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Peer Review File

Higher but more variable annual CO2 emissions from lakes in drier Arctic landscapes

Corresponding Author: Dr Vaclava Hazukova

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Dr Hazukova,

Your manuscript titled "Highly Variable Annual Lake CO2 Emissions in Drier Arctic Regions Compared to Wetter Regions" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Comment on COMMSENV-25-5020
Title: Highly variable annual lake CO_2 emissions in drier Arctic landscapes compared to wetter regions

Hydrological connectivity is a key but underexplored factor controlling catchment carbon inputs and lake water residence times in Arctic permafrost regions, which in turn affect lake CO_2 emissions. It is often assumed that hydrologically well-connected lakes in wetter regions are higher CO_2 sources, fueled by stronger lateral fluxes of external carbon relative to drier regions. In this study, the authors integrated annual CO_2 emission data from over 200 Arctic lakes and, unexpectedly, found that lakes in drier regions can exhibit overall higher CO_2 emissions than those in wetter regions, despite also showing lower minimum values. They further compiled catchment attributes, lake morphometry, and water chemistry data to qualitatively describe potential regulatory mechanisms and presented an excellent conceptual framework illustrating the contrasting emission patterns and dominant controls in dryland versus wetter-region lakes. The study provides a novel mechanistic framework linking terrestrial inputs, hydrological connectivity, and internal lake dynamics, highlighting dryland lakes as “reactors” of carbon transformation. The manuscript is well-written, thoroughly discussed, and highly relevant for understanding Arctic carbon–climate feedbacks from aquatic ecosystems considering their high sensitivity to intensifying climate change. Overall, it represents an important and innovative contribution to Arctic lake biogeochemistry and is suitable for publication after minor revisions addressing a few methodological clarifications and discussion points:

Major comments:
1. One of the central questions in this manuscript is why lakes in drier Arctic permafrost regions show generally higher CO_2 emissions than those in wetter regions, and I suggest adding a brief mechanistic statement in the Abstract to reflect this more explicitly. While the discussion focuses mainly on seasonal hydrological pulses, another potentially relevant factor is that soils in drier watersheds may contain higher OC stocks. It would be helpful for the authors to clarify why wetter Arctic watersheds would have lower soil OC (this opposites to the typical pattern that greater precipitation enhances vegetation development and soil OC contents), as this is not directly concluded in Mishra et al. (2021), and to briefly consider whether higher soil OC in drier regions could also contribute to generally higher lake CO_2 emissions, even if dryland lakes show higher $SUVA_{254}$ and stronger autochthonous or photodegraded signatures. Incorporating this clarification would strengthen the mechanistic interpretation and improve coherence.
2. The authors use summertime watershed water balance (precipitation minus potential evapotranspiration, P–PET) as a proxy for potential lateral transport of carbon from terrestrial to aquatic systems. However, do the permafrost area, permafrost types, and air temperature differ across these lake catchments? For example, lower-elevation arid permafrost regions may experience stronger thaw-induced subsurface runoff (Fig. 3A), potentially transporting generally higher carbon inputs into lakes, yet such process may not be captured by the P-PET proxy. It would be helpful if the authors could clarify whether these catchment-level differences were considered or include a brief discussion in the manuscript.
3. What are the buffering conditions of these ~200 lakes? In arid lakes, evaporative concentration may result in higher carbonate and bicarbonate levels than in humid lakes, which could promote carbonate precipitation and CO_2 release during summer photosynthesis by algae or aquatic plants. Alternatively, if arid lakes have substantially lower buffering capacity than humid lakes, their ability to dampen CO_2 fluctuations may be weaker, leading to greater CO_2 variability. It may therefore be useful to present pH and alkalinity (if available) for humid versus arid lakes in the manuscript or supplementary material and briefly discuss in the manuscript how inorganic carbon cycling may contribute to generally higher CO_2 emissions in arid lakes.

Minor comments:
1. Line 19: Please change the abbreviation ‘C’ to the full term ‘carbon’ in the abstract.
2. In Figure 1, please include the latitude information for the southernmost extent of the map to improve geographic readability and allow readers to better contextualize the spatial coverage.
3. Line 188-235: Several statistical terms and symbols (e.g. $F_{2,204}$和F_2, H_3, W, β, $F_{1,92}$, $F_{1,101}$, $F_{1,89}$) are not defined. Please provide more clarifications either within the Methods section or in the supplementary materials.
4. The manuscript refers to ‘Seasonal water (%)’ but does not provide a definition. Please clarify how this variable is calculated.

Reviewer #2 (Remarks to the Author):

How lake CO_2 emissions vary spatially and temporally in pan Arctic remain poorly understood. The authors explored the spatial pattern of CO_2 emissions from 220 lakes in Arctic region focusing on the driver of hydrological connectivity that is controlled by different factors such as hydroclimate, the presence of wetlands, topography, and seasonal water storage of a catchment. Results suggest hydrologic connectivity could largely explain the spatial variability of lake CO_2 emissions between drier and wetter regions, as well as between catchments with and without wetlands. In general, the topic is very interesting. However, it is not well written and several major limitations need to be solved before considering it for publication.
Firstly, the aims and objectives of this study are not clear and consistent especially in the sections of Abstract, Discussion and Implication. For instance, what would the results “high lake CO_2 emissions and its large variability in drier regions, as well as large amounts of lakes that are water-limited in summer” imply in the future under increasing precipitation? Why would hydrologic connectivity be important for lake CO_2 emissions in Arctic? Anything special compared to other regions, e.g., temperate and tropic?
Secondly, hydrological connectivity is not clearly defined/explained. For instance, how lakes are connected to stream networks, e.g., adjacent to headwater streams or downstream stream? How far are wetlands from lakes? Without these indicators, it is hard to understand how hydrological connectivity would influence lake CO_2 emissions? Currently, the authors only simply used aridity metric, that is, either dry or wet region, to indicate the high/low hydrological connectivity. In my opinion, hydroclimate rather than hydrological connectivity would be a more appropriate word.
Thirdly, how the lake CO_2 emission were quantified/measured are not explained. Lake CO_2 emission could be modelled using wind speed, lake surface area, temperature, and partial pressure of CO_2 in lake water. Any measurements of these parameters? Why didn’t authors investigate these factors when exploring the spatial heterogeneity of lake CO_2 emissions? What about the factor of “permafrost” such as active layer thickness? Corresponding data is available to download online (e.g., https://apgc.awi.de/dataset/permafrost-cci-alt-north-hemisphere-v4-1997-2021).
Lastly, the authors selected lakes with available seasonal measurements of CO_2 emissions. Can the authors investigate the seasonal cycle of lake CO_2 emissions and its drivers between dry and wet regions? Seasonal water storage and its correlation to lake CO_2 emissions, studied in the current manuscript, would not explicitly explain the seasonality of lake CO_2 emissions.

Minor comments:
1. Please explain the abbreviations such as F2, H3, W, F2204, etc., in the Result section.
2. Line 200: "… only explained 29% of the variation", any result to support this? How to assess/accept this "low" explanation power?
3. Why there is no difference in DOC concentration between lakes with and without wetlands in drier regions?
4. Can the authors provide the result of CO_2 flux vs P-PET? It will be more straight forward to see the changes of lake CO_2 emission over different hydroclimate condition.
5. Line 304: "in lakes with no fluvial export, … recycled with temporal delay.." what does "temporal delay" mean?
6. Line 366-367: "we did not find any differences in the magnitude of CO_2 emissions across permafrost zones". Where to see this?
7. Line 372-373: How to understand the lower magnitude of lake CO_2 emissions of Swedish lakes with permafrost compared to that of Russian lowlands in terms of hydroclimate and topographic setting?
8. In the section "seasonal variability of carbon dynamics in high-latitude regions", the discussions of storage capacity and carbon sourcing capacity seem irrelevant to the topic of this section.
9. Section "lakes in drier regions as hotspots of carbon transformation and accumulation", how to understand this "hotspot"?

Reviewer #3 (Remarks to the Author):

Summary
This is a very detailed and interesting study in pan-arctic lake CO_2 emissions showing that lakes in drier regions lakes have higher, but variable flux. Data are collated from multiple sources, expanding the impact and pan-Arctic relevance. The results are contrary to the hypothesis that lakes in wetter regions would have increased CO_2 flux due to increased lateral flow. The articles was clearly written and I genuinely enjoyed reading it and thinking about how my study systems fit into this paradigm.

