Climate signatures on lake and wetland size distributions in arctic deltas

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Key Points:

1. Lake areas in arctic deltas exhibit a lognormal distribution associated with a simple mechanistic growth process.
2. Wetland areas exhibit a power law distribution consistent with inundated fractal topography.
3. Colder arctic deltas have larger average lake sizes, likely due to thicker permafrost restricting sub-lake hydrologic connectivity.

ABSTRACT

Understanding how thermokarst lakes on arctic river deltas will respond to rapid warming is critical for projecting how carbon storage and fluxes will change in those vulnerable environments. Yet, this understanding is currently limited partly due to the complexity of disentangling significant interannual variability from the longer-term surface water signatures on the landscape, using the summertime window of optical spaceborne observations. Here, we rigorously separate perennial lakes from ephemeral wetlands on 12 arctic deltas and report distinct size distributions and climate trends for the two waterbodies. Namely, we find a lognormal distribution for lakes and a power-law distribution for wetlands, consistent with a simple proportionate growth model and inundated fractal topography, respectively. Furthermore, while no trend with temperature is found for wetlands, a statistically significant decreasing trend of mean lake size with warmer temperatures is found, attributed to colder deltas having deeper and thicker permafrost preserving larger lakes.

Plain Language Summary

Arctic river deltas are landscapes facing significant risk from climate change, in part due to their unique permafrost features. In particular, thermokarst lakes in ice-rich permafrost are expected to both expand and drain under warming-induced permafrost thaw, reconfiguring deltaic hydrology and impacting the arctic carbon cycle. A limitation in understanding how thermokarst lake cover might be changing, is the significant interannual variability in water cover in flat regions such as deltas, which makes it difficult to distinguish between perennially inundated, thermally relevant waterbodies, and ephemerally inundated waterbodies. Here, we present a pan-Arctic study of 12 arctic deltas wherein we classify observed waterbodies into perennial lakes and ephemeral wetlands capitalizing on the historical record of remote sensing data. We provide evidence that thermokarst lake sizes are universally lognormally distributed and that historical temperature trends are encoded in lake sizes, while wetland sizes are power law distributed and have no temperature trend. These findings pave the way for quantitative insight into lake cover changes on arctic deltas and associated carbon and hydrologic cycle impacts under future climate change.

1. Introduction

Coastal river deltas are landscapes at significant risk from sea level rise and sediment deprivation (Nienhuis et al., 2020; Syvitski et al., 2009). Arctic deltas are likely more vulnerable than their temperate counterparts due to the presence of thermokarst lakes in permafrost, which are sensitive to rapid Arctic warming (Emmerton et al., 2007; Piliouras & Rowland, 2020; Walker, 1998). Pan-arctic thermokarst lake coverage is responding to warmer temperatures in complex ways, as temperature-driven ground ice loss drives lake growth via retrogressive thaw slumping along lake shorelines (Grosse et al., 2013) but also generates surface and sub-surface hydrologic connectivity that can cause lake drainage (Grosse et al., 2013; Jones et al., 2020; Rowland et al., 2011; Yoshikawa & Hinzman, 2003). Observed changes in lake area over the last 50 years have shown both positive and negative trends depending on local hydrology, climate, permafrost zonation, ice content, landscape age, and geomorphic setting (Arp et al., 2011; Chen et al., 2012; Jones et al., 2011; Nitze et al., 2018; Plug et al., 2008; Smith et al., 2005). Irrespective of whether lake coverage is expanding or decreasing, change is expected to have consequences for the permafrost carbon cycle, as thermokarst lake expansion accelerates permafrost thaw and expedites the release of previously frozen carbon into the atmosphere as methane and CO_2, while lake drainage may slow permafrost-thaw and associated carbon emissions (van Huissteden et al., 2011). Major arctic deltas store approximately 91 ± 39 Pg-Carbon, potentially making them significant sources of future carbon emissions (Schuur et al., 2015). Moreover, thermokarst lakes in deltas modulate transport of riverine freshwater, sediment, and nutrient fluxes to the Arctic ocean, by trapping and holding sediment (Marsh et al., 1999; Piliouras & Rowland, 2020) and modifying the residence times and pathways of nutrient transport through the delta (Lesack & Marsh, 2010; Squires et al., 2009; Tank et al., 2009). Therefore, changing deltaic lake coverage and its spatial distribution will also alter the timing and magnitudes of riverine fluxes to the Arctic Ocean, which has broader implications for near-shore circulation and ecosystem productivity (Lique et al., 2016).

