Detailed review replies of

Interactive comment on

“First Pan-Arctic Assessment of Dissolved Organic Carbon in Lakes of the Permafrost-Region” *by* Lydia Stolpmann et al.

Anonymous Referee #3

Received: May 6th, 2021

General Comments:

The paper presents so far the largest available database on the DOC concentration in Northern permafrost lakes. It will be important contribution to further research of Pan-Arctic carbon budget, which still suffers from significant uncertainties, among which the freshwater ecosystems role is not the least. The manuscript is in a good shape and should be published after a number of comments listed below are addressed.

> Thank you very much for acknowledging the importance of the data presented in our paper. We are grateful for the review and acknowledge the reviewer’s comments, which improved and strengthened the paper.

A potentially important and still poorly quantified source of errors for such global or regional estimates is that the samples from individual sites are taken at different seasons of a year, thus representative of different phases of annual cycle; this makes a month of sampling to be one more factor of DOC concentration in addition to a list of factors studied in the paper; this factor is addressed in Section 4.1 (and it is shown, that for some lakes DOC difference between seasons attains an order of magnitude), but no implications are formulated for analysis carried out in subsequent Sections; in fact, neglecting the difference in season of sampling between lakes imposes uncertainty which is additional to the factors either omitted in this study like climate parameters and local hydrological conditions; I suggest to add analysis of this factor in Discussion.

> We agree that treating all samples from different sampling periods equally leads to further uncertainties that need more attention in our discussion. We added the discussion on differences in DOC concentration over the sampling period in section 5.3 and supplemented to the following paragraph:
>
> “Beside our analysis of temporal variability of a subset of our dataset, the sampling month of each sample was not included in the statistical analysis of our pan-Arctic dataset, which may result in uncertainties due to variations in lake DOC concentration over the ice-free period. For Qeqqata, Greenland, higher DOC concentrations were found in samples collected in April (under ice) and August compared to June samples. In winter, nutrients as well as DOC do concentrate in lakes (Manasypov et al., 2015; Vonk et al., 2015; Grosbois et al., 2017), resulting

in higher DOC concentrations in under-ice samples from April. The spring flood transports large amounts of allochthonous DOC to the lakes, fueling them with DOC and resulting in higher lake DOC concentrations in spring (Manasypov et al., 2015). During summer, low precipitation in this region, evapoconcentration is a major cause for increasing DOC concentration (Anderson & Stedmon, 2007). Considering a seasonality of DOC concentration in our dataset, we found two different patterns in two different study sites. This highlights the complexity of regulators and mechanisms of the DOC concentration in a lake over a season and the need to expand multi-temporal sampling of lake systems."

In the study, the individual correlations of DOC with different factors are estimated, whereas the joint effect of these factors and predictive skill of a set of respective parameters on lake DOC content may be estimated as well, concomitantly quantifying the remaining uncertainty imposed by not taking into account the other factors; multiple correlation analysis could be a natural extension of the method used in the paper to achieve such estimates. I suggest that the authors elaborate on this topic in the paper.

Because our data does not follow a normal distribution we decided not to use a multiple correlation analysis. Instead, we performed a principal component analysis (PCA) to estimate the joint effect of DOC and all analysed parameters. Since this effect was not very strong we originally decided to not include the PCA in our manuscript. However, following your comment, we recognized that the PCA is nevertheless of interest and visualizes some correlations in our dataset. We revised section 3.3 (see below) and added the PCA to the appendix as Figure A2:

"To conduct statistical tests, we used RStudio (version 1.0.153). We tested normality by using the Shapiro–Wilk test. Because our data does not follow a normal distribution, we used the Spearman rank correlation coefficient (ρ) to measure each relationship between DOC concentration and a further parameter (latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC) for all lakes in our dataset. We used the Wilcoxon-Mann-Whitney test to determine the difference in means between two populations. To analyse the relationship of DOC and multiple parameters we performed a principal component analysis (PCA). Our dataset contains six samples from Qeqqata on Greenland (Osburn et al., 2017), collected in April with under-ice conditions. For the sake of comparability, these data have not been included in the statistical analysis."

We refer to the PCA in section 4.2 to 4.7:

"We found that lake DOC concentration was negatively correlated with geographic latitude of a lake ($\rho = -0.3$; $p < 0.05$; Table 4; Fig. A2). The DOC concentration of lakes in the southernmost study sites (Yukon Flats and Yukon-Charley Rivers National Preserve) showed a large range from 10.2 to 1,300 mg L-1, and 5.0 to 66.7 mg L-1, respectively (Table A3)."