Edits/comments
Line 96 etc: It is not clear how the "ice-break up period" of 14 days was justified. I tried to see if that was from the Karlsson reference but could not easily find it there. If this is just a approximation – then some sort of error term might be justified.

Fig. 1: The author used 3 different time periods in discussion and presentation of P-PET trends. Water balance over a 30 year period (1994-2023) was used to classify arid vs wet landscapes (Fig 1a). And then Fig 1b compares mean P-PET over the last decade (2014-2023) with historical average (1960-2013) (Fig 2). These periods could be justified or standardized.

Line 159: I think the colon between lateral fluxes and aridity metric could be changed to something like "including". I spent a minute trying to understand what a "lateral flux: aridity metric" could be! Also – if the aridity metric is P-PET, I would suggest just writing that. The term aridity metric is only used ~1x, in addition to metric of aridity (1x).

Line 161-3: … we explored EXPLORED(written 2x)… correlations between CV and ??? (this whole sentence is somewhat unclear)

Line 186-7: are values per catchment shown graphically or just written in text.

Line 199: was the P-PET used in the models from the same year CO_2 was measured or was it from the long-term averages. Could the results differ?

Line 203-205: it is not clear where I should be looking to help understand/see this statement: "While lower aridity led to…". Figure S1? I think this could be more clearly explained.
Line 224: wetlands (plural)? Or wetland influences.

Line 292: "Here, lakes in wetter regions also tend to be located at higher elevations and in topographically more rugged landscapes". Perhaps this identifies a need for further work on lakes in lower elevations in these wetter regions.

Line 334: "When comparing watersheds of similar storage capacity…" and slope?

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Version 1:

Decision Letter:

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Dear Dr Hazukova,

Your manuscript titled "Higher but more variable annual CO_2 emissions from lakes in drier Arctic landscapes" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Nicola Colombo, PhD

Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have provided a thorough revision of the manuscript that adequately addresses the concerns I raised. I appreciate the more forthright acknowledgement of uncertainties and the expanded and clarified discussion throughout. I feel that the manuscript is now suitable for publication and will provide an interesting and relevant contribution to the literature on this topic.

Reviewer #2 (Remarks to the Author):

Good job and nice rebuttal. It reads great.

Reviewer #3 (Remarks to the Author):

This is a very detailed and interesting study in pan-arctic lake CO_2 emissions showing that lakes in drier regions lakes have higher, but variable flux. It is based on an impressive dataset and the paper itself is very well written, clear, and enjoyable to read. This work represents a significant contribution to the field. All of my concerns were addressed by revision.

Response to reviewers

Higher but more variable annual CO_2 emissions from lakes in drier Arctic landscapes (manuscript ID: COMMSENV-25-5020)

We would like to thank all the reviewers for their constructive, thoughtful comments, and their efforts to improve the manuscript. Below, we provide point-by-point responses to all the comments of the reviewers. Reviewers' comments are highlighted in bold, our responses are in regular font, and excerpts from the amended manuscript are in italics.

Reviewer #1

Hydrological connectivity is a key but underexplored factor controlling catchment carbon inputs and lake water residence times in Arctic permafrost regions, which in turn affect lake CO2 emissions. It is often assumed that hydrologically well-connected lakes in wetter regions are higher CO2 sources, fueled by stronger lateral fluxes of external carbon relative to drier regions. In this study, the authors integrated annual CO2 emission data from over 200 Arctic lakes and, unexpectedly, found that lakes in drier regions can exhibit overall higher CO2 emissions than those in wetter regions, despite also showing lower minimum values. They further compiled catchment attributes, lake morphometry, and water chemistry data to qualitatively describe potential regulatory mechanisms and presented an excellent conceptual framework illustrating the contrasting emission patterns and dominant controls in dryland versus wetter-region lakes. The study provides a novel mechanistic framework linking terrestrial inputs, hydrological connectivity, and internal lake dynamics, highlighting dryland lakes as "reactors" of carbon transformation. The manuscript is well-written, thoroughly discussed, and highly relevant for understanding Arctic carbon–climate feedbacks from aquatic ecosystems considering their high sensitivity to intensifying climate change. Overall, it represents an important and innovative contribution to Arctic lake biogeochemistry and is suitable for publication after minor revisions addressing a few methodological clarifications and discussion points:

Major comments:

1. One of the central questions in this manuscript is why lakes in drier Arctic permafrost regions show generally higher CO2 emissions than those in wetter regions, and I suggest adding a brief mechanistic statement in the Abstract to reflect this more explicitly.

According to the reviewer's suggestion, we have replaced the last section of the abstract with a statement that more explicitly states the suggested mechanism behind the observed pattern in CO2 emissions.

The abstract now reads as follows:

"Land-to-water hydrological connections represent a key regulatory mechanism of carbon transport, controlling carbon dioxide (CO2) emissions from lakes; however, as of yet, there is no assessment of its role at a pan-Arctic scale across large climatic and topographical gradients. We hypothesized that hydrologically well-connected lakes in wetter regions are CO2 sources fueled by stronger lateral fluxes of external carbon relative to drier regions. However, based on data from >200 Arctic lakes, we found that lakes in drier regions have higher and more variable annual CO2 emissions (37.0[146.0, 6.2] gC m-2 yr-1, median [Q3,Q1]) compared to lakes in wetter regions (8.0[17.3, 1.7] gC m-2 yr-1), with both the lowest and the highest fluxes recorded among dryland lakes. We hypothesize that with increasing wetness, the relative proportion of fluvial emissions increases, whereas in drier landscapes where lakes often have limited fluvial export, carbon inputs can be retained and more efficiently emitted from lakes."

We also slightly amended the title for clarity:
"Higher but more variable annual CO2 emissions from lakes in drier Arctic landscapes"

2. While the discussion focuses mainly on seasonal hydrological pulses, another potentially relevant factor is that soils in drier watersheds may contain higher OC stocks. It would

be helpful for the authors to clarify why wetter Arctic watersheds would have lower soil OC (this opposites to the typical pattern that greater precipitation enhances vegetation development and soil OC contents), as this is not directly concluded in Mishra et al. (2021), and to briefly consider whether higher soil OC in drier regions could also contribute to generally higher lake CO2 emissions, even if dryland lakes show higher SUVA254 and stronger autochthonous or photodegraded signatures. Incorporating this clarification would strengthen the mechanistic interpretation and improve coherence.

Thank you for the suggestion, we have now further developed sections of the discussion where we clarify how the interactions between hydrology and topography might affect soil development and accumulation of soil OC stock. We also expand the treatment of how responses of permafrost soils to hydrological pulses might differ given antecedent conditions and active layer development.

In our dataset, we show that in wetter regions, catchments tend to be steeper and located at higher elevations. We also show that soil organic carbon stocks tend to be lower, likely due to the topographical controls that lead to thinner soil developments that is further aided by higher precipitation that contributes to soil erosion and flushing. Soil OC data layers are spatially coarser but, in our dataset, soil OC stocks are well correlated with slope for (r = 0.51)

that has been derived from 2m-DEMs and likely provides a higher-resolution surrogate for OC considering the underlying control of topography on soil development. However, since the purpose of our manuscript was not to elucidate spatial patterns of soil OC stocks, we build our discussion on the findings of Mishra et al. (2021) that shows that flat areas in the circumpolar regions have the highest stocks while stocks were lowest at higher elevations. They also show non-linear shifts in predicted OC stocks along precipitation gradient with the highest in stocks in regions that get between 200 - 600 mm of precipitation per year but OC stocks decrease substantially as precipitation increases above 600 mm per year. They suggest that this is likely due to direct effects of precipitation but also its interactions with topography as it influences erosion and deposition patterns. Instead of the vegetation growth, high SOC stocks in the northern likely result from interaction between low temperatures, peat formation, and also accumulation of eolian and alluvial sediments in flatter areas.

We expanded discussion and created a separate section to discuss the role of OC stocks (lines 362-418).

"Spatially and temporally heterogeneous pulses of external C can be substantial—especially after rewetting of dry soils that in the arid regions tend to have higher OC stocks (Fig. 2), and likely further contribute to large across-lake differences in annual CO_2 emissions observed across the arid Arctic regions (Gómez-Gener et al., 2020; Koch et al., 2022; Tiwari et al., 2022)."