We hypothesize that lake size variability and spatial arrangement across arctic deltas (Figure 1) may encode information on climate influence in permafrost environments, akin to how channel network structure is a signature of the riverine, tidal, and fluvial fluxes which shape temperate deltas (Nienhuis et al., 2016, 2018; Tejedor et al., 2015b, 2015a, 2016, 2017). In particular, we hypothesize that two primary drivers of lake size variability across deltas are ice content and climate and test this hypothesis quantitatively. Physically we expect that colder deltas have thicker permafrost which is able to support larger lakes, by preventing connection to the sub-permafrost groundwater table that can lead to eventual lake drainage (Grosse et al., 2013; Walvoord & Kurylyk, 2016; Yoshikawa & Hinzman, 2003) or diminished lake growth rates. We also expect that deltas with greater soil ice fraction will have larger lakes as soil ice acts as a subsurface hydraulic barrier, while soil ice melt induces subsidence and therefore lake growth. Discovering and quantifying data-driven relationships between lake size and ice content or temperature will be useful for constraining physical models and predicting future arctic delta morphology in a warmer climate.

However, a challenge in assessing the climatic signature on thermokarst lake sizes is the significant interannual (Grosse et al., 2013; Rey et al., 2019) and seasonal variability (Chen et al., 2012, 2013; Cooley et al., 2019; Vulis et al., 2020) in lake area which makes it difficult to distinguish perennial waterbodies (lakes) from ephemerally inundated depressions (wetlands) using the short summertime window of available spaceborne observations. In particular, seasonal water may inundate ephemeral wetlands, which would be misidentified as perennially inundated lakes from remote sensing imagery. The processes underlying ephemeral wetland versus perennial lake formation are distinct, as lakes are the result of thermokarst-driven growth and evolution (Grosse et al., 2013), while wetlands are the result of hydrologic variability, and as defined in this study only seasonally inundated (Le & Kumar, 2014). Mixing of the two waterbodies is certain to hide causative patterns and signatures, as lakes and wetlands have different time scales of thermal impact on the landscape, and are thus expected to show different expressions of their size distribution and their dependence on climate.

2. Study sites, data, and lake and wetland extraction

Lake and wetland size distributions on 12 arctic deltas characterized by a range of air temperature and ice content across Siberia (Indigirka, Kolyma, Lena, Nadym, Ob, Pur, Yana, and Yenisei), Canada (Mackenzie), and Alaska (Colville, Kobuk, and Yukon) were examined (Figure 1). The deltas include those formed by the six arctic rivers with the greatest discharge and other major rivers along the Siberian and Alaskan coastlines. Lakes and wetlands were extracted over the subaerial portion of each delta, which was delineated using Google Earth. Delta Mean Annual Air Temperature (MAAT) was obtained from 2000-2016 using the 15-km spatial resolution Arctic Systems Reanalysis V2 (Bromwich et al., 2017). Delta soil ice content was estimated from a 12.5-km spatial resolution ice classification map (Brown et al., 1997).

To distinguish between hydrologically perennial lakes and ephemeral wetlands, we utilized the spatiotemporal interannual variability of water coverage over each delta from 1999 to 2018. We used the Landsat-derived, 30-m spatial resolution Global Surface Water (GSW) dataset which provides monthly-composited water masks from March 1984 to December 2018 that classify the landscape into 30-m pixels that are land, water, or no data (i.e. unable to classify due to cloud cover, Landsat-7 striping, or snow and ice cover) (Pekel et al., 2016). Due to sparse data availability prior to 1999 on most deltas, we only analyzed the period from 1999 to 2018, and to remove the effect of significant snowmelt and spring time flooding we only analyzed July water masks, similar to other studies (Muster et al., 2019; Nitze et al., 2018). We only examined the subaerial portion of each delta, manually delineated using Google Earth.

To identify and separate lakes from wetlands, we first computed for every pixel i the July "water pixel occurrence", w_i, as the fraction of Julys from 1999 to 2018 for which the pixel was classified as water, discarding no-data pixels (Figure 2a). The water pixel occurrence w_i can take values from 0 to 1, with $w_i = 1$ if and only if the pixel was classified as water for the whole record and $w_i = 0$ if and only if the pixel was classified as land for the whole record. Second, we identified a reference year, y^*, with water coverage on the subaerial delta closest to that of the temporal average over the 20-year period of record and sufficient data quality, i.e. greater than 99% pixels classified as land or water and no significant geo-referencing (collocation) errors, and used this year to identify individual waterbodies using 8-neighbor connected component analysis (see Supplementary Material, Figures S1 to S3 for details on selection of y^*). Third, we classified the waterbodies identified in year y^* into lakes and wetlands using the water pixel occurrence, w_i. For each waterbody, $O_k^{y^*}$, we computed the "occurrence index" B_k as the mean of w_i for all pixels i within $O_k^{y^*}$, which corresponds to the fraction of pixels within the waterbody that were on average occupied by water over the 20 years (Julys) of record. A waterbody was then classified as a lake if B_k exceeded a threshold value θ and as a wetland if B_k was less than θ. We evaluated the results over a range of θ values, from $\theta = 0.80$ to $\theta = 0.90$, to account for differences in the flooding regime across different deltas and to test the robustness of our results (Tables S1 to S3, Figures S4 and S5). The lake and wetland size distributions shown in Figures 3 and 4 are extracted at a threshold value of $\theta = 0.85$. Only waterbodies at least 5,400 m^2 (i.e. 6 pixels) in size were included in our analysis to reduce estimation errors at small areas. We tested the robustness of our methodology by performing a duplication, wherein we selected an alternative reference year, y^*_{alt}, with similar water coverage and data quality to extract waterbody extents and repeated the analysis (Supplementary Material, Table S4, and Figures S4 and S5). All analyses were performed in R using geospatial and image processing packages (Gillespie, 2015; Hijmans, 2020; Pau et al., 2010; Pebesma, 2018, 2020).