“In our dataset, 43.7 % of the lakes were located in the boreal forest ecoregion, 42.6 % in the tundra region, and 13.7 % in a boreal-tundra transition zone. We found a significant relationship between lake DOC concentration and the lake surrounding ecoregion ($\rho = 0.31$; $p < 0.05$; Table 4; Fig. A2), with significantly lower DOC concentrations in lakes of the tundra region ($p < 0.05$).”

“Median DOC concentrations were highest in lakes of the sporadic permafrost zone (17.3 mg L-1) and were negatively correlated with permafrost extent ($\rho = 0.37$; $p < 0.05$; Fig. 3; Table 4; Fig. A2).”

“Our analysis shows a weak significant relationship of the lake surrounding deposit type and lake DOC concentration ($\rho = -0.2$; $p < 0.05$; Table 4; Fig. A2).”

“We found a weakly positive relationship between ground ice content and lake DOC concentrations ($\rho = 0.05$; $p < 0.05$; Table 4; Fig. A2).”

“We analysed the relationship between lake DOC concentrations and lake surrounding SOCC and found a weakly significant relationship for SOCC of the upper 100 cm ($\rho = 0.1$; $p < 0.05$; Table 4; Fig. A2). The significance of the relationship was getting weaker for SOCC in the upper 300 cm ($\rho = 0.09$; $p < 0.05$; Table 4, Fig. 4; Fig. A2).”

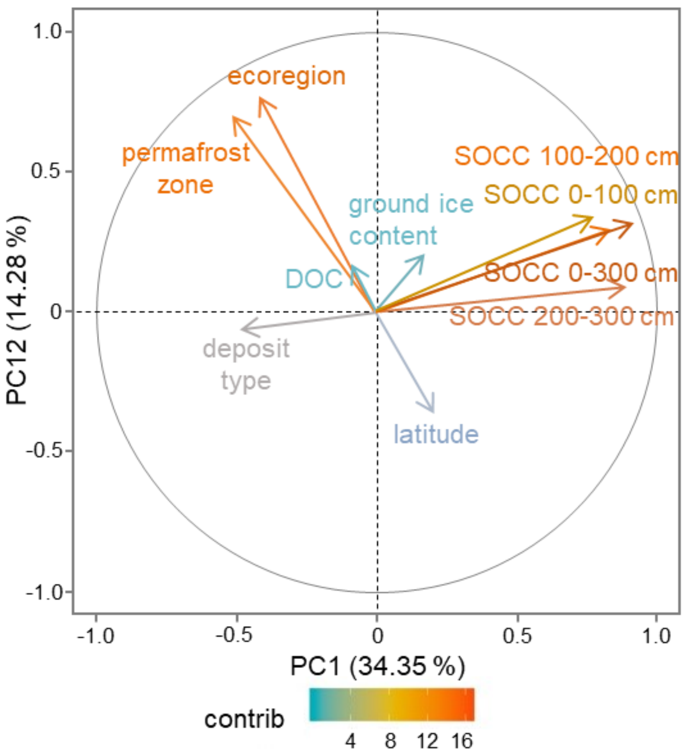

Figure A2: Principal component analysis showing a variables factor map with a color gradient showing the contribution to the plane construction. The first two principal components explained 34.35 % (PC1) and 14.28 % (PC2) of the variance in the analysed parameters (DOC, latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC). The scores of PC1 had *positive loadings with SOCC in all depths and negative loadings with deposit type, while PC2 scores had negative scores of latitude and positive scores of DOC, permafrost zone, ecoregion and ground ice content.*

Specific comments:

Page 2, Line 10: better to specify which is the part of Siberia, where individual boreholes demonstrate significant positive temperature trend.

We changed this accordingly as follows:

"More recently, permafrost warmed globally by an average of 0.29 °C +/- 0.12 °C over the 2007-2016 period due to higher air temperatures, with some of the strongest warming trends (about 0.9 °C per decade) measured in individual boreholes at the polar stations Marre Sale in northwest Siberia and Samoylov Island in northeast Siberia (Biskaborn et al., 2019)."

Page 2, Line 25: is there direct chemical pathway from DOC to CH4? Anyway, this is not mineralization. If you mean that DOC is stored in sediments after flocculation, and then decomposed to CH4, please rephrase the sentence to make it clear.