"Therefore, we could expect the effect of hydrological and C inputs to differ across hydroclimate categories but also among watersheds owing to variability in storage capacity due to differences in (micro)topography, active layer thickness, and soil properties (McDonnell et al., 2021; Spence & Woo, 2003). While the active layer thickness did not vary across regions, soils may respond differently to hydrological events on a seasonal scale (Magnusson et al., 2022; 2024). Heavy rain can decrease active layer thickness in maritime areas whereas the effect on soils in more continental Arctic regions tends to be warming and deepens the active layer (Hamm et al., 2023). These differing responses of soils to precipitation can also contribute to the high variability in C fluxes in arid regions where soil OC content tends to be higher (Fig. 3) and deepening of the active layer can affect DOC export differently (Striegl et al., 2005; Tank et al., 2018)."

"Variability in watershed OC stocks across regions

While hydrological mechanisms shape the magnitude and variability of emissions from high-latitude lakes, watershed C sourcing capacity also plays a critical role. Soils are typically thinner and have lower OC content in wetter, high-gradient watersheds compared to drier regions where flatter topography enhances soil accumulation (Fig. 3, Mishra et al., 2021). Across the circumpolar regions, the highest OC stocks are located in flat regions with moderate precipitation regime (200 - 600 mm per year) and decrease substantially as precipitation increases above that threshold (Mishra et al., 2021). Patterns in soil OC stocks in the northern regions are likely shaped by interactions between climate and topography that together affect soil erosion, the potential for peat formation, and accumulation of sediments (Tarnocai et al., 2009; Mishra et al., 2021).

While OC content tends to be higher in arid catchments, the availability of leachable C and export is further spatially and temporally heterogeneous due to differences in active layer depths, soil types, and potential for thermokarst activity that will modulate surface and subsurface flowpaths (Koch et al., 2022; Olefeldt et al., 2016; Tank et al., 2020). We did not find any differences in the magnitude of CO2 emissions across permafrost zones nor along the gradient of active layer thickness (Fig. S4), possibly due to the coarse resolution of the data layers relative to the *studied catchments. Here, the highest regional annual CO2 emissions were observed among lakes in Russian Lowlands (Fig. 2B), where peatlands and thermokarst processes amplify C mobilization and transformation (Serikova et al., 2019; Zabelina et al., 2021). However, the potential for high C inputs alone does not explain the observed differences in CO2 emissions; for example, emissions from Swedish lakes affected by peatlands are an order of magnitude lower. Northern Scandinavia receives ~2x as much precipitation and has more rugged topography that would enhance flushing of lakes relative to the flatter Russian Lowlands, further emphasizing the importance of hydroclimatic and topographic setting (Fig. 2, 3).“*

3. The authors use summertime watershed water balance (precipitation minus potential evapotranspiration, P–PET) as a proxy for potential lateral transport of carbon from terrestrial to aquatic systems. However, do the permafrost area, permafrost types, and air temperature differ across these lake catchments? For example, lower-elevation arid permafrost regions may experience stronger thaw-induced subsurface runoff (Fig. 3A), potentially transporting generally higher carbon inputs into lakes, yet such process may not be captured by the P-PET proxy. It would be helpful if the authors could clarify whether these catchment-level differences were considered or include a brief discussion in the manuscript.

We initially collated the type of permafrost and ice content for each catchment and now, upon suggestion of reviewer 2, we also include a brief discussion of active layer thickness. Somewhat surprisingly, the type of permafrost ($p = 0.26$), ice content ($p = 0.11$), nor the active layer thickness ($p = 0.26$) did not have an apparent effect on CO2 fluxes across the studied catchments. However, that could also be due to the relatively coarse resolution of these various spatial layers relative to the catchment data. Most lakes included in this study are located in areas of dis-/continuous permafrost with low ice content. The active layer thickness spanned from 0.08 to 2.2 m and there was no clear relationship with CO2 fluxes. Active layer thickness is also not significantly different between drier and wetter regions ($W = 2842$, $p = 0.08$), with higher variability in wetter regions.

In terms of air temperatures, there are significant differences across regions (air temperature differences are somewhat reflected in potential evapotranspiration that is included in P-PET that we use here), with average annual air temperatures being -5.1ºC and -2.6ºC in arid and wetter regions ($W = 2212$, $p < 0.001$), respectively. Summertime temperatures are higher in arid regions (13.3ºC) compared to wetter regions (9.1ºC), but wintertime temperatures are lower in arid (-22.3ºC) compared to wetter regions (-12.6ºC) suggesting differences in air temperature seasonality. We also then calculated Conrad’s continentality index to compare climate along maritime-continental gradient. Arid regions are more continental (CCI = ~50) and wetter regions have much more maritime climate (CCI = ~20) ($W = 11675$, $p < 0.001$). We added a figure of the CCI and active thaw layer to the supplement and expand discussion, mainly here:

Added in Results (lines 103-106, 132-140):

‘There were no differences in the magnitude, nor variability of CO_2 emissions across permafrost zones ($F_{2,217} = 1.3$, $p = 0.27$; $F_{2,217} = 1.8$, $p = 0.17$), with changing ice content ($F_{2,217} = 2.21$, $p = 0.11$), nor along the gradient of active layer thickness ($R_2 = 0.0$, $F_{1,171} = 1.3$, $p = 0.26$; Fig. S4).’

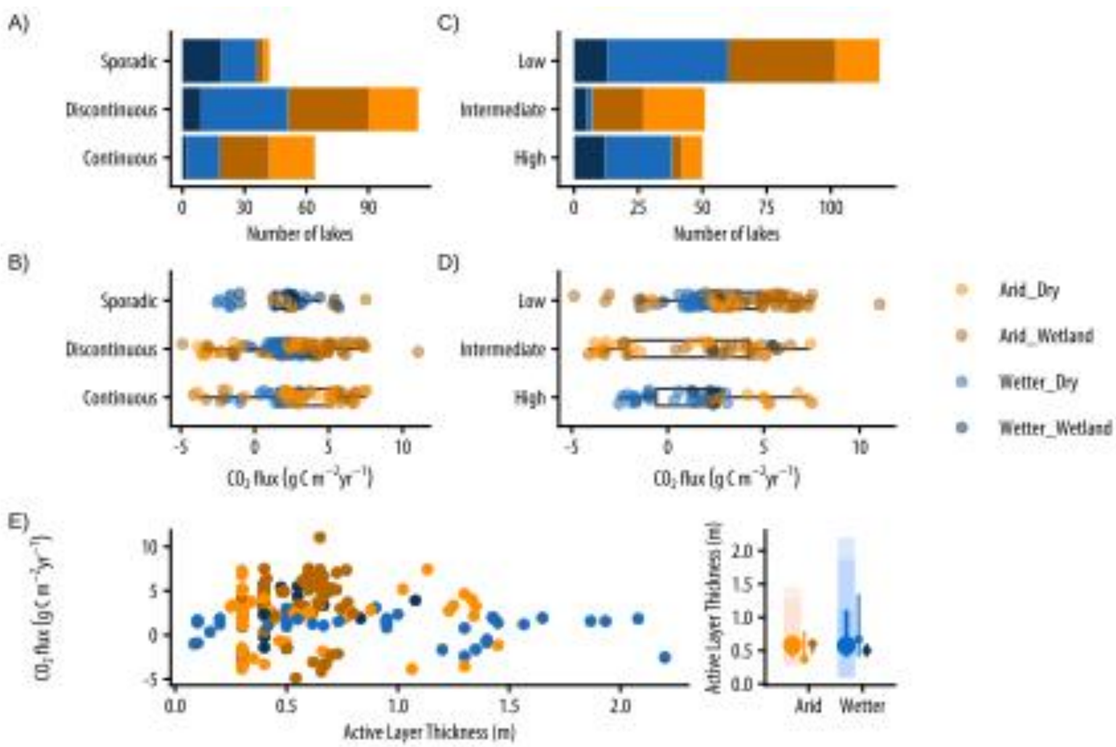
‘Lakes in wetter regions experience more seasonally stable, maritime climate ($t = 20.6$, $p < 0.001$, Fig. S8), were located at higher elevations ($W = 942$, $p < 0.001$), and in topographically more rugged landscapes with steeper watersheds ($W = 2148$, $p < 0.001$; Fig. 3), higher WA:LA ($W = 4358$, $p < 0.001$, Fig. 3), lower soil OC content ($W = 7684$, $p < 0.001$; Fig. 3), but active layer thickness was similar across regions ($W = 2842$, $p = 0.08$, Fig. S3).’

