

Water Resources Research

RESEARCH ARTICLE

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Key Points:

- Five hundred and thirty five water isotope samples taken over 2 years in Pituffik, Greenland, provide insight into High Arctic isotope hydrology
- Spatially, lake water isotopic composition reflects the degree that evaporation losses are offset by precipitation and snowmelt recharge
- Evaporation drives summer-long lake water isotopic evolution and best explains interannual isotopic differences

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Pivotal Role of Evaporation in Lake Water Isotopic Variability Across Space and Time in a High Arctic Periglacial Landscape

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Abstract Rapidly changing climate is disrupting the High Arctic's water systems. As tracers of hydrological processes, stable water isotopes can be used for high quality monitoring of Arctic waters to better reconstruct past changes and assess future environmental threats. However, logistical challenges typically limit the length and scope of isotopic monitoring in High Arctic landscapes. Here, we present a comprehensive isotopic survey of 535 water samples taken in 2018 and 2019 of the lakes and other surface waters of the periglacial Pituffik Peninsula in far northwest Greenland. The $\delta^{18}\text{O}$, $\delta^2\text{H}$, and deuterium-excess values of these samples, representing 196 unique sites, grant unprecedented insight into the environmental drivers of the regional hydrology and water isotopic variability. We find that the spatial variability of lake water isotopes can best be explained through evaporation and the hydrological ability of a lake to replace evaporative water losses with precipitation and snowmelt. Temporally, summer-long evaporation can drive lake water isotopes beyond the isotopic range observed in precipitation, and wide interannual changes in lake water isotopes reflect annual weather differences that influenced evaporation. Following this, water isotope samples taken at individual times or sites in similar periglacial landscapes may have limited regional representativeness, and increasing the spatiotemporal extent of isotopic sampling is critical to producing accurate and informative High Arctic paleoclimate reconstructions. Overall, our survey highlights the diversity of isotopic compositions in Pituffik surface waters, and our complete isotopic and geospatial database provides a strong foundation for future researchers to study hydrological changes at Pituffik and across the Arctic.

Plain Language Summary Water isotopes can help us track how rapidly changing climate is disrupting High Arctic water systems, but the challenging Arctic environment has limited the monitoring required to understand these isotopes. To address this, we collected 535 water isotope samples from lakes and other waters on the Pituffik Peninsula in northwest Greenland in 2018 and 2019. We found that differences in lake water isotopes are mainly due to water evaporation and how connected a lake is to sources of precipitation and snowmelt that can replace evaporated water in the summer. The information we collected about isotopes is a good starting point for other scientists who want to study how water is changing, not just in Pituffik, but also in the whole Arctic. Our findings tell us that if we only collect water samples once or twice, or only in one place, we might not get the full picture of what is happening with the isotopes across the whole region. To get a better understanding of how the climate is changing in the High Arctic, water isotopic samples should be collected from a wide range of locations over long periods of time.

1. Introduction

Anthropogenic climate change is transforming periglacial water systems in the Arctic by shifting the seasonality, intensity, and sources of precipitation, as well as thawing permafrost, increasing surface evaporation, and lengthening snow- and ice-free summers (Bailey et al., 2021; Bintanja & Selten, 2014; Box et al., 2019; Farquharson et al., 2019; Lupascu et al., 2014; Mellat et al., 2021; Vonk et al., 2015). These transformations are greatly disrupting existing ecosystems and biogeochemical cycles (e.g., N. J. Anderson et al., 2017; Bhatt et al., 2017; Buchwal et al., 2020; Gimeno et al., 2019; Hiltunen et al., 2022), as well as threatening long-established livelihoods of indigenous Arctic communities (Hauser et al., 2021; Wesche & Chan, 2010).

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Despite the Arctic experiencing some of the most rapid climate change on Earth (Serreze & Barry, 2011), freshwater systems in the Arctic (e.g., lakes, streams, supra-permafrost flow) are less studied and monitored than systems in other regions of the world due to their remoteness, harsh environments, and relatively lower magnitude of use by human populations (Linderholm et al., 2018). As a result, this lack of baseline studies and data can make it difficult to quantify how the hydrology of an Arctic region has changed or is currently changing. Here, we provide one such baseline study through a foundational overview of the surface freshwater system across the periglacial Pituffik Peninsula in northwest Greenland using water stable isotopes.

In recent years, water isotopic compositions (discussed here through $\delta^{18}\text{O}$ and $\delta^2\text{H}$, where $\delta = \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1$ and R is the measured ratio of rare to abundant isotopologue) have been harnessed with great success in the Arctic to identify moisture sources of precipitation and water vapor (e.g., Akers et al., 2020; Bailey et al., 2021; Bonne et al., 2014; Cluett et al., 2021; Kopec et al., 2019; Mellat et al., 2021), to estimate lake water balances (e.g., L. Anderson et al., 2013; Arp et al., 2015; Cluett & Thomas, 2020; Gibson & Reid, 2014), to examine plant ecophysiology (e.g., Jespersen et al., 2018; Muhic et al., 2023), and to reconstruct past climate (e.g., Daniels et al., 2021; Lasher et al., 2017; MacGregor et al., 2020; McFarlin et al., 2019). Provided that the isotopic ratios of water sources are known or can be estimated, the isotopic composition of environmental waters in lakes, streams, and the subsurface can also be used to track water movement and calculate hydrological budgets across the landscape (e.g., Bowen et al., 2018; I. D. Clark & Fritz, 1997; Gibson et al., 2016; Kendall & McDonnell, 1998; Noor et al., 2023; Wilcox et al., 2022).

Our study presents isotopic data for over 500 individual water samples from 200 unique sites across Greenland's Pituffik Peninsula along with an associated hydrological geospatial database. By systematically sampling nearly all water bodies in this large ($>800 \text{ km}^2$) study region over two consecutive summers, we provide a comprehensive isotopic baseline data set of the lakes, streams, and other surface waters. We then use these survey data to determine the environmental drivers of Pituffik lake water isotopes and advise best practices for environmental and paleoclimate researchers working in similar polar landscapes. In all, these data offer a spatially and temporally detailed snapshot of a largely intact High Arctic hydrological landscape that gives future researchers a reference point for how much the environment will have changed since the early 21st century.

2. Background

2.1. Water Isotopes as Environmental Tracers

The stable isotopic compositions of water serve as key environmental tracers for hydrological processes (Craig, 1961; Dansgaard, 1964; Gat, 1996; Gonfiantini, 1986; Rozanski et al., 1993). Tracing is possible because water molecules containing heavier isotopes of oxygen and/or hydrogen are discriminated against through isotopic fractionation during phase transitions from solid to liquid to vapor and favored during the reverse transitions. This fractionation leads to a strong linear relationship in oxygen and hydrogen isotopic ratios in precipitation that is described globally with the global meteoric water line (GMWL) where $\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10\text{‰}$ (Craig, 1961). At a local scale, this isotopic relationship can be described for precipitation with local meteoric water lines (LMWL) (Putman et al., 2019; Rozanski et al., 1993) and for atmospheric water vapor as local water vapor lines (LWVL). As a result, the stable isotopic ratios of two identical source waters will diverge from each other in predictable ways as they experience different histories of evaporation, condensation, and transportation.

Along with $\delta^{18}\text{O}$ and $\delta^2\text{H}$, the second-order isotopic parameter of deuterium-excess (dxs) provides additional insight into hydrological processes experienced by a sampled water. Diffusion across a humidity gradient during evaporation will slightly favor the vapor phase enrichment of H^2HO relative to the more slowly diffusing H_2^{18}O molecule, and the impact of this nonequilibrium process can be quantified through dxs , where $dxs = \delta^2\text{H} - 8 \cdot \delta^{18}\text{O}$ (Craig & Gordon, 1965; Merlivat & Jouzel, 1979). Due to this process, open bodies of water that experience sustained evaporative losses will have lower dxs values, and their $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values will plot along a local evaporation line (LEL) that falls below the GMWL and LMWL in $\delta^2\text{H}$ – $\delta^{18}\text{O}$ space (i.e., the slope value of the $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$ linear relationship will be lower than the slope values of the GMWL and LMWL). Together, these isotopic characteristics permit both relative and quantitative comparison of evaporative impact across a water system.

Water stable isotopes are particularly valuable for offering a quantitative method to determine and compare water balance changes in lakes. The isotopic composition of a lake at a given point in time reflects its current isotope-mass balance (Gibson et al., 2016; Gonfiantini, 1986), represented as

$$V \frac{d\delta_L}{dt} + \delta_L \frac{dV}{dt} = I\delta_I - Q\delta_Q - E\delta_E \text{ (‰} \cdot \text{m}^3 \cdot \text{year)} \quad (1)$$

where V is the lake volume, t is time, I is total lake inflow, Q is total lake outflow, E is evaporation, and δ_L , δ_I , δ_Q , and δ_E are the respective isotopic compositions of the lake, inflow, outflow, and evaporation flux. Based on Equation 1, we expect lakes with different environmental characteristics related to volume, inflow, outflow, and evaporation to exhibit spatial isotopic variability. Likewise, local weather and seasonal climate changes that affect these hydrological parameters will drive temporal lake isotopic variability. Following this understanding, an isotopic survey of lakes across a region can help determine which environmental parameters are most important in controlling the hydrological budget of the local surface water system.

2.2. Geographic Overview of the Pituffik Region

Our study focuses on the “Pituffik region” of northwest Greenland which we define here as synonymous with the Pituffik Peninsula and its nearby offshore waters (Figure 1). The region covers roughly 880 km² of ice-free land bounded by the Greenland Ice Sheet (GrIS) to the east, Baffin Bay and Bylot Sound to the west, and Ummannap Kangerlua (Wolstenholme Fjord) to the north (76.25°–76.60°N, 67.60°–69.70°W). This region is also known as “Thule” in reference to its original Danish placename and a subsequent United States military base. Place name priority throughout this text will be given as indigenous Greenlandic names first if known (Oqaasileriffik, 2022), followed by common English and Danish names, and finally informal names that we assigned to features with no known names. Despite extensive efforts, we could not find indigenous names for Pituffik lakes and found only a few local English or Danish names; therefore, most lake names are informal.

The Pituffik region holds an outsized role in the ecology and history of the Greenlandic and Canadian High Arctic. Alongside large populations of marine mammals and waterfowl, Pituffik is well-known for its immense seabird colonies that cloak coastal valleys (Burnham et al., 2014; Hastrup et al., 2018; Heide-Jørgensen et al., 2016; Mosbech et al., 2018). This biological productivity, supported by the relatively close North Water polynya, has drawn humans to the region for thousands of years (Gronnow, 2016; Hastrup et al., 2018), and the Thule culture, ancestral to modern Inuit and Greenlandic peoples, was first formally described from excavations conducted on the northern coast of the Pituffik Peninsula (Jenness, 1925). Today, most of the entire peninsula surface is covered by coarse glacial deposits with sparse polar desert vegetation (Corbett et al., 2015; Funder, 1990; Nichols, 1953). More lush vegetation occurs in low-lying moss wetlands and within the seabird colony valleys (Cuyler et al., 2022; Mosbech et al., 2018) in contrast to vast stretches of boulder and cobble outwash plains that extend out from the GrIS margin and support only lichens (Davies & Reitzel, 1963).

With the construction of Thule Air Base (now Pituffik Space Base) in the 1950s, the Pituffik Peninsula became a focal point for environmental studies of the Arctic and cryosphere (Nichols, 1953; Ries, 2012; Schytt, 1955; Swinow, 1962). This American military funding laid foundations for modern ice core drilling and paleoclimate studies (E. F. Clark, 1965; Dansgaard et al., 1969; Hansen & Langway, 1966), but the base also ushered in a period of forced indigenous community relocations, environmental degradation, and novel resource access that has major ongoing impacts on Greenlandic culture and politics (Colgan et al., 2016; Eriksson et al., 2004; Gronnow, 2016; Takahashi, 2019). Today, the logistical ease offered by the base's transport and housing infrastructure enables multiyear environmental research projects that would otherwise be extremely difficult in the High Arctic (e.g., Akers et al., 2020; Burnham et al., 2014; Corbett et al., 2015; Jespersen et al., 2022; Leffler & Welker, 2013).

The landscape of the Pituffik Peninsula has numerous distinctive landmarks, including the flat-topped Ummannap (Mount Dundas) and the broad valley now filled by Pituffik Space Base (Figure 1a). The southern peninsula has relatively gently sloped uplands culminating in the 815 m Pingorsuit massif while the northern peninsula near the military base has many broad ridges, steep-faced outcrops, and lakes (Davies & Reitzel, 1963). To the east, the Tuto ice dome of the GrIS covers ≈1,000 km², rising gently from the tundra to reach maximum elevations over 1,000 m. Although connected to the main GrIS, the Tuto dome has a largely independent mass balance regulated by local precipitation, extensive summer surface melt, and discharge through several large marine terminating glaciers. The Tuto dome has substantially thinned in recent decades due to climate change that is also driving the loss of permanent snowfields across the peninsula and 1–5 km retreat of tidewater glaciers (Copernicus, 2019; Korsgaard et al., 2016; Müller et al., 2021).

