Responses to Reviewer #1

General comments

This model seems to have a lot of potential to improve predictions and upscaling of lake methane emissions, which is a global need.

Response: Thank you very much for your positive feedback. The point-by-point responses to your comments are provided below in blue, with the corresponding revisions to the manuscript in red.

However, a few overarching concerns need addressing:

1. The data currently presented for model testing do not show improved model performance compared to existing models. For instance, how does this model compare to the other processed-based models mentioned in the introduction, including Lake 2.0, bLake4Me, ALBM, and the Canadian Small Lake Model? Why was this model an expansion of CSLM rather than using the other models? It would be useful to run these models and show how FLaMe improves estimates. It needs to be better than the others to become most useful.

Response: Thank you very much for this valuable comment. We agree that it is important to evaluate model performance but would like to challenge the notion that our model "needs to be better than others" or "needs to be most useful". Indeed, each model has its own strengths and weaknesses and probably the best way forward to quantitatively assess present-day and future lake CH_4 emissions and their uncertainties (will) require ensembles of simulations performed by different models, as applied in the field of global climate-carbon cycle science (model ensembles used for the global C budget (Friedlingstein *et al.*, 2022) or for wetland emissions in global CH_4 budget (Saunois *et al.*, 2025). In fact, by explicitly representing additional processes in our model (e.g., primary production, organic carbon cycling, oxygen dynamics associated to autochthonous C cycling, phosphorus inputs from the catchments, etc.) as compared to previous model configurations for lake CH_4 emissions, which did not explicitly represent these processes (e.g., relying on C_{labile} concentrations from existing database), our approach introduces greater degrees of freedom. As a result, accurately reproducing observations is expected to be more challenging. Therefore, we do not want to advocate that our model is better than others, but rather that it can shed a new light on the environmental controls of CH_4 emissions, e.g., the impact of eutrophication on lake CH_4 emissions. To stress this point, we now have added a new Table in supplementary (Table S1) that compares the FLaMe-v1.0 model configuration with other existing process-based models. This comparison shows the advances achieved by our model, but also highlight that some processes/variables included in other models are currently omitted in the v1.0 version of FLaMe. This comparison is also presented as Table R1:

Table R1. The comparison of FLaMe-v1.0 with the existing lake models

	GLM3.0	LAKE2.0	bLake4Me	ALBM	FLaMe-v1.0
Lake shape	User-specified	Bucket/Valley	Bucket	User-specified/Valley	Valley
Application	Site	Site/Regional	Site/Global	Site/Global	Regional/Global
Physical processes					
Water temperature fields	√	√	√	√	√
Lake stratification & turnover	√	√	√	√	√
Ice dynamics	√	√	√	√	√
Sedimentary temperature fields	√	√	√	√	×
Hydrological routing	√	×	×	×	×
Biogeochemical processes					
Autochthonous C dynamics	×	√	×	√	√
P limitation with C	×	×	×	√	√
N limitation with C	×	×	×	×	×
Allochthonous C input from thawing	×	√	√	√	×
Oxygen profile	×	×	×	√	√

Sedimentary methane production & its split between diffusion and ebullition	×	√	√	√	√
Methane oxidation in water and dissolution in gas bubbles	×	√	√	√	√
Gas exchanges with air	×	√	√	√	√

a. Red ticks indicate the model has the capability but it was only applied at site level and not to regional or global to scales.

In the revised manuscript, we added a brief statement to highlight the advances of FLaMe-v1.0 (lines 182–186): "Compared to other lake models (Table S1), the most important improvements in FLaMe-v1.0 are the adoption of a "valley" shape lake morphology and the incorporation of autochthonous carbon dynamics (i.e., explicit simulation of primary production, decomposition, and associated oxygen processes) and its phosphorus limitation, which have been shown to be key control factors of CH_4 dynamics (Søndergaard *et al.*, 2017; Guildford and Heckay, 2000; Schindler, 1977)."

Moreover, at the current model development stage, we consider that the model should be evaluated against observations rather than against other models. Thus, we evaluated our model against observations in four well-surveyed real lakes (section 3.2) and 47 boreal and central European lakes (Rinta *et al.*, 2017; section 3.3.1). We agree with the reviewer that the comparison across models would be of interest, but consider that such model intercomparison is out of the scope of the current study. It should nevertheless be conducted in the near future, using commonly agreed model protocols and scenario designs, identical meteorological forcings, and nutrient inputs from the catchments to allow evaluating the uncertainties arising from distinct model structures and parameterizations. This comparison should not only be done for present-day, but also for future projections, for which we can only resort to model assessments.

Finally, FLaMe-v1.0 adopted the representation of lake physical processes from CSLM, but the newly developed biogeochemical modules could be combined with any other lake physics models or even with model outputs such as vertical profiles of physical variables. "We selected the CSLM as the basis for the representation of lake physical processes in FLaMe-v1.0, because CSLM was designed for small lakes that account for >90 % of lakes (by number, mean depth <7.8 m) but contribute disproportionally to lake CH_4 emissions in the European domain (HydroLAKES; Messager *et al.*, 2016), as well as due to the expertise in our research team." (lines 169–173). Again, we want to stress here that we do not claim that CSLM is better than other lake physics model; only that it is a suitable model platform for our purpose.

2. The lakes selected for testing and comparison should report every value that is used in the model and should fit within the size limits specified by the model. This was attempted with the four lakes chosen, but two of the four testing lakes seem inappropriate for model testing.

i) Lake Erssjon has a surface area that is too small to fit within the smallest size bin specified by the model;

ii) Lake Villasjon lacks a reported mean depth, and the model states that maximum depth must be >2x mean depth.

Response: Thanks a lot for this comment. First, we would like to stress that the observations of CH_4 emissions (especially time-series) are quite limited, such that a strict comparison between observations and simulations remains difficult. Thus, our local model evaluation against four well-surveyed real lakes follows what can be achieved at regional or global scale applications, i.e., local meteorological forcings and variations in water level/area are not available. This point has been clarified in lines 602–607: "Since the lack of concomitant *in-situ* observations of climatic drivers and variations in lake water levels affect the model's ability to capture the full variability in the time-series of observed CH_4 emission, we here focus our evaluation on the magnitude and broad seasonal patterns in observed CH_4 emissions, following what can be achieved for regional and global scale applications. Thus, we evaluated the simulated statistics (mean and SD represented by boxplots) of CH_4 fluxes over the annual cycle against the observational data." Moreover, we would like to stress again that the regional scale evaluation against the dataset from Rinta *et al.* (2017) is also a critical part of the model evaluation, illustrating the model's capacity to capture CH_4 emission rates across large gradients of climate and trophic levels.

Second, we believe that the reviewer might have misunderstood our argumentation regarding model applicability, and we apologize for not having been clearer. In principle, our model can indeed be applied to any lake for which morphological characteristics, phosphorus concentration, and meteorological conditions can be constrained. The points related to the two real lakes, Erssjon and Villasjon, are clarified as follows:

(1) When FLaMe-v1.0 is applied to large-scale (regional or global) estimates of methane emissions from lakes, we have adopted a computationally-efficient clustering strategy that divides lakes of different areas into different bins (e.g., $0.1 \le A_0 < 1$ km^2, $1 \le A_0 < 10$ km^2, $10 \le A_0 < 100$ km^2 and $100 \le A_0 < 1000$ km^2 in this study; this lower bound is due to the limitation of HydroLAKES database). This approach also follows previous modelling studies as well as global scale studies based on limited observations (Tan *et al.*, 2015; Tan *et al.*, 2016; Tan *et al.*, 2024). But this does NOT mean that our model can only be applied to lakes with areas falling within the prescribed bins for large scale application. Our model is applicable to Lake Erssjon (with an area of 0.062 km^2, not that far from the lower bound of our smallest lake size class). Moreover, we want to clarify again here that observations

remain very limited, and currently, comprehensive observational datasets required for validation are not available for each of the prescribed bins.

(2) In FLaMe-v1.0, only one depth information is required for the model set-up, and we can select either the mean depth or the maximum depth. But this does not mean that the maximum depth must be >2x mean depth, but rather that either h_{mean} or h_{max} can be used for the model setup. Thus, Lake Villasjon, for which the maximum depth is provided, can also be used to test our model.

Third, we would like to stress again that our selected four lakes cover a wide range of depths (1.3–45m), climate (temperate to boreal) conditions and trophic (oligotrophic to eutrophic) statuses, such that the evaluation can be considered representative of lakes of different types.

3. Recent papers have highlighted that laterally transported methane may better explain surface CH_4 concentrations in lakes, yet this is not accounted for or discussed as a shortcoming. This needs to be mentioned.

