopted (Table 1). Holgerson and Raymond (2016) added a large number of small ponds (<0.001 km^2) to global lake CH_4 simulation, accounting for the important role that small ponds play in global lake CH_4 emissions. That study estimated that global lake diffusive CH_4 emission is approximately 16 Tg CH_4/yr, in which small ponds (<0.001 km^2) contributed 6.5 Tg CH_4/yr. If emissions of the small ponds (<0.001 km^2) were subtracted from their estimate, global diffusive CH_4 emission estimated by Holgerson & Raymond (2016) would be approximately 9.5 Tg CH_4/yr, which is closer to our estimation (11.2 Tg CH_4/yr). Our more conservative results were

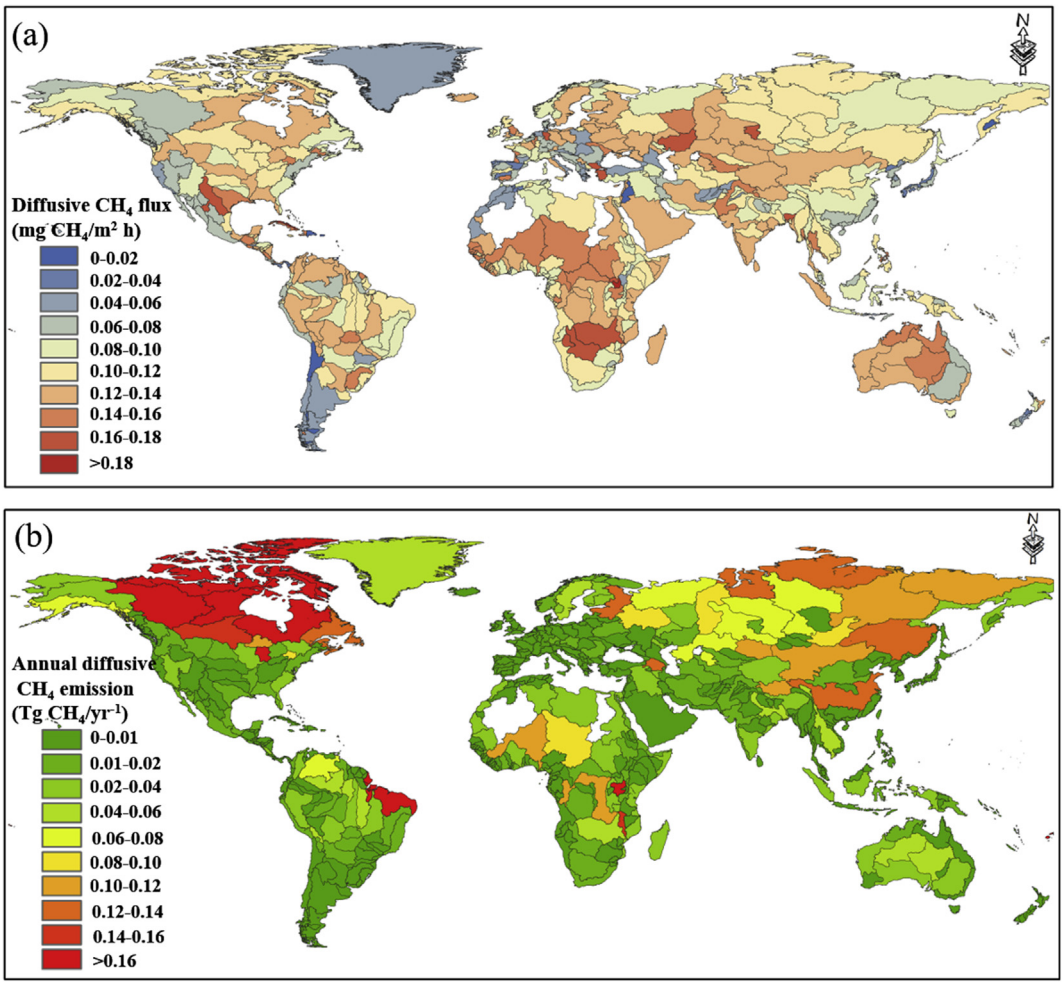

Fig. 4. Spatial distribution of diffusive methane emissions from global lakes. Note that this database contains approximately 117 million lakes, which makes it difficult to display CH_4 emissions from each lake within a single map. Accordingly, we only provided the spatial patterns of mean diffusive CH_4 lake flux (**a**: mg CH_4/m^2 h) and annual diffusive CH_4 emission (**b**: Tg CH_4/yr) data from different hydrographical basins. The hydrographical basins were obtained from the Global Runoff Data Centre (GRDC, http://grdc.bafg.de). The unit m^2 represents lake surface area here.