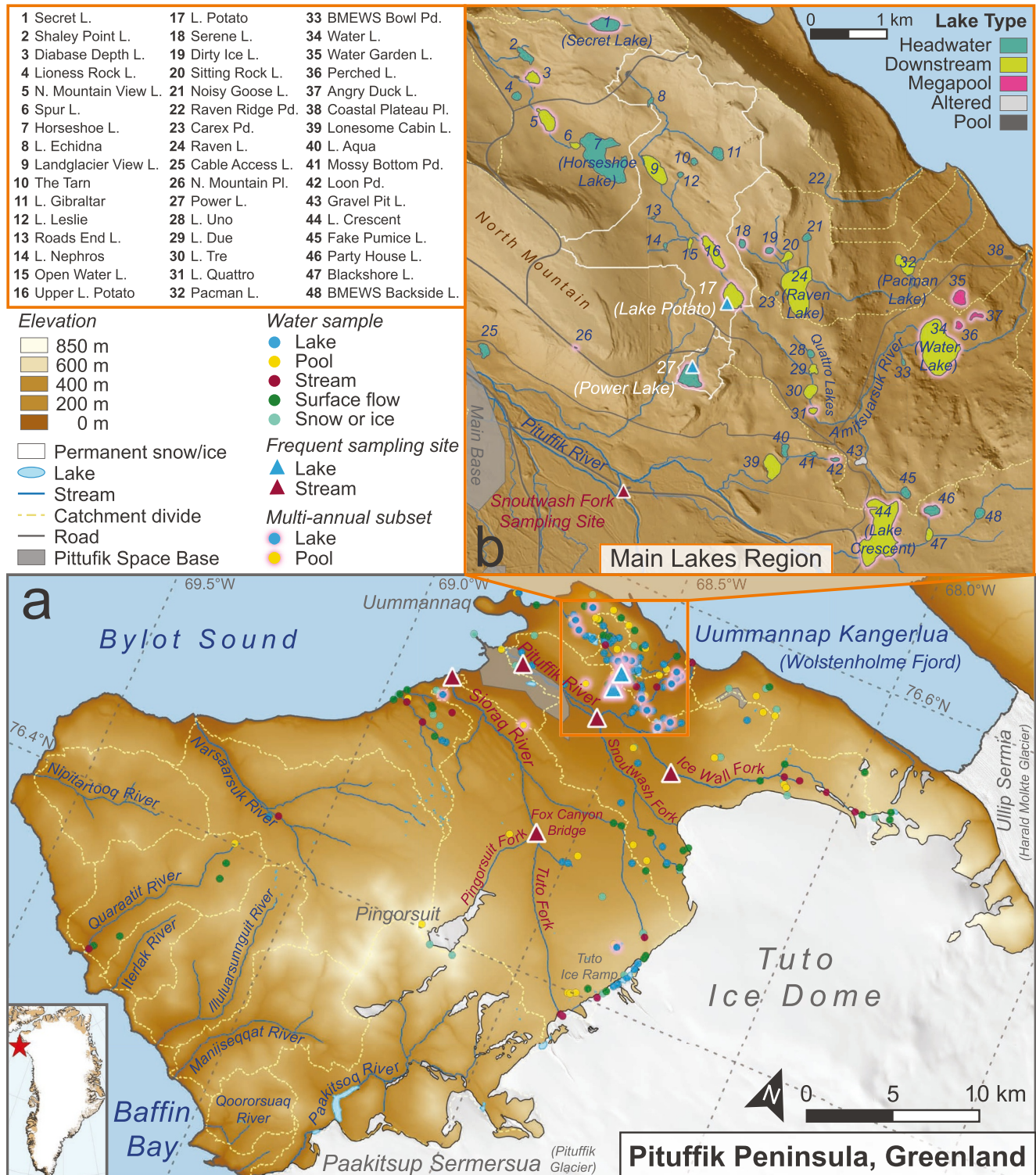


Figure 1. Map of the Pituffik region of northwest Greenland. Across the full Pituffik Peninsula (a), water sample sites (circles) are colored according to the type of surface water sampled. The eight lake and stream sites frequently sampled for temporal study are shown by triangle icons, and samples for the Pingorsuit and Tuto Forks of the Sioraq River were both taken at the Fox Canyon Bridge where the forks join. Lakes and pools sampled during each of the three main sampling periods for local evaporation line (LEL) and interannual analyses are highlighted by pink. The main lakes region is given additional focus (b) to show the spatial distribution of the main lakes and their lake type categories. Note that no vale or proglacial lakes are present in the main lakes region. The catchment boundaries for Lake Potato and Power Lake are shown as white outlines. Geospatial data used to construct the map includes ArcticDEM (Porter et al., 2019), ice and ocean masks from the Greenland Ice Mapping Project (Howat, 2019), and place names from the Language Secretariat of Greenland (Oqaasileriffik, 2022).

Pituffik Climatology

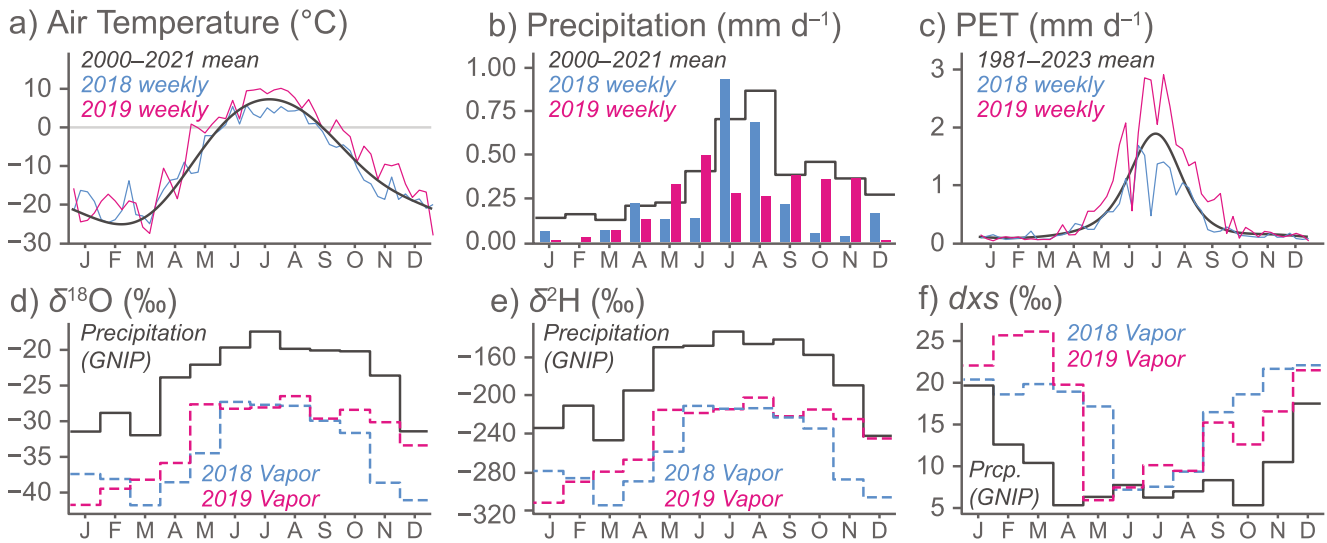


Figure 2. Pituffik climate and water isotopic data. Mean values for daily air temperature (a) and monthly precipitation rate (b) are taken from 2000 to 2021 USAF weather observations at Thule Airport (USAF, 2019). Climate data for 2018 and 2019 are taken from the nearby SMT weather station (temperature; Muscari, 2018) and USAF airport observations (precipitation; USAF, 2019). Potential evapotranspiration (PET) values (c) of both daily mean and weekly values for 2018 and 2019 are extracted for Pituffik from the global database provided by Singer et al. (2021). Monthly isotopic means of $\delta^{18}\text{O}$ (d), $\delta^2\text{H}$ (e), and dxs (f) are provided for precipitation from GNIP 1966–1971 observations (IAEA/WMO, 2022) and for near surface water vapor at SMT station in 2018 and 2019 (Akers et al., 2020).

2.3. Pituffik Climate and Hydrology

The Pituffik climate has extreme seasonal changes between its brief summer thawed season and the long frozen season. On average, mean daily temperatures at Pituffik are above freezing only from 01 June to 12 September, and the bitterly cold winters regularly drop well below -20°C (Figure 2a). The mean annual precipitation over the period 2000–2021 is 130 ± 15 mm (95% confidence interval) with the highest precipitation rates occurring from mid to late summer (Figure 2b) when nearby Baffin Bay is largely ice-free and can supply and/or support atmospheric moisture transport (Akers et al., 2020). Precipitation is highly variable year to year in both total amount and seasonality, but it must be noted that official records struggle with accurately separating snowfall from blown snow in winter, have inconsistent calculations of snow water-equivalence, and had frequent changes ($\sim$ annual) in the weather observer. Relative to 2000–2021 climate means, summer 2018 had near normal temperatures and precipitation with below average potential evapotranspiration (PET) while summer 2019 was much warmer than normal, rather dry, and had much higher than normal PET (Figures 2a–2c).

Water isotopes in precipitation and atmospheric vapor (Figures 2d–2f) monitored at Pituffik exhibit seasonal cycles linked to both air temperature and changing water sources (Akers et al., 2020; IAEA/WMO, 2022). The LMWL ($\pm 95\%$ confidence intervals) calculated from GNIP samples taken between 1966 and 1971 is $\delta^2\text{H} = (7.5 \pm 0.2) \cdot \delta^{18}\text{O} - (3 \pm 5) \text{‰}$ (IAEA/WMO, 2022). For 2018 and 2019, the LWVL as calculated through daily water vapor isotopic means was $\delta^2\text{H} = (7.0 \pm 0.0) \cdot \delta^{18}\text{O} - (18 \pm 5) \text{‰}$ (Akers et al., 2020). Summer water vapor isotopic values were similar in 2018 and 2019, despite the weather differences (Figures 2d–2f).

The Pituffik hydrological system is highly reactive to the thaw of waters frozen in snowpack, glacial ice, and surface waters brought on by both regular seasonal warming and irregular short-term heat events. Although Pituffik surface waters are dry and/or frozen for 7 and 8 months of the year, the melting of the winter snow cover in May and June (Figure S2 in Supporting Information S1) brings an initial freshet period of high surface flow and numerous small pools left in depressions across the tundra. These pools drain in 2 and 3 weeks as summer progresses and the active layer deepens to 1 m or more (Horwath et al., 2008), and summer flows for streams not sourced at the GrIS are sustained largely by melting residual snow patches. For stream basins linked to the GrIS, water discharge often exhibits two seasonal peaks from the early summer snowpack melt and later summer surface melting of the GrIS (Csank et al., 2019). During extreme heat events, such as in 2012 and 2019

Examples of Pituffik lake types

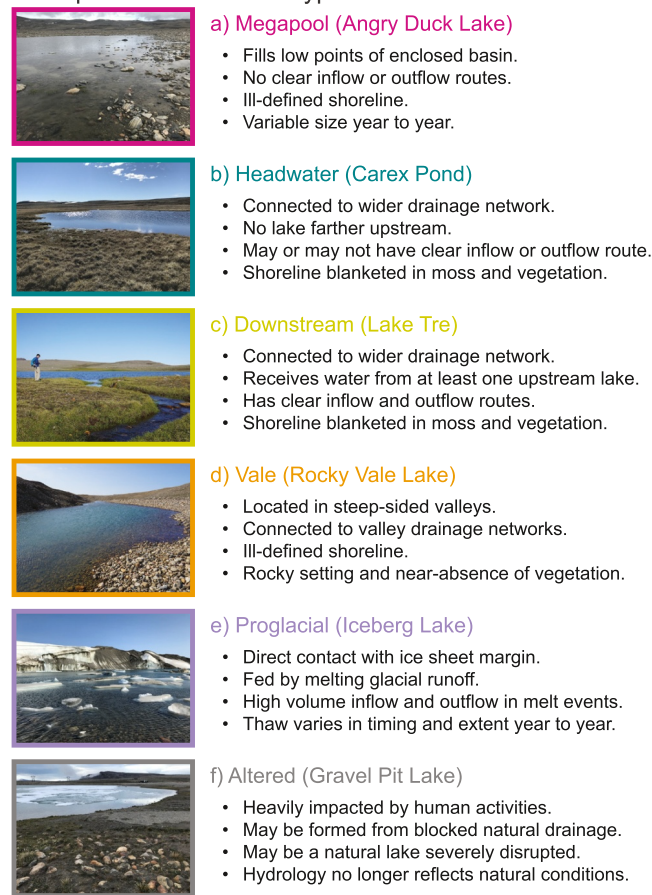


Figure 3. Summaries of the six lake type categories assigned to Pituffik lakes. Each lake category has a named example lake with a photograph that exhibits the major defining characters of its lake type.

(Cullather et al., 2020; Nghiem et al., 2012; Sasgen et al., 2020), massive volumes of glacial runoff greatly swell GrIS-sourced streams and can threaten local infrastructure.

The Pituffik region also hosts numerous permanent lakes most commonly formed in Late Pleistocene moraines and till (Figure S3 in Supporting Information S1). These lakes are typically frozen over between September and April, with ice-out beginning in late May to early June (Figures S2 and S4 in Supporting Information S1). Ice cover is largely intact through June for the largest lakes, and some ice may remain even into August in colder summers. The construction of military buildings and roads affected some lakes and surface drainage networks, most notably with the conversion of Lake Crescent into a dammed reservoir (Davis, 1966). However, aerial photographs predating the military base's construction (Figure S5 in Supporting Information S1) show that the vast majority of lakes still retain their natural layout (Historiske Kort, 2023).

3. Materials and Methods

3.1. Hydrological Survey and Geospatial Database

Our Pituffik field campaigns took place in June–August 2018, November 2018, and July 2019. To support the isotopic field sampling, we created a new hydrological geospatial database for the Pituffik region at a higher resolution and detail than previously offered. Field observations of the regional hydrology taken during the isotopic sampling provided the foundation and ground-truthing for later geospatial analyses. These analyses were performed through QGIS with *GRASS*, *GDAL*, *SAGA*, and *Point Sampling* packages. Surface drainage catchments and stream networks for the Pituffik region were extracted from the 2 m ArcticDEM (PGC, 2019; Porter et al., 2019) with *GRASS* flow and drainage tools. Lakes and roads were hand digitized based on both Sentinel 2 satellite imagery from 15 August 2019 (Copernicus, 2019) and orthorectified aerial imagery from summer 1985 (Korsgaard et al., 2016). Each lake was assigned a lake type category prior to any isotopic analysis from a list of megapool, headwater, downstream, vale, proglacial, and altered based on the lake's environmental character observed in the field (Figure 3).

Geographic coordinates for water sampling sites and notable landmarks were taken with an iPhone 7 GPS and later validated for accuracy with the satellite and aerial imagery. Elevations for sampling sites were extracted from the 2 m ArcticDEM using validated site geographic coordinates. For each lake, the distances to the ocean and to the GrIS (i.e., the Tuto dome margin) were calculated in QGIS as the minimum horizontal distance between the centroid of each lake and the perimeter of the polygons enclosing the ocean and the ice sheet, respectively, using ocean and ice masks defined from the Greenland Ice Mapping Project (GIMP) (Howat, 2019; Howat et al., 2014). Perennial snow patches were excluded from the GIMP ice mask for this calculation to ensure that distances were to the actual GrIS margin.

3.2. Field Sampling

Field sampling of Pituffik surface waters occurred during each of the three campaigns. No marked trail systems exist in Pituffik aside from the local military road network, and sample sites were accessed through overland hiking to geographic coordinates identified through satellite imagery. Surface waters were sorted into seven categories: lakes (standing body of water with a defined shoreline and $>1,000 \text{ m}^2$ surface area), pools (shallow standing body of water with a defined shoreline and $<1,000 \text{ m}^2$ surface area or any size with no defined shoreline), streams (continuous summer flow in a defined channel), surface flow (sheet flow/seeps with undefined channels or very small intermittent streams), snow or ice (fresh or aged snow patches, remnant lake ice, glacial/multi-annual ice, or frost), and both rain and snow precipitation events. Sampling in November 2018 was restricted to precipitation events and the local snowpack as all lakes, streams, and other surface waters were frozen or dry.