Response: Thank you very much for this valuable comment. The horizontal transport of materials (oxygen and methane) by littoral-pelagic advective fluxes was recently reported to be important in interpreting the anomalies observed in pelagic gas concentrations (Doda *et al.*, 2024; Bouffard *et al.*, 2025). We agree that the absence of lateral transport is a limitation in our current model configuration, because (1) FLaMe-v1.0 only accounts for the vertical gas ascent and diffusive fluxes, while explicit representation of the laterally transferred methane would require at least a two-dimensional framework; (2) the observations related to this newly identified process are extremely limited, such that accounting for this process in generalized regional/global applications would remain highly challenging. It is also doubtful whether running two-dimensional representation of lake CH_4

dynamics over a large number of lakes will be achievable in the near future and this process might thus need an empirically-derived (simplified) representation based on a larger set of observations.

In the revised manuscript, we added a short discussion on this point in section 4 (lines 1044–1049):

"Moreover, a recently reported process, i.e., the horizontal, advective littoral-pelagic transport of oxygen and methane (Doda *et al.*, 2024; Bouffard *et al.*, 2025) was ignored for the following reasons: (1) The current FLaMe-v1.0 relies on a 1-D vertical representation while explicitly accounting for horizontal transport would require at least a 2-D framework; and (2) observations related to horizontal transport remain limited, and whether this is an ubiquitous feature of the CH_4 dynamics across a wide range of lakes will require further observational evidence."

Specific comments

1. Line 31: add minimum size

Response: The minimum size of 0.1 km^2 is added, and this sentence is modified as follows:

"…we provide a first assessment of the spatio-temporal variability in CH_4 emissions from European lakes with a surface area comprised between 0.1–1000 km^2 (n=108407, total area = $1.33x10^5$ km^2), indicating a total emission of 0.97±0.23 Tg CH_4 yr^{-1}…"

2. Line 37: is this due to ice blocking emissions (mention role of ice)?

Response: The ice-blocking effects has already been included in the strong seasonality, and this sentence is revised as follows:

"Our simulations reveal a strong seasonality (with ice-blocking effects accounted for) in

European lake CH_4 emissions, with nearly ten times higher emissions during late summer than during winter."

3. Lines 49-52: wetlands are not included as inland waters for the Global Methane Budget; they are estimated to be bigger emitters than inland waters (see Saunois recent budget).

Response: Agreed. This sentence has been revised as follows:

"This budget identified inland freshwaters (lakes, reservoirs, ponds, rivers, etc.) as an important, yet highly uncertain atmospheric CH_4 source (Jackson *et al.*, 2020, 2024; Saunois, *et al.*, 2020, Canadell *et al.*, 2021)."

4. Lines 102 - 103: The wording tripped me up here…there may be a typo "However, including an explicit description of these processes is challenging, because it requires to account for a…"

Response: This sentence has been revised as follows:

"However, it is challenging to explicitly describe the suite of key physical and biogeochemical processes controlling the coupled C-O_2-CH_4 cycles while at the same time maintaining model complexity, as well as…"

5. Line 113: Explain why you're building from the CSLM model instead of one of the newer models

Response: The reason of selecting CSLM as the prototype has been added (lines 169–173): "We selected the CSLM as the basis for the representation of lake physical processes in FLaMe-v1.0, because CSLM was designed for small lakes that accounts for > 90 % of lakes (by number, mean depth <7.8 m) but contribute substantially to lake CH_4 emissions in the European domain (HydroLAKES; Messager *et al.*, 2016), as well as due to the expertise in our current authorship."

Although FLaMe-v1.0 was built based on CSLM, the new biogeochemical modules could be combined in the future with any other lake physics models or even with model outputs of vertical profiles of physical variables, such as those produced in the lake sector of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, https://www.isimip.org/).

6. Lines 145 -146: Explain why these size bins were selected. The upper and lower bounds will exclude the very smallest and largest systems

Response: These size bins were selected based on the HydroLAKES database (Messager *et al.*, 2016). The lower bound is set as 0.1 km^2 since it is the smallest lake area in HydroLAKES database, and the upper bound is set as 1000 km^2 because FLaMe-v1.0 builds on the small lake physics model CSLM and it is challenging to represent these very large lakes using a "pseudo-1D" framework. In the European domain, there are only 21 very large lakes with a surface area ≥1000 km^2. In the revised manuscript, following reviewer 2's suggestion, we now provide a back of the envelope estimate of methane emissions from European lakes with a surface area ≥1000 km^2.

7. Fig 1. Line 160: Consider changing the arrow size to represent the magnitude of flux from each size class; this would likely have more impact.

Response: Thanks a lot for this suggestion. We have now used different arrow sizes to represent the magnitude of flux from each lake size, and revised the figure as follows:

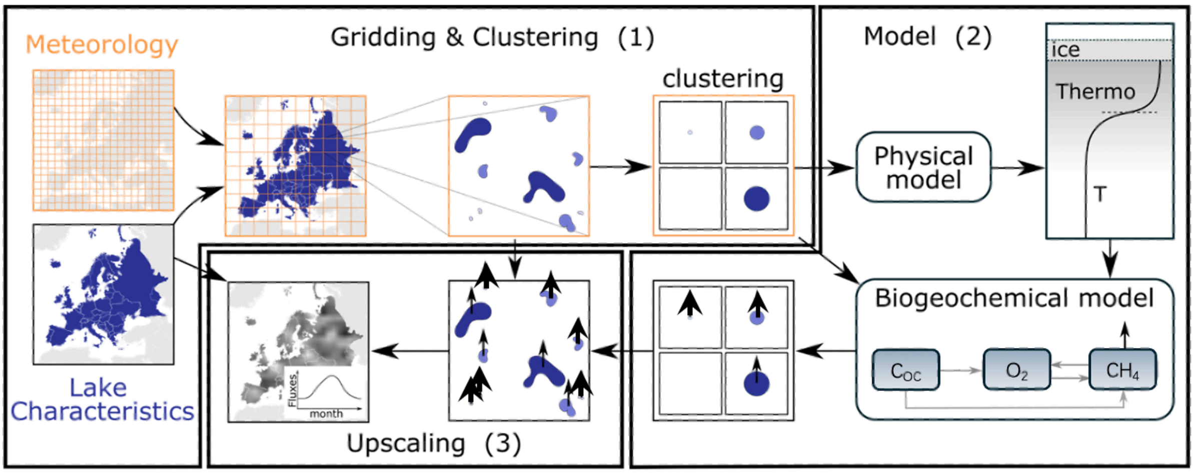

Fig. R1. Illustration of the lake clustering and upscaling strategy for the continental application of FLaMe (Europe as an example). (1) Gridding and clustering: The European domain was divided into grid cells at a coarse spatial resolution of 2.5°×2.5°. Within each grid cell, lakes are clustered into four classes according to their surface areas. (2) FLaMe parallelization: FLaMe simulates the lake metabolic dynamics, vertically resolved concentration and rate profiles of the coupled O_2-CH_4 cycle as well as diffusive and ebullitive CH_4 fluxes through the water-air interface. The model was parallelized under transient conditions for each grid cell and each lake class. (3) Upscaling: The areal rates (i.e., fluxes per unit lake surface area) simulated by FLaMe were then multiplied by the total surface area of each lake class within each grid cell (available from HydroLAKES) and aggregated at the monthly timescale. The arrows pertaining to clustered and original lakes represent the CH_4 emissions and the arrow size represent the magnitude of the flux (i.e., a lower per area flux rate for larger lakes).

Moreover, the representation of fluxes using arrows with different sizes has been explained in the figure caption as follows:

"The arrows pertaining to clustered and original lakes represent the CH_4 emissions and the arrow size represents the magnitude of the flux (i.e., a lower per area flux rate for larger lakes)."

8. Line 166: Please define thermocline depth and photic depth as they are used in this study

Response: The definitions of thermocline depth and photic depth have been added in this sentence:

"CSLM simulates the following physical variables: temperature profile (*T*), thermocline depth (h_{mix}, at which the vertical temperature gradient reaches its maximum), photic depth (h_{phot}, down to which the sunlight can penetrate, with a radiation density of at least 1% of that at the lake surface), and ice cover…"

9. Lines 186-188: What are the impacts of the maximum depth needing to be >2x mean depth? I assume there are lakes that don't fit this relationship—what are the effects on modeled CH_4 if the lake does not meet the assumption? What is the minimum depth for the model?

Response: We believe the reviewer might have misunderstood the setting of $h_{\mathrm{max}} = 2h_{\mathrm{mean}}$, and we apologize for not being clear. In FLaMe-v1.0, the model requires only a single depth value for setup, and users can choose to provide either the mean depth or the maximum depth. This does not imply that the maximum depth must be greater than twice the mean depth, rather, it simply indicates that either h_{mean} or h_{max} can be used as the input parameter, depending on the data available.