3. Lake size distributions and a proportionate growth model

From a simple thermodynamical perspective, thermokarst lakes are thermal reservoirs, which interact with their surroundings via heat exchange. In particular, unfrozen lake waters are net heat sources, thawing the surrounding ice-rich soil which leads to lake basin expansion (Grosse et al., 2013). As larger lakes have a larger thermal inertia, they remain unfrozen for longer periods (Grosse et al., 2013) and maintain larger lake to soil temperature gradients, which enables them to grow at faster rates. Thus, based on this simple thermodynamical argument, and on field observations (Jones et al., 2011), we can postulate that thermokarst lake growth is compatible with a stochastic proportionate growth model (Crow & Shimizu, 1988; Mitzenmacher, 2004) (i.e. growth rate proportional to lake size), where stochasticity arises from the variability of soil properties which modulate growth. A key property of this general class of proportionate growth models is that they generate objects (in our case lakes) with sizes obeying a lognormal (LN) distribution (Supplementary Material) (Crow & Shimizu, 1988). Thus, our expectation based on simple physical arguments is that arctic deltas should universally exhibit lakes whose sizes are lognormally distributed. In particular, since we only observe lake sizes above 5,400 m^2 (6 pixels) we expect lake sizes to follow a truncated lognormal distribution (Equation 1):

$$f_x(x;\nu,\beta^2) = \begin{cases} 0 & for\ x < x_{min} \\ \dfrac{\frac{1}{x\beta\sqrt{2\pi}} e^{\frac{-(ln(x)-\nu)^2}{2\beta^2}}}{\left[1-\Phi\left(\frac{ln(x_{min})-\nu}{\beta}\right)\right]} & for\ x \geq x_{min} \end{cases}, \qquad (1)$$

where $\Phi(\cdot)$ is the cumulative distribution function (CDF) of a standard normal variable, ν is the scale parameter, β the shape parameter, and x_{min} the minimum value at which the LN is observed, here 5,400 m^2 (Clauset et al., 2009). When x_{min} approaches zero, the denominator approaches unity and Equation (1) is simply the LN distribution.

Having separated lakes and wetlands based on the methodology outlined in section 2, we examined the empirical probability density function (PDF) of lake sizes (Figure 3a). As postulated, we found that the examined lake sizes can be accurately described by a truncated LN distribution for the whole range of lake sizes (spanning 3.5 orders of magnitude) in the 12 deltas under study (see Quantile-Quantile (Q-Q) plots in Figure 3b). The rigorous Lilliefors-corrected Kolmogorov-Smirnov (KS) test (Clauset et al., 2009), shows that for every delta, the fitted LN distribution could not be rejected at the 5% significance level within the range of thresholds θ utilized for the identification of lakes from the general waterbody population (Tables S1 to S3). For most deltas, the LN fit could not be rejected over the entire range, but in several deltas the test outcome depended on the threshold, due to the fact that the hydrogeomorphological specificities of the different deltas can lead to potential suboptimal lake/wetland separation for certain threshold values and ranges of waterbody sizes. Furthermore, the robustness of the revealed universality of the LN distribution of lake sizes was confirmed by successfully testing that lake sizes are LN distributed when alternative years were used as reference to extract waterbodies (Table S4, Figure S4). Previous empirical (suggesting different distributions for arctic waterbodies) (Muster et al., 2019) and theoretical (suggesting a proportionate growth model) (Victorov et al., 2019) studies have failed to demonstrate this universality because thermokarst lakes and wetlands were analyzed together (Table S5 and Figure S6), and as we show in the next section wetlands do exhibit a different distribution.

4. Wetland size distributions and an inundated topography model

Arctic delta wetlands are, by definition, ephemeral waterbodies emerging on the delta top due to local ice/snow melt and riverine flooding. Therefore, wetland sizes are expected to be highly dependent on the seasonal delta hydrology, which controls overall delta wetness (hydrologic forcing), and delta topography; the topography in turn constitutes the spatial layout for inundation, and controls both the emergence of disjoint wetlands and their sizes for a given forcing. The prevalence of power-law distributions describing the sizes of waterbodies emerging from landscape inundation has been extensively documented (Bertassello et al., 2018; Cael & Seekell, 2016; Le & Kumar, 2014; Mandelbrot, 1982). For instance, recent analysis of the sizes of waterbodies identified from inundating low-relief topography and observed wetlands in the contiguous United States were found to exhibit power law distribution of areas consistent with inundated fractal topography (Bertassello et al., 2018; Le & Kumar, 2014). Therefore, our hypothesis was that the Arctic delta wetlands will follow a similar distribution. The form of the power law PDF used in this study is given in Equation (2), where x_0 is the minimum size above which the power law is fit and α is the power law exponent (Clauset et al., 2009):

$$f_X(x;\alpha) = \frac{\alpha-1}{x_0}\left(\frac{x}{x_0}\right)^{-\alpha}, x > x_0 \qquad (2)$$