We sorted the summer sampling into three main periods: early summer 2018 (14 June and 18 July), late summer 2018 (19 July–23 August), and mid-summer 2019 (19 July–01 August). Although most lakes and streams were only sampled once each sampling period due to remoteness, we frequently sampled (i.e., 10–18 times each) two lakes and six stream sites that were easily accessed by road (Figure 1). Eighteen lakes and two large permanent pools that were also readily accessed were chosen as a representative selection of Pituffik lake types and sampled once in each of the three main periods, and these 20 lakes and pools (referred to as the “multi-annual lake set”) were the focus of many later analyses.

Water samples were collected in clean and dry 50 ml plastic centrifuge tubes that were closed tightly and sealed with Parafilm. For lakes and pools, water was sampled 10–20 cm below the surface from a downwind shore. For streams, water was collected for 3–10 times the duration required to fill the tube (~5–30 s). For snow and ice sampling, enough snow or ice was collected to fill the tube whereupon it was sealed and allowed to melt at ambient air temperature. Rain and snow precipitation were sampled as soon as possible outside building 345 on Pituffik Space Base after each event ended from accumulation in clean rain gauges or, in the case of some snow events, in bowls or the ground surface. For all water samples, tubes were filled as full as possible to limit evaporation into the head space and shipped in liquid state for storage and later aliquot sampling.

Supporting isotopic and climatological data were also collected from multiple sources. Monthly GNIP precipitation data collected at Thule Airport between 1966 and 1971 (IAEA/WMO, 2022) were downloaded to construct a LMWL for isotopic comparison. Meteorological data for 2018 and 2019 were collected through weather stations at two sites on the military base (Muscari, 2018; USAF, 2019), and daily water vapor isotopic means were obtained from a Picarro L2130-i analyzer also installed on the base (Akers et al., 2020). Although archived weather data is available for Pituffik for 1951–present through the Global Historical Climatology Network (GHCN-Daily, 2012), our review of this data found that it had poor quality, especially in precipitation records, and we instead reference a higher quality 2000–2021 weather record directly supplied from the United States Air Force (USAF, 2019) for climatological context. Daily potential evapotranspiration (PET) rates for Pituffik were downloaded from a global 0.1° spatial resolution data set modeled with ERA5-Land reanalysis data (Singer et al., 2021).

Stable isotopic ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) of 2 ml water sample aliquots were measured at the University of Oulu using a Picarro L2130-i isotope and gas concentration analyzer fitted with an autosampler (A0325) and vapourizer unit (A0211). Reference standards of USGS-45 ($\delta^{18}\text{O}$: -2.2‰ , $\delta^2\text{H}$: -10.3‰) and USGS-46 ($\delta^{18}\text{O}$: -29.8‰ , $\delta^2\text{H}$: -235.8‰) were used within each analytical run to monitor and correct for instrumental drift as well as to calibrate to the SMOW-SLAP scales for reporting. Each water sample was measured seven times with data from the first three measurements discarded to limit potential memory effects. Samples were reanalyzed if the standard deviation exceeded 0.3‰ for $\delta^{18}\text{O}$ or 3‰ for $\delta^2\text{H}$, or if the reference standard used in the run differed from the known isotopic value by greater than $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$ or $\pm 2\text{‰}$ for $\delta^2\text{H}$. These standards span the full isotopic range of our Pituffik water samples except for seven winter snow events and two snowpack samples. Although these snow samples' involvement in further analyses was limited, we are still confident of their values as the calibrated Picarro instrument linearly infers isotopic ratios to values well below any of our samples (Casado et al., 2016). Based on within-run replicate analyses of standard waters, mean analytical precision was $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.6\text{‰}$ for $\delta^2\text{H}$. Eighteen water samples were flagged during quality control for having visibly cracked and/or leaking vials after transport, and these samples, along with two tap water samples taken on Pituffik Space Base, were not included in further analyses.

3.3. Spatial and Temporal Analyses of Lake Water Isotopes

To examine Pituffik lake hydrology, we modeled water inflow sources and evaporation from the isotopic data in the multi-annual lake subset. For each non-glacially influenced lake in the subset ($n = 18$), we calculated an LEL and then used these LELs and the LMWL supplied by GNIP data to infer the lakes' inflow source water isotopic compositions with a Bayesian inference model through the *isoWater* package in R (Bowen et al., 2018). Importantly, we note that the inferred inflow source isotopic values represent the lake's isotopic composition if all post-precipitation evaporation influences were removed, and this is not the same as the isotopic composition of the water physically flowing into the lake (which may have accumulated evaporative losses prior to entering the lake).

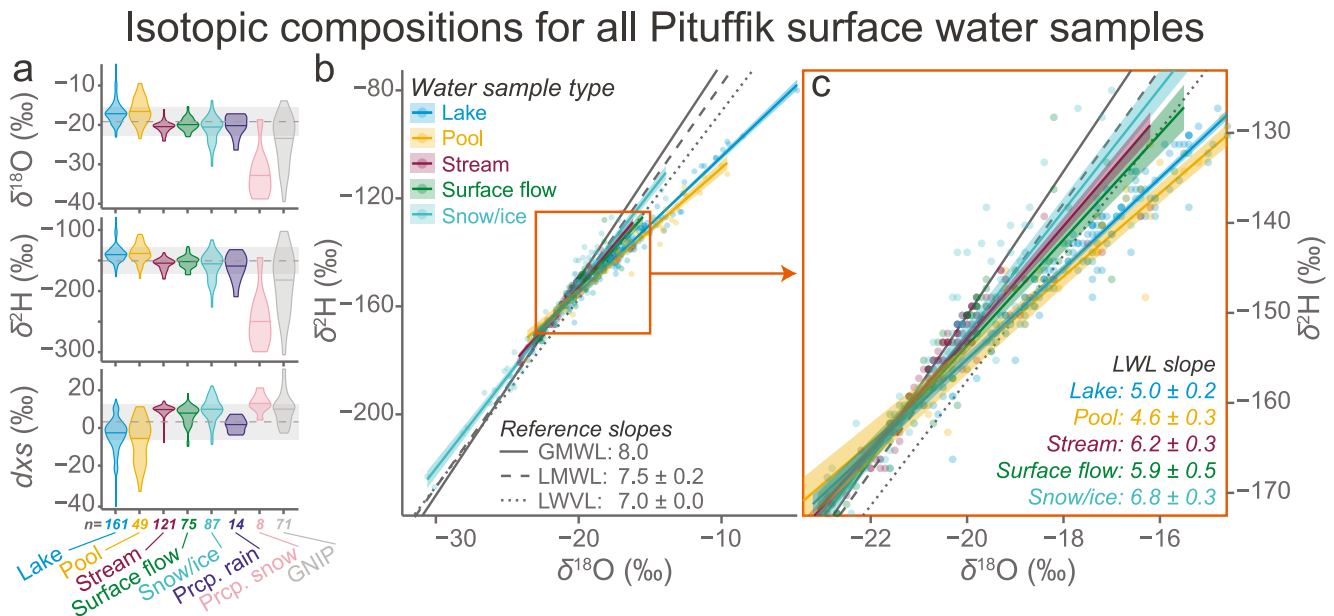


Figure 4. Isotopic compositions of Pituffik surface waters. Violin plots (a) show the distributions of isotopic ratios of Pituffik water samples, grouped by sample source type. The mean isotopic values $\pm 1\sigma$ of all water samples are shown by the dashed line and gray shaded bar crossing all violins, and data are plotted so that the maximum width is equivalent between groups, regardless of sample count (shown at bottom). Within each violin, the median value per group is shown by a solid horizontal line. GNIP samples are monthly precipitation means collected between 1966 and 1971 (IAEA/WMO, 2022). In (b), linear regressions between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ illustrating local water lines (LWLs) are shown for the different sample source types with shading representing the 95% confidence interval of the regression. The global meteoric water line (GMWL, solid gray), local meteoric water line (LMWL, dashed gray) based on GNIP data (IAEA/WMO, 2022), and local water vapor line (LWVL, dotted gray) (Akers et al., 2020) are shown for reference. The plot in (c) is a magnified version of the area indicated with the orange square in (b), and LWL slope values with 95% confidence intervals are provided for each sample type at lower right. Regressions for precipitation data are provided in Figure S6 in Supporting Information S1.

Using a mixing model from the *simmr* R package (Govan & Parnell, 2019), fractional contributions of frozen (September–May) versus thawed (June–August) seasonal precipitation were calculated from these inferred source water isotopic values and GNIP precipitation data. Active layer water that thaws above the permafrost has been noted as an important contributor to Arctic lake water balance (Gorbey et al., 2022), but we do not treat it as distinct from precipitation runoff in considering its isotopic influence on lakes. Sampled surface runoff was isotopically similar to surface snow and ice sampled on the landscape (Figure 4), and we must assume due to lack of other evidence that it does not spatially vary substantially. Furthermore, an evaporation/inflow (E/I) ratio for each lake with an LEL was calculated following the isotopic mass balance equations derived from Equation 1 as summarized in Gibson et al. (2016) and whose full methods are detailed in Text S1 in Supporting Information S1 (Biggs et al., 2015; Cui et al., 2017; Gat, 1995; Horita et al., 2008; Horita & Wesolowski, 1994; Zuber, 1983). Notably, E/I can be calculated for either $\delta^{18}\text{O}$ or $\delta^2\text{H}$, and the results are generally similar but not identical (e.g., Gibson & Reid, 2014).

Although our E/I ratios were calculated using air temperature instead of lake surface temperature, sensitivity testing using a range of possible temperature values suggests that any difference would likely only affect our E/I values by <0.02 . Additionally, since the mean summer Pituffik air temperature, relative humidity, and water vapor isotopic composition leading up to the sampling date are input parameters in the E/I calculations, seasonal weather differences will produce E/I variability that does not derive from the lake water isotopic values alone. Additional sensitivity testing found that using constant values for the atmospheric parameters merely changed the resulting lake E/I output by an average of ± 0.007 (maximum of ± 0.018), and only an average of 4.8% of the E/I value can be attributed to the atmospheric input parameters.

For the spatial analyses of lake water isotopic variability, we first performed multiple linear regression and LASSO regression between the three isotopic variables ($\delta^{18}\text{O}$, $\delta^2\text{H}$, dxs) and six environmental parameters (surface elevation, surface area, catchment area, distance from nearest GrIS margin, distance from nearest ocean coast, and day of year sampled). We restricted this regression analysis to include all 42 headwater and downstream lakes located in the main lakes region (Figure 1) that were sampled in the 2-week mid-summer 2019

sampling period. By only examining lake samples from similar hydrological environments and a short time window, we aimed to increase the sensitivity to subtle lake parameter influences and reduce the impact of temporal isotopic evolution. These regression results then provided the foundation for a broader spatial lake water isotopic overview of all 63 lakes sampled in mid-summer 2019 that combined a hierarchical cluster analysis of $\delta^{18}\text{O}$ and d_{xs} values with contextual support from LEL and E/I results.

The temporal analysis of lake water isotopes focused on isotopic evolution over the 2018 summer season as well as between the summers of 2018 and 2019. For these analyses, we used the frequently sampled data from Lake Potato and Power Lake as well as the multi-annual subset. Lake isotopic changes over time were compared with local weather records (Muscari, 2018; USAF, 2019) and modeled PET (Singer et al., 2021) to interpret the roles that key climatological parameters played in the observed isotopic changes over time. Statistical analyses and figure creation for the entire research were performed in RStudio using the R language with packages *ape*, *broom*, *clock*, *cowplot*, *dendextend*, *gridExtra*, *ggdendro*, *glmnet*, *gridgraphics*, *ncdf4*, *isoWater*, *raster*, *reshape2*, *Rmisc*, *simmr*, and *tidyverse*, and figures were aesthetically adjusted in Adobe Illustrator. Uncertainties for statistical values are given as 95% confidence intervals unless otherwise noted.

4. Results

4.1. Hydrological Survey and Geospatial Database

The geospatial data resulting from our hydrological survey has been made openly available as a geospatial database (Akers et al., 2023b). Individual vector files in the database include points of field observations and place names, polylines of elevation contours, roads, stream networks, and drainage divides, and polygons for lakes, lake drainage basins, stream drainage basins, ice-covered land, and ice-free land. Raster data of digital elevation models (PGC, 2019), aerial imagery (Korsgaard et al., 2016), and satellite imagery (Copernicus, 2019) for the Pituffik region are not provided in the geospatial database due to file sizes, but can be downloaded from their original, openly available sources. Using the geospatial database, we created a hydrology and surface features map for Pituffik that is offered as both a large poster (Figure S1) and as a multipage atlas (Akers et al., 2023b). A general overview of the Pituffik surface water landscape as informed by our hydrological survey results follows.

The surface drainage system of the peninsula is dominated by four main river and stream networks (hereafter referred to collectively as streams) that each drain over 100 km². Together, these four basins of the Sioraq (South River), Paakitsoq (Pituffik Glacier River), Pituffik (North River), and Narsaarsuk Rivers cover half of the non-glaciated land surface of the Pituffik region. An additional seven streams (Maniiseqqat, Illuluaarsunnguit, Quaraatit, Nipitartooq, Qoororsuaq, Iterlak, and Amitsuaarsuk Rivers) drain basins each larger than 10 km² while numerous smaller basins directly drain coastal lands into the ocean. Of these 11 largest stream catchments, only three directly drain meltwater from the GrIS: the Sioraq, Paakitsoq, and Pituffik Rivers. Outside of these streams, well-defined channels are rare across the landscape with most local drainage occurring as sheet flow across the surface or subsurface flow through the coarse rocky active layer.

Around 70 non-proglacial lakes across the peninsula have a surface area greater than 5,000 m², and several very large proglacial and ice-dammed lakes occur along the margins of the Tuto ice dome and its outlet glaciers. Although lakes can be found across the environmental gradient from the coast to the margin of the GrIS at ~500 m a.s.l., over half of the region's lakes are clustered in a 23 km² zone north of Pituffik River and northeast of the military base which we refer to as the “main lakes region” (Figure 1b). The main lakes region includes Lake Crescent, the largest non-proglacial lake on the peninsula at nearly 260,000 m². In total, approximately 3.8 km² of the Pituffik surface is covered by lakes, of which 2.4 km² are non-proglacial.