To clarify we rephrased the paragraph:

"In lakes, dissolved organic carbon (DOC) is one of the main C fractions (Tranvik et al., 2009). It is mobile and can be chemically labile (Vonk et al., 2013a, b). DOC in lakes can be produced in the lake itself (autochthonuous DOC) or in the catchment of the lake (allochthonuous DOC) (Sobek et al., 2007). The organic carbon (OC) content of terrestrial soils is the main source for allochthonuous DOC. DOC in lakes can be transferred to and stored in lake sediments due to flocculation (Tranvik et al., 2009). DOC can also be degraded by photo oxidation or microbial activity, resulting in the mineralization of OC to carbon dioxide (CO_2) and methane (CH_4) (Battin et al., 2008; Tranvik et al., 2009; Vonk et al., 2013a, b)."

Page 2, Lines 26-29: "The mineralization of DOC in a lake is a major component of the global C cycle..." is too strong statement. "one third to one-half" – does this contribution include river C fluxes? Please rephrase to make understandable.

To clarify our statement we rephrased the sentences as follows:

"DOC in lakes can be transferred to and stored in lake sediments due to flocculation (Tranvik et al., 2009). DOC can also be degraded by photo oxidation or microbial activity, resulting in the mineralization of OC to carbon dioxide (CO_2) and methane (CH_4) (Battin et al., 2008; Tranvik et al., 2009; Vonk et al., 2013a, b). These processes are important components of the northern C cycle and affect greenhouse gas emissions from lakes."

"Vonk et al. (2015) suggested that the C flux from surface waters to the atmosphere and from land to ocean represents roughly one third to one-half of the net C exchange from land to the atmosphere in the Arctic."

From which lacustrine layer DOC has been sampled in lakes? I guess, epilimnion. Please provide the info.

Samples taken by the authors of this study were mostly taken from or near the water surface. Some of the DOC datasets we harvested from the literature do not provide information on the sampling depth in the meta-data or whether water bodies are stratified. A differentiation into epilimnion, metalimnion, hypolimnion would require CTD data, which presumably were not acquired in the vast majority of the synthesized data. Ultimately, many of our samples originate from shallow arctic lakes or ponds, which are known to be well mixed and rarely develop stratification.

We added a short information to section 3.1:

"Samples from the author team were taken from or near the water surface as well as the vast majority of the synthesized data. Although, some of the synthesized data do not provide the sampling depth we can assume that the majority of these arctic lakes and ponds are shallow and well mixed."

Section 3.3: I would expect, that in order to isolate the influence of a single factor on lake DOC, you should compute correlation coefficient for a series of DOCs from all lakes, for which the other factors are fixed. Or you computed each correlation coefficient for the total number of lakes? Please precise.

We rephrased section 3.3 find in the general comments and copied here:

"To conduct statistical tests, we used RStudio (version 1.0.153). We tested normality by using the Shapiro–Wilk test. Because our data does not follow a normal distribution, we used the Spearman rank correlation coefficient (ρ) to measure each relationship between DOC concentration and a further parameter (latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC) for all lakes in our dataset. We used the Wilcoxon-Mann-Whitney test to determine the difference in means between two populations. To analyse the relationship of DOC and multiple parameters we performed a principal component analysis (PCA). Our dataset contains six samples from Qeqqata on Greenland (Osburn et al., 2017), collected in April with under-ice conditions. For the sake of comparability, these data have not been included in the statistical analysis."

Table 4: not clear, how the rank correlation coefficient have been computed for qualitative predictors: permafrost region, ecoregion, ground ice content, deposit type. Please provide details.

We revised the methodological description of our statistics find above and as follows:

“To conduct statistical tests, we used RStudio (version 1.0.153). We tested normality by using the Shapiro–Wilk test. Because our data does not follow a normal distribution, we used the Spearman rank correlation coefficient (ρ) to measure each relationship between DOC concentration and a further parameter (latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC) for all lakes in our dataset. We used the Wilcoxon-Mann-Whitney test to determine the difference in means between two populations. To analyse the relationship of DOC and multiple parameters we performed a principal component analysis (PCA). Our dataset contains six samples from Qeqqata on Greenland (Osburn et al., 2017), collected in April with under-ice conditions. For the sake of comparability, these data have not been included in the statistical analysis.”

What is the reason for ultrahigh DOC concentrations in some Alaskan lakes?