In principle, the lakes of any depth can be simulated by FLaMe-v1.0 provided with suitable grid spacing. Currently, the vertical grid spacing of 50 cm, and the minimum of the mean depth of the lake can be simulated by our model is approximately 1.5 m. As shown in Fig. R2, the lakes shallower than 1.5 m (mean depth) accounts for only 6% of lakes (n =108384) within European domain. Moreover, for the 953 representative lakes used in our clustering strategy, the lakes shallower than 1.5 m (mean depth) accounts for only 5%. Thus, the current grid spacing of 50 cm may cause some biases in the assessment of European lake methane emissions. However, we adopted this spacing grid because we are trying to find a tradeoff between resolution and computational costs at regional and global scales, e.g., when FLaMe-v1.0 is applied at global scale, a full assessment of lake CH_4 emissions in both historical and future scenarios using such a resolution typically consumes ~0.5 million CPU hours.

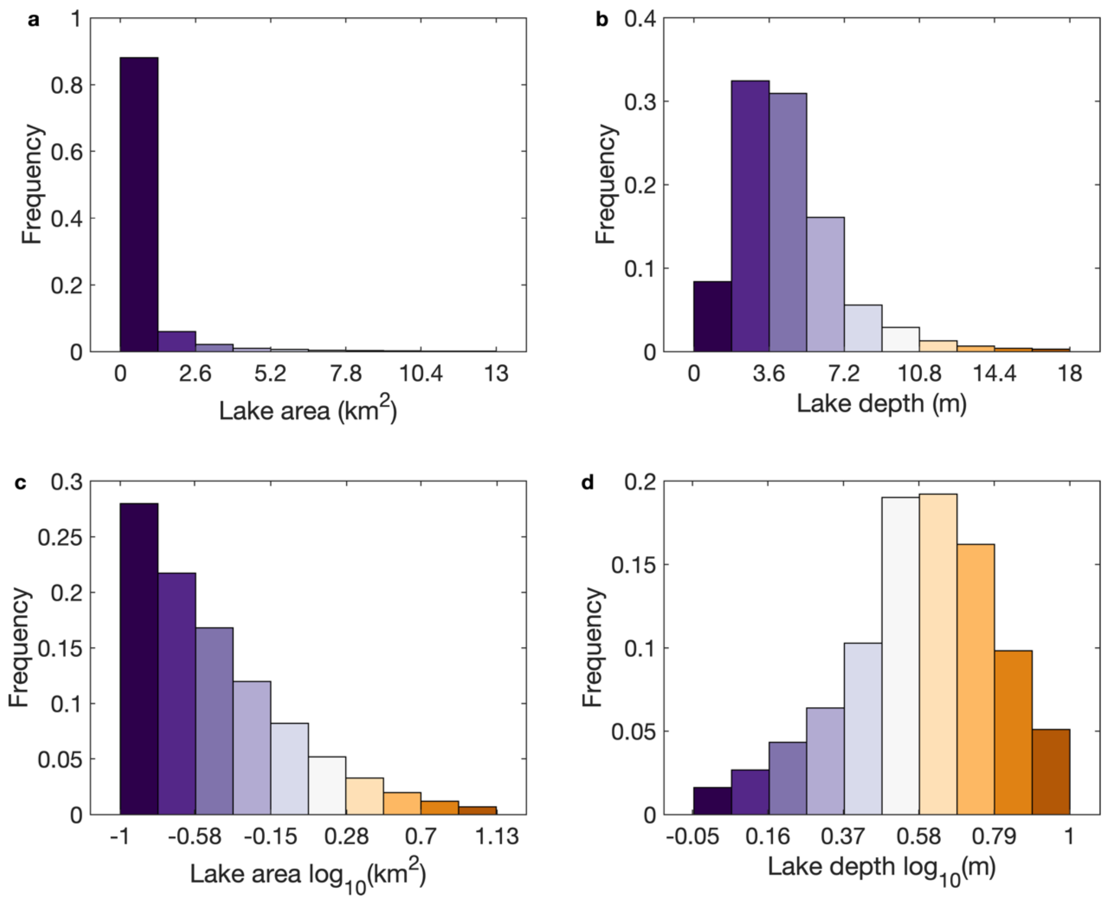

Fig. R2. Frequency distributions of lake area and depth within European domain (n =108384). Frequency distributions of (a) lake area (km^2), (b) depth (m), (c) lake area (log10(km^2)), and (d) lake depth (log10(m)).

To evaluate the biases caused by the grid spacing, we tested a finer resolution with the grid spacing set as 25 cm. We found that decreasing the spacing from 50 cm to 25 cm would increase European lake methane emissions by 7% (from 0.97 to 1.04 Tg CH_4 yr^{-1}) (which is considered as acceptable for a regional scale assessment), while the spatial distribution and seasonality of methane emissions remain almost the same (Fig. R3). However, we acknowledge this current model limitation and consider that this shortcoming could be solved in the future by adopting a variable grid spacing scaling to the maximum lake depth, despite the challenge it represents in terms of CPU time. To clarify this point, we have added a statement in the model limitation (section 4; lines 1067–1069):

"In addition, we acknowledge that the fixed grid spacing currently limits the model application to very shallow lakes, which could be solved by adopting a variable grid spacing scaling to the maximum lake depth."

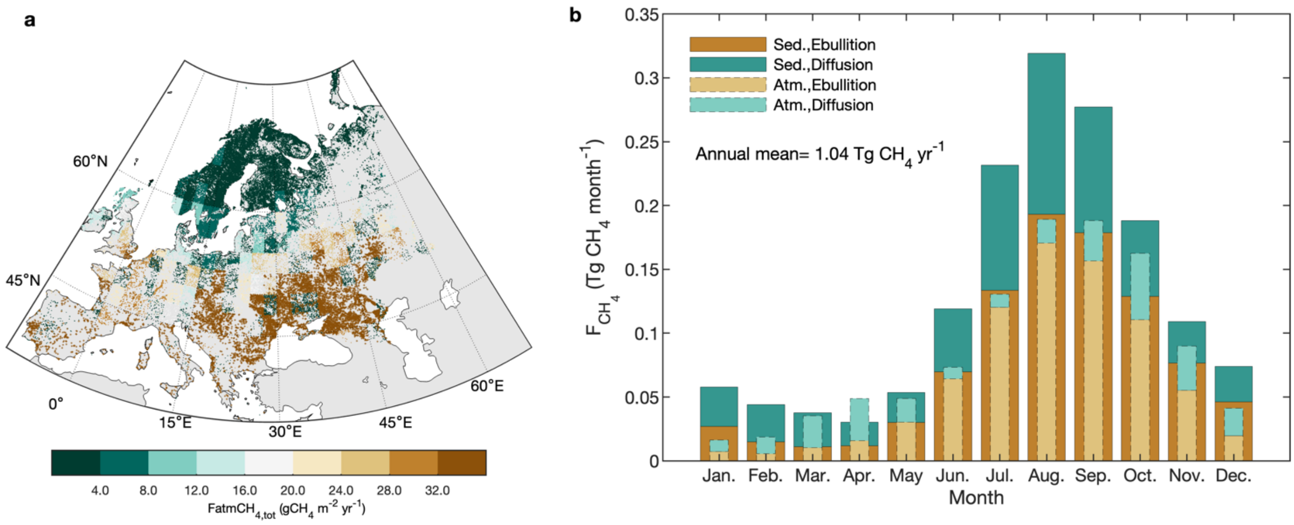

Fig. R3. Methane (CH_4) emissions from European lakes. (a) Spatial distribution of annual mean total CH_4 emissions (sum of diffusion and ebullition) for the period of 2010-2016, expressed in per unit of lake area. (b) Seasonality of total CH_4 production (wide bars with full lines) and emission (narrow bars with dashed lines) fluxes and their split between ebullitive and diffusive pathways (period 2010-2016).

