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Biogeosciences Discussions



# *Interactive comment on* "Methane dynamics in different boreal lake types" *by* S. Juutinen et al.

**S. Juutinen et al.**

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We would like to thank both referees for the careful reviewing and valuable comments on our manuscript. These comments give new insights and help improve the manuscript to get better understanding of the characteristics of this data and CH4 dynamics in lakes. In the following we will answer all the comments and the addressed issues of both reviewers. We are ready to revise the manuscript.

Responses to the comments by referee David Bastviken

2. The aim to use the lake typology and lake variables used for environmental monitoring and link those to lake CH4 is valuable and definitely should be tried. However, given the outstanding dataset it would be sad to not explore if other variables or other ways to analyze the data can yield even better understanding of lake CH4 dynamics.



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It is not clear if this alternative analysis, focusing not on the environmental monitoring perspective but rather on extracting the maximum knowledge about CH4 from the data, have been done and some specific questions below address this.

Answer: We admit that the outcome of our manuscript may seem limited in respect to variables explored, and ending to report responses to the variables that are used in environmental monitoring as a conventional solution, particularly with this large data. These variables, however, are important indicators of conditions affecting biological processes. The statistical relationships between CH4 concentration/flux and environmental variables were commonly rather modest. Lake typification was applied, because it allowed us to reasonably group lakes with more similar physical and biological processes. This helps to clarify the main lake characteristics impacting variation in the CH4 data, because otherwise large overall variability and forces affecting to different directions tend to obscure the relationships between CH4 and environmental variables. Prior explorations using regression and factorial analyses supported the use of this typification and these variables. Moreover, the findings of previous studies on lake CH4 dynamics encouraged to examine how well patterns of relatively large CH4 data match with the defined lake types. Exploration with different variables and variable combinations to find those driving the variation in methane concentrations or estimated fluxes has been done. We agree that more of this knowledge should be shared and included in the manuscript. Reviewer also gave valuable suggestions about relevant variables.

Specific comments: 3. P3458 L9-13 Somewhat unclear if statements regard NRC and shallow lakes only or all lakes. Surface water concentrations are mentioned in two different sentences partly having the same meaning (?)

Answer: This statement regards all lakes. The surface water concentration is mentioned there referring firstly the trends shown by lake type averages, and secondly the results of regression analyses. We will reword this part.

4. Section 2.4 and elsewhere I think the estimates of the diffusive flux is uncertain.



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If I understand it right k was kept constant for all alkes at all times regardless of lake size. An average wind speed (U10) of 3 m/s yields a k600 of 3.46 cm/h or 0.83 m/d according to the equation 2. I fear that this is an overestimate for the smallest probably wind sheltered lakes while it is almost certainly an underestimate for the large lakes in the dataset. However, I have no better alternatives to offer at this point, but please consider (1) to clearly discuss these problems, and (2) to focus more on the storage fluxes, which are more robust and for which you obviously have the most extensive data in the world so far. Also, please point out more clearly earlier in the text that ebullition, representing a very large open water flux component was not included. This sometimes gets confusing, e.g. when expressions like "total flux"; or "annual flux" is used. For example, in section 3.4 it is not always clear that ebullition was not included.

Answer: (1)We agree that the estimate of diffusive flux is uncertain. We will add this discussion about the lake size, wind speed and k factor relationships where relevant. It is important to understand the nature of this data when interpreting the results. As suggested, we will mention earlier in the text (e.g. in the end of introduction) that with this data we can make estimations of storage flux, diffusive flux and their sum, but not of ebullition or other components. The uncertainty in the flux estimation was the reason for focus more on the concentration data when comparing lakes. (2) We will give more results and discussion about the whole lake storages and storage changes occurring during the seasonal turn-over periods. Small proportional contribution of the storage flux, particularly lake wide, was the reason for the small contribution in the text. However, keeping in mind the uncertainty in flux estimation, storage component should get more space.

5. P3466 Section 2.5 and Table 4 The variables explored to explain CH4 concentrations and mentioned in the text are O2, Ptot, TOC, lake area, and depth. What other variables or combination variables were tried but not reported? Potentially several other variables could show stronger relationships with CH4 concentrations, particularly for surface water showing relatively low r2 in Table 4.