Added in Discussion (lines 284-294, 296-319):

Even though the active layer thickness did not vary across regions (Fig. S4), soils may respond differently to hydrological events on a seasonal scale depending on historical and antecedent hydroclimate conditions (Magnusson et al., 2022; 2024 More continental, drier regions tend to experience larger annual temperature amplitude with warmer summers and cooler winters, whereas wetter regions have on average more maritime, seasonally more stable, climate (Fig. S8). Precipitation can cool subsoils and slow deepening of the frost table in maritime, wetter, areas, while the soils in more continental Arctic regions tend to respond by increasing soil temperature and the rate of thaw (Hamm et al., 2023). Deepening of the active layer can affect DOC export differently (Striegl et al., 2005; Tank *et al., 2018); these processes can further contribute to the high variability of lake C fluxes, especially where soil OC content is high (Fig. 3).*

While hydrological mechanisms shape the magnitude and variability of emissions from high-latitude lakes, watershed C sourcing capacity also plays a critical role. Soils are typically thinner and have lower OC content in wetter, high-gradient watersheds compared to drier and flatter regions where topography enhances soil accumulation (Fig. 3, Mishra et al., 2021). While OC content tends to be higher in arid catchments, the availability of leachable C and export are further spatially and temporally heterogeneous due to differences in active layer depths, soil types, and potential for thermokarst activity that will modulate surface and subsurface flowpaths (Koch et al., 2022; Olefeldt et al., 2016; Tank et al., 2020). However, we did not find any differences in the magnitude of CO_2 emissions across permafrost zones nor along the gradient of active layer thickness (Fig. S4), possibly due to the coarse resolution of the data layers relative to the studied catchments.

We also now include figure below in the Supplementary material. It shows distribution of lakes and CO2 fluxes across different permafrost contexts and also along the gradient of active layer thickness.



4. What are the buffering conditions of these ~200 lakes? In arid lakes, evaporative concentration may result in higher carbonate and bicarbonate levels than in humid lakes, which could promote carbonate precipitation and CO2 release during summer photosynthesis by algae or aquatic plants. Alternatively, if arid lakes have substantially lower buffering capacity than humid lakes, their ability to dampen CO2 fluctuations may be weaker, leading to greater CO2 variability. It may therefore be useful to present pH and alkalinity (if available) for humid versus arid lakes in the manuscript or supplementary material and briefly discuss in the manuscript how inorganic carbon cycling may contribute to generally higher CO2 emissions in arid lakes.

Unfortunately, we only have pH measurement for ~1/3 of the lakes and we do not have available measurements of alkalinity. From the pH measurements, we can see that pH is slightly lower in wetter regions (pH = 7.2+-0.8) compared to arid regions (7.5+-1.0, W = 1034, p = 0.03); but this difference is mostly driven by the more acidic pH in wetter catchments with wetlands (6.0+-0.8).

We expanded discussion section focused on calcite precipitation in the discussion as follows (lines 376-387):

"However, even productive lakes can be net CO2 sources if catchment-derived or internally produced (i.e., calcite precipitation) DIC exceeds autotrophic consumption (Bogard & del Giorgio, 2016; Weyhenmeyer et al., 2015). Intense primary production at sites with extensive macrophyte beds may be associated with elevated pH and calcite precipitation converting bicarbonates into calcite and CO2. Calcite precipitation in particular can lead to substantial net contribution to annual CO2 emissions and reduce seasonal differences due to CO2 drawdown associated with high primary production (Many et al., 2024). Among lakes in drier regions where evaporative concentration can elevate alkalinity, calcite precipitation can play an outsized role (Anderson et al., 2001; Li et al., 2025). Here, sparse pH measurements (available for ~1/3 of the lakes) suggest that most lakes have circumneutral pH (Fig. S8), but it is possible that differences in internal inorganic C cycling contribute to the observed variability across sites and enhance annual emissions in more alkaline systems (Many et al., 2024)."

Minor comments:

1. Line 19: Please change the abbreviation 'C' to the full term 'carbon' in the abstract.

Done!

2. In Figure 1, please include the latitude information for the southernmost extent of the map to improve geographic readability and allow readers to better contextualize the spatial coverage.

Done!

3. Line 188-235: Several statistical terms and symbols (e.g. F2,204和F2, H3, W, β, F1,92, F1,101, F1,89) are not defined. Please provide more clarifications either within the Methods section or in the supplementary materials.

We have added additional information in the method section clarifying which test statistics are being reported for different analyses.

The relevant methods sections now read as:

'We compared distributions of annual CO_2 flux estimates between lakes in drier and wetter regions and differences in lake catchments properties using Wilcoxon rank-sum (reported with test statistic W); Kruskal-Wallis test (reported with test statistic H) and ANOVA (reported with F statistic) were used to test interactions between catchment aridity and wetland classes as appropriate….."

"We used generalized least squares (GLS) models and quantile regression to model annual CO_2 fluxes using a combination of variables that characterize the potential for lateral fluxes: P-PET, catchment topography, land cover, and lake morphometry. We report effect sizes of explanatory variables with a scaled β coefficient."

4. The manuscript refers to 'Seasonal water (%)' but does not provide a definition. Please clarify how this variable is calculated.

We now provide clarification in the methods section. The sentence now reads as follows:

"To estimate seasonal variability in water surface coverage (hereafter called 'Seasonal water (%)), we extracted seasonality data layers from Global Surface Water as available and determined the proportion of each catchment that does not represent permanent water during unfrozen periods (Pekel et al., 2016)."

Reviewer #2 (Remarks to the Author):

How lake CO2 emissions vary spatially and temporally in pan Arctic remain poorly understood. The authors explored the spatial pattern of CO2 emissions from 220 lakes in Arctic region focusing on the driver of hydrological connectivity that is controlled by different factors such as hydroclimate, the presence of wetlands, topography, and seasonal water storage of a catchment. Results suggest hydrologic connectivity could largely explain the spatial variability of lake CO2 emissions between drier and wetter regions, as well as between catchments with and without wetlands. In general, the topic is very interesting. However, it is not well written and several major limitations need to be solved before considering it for publication.

Major comments:

1. Firstly, the aims and objectives of this study are not clear and consistent especially in the sections of Abstract, Discussion and Implication. For instance, what would the results "high lake CO2 emissions and its large variability in drier regions, as well as large amounts of lakes that are water-limited in summer" imply in the future under increasing precipitation? Why would hydrologic connectivity be important for lake CO2 emissions in Arctic? Anything special compared to other regions, e.g., temperate and tropic?

Thank you for pointing out the inconsistencies in our manuscript. We changed the abstract (also in line with suggestions of reviewer 1), added clarifications in the introduction, and added an opening paragraph to the Implication section. With regards to the motivation of 'why Arctic', in the Introduction section, we highlight that Arctic is both lake and carbon rich and that amplified climate change is altering the aquatic-terrestrial linkages.

The abstract now reads as follows:

"Land-to-water hydrological connections represent a key regulatory mechanism of carbon transport, controlling carbon dioxide (CO_2) emissions from lakes; however, as of yet, there is no assessment of its role at a pan-Arctic scale across large climatic and topographical gradients. We hypothesized that hydrologically well-connected lakes in wetter regions are CO_2 sources fueled by stronger lateral fluxes of external carbon relative to drier regions. However, based on data from >200 Arctic lakes, we found that lakes in drier regions have higher and highly variable annual CO_2 emissions ($37.0_{146.0}^{6.2}$ gC m^{-2} yr^{-1}, $median_{Q3}^{Q1}$) compared to lakes in wetter regions ($8.0_{17.3}^{1.7}$ gC m^{-2} yr^{-1}), with both the lowest and the highest fluxes recorded among dryland lakes. We suggest that with increasing wetness, the relative proportion of fluvial emissions increases whereas in drier landscapes where lakes often have limited fluvial export, carbon inputs can be retained and more efficiently emitted from lakes."

We added an opening paragraph to the last section of the discussion (lines 388-412):

Given that ~60% of the northern permafrost regions are currently water-limited during summertime, have ~3x higher lake abundance compared to wetter parts of the Arctic, and also often higher soil OC stocks, better understanding of how changes in water balance and hydrological connectivity affect aquatic CO_2 emissions is crucial for future prediction of Arctic carbon cycle responses to climate. While precipitation is predicted to increase across many Arctic regions (McCrystall et al., 2021), so far, trends in summertime P-PET have been quite heterogeneous across different Arctic regions (Fig. 1B) and here we show that responses of lake CO_2 emissions to hydroclimate can vary substantially with catchment topography and lake properties.