We observed that wetland size distributions in the 12 arctic deltas indeed show strong evidence of being power law distributed (log-log linearity over two orders of magnitude in Figure 3c). Using the robust methodology of Clauset et al. (2009) for power law testing and fitting, we found that the power-law hypothesis for wetland sizes could not be rejected at the 5% significance level with a Lilliefors-corrected KS test for all 12 deltas (Tables S1 to S3). As with lakes, the power law distribution of wetland sizes is robust with respect to the threshold θ, which establishes the separation of waterbodies into lakes and wetlands (Tables S1 to S3). Moreover, the robustness of our hypothesis was verified by extracting waterbodies and identifying wetlands in an alternative reference year, wherein again most deltas displayed power law wetland size distributions (Table S4, Figure S4).

Recent literature has hypothesized that lakes in the Arctic are consistent with landscape inundation mechanisms (Muster et al., 2019). This hypothesis was grounded on the finding that empirical statistics of waterbodies obey two relationships (a linear relationship between conditional mean and conditional variance and a hyperbolic relationship between conditional mean and conditional skewness) which are consistent with those arising from an inundation model experiment (Muster et al., 2019). However, as we show here (Supplementary Material, Figure S8) these same relationships arise from a proportionate growth model and a LN distribution, cautioning their use for distinguishing between the power-law and LN probability distributions and making physical inferences.

5. Climate trends

How will the Arctic look like in a warmer future is a question of interest due to the critical impacts that changes in lake and wetland coverage will have on methane emissions (Engram et al., 2020; van Huissteden et al., 2011; Petrescu et al., 2010), release of old carbon (Grosse et al., 2013; Rowland et al., 2010), re-plumbing of surface-subsurface hydrologic partitioning (Walvoord & Kurylyk, 2016), and changes in water and biogeochemical cycling to the ocean (Piliouras et al., 2021; Piliouras & Rowland, 2020). Although physical models could be used to project such changes, their complexity and uncertainty in parameterizations makes it difficult to implement them over large areal extents and long periods of time (van Huissteden et al., 2011; Kessler et al., 2012; Plug & West, 2009). We posit that if robust relationships between lake size distributions and climate variables can be established based on analysis of deltas across a gradient of temperature, soil ice content and permafrost coverage, valuable quantitative insight can be gained for the future. More specifically, we pose the hypothesis that lake sizes encode the signature of climate while ephemeral wetlands are mostly agnostic to it.

We have tested this hypothesis by analyzing the relationships between mean lake and wetland size (areal extent) with respect to MAAT and soil ice content. The data suggest that the mean thermokarst lake size increases by $9 \cdot 10^4$ m^2, i.e. doubling, over a 12°C decrease in the average 2000 to 2016 MAAT (Bromwich et al., 2017), indicating that colder deltas have significantly larger lakes on average (Figure 4a). Modern MAAT may not be representative of paleoclimatic temperature variability; however mean lake size also has a significant linear relationship (p = 0.028, R^2 = 0.40) with delta apex latitude, which is a reasonable proxy for historical temperature differences between the deltas, strongly supporting a temperature to lake size relationship. Mean lake size also generally positively relates to soil ice content, as higher ice content on the delta may support lake growth due to greater settlement from ice melt (Grosse et al., 2013), with lower ice content associated with smaller lakes (Figure 4a). A similar trend between lake sizes and MAAT is observed when an alternative reference year is used to extract waterbodies in (Figure S5a), supporting the robustness of this dependence. On the other hand, the data show no relationship between mean wetland size and MAAT (Figures 4b, Figure S5b). Also expected, but confirmed, mixing the two waterbodies makes it hard to detect the climatic signal on the landscape. Indeed, a joint analysis reveals a non-significant relationship with MAAT (Figure S6d).

The observed relationship for mean lake size and MAAT is attributed to the greater capacity of colder deltas to support large lakes due to their presumably thicker and cooler permafrost, which prevents sub-lake taliks from connecting to the sub-permafrost groundwater table (Walvoord & Kurylyk, 2016). This connection in low relief deltaic environments would reduce lake level as river stage recedes through the summer, transitioning the margins of perennially inundated lakes to ephemerally inundated, thereby reducing lateral thermal fluxes from the lake to the surrounding permafrost, i.e. diminishing lake growth and decreasing the observed size of perennially inundated lakes (Figures 4c and 4d). Such an effect would be clearest in large lakes which have deep taliks (Grosse et al., 2013), and indeed, we found that the peripheries of large lakes were inundated more often on average over the period of record on warmer deltas compared with colder deltas (Figure 4e). Note that the fraction of the periphery that remains water (inundated) on average over the period of record (Figure 4e) is computed as the average w_i of all pixels bordering the lake (in an 8-neighbor sense), and then the average of large lakes (defined as those with areas between 10^5 and 10^6 m^2) over the entire delta computed to obtain a representative value.