Table 1
Estimates of diffusive methane emissions from global lakes.

Spatial unit	Lake area (10^3 km^2)	Lake mean depth (m)	Annual diffusive CH_4 emission (Tg CH_4/yr)
Depth class (m)			
0–1	118.1	0.86	0.99 (0.52–1.79)
1–5	3064.3	3.01	8.46 (5.01–14.63)
5–10	928.8	7.47	1.03 (0.44–1.92)
10–100	666.1	54.99	0.73 (0.24–1.19)
>100	5.6	279.25	0.0004 (0.001–0.007)
Biome type			
Tundra	544.1	6.31	0.77 (0.49–1.22)
Boreal	901.5	4.55	1.62 (1.02–2.62)
Temperate	742.7	7.64	1.60 (0.94–2.76)
Tropical	1239.6	6.08	3.88 (2.18–7.05)
Others[a]	1355.1	6.03	3.36 (1.58–5.88)
Continent			
Asia	511.7	5.33	1.49 (0.58–2.34)
Europe	568.1	6.45	1.52 (0.88–2.66)
North America	612.0	5.16	2.32 (1.21–4.49)
South America	1508.0	6.54	2.94 (1.72–5.15)
Africa	1157.4	5.58	2.14 (1.33–3.50)
Oceania	425.8	6.58	0.82 (0.49–1.39)
Global	4783	7.12	11.23 (6.21–19.53)

[a] Other biomes include desert, rock, ice, mangrove, etc. The biome class was modified and revised from the Köppen-Geiger climate classification map (Kottek et al., 2006).

the result of difficulty in identifying small ponds (<0.001 km^2) using current remote sensing technology (Holgerson and Raymond, 2016). Additionally, we made some efforts to conduct a more comprehensive and improved assessment. On the one hand, most previous estimations just calculated the mean (or median) CH_4 flux of each area class and then upscaled results to regional or global lake scales (Bastviken et al., 2004; Juutinen et al., 2009; Wik et al., 2016). In contrast, we initially adopted an empirically integrated effect-based hypothesis (i.e., that lake morphometry is correlated to CH_4 emissions) in our assessment, specifically for maximum depth. Results from our study indicated that greater than 84% of diffusive CH_4 flux is emitted from lakes with a mean water depth less than 5 m. Therefore, shallow lakes play an important role in global lake diffusive CH_4 emissions. Additionally, we analyzed spatial patterns of diffusive CH_4 emissions, and found high variability in different regions. For example, we found that lakes between coordinates 40−70° N (30.4%) and 20° S~10° N (37.4%) were the dominant contributors of diffusive CH_4 emissions globally. Further analysis revealed that high diffusive CH_4 emissions from these two regions could be related to the large total area and extensive shallow lakes distributed. Moreover, our estimate also revealed that lakes in high northern latitude zones (i.e., boreal and tundra biomes) only comprise of approximately 21% of the global lake diffusive CH_4 emission, even though such regions are regarded as the crucial zones in the global lake CH_4 budget (Juutinen et al., 2009; Wik et al., 2016) considering that both the number and the total area of lakes in high northern latitude zones are greater than other regions (Downing et al., 2006; Juutinen et al., 2009; Verpoorter et al., 2014; Wik et al., 2016). Being a more important component of the global lake CH_4 budget (i.e., 34% of global lake CH_4 diffusion), more attention should be paid to researches related to current CH_4 measurements and mechanisms from shallow lakes in tropical regions.