We focused on patterns across space; however, the proposed hydrological mechanisms have been observed temporally within regions as well. For example, in southeast Norway, a historical record shows that higher precipitation led to reduced retention of C in lakes due to higher discharge despite its stimulating effect on lateral DOC fluxes (de Wit 2018); however, in West Greenland—a historically arid region, terrestrial inputs of C mobilized by an extreme precipitation event flipped lakes from summer sinks to sources of CO_2 (Saros et al., 2025). These examples suggest that lake C cycling responses will likely vary depending on historical hydroclimate, topography, and the capacity of watersheds to export C (D'Arcy & Carignan, 1997; Mishra et al., 2021). Further, continuing permafrost degradation can open new subsurface flowpaths, changing hydrological connectivity and ultimately affecting water and C budgets of lakes (Walvoord & Kurylyk, 2016). While it is clear that permafrost soils are responding to changing precipitation and increasing air temperatures, the resulting impact on soil C export is heterogeneous, even at relatively small scales (Hamm et al., 2023; Koch et al., 2022), and further research focusing on regions where hydroclimate and topography patterns are not linked (e.g., wet and flat regions) is needed."

2. Secondly, hydrological connectivity is not clearly defined/explained. For instance, how lakes are connected to stream networks, e.g., adjacent to headwater streams or downstream stream? How far are wetlands from lakes? Without these indicators, it is hard to understand how hydrological connectivity would influence lake CO2 emissions? Currently, the authors only simply used aridity metric, that is, either dry or wet region, to indicate the high/low hydrological connectivity. In my opinion, hydroclimate rather than hydrological connectivity would be a more appropriate word.

We acknowledge that there are many uses and differences in how different subdisciplines and researchers use the term hydrological connectivity. We use a broad, watershed-scale, definition of hydrological connectivity defined as 'water-mediated transfer of material to a lake from its catchment', consistent with the broader definitions assessed in the review by Bracken et al., 2013. We posit that it is a key regulatory mechanism of lateral C transfer between land and aquatic systems. As we now further clarify in the Introduction, we use P-PET to classify lakes since water availability will fundamentally constrain the potential for connectivity. We interpret our results in the context of topography and lake properties since they will further modulate lateral connections.

We have modelled stream networks during the process of watershed delineation but from our work in the regions and from published literature, we know that the flowpaths are often not hydrologically active at all or they are ephemeral, particularly in the dry areas; for example, vast majority of the lakes in West Greenland or Yukon Flats are closed-basin lakes. In comparison, all lakes in Scandinavia (wetter region) included in this study have outflows and often also inflows. Since P-PET reflects these differences quite well, we decided to use it for its simplicity and ease of implementation at a large scale. We hope however, that our study will provide a simple starting off point for more detailed, direct assessments in the future.

Since most of the discussion focusses on process-based understanding of the observed differences, we believe that the use of hydrological connectivity that implies a process shaped by interactions between hydroclimate, topography, and lakes is more useful than simply using hydroclimate.

We clarified the following sections throughout the manuscript:

"Hydrological connectivity (defined here broadly as water-mediated transfer of materials to a lake from its catchment) is a key regulatory mechanism of lateral carbon (C) transport between land and aquatic systems (Bracken et al., 2013); and hence, C processing across the land-water continuum (Tank et al., 2020)."

"We use a broad definition of hydrological connectivity at a watershed scale where the potential for water-mediated transport of land C to lakes is fundamentally constrained and characterized by hydroclimatic conditions and further modulated by watershed topographic properties (Tetzlaff et al., 2007; Bracken et al., 2013)."

"In drier Arctic regions where connections to stream networks are often limited or non-existent—due to hydrological, but among lakes in this study, also topographical (Woo, 2012, Fig. 3) and morphometric constraints (Seekell et al., 2021, Fig. 3), fluvial transport is presumably less important and lakes are more likely to be hotspots of C cycling at the catchment-scale as highlighted by higher CO_2 emissions per catchment area (Vachon et al., 2021, Fig. S3)."

3. Thirdly, how the lake CO2 emission were quantified/measured are not explained. Lake CO2 emission could be modelled using wind speed, lake surface area, temperature, and partial pressure of CO2 in lake water. Any measurements of these parameters? Why didn't authors investigate these factors when exploring the spatial heterogeneity of lake CO2 emissions?

In the results section we describe that we used the Cryosphere Inland Water Greenhouse Gases Database for the vast majority of the data and also included some additional data from Scandinavia and Greenland (references Karlsson et al, 2024; Verheijen et al., 2023; Saros et al., 2024). The methods for calculating or measuring fluxes have been described in the primary literature. Most of the fluxes were calculated from the parameters that the reviewer mentions above (with k based on either Cole and Caraco or Vachon and Prairie calculations) and some measurements were also done measured in flux chambers. We do not have access to the raw data (temperature, wind speed, etc.) that yielded those estimates. We highlight in the methods section that we excluded fluxes that were based on calculated CO2 concentrations. We also dedicate a now expanded paragraph in the Methods section to describe how the total annual fluxes were estimated.

The purpose of the GLS model is to capture the effect of hydrological connectivity as modulated by P-PET, land cover and other catchment properties such as slope, WALA, elevation, and lake size, not necessarily to create the best possible model that would include all possible predictors.

4. What about the factor of "permafrost" such as active layer thickness? Corresponding data is available to download online (e.g., https://apgc.awi.de/dataset/permafrost-cci-alt-north-hemisphere-v4-1997-2021).

Thank you for the suggestion and for providing a link to the data! We have now added a further commentary on ALT, permafrost types, and the effect of hydroclimate on these environmental variables and also included additional supplementary figures showing these relationships.

The active layer thickness ($p = 0.26$) did not have an apparent effect on CO2 fluxes across the studied catchments, nor did it vary significantly between drier and wetter regions ($W = 2842$, $p = 0.08$).

Added in Results (lines 103-106, 132-140):

'There were no differences in the magnitude, nor variability of CO_2 emissions across permafrost zones ($F_{2,217} = 1.3$, $p = 0.27$; $F_{2,217} = 1.8$, $p = 0.17$), with changing ice content ($F_{2,217} = 2.21$, $p = 0.11$), nor along the gradient of active layer thickness ($R_2 = 0.0$, $F_{1,171} = 1.3$, $p = 0.26$; Fig. S4).'

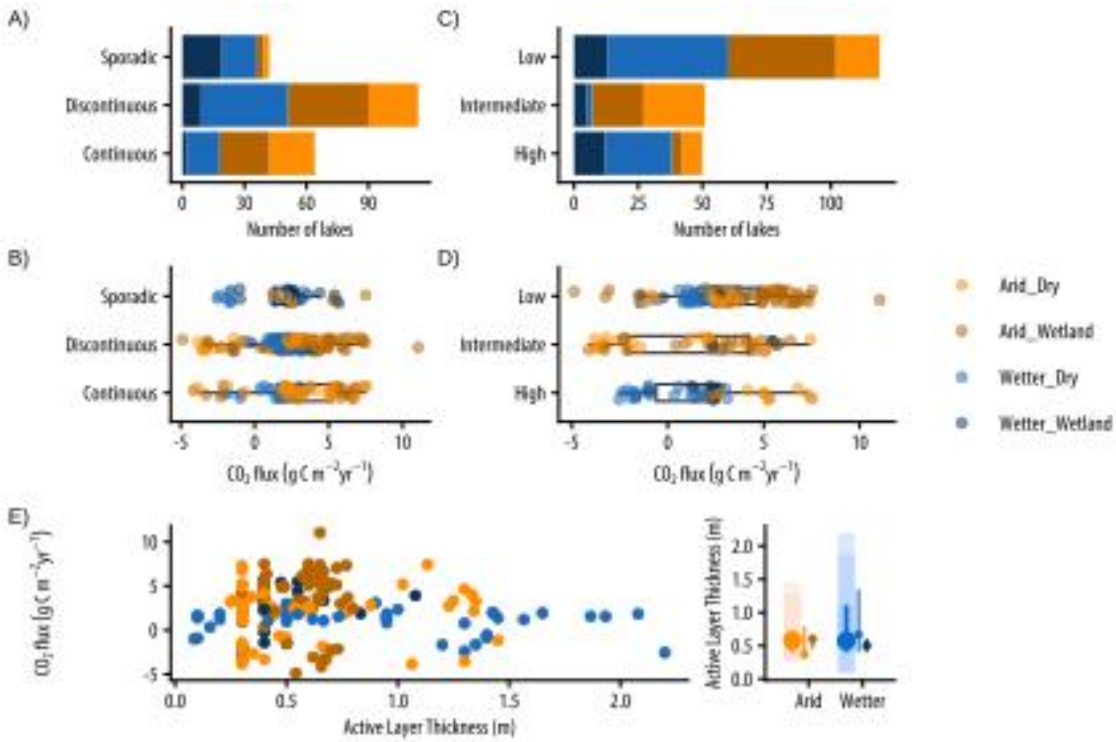
'Lakes in wetter regions experience more seasonally stable, maritime climate ($t = 20.6$, $p < 0.001$, Fig. S8), were located at higher elevations ($W = 942$, $p < 0.001$), and in topographically more rugged landscapes with steeper watersheds ($W = 2148$, $p < 0.001$; Fig. 3), higher WA:LA ($W = 4358$, $p < 0.001$, Fig. 3), lower soil OC content ($W = 7684$, $p < 0.001$; Fig. 3), but active layer thickness was similar across regions ($W = 2842$, $p = 0.08$, Fig. S3).'