Such a relationship may also occur due to evapotranspiration rates being higher on warmer deltas, which lead to greater lake margin loss. However, we found that average June-July precipitation minus evapotranspiration (P-ET, i.e. the vertical hydrologic budget) (Bromwich et al., 2017) over the delta is uncorrelated with MAAT, and therefore P-ET does not explain the relationship between delta temperature and how often lake peripheries are inundated (Figure S5d). This mechanism could be validated in future studies by imaging subsurface permafrost structure across the deltas which has been done in other permafrost environments (Rey et al., 2019).

6. Perspectives and Conclusions

By harnessing more than 20 years of remote sensing data over the Arctic, we have developed a methodology to classify waterbodies, depending on their year-to-year variability, as lakes (perennial) and wetlands (ephemeral). The statistical distributions of lake and wetland sizes are distinct and appear to be universal across arctic deltas, reflecting the respective underlying mechanisms driving the formation and evolution of those waterbodies. Specifically, it was found that thermokarst lake sizes obey a lognormal distribution, which can be interpreted as the emergent signature of the thermal mechanism driving lake formation and growth. On the other hand, wetland sizes were found to exhibit a power law distribution compatible with landscape inundation models relevant to ephemeral waterbodies (Bertassello et al., 2018; Le & Kumar, 2014). The difference between the underlying forming mechanisms leads also to different expectations with respect to possible relationships with climatic variables. Indeed, our results reveal a significant trend between mean lake size and mean annual air temperature, supporting the hypothesis that colder environments are able to grow and sustain larger thermokarst lakes, while no signature of climate is found in the mean wetland sizes. The power law exponents of the wetland size distributions were found to range between 1.8 and 2.8 (a smaller exponent indicates a thicker tail of the PDF) and further analysis of high-resolution topography is expected to provide additional insight on this range. The decreasing trend of mean lake size with warmer temperatures found here can form the basis for future lake area change projections, recognizing however that the relationship from the 12 examined deltas, although statistically significant, explains only 40% of the variance and lake change may display significant spatial variability (Chen et al., 2012). Spatially resolved permafrost depth and ground ice content on the deltas (Rey et al., 2019), as well as analysis of physically-based models forced with different climate scenarios (Coon et al., 2019; Overeem et al., 2018) is needed to better understand cause-and-effect and derive relationships that can serve as the basis of projections of landscape change (e.g. increased water ephemerality under warming scenarios) and associated carbon cycle impacts in specific delta environments.

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Data Availability

The Global Surface Water monthly water masks are available via Google Earth Engine (https://earthengine.google.com/). The Arctic Systems Reanalysis V2 data is available from University Corporation for Atmospheric Research (UCAR) Research Data Archive (RDA) (https://rda.ucar.edu/datasets/ds631.1/). The ice content data is available from the National Snow and Ice Data Center (NSIDC) (https://nsidc.org/data/ggd318). Code to reproduce this analysis are available from the corresponding author upon request.