4.2. General Isotopic Summary of Surface Waters

In total, we collected 535 samples from 196 unique sites across the Pituffik region, representing 67 lakes, 37 pools, 24 sites along major streams, 50 sites with surface flow, and 57 snow or ice deposits. Multiple sample types (e.g., both snow deposits and surface flow) were collected at some sites. The $\delta^{18}\text{O}$, $\delta^2\text{H}$, and d_{xs} of the samples largely fall within similar ranges regardless of origin with mean $\pm 1\sigma$ isotopic values for all samples of $\delta^{18}\text{O}$: $-19.3 \pm 3.6\text{‰}$, $\delta^2\text{H}$: $-151 \pm 22\text{‰}$, and d_{xs} : $+3 \pm 9\text{‰}$ (Figure 4a). The winter snow precipitation events are an exception to this general similarity, being much isotopically lighter than the mean. Across the other samples, we observe that lakes and pools are generally isotopically heavier than other sample types with d_{xs} lower on average

than other types. Lake and pool d_{xs} also have a substantial skew toward extreme lower values of -10 to -40‰ . This wide range in Pituffik lake isotopic values is comparable in magnitude to the isotopic range reported from lakes 1,300 km south in Kangerlussuaq, Greenland (Cluett & Thomas, 2020; Leng & Anderson, 2003). The mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of streams, surface flow, and snow/ice deposits are similar to our observed rain events and much higher than snow events with d_{xs} values intermediate between rain and snow events.

Linear regressions of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ (the local water lines, or LWLs) show that different water source types isotopically diverge from the GMWL and the LMWL to different degrees (Figures 4b and 4c, Table S1 in Supporting Information S1). Precipitation events of both snow and rain have slopes that are similar to the isotopic reference lines (Figure 4, Figure S6 in Supporting Information S1) while snow and ice sampled from across the landscape have slightly lower slope values than the water lines and precipitation, which is likely due to sublimation and melt loss of the aged snowpack (Madsen et al., 2019; Sokratov & Golubev, 2009; Uemura et al., 2005). The liquid surface waters of lakes, pools, streams, and surface flow all display LWL slopes lower than the GMWL and LMWL that we interpret as evaporation driven LELs (Figure 4, Table S1 in Supporting Information S1) with lakes and pools diverging the most.

Theoretically, the intersection of an LEL and the LMWL defines the isotopic values of the initial source water prior to evaporation (Welhan & Fritz, 1977), although this approach has known flaws when the LELs are defined by samples from multiple sources that likely do not share identical initial water isotopic values (Bowen et al., 2018). Acknowledging these limitations, the source-grouped LELs for lakes, pools, streams, and surface flow all predict very similar initial water isotopic values between -20.0 and -21.0‰ for $\delta^{18}\text{O}$ and -153 and -160‰ for $\delta^2\text{H}$. These values are slightly higher than the amount-weighted GNIP annual mean values of -22.5‰ and -173‰ , which suggests that the surface waters are slightly biased toward summer precipitation. However, we note that conclusive comparisons are difficult as the Thule GNIP data is limited in time coverage with several missing months of isotopic data, and mean isotopic values for precipitation today may be higher than during GNIP's 1966–1971 collection period due to climate change. Further examination of lake inflow source water isotopes and lake-specific LELs will be covered in the following section.

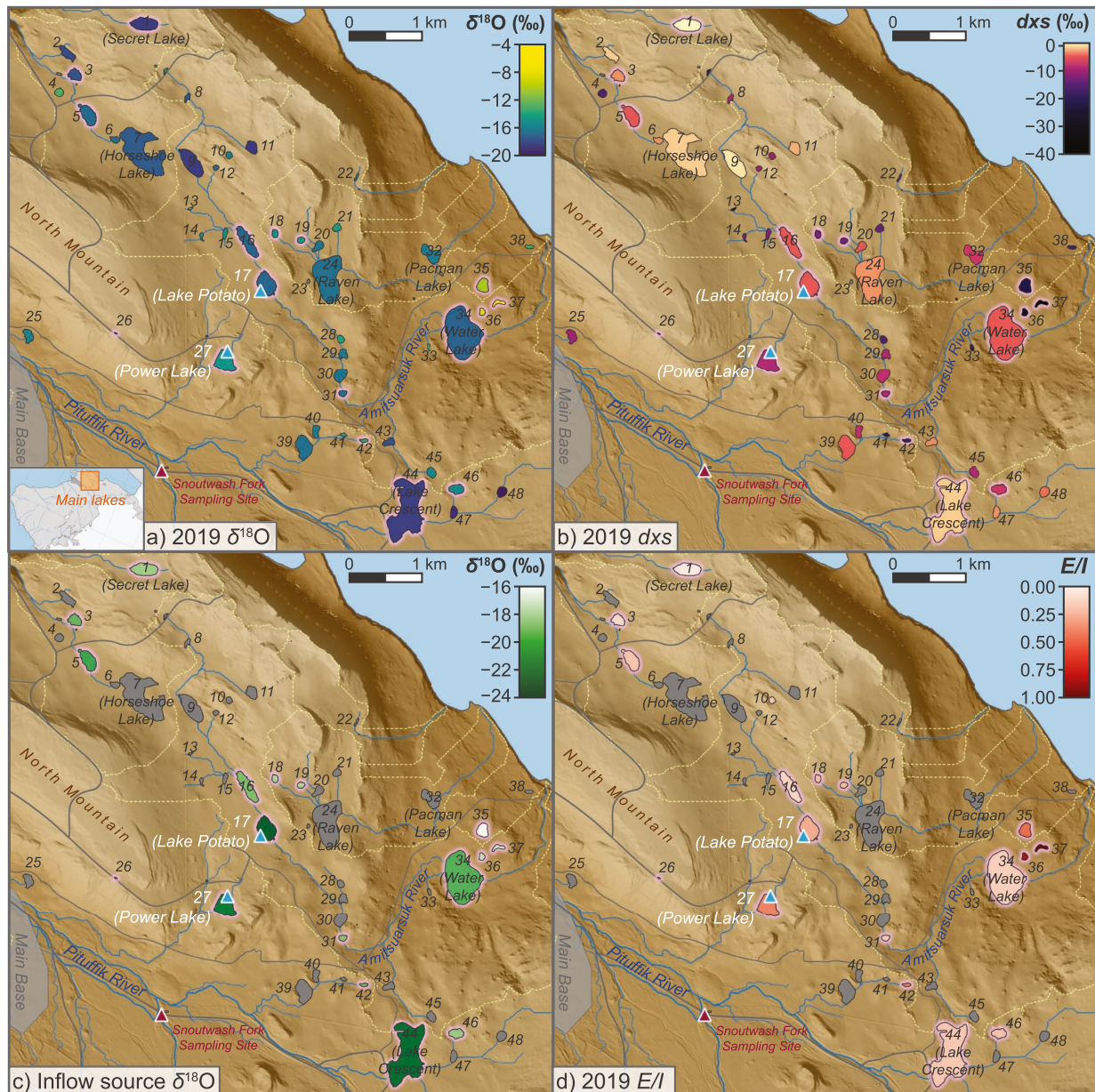
The 67 lakes included in our isotopic data set represent a near-comprehensive sampling of lakes on the Pituffik Peninsula (Figure 1). The lake water isotopic compositions vary widely across both space and time (Figures 4 and 5). The highest lake water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are observed in megapool lakes, and these lakes also host the lowest observed d_{xs} values. In contrast, lakes abutting permanent snow patches and the GrIS have the lowest $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and highest d_{xs} values. In all, we observe total lake water isotopic ranges of 18.5‰ for $\delta^{18}\text{O}$, 97‰ for $\delta^2\text{H}$, and a staggering 57‰ for d_{xs} . Despite these wide extremes, most lake samples fall within a much more limited isotopic range (25%–75% quantile ranges: $\delta^{18}\text{O} = -18.6$ to -15.9‰ , $\delta^2\text{H} = -148$ to -134‰ , $d_{xs} = -7$ to $+1\text{‰}$).

Building off this foundation of Pituffik surface water isotopic compositions, we focused on examining the drivers of lake water isotopic variability across both space and time. We used the pool, stream, surface flow, snow/ice, and precipitation data for environmental context when interpreting the lake water isotopes, but deeper examination of their isotopic variability is not discussed here. Those with further interests in these non-lake data are directed to our open access database (Akers et al., 2023a).

4.3. Lake LEL Results

The mean lake LEL slope value differs depending on the method of calculation (Bowen et al., 2018), and this difference is important when comparing LEL slopes across studies. The Pituffik lake LEL slope is 5.1 ± 0.1 when calculated from combining all the lake data into a single regression, as is typically reported in other relevant studies (e.g., Gibson & Edwards, 2002; Kopec et al., 2018; Leng & Anderson, 2003; Stansell et al., 2017). This slope is lower than reported for coastal lakes in central West Greenland and Arctic Alaska (Leng & Anderson, 2003; MacDonald et al., 2017) and inland lakes in Scandinavia (Kjellman et al., 2022), but higher than more inland lakes in central West Greenland and the Canadian Arctic (Gibson & Edwards, 2002; Kopec et al., 2018; Leng & Anderson, 2003). The intermediate slope values for Pituffik suggest that the arid High Arctic summer coupled with the proximity to the GrIS and its drying katabatic winds promote a more evaporative environment than might be expected for its coastal location.

However, if the LELs are regressed individually for lakes and then averaged, the mean Pituffik lake LEL slope value is 4.6 ± 0.5 . Few Arctic studies report lake LELs based on this method, but this different slope value



Lake water isotopic character of the Pituffik main lakes region

1 Secret L.	9 Landglacier View L.	17 L. Potato	25 Cable Access L.	33 BMEWS Bowl Pd.	41 Mossy Bottom Pd.
2 Shaley Point L.	10 The Tarn	18 Serene L.	26 N. Mountain Pl.	34 Water L.	42 Loon Pd.
3 Diabase Depth L.	11 L. Gibraltar	19 Dirty Ice L.	27 Power L.	35 Water Garden L.	43 Gravel Pit L.
4 Lioness Rock L.	12 L. Leslie	20 Sitting Rock L.	28 L. Uno	36 Perched L.	44 L. Crescent
5 N. Mountain View L.	13 Roads End L.	21 Noisy Goose L.	29 L. Due	37 Angry Duck L.	45 Fake Pumice L.
6 Spur L.	14 L. Nephros	22 Raven Ridge Pd.	30 L. Tre	38 Coastal Plateau Pl.	46 Party House L.
7 Horseshoe L.	15 Open Water L.	23 Carex Pd.	31 L. Quattro	39 Lonesome Cabin L.	47 Blackshore L.
8 L. Echidna	16 Upper L. Potato	24 Raven L.	32 Pacman L.	40 L. Aqua	48 BMEWS Backside L.

Figure 5. Water isotopic compositions of lakes sampled in mid-summer 2019 in the main Pituffik lakes region. Lakes are colored according to their measured $\delta^{18}\text{O}$ (a) and d_{xs} (b) values. Although $\delta^2\text{H}$ values are not shown here, their relative spatial distribution appears extremely similar to the $\delta^{18}\text{O}$ values (a). Inferred inflow source water $\delta^{18}\text{O}$ values are shown (c) for the select lakes where a local evaporation line was available. Evaporation/inflow ratios (E/I) calculated using $\delta^{18}\text{O}$ for the same select lakes are also provided for mid-summer 2019 (d). Lake E/I values greater than 1 are considered to equal 1 for plotting. Broader regional context, minor icon identification, and geospatial data sources can be found in Figure 1.

Table 1

Pearson Correlations Between Inferred Lake Inflow Source Water Isotopic Composition and Environmental Parameters

Environmental parameter	Inflow source water $\delta^{18}\text{O}$		Inflow source water $\delta^2\text{H}$		Inflow source water d_{xs}	
	Pearson correlation (r)	p -value	Pearson correlation (r)	p -value	Pearson correlation (r)	p -value
<i>Surface area (log)</i>	<i>−0.58</i>	<i>0.012</i>	<i>−0.58</i>	<i>0.012</i>	<i>+0.59</i>	<i>0.011</i>
<i>Watershed area (log)</i>	<i>−0.63</i>	<i>0.005</i>	<i>−0.63</i>	<i>0.005</i>	<i>+0.63</i>	<i>0.005</i>
Elevation	−0.30	0.227	−0.30	0.225	+0.32	0.194
<i>Distance from ocean</i>	<i>−0.55</i>	<i>0.019</i>	<i>−0.54</i>	<i>0.019</i>	<i>+0.55</i>	<i>0.017</i>
Distance from GrIS	−0.03	0.917	−0.03	0.909	+0.02	0.926

Note. The lakes analysed here are the subset of 18 lakes that had a source water isotopic composition estimated based on their local evaporation lines. Parameters that are statistically significant where $p < 0.05$ are bolded and italicized.

highlights the flawed assumption of identical initial water isotopic compositions that is made in the previous approach that aggregates all regional lake data points into a single LEL regression (Bowen et al., 2018; MacDonald et al., 2017). Indeed, the intersections between individual Pituffik lake LELs and the LMWL (Section 5.2) suggest that the initial isotopic composition of lakes differs by lake type due to different source water isotopic compositions (Bowen et al., 2018; Cluett & Thomas, 2020), which violates the assumptions needed for a single regional LEL.

We note, however, that our individual lake LELs are calculated from as few as three samples covering 2 years and that further investigation into LEL methodology differences would benefit from further sustained and frequent monitoring focused specifically on developing robust LELs. For the 18 non-glacially influenced lakes where we could calculate a lake-specific LEL, we modeled both lake specific inflow source water isotopic composition and E/I values (Figures 5c and 5d). As this represents only a small subset of all the sampled lakes, these results were primarily used as Supporting Information S1 rather than serving as an integral component of the later lake spatial analyses.

Inferred inflow source water isotopic compositions for these lakes were on average $\delta^{18}\text{O} = -20.2 \pm 0.9\text{‰}$, $\delta^2\text{H} = -153 \pm 7\text{‰}$, and $d_{\text{xs}} = +8 \pm 1\text{‰}$. This mean Pituffik inflow isotopic composition is lighter than inferred inflows further south in central west Greenland (mean $\delta^{18}\text{O} = -17.5\text{‰}$, Cluett & Thomas, 2020) and northern Scandinavia (median $\delta^2\text{H} = -114\text{‰}$, Kjellman et al., 2022) as would be expected due to poleward precipitation generally becoming isotopically lighter. The isotopic source mixing model found that lakes' water inflow is on average sourced $31.8 \pm 3.7\%$ from frozen season precipitation (September–May) while $68.2 \pm 3.7\%$ is thawed season (i.e., summer) precipitation (June–August). This seasonal contribution split fits the trend noted in eastern Arctic Canadian lakes where lakes farther north had greater summer precipitation contributions (Gorbey et al., 2022). Finally, based on linear regressions of these inferred inflow values against the lake water isotopic values observed in mid- to late summer, the inferred inflow isotopic compositions can explain 44%–51% of the spatial variability in observed lake water isotopes at Pituffik.