10. Lines 194-195: provide citations for 5 m depth

Response: The citation has been added as follows:

"Each layer of the water column is connected to a vertically integrated lake sediment column of

5 m depth (h_s, m) (Langenegger *et al.*, 2019) (Fig. 2). Since the CH_4 production rate decreases exponentially with sediment depth (not applicable to thermokarst lakes), it is typically negligible at 5 m within the sediment column (Langenegger *et al.*, 2019), …"

11. Line 198: Explain the rationale for ignoring horizontal material and gas exchanges

Response: The horizontal material exchanges (O_2 and CH_4) between the sediments and water columns were ignored because of their relatively minor magnitudes compared to vertical exchanges (Stepanenko *et al.*, 2016; Tan *et al.*, 2024), as well as the lack of observational data for calibration and validation. This point has been clarified in lines 214–219:

"…it should be noted that we assume no ***horizontal*** material exchanges (O_2 and CH_4) between the sediments and water columns (i.e., across the interface where left and right edges of a water layer touch the sediment box; Fig. 2) because of its relatively minor magnitude compared to the vertical exchanges (Stepanenko *et al.*, 2016; Tan *et al.*, 2024) as well as the lack of observational data. Therefore, only the vertical exchanges are simulated in this first version of the model (see details in the following sections)."

12. Lines 228 – 229 and throughout: Are European lakes largely P limited? To what extent has this been explored? Please address and provide citations.

Response: Thank you very much for this comment. Early studies revealed higher dependence of Chl-a on TP over TN concentrations in freshwater lakes, suggesting that P is the limiting nutrient of primary production (Guildford and Heckay, 2000; Schindler, 1977). However, recent works suggested that the fraction of lakes with N limitation or N- and P-colimitation is increased, especially when the trophic level is increased from oligotrophic to hypereutrophic statuses. With a dataset from 871

Danish lakes, Søndergaard *et al.* (2017) revealed that P is of key importance for the ecological quality but that increased N concentrations, particularly in shallow lakes with moderate to high TP, may have significantly adverse effects on lake water quality and ecological status in summer. A global meta-analysis (annual average data from 831 lakes) suggests that total nitrogen (TN): total phosphorous (TP) ratios declined significantly as lakes become eutrophic, and from oligotrophic to hypereutrophic lakes, the probability of N and P co-limitation significantly increases from 15.0 to 67.0%, while P-only limitation decreases from 77.0 to 22.3% (Zhou *et al.*, 2022).

In this study, we assume that TP is a key control variable of primary production in the lake (DelSontro *et al.*, 2018; Mavaara *et al.*, 2017; Reynolds, 2006) and represented the primary production as a Michaelis-Menten equation related to TP concentration. Thus, whether the lakes are P limited depends on the total phosphorus (TP) concentration, which were obtained from GlobalNEWS model (Mayorga *et al.*, 2010; Lauerwald *et al.*, 2019). Based on the Michaelis-Menten equation, we have produced a figure to show the P limitation in European lakes (Fig. R4; added as Fig. S7b in the revised manuscript).

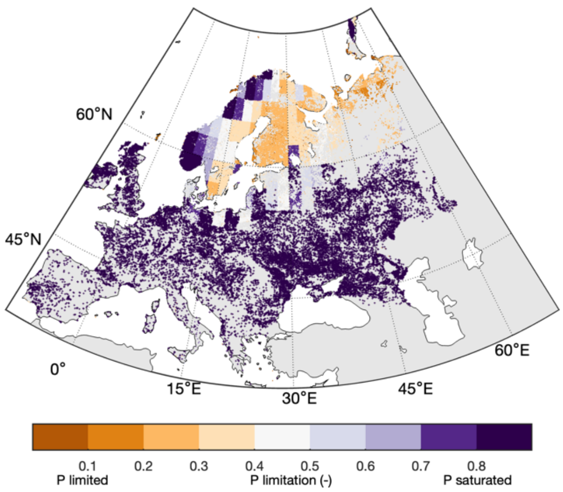

Fig. R4. Spatial distribution of phosphorus (P) limitation of European lakes. The P limitation is evaluated based on the Michaelis-Menten equation with total phosphorus concentration from IMAGE-GNM model.

13. Lines 252-255: If allochthonous / stained DOC is not considered in the model, how does Kd account for light attenuation from cDOM?

Response: As specified in Eq. (6), K_{dg} accounts for the light attenuation from autochthonous OC:

$$\ln(K_{dg}) = -4.44 + 1.80\ln([C_{\mathrm{OC,auto}}]) - 0.149(\ln([C_{\mathrm{OC,auto}}]))^2. \quad (6)$$

We agree that neglecting the controls of allochthonous OC inputs may cause biases in the estimation of K_{dg} and also methane emissions, and this point has been discussed in the model limitations (section 4; lines 1023–1039):

"First, the organic carbon module only accounts for autochthonous OC production as the substrate for methanogenesis, but ignores the contribution of allochthonous OC inputs leached from the catchments. This is based on the distinct reactivity of autochthonous vs. allochthonous OC inputs, with the latter being more refractory to mineralization and decomposition). As a result, FLaMe-v1.0 may provide conservative estimates of CH_4 production and emission. However, neglecting the allochthonous C inputs may at the same time minimize the feedback of OC on light penetration, leading to systematically biased estimates of autochthonous production (section 2.2.2.1). Moreover, transient lake phosphorus dynamics and the co-limitations by nitrogen, albeit assumed to be less important, are neglected and might increase the uncertainty in the estimates of CH_4 production and emission. … In future model developments, these limitations could be addressed by (i) integrating or routing the lake water, carbon and nutrient fluxes along the global river network, which would allow to simultaneously solve the issue of time-invariant lake water levels in current global lake models

(Golub *et al.*, 2022), including ours; (ii) refining the carbon module by incorporating more dynamic models for algal growth as well as P and N uptake and recycling processes within lakes."

14. Lines 270-272: What is the range/ variability in C burial and mineralization rates? Assuming that burial is half of mineralization seems problematic. Could it be modeled based on DO and OM source?

Response: According to Maavara *et al.* (2017), the mineralization rate constant at a reference temperature of 20 °C is within the range of 0.003–0.01 d^{-1}, which is presented in Table 1 in the revised manuscript. The burial rate constant is set as half of the mineralization rate constant following the ratios (0.1–0.7) between these two processes reported in the global lake dataset (*n*=230) assembled by Mendonça *et al.* (2017). This ratio is likely an upper bound because it accounts for contributions of both autochthonous and allochthonous carbon sources in the dataset, while allochthonous inputs should have higher burial/decomposition ratios than autochthonous ones (Mendonça *et al.*, 2017; Guillemette *et al.*, 2017). Considering the uncertainty related to this ratio, we conducted a sensitivity analysis of CH_4 emissions with respective to this parameter (see section 3.3.3). The results indeed reveal that using a lower burial to mineralization ratio (0.25) leads to significantly higher CH_4 emissions, by up to 36%. In the next version of FLaMe that will also include allochthonous C inputs, the model parameterization will then be able to rely more directly on the global observational dataset of Mendonca et al. (2017). In addition, we agree that DO profiles should be given more weight in future.

15. Lines 278-281: What about transport of littoral methane? (e.g., DelSontro et al 2018, Khatun et al. 2024, Doda et al. 2024)

Response: Thank you very much for this comment. As replied in the Response to General Comment

#3, the laterally transferred methane is not included in our current model (similar to all existing models estimating large scale lake CH_4 emissions), because (1) FLaMe-v1.0 only accounts for the vertical advective and diffusive fluxes, while explicit representation of the laterally transferred methane would require a 2-D framework; (2) the observations related to this newly identified process are extremely limited, such that accounting for this process in generalized regional/global applications would remain highly challenging. Here, we would however like to reiterate that the CH_4 production includes benthic sediment columns in both littoral and deeper zone of the lake, a key novel feature compared to previous assessments of lake CH_4 emissions. As we adopted a “valley” shape lake set-up, we have sediment columns pertaining to water layers at different depths such that we can simulate the CH_4 production in benthic sediment columns in littoral and deeper zones of the lake. It would certainly be interesting to implement the lateral transport of methane within lakes as an additional process, but the effect of this process on whole lake CH_4 emissions should first be assessed, that is, is it merely a redistribution of emissions within the lake, and whether this process will significantly affect the volume-integrated lake CH_4 emissions remain unclear.

16. Figures: consider changing lines / line types to print black/white friendly. Figure 3: please define i and j in the caption

Response: Thank you very much for this comment. We have modified the lines and made sure that the lines can be printed as black/white version. In addition, we added the definition of i and j in the figure caption, which is presented as follows:

"… i and j are the indexes of water layers and sediment columns. Note that the sediment column pertaining to a particular water layer has the same index as that water layer."

17. Lines 305-306: Describe f_{mm} range and calculations from the Hanson and Bastviken papers

Response: The range of f_{mm} is 1/6–1/2, and it is set according to the observations from Hanson *et al.* (2014) and Bastviken (2009). The value and range of f_{mm} are provided in Table 1, which is cited at the beginning of the model description (lines 188–189).

18. Section 2.2.2.2: Bring the table of parameters up earlier and begin referencing them. There is a lot to keep track of, and referencing that table early in this section would be helpful.