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Answer: Our data consisted of a large set of water chemical variables, and morphometric data consisted area, depth and volume. The fact that we had to estimate volume and mean depth in some cases is one limitation in the data. Different variables, their combinations, and ratios have been explored to find out the secrets behind CH4 variation. We will include the main features of this process in the text. We will test the suggested variables if it is not already done.

See some examples below: (a) How about mean depth (assuming that only max depth was tried; unclear in the text)?

Answer: Mean depth was tested, and the result was more or less similar. Maximum depth was selected, because it is a true measurement for all of the lakes, while mean depth is an estimate for some of the lake.

(b) Was Ptot tried alone? It does not seem so in Table 4. In general it is unclear if Table 4 only show significant relationships or all that were tried. With such a large n many relationships with low r2 will still be significant, so is may be better to select what relationship to show based on a r2 treshold. It is also unclear to what extent the order of the variable in the stepwise analysis makes a difference or not.

Answer: Ptot and other key variables were tested alone. As reviewer noted, order and combination of variables used in regression analyses can make a considerable difference in the results. This set of variables was chosen on the basis of prior explorations, reasoning related to biology of methane dynamics and lake typification aspect.

(c) Figure 3 indicates that summer surface concentrations vs log lake area for all lakes should yield a much stronger relationship than relationships with depth as the primary variable, but no such relationship is presented in Table 4.

Answer: We will examine this relationship again.

(d) Surface water CH4 during stratification periods seems to come from epilimnetic sediments and is lost by oxidation and emission. Hence it could be expected that a



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large epilimnetic sediment area relative to the epilimnetic volume would favour high concentrations while a large lake area resulting in a higher piston velocity should increase emissions lowering surface water concentrations. Could this be expressed by combination variables in some way? Maybe a first test could be done with a simple "area to mean depth ratio" and/or "area to volume ratio".

Answer: We will examine this variable with CH4 concentration data, and show relationship between bottom and surface water CH4 concentrations. Area to volume ratio and mean depth have the same information?

(e) One interesting problem with all this is that the concentrations are a result of processes occurring at different scales. For example, the volumetric concentrations of different variables used in Table 4 rely on not only what happens in the volume itself but also from import and export to the surroundings across surfaces. The concentrations of different variables are obviously regulated by very different processes and this may reduce the strength of relationships where the concentration of one variable (e.g. CH4) is related to concentrations of other variables (Ptot, O2, ...). One way to handle this could be to compare whole lake integrated variables. For example instead of comparing bottom concentrations of CH4 and O2 one could compare total lake storage of CH4 and O2, or whole lake average concentrations, or as previously tried anoxic volume fraction and total lake CH4 storage. Similar approaches could be tried for other variables as well.

Answer: Reviewer points out importantly the scales and how concentration is a net effect of different processes. Regarding amount of anoxic and oxic water of the total water column, the volume integrated variable could make sense; with other variables, concentrations should work well. We hope to study the profiles more detailed in the future with selected data.

(f) Was residence time tired as a variable? I have never seen this tried but it could be interesting given this data set. Residence time should partly affect TOC but could



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also be related to ground water inflow. Perhaps it can say something about possible groundwater CH4 contribution which is largely ignored in many studies.

Answer: Residence time was ignored. Small lakes usually have short residence time and this issue might be studied with size classified data. We doubt the that the groundwater impact could be detected with this data, even though the question is interesting.

(g) Were simple ratios between the tested variables tried. E.g. an intermediate Ptot does not necessarily mean intermediate productivity fuelling CH4 production if most P is bound to TOC and the Ptot to TOC ratio could be used to explore this.

Answer: This ratio was in analyses in some point. We will check it. Reasons to use it are good, but the results might not be the desired as ratios can sometimes be complicated variables.

(h) The data cover a relatively large latitude gradient. Was any climate variables such as average temperatures tried for all lakes or within the different groups? The above are just examples of how I think and if such approaches have not been tried already, I am sure other more clever/elegant approaches can be identified with greater knowledge about the data than I have.

Answer: Climatic variables, i.e. mean annual temperature (data from weather stations), water temperature, and length of ice covered period have been tested for all lakes and the groups. No significant effects were found. This is an important result and this information should be added to the manuscript. With the whole data the soil properties and land use differences between south and north in the region of the study apparently hinder the weaker effects of the temperature related variables. We hope that this discussion will provide the greater knowledge.