Correlations with environmental factors reveal that the lakes sourcing isotopically heavier water with lower d_{xs} values (i.e., more summerlike precipitation) are associated with having smaller surface area, having smaller catchment areas, and being closer to the ocean (Table 1). Elevation and distance from the GrIS show no relationship with source water isotopes. Combined in a multiple linear regression, these three factors explain 54%–55% of the inferred inflow isotopic variance across the 18 lakes. We propose that catchment area has the strongest and clearest mechanistic control over inferred inflow source water isotopes. A small local catchment may promote more sourcing of summer precipitation as all of its snowpack will likely melt in a short window of time in early summer. Since most of the Pituffik lakes are still ice-covered when the tundra snowpack melts, much of this snowmelt inflow may not even mix much into the lake waters due to snowmelt bypass due to stratification in ice-covered lakes (Bergmann & Welch, 1985; Edwards & McAndrews, 1989; Wilcox et al., 2022). However, after the ice cover retreats, summer precipitation runoff will be mixed readily into the lakes. In contrast, lakes with larger catchment areas are more likely to source snowmelt over a longer period as their catchments may cover a wider elevation range and/or include residual snow patches that last longer into summer.

Following catchment area, distance from the ocean consistently emerged as an independently important parameter for determining inflow isotopic composition. Although the total range of distance from the ocean is

small (<4 km) in the 18 lakes, the observed pattern of lighter isotopic inflow water farther from the ocean matches that expected from isotopic distillation during inland moisture transport (e.g., Kjellman et al., 2022). Finally, lake surface area lacks a mechanistic connection to inflow isotopic variability, but we note that surface area covaries with catchment area in this data set of 18 lakes ($r = +0.71$), and thus the correlation between surface area and inflow source water isotopes may simply be due to covariance with the mechanism previously described for catchment area.

The E/I estimates for these 18 lakes spanned a wide range from 0 observed in a proglacial lake to values greater than one in 2 of the megapool lakes. E/I values greater than 1 suggest that these lakes violate steady-state lake assumptions, which is plausible given the changeable extents of megapool lakes observed over time. The median lake E/I was 0.18 when calculated from $\delta^{18}\text{O}$ and 0.19 from $\delta^2\text{H}$, revealing that evaporation is a substantial factor in the water balance of most lakes but also that the majority of water inflow across sampled lakes must be lost to outflow. Unlike a similar study in central west Greenland that found E/I to increase with proximity to the GrIS (Cluett & Thomas, 2020), spatial differences in Pituffik lake E/I values are best explained by hydrological connection as described through lake type category with lakes with high inflow rates from being connected to streams and/or permanent snow having lower E/I values. We note, though, that the distance from ocean to GrIS is much smaller in our Pituffik study area than the west Greenland transect studied by Cluett and Thomas (2020) which limits the ability of an isotopic gradient to emerge based on ice sheet proximity alone.

5. Spatial Variability in Summer Lake Water Isotopic Composition

5.1. Environmental Parameters Influencing Isotopic Variability

Our multiple and LASSO regressions used mid-summer 2019 data from 42 headwater and downstream lakes to investigate the environmental influences on observed lake water isotopes. This regression analysis identified catchment area, surface area, and elevation as having notable relationships with lake water isotopic values while day of year sampled and the distances from the GrIS and ocean did not. Combined into a multiple linear regression, the three important parameters explain 60%, 48%, and 74% of the observed variability in the lake water data set's $\delta^{18}\text{O}$, $\delta^2\text{H}$, and d_{xs} , respectively. For the subset of 18 lakes with inferred inflow source water isotopes (Section 4.3), the variance of their observed mid-summer 2019 isotopes is explained more by the three parameters of lake surface area, catchment area, and elevation (77%) than by their source water isotopic composition alone (54%–55%). This fact strongly argues that processes beyond just initial water sourcing differences, such as evaporation, are critical to determining the spatial variability in lake water isotopic composition at Pituffik.

Both lake catchment area and surface area are known as key components of lake water balance in the Arctic (e.g., Gibson & Reid, 2014; Wilcox et al., 2023) and are expected to influence lake isotopic composition, but prior studies in Søndre Strømfjord, Greenland (Kopec et al., 2018; Leng & Anderson, 2003), and in northern Scandinavia (Kjellman et al., 2022) also detected clear isotopic relationships with distance from the ocean. However, these two latter studies examined lakes on much longer transects away from the coast (150–460 km) than available at Pituffik (<20 km). While a weak relationship between distance from the ocean and inflow source water isotopes was found in the 18 lake subset (Section 4.3), the lack of this parameter's importance in observed summer lake water isotopes suggests that any isotopic signal initially imparted by the distance to the ocean must be obscured by post-inflow sourcing processes such as evaporation. At Pituffik, we interpret the significant parameters of catchment area, surface area, and elevation in terms of their isotopic influence on lake waters through evaporation and runoff recharge.

As noted in the source water isotopic discussion, catchment area is most closely linked with runoff recharge, assuming other parameters are held equal, as the size of the catchment area would determine the volume of runoff input a lake receives relative to its capacity and losses to evaporation. Since runoff from precipitation and the snowpack is isotopically lighter with higher d_{xs} values than average lake water (Figure 4a), lakes with larger catchments tend to have lower $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and higher d_{xs} values reflecting their greater relative input of runoff (Figure 6). As previously noted, lakes with larger catchments are more likely to receive snowmelt runoff over a longer window than those with smaller catchments which also promotes lower $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values with higher d_{xs} values. Lakes with smaller catchment areas would thus be expected to be more sensitive to summer precipitation which is important for targeting potential paleoclimate archives.

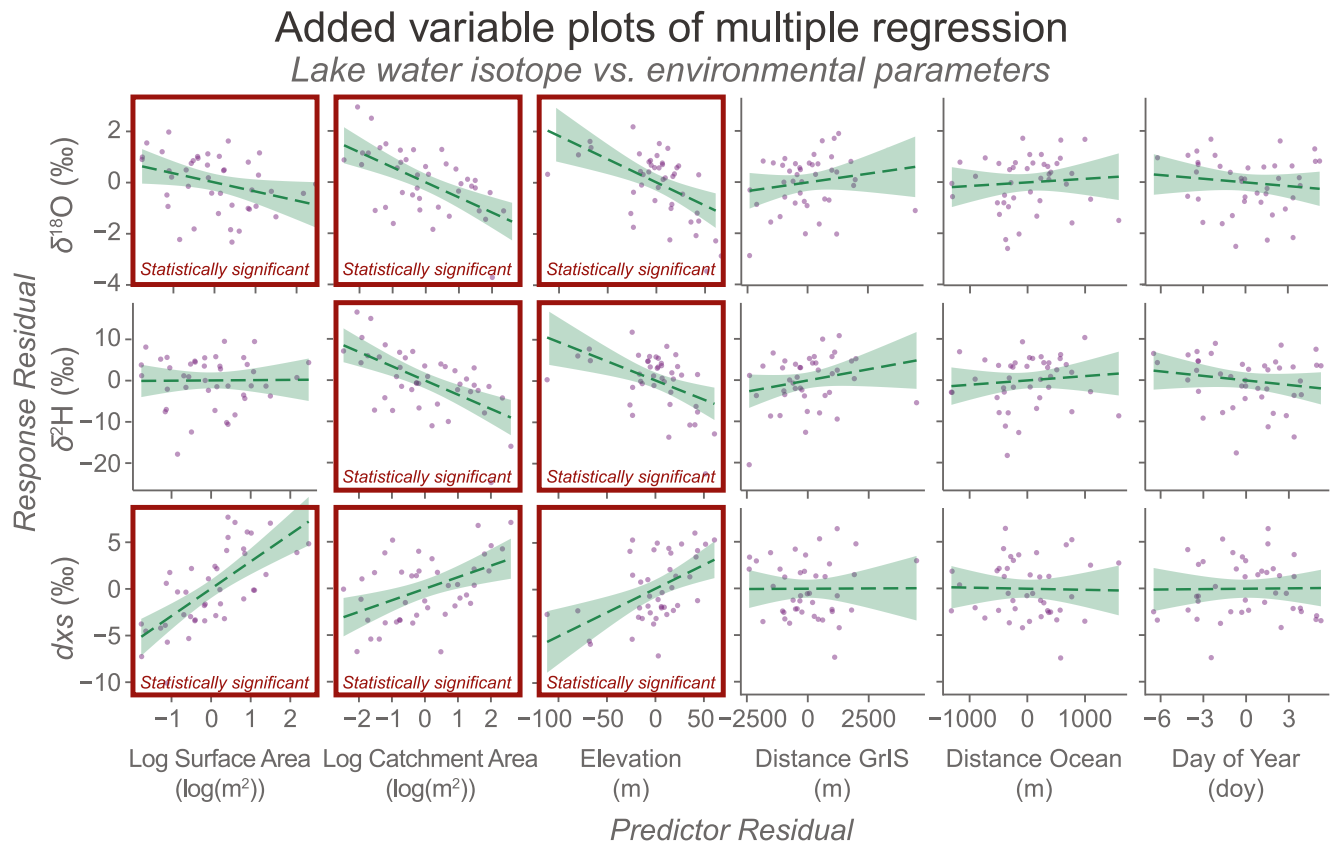


Figure 6. Added variable (i.e., partial regression) plots of the multiple regression of each lake isotopic variable versus six environmental parameters. Regressions are shown as green dashed lines with 95% confidence intervals of the regression shown in green shading. Lake samples included in the multiple regressions were restricted to headwater and downstream lakes sampled in mid-summer 2019 from the main lakes region north of the air base. Parameters that produced statistically significant multiple regression coefficients for specific isotopic variables (Table S2 in Supporting Information S1) are outlined by red boxes.

In contrast, lake surface area is more closely related to evaporation. In the examined Pituffik lakes, a larger surface area is correlated with lower $\delta^{18}\text{O}$ values and higher d_{xs} values (Figure 6), indicative of less evaporative water loss. This is counter-intuitive at first glance because a lake with a larger surface area would have more potential for evaporative water loss than a smaller area lake. However, we noted in the field that the smaller area lakes in Pituffik are often much shallower than larger lakes. As a result, these lakes' isotopic compositions can change relatively quickly under strong evaporative conditions (Kopeck et al., 2018). Additionally, these smaller lakes likely freeze to their beds in winter, and these “bedfast ice” lakes melt out earlier and have longer seasonal exposure to evaporation than larger lakes that have floating ice (Arp et al., 2015). Satellite imagery confirms that the smaller Pituffik lakes are ice-free much sooner than larger lakes in the early summer (Figure S4 in Supporting Information S1). Thus, the potential evaporative loss per unit lake volume appears higher for lakes with smaller surface areas than for larger lakes, at least in our Pituffik lakes. Ideally, a lake volume component would improve this parameter analysis, but the bathymetric data needed to estimate lake volumes do not exist for these lakes to our best knowledge.

Finally, elevation relates to both runoff recharge and evaporation. Interestingly, elevation did not appear as a significant influence on source water isotopes which suggests that its impact on observed lake water isotopes must derive largely from factors unrelated to seasonal water sourcing. Higher elevation lakes are isotopically lighter with higher d_{xs} values than lower elevation lakes, and the strength of this relationship is most driven by the clear isotopic differences between lakes at the highest and lowest elevations. Most likely, the colder temperatures and longer ice coverage of lakes at higher elevations reduces evaporative water losses compared to lower elevation lakes, and these higher elevation lakes may source isotopically light snowpack runoff for a longer period into summer as well. Notably, lakes at middle elevations have a much less clear trend which probably reflects the

diverse water source elevations of these lakes and the relative weakness of elevation as a determining parameter over such a small overall elevation range.

These differences in the parameters' relationship to runoff and evaporation cause the relative importance of lake catchment area, surface area, and elevation to change depending on specific isotopic variable (Figure 6, Table S2 in Supporting Information S1). For both $\delta^{18}\text{O}$ and $\delta^2\text{H}$, the most influential parameter determined by the regressions is the lake catchment area, followed by elevation, and then lake surface area. In contrast, lake surface area is the most influential parameter for d_{xs} , then elevation, and thirdly lake catchment area (Figure 6, Table S2 in Supporting Information S1). These differences suggest that $\delta^{18}\text{O}$ and $\delta^2\text{H}$ variability most prominently reflects runoff-related factors while d_{xs} most prominently reflects differences in water loss due to evaporation. Still, it must be emphasized that all isotopic species are influenced by both factors to some significant degree, and the covariance between lake surface area and catchment area makes clearly distinguishing their precise individual contributions very difficult.

Together with the source water results, we use this analysis to present a conceptual model where the spatial variability of water isotopes observed in Pituffik lakes is a combined product of seasonal water source differences further affected by evaporative water losses. A lake's catchment area determines the initial source water isotopic composition by controlling whether the supply of isotopically light winter snowpack melt is brief (smaller catchment) or extended (larger catchment). Isotopically heavier summer precipitation will be more influential in lakes with smaller waters as it will be the sole source of runoff supply while larger catchments are more likely to continue sourcing residual snow patches. Evaporative water loss will occur at all lakes over the course of the summer resulting in an enrichment in heavier water isotopes and a drop in d_{xs} values, but evaporation will be more impactful in shallower lakes and in lakes that lose their ice cover earlier. Finally, lakes that have high volumes of inflow and outflow (usually lakes with large catchments) can replenish water lost to evaporation more efficiently with precipitation and snowmelt runoff, and thus these lakes will show less isotopic change from evaporation. In contrast, lakes with limited inflow (usually lakes with small catchments) must likely replace evaporative losses with water slowly flowing through the active layer that has also experienced evaporation or the lake may simply steadily lose water over the summer due to lack of inflow outside of precipitation events. For these lakes, we expect that isotopic changes from evaporation will be very noticeable.

5.2. Lake Type Isotopic Distributions and Modeling

After our environmental parameter analysis identified the importance of factors affecting evaporation and runoff recharge in lake isotopic spatial variability, we expanded our study to examine how lake type relates with lake isotopic composition with the full set of 63 lakes sampled in 2019. The 63 lakes in this analysis were classified into 26 headwater, 17 downstream, 4 megapool, 6 vale, 5 proglacial, and 5 altered lakes. The isotopic compositions of the different lake types during this period are generally well-grouped per type with mean type values evenly distributed across the continuum of lake isotopic values (Figure 7a) from megapool to proglacial lakes. We found that the altered lake isotopic compositions are not distinct as they overlap with the compositions of headwater and downstream lakes. This isotopic similarity suggests that human disruptions have not dramatically changed the isotopic hydrology of the altered lakes beyond what might be expected in a natural lake, but we still exclude these lakes from subsequent analyses out of caution.