Added in Discussion (lines 284-294, 296-319):

Even though the active layer thickness did not vary across regions (Fig. S4), soils may respond differently to hydrological events on a seasonal scale depending on historical and antecedent hydroclimate conditions (Magnusson et al., 2022; 2024 More continental, drier regions tend to experience larger annual temperature amplitude with warmer summers and cooler winters, whereas wetter regions have on average more maritime, seasonally more stable, climate (Fig. S8). Precipitation can cool subsoils and slow deepening of the frost table in maritime, wetter, areas, while the soils in more continental Arctic regions tend to respond by increasing soil temperature and the rate of thaw (Hamm et al., 2023). Deepening of the active layer can affect DOC export differently (Striegl et al., 2005; Tank et al., 2018); these processes can further contribute to the high variability of lake C fluxes, especially where soil OC content is high (Fig. 3).

While hydrological mechanisms shape the magnitude and variability of emissions from high-latitude lakes, watershed C sourcing capacity also plays a critical role. Soils are typically thinner and have lower OC content in wetter, high-gradient watersheds compared to drier and flatter regions where topography enhances soil accumulation (Fig. 3, Mishra et al., 2021). While OC content tends to be higher in arid catchments, the availability of leachable C and export are further spatially and temporally heterogeneous due to differences in active layer depths, soil types, and potential for thermokarst activity that will modulate surface and subsurface flowpaths (Koch et al., 2022; Olefeldt et al., 2016; Tank et al., 2020). However, we did not find any differences in the magnitude of CO_2 emissions across permafrost zones nor along the gradient of active layer thickness (Fig. S4), possibly due to the coarse resolution of the data layers relative to the studied catchments.

We also now include figure below in the Supplementary material. It shows distribution of lakes and CO2 fluxes across different permafrost contexts and also along the gradient of active layer thickness.



5. Lastly, the authors selected lakes with available seasonal measurements of CO2 emissions. Can the authors investigate the seasonal cycle of lake CO2 emissions and its drivers between dry and wet regions? Seasonal water storage and its correlation to lake CO2 emissions, studied in the current manuscript, would not explicitly explain the seasonality of lake CO2 emissions.

The main purpose of selecting lakes that have a seasonal record was to provide a more constrained, better, estimate of annual emissions, not to investigate seasonality of emissions specifically. For many lakes there are only ~ 3 measurements per year, and it would be quite challenging to try to seasonally standardize those measurements to properly characterize seasonal fluxes across such a large spatial gradient.

The reason we highlight the correlation between the proportion of seasonal water coverage in each watershed and variability of fluxes is that it provides some support to the idea that hydrological pulses increase variability of CO2 fluxes across the spatial gradient.

We clarify that further in the Methods section:

"Lakes in this dataset are located across Alaska, Siberian Lowlands, Northwest Territories and Nunavut in Canada, West Greenland, and Scandinavia—spanning gradients of precipitation, temperature, and ecotypes (Fig. 1A). We used the Cryosphere Inland Water Greenhouse Gases Database (Song et al., 2024) and added data from more recent publications and data releases (Karlsson et al., 2024; Saros et al., 2024; Verheijen et al., 2022). We included 220 lakes in northern permafrost regions above 60□N that have measurements of CO2 concentrations and fluxes taken multiple times (> 3x) over the course of the annual cycle, to allow for calculation of average annual estimates as there is increasing recognition that non-growing season emissions can lead to substantial contribution at an annual scale (Fig. 1A , Karlsson et al., 2024). Even though CO2 fluxes were measured in more lakes, we choose to limit our analyses only to lakes with available seasonal data which allowed us to better constrain annual fluxes. Similarly, sites where fluxes were estimated from concentrations calculated based on pH and alkalinity were excluded here.

Considering that ice-out fluxes can be very high, but short-lived, we weighted spring ice-out fluxes and the rest of the open-water measurements differently to avoid biasing annual average estimates. It has been estimated that CO2 accumulated over winter likely degases approximately during the first two weeks since ice-out (Karlsson et al. 2024). Theoretical water column equilibration times vary from depending on gas transfer velocity and lake depth *from less than a day to more than one month (Tab. S1, Fig. S1). Here, we multiplied daily flux estimates characterizing the period of ice-break 14 days and summer-autumn measurements were averaged and multiplied by the number of ice-free days minus the ice-break up period (14 days). We tested the effect of the timing of degassing from 3 days to 21 days on the resulting annual CO2 fluxes vary and then median differences are <±1.5%; however, if we simply averaged all seasonal fluxes, the estimates would increase by ~ 12%, likely artificially overestimating annual emissions (Fig. S2). Annual fluxes have been calculated as a sum of spring ice-out fluxes and average summer-autumn fluxes and the number of ice-free days has been implemented as in Song et al., 2024. When available, we also collated dissolved organic C (DOC) concentrations, specific ultraviolet absorption coefficient at 254 nm (SUVA254), and total phosphorus (TP) concentrations from publications and/or authors. Analysis of methane fluxes is outside of the scope of this study; however, we acknowledge that methane production in inland waters can be substantial, with differing drivers compared to CO2 fluxes (Song et al., 2024).”*

Minor comments:

1. Please explain the abbreviations such as F2, H3, W, F2204, etc., in the Result section.

We have added additional information in the method section clarifying which test statistics are being reported for different analyses.

The relevant methods sections now read as:

‘We compared distributions of annual CO_2 flux estimates between lakes in drier and wetter regions and differences in lake catchments properties using Wilcoxon rank-sum (reported with test statistic W); Kruskal-Wallis test (reported with test statistic H) and ANOVA (reported with F statistic) were used to test interactions between catchment aridity and wetland classes as appropriate…..”

“We used generalized least squares (GLS) models and quantile regression to model annual CO_2 fluxes using a combination of variables that characterize the potential for lateral fluxes: P-PET, catchment topography, land cover, and lake morphometry. We report effect sizes of explanatory variables with a scaled β coefficient.”

2. Line 200: “… only explained 29% of the variation”, any result to support this? How to assess/accept this “low” explanation power?

There was a missing reference to the supplementary material where we provide additional text regarding the modelling and a plot. The section now reads as follows:

“The best performing GLS model that included summertime P-PET, watershed characteristics (WA:LA, slope, %wetland), and lake size only explained 29% of the variation (Text S1, Fig. S1). Drier conditions ($\beta = -0.30$, $p = 0.09$, Fig. S1A), higher proportion of wetland cover ($\beta = 1.23$, $p < 0.001$, Fig. S1E) together with lower relief ($\beta = -0.13$, $p = 0.55$, Fig. S1D) of watersheds increased CO_2 emissions. While lower aridity led to higher emissions in the lower quartile, high aridity was linked to high emissions in the upper quartile (Fig. S1A). The effect of aridity was strongest in the lowest ($\tau < 0.2$, $p < 0.001$) and highest quantiles ($\tau > 0.7$, $p < 0.001$). On average, CO_2 emissions also increased with higher WA:LA ($\beta = 0.69$, $p < 0.001$, Fig. S1C) and smaller lake surface area ($\beta = -0.52$, $p = 0.006$, Fig. S1B).”