3.3. Why shallow lakes emit more diffusive CH_4 than deep lakes?

Our results indicated that lake morphometry (maximum depth and area) had an effective impact on diffusive CH_4 emissions from global lakes. As the two important physical factors, maximum depth and area could affect water column mixing, the anoxic state of volume fraction, piston velocity, and sediment carbon accumulation (Fee et al., 1996; Bastviken et al., 2004; Ferland et al., 2012; Read et al., 2012), as well as further influence CH_4 production and oxidation. Diffusive CH_4 flux reflects a balance between CH_4 production from sediment and oxidation in the water column. Previous regional investigations reported two potential causes for high CH_4 diffusive flux from shallow lakes: abundant organic C storage in sediment or a short residence time, namely, either high CH_4 production or low CH_4 oxidation (Bastviken et al., 2008; Holgerson and Raymond, 2016). In our study, we attempted to identify the most pivotal depth-dependence driver of global diffusive CH_4 emissions from the two possible causes mentioned above. Previous studies suggested that most of CH_4 is produced in lake sediment, where the anaerobic environment can promote the conversion of carbon dioxide (CO_2), hydrogen (H_2), or acetate ($C_2H_3O_2^-$) into CH_4 by means of methanogenic bacteria (Jarrell, 1985; Michmerhuizen et al., 1996). Sediment conditions, including temperature, the absence of oxygen, and organic carbon content, determine CH_4 production, ultimately affecting lake CH_4 emissions (Kotelnikova, 2002; Hanson and Hanson, 1996). In fact, we also compiled sediment CH_4 flux data from 79 global lakes, but we found no significant correlation between sediment CH_4 flux and lake maximum depth (Fig. 5, b). Accordingly, it was concluded that there was no obvious difference in sediment CH_4 production among the global lakes investigated. In other words, the high diffusive CH_4 flux in shallow lakes could be most likely correlated to its lesser CH_4 oxidation than deep lakes.

CH_4 production in sediment is transported upward to the lake surface along the water column, wherein most CH_4 will be oxidized by aerobic or anaerobic methanotrophic bacteria (Thauer et al., 2008). Being influenced by gradients in water temperature, some dissolved substances (e.g., dissolved oxygen and chlorophyll *a*) commonly found in many lakes are vertically stratified (Boehrer and Schultze, 2008; Shade et al., 2012). Similarly, CH_4 profiles also exhibit vertical stratification in some lakes, wherein dissolved CH_4 significantly decreases from the bottom of the water column to the lake surface (Fig. S2 in Appendix A). In general, lake CH_4 oxidation could be related to the length of CH_4 transportation pathway, absence/presence of oxycline layer and the trophic status in the water. First, for shallow lakes, the shallow water column causes a shorter transportation pathway (including vertical diffusion and lateral transport), resulting in a significant proportion of CH_4 production to rapidly be emitted into the atmosphere. In contrast, deep lakes usually are physically stratified into three layers: hypolimnion, oxycline and epilimnion. Many studies indicated that the highest CH_4 oxidation rate generally occurs at the oxycline layer, where the high CH_4 concentration and low oxygen concentration meets (Joye et al., 1999; Oswald et al., 2015, 2017). Due to the presence of oxycline, large proportion of CH_4 production in deep lakes could be oxidized at the oxycline, before reaching the surface water layer. Besides, the CH_4 oxidation rate will gradually decrease in the epilimnion layer, resulting from the depletion of CH_4 availability.

Moreover, compared to deep lakes, the shallow lakes are vulnerable for eutrophication, as a result of high nutrient loadings and poor physical self-cleaning capacity (Havens et al., 2001; Janse, 2005). In this study, we found that lake diffusive CH_4 flux significantly increased with the increasing nutrients concentration, such as the DOC (dissolved organic carbon), chl *a* (chlorophyll *a*), TN (total nitrogen) and TP (total phosphorus) (Fig S8 in Appendix A). The nutrient-rich environment in shallow lakes not only provide more liable organic substrate to enhance the CH_4 production by methanogenesis, but also cause a depletion of dissolved oxygen (DO) in the water body (West et al., 2012; Beaulieu et al., 2019), resulting in low CH_4 oxidation in shallow lakes. Thus, the high diffusive CH_4 emission in shallow lakes could be also related to its nutrient-rich environment. In summary, compared to shallow lakes, the deep lakes showed lower diffusive CH_4 flux, which could be related to the longer oxidation pathway, presence of oxycline layer, and its lower nutrient environment. Besides, lake CH_4 oxidation could also be influenced by other environment factors, such as hypolimnetic DO, CH_4 availability, water temperature, etc. (Hershey et al., 2015; Denfeld et al., 2016).