The isotopic composition of the lakes points to evaporative water loss being a substantial component of their water balance. In particular, the d_{xs} values observed in some downstream lakes, most headwater lakes, and all megapool lakes are lower than any d_{xs} value reported in Pituffik precipitation. Evaporative mass loss from the lakes (and/or their inflow) is the most probable driver of the isotopic fractionation needed to achieve d_{xs} values lower than local precipitation. This is supported by the modeled E/I values which show an increasingly higher proportion of evaporation for lakes and lake types with lower d_{xs} values (Figure 7b).

The slope values of individual lake LELs are also well-grouped by lake type (Figure 7c), and lakes and lake types with isotopically heavier waters have LELs with lower slopes. This observation further supports evaporation as a primary driver of isotopic differences across lake types with the water balance of isotopically heavier lakes more substantially impacted by evaporative water loss than isotopically lighter lakes. This importance of evaporation agrees with isotopic results from some lake systems elsewhere in Greenland and boreal Canada (Gibson, 2002; Gibson & Reid, 2014; Kopec et al., 2018; Leng & Anderson, 2003), but is notably greater than reported for subarctic lakes in Sweden (Jonsson et al., 2009) and parts of Arctic Canada (Gorbey et al., 2022). Notably, the

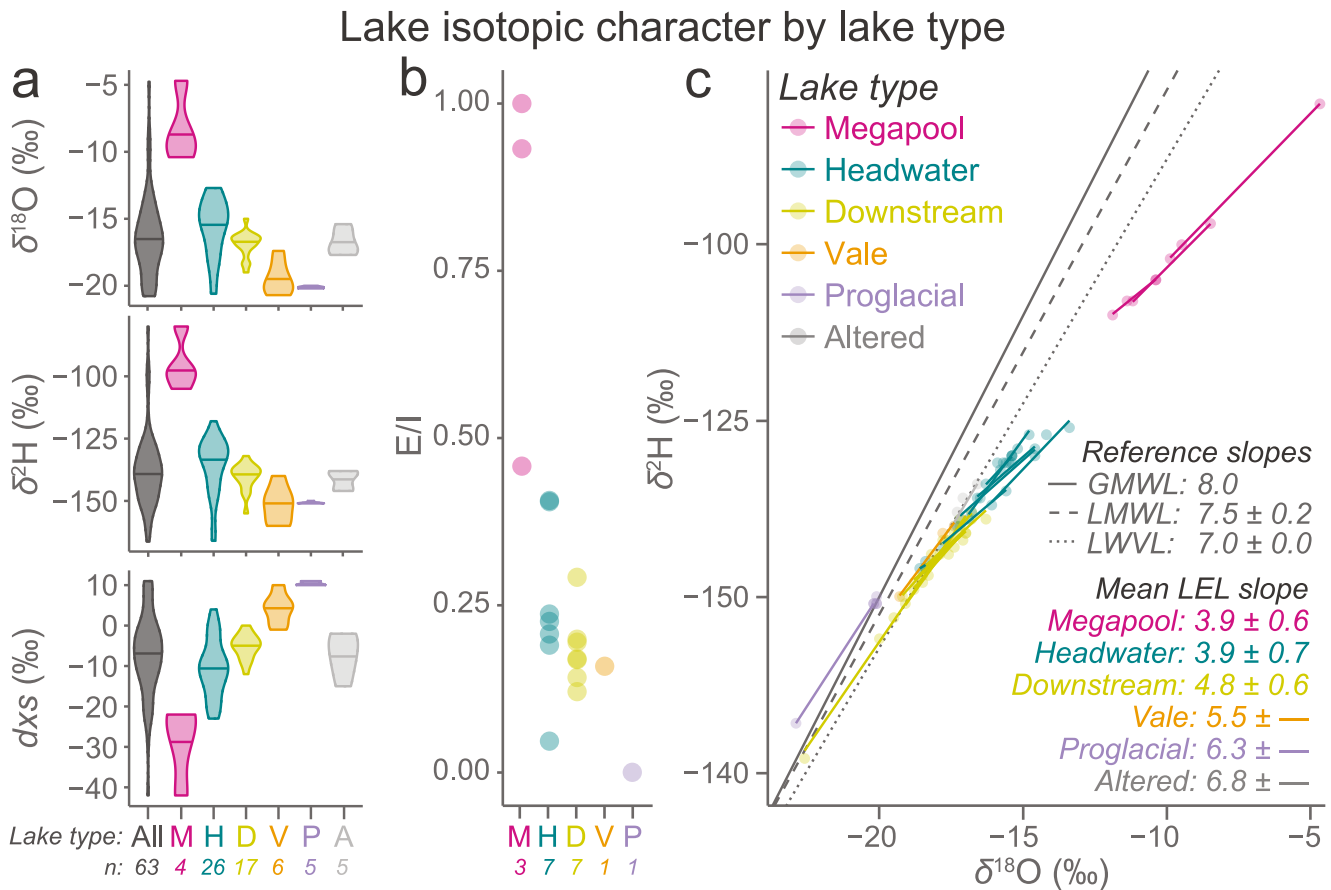


Figure 7. Isotopic composition of lakes sampled across Pituffik grouped by lake type category. In (a), violin plots show the isotopic composition distribution of all lakes sampled in 2019 (black) as well as split by lake type (colored). Data are plotted so that the maximum width is equivalent between groups, regardless of sample count. Within each violin, the median value per group is shown by a solid horizontal line. In (b), modeled E/I values for lakes with individual LELs are plotted by lake type (note that one altered lake is not plotted due to weak modeling results). In (c), $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ is plotted to show local evaporation lines (LELs) for every lake that was sampled at least 3 times across 2018 and 2019. Each LEL represents a single lake or pool, and the LELs are colored according to lake type. The mean and 95% confidence interval of LEL slope values are displayed per lake type at lower right. Note that the vale and altered lake slopes have no confidence interval as there is only one lake per type that was sampled at least three times, and also that the proglacial lakes do not display a true LEL as the values do not fall below the LMWL in $\delta^{18}\text{O}$ – $\delta^2\text{H}$ space. The global meteoric water line (GMWL, solid gray), local meteoric water line (LMWL, dashed gray) based on GNIP data (IAEA/WMO, 2022), and local water vapor line (LWVL, dotted gray) (Akers et al., 2020) are shown for reference.

proglacial lakes are an exception as they do not produce an LEL that extends to the right of the LMWL in $\delta^{18}\text{O}$ – $\delta^2\text{H}$ space (c), suggesting that their waters have not had substantial evaporative loss.

The inferred inflow source water isotopic compositions of the different lake types mirror their observed compositions, with heaviest mean initial values for megapool lakes ($\delta^{18}\text{O} = -17.1 \pm 0.9\text{‰}$, $\delta^2\text{H} = -131 \pm 7\text{‰}$), followed by headwater lakes ($\delta^{18}\text{O} = -19.7 \pm 0.8\text{‰}$, $\delta^2\text{H} = -150 \pm 6\text{‰}$), and then downstream lakes ($\delta^{18}\text{O} = -20.9 \pm 0.8\text{‰}$, $\delta^2\text{H} = -159 \pm 6\text{‰}$) and vale lakes ($\delta^{18}\text{O} = -20.6\text{‰}$, $\delta^2\text{H} = -157\text{‰}$, based on single LEL). As previously discussed, this variability in source water isotopic composition appears best linked to catchment area, and megapool and headwater lakes generally have smaller catchments than downstream and vale lakes. However, the summer lake water samples have much wider isotopic differences between lake types (Figure 7a) than present in the inferred inflow source waters, and therefore evaporation seems to greatly exaggerate whatever isotopic difference that may initially be present from the source water.

5.3. Lake Type Hierarchical Clustering

Hierarchical clustering based on the lake water $\delta^{18}\text{O}$ and d_{xs} values (Figure 8) sorts the lakes into four main clades (α – δ) and supports our lake type categorization as reflecting real differences in lake hydrology. Although the lake types are not perfectly sorted into the clades, the clades are still better explained by lake type category than by

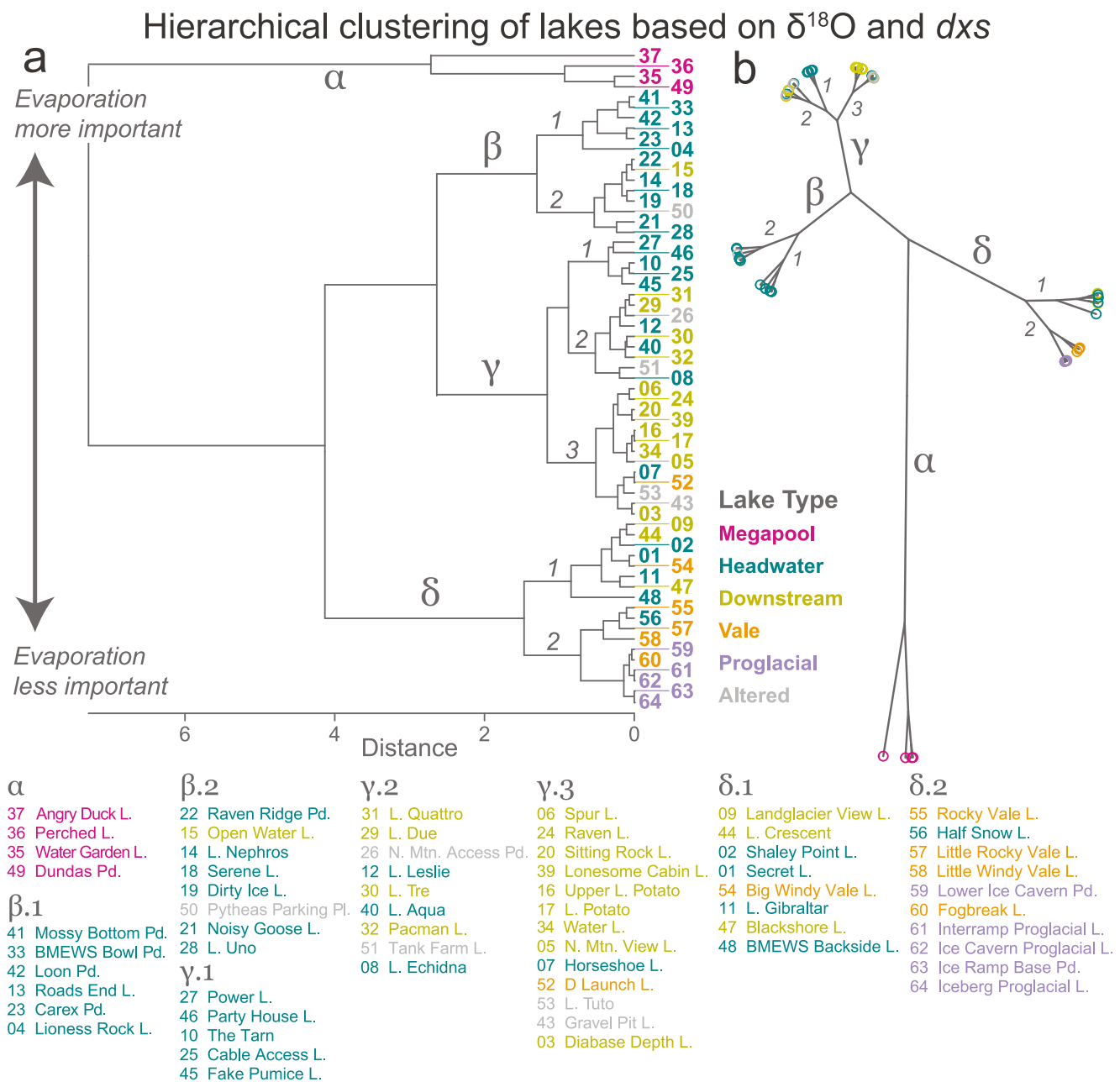


Figure 8. Hierarchical clustering results for Pituffik lakes based on $\delta^{18}\text{O}$ and d_{xs} values. Results are shown in two forms of dendrogram (a, b) with individual lakes colored according to lake type. Individual lakes in (a) are identified by numbers matching those in Figures 1 and 5 with lake names provided at bottom. Four prominent clades are identified with Greek letters, and subclades are numbered. The presented vertical order of clades reflects a general continuum of the influence of evaporation on lake isotopic compositions.

specific lake parameters such as size, elevation, or particular parent catchment basin. This argues that lake isotopic composition is strongly controlled by how hydrological connectivity to the wider landscape (a factor central to lake type character and categorization) influences the balance between evaporation and runoff recharge. Combined with the evaporation insights provided by the LELs, the variability in lake type isotopic compositions appears to be best explained by the ability of a lake to regularly replenish water that is lost to evaporation over the summer.

Megapool lakes comprise their own clade (α) well-separated from all other lakes due to their distinct isotopic character of very high $\delta^{18}\text{O}$ and $\delta^2\text{H}$, very low d_{xs} , and lowest mean LEL slope (Figure 8). Megapool lakes have

small, endorheic catchments, and this hydrological isolation limits their ability to replenish water lost to evaporation. With no connections to lingering snowpack or upstream lakes, summer precipitation is a relatively larger contributor to the megapool lakes which is reflected in their isotopically heavier inferred inflow compositions. Being underlain by permafrost, megapool lakes function similarly to idealized evaporation pans with lake levels that change from year to year based on water supply, and some the megapool lakes are observed to disappear in presumably drier years such as 2016 (Copernicus, 2019) and 1949 (Figure S5 in Supporting Information S1).

In contrast, proglacial lakes have isotopically light waters with high δx_s values and LELs that are not distinguishable from the LMWL. Isotopically, these lakes are very similar to the mean values of Pituffik snow and ice samples (Figure 4) and show no sign of evaporative water losses. This is logical, as most of the GrIS surface runoff supplying the proglacial lakes would have only very recently melted, the cold and humid conditions near the surface of a melting ice sheet limits evaporative losses, and the high volume of GrIS runoff into the proglacial lakes results in short lake water residence times. In the hierarchical cluster analysis, all proglacial lakes are grouped in a single subclade ($\delta.2$) along with a hydrologically similar vale lake (Fogbreak Lake) that is in contact with a permanent snow patch. The other vale lakes are clustered close to proglacial lakes as also have similar limited evaporation and steady supplies of fresh snowmelt due to forming in steep-sided valleys whose shaded slopes support numerous late-lasting and permanent snow patches.

The isotopic character of headwater and downstream lakes lies between the extremes of the previously described lake types. These lakes are more hydrologically connected than megapool lakes which allows them to offset evaporative losses better through snowmelt and precipitation runoff, but they lack the direct connection to snowmelt sources that supply fresh recharge water throughout the summer like the proglacial and vale lakes. Interestingly, headwater lakes have, on average, greater evaporative water losses than downstream lakes based on their isotopic composition, LELs, and E/I ratios (Figure 7). Although this finding appears counterintuitive because evaporation in downstream lakes should only enhance the evaporation signal received from headwater lake water, a closer examination of the entire hydrological supply of downstream lakes provides a clearer answer.