With regards to the relatively low predictive power, we discuss that it represents an issue for upscaling, but 1/3 of explained variability is not necessarily a bad performance for a model incorporating highly variable data across large spatial scales that has been collated from different sources. There is of course a lot of residual variability, but the relationships with selected variables certainly play a role that we cautiously discuss in the manuscript.

3. Why there is no difference in DOC concentration between lakes with and without wetlands in drier regions?

That is a good question, as we discuss, we believe—based on other research that focuses on lakes that are included in this study—that evapoconcentration plays a major role in keeping DOC concentrations high in lakes in drier areas. SUVA254 also suggests that the sources of DOC may be quite different between the two types of catchments in the drier regions. However, our study is not designed to answer this question in detail.

4. Can the authors provide the result of CO2 flux vs P-PET? It will be more straight forward to see the changes of lake CO2 emission over different hydroclimate condition.

Yes, it’s currently included as part of Figure S1 and it shows well how variability increases with P-PET. It is now being referred here:

"The best performing GLS model that included summertime P-PET, watershed characteristics (WA:LA, slope, %wetland), and lake size only explained 29% of the variation (Text S1, Fig. S1). Drier conditions (β = -0.30, p = 0.09, Fig. S1A), higher proportion of wetland cover (β = 1.23, p < 0.001, Fig. S1E) together with lower relief (β = -0.13, p = 0.55, Fig. S1D) of watersheds increased CO_2 emissions. While lower aridity led to higher emissions in the lower quartile, high aridity was linked to high emissions in the upper quartile (Fig. S1A). The effect of aridity was strongest in the lowest (τ < 0.2, p < 0.001) and highest quantiles (τ > 0.7, p < 0.001). On average, CO_2 emissions also increased with higher WA:LA (β = 0.69, p < 0.001, Fig. S1C) and smaller lake surface area (β = -0.52, p = 0.006, Fig. S1B)."

5. Line 304: "in lakes with no fluvial export, … recycled with temporal delay.." what does "temporal delay" mean?

We mostly think of higher residence times increasing the potential for in-lake processing of the external C subsidies. For example, post-depositional mineralization of material in the surface sediments but it is also possible that organic material in closed-basin lakes could also accumulate and eventually be mineralized later with inputs of nutrients that would aid in processing under limiting conditions (e.g., Cotner et al., 2023; 10.1002/lol2.10265).

We clarified the sentence as follows:

"In lakes with limited or no fluvial export, pulses of terrestrial material into lakes can be processed and recycled with temporal delay, i.e., post-depositional mineralization of sediment organic matter, contributing to high variability of CO_2 emissions."

6. Line 366-367: "we did not find any differences in the magnitude of CO2 emissions across permafrost zones". Where to see this?

More information regarding permafrost, its characteristics, and effect on CO2 fluxes is now included in the supplement as described in more detail above.

7. Line 372-373: How to understand the lower magnitude of lake CO2 emissions of Swedish lakes with permafrost compared to that of Russian lowlands in terms of hydroclimate and topographic setting?

Northern Scandinavia represents a wet end member in this dataset with much more rugged landscapes compared to Siberia. In line with our reasoning in the initial sections of the discussion, we suggest that higher precipitation together with higher slopes aids flushing rather than retention of terrestrial subsidies. Even though some parts of Northern Scandinavia are also affected by peatlands and can have high OC stocks, the flushing effect may exceed the effect of subsidies compared to the very flat Russian Lowlands.

We tried to clarify this section as follows:

'However, the potential for high C inputs alone does not explain the observed differences in CO2 emissions; for example, emissions from Swedish lakes affected by peatlands are an order of magnitude lower compared to Russian Lowlands, further emphasizing the importance of hydroclimatic and topographic setting (Fig. 2, 3). Northern Scandinavia has much higher P-PET and more rugged topography that would enhance flushing of lakes relative to flatter Russian Lowlands.'

8. In the section "seasonal variability of carbon dynamics in high-latitude regions", the discussions of storage capacity and carbon sourcing capacity seem irrelevant to the topic of this section.

We have now expanded the discussion of the role of OC stocks and created a separate section for this portion and the two related topics are now discussed in separate sections.

" Variability in watershed OC stocks across regions

While hydrological mechanisms shape the magnitude and variability of emissions from high-latitude lakes, watershed C sourcing capacity also plays a critical role. Soils are typically thinner and have lower OC content in wetter, high-gradient watersheds compared to drier regions where flatter topography enhances soil accumulation (Fig. 3, Mishra et al., 2021). Across the circumpolar regions, the highest OC stocks are located in flat regions with moderate precipitation regime (200 - 600 mm per year) and decrease substantially as precipitation increases above that threshold (Mishra et al., 2021). Patterns in soil OC stocks in the northern regions are likely shaped by interactions between climate and topography that together affect soil erosion, the potential for peat formation, and accumulation of sediments (Tarnocai et al., 2009; Mishra et al., 2021).

While OC content tends to be higher in arid catchments, the availability of leachable C and export is further spatially and temporally heterogeneous due to differences in active layer depths, soil types, and potential for thermokarst activity that will modulate surface and subsurface flowpaths (Koch et al., 2022; Olefeldt et al., 2016; Tank et al., 2020). We did not find any differences in the magnitude of CO2 emissions across permafrost zones nor along the gradient of active layer thickness (Fig. S4), possibly due to the coarse resolution of the data layers relative to the studied catchments. Here, the highest regional annual CO2 emissions were observed among lakes in Russian Lowlands (Fig. 2B), where peatlands and thermokarst processes amplify C mobilization and transformation (Serikova et al., 2019; Zabelina et al., 2021). However, the potential for high C inputs alone does not explain the observed differences in CO2 emissions; for example, emissions from Swedish lakes affected by peatlands are an order of magnitude lower. Northern Scandinavia receives ~2x as much precipitation and has more rugged topography that would enhance flushing of lakes relative to the flatter Russian Lowlands, further emphasizing the importance of hydroclimatic and topographic setting (Fig. 2, 3)."

9. Section "lakes in drier regions as hotspots of carbon transformation and accumulation", how to understand this "hotspot"?

The idea was to highlight their role as 'reactors' in the landscape that emit disproportionately more per catchment size relative to wetter sites, but it is probably confusing. We changed the header to:

'Lakes in drier regions as sites of C transformation and accumulation'

Reviewer #3 (Remarks to the Author):

Summary

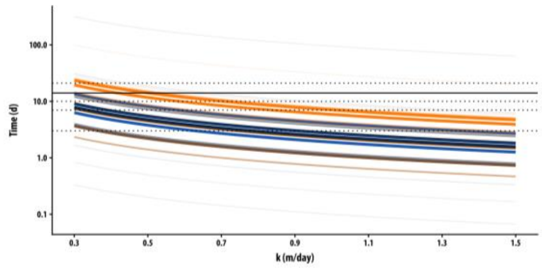
This is a very detailed and interesting study in pan-arctic lake CO2 emissions showing that lakes in drier regions lakes have higher, but variable flux. Data are collated from multiple sources, expanding the impact and pan-Arctic relevance. The results are contrary to the hypothesis that lakes in wetter regions would have increased CO2 flux due to increased lateral flow. The articles was clearly written and I genuinely enjoyed reading it and thinking about how my study systems fit into this paradigm.

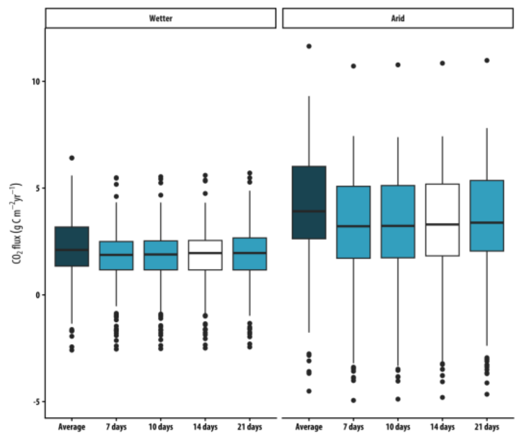
Edits/comments

1. Line 96 etc: It is not clear how the "ice-break up period" of 14 days was justified. I tried to see if that was from the Karlsson reference but could not easily find it there. If this is just a approximation – then some sort of error term might be justified.

Karlsson et al., 2024 shows that winter build up is largely released within approximately the first two weeks since ice-out. Their sampling scheme included sampling ~10 days after ice-out but they also provide a calculation of theoretical water column equilibration times given different methods for estimating gas transfer velocity. The estimates vary from less than 1 day to just over 13 days. We chose 14 days to cover the entire range as in the present dataset there are more differences in lake mean depth and it is also reasonable to assume that the theoretical estimates represent a lower boundary of the times as they do not account for any variability in physical processes or any biological activity in the period since ice-out.