6. P3466 L15. I do not understand the use of "production and oxidation". Was this measured? From my understanding concentrations were measured - not processes?

Answer: Only concentrations were measured. Our aim was to express that concentra-



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tion is a net effect of production, and oxidation and, in addition, of transportation. We will make this clear in the text.

7. P3466 L31 Please, clarify what is meant with "angular transformation". Arcsin of the square root of x?

Answer: Transformation Arcsin of the square root of x was used

8. P3467 L1-10 The classification according to Ptot or bottom O2 based on environmental monitoring is interesting and fine, but could potentially also (1) result in a classification possibly being irrelevant for some aspects of the CH4 cycling (e.g. surface concentrations if lake physical properties are more important) or (2) limit the use of the findings for readers in countries where lake classifications are made in different ways. I write this comment not to criticize the classification but rather to stress the importance of the parallel efforts to find and present general results valid for all lakes.

Answer: 1) Results showed irrelevance caused by surface processes. We think that it is an importnat information. 2) Classifications can be different, but the idea can be adopted. We did not assume that our data is a valid training set and we did not produce a tool ready to use. We will emphasize this in the revised text.

9. P3469 L14-15 Please, consider moving the explanation about the choice of variables to the methods section (and also to consider additional variables according to above comments).

Answer: We take this comment into account.

10. Results and discussion Would it be possible to have sub-headings (e.g. summer surface concentrations, summer bottom concentrations, winter surface concentrations, and winter bottom concentrations, or equivalent to enhance readability? I frequently got confused and mixed up various parts of the text having similar statements for different seasons and depths. A conceptual table showing the strongest predictors could also help. This table would need two columns for summer and winter and rows for surface



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and bottom. The table text could be: Variables being related to CH4 concentrations at different depths and seasons (linear regression; r2 $>$ "selected threshold value". Plus or minus signs indicate positive and negative relationships, respectively. Details about relationships are shown in Table 4. (I can give a better example by e-mail since the web formatting does not allow me to put a table here).

Answer: We promise to clarify the text regarding different depths or seasons, and apply the suggested conceptual table to ease the reading.

11. Section 3.4 (P 3471) and Figure 5. When there is the option to determine lake integrated flux per m2 I think this is always preferable relative to flux per m2 sampled water column at the deepest point. The latter is not representative for whole lakes and makes comparisons between lakes much more difficult. In the case of CH4 this is particularly important since concentrations depend on sediment surface area to whole water layer volumes, and not on what happens in just one m2 of the water column. Hence, a storage flux valid for only 1 m2 of the total lake area does not seem relevant for this excellent material enabling outstanding between lake comparisons and this is also mentioned in the discussion. Hence, I suggest that only lake integrated values should be regarded. In line with this I suggest panels A and C in figure 5 should be omitted. (At the same time I would like to thank the authors for clearly discussing these two different areal units and their difference. In far too many papers it is unclear which was used making interpretation very difficult.)

Answer: We agree with the referee regarding the relevance of different estimates, and will remove the other estimate when unnecessary. We would, however, like to mention the different estimates to introduce the possible uncertainties associated with those.

12. P3474 L4-6 If the shallow lakes were also the smallest they should have been more wind sheltered implying a lower k600 which also could contribute to higher surface concentrations.

Answer: We will mention this in the text.



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13. P3477 L19-20 The flux information form the 8 Swedish lakes represent whole lake integrated values and should perhaps not be compared to sampling point areal values. If lower values were found for the Finish lakes this could depend on differences in lake morphometry. The Swedish lakes were likely most comparable to the smaller lakes in the Finish dataset and not to all the lakes.

Answer: We will compare only the lake integrated values, and point out the size difference.

14. P3477 L23-29: The Wisconsin lakes had higher CH4 concentrations and I partly agree with the explanation regarding their small size implying large sediment area to water volume, but also think this has connections to climate. Due to a more continental climate the Wisconsin lakes warm up quickly and develop stable stratification during longer periods of the year. This results in a higher CH4 storage in the water column and hence a leager storage flux. On top of this the epilimnetic sediment was warmer than in Sweden (and presumably Finland) which could explain higher CH4 flux into the water and higher diffusive emissions.