At this point, we did not find the ultimate cause for the very high DOC concentrations in some of the lakes in the Yukon Flats in Interior Alaska. We discussed possible causes in the sections of our discussion. In 5.1 we described the connection between DOC concentration and ecoregion, also referring to the high concentrations in lakes in the Yukon Flats:

“We particularly found that lakes in the boreal forest region have higher DOC concentrations compared to tundra region lakes (Fig. 3). Soils of boreal forests are rich in organic material and microbial degradation is low (Sobek et al. 2007). In areas of boreal forest, the frost-free period is extended and the surface water can be in contact with soil C for a longer time resulting in higher DOC concentrations in boreal lakes. Previous studies confirm that vegetation is an important driver for DOC in permafrost catchments (Harms et al., 2016; Coch et al., 2019). Coch et al. (2019) found higher DOC concentrations in moss and plant rich Low Arctic catchments on Herschel Island in Northwest Canada compared to a High Arctic catchments at Cape Bounty, Northeast Canada. In our database we found high lake DOC concentrations in the boreal forest regions of Interior Alaska which are dominated by white and black spruce (Halm & Griffith, 2014).”

To clarify we rephrased the last sentence of the upper paragraph:

“This relationship may explain high lake DOC concentrations we found in the Yukon Flats in Interior Alaska, a study area in the boreal forest and dominated by white and black spruce (Halm & Griffith, 2014).”

Additionally, we discussed the high DOC concentrations in the Yukon Flats in section 5.2:

“While we showed that lake DOC concentration is influenced by permafrost extent and type of ecoregion they do not explain all of the variability in the dataset. Additional factors are regulating DOC. For example, air temperature, precipitation and solar radiance have an influence on surface water DOC concentration (Cole et al., 2002; Molot et al., 2005; Anderson & Stedmon, 2007). Anderson & Stedmon (2007) analysed lakes in low Arctic Greenland and found highest lake DOC concentrations in areas of low precipitation and low discharge. In those areas, evaporation is high leading to higher DOC concentrations. For our database, the role of evaporation may also explain the relatively high DOC concentrations of lakes in the Yukon basin. Here, the lakes are less hydrologically connected and the region is very arid, allowing evaporation-driven concentration of DOC (Johnston et al., 2020).”

Here, we also rephrased the penultimate sentences of the upper paragraph to be more precise:

“For our database, the role of evaporation may also explain the high DOC concentrations of lakes in the Yukon Flats in Interior Alaska. Here, the lakes are less hydrologically connected and the region is very arid, allowing evaporation-driven concentration of DOC (Johnston et al., 2020). ”

Finally, we discussed the high DOC concentrations in Yukon Flats lakes in section 5.3 and rephrased to give more information:

“However, it is known for example that less allochthonous DOC is transported to a hydrologically isolated lake than to a connected lake (Bogard et al., 2019). In arid regions with rather isolated lakes, such as in the Yukon Flats in Interior Alaska, evapoconcentration of DOC plays an important role (Johnston et al., 2020). Water bodies with highest DOC concentrations in the Yukon Flats have a water depth less than 1 m. Studies in West-Siberia showed, that ponds receive the highest impact of allochthonous input due to the high ratio of lake drainage area vs. small water volumes. This results in short water residence time leading to highest concentrations of DOC (Shirokova et al., 2013; Manasypov et al., 2014, 2015). In addition to allochthonous DOC, autochthonous DOC, including phytoplankton productivity as well as heterotrophic bacterioplankton respiration processes (Chupakov et al., 2017), is influencing the DOC concentration, especially in lakes with low connectivity. For lakes in the Yukon River Basin, Bogard et al. (2019) described a minor importance of allochthonous DOC in lakes and highlighted the carbon fixation from atmospheric CO_2.”

Page 16, Lines 30-31: an unfinished sentence

Thank you very much. We changed this accordingly:

“This might be attributed to the mobilization of old labile yedoma carbon by thermo-erosion along rapidly expanding lake shores and by active thermokarst processes (Strauss et al., 2017).”

Page 17, Line 22: I guess you meant “occupied by wetlands”

We changed it accordingly:

“For example, Xenopoulos et al. (2003) analysed catchment characteristics of lakes and found that lake perimeter and the proportion of the watershed occupied by wetlands are strongest predictors for DOC in lakes of temperate forests. On a global scale, lake elevation and the proportion of wetlands in a watershed are strongest predictors for lake DOC.”