Response: Thank you very much for this comment. To address this point, we have added a reference to Table 1 at the beginning of the model description (lines 186–189):

"In what follows, we provide a detailed description of the vertically resolved 1D model set-up (section 2.2.1) used here, as well as of the novel biogeochemical modules (section 2.2.2). All the involved model parameters, their values, and ranges are summarized in Table 1 (section 2.3)."

19. Lines 396-397: Turnover often happens at much warmer temps than 4°C. How does this affect the model?

Response: It is widely recognized that the stratification and turnover can significantly affect the physical and biogeochemical processes in lakes. Following the definitions in Lewis (1983) and Woolway and Merchant (2019), the lake mixing regimes could be classified into amictic (persistently ice-covered), polymictic (mix frequently), monomictic (with one mixing per year), dimictic (with two mixing per year), meromictic (persistently stratified), and oligomitctic (stable in most years except fully mixing in some years). The lake suggested by the reviewer (i.e., the turnover often happens at much warmer temperature than 4°C) is therefore typical of polymictic lakes.

In principle, CSLM can handle polymictic lakes because the CSLM computes a turbulent surface mixed layer (i.e., thermocline) which deepens based on well-known processes (e.g., wind stirring, buoyancy production, and etc.; MacKay, 2012). In the biogeochemical modules of FLaMe-v1.0, we adopted a much higher eddy diffusion coefficient in the mixed layer than the deeper layers (i.e., 100-fold enhancement in the mixed layer) such that the materials (oxygen and methane) could be fully mixed in the mixed layer through enhanced eddy diffusion when the thermocline breaks. In case the eddy diffusion is not large enough to fully mix the materials when the thermocline deepens into bottom layers and the lake is too deep, we also implemented a full mixing condition across all water layers when the surface water temperature approaches 4°C, the critical temperature corresponding to the maximum density and thus indicating turnovers in monomictic/dimictic lakes. However, some mixing events may not be adequately captured because of the low temporal resolution/frequency (daily) of meteorological forcing data in this study. Thus, the use of higher frequency meteorological data should be considered in future work.

To illustrate the capability of FLaMe-v1.0 in handling polymictic lakes, we selected a lake that is explicitly identified as polymictic by Woolway and Merchant (2019), i.e., Lake Mirim at 32.89 °S and 53.25 °W with a mean depth of 6.0 m. By adopting the meteorological forcings extracted from ISIMIP3a and TP concentration from IMAGE-GNM model, we adopted the FLaMe-v1.0 to simulate the vertical profiles of temperature, methane and oxygen concentrations (Figs. R5–R7). We found that FLaMe-v1.0 can capture multiple mixing events during a single year of the selected lake, consistent with the definition of polymictic lakes.

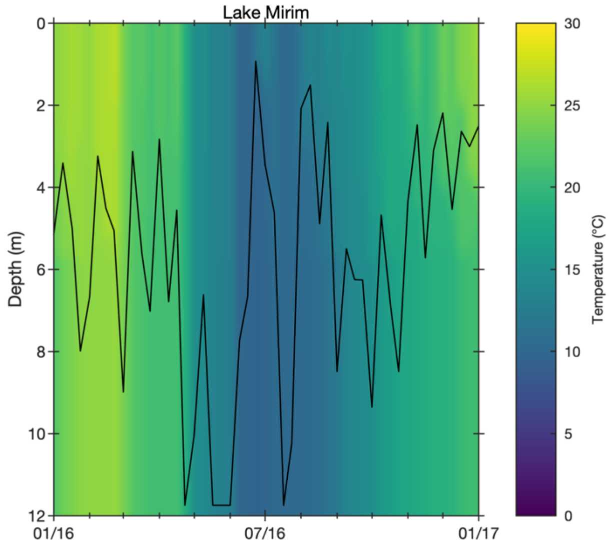

Fig. R5. Vertical temperature profiles of Lake Mirim simulated by FLaMe-v1.0. The black solid line is the thermocline or mixed depth.

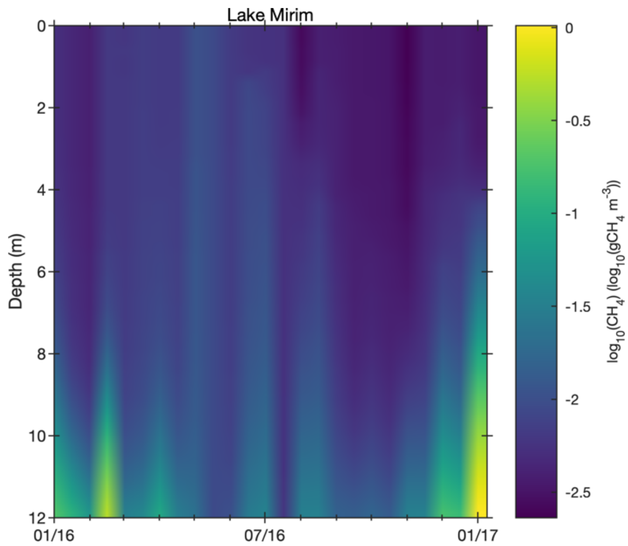

Fig. R6. Vertical profiles of methane concentration (log scale) in Lake Mirim simulated by FLaMe-v1.0.

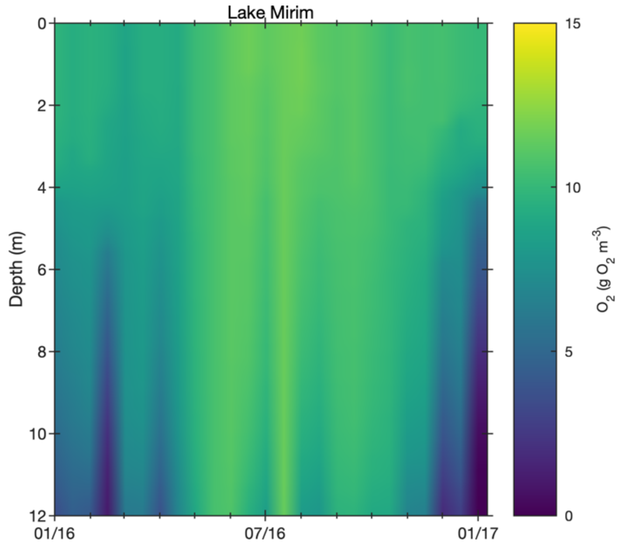

Fig. R7. Vertical profiles of oxygen concentration in Lake Mirim simulated by FLaMe-v1.0.

20. Lines 395 - 406: Please address how the balance between emissions and oxidation is addressed during storage release events

Response: Before lake turnover, the lake water is highly stratified, blocking the material exchange between upper and lower water layers, such that bottom water has high CH_4 concentration (even oversaturated) and low O_2, while the upper water has high O_2 concentration and low CH_4 concentration. During lake turnover, the CH_4 stocks in the bottom water layers can be released to upper layers, and the O_2 stocks in the upper layers can penetrate to bottom water layers. In our current model, the occurrence of lake turnover is simulated as a full mixing event, and CH_4 emissions are simulated by the diffusive transport after mixing, and the CH_4 oxidation is simulated based on the O_2 and CH_4 concentrations within each water layers after mixing.

To address this point, this paragraph (lines 419–436) has been revised as follows:

"In addition to diffusive and ebullitive pathways, FLaMe-v1.0 also calculates a storage flux (F_{stor}) that encapsulates the changes in the total CH_4 mass stored in hypolimnion due to the weakening of lake stratification or turnover events when the lake surface temperature approaches the critical temperature 4°C (MacKay, 2012; MacKay *et al.*, 2017). This results in a full mixing of the lake that releases the previously accumulated CH_4 in the anoxic portion of the lake and concomitantly fully aerates the water column. Lake turnovers thus lead to a complete homogenization of O_2 and CH_4 concentration across the vertically resolved water column. Before lake turnover, the lake water is highly stratified, blocking the material exchange between upper and lower water layers, such that bottom water has high CH_4 concentration (even oversaturated) and low O_2, while the upper water has high O_2 concentration and low CH_4 concentration. Upon full mixing, remobilization of larger CH_4 stocks that accumulated in the hypolimnion abruptly increase the CH_4 concentration near the lake surface, and hence strongly enhance the diffusive flux through the air-water interface; in the meantime, O_2 in the upper layers can penetrate to deep water layers and start oxidizing the CH_4 throughout the entire water column. After full mixing, the CH_4 emissions and oxidation are both simulated based on O_2 and CH_4 concentrations within each water layers. That is, the storage flux in FLaMe is not simulated separately but it is implicitly incorporated into the diffusive flux F_{diff} which increases dramatically following the formation of a very sharp CH_4 concentration gradient at the lake surface."