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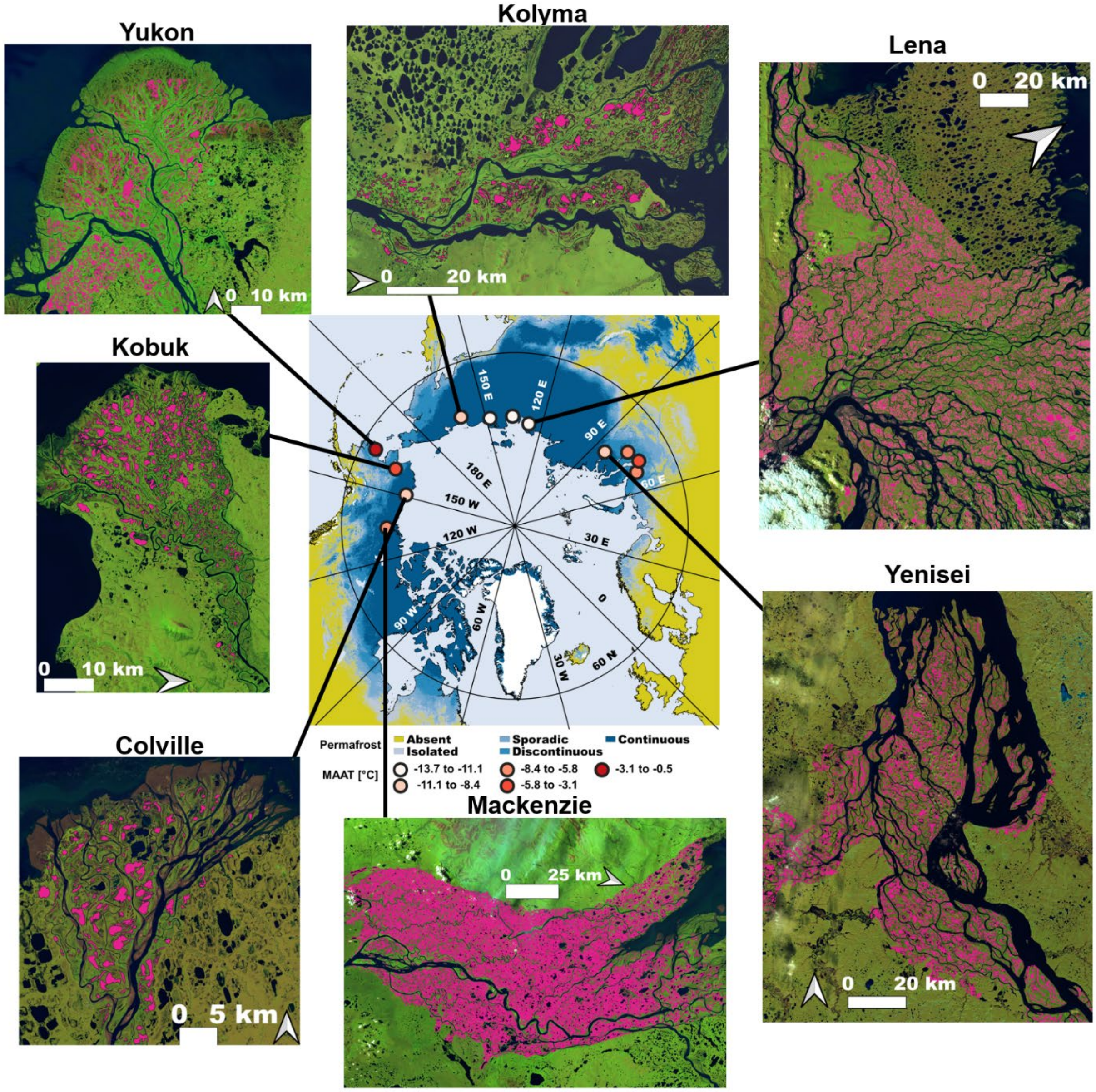

Figure 1. Arctic deltas examined in this study. Twelve arctic deltas (see colored open circles in the central panel for location) were examined along a range of Mean Annual Air Temperature (MAAT) and ice content. The central map shows delta locations, colored by 2000-2016 mean MAAT, estimated from the Arctic Systems Reanalysis V2 (Bromwich et al., 2017), and underlain by Arctic permafrost zonation (Obu et al., 2019). Summertime Landsat-8 scenes of 7 out of the 12 delta are shown with waterbodies identified from a single July Global Surface Water mask (Pekel et al., 2016) colored in pink.