Answer: We will discuss these other aspects when comparing lakes and drawing conclusions.

15. P3478 L3-7 I am not sure that lake area integrates other variables particularly well. More likely it more directly reflects the surface area across which CH4 is exchanged. For example, lake integrated areal flux range from 1.6 to 727 mmol m-2 a-1 (stated on P3477 L15- 17). This represents 2-3 orders of magnitude while lake area ranges over more than 5 orders of magnitude (e.g. fig. 6). This explains why lake area should be more important for whole lake fluxes than variables showing less between lake variability (e.g. depth, Ptot, O2 ...). However, these other variables should do a better job explaining the areal flux (flux m-2).

Answer: Shallow lakes and/or lakes small in area tend to have the highest surface water CH4 concentrations, i.e. also high CH4 emissions estimates per unit area.



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16. Table 1 Are there some minor errors in the table? HSm: Color 30-60? VHSh: Color as for VH?

Answer: These errors have been corrected.

17. Table 3 It would be interesting to know the fraction of the lakes having bottom water CH4 concentrations $>$ 2 microM. The data gives the impression that just a few lakes had very high bottom water CH4 concentrations while the majority had very low bottom water concentrations.

Answer: Majority of lakes had low concentrations. We will give the fractions in Table 3.

18. Table 4 - Does "a" denote the intercept of the relationships? - See also above comments Answer: "a" denotes the intercept. The table explanation will be improved.

19. Table 5 - Are some words missing in the text explaining the table? - I cannot find the notes, a, b, and c.

Answer: We apologize that the table was poorly explained and it will be clarified.

20. Table 7 "Total flux" can make the reader think all flux pathways were included. Please, clarify that estimates are based on diffusive and storage flux. Does it make any sense that flux was best correlated max depth or does depth just reflect something else that could provide a better explanation? I could not find much about this in the discussion. I also wonder if it may be better to look at diffusive and storage fluxes separately since they depend on different factors. Considering them together may result in more diffuse patterns.

Answer: We will keep clear that our estimate is only the sum of diffusive and storage flux. It is true that diffusive and storage flux are products of different processes and thus deserve to be analyzed separately. We reported less detail of the relationships between environmental variables and emission estimate, because of the great degree of estimation behind emission number. Uncertainty in the diffusion component has been discussed here. In addition, the proportional share of storage flux in the lake wide



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estimate was generally small. However, we will do more work with the components. Referee hit the point that many factors may just reflect something else. The fact, also regarding the depth, is worthy of better discussion.

21. Figure 2 Please consider having different scale for different panels to make all data visible. It would also be good to give more information of the relative sizes of diffusive and Storage fluxes, respectively. At the moment This is not easy to access from Fig 2 and the texts primarily mention that storage flux was more than 1/3 of the flux in half of the lakes. This is an important issue for how to prioritize in future efforts measuring fluxes and providing percent contribution of storage at least for each lake type would be very valuable.

Answer: Figure 2. illustrates the effect of seasonal changes on the CH4 content in the water column. Consequently, the spring and autumn in the same scale with winter and summer is almost invisible. We would modify figure to show the change in total lake storages, i.e. storage fluxes per m2, in the different lake types. The percentage contribution of storage component is already shown in the figure 5.

22. Figure 3 How about having open symbols for clear water lakes, grey for humic and black for very humic to get a more logical connection between symbols and lake characteristics? NRC could have X symbols. How would a contour plot look like? Right now it is difficult to comprehend the density of lakes in certain areas of the graphs since the symbols may overlap.

Answer: Original figures have the suggested open-grey-black-logic. We will improve the figure. Contour plot sounds interesting, but how would it work here?

23. Figure 4 I only had open and black symbols in my version, while grey symbols are mentioned in the figure text. There is also a peculiar tick mark on the error bars.

Answer: There is some grey, but we will improve the figure. The peculiar tics mark quartiles, unfortunately the explanation was missing.



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24. Figure 5. Something looks strange with the HM lakes in my copy. I can see the quartiles but no median or mean values.

Answer: This is strange, because there were only two HM lakes and ticks marks those lakes. This is now explained in the figure text.