The headwater lakes generally have smaller extents than the downstream lakes, and high evaporative losses are favored in these small lakes for multiple reasons. We observed that many of the smaller headwater lakes are also rather shallow (<2 m), and they presumably have a much higher surface area to volume ratio that enhances evaporation impacts compared to the generally larger and deeper downstream lakes (Kopec et al., 2018). These headwater lakes are also shallow enough to freeze to their beds in winter, resulting in earlier spring ice melt and greater potential summer evaporative loss compared to the deeper downstream lakes that hold their ice cover much later (Arp et al., 2015). Finally, many of the small headwater lakes lack a clear outlet channel, and some of these lakes may be functionally endorheic outside of high lake level periods in early summer. As might be expected from these characteristics, one clade identified in the cluster analysis (β) is almost entirely restricted to particularly small headwater lakes (surface area mean $\pm 95\%$ CI = $5,750 \pm 1,630$ m²) that share isotopically heavy waters with low δx_s indicative of high evaporation.

For any lake downstream from these small headwater lakes, the volume of isotopically heavy water supplied from the headwater lakes would be limited, and much or even most of the water supplying these downstream lakes will instead come from isotopically lighter precipitation and snowpack runoff in their local drainage basin. Additionally, the generally greater volume of the deeper downstream lakes will buffer their isotopic composition against evaporative changes. Notably, nearly half of all downstream lakes are exclusively clustered in a single subgroup within the $\gamma.3$ subclade despite belonging to four different catchment basins, and this clustering supports that the downstream nature of these lakes is a stronger determinant of isotopic composition than their particular hydrologic basin.

Overall, it is important to note that while each lake type can be said to have a typical isotopic and environmental character, the lake type categories do not have hard boundaries, and several lakes show hybrid or transitional lake type characteristics. Additionally, hydrological factors specific to each lake other than the simple lake type category (e.g., presence of local snow patches, depth and volume, etc.) can skew individual lake summer isotopic compositions away from what would be expected based solely on their lake type. Still, our complete lake type analysis of isotopic distributions, LELs, and cluster analysis reveals that Pituffik lakes' water balances can generally be sorted along a single-dimensional gradient ranging from nearly completely dominated by evaporation losses (i.e., megapool) to nearly completely lacking evaporation losses due to steady fresh recharge supply from snowmelt (e.g., proglacial) (Figure 8).

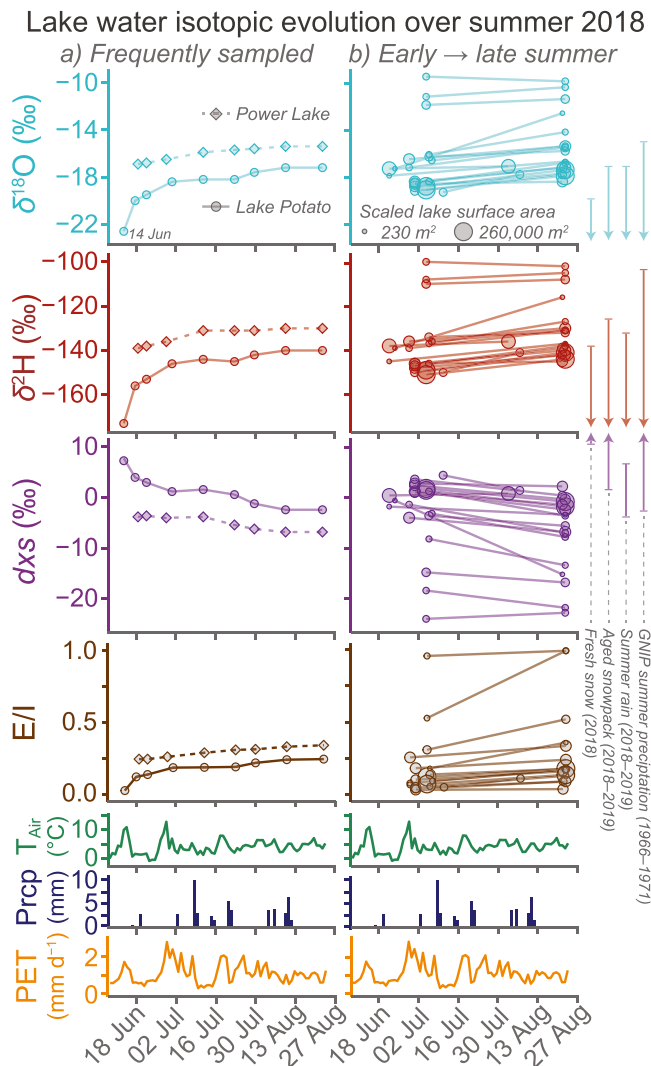


Figure 9. Water isotopic composition changes in select Pituffik lakes over summer 2018. In (a), isotopic and E/I changes over the summer are shown for the frequently sampled Power Lake (diamonds, dashed line) and Lake Potato (circles, solid line) while (b) shows the isotopic and E/I differences in lakes from early to late summer 2018. Lakes included in (b) are part of the multi-annual subset of 18 lakes and two pools that were sampled during each of the three main sampling periods. The size of each point represents the relative log-scaled surface area of the lakes, which was identified as a primary factor in evaporation's impact on isotopic composition. Lake Tuto and the two pools did not have E/I values and were excluded from the E/I plot. Isotopic ranges for precipitation and snowpack observed at Pituffik are provided at right. Daily mean air temperature, precipitation amount, and potential evapotranspiration over summer 2018 are shown at the bottom of (a) and (b) for environmental context (Muscari, 2018; Singer et al., 2021; USAF, 2019).

6. Temporal Variability in Lake Water Isotopes

6.1. Lake Isotopic Variability Over Summer 2018

The frequent water sampling taken from 14 June through 23 August 2018 at Lake Potato and Power Lake offers more detailed insight into isotopic evolution of lake waters over time. These two lakes are located only 1 km apart with similar surface elevations (190 and 178 m a.s.l., respectively) and surface areas (60,289 and 59,537 m², respectively) but belong to different stream catchment basins. Additionally, Lake Potato is the fourth lake in a chain along the Amitsuarsuk River (Potato Creek) and has a large upstream catchment of 4.9 km² while Power Lake is a headwater lake with a small 0.3 km² catchment and limited outflow. Together, these two lakes are broadly representative of the most common lakes in the Pituffik region.

Over summer 2018, both lakes share generally increasing $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and decreasing dxs values (Figure 9a). These trends are consistent with observations in other high latitude lakes where lake waters are isotopically lighter in spring and early summer due to snowpack melt inflow but become enriched in heavier isotopes by late summer due to evaporation losses and/or summer precipitation inflow (Gibson & Reid, 2014; Leng & Anderson, 2003). The summer-long isotopic evolution observed in these lakes appears more likely to be driven by evaporation than precipitation, as lake isotopic changes are observed even when no precipitation occurred. Active layer water that has also experienced prior evaporation may also contribute to the observed lake water isotopic evolution (Gorbey et al., 2022), but we lack field observations to quantify this further.

Additionally, the lake isotopic values approach and, for Power Lake, even exceed the isotopic range limits observed in summer precipitation and surface water flows, implying that evaporation-driven fractionation must modify existing lakes and/or their inflow to reach such values. Finally, E/I ratios, calculated using inferred inflow source water isotopic compositions and hydrometeorological conditions leading up to the sampling date, generally increase in line with isotopic changes over the summer.

We also observe similarly consistent isotopic changes across the multi-annual lake set (Figure 9b). Nearly all these lakes are isotopically heavier (19 of 20 lakes) with lower dxs values (18 of 20 lakes) at the end of summer than in early summer. The two lakes that did not fully follow this isotopic evolution can likely be explained by their particular lake environments as one is a very shallow megapool lake sensitive to recent precipitation events and the other is a large, high altitude lake less sensitive to evaporation and fed by melting snowpack well into the late summer. As seen in Power Lake and Lake Potato, E/I ratios across the multi-annual lake set reflect isotopic changes with higher values at the end of summer. Although we found that lake surface area is a partial driver of spatial isotopic variability through influencing evaporation (Figure 6), lake surface area does not have a consistent impact on the rate and magnitude of temporal isotopic change over summer 2018 (Figure 9b).

Notably, although Lake Potato and Power Lake share similar patterns of isotopic evolution over the summer, there is an offset between the lakes where

Power Lake is consistently isotopically heavier with lower dxs values than Lake Potato. This difference can partly be explained by the differences in their inferred inflow source water isotopic compositions. As previously discussed in the spatial lake water isotopic section, Power Lake's smaller catchment would promote relatively greater sourcing of summer precipitation compared to the snowpack that develops in the frozen season. Additionally, Lake Potato's location along Amitsuarsuk Creek grants it a summerlong rapid supply of runoff to replace water

lost to outflow or evaporation. Indeed, the inferred inflow for Power Lake is 0.8 and 6‰ higher in $\delta^{18}\text{O}$ and $\delta^2\text{H}$, which the mixing model translates into Power Lake's summer water sourcing fraction being $57 \pm 19\%$ compared to Lake Potato's $52 \pm 19\%$. These initial isotopic differences are then exaggerated by the greater influence of evaporation on Power Lake's water balance (mean E/I: 0.32) compared to Lake Potato (mean E/I: 0.18).

The first lake water samples taken in Lake Potato highlight the rapidly changing Pituffik hydrology during the early summer thaw and hold a warning for isotopically sampling lakes during this time. Between 14 and 18 June 2018, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values increased 2.6 and 17‰, respectively, and this 4-day rise is the same magnitude of isotopic change as then observed over the next 2 months of summer in Lake Potato from 18 June to 23 August. We attribute this large observed isotopic change to the phenomenon of snowmelt bypass that is widely reported in other high latitude lakes (e.g., Bergmann & Welch, 1985; Edwards & McAndrews, 1989; Gorbey et al., 2022; Wilcox et al., 2022). When snowmelt runoff enters a lake with a floating ice cover, much or most of this runoff will pass through the lake in a shallow uppermost layer under the ice. Temperature and density differences limit mixing between this runoff layer and deeper pre-existing lake water, and wind-driven mixing is also prevented by the ice cover. We would thus expect such a lake to also exhibit isotopic stratification during snowmelt bypass reflecting the different source histories of these waters.

Indeed, very warm and sunny conditions on 14 June led to extensive snowpack melt across the tundra, and large volumes of surface runoff were observed in Lake Potato's inflow and outflow channels while the lake held a nearly intact ice cover. A water sample taken of the surface lake water (where the ice cover had slightly retreated) had the second lowest $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of any lake water sample in our database. Although unusually low for Pituffik lake water, this isotopic composition was very similar to that of samples taken directly of snowpack surface runoff around Pituffik that day and suggests that our "lake" sample had only captured the snowmelt bypass layer. By 18 June, the lake ice had more fully retreated, and the heavier $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of this date's lake sample reflect that pre-existing lake waters had now mixed up toward the surface. In further support, the Lake Potato δx_s values drop from a relatively high +8‰ on 14 June (suggesting a source with limited past evaporation, such as snowmelt) to +4‰ on 18 June (suggesting the mixing in of waters with greater past evaporation, such as last summer's residual lake water).

Slight differences between the early summer isotopic evolutions of Lake Potato and Power Lake may also be related to differences in their early season ice coverage and hydrological connections. Lake Potato's $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values increase at a faster pace than Power Lake during the early summer period from 18 June to 01 July 2018. One possible explanation is that Power Lake lacked a strong snowmelt bypass effect as it does not have a channelized inflow and has a drainage basin 16 times smaller than Lake Potato (Figure 1b). With a more limited snowmelt supply volume, the surface waters of Power Lake do not exhibit as large of an isotopically light pulse at the start of summer. Additionally, Lake Potato's ice cover retreated earlier than Power Lake which allowed evaporative water losses to affect its isotopic composition earlier. A delayed evaporation start in Power Lake is supported by its very stable δx_s values observed from 18 June to 12 July while the lake held near-continuous ice cover (Figure S4 in Supporting Information S1).

A general evaporative enrichment in heavier lake water isotopes with a coinciding decrease in δx_s values commenced in both lakes after the early summer thaw in June. However, the initial trend of increasing $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and decreasing δx_s values at Lake Potato is interrupted in July by a plateauing of values less strongly observed in Power Lake (Figure 9b). This pause in evaporative enrichment occurs despite nearly all the ice cover in Lake Potato being melted by 04 July 2018 (Figure S4 in Supporting Information S1) and relatively high PET. This plateauing appears to be due to a series of July rain events whose isotopic values (mean $\delta^{18}\text{O}$: −19.1‰; $\delta^2\text{H}$: −150‰; δx_s : +2.6‰) would serve to counteract any isotopic effect from evaporation. Amitsuarsuk Creek rapidly supplies Lake Potato with precipitation runoff while runoff to Power Lake must more slowly seep through the active layer and likely experience evaporation along the way. As a result, Lake Potato was able to replenish its evaporative losses with "fresh" precipitation runoff more effectively than Power Lake, and this difference is reflected in their July isotopic evolution differences. Under drier and warmer conditions with greater PET in late July and early August, the $\delta^{18}\text{O}$ values of both lakes resumed steady evaporative enrichment in heavier isotopes (Figure 9b) until evaporation greatly reduced after 10 August as daily mean temperatures cooled to near freezing.