21. Table 1: I suggest merging with Table 3 to reduce repetition and show the ranges for these parameters. Ranges for all parameters should be shown, and the variables used in the sensitivity analysis could be bold or starred.

Response: Agreed. The Table 3 has been merged into Table 1 to avoid repetition and redundancy.

22. Table 1: I think the units for mineralization and C burial are incomplete – should then be g C / m2 / day?

Response: The mineralization and burial processes are represented by a first-order formulation ($F = kC$, where F [g C d^{-1}] and C [g C] are flux and stock, respectively, and k [d^{-1}] is the rate constant). Thus, the parameters used here to describe the mineralization and burial rates are the first-order rate constants with a unit of d^{-1}.

23. Lines 546-548: What is the area of the theoretical lakes?

Response: The areas of theoretical lakes are set to 5 km^2, and the values of area were tested to have limited effects on the simulation results. Thus, we have added a sentence in the revised manuscript (lines 581–582):

"The lake areas of these two theoretical lakes were set as 5 km^2, which was tested to have limited effects on the simulation results."

24. Table 2: What is the mean depth for Villasjon? Is max depth > 2x mean depth as needed for the model?

Response: Detailed clarification of this point can be found in the Responses to the General comment #2.

25. Table 2: Erssjon is 0.062 km2, which is below the size range that FLaMe can model. This seems problematic. It seems like two of the four modeled lakes do not meet model assumptions based on depth or area.

Response: Detailed clarification of this point can be found in the Responses to the General comment #2.

26. Section 3.1: Is the shallow, eutrophic lake polymictic? If it is large, a 10 m (zmax) and 5 m (zmean)

system may mix in summer. Can the model handle polymixis? Similarly, is Villasjon polymictic? Is that what could explain the wide margins of error for Villasjon (Fig 6)? Similarly, Erssjon may be polymictic.

Response: In principle, CSLM can handle polymictic lakes because the CSLM computes a turbulent surface mixed layer which deepens based on well-known processes (e.g., wind stirring, buoyancy production, and etc.; MacKay, 2012). However, some mixing events may not be adequately captured because of the low temporal resolution/frequency (daily) of meteorological forcing data in this study. Thus, the use of higher frequency meteorological data should be considered in future work.

To illustrate the capability of FLaMe-v1.0 in handling the polymictic lakes, we selected a lake that is explicitly identified as polymictic by Woolway and Merchant (2019), and simulated the vertical profiles of temperature, methane and oxygen concentrations (Figs. R5–R7). Results show that FLaMe-v1.0 can capture multiple mixing events during a single year of the selected lake (details can be found in the Responses to Detailed Comment #19).

In addition, from the literature, Lake Erssjon was reported as dimictic while the mixing regime of Lake Villasjon is polymictic.

27. Fig 5. Please increase and equalize axis font sizes to match the aesthetics of boxes g and h. Ebullitive fluxes are not visible in box g, though I believe there is a faint line at the bottom of the figure…please extend the y-axis below zero to show ebullitive fluxes more visibly. Apply unique labels to the y-axis of boxes g and h (as with the rows above) to make the scale of h more apparent and move the location of the “x10-4” to the axis label so it’s more obvious.

Response: Thank you very much for this practical comment. Following your suggestion, we have (1) set the font sizes for all panels equal for the purpose of the aesthetics, (2) extended the y-axis in panels g and h to below zero to the ebullitive fluxes, and (3) converted the units of g CH_4 m^{-2} d^{-1} into mg CH4 m^{-2} d^{-1} in panels g and h, and thus the "x10^{-4}" is not needed any more. In addition, since the methane emission rates and ice cover are both very important variables needed to be illustrated, these two different variables cannot be represented with a single y-axis. Thus, we keep the double y-axis in panels g and h. As a result, Figure 5 has been revised as follows:

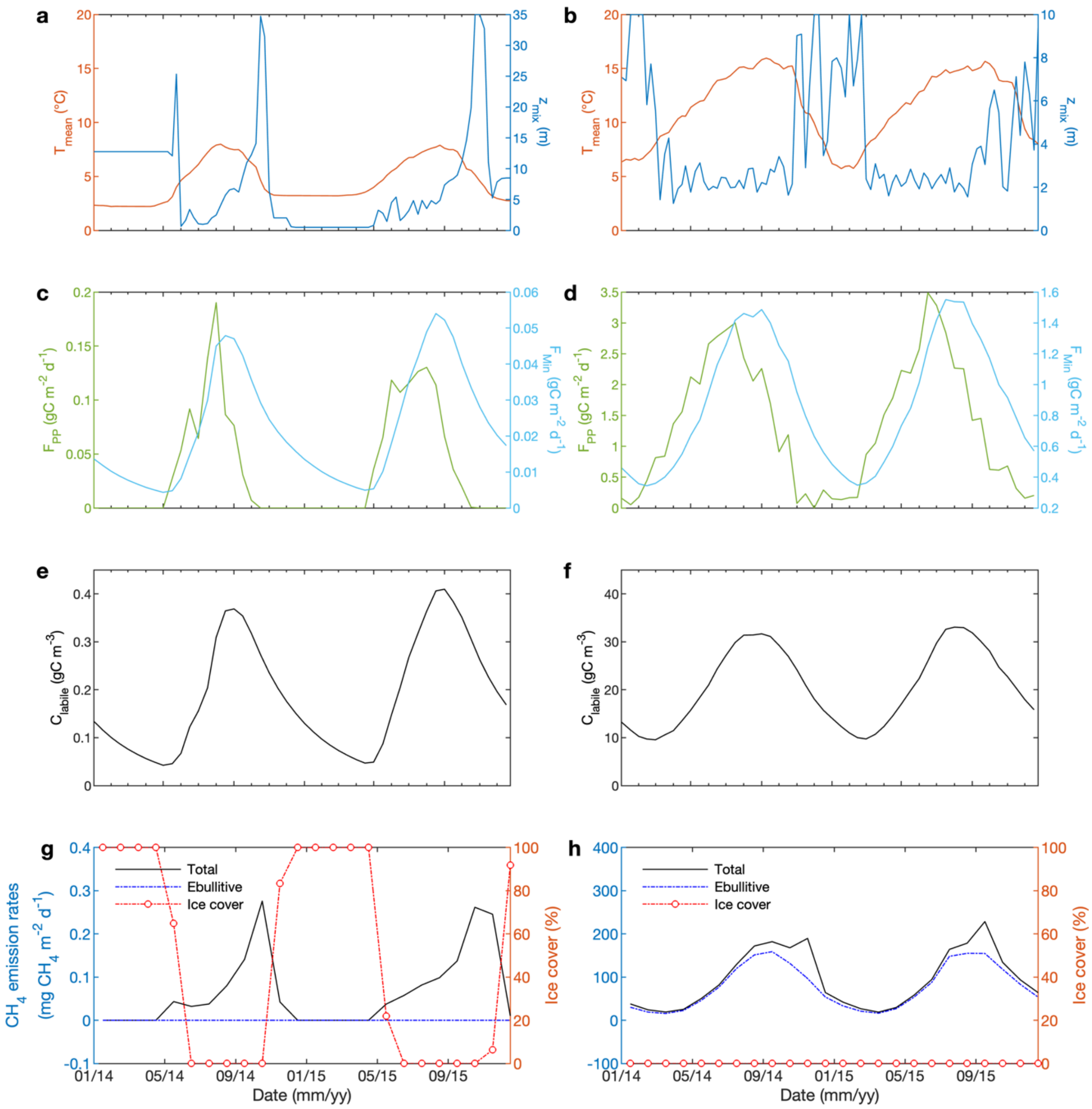

Fig. R8. Depth-integrated temporal evolution of variables and processes in two theoretical representative lakes. The deep oligotrophic lake (left) has a maximal depth of 35 m and [TP] of 3 μg*P*

L^{-1}, and is driven by the climate forcings at the location of 63.75°*N*, 26.25°*E*. The shallow eutrophic lake (right) has a maximal depth of 10 m and [TP] of 80 μg*P* L^{-1}, and is driven by the climate forcings at the location 43.75°*N*, -6.25°*E*. (a) and (b) show the evolution of lake mean temperature and mixing depth; (c) and (d) show the evolution of primary production (F_{PP}) and mineralization rate (F_{Min}); (e) and (f) show the evolution of concentration of autochthonous organic carbon ($C_{OC,auto}$); (g) and (h) show the evolution of CH_4 emission rates and ice cover. Note the difference scales between the left and right panels.

28. Lines 693-695: What if lake depth was decreased from 15 m to 5 m? How shallow can the model go? What is the distribution of lake depths in Europe?

