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Interactive comment on "Hydrology drives chemical synchronicity in subarctic tundra ponds" *by* Matthew Q. Morison et al.

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General author responses: We appreciate the time and careful effort taken by the referee to review our manuscript. The comments provide very helpful, constructive, and specific feedback/suggestions to improve the manuscript, and we are particularly grateful for the attention paid with ideas to enhance the discussion section. This will include the addition of an instructive figure to provide an outline of the implications of this work on future sampling designs. We address each general and specific comment by the referee below and leave our comments on the changes we plan to make to the manuscript, as well as references to literature and our data presented to support the changes. We mark referee comments with an (R): and author responses with an (A).

(R): The study by Morison et al. presents some interesting data on the variability of water chemistry in shallow subarctic ponds. Authors make a point that most studies in high latitude lakes are based on few water samples taken during the summer and do not account for temporal changes driven by, for example, hydrological events. This is a strong and valid statement, and the dataset presented in this manuscript is certainly unique by showing how variable water chemistry in thermokarst ponds can be during the ice-free season. Authors attempt to relate this variability to local hydrology by calculating index of hydrological dependence that is somehow arbitrary. Perhaps, in the general approach, it would be better to calculate a simplified mass balance for some ions of interests; knowing the catchment area for each pond (run-off) and temporal changes in concentrations through the water column?

(A): We agree that providing catchment characteristics would better allude to some of the processes on which we speculate on in the paper. Thus we have now included some additional hydrometric data in the paper which we had collected in the field but initially had not included in this paper (runoff measured into each pond over the course of the study period as well as catchment area) although to further reduce speculation we present this data as a depth of water over the pond surface as opposed to the catchment surface. We show this as a depth over the pond surface as we recognize that the variable contributing area concept applies here due to the very flat topography (regional gradient of < 1 m/km, Dyke and Sladen, 2010) and the confining role of ground frost in prohibiting or redirecting subsurface flow at different periods over the course of the season (Wright et al., 2009) and not all of the catchment may be contributing during a given event (and hence why we give runoff over the pond surface, which is also more relevant to the dilution effect).

(R): The manuscript lacks context data that would allow better understanding of the processes driving water chemistry. For example, many shallow thermokarst ponds show strong thermal and oxygen stratification; were the 6 studied ponds stratified or mixed? What was the approximate rate of water exchange both vertically and hori-

zontally? Water samples were taken from the shore or from the middle of each pond? How representative were studied ponds in terms of nutrient concentration and biological production for other ponds and lakes in the area. Authors discuss biological processed that may be responsible for rapid uptake of nutrients but do not include any indices of the trophic status or plankton biomass in studied ponds. Indeed part of the variability in chemistry between ponds can be probably explained by different patterns of uptake. All these information are required to better appreciate presented data and would much improve the manuscript.

(A): We appreciate the referee's comments and overview of information we could provide to better contextualize our results within the greater literature on permafrost pond chemistry. In particular we have included in the methods section that these ponds have been found to be well-mixed (Bello and Smith, 1990), and that water samples were taken approximately 3 meters from each pond edge. The ponds are representative of a greater set of study ponds in the region in terms of nutrient concentrations (White et al., 2014; Bos and Pellatt, 2012; Jacques et al., 2016). In-situ mesocosm experiments in ponds of this region have shown ponds to be nutrient-limited (Symons et al 2012) with uptake of nutrient additions occurring within a matter of hours to day (Eichel et al., 2014) motivating our discussion of rapid nutrient uptake. A key motivation for future work is more intensive measurements which can capture individual biogeochemical processes in the cycling of each of the elements in these ponds, particularly of those which are most reactive, such as inorganic nitrogen species. We will adapt the language to be clearer and less speculative regarding the lack of data on individual biogeochemical process and that inferences we make on process are guided by our measurement of patterns of chemical concentrations.

(R): Authors attempt to compare temporal and spatial variability; Is 6 (5?) ponds enough to encompass spatial variability, particularly if temporal variability is assessed with 12 time points? This would probably bias the entire analysis toward higher temporal variability. Finally, in the Discussion authors provide an outline on how to better

plan field campaigns for sampling of high latitude lakes. Such guidelines are much needed and some unification of methods would help greatly to determine effects of recent environmental changes in Arctic freshwaters. However, I think that this can be done with instructive diagram that would be readily accessible for broad scientific community rather than by quoting and refuting methods used by others. Focus on the positives and how much your own research can add to future improvements.

(A): We address this concern more specifically below in the response to the referee comments on the methods section, with reference to our data being representative of spatial variability in the region. In short, we believe from comparing our data to many other studies of permafrost ponds that additional sample points may strengthen the statistical power of our analysis, however there is adequate variation in the spatial survey of six ponds for the purposes of comparing the two degrees of variation among the chemical constituents we measured in this study. As well, we appreciate the comment suggesting an instructive diagram and a constructive approach in building on method development in writing the text as opposed to a refuting tone. We will create and insert an instructive diagram to inform future sampling designs (including direction on research questions regarding different specific chemical constituents).