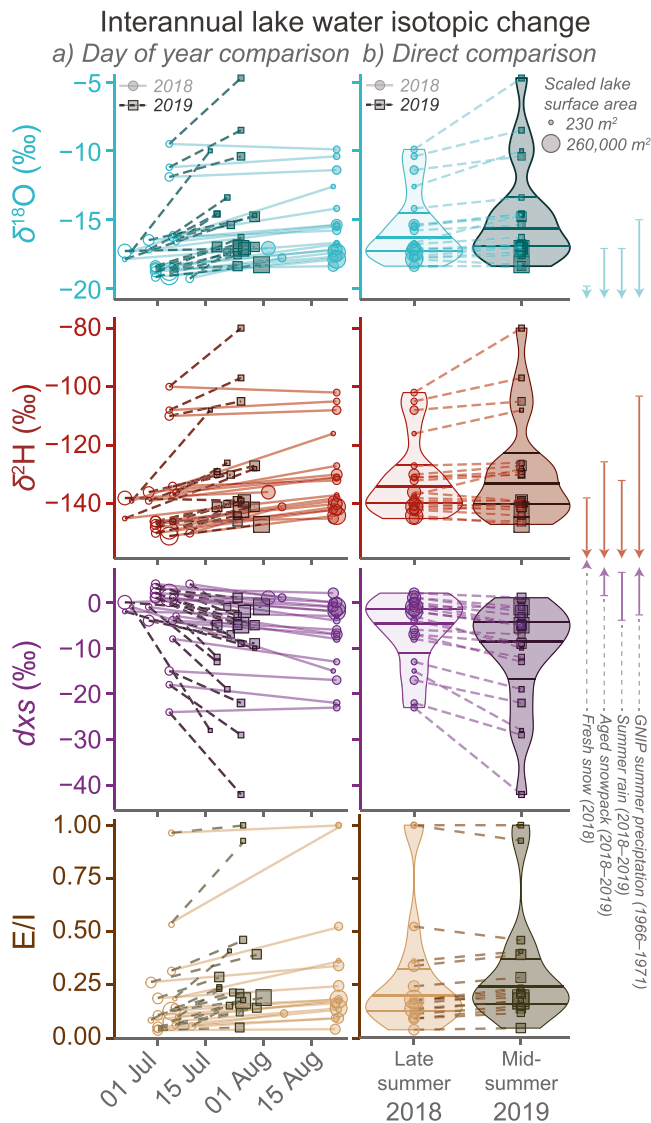


Figure 10. Water isotopic composition changes in select Pituffik lakes over summers 2018 (circles) and 2019 (squares). Lakes included here are part of the multi-annual subset of 18 lakes and two pools that were sampled during each of the three main sampling periods. The size of each point represents the relative log-scaled surface area of the lakes, which was identified as a primary factor in evaporation's impact on isotopic composition. In (a), isotopic values are plotted by sampling day of year. Lines connect early summer 2018 values to late summer 2018 values (solid lines) and to mid-summer 2019 (dashed lines) values for each individual lake and pool. In (b), isotopic values are directly compared between late summer 2018 and mid-summer 2019 samples with overall value distributions illustrated with violin plots. The isotopic values for each individual lake and pool are connected by dashed lines. Isotopic ranges for precipitation and snowpack observed at Pituffik are provided at right. Most, but not all, lakes in the isotopic plots are represented in the E/I plots.

6.2. Interannual Summer Lake Isotopic Values in 2018 Versus 2019

Our 2019 lake sampling took place over the last 2 weeks in July, and we use the isotopic composition of these samples relative to those taken in 2018 to gain insight into how lake water isotopes can change from year to year. However, because the timing of the 2019 sampling falls between the two sampling periods in 2018, we cannot directly compare values between the years because the lake isotopic composition is constantly evolving over the summer (Section 6.1). Based on observations at Potato Lake and Power Lake (Figure 9a), we assume that $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in Pituffik lakes generally increase and δx_s values generally decrease from the time of early season snowpack melt in late May/early June until the middle of August. Thus, the isotopic values of the lakes in middle to late August should be their maximum $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and minimum δx_s values, with the degree of isotopic change over the summer primarily reflecting the amount of evaporative water loss.

Overall, the isotopic values of our lake data set suggest that more evaporation occurred in 2019 than in 2018 (Figure 10). By late July 2019, 95% of the 20 lakes in the multi-annual subset already had lower δx_s values than the values measured in late August 2018, signifying greater evaporative loss. Similarly, 85% and 65% of lakes had respectively higher $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values (also indicative of greater evaporation) in late July 2019 compared to late August 2018 (Figure 10). For many lakes, the differences in δx_s values between the 2 years were extremely large: five lakes had δx_s values $>7\text{‰}$ lower in 2019 than 2018 with the largest difference of 20‰ lower δx_s observed in an isolated roadside pool. Additionally, the LEL calculated from these lakes in mid-summer 2019 had a lower slope value (4.9 ± 0.2) than either early or late summer 2018 (5.3 ± 0.2 and 5.1 ± 0.2 , respectively) (Figure S7 in Supporting Information S1), also suggesting that a more arid environment that promoted evaporation existed in 2019 than in 2018. Finally, all but two of the lakes had higher E/I ratios in mid-summer 2019 than end of summer 2018 (Figure 10), and the two lakes with lower ratios in 2019 were megapool lakes whose late summer 2018 E/I values were near 1. All together, these values suggest that substantially more evaporative water loss had occurred across Pituffik lakes by the end of July in 2019 than during the entire summer of 2018.

Weather differences between the summers 2018 and 2019 support conditions being more favorable for evaporation in 2019. Although the weather (Figure 2) and GrIS surface melt extent in summer 2018 were close to 1981–2010 averages (Mote, 2020; USAF, 2019), summer 2019 was one of the warmest and sunniest seasons on record for Greenland under remarkably stable anticyclonic conditions. Massive volumes of surface ice melted from the GrIS across the island in 2019 (Sasgen et al., 2020; Tedesco & Fettweis, 2020) and peaked with an extraordinary GrIS surface melt event at the end of July (Mote, 2020; Tedesco & Fettweis, 2020). At Pituffik, these persistent anticyclonic conditions resulted in the 2019 summer being 4.5°C warmer and having an atmospheric pressure 12 hPa higher than the same period in 2018 (Muscari, 2018). Summer 2019 was also drier than summer 2018, both in total precipitation (32 vs. 54 mm, respectively) and in mean relative humidity (68% vs. 79%, respectively) (Muscari, 2018; USAF, 2019).

When summed over each summer, modeled daily PET (Singer et al., 2021)

for Pituffik was almost 2 times greater in 2019 than 2018 (177 vs. 96 mm, respectively). In fact, the summer PET in 2019 was higher than all other years in the database (1981–2023) except 2015 while the PET summed over the entire 2019 years was the absolute highest.

Beyond simply having warmer air temperatures, 2019 also had other weather factors that promoted greater evaporation. Indices for the North Atlantic Oscillation and Arctic Oscillation show that atmospheric circulations were very different between the 2 years, with consistent positive indices in 2018 and consistent negative indices in 2019. A negative North Atlantic Oscillation is associated with greater evaporation of Pituffik surface waters due to the local foehn-like conditions as southerly winds are forced over the GrIS and Tuto ice dome (Akers et al., 2020). The enhanced pressure gradients of the negative North Atlantic Oscillation also drive stronger katabatic winds that also increase evaporative potential (Kopeck et al., 2018). Finally, the consistently warmer conditions in 2019 brought much earlier ice-free conditions to the Pituffik lakes that lengthened the evaporation exposure period, with ice coverage in July 2019 running 16–20 days ahead of conditions in 2018 (Copernicus, 2019).

Other than evaporation, interannual lake isotopic variability has also been suggested to reflect isotopic differences in the winter snowpack resulting from varying winter storm sources and air temperature (Kjellman et al., 2022). Although we do not have early summer water samples from 2019 to directly compare the isotopic composition of tundra snowpack meltwater with our samples from 2018, snowpack isotopic variability does not appear to best explain the observed interannual differences in Pituffik lake isotopic composition. Our 2019 lake water isotopic results would require the 2018 and 2019 winter snowpack to have been isotopically heavier than the 2017–2018 snowpack. This seems unlikely for Pituffik because the winter 2018 and 2019 had a colder mean air temperature and synoptic conditions which would suggest that the snowpack melting in spring 2019 would more likely be isotopically lighter than the 2018 spring snowpack, and indeed, the water vapor $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values at Pituffik from September 2018 to May 2019 were on average 1.3 and 9‰ lower than the equivalent period in the previous year (Akers et al., 2020).

Differences in snowpack volume could also potentially alter the seasonal sourcing balance from year to year. More precipitation occurred in the winter leading to June 2018 than June 2019 (53.4 vs. 29.6 mm water equivalent), possibly resulting in a greater tundra snowmelt supply and isotopically lighter lakes in 2018. However, the volume of snowmelt that a lake can incorporate is often limited by the lake's ice coverage blocking inflow and snowmelt bypass (Wilcox et al., 2022), and these limits likely dampen the isotopic impact that different snowpack volumes can impart on eventual summer lake water isotopic compositions. Overall, the sheer magnitude of isotopic change between 2018 and 2019, the exceptionally negative δx_s values in 2019, and the lower lake LEL slope in 2019 strongly support our conclusion that the isotopic differences between the 2018 and 2019 are primarily due to differences in summer weather that affected evaporation rather than different snowpack isotopic compositions. Still, we note that despite interannual snowpack isotopic influences not being captured by our monitoring, its importance noted in other studies (Kjellman et al., 2022) warrants further investigation.

7. Implications and Conclusions

Overall, our comprehensive study of the surface waters of the Pituffik region repeatedly finds evaporation to be a central determinant of observed isotopic variability in summer lake waters. Although differences in seasonal precipitation sourcing of inflow waters set an foundation for spatial isotopic variability in lakes, summer lake water observations show that evaporation enhances the isotopic signal of this inflow sourcing from some lake environmental parameters (i.e., catchment area, surface area) but obscures others (e.g., distance from the ocean). Evaporation even holds a determining role for lakes whose water isotopic composition shows little evidence of evaporation (i.e., proglacial and vale lakes) because it is precisely their hydrological capacity to limit and/or rapidly replace evaporative water losses that makes these lakes isotopically distinguishable in Pituffik. Moreover, the stark isotopic differences in summer lake waters between 2018 and 2019 match isotopic changes expected from enhanced evaporation based on the much warmer and drier 2019 summer. These results gained from our intensive water sampling program offer advice for those that intend to use lake water stable isotopes as proxies for past climate changes in similar periglacial and Arctic environments.

Studies of this nature often create transfer functions from modern observations of lake stable isotopes and environmental parameters to convert isotopic values archived in sediment or faunal remains into reconstructed climate histories (Van Hardenbroek et al., 2018). However, observational data sets are usually limited in scope by logistics and cost, particularly in the remote Arctic, and thus data sets collected over short time windows and/or limited spatial coverage are assumed out of necessity to represent norms (e.g., Lasher et al., 2017, 2020; McFarlin

et al., 2019). Our study, however, reveals that differences in lake type and hydrological connectivity can produce wildly different isotopic compositions between lakes located <500 m apart (Figure 5). Temporal evolution of lake water isotopes over the course of summer (Figure 9) and between summers (Figure 10) also makes the timing of water sampling an important factor when collecting modern training data sets for transfer functions. As a result, a water sample taken on a single date at one body of water can neither be assumed representative for other regional water bodies nor assumed representative of the sampled body of water's isotopic composition at other dates throughout the season or even the same date in a different year.

However, this does not mean that Arctic surface water isotopes are inherently too complex to perform as climate proxies. Our results first highlight the simple rule that water samples used to develop an isotopic transfer function must be taken from the source of the archived isotopes to be studied (i.e., the modern lake) rather than assuming that samples from other water sources in the region will be similar and applicable. Sampling more broadly across other regional lakes is also strongly encouraged in order to establish the regional lake water isotopic response to climate variations and determine how representative the chosen lake of focus is within the larger suite of lakes.

Secondly, to capture and model the seasonal evolution and environmental sensitivity of a lake's water isotopes, sampling should ideally take place multiple times over a full thaw season. In particular, lake water samples taken only on a single date risk being substantially different in isotopic composition from other dates and from the summer-long mean. For example, our season-long isotopic monitoring of Pituffik lakes was crucial to developing a seasonally resolved lake water isotopic proxy through aquatic moss $\delta^{18}\text{O}$ (Puleo et al., 2024). However, few Arctic field campaigns can perform season-long sampling. For time-limited sampling, we recommend taking multiple samples across whatever time is available, particularly before and after major weather events to determine sensitivity to precipitation and stream discharge changes. Sampling during early summer and the freshet must acknowledge that snowpack melt and residual lake ice cover greatly skew lake isotopic compositions relative to their more consistent middle and late summer values. The timing of sampling during the summer should also ideally match when it is expected that the lake water isotopes are being archived, but in general we recommend sampling as late in summer as possible.

Thirdly, many studies assume that archived water isotopic values in Arctic lake sediments directly reflect the local precipitation and thus can be used to reconstruct past precipitation isotope changes. However, our findings suggest that this assumption cannot be broadly applied and must be verified for each lake. Nearly every Pituffik lake shows signs of isotopic alteration from evaporative loss, and many of the lakes that might be considered ideal for paleoenvironmental study (e.g., limited connectivity, small localized catchments) are the most strongly impacted by evaporation. Isotopic changes from individual summer precipitation events were difficult to clearly detect in our two frequently monitored lakes, and, in contrast to the results in another Arctic lake study (Gorbey et al., 2022), most likely had the effect of making the lakes isotopically lighter (Figure 9). For lakes most strongly influenced by evaporation, archived lake water isotopes might therefore be more accurately capturing summer temperature, humidity, and wind values that drive evaporation rather than purely changes in summer precipitation isotopes as is often presumed. Identifying an accurate archiver of lake δx s values such as biomarkers or cellulose (e.g., Eensalu et al., 2024; Loader et al., 2015) would be an important development in constraining the relative importance of evaporation in a lake archive.

Finally, while the many environmental drivers of lake isotopic variability can make it challenging to parse out which exact paleoclimate changes might have led to a given isotopic change in an individual lake, a more consistent response often emerges when comparing climate proxy variability across a suite of lakes in a region (e.g., Cluett & Thomas, 2020; Engstrom et al., 2000; Gibson & Edwards, 2002; Kopec et al., 2018; Shuman & Serravezza, 2017). Given this consistency, collecting and analyzing sediment cores from multiple lakes in a given region would offer the most effective means of confidently capturing a regional climate signal. Increasing the number of cores to collect and analyze obviously brings logistical challenges, but records from multiple lakes not only reduce the uncertainty of identifying environmental drivers of isotopic change but also eliminates the risk that a single lake happens to have an unusual local hydrological environment that adversely impacts its isotopic archive. Additionally, taking paleoclimate proxies from different lake types may allow us to capture different aspects of environmental change through comparative lake record study (e.g., Thomas et al., 2020). We suggest that small, isolated headwater lakes are more likely to record evaporation changes in their archived lake water

isotopes and show greater interannual variability while larger downstream lakes may better reflect annual precipitation runoff with more buffered changes over time.

Our Pituffik results offer one example of the potential power of a regional lake suite approach. Pituffik lakes displayed a common isotopic response to more evaporative summer conditions in 2019 relative to 2018 (Figures 9c and 9d) that were favored by a shift to a strongly negative North Atlantic Oscillation phase in 2019. The consistent isotopic response across the peninsula's lakes strongly supports a connection to a regional to synoptic scale environmental driver like the North Atlantic Oscillation, but arguing the same climate connection based on an isotopic record from only a single lake would be much less certain due to the potential interference of local lake-specific influences. Looking farther afield