3.4. Potential impacts of global warming on lake methane emissions in the future

Recent studies reported a profound change taking place in lake water levels and areas under a background of global warming (Fig. S9 in Appendix A) despite the different variation patterns of different regions (Donchyts et al., 2016; Pekel et al., 2016). For example, due to the rise in net precipitation and ice melt in the Qinghai−Tibet Plateau, according to our findings, water levels of most lakes in these regions have been markedly increased (Zhang et al., 2017), which could further affect diffusive CH_4 emissions. More specifically, previous studies have indicated that lake water depth and area in the Qinghai−Tibet Plateau (TP) have increased by approximately 15% and 40%, respectively, from 2002 to 2010, as a result of global warming (Tan et al., 2017). According this information and Eq. (1), we estimated that mean diffusive CH_4 flux of TP's lake decreased by 11.0% during 2002−2010. But due to the

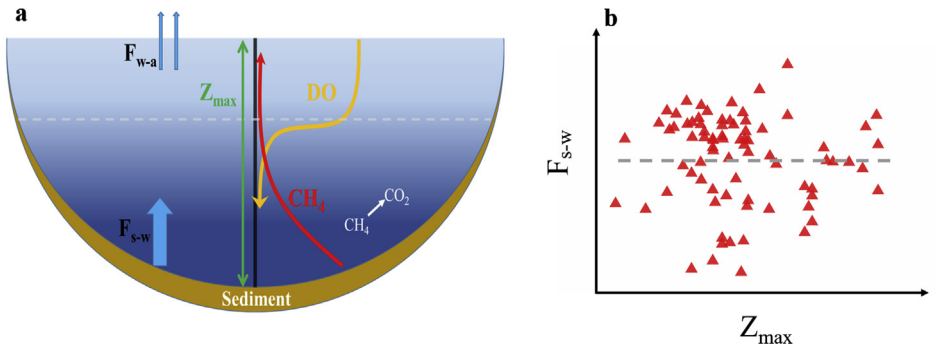

Fig. 5. Hypothesis for interpreting variation in diffusive methane emissions from lakes of different depth. a: Shows CH_4 flux dynamics along the sediment-water column-atmosphere continuum in a stratified lake (modified and revised from Tang et al., 2016). **b**: Shows no significant quantitative differences in sediment CH_4 production (F_{s-w}) from lakes of different depths ($p > 0.05$; $n = 79$). F_{w-a} represents CH_4 flux from surface water. The sediment CH_4 production (F_{s-w}) and the corresponding lake maximum depth (Zmax) data, were directly collected from published papers. Data and their relevant references are listed in Appendix B.

remarkable increasing of lake area, our estimation suggested that the total diffusive CH_4 emission from the lakes in the Qinghai–Tibet Plateau significantly increased by 24.3% from 2002 to 2010. Of course, this prediction is obviously simplistic, and actual situation are far more complex. On one hand, global warming could accelerate the permafrost thaw and glaciers melting in ice-rich regions, causing lake area increasing or new lakes formation, which finally resulting in higher CH_4 emissions (Knoblauch et al., 2018; Walter et al., 2006). On the other hand, the temperature rising could also cause the increasing of CH_4 oxidation or even the disappearance of many lakes or ponds in some regions (Walter et al., 2007; Martinez-Cruz et al., 2015), leading to the mitigation of lake CH_4 emissions. Therefore, although much effort has been invested in how diffusive CH_4 emissions respond to global warming, our understanding of this process clearly remains very limited (Walter et al., 2006; Aben et al., 2017; Davidson et al., 2018).

3.5. Limitations and uncertainties

Despite the various efforts having been made, there remains some limitations that could result in significant uncertainties in the quantification of the spatio-temporal variations and estimations of total CH_4 emissions (diffusion + other CH_4 flux component) from global lakes. For instance, an accurate survey of the abundance and seasonality of global lakes is crucial for an accurate global CH_4 emission estimation. In this study, we adopted the GLOWABO database due to its high resolution (0.002 km^2) in comparison to other lakes database and compared our results with previous estimations that had also adopted the GLOWABO database (Holgerson and Raymond, 2016; Wik et al., 2016). However, a recent estimate suggested that greater than 40% of global diffusive CH_4 flux could be emitted from very small lakes or ponds (<0.001 km^2) (Holgerson and Raymond, 2016). Such small lakes are extremely difficult to map using current remote sensing and geographical information systems (GIS) technology, and they were thus not included in current global lake databases, such as the GLOWABO database (Lehner and Döll, 2004; Holgerson and Raymond, 2016). This is important because the exclusion of these small lakes (<0.001 km^2) could result in an underestimation of global lake CH_4 diffusion estimations. Additionally, maximum depth data used in this study were calculated from the HydroLAKES database, which has adopted a geo-statistical model to simulate the mean depth of global lakes (Messager et al., 2016). However, it should be noted that even though mean depth simulated in the HydroLAKES database agreed well with observed mean depth for the lakes with an area greater than 1 km^2 (e.g., $R^2 > 0.55$), this data may produce large errors in smaller lakes (area<1 km^2, $R^2 = 0.24$) (Messager et al., 2016). For small lakes (area<1 km^2), the HydroLAKES database tends to underestimate mean depth in mountain lakes of the Andes in South America and European Alps, or tends to be overestimated in shallow lakes from low-land regions. Failure to estimate mean depth in small lakes could be result of the spatial variability in mean depth in these small lakes, and this could have resulted in high uncertainty of our CH_4 estimations for lakes with an area less than 1 km^2.