25. Figure 6. I. The series "All" and "Statistic sample" seem to overlap almost completely. Is it necessary to have them both in this figure? II. I assume the Bastviken et al values were obtained from Table 1 in Bastviken et al 2004. I wonder about some of these values: (a) The star at 1200 mmol m-2 a-1 looks like Lake Mendota studied by Fallon et al1980? If so and it is preferred to keep the point in spite of being representative of a system with high anthropogenic nutrient load, I suggest mentioning the original reference. (b) I could not identify all the points. E.g. one of the stars at about 500 mmol m-2 a-1 should be Illersjön, but where comes the other star at this level from? Why are not all 11 Wisconsin lakes for which there could be triangles present? (Where are Morris and Peter Lake?) For all of these lakes there is also the option of selecting diffusive and storage flux data only and make a corresponding star. (c) When discussion data including ebullition (triangles) it could be mentioned that ebullition should not be taken as long term averages but rather as an indication of its potential contribution on top of diffusive flux and storage, since ebullition is highly variable over time but was based on short term measurements. (d) I wonder if the stars that seems to correspond to the areas of Swedish lakes Mårn and Lillsjön should not be at a level of 139 - now they look like being below 100. (e) Is Crystal Lake from Michmerhuisen & Striegl 1996 included among the stars? If so it would be fair to mention the original reference as for Fallon.

Answer: We will have only one estimate in the figure. The values compared in the figure are from the Table 1 in Bastviken et al. (2005). Precise references to the table and also to the other original works are now added to the caption. Moreover, the mistakes in values have been corrected.

Responses to the comments of referee 2



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Why not to extrapolate the results from 207 lakes and present an estimate of total CH4 efflux from the lakes of the boreal area, or a global estimate for all freshwater lakes by applying a recent estimate of the number and area of lakes on the Earth presented by Downing et al. (2006)? Several authors have presented such estimates with much lower number of lakes studied. The authors conclude that "In the absence of more accurate data, lake area from remote surveys could be used as an approximation for the CH4 emissions in boreal and arctic landscapes with similar glacial history" (page 3478, lines 24-26). Thus, I suggest that this conclusion could be applied in this paper. Somebody else is certainly soon keen to do such "a new global estimate" applying the results of this profound study, please do it by yourself.

Answer: We will compile the estimates.

Some remarks:The timing of the sampling was planned to cover the most critical periods (late winter, after thaw in May-June, late summer, October) for water column stratification and mixing, and, thus, for the gas exchange between lake surface and the atmosphere. The extensive sampling during two years and four times per year and lake has certainly, for an unknown extent, contributed to the wide variation observed in the dataset, which cannot in practice be avoided in this kind of study. The timing of turnover periods may vary for several weeks in lakes close to each other; this is influenced by water quality (colour) and morphometry of the lakes and the surrounding catchment. E.g. the observations of the largest methane storage in spring in 6.3% and in autumn 8.7% of the lakes (page 3468, line 11) may be related to sampling before the complete mixing, or that the lakes are meromictic (less probable). Annual variation in weather conditions may also remarkably impact stratification of the water masses as well as variation in precipitation may influence on the availability of the substrates for methanogens producing methane. In some cases rather modest, although significant, relationship found between CH4 concentration and some other variables found in tables 4-7, may have had influenced by the sampling frequency. Was there more intensively sampled data of CH4 from any of these lakes? And if there were, could the



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impact of sampling frequency on the annual flux be compared with that obtained by four times/yr sampled data.

Answer: We cannot do much with this uncertainty, but we are going to give more results about the storages as referee 1 suggested. At least this will reveal better the sampling situations regarding CH4. We think that we are not able to compare detailed lake data with these measurements.

Page 3478, lines 1-3, Table 7: "Both the regression analyses and lake type comparisons indicate increasing CH4 emissions with decreasing depth, increasing total phosphorus concentration and decreasing lake area." However, Table 7 shows that the relationship was negative to totP and positive to area. Table 4 shows that in some lake types CH4 concentration was positively related to totP, but negatively to O2, depth and area. How to explain this discrepancy?

Answer: Table 7. Column headings Ptot and Area changed place and this mistake has been corrected. The table should show negative relationship to Area and positive relationship to Ptot.

Table 4 second last line: parameter value for depth is missing.

Answer: This is corrected.

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Interactive comment on Biogeosciences Discuss., 5, 3457, 2008.