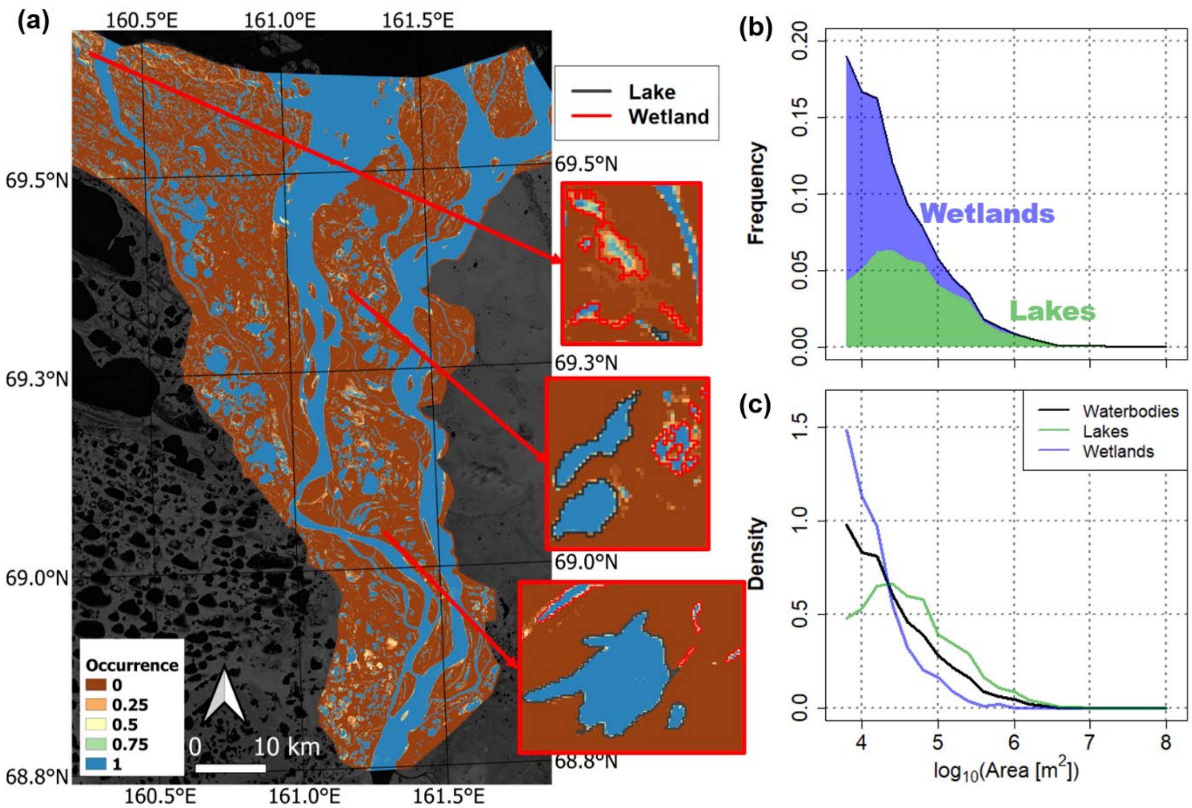

Figure 2. Example of waterbody classification procedure on Kolyma Delta. The waterbody classification procedure which marks waterbodies as either perennial lakes or ephemeral wetlands based on their July occurrence index, and the resulting size distribution. (a) July pixel water occurrence w_i over the Kolyma delta from 1999 to 2018. Brown indicates land pixels ($w_i = 0$) and blue indicates perennially inundated water pixels ($w_i = 1$), with colors in between indicating water pixels indicated only a fraction of the time. (b) The histogram of waterbody sizes is partitioned into the relative fraction of lakes (green) and wetlands (blue) at an occurrence index threshold $\theta = 0.85$. (c) The probability density function (PDF) of lake sizes in green and wetland sizes in blue, compared with waterbody sizes in black.

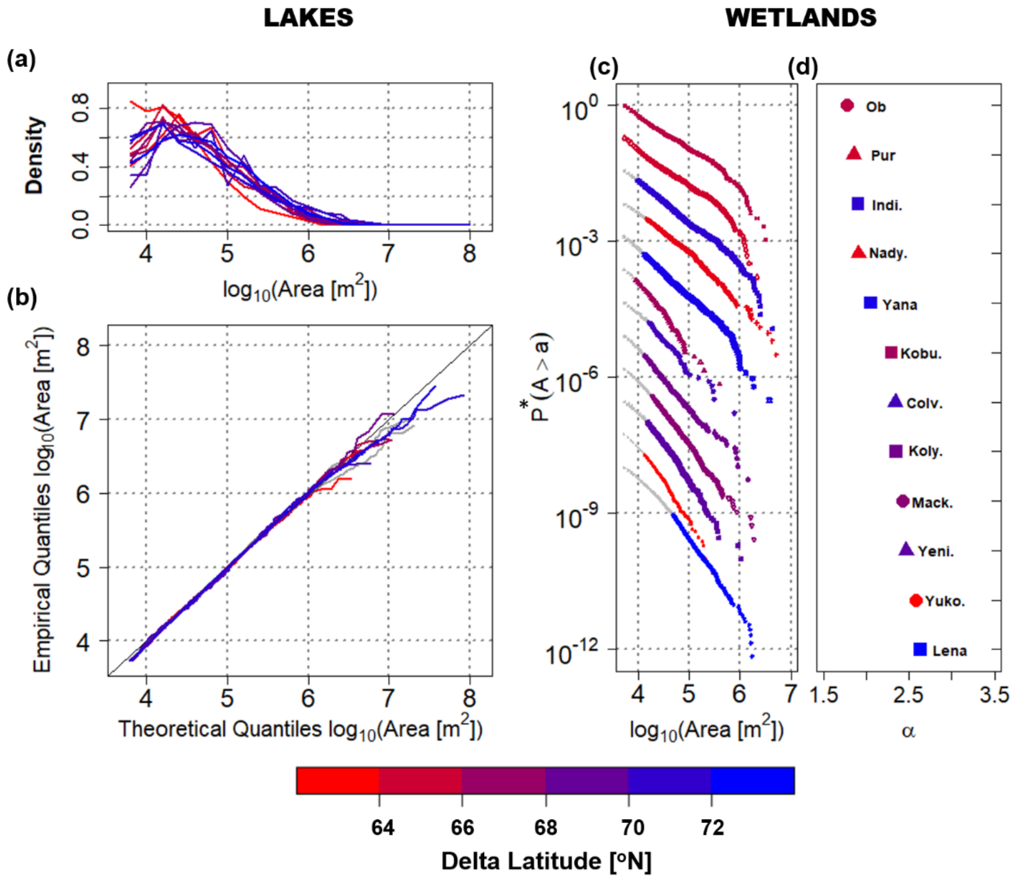

Figure 3. Size distributions of lakes and wetlands extracted at occurrence index threshold $\theta = 0.85$. (a) Lake size PDFs for the 12 deltas, (b) quantile-quantile plots of the lognormal with truncation from below at the minimum lake size (5,400 m^2) fitted to the lake size distribution. In (b) fitted distributions whose fit to data is rejected at the 5% significance level (KS test) are in grey. (c) Wetland size exceedance probability, (d) fitted power law exponent, α, of all 12 deltas. The exceedance probabilities in (c) are rescaled by a factor τ, i.e. $P^* = P\tau$, for visual display, and are ordered by increasing values of α to highlight the range of observed α. For each delta, power laws are fit to the colored points above the minimum wetland size, x_0, which was optimally determined using the procedure of Clauset et al. (2009). The power law parameter α in (d) is the scaling exponent of the PDF.