Another limitation of our estimation is related to temporal variation in annual diffusive CH_4 flux. According to Eq. (1), temporal variation in CH_4 flux could be simulated by seasonal or interannual variation in lake water depth and surface area. Unfortunately, due to a lack of a long-term database on the morphometry dynamics of global lakes, here we just assumed that there was no seasonal/interannual variation in morphometric characteristics (water depth and surface area) for global lakes. However, for most lakes, both lake water depth (i.e., maximum or mean depth) and surface area are highly variable with climate change or seasonal/interannual inundation, particularly small lakes. For example, seasonal or interannual inundation will largely alter its hydrological conditions (e.g., water level) and the biogeochemical cycles of small lakes, and will significantly affect the CH_4 emission from global lakes. Furthermore, based on our empirical model (Eq. (1)), during flood inundation, rising water level could increase the length of the CH_4 oxidation pathway and ultimately reduce the diffusive CH_4 emission from lakes. In addition, flood inundation also could result in an increase in organic matter input and cause a shift from aerobic to an anaerobic environment, resulting in more CH_4 production. Previous field experiments also found that lake CH_4 emissions could increase or decrease during flood inundation. For instance, Wassmann and Thein (1996) found that CH_4 flux would immediately start to increase at the beginning of flood inundation, and continue a rise before the water level reach to maximum. However, Forsberg et al. (2015) reported that CH_4 emission from lakes in the Amazon floodplain were relative lower during high water periods compared to low water periods from 2014 to 2015. Thus, the variation in CH_4 emission during flood inundation could differ and will depend on balance between CH_4 production and oxidation. It is interesting to note that seasonal drought could also alter the GHGs emission from global lakes (Marcé et al., 2018).

Moreover, this study mainly focused on the relationship between diffusive CH_4 flux and morphometric characteristics (maximum depth and lake area). It also provided an updated estimation of CH_4

diffusion from global lakes, although the contribution of diffusive flux to the total CH_4 emission is relatively small (~13%) according to a recent global estimation (Bastviken et al., 2011). For major contributor of lake CH_4 emission (i.e., ebullitive CH_4), we did not find an effective index to predict the global ebullitive CH_4 flux (Fig. 3). This could be due to the high spatiotemporal variability of ebullitive CH_4 flux and the relative scarcity of CH_4 ebullition measurements in current databases. Recently, some studies reported that CH_4 ebullition could be more sensitive to sediment conditions (e.g., sediment temperature) and carbon availability (e.g., DOC and chlorophyll *a*) in lake ecosystems (DelSontro et al., 2016, 2018; Wik et al., 2016).

4. Conclusions

This study showed that diffusive CH_4 flux from global lakes varies significantly with maximum depth. In view of this finding, we estimated the global lake diffusive CH_4 emission and its spatial distribution. We found that greater than 84% of CH_4 is emitted from shallow lakes (with a mean depth less than 5m) distributed within high northern latitudes and regions with large tropical river basin.

Considering the limitations and uncertainties of the current estimate, urgent efforts or new directions need to be considered for future analysis in terms of the (1) developing of higher resolution lake database that records relevant morphological indexes (e.g., maximum depth and surface area) and trophic status (i.e., DOC, chlorophyll *a*, total phosphorus, etc.), as well as their associative seasonal/interannual variation, especially for small lakes or ponds; (2) quantifying CH_4 dynamics during each process (including CH_4 production, oxidation, and transportation), particularly CH_4 oxidation at the oxycline layer, applying precision methods, such as isotope tracers and automatic GHG analyzers (Paranaíba et al., 2018); (3) developing a process-based model that integrates a CH_4 dynamics module which is able to simulate CH_4 variation along the sediment-water column-atmosphere continuum of lakes and a hydrology module which can simulate seasonal variation in water levels and its response to global change; (4) investigating field measurements of other CH_4 flux components (e.g., ebullitive flux, storage flux and plant-mediated flux) from global lakes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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