We now also provide these theoretical calculations for ranges of mean lake depths included in this study and also a simple sensitivity analysis to show how would the resulting C fluxes change if we chose different equilibration times. Anywhere from 3 days to 21 days, the ultimate median effect on C fluxes is <±1.5%. However, if we simply averaged all fluxes together, they would be inflated by ~12% compared to the current estimates presented in the manuscript.





We updated the Supplementary material and the relevant section in Methods now reads:

"Considering that ice-out fluxes can be very high, but short-lived, we weighted spring ice-out fluxes and the rest of the open-water measurements differently to avoid biasing annual average estimates. It has been estimated that CO_2 accumulated over winter likely degases during the first two weeks since ice-out (Karlsson et al. 2024). Theoretical water column equilibration times vary from depending on gas transfer velocity and lake depth from less than a day to more than one month (Tab. S1; Fig. S1). Here, we multiplied daily flux estimates characterizing the period of ice-break 14 days and summer-autumn measurements were averaged and multiplied by the number of ice-free days minus the ice-break up period (14 days). We tested the effect of the timing of degassing from 3 days to 21 days on the resulting annual CO_2 fluxes vary and then median differences are <±1.5%; however, if we simply averaged all seasonal fluxes, the estimates would increase by ~ 12% (Fig. S2)."

2. Fig. 1: The author used 3 different time periods in discussion and presentation of P-PET trends. Water balance over a 30 year period (1994-2023) was used to classify arid vs wet landscapes (Fig 1a). And then Fig 1b compares mean P-PET over the last decade (2014-2023) with historical average (1960-2013) (Fig 2). These periods could be justified or standardized.

The reasoning was that the long-term average should cover the collection of all data points (the earliest points were collected in 1994 but the bulk of the data comes from the period between 2010 and 2020). Also, thirty years is often used in climatology to provide meaningful long-term averages. In a similar vein, the purpose of calculating the climate anomalies was to show just how rapidly have these systems changed over the last decade and that the trends are quite heterogeneous across the Arctic. In the literature, anomalies are often compared against the available historical record, which in this case was going back to 1960.

We provide some small clarifications in this section:

"Here, we classify lakes with long-term (1994-2023) negative summer (June – August) P-PET as 'arid' and lakes with positive summer P-PET as 'wetter'; we use a time span that covers collection of all measurements included in the dataset. We emphasize water balance during summer because a) it largely represents the open-water season at high-latitudes (Li et al., 2022) and is therefore important from both hydrological and biogeochemical perspective, and b) most precipitation falls during summer across the investigated regions (34±7% in wetter and 41±4% in arid). Using seasonal temperature data (1994-2023), we also calculated Conrad's Continentality Index (CCI) for each catchment as follows:

$$CCI = \frac{1.7(T_{max} - T_{min})}{sin(latitude+10)} - 14,$$

to characterize climate of different sites on a gradient from maritime to continental based on annual temperature maxima and minima and latitude of each site (Conrad). To estimate density of lakes across the two water balance categories, we used the Prior Lake Database (Wang et al., 2025). For each region that includes lakes in this study, we also calculated P-PET anomalies, comparing mean P-PET over the last decade (2014-2023) with historical average (1960-2013) to emphasize more recent changes in P-PET compared to the available reanalysis data."

3. Line 159: I think the colon between lateral fluxes and aridity metric could be changed to something like "including". I spent a minute trying to understand what a "lateral flux: aridity metric" could be! Also – if the aridity metric is P-PET, I would suggest just writing that. The term aridity metric is only used ~1x, in addition to metric of aridity (1x).

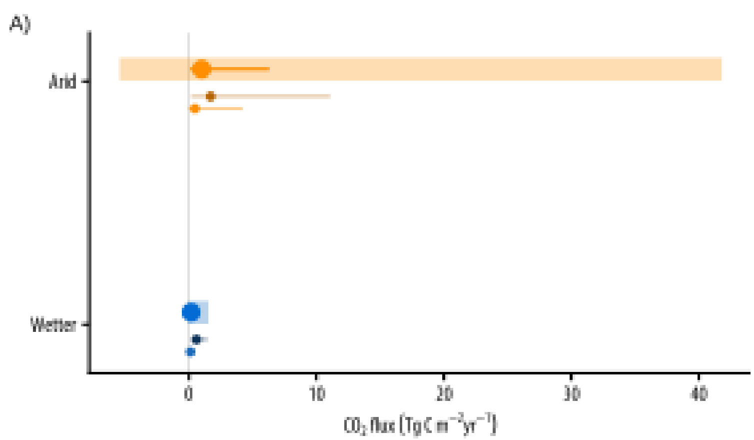
Thank you, we changed it to P-PET!

Line 161-3: … we explored EXPLORED(written 2x)… correlations between CV and ??? (this whole sentence is somewhat unclear)

The sentence now reads:
"Considering that linear models failed to adequately capture variability in lake annual CO2 emissions, we explored correlations between coefficient of variation (CV) and environmental covariates. To calculate CV, we binned CO2 data a) along the P-PET gradient in groups varying by 50 mm, and b) across regions."

Line 186-7: are values per catchment shown graphically or just written in text.

We just reported them in the text for context, but now we also include a plot in the Supplementary material.



Line 199: was the P-PET used in the models from the same year CO2 was measured or was it from the long-term averages. Could the results differ?

We did use the long-term average in all analyses presented in the paper; however, we did initially test the effect of antecedent P-PET conditions to acknowledge the importance of antecedent conditions. We calculated a P-PET average during the 3-month window prior to each sampling event, but the results remain qualitatively the same. The wet and dry regional groupings remain the same, except for 'High Arctic' that has a long-term average of -2 mm but would be considered slightly 'arid' if antecedent conditions were used. We opted for using the long-term averages for its simplicity, as it allows for a more ready comparison across new sites.

Line 203-205: it is not clear where I should be looking to help understand/see this statement: "While lower aridity led to…". Figure S1? I think this could be more clearly explained.

Yes, correct, it is figure S1A. The reference was missing and we have now referenced this section more clearly.

"The best performing GLS model that included summertime P-PET, watershed characteristics (WA:LA, slope, %wetland), and lake size only explained 29% of the variation (Text S1, Fig. S1). Drier conditions ($\beta = -0.30$, $p = 0.09$, Fig. S1A), higher proportion of wetland cover ($\beta = 1.23$, $p < 0.001$, Fig. S1E) together with lower relief ($\beta = -0.13$, $p = 0.55$, Fig. S1D) of watersheds increased CO_2 emissions. While lower aridity led to higher emissions in the lower quartile, high aridity was linked to high emissions in the upper quartile (Fig. S1A). The effect of aridity was strongest in the lowest ($\tau < 0.2$, $p < 0.001$) and highest quantiles ($\tau > 0.7$, $p < 0.001$, Fig. S1A). On average, CO_2 emissions also increased with higher WA:LA ($\beta = 0.69$, $p < 0.001$, Fig. S1C) and smaller lake surface area ($\beta = -0.52$, $p = 0.006$, Fig. S1B)."

Line 224: wetlands (plural)? Or wetland influences.

The sentence was reformulated as follows:

"In wetter regions, lakes with wetlands in their catchments had elevated DOC concentrations."

Line 292: "Here, lakes in wetter regions also tend to be located at higher elevations and in topographically more rugged landscapes". Perhaps this identifies a need for further work on lakes in lower elevations in these wetter regions.

Yes, thank you! We have now added a call to further research in the last section of the discussion as highlighted below:

"While it is clear that permafrost soils are responding to changing precipitation and increasing air temperatures, the resulting impact on soil C export can be highly heterogeneous, even at relatively small scales (Hamm et al., 2023; Koch et al., 2022), and further research focusing on regions where hydroclimate and topography patterns are not linked (e.g., wet and flat regions) is needed."

Line 334: "When comparing watersheds of similar storage capacity…" and slope?

We added 'topography' in the sentence and it now reads as follows:

'When comparing watersheds with similar storage capacity, drier conditions will increase water residence time, while in wetter regions, higher discharge will shorten residence time. Within each hydroclimatic envelope, catchment topography and lake-level differences will further regulate water storage capacity and the potential for lateral C fluxes.'