(R): Abstract - This part can be much improved; mainly by streamlining and including some key point data. For example first sentence is confusing and introduces biology; biogeochemistry and climate change with mentioning feedbacks. This is probably not a right place for such a broad and somewhat conclusive statement. Focus on importance on variability in pond biogeochemistry and controlling processes. Please do not use very general descriptions such as "most ions; either mention % or which species.

(A): We have rewritten the first sentence of the abstract to be more specific without introducing such a broad range of topics simultaneously. We have removed any vague phrasings, including "most ions", and replaced with a specific list of ions which meet the criterion.

(R): Introduction Again already in the first paragraph there is a need for editing. Two sentences start with similar phrase: “these ponds”. Also first sentence from the abstract is repeated almost word-by-word.

(A): We have edited the first introductory paragraph to have less repetition, both within the wording (ie, not repeating the phrasing “these ponds”), as well as expanding on the first sentence in the introduction instead of merely repeating the first sentence of the abstract.

(R): Page 2; Recently Przytulska et al (2016, Biogeosciences) described inter-annual variability in thermokarst pond chemistry.

(A): Thank you for drawing our attention to this reference. We have included this in our literature review of varying length of study periods of permafrost pond chemistry, which includes valuable data on nutrient speciation.

(R): Page 3 First paragraph; this is all true and most of the studies in the Arctic are based on the few samples taken within short time frame. However please consider also recent research showing that some shallow high latitude ponds are remarkably stable in terms of oxygen and temperature stratification during the open water period (Deshpande et al 2015).

(A): Again, thank you for drawing our attention to this reference. The stability in stratification observed in this work is remarkable, considering their relatively shallow depths. We will include this reference in our text to note the stability observed in some regions, although prior work in this area (northern Manitoba) of the Hudson Bay Lowlands has found study ponds to be well-mixed, as they are considerably shallower than the pond depths recorded in Nunavik in this study. However, the issue of stratification impacting chemical variability is an important point to raise either in the introduction or discussion section, particularly if the objective regarding informing sampling design is to be properly answered (as this study addresses chemical variability in nonstratified ponds), and we thank the referee for raising this concern.

(R): Page 4 Water for chemical analyses was taken in profiles? Why these profiles are not shown?

(A): Water samples were taken as a depth-integrated sample of the water column, due to the lack of stratification noted earlier. We will make this more explicit in the method section.

(R): Statistical techniques. I question the design of the variability analysis. If I understand correctly for the spatial deviation score Authors used mean from all ponds sampled on the same date (n=6?) and for the temporal variability authors used mean from each single pond over the entire study period (n=12); this would probably introduce some bias. Anyway it should be clearly stated how many samples have been used for this calculations.

(A): We have included a more explicit description of the sample sizes which resulted from each normalization treatment. To clarify, for each chemical measurement, both a temporal deviation and spatial deviation score is computed, so the Mann-Whitney test was applied to equal sample sizes. For computation of the deviation scores themselves, we believe the concern is valid regarding the normalization procedures varying in terms of how many points were included to determine a mean value to normalize by in each instance (6 vs. 12). However, we also believe that we have captured a sufficient degree of spatial variation within our 6 ponds for this work despite the great deal of spatial sampling which is typically captured (as outlined more explicitly in Table 1) to compare with our 12 temporal points at each pond. We suggest this is the case we observed approximately 1-2 orders of magnitude difference in absolute chemical concentrations of most chemical species among the six ponds in our dataset (see Supplementary Table 1) which is in line with the degree of spatial variance in much of the work outlined in Table 1 (and more specifically, in line with the variance observed by other authors who have studied ponds in our specific region, Bos and Pellatt, 2012; White et al., 2014; Jacques et al., 2016).

(R): "and stage data to represent the geometry of conical bathymetry in the non-linear pond stage volume relationship. In this case, the parameter $\beta 2$ is invariant under linear translation, such as spatial-normalization, and is expected to maintain a negative value with the magnitude depending on the bathymetry of the pond." This is unclear to me. Data on bathymetry were available or modelled? Even if for one pond Authors do not record the average depth? How was this accomplished?

(A): To clarify, bathymetry data were not presented in this study (although some sparse measurements were collected in the field). Based on our observations of very gently sloping conical bathymetry, we chose the power function to capture this and allowed the exponent in the function to vary. Theoretically, for a height-volume relationship (and under the assumption of some ions being conservative, we extend this to height-concentration relationship) the value of this coefficient should be between 0, for a perfectly cylindrical pond basin with a flat bottom, to highly negative, for a very steep cylindrical pond basin. We will clarify this in-text in the methods section.

(R): In this paragraph Authors introduced pond-stage; this should be clearly explained as pond stage is later used in analyses and discussion. Stage means volume, depth? and how was it classified based on the dataset from pressure transducers?