Response: We have tested the case of decreasing the lake depth from 15 m to 5 m (not presented), which is similar to the case of decreasing lake depth from 15 m to 10 m (presented in the supplementary section S4.4). The lake with a shallower depth (h_{max} = 10 m) has a slightly lower CH_4 production rate. This is attributed to the photic zone being truncated by morphological constraints (i.e., the lakebed is shallower than the "natural" photic depth), which decreases the depth-integrated primary production and further the mineralization and CH_4 production (note that our model does not account for benthic algal production). Lake depth has a more evident effect on the fraction of sedimentary CH_4 production channeled into the ebullitive pathway (52% versus 28%), because this pathway is favored in a shallower lake with lower CH_4 solubility due to higher temperature and lower hydrostatic pressure.

In principle, the lakes of any depth can be simulated by our FLaMe-v1.0 model provided with suitable grid spacing. Currently, the vertical grid spacing of 50 cm, and the minimum of the mean depth of the lake can be simulated by our model is approximately 1.5 m considering the vertical grid spacing of 50 cm. As shown in Fig. R2, the lakes shallower than 1.5 m (mean depth) accounts for only 6% of lakes (n =108384) within European domain. Moreover, for the 953 representative lakes used in our clustering strategy, the lakes shallower than 1.5 m (mean depth) accounts for only 5%. Thus, the current grid spacing of 50 cm may cause some biases in the assessment of European lake methane emissions. The effects of grid spacing on European lake methane emissions could be found in the Responses to the Detailed Comment #9.

From HydroLAKES database (Messager *et al.*, 2016), the frequency distribution of lake depth is shown in Fig. R2 while spatial distribution of lake depths in European domain is presented as below (Fig. R9):

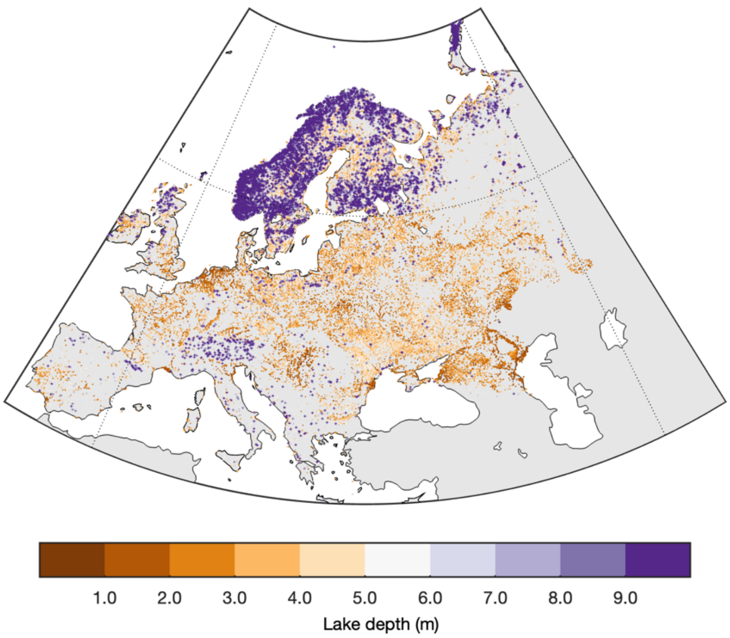

Fig. S9. Spatial distribution of the mean lake depth within European domain. The information of mean lake depth is from HydroLAKES database (Messager *et al.*, 2016).

29. Lines 795-796: The dataset of 47 European lakes was not described in the Methods; please provide more details on this dataset and analysis. For instance, what environmental variables were measured

that could be incorporated into the models?

Response: Thanks a lot for this comment. We have added a paragraph in the Methods (section 2.5.3, lines 640–659) to elaborate on the model evaluation for the European domain, with more details related to this dataset of 47 European lakes included as follows:

"To validate the FLaMe-v1.0 model for European lakes, we will evaluate the simulated F_{PP} and CH_4 emission rates against the ranges/values reported in the literature and/or from observations. First, the simulated F_{PP} will be evaluated against empirical ranges reported by Wetzell (2001) for lakes from ultraoligotrophic (0–5 μgP L^{-1}), oligotrophic (5–10 μgP L^{-1}), mesotrophic (10–30 μgP L^{-1}), to eutrophic (>30 μgP L^{-1}) conditions. Next, the simulated diffusive and ebullitive CH_4 emission rates will be evaluated against *in-situ* measurements compiled by Rinta *et al.* (2017) from 17 boreal lakes (in southern Finland and Sweden) and 30 central European lakes (in The Netherlands, Germany and Switzerland). This dataset is adopted because it can not only differentiate the ebullitive and diffusive CH_4 fluxes during late summer (August and September, 2010–2011) but also provides information regarding environmental conditions of the study area (mean annual air temperature, annual precipitation, percentage of forests and managed land in the catchment) and water chemistry of the studied lakes (temperature, conductivity, pH, absorbance, TP and TN in surface water, and average TP and TN in the water column), which are helpful for understanding the lake methane dynamics within these two contrasted regions. However, this dataset of 47 lakes still has some limitations such as lacking the measurements of long time-series of CH_4 emissions (that may comprise turnover events and other hot moments) and climate drivers, as well as the potential biases induced by the calculation methods used for separating the measured CH_4 fluxes into diffusive and ebullitive pathways. In particular, Rinta *et al.* (2017) used the floating chambers over a relatively short duration (6hr) and did not employ bubble traps to estimate the ebullitive flux."

Although a lot of environmental variables were measured and provided in this dataset, only part of these variables can be incorporated into the model (e.g., lake area, and depth, TP), whereas the other variables (e.g., climate variables) are incomplete to be incorporated as model forcings. More specifically, as elaborated in section 2.5.3, the meteorological conditions needed for FLaMe model include long time-series of shortwave solar radiation (W m^{-2}), longwave solar radiation (W m^{-2}), precipitation (mm s^{-1}), near surface air temperature (at 10 m height, °C), specific humidity (kg kg-1), near surface wind velocity (at 10m, m s^{-1}), and atmospheric pressure (Pa).

30. Lines 799-803: Provide average values or percent differences between observed and estimated in the text or a table

Response: Thank you very much for this comment. We have added the comparisons of means and medians between observed and simulated methane emission rates in boreal and central European lakes as Table S2, which is also presented as follows:

Table R2. Comparison of means and medians (g CH_4 m^{-2} d^{-1}) between observed and simulated methane emission rates in boreal and central European lakes. See Fig. 8 and Fig. S19 for a graphical representation.

	Mean				Median			
	Boreal		Central Europe		Boreal		Central Europe	
	Obs.	Sim.	Obs.	Sim	Obs.	Sim.	Obs.	Sim.
Diffusion	0.0042	0.0029	0.0337	0.0084	0.0026	0.0025	0.0170	0.0088
Ebullition	0.0051	0.0179	0.0846	0.0722	0.0019	0.0146	0.0402	0.0700

Total	0.0089	0.0199	0.1177	0.0807	0.0046	0.0164	0.0642	0.0801

31. Line 832: provide lower bound number as well as upper bound

Response: We consider that the readers are more interested in the uncertainty range of European lake CH_4 emissions induced by the uncertainty of model parameters, rather than the uncertainty range induced by the interannual variability. Thus, in the following sections (section 3.3.3), we combine the machine learning approach and FLaMe-v1.0 model to assess the uncertainty, and finally, we provide the estimates of European lake CH_4 emissions as 0.97±0.23 Tg CH_4 yr^{-1}.

32. Line 838-840: How much of this is also due to ice cover (i.e., reduced fraction of year with emissions)?

Response: We tested the effects of ice cover by turning off the relevant processes in biogeochemistry modules and estimated that the total CH_4 emissions from European lakes have increased by 7% (from 0.97 to 1.04 Tg yr^{-1}). To clarify this point, we have added a sentence in the revised manuscript (lines 904–906):

"The ice-cover in northern lakes also contribute to the south-to-north gradient of CH_4 emission rates, and was estimated to decrease the European lake emissions by 7%."

33. Line 846: continuous makes it seem like fluxing through the ice. Clarify.

Response: We have clarified that "European lakes as a whole", and "individual lakes during ice periods will not emit CH_4". The sentence has been revised as follows:

"…European lakes as a whole act as a continuous CH_4 source including during the winter months (individual lakes during ice-covered periods do not emit CH_4)."

34. Lines 880-882: suggests whether lake is N or P limited is important to consider. How much would N-limitation change model outputs? To what extent are lakes N or P limited in Europe?