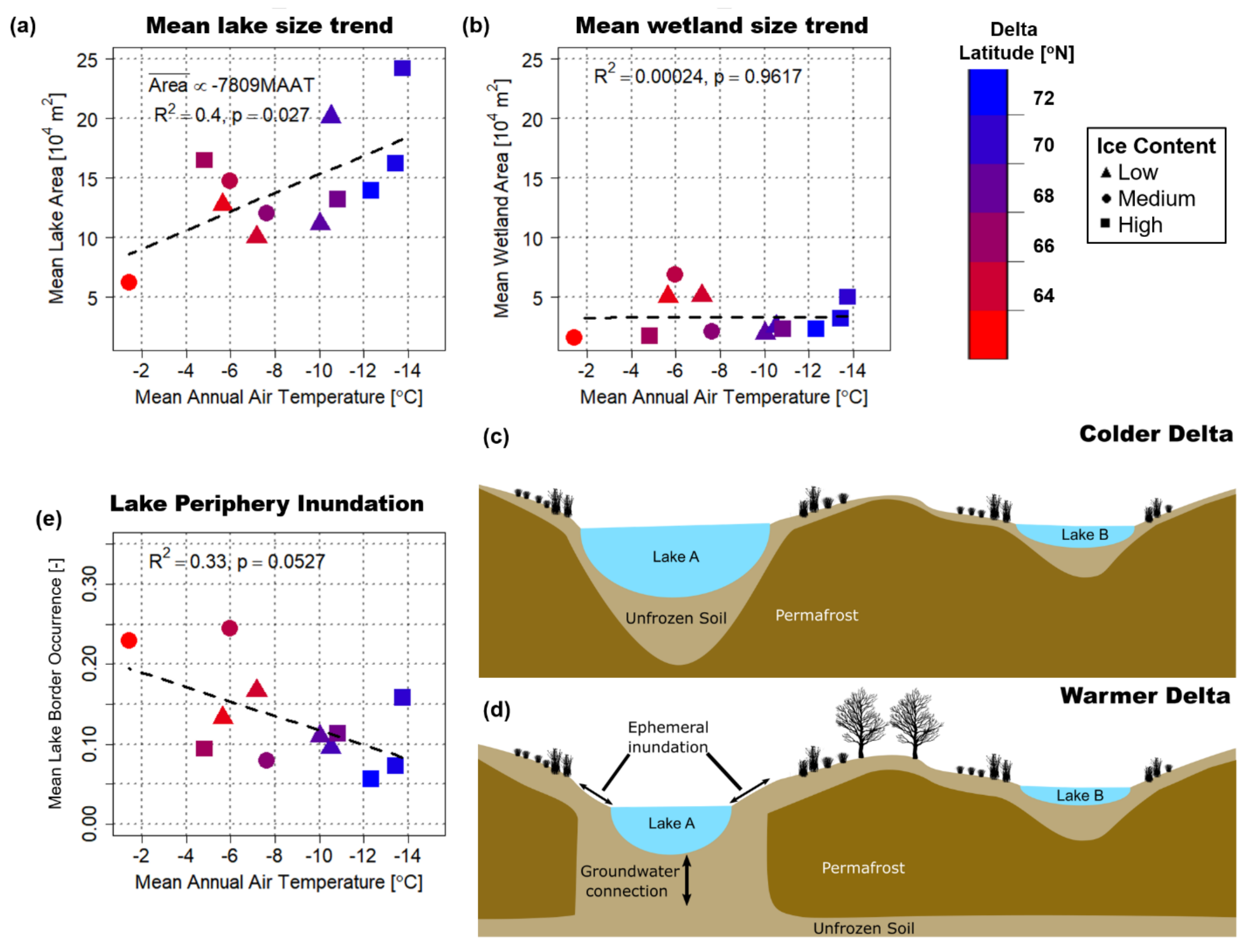

Figure 4. Lake and wetland size climate trends. (a) Scatterplot between mean lake size and MAAT showing a significant relationship between the two. (b) Scatterplot between mean wetland size and MAAT showing lack of a significant relationship. (c, d) The relationship between lake size and MAAT is attributed to colder deltas having thicker permafrost which prevents lakes from connecting to the sub-permafrost aquifer. In warmer deltas, connection to the sub-permafrost aquifer leads to greater lake level change over the summer, driving increased variability in inundation along the peripheries of lakes, and diminishing rates of thermally-driven lateral expansion. (e) Scatterplot between the fraction of the periphery of large lakes that remains water on average over the period of record and MAAT shows a weak (i.e. p~0.05) linear relationship, supporting this mechanism.