(A): By stage we are referring to the water level (height) in the pond. This was logged hourly by a pressure transducer in a standpipe in the pond which was barometrically corrected. We will clarify this in-text in the methods section.

(R): Definition of the PCA is not needed, citation would suffice.

(A): We have removed the broad background on PCA and replaced with a citation to standard methods.

(R): PCA can be also used to elucidate relationships between control variables (hydrology) and controlled variables (chemistry). For this you would need to use PCA on your meteorology/hydrology dataset, extract components and relate these to concen-

trations of different ions using stepwise forward lineal regression. Perhaps this would be a clearer method for this analysis. Alternatively citations for the method used to differentiate between hydrologically driven and nothydrologically driven ions is needed.

(A): To our knowledge our specific method of categorizing hydrologically driven ions is novel, although it is not dissimilar to the approach of an evaporative normalization factor (Borghini et al., 2013). We may lack sufficient hydrological measurements to employ a separate PCA on those data, but this suggestion sounds promising if we are able to do so, and will attempt it to determine if it is feasible to include in the revised manuscript.

(R): Results - Any data on changes in temperature and oxygen stratification?

(A): We do not present data on stratification. In these ponds, the water column which has been shown to be well-mixed by wind action given the very shallow depth (< 1 m) of these ponds in the region (Bello and Smith, 1990) – we will add a note of this in the description of the study region. As a quality measure to ensure well-mixing we occasionally took simultaneous duplicate samples at multiple points in the lake, which produced nearly identical chemical results (data not presented in this paper).

(R): Does this paragraph belong in the results? "Seasonal patterns in pond hydrology were compared with water chemistry to determine if pond water chemistry parameters were hydrologically driven. The hydrologic control of different nutrient species was categorized by the performance of the fitting of a power curve to each set of normalized concentration data against pond stage for each of the five instrumented ponds. As noted earlier, a linear fit is not possible due to the somewhat conical bathymetry of ponds, which causes greater drops in water levels as ponds dry and sediments are exposed. In each case, species with a consistent pond-specific value of $\beta 2$ (the slope of the power curve) with low root mean square error (S) were categorized as hydrologically driven, where species with either a $\beta 2$ value inconsistent with other hydrologically driven species or poor performance (greater root mean square error; Figure

5, Table 5) were categorized as non-hydrologically driven. DON, Cl-, Na+, K+ .and Mg2+ were classified as hydrologically driven species and Ca2+, NH4+, NO3-, and SO42- were classified as non-hydrologically driven (Table 5). Slight differences in $\beta 2$ values between ponds for hydrologically driven species are driven by the differences in bathymetry driving the stage-volume relationship"

(A): We have modified this paragraph and transferred appropriate sections to the methods section to better differentiate between on reporting actual reports as opposed to methodological approaches in this section.

(R): Discussion - In general well written; needs some trimming i.e., first and second paragraph are superfluous.

(A): We have reduced the redundancy at the beginning of the discussion section by combining the key messages of the first two paragraphs into a single paragraph.

(R): Some paragraphs rewind the results e.g, detailed PCA description

(A): The discussion around the PCA has been shortened in order to reduce repetition with the results and focus instead primarily on contextualizing our results in literature from other permafrost regions, and the implications of the alignment of data from certain ponds along the two PC axes.

(R): I question utility of Table 1 and Table 3; I Authors need to provide an outline of similar studies

(A): We have included an outline of similar approaches (using correlation coefficients between ponds for various chemical species as a measure of coherence) in the introduction section.

(R): Table 1 can be included as Supplementary Material

(A): We have now included Table 1 as supplementary material instead of being contained within the main text.

(R): Results from Table 2; showing coherence between different ponds can be outlined in the text.

(A):We have outlined in the text the link between our coherence results and the hydrologic/geometric characteristics of the study ponds listed in Table 2.

(R): Table 5 need to be revised, less spacing between numbers, less vertical lines

(A): Table 5 has been visually modified to read more clearly as per the referee's suggestion.

(R): Figure 1 needs improvement, maybe provide a high quality map go the province

(A): Figure 1 has been re-made with an included inset map of the province

(R): Figure 3 Description of axes not symmetrical, should be "temporal variation does not exceed spatial variation"

(A): Axes have been aligned and the prior text "No significant difference" has been clarified as per the referee's suggestion.

(R): Figure 4 Caption unclear, what is pond stage? Ice-free rather than snow-free season.

(A): Pond stage has been clarified throughout the document as pond height, and the text "snow-free" has been replaced with "ice-free" here and elsewhere throughout the text where appropriate.

(R): Figure 6 Normalize fonts style and size with other figures, perhaps enlarge the symbols and remove thin horizontal lines

(A): We have normalized the text size between this figure and others, as well as enlarged the symbols.

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lake in the Hudson Bay Lowlands, Canada. Arc. Ant. Alp. Res., 22: 98-107, 1990.

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