Response: Early studies revealed higher dependence of Chl-a on TP over TN concentrations in freshwater lakes, suggesting that P is the limiting nutrient of primary production (Guildford and Heckay, 2000; Schindler, 1977). However, recent works suggested that the fraction of lakes with N limitation or N- and P-colimitation is increased, especially when the trophic level is increased from oligotrophic to hypereutrophic statuses. With a dataset from 871 Danish lakes, Søndergaard *et al.* (2017) revealed that P is of key importance for the ecological quality but that increased N concentrations, particularly in shallow lakes with moderate to high TP, may have significantly adverse effects on lake water quality and ecological status in summer. A global meta-analysis (annual average data from 831 lakes) suggests that total nitrogen (TN): total phosphorous (TP) ratios declined significantly as lakes become eutrophic, and from oligotrophic to hypereutrophic lakes, the probability of N and P co-limitation significantly increases from 15.0 to 67.0%, while P-only limitation decreases from 77.0 to 22.3% (Zhou *et al.*, 2022).

In FLaMe-v1.0, we assume that P is the only limiting nutrient, such that the effects of N limitation cannot be assessed. The N limitation will be added in the next version of the model.

35. Table 4: Add more description to the caption. How was this done and what are the mean values representing? I suggest adding % change to the estimates.

Response: Following your comment, we have now added more description in the table caption, and added the percentage change of CH_4 emissions relative to baseline simulation; the revised table (Table

3 in the revised manuscript) is also presented as follows:

Table R3. Sensitivity of European lake CH_4 emissions (Tg CH_4 yr^{-1}) to key model parameters. Mean and SD are the mean and standard deviation of a particular parameter. Mean±SD indicates that the parameter values are adjusted by ± one SD, and Mean±0.5SD indicates that the parameter values are adjusted by ±0.5 SD.

Parameter setting		Mean±SD				Mean±0.5SD			
		–SD		+SD		–0.5SD		+0.5SD	
		Absolute/percent		Absolute/percent		Absolute/percent		Absolute/percent	
Primary production	P_{chl_max}	0.344	-65%	1.743	+80%	0.642	-34%	1.376	+42%
	$K_{s,P}$	1.432	+48%	0.754	-22%	1.170	+21%	0.852	-12%
Mineralization and burial rates	k_{20}	0.578	-40%	1.164	+20%	0.758	-22%	1.141	+18%
	k_{bur}	1.317	+36%	0.761	-22%	1.107	+14%	0.856	-12%
	θ	1.028	+6%	0.928	-4%	0.989	+2%	0.968	0%
	f_{mm}	0.302	-69%	1.888	+95%	0.605	-38%	1.437	48%
Methane oxidation	k_{max}	1.057	+9%	0.930	-4%	1.009	+4%	0.953	-2%
	$Q_{10,ox}$	0.992	+2%	0.983	+1%	0.978	+1%	0.973	0%
Diffusion coefficient	k_{diff}	1.124	+16%	1.046	+8%	1.068	+10%	1.048	+8%
Base value of the shape parameter	α_{min}	1.222	+26%	0.840	-13%	1.077	+11%	0.891	-8%

36. Sensitivity analysis did not look at diffusion rates; are these uncertain? How important can that be?

Response: Thank you very much for this comment. We have added the sensitivity analysis related to the eddy diffusion coefficient by varying this parameter by ±50% (SD) and ±25% (0.5SD) (see Table R3 or Table 3 in the revised manuscript). We found that either increasing or decreasing the eddy diffusion coefficient will increase the total methane emissions, which could be explained as follows. Increasing the eddy diffusion coefficient will accelerate the exchange between atmosphere and water, such that the methane emissions are increased. Decreasing the eddy diffusion coefficient will decrease the exchange such that the oxygen content in bottom water is lower, which increases the methane production significantly, thus compensating the effects of decreasing the diffusive exchange. But this does not mean that the current value of k_{diff} results in the minimum methane emissions (i.e., it is a coincidence). Note that our sensitivity analysis with respective to this parameter k_{diff} might slightly change if the grid spacing woule be finer.

37. Lines 1020-1021: add lower bound to lake size

Response: Lower bound of lake size is added, and this sentence has been revised as follows:

"Finally, at the European scale, FLaMe estimates total CH_4 emissions from lakes with areas of 0.1–1000 km^2 (n=108407, total area = 1.33x10^5 km^2) as 0.97±0.23 Tg CH_4 yr^{-1}."

References

Bastviken, D. (2022). Methane. In T. Mehner & K. Tockner (Eds.), *Encyclopedia of Inland Waters (Second Edition)* (pp. 136-154). Oxford: Elsevier.

Bouffard, D., Doda, T., Ramón, C. L., Ulloa, H. N.: Thermally driven cross-shore flows in stratified basins: a review on the thermal siphon dynamics. *Flow*. 5, E1. https://doi.org/10.1017/flo.2024.31, 2025

Doda, T., Ramón, C. L., Ulloa, H., N., Brennwald, M. S., Kipfer, R., Perga M.-E., Wüest, A., Schubert, C. J., Bouffard, D.: Lake surface cooling drives littoral-pelagic exchange of dissolved gases.*Sci. Adv.***10**,eadi0617. https://doi.org/10.1126/sciadv.adi0617, 2024.

Guillemette, F., von Wachenfeldt, E., Kothawala, D. N., Bastviken, D., Tranvik, L. J.: Preferential sequestration of terrestrial organic matter in boreal lake sediments, *J. Geophys. Res. Biogeosci.*, 122, 863–874, https://doi.org/10.1002/2016JG003735, 2017.

Hanson, P. C., Buffam, I., Rusak, J. A., Stanley, E. H., Watras, C.: Quantifying lake allochthonous organic carbon budgets using a simple equilibrium model, *Limnol. Oceanogr.*, 59, https//doi/org/10.4319/lo.2014.59.1.0167, 2014

Lauerwald, R., Regnier, P., Figueiredo, V., Enrich-Prast, A., Bastviken, D., Lehner, B.: Natural lakes are a minor global source of N_2O to the atmosphere. *Global Biogeochem. Cycles*, 33, 1564–1581. https://doi.org/10.1029/2019GB006261, 2019.

Maavara, T., Lauerwald, R., Regnier, P., Van Cappellen, P.: Global perturbation of organic carbon cycling by river damming, *Nat. Commun.* **8**, 15347. https://doi.org/10.1038/ncomms15347, 2017.

Mayorga, E., Seitzinger, S. P., Harrison, J. A., Dumont, E. Beusen, A. H. W., Bouwman, A. F., Fekete, B. M., Kroeze, C., Van Drecht, G.: Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation, *Environ. Model. Softw.*, 25, 7, 837-853, https://doi.org/10.1016/j.envsoft.2010.01.007, 2010.

Messager, M., Lehner, B., Grill, G., Nedeva, I., Schmitt, O.: Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nat. Commun.*, 7, 13603, https://doi.org/10.1038/ncomms13603, 2016.

Mendonça, R., Müller, R.A., Clow, D., Verpoorter, C., Raymond, P., Tranvik, L. J., Sobek, S.: Organic carbon burial in global lakes and reservoirs, *Nat. Commun.,* 8, 1694, https://doi.org/10.1038/s41467-017-01789-6, 2017

Reynolds, C. S.: The ecology of phytoplankton, Cambridge University Press, 2006

Rinta, P., Bastviken, D. Schilder, J., van Hardenbroek, M., Stötter, T., Heiri, O.: Higher Late Summer Methane Emission from Central Than Northern European Lakes, *J. Limnol.*, 76 (1), https://doi.org/10.4081/jlimnol.2016.1475, 2017.

Søndergaard, M., Lauridsen, T.L., Johansson, L.S. *et al.*: Nitrogen or phosphorus limitation in lakes and its impact on phytoplankton biomass and submerged macrophyte cover. *Hydrobiologia* **795**, 35–48. https://doi.org/10.1007/s10750-017-3110-x, 2017.

Stepanenko, V., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., and Vesala, T.: LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes, *Geosci. Model Dev.*, 9, 1977–2006, https://doi.org/10.5194/gmd-9-1977-2016, 2016.

Tan, Z., Yao, H., Melack, J., Grossart, H.-P., Jansen, J., Balathandayuthabani, S., *et al.*: A lake biogeochemistry model for global methane emissions: Model development, site-level validation, and global applicability. *J. Adv. Model. Earth Syst.*, 16, e2024MS004275. https://doi.org/ 10.1029/2024MS004275, 2024.

Zhou, J., Han, X., Brookes, J. D., Qin, B.: High probability of nitrogen and phosphorus co-limitation occurring in eutrophic lakes, Environmental Pollution, Volume 292, Part A,118276, https://doi.org/10.1016/j.envpol.2021.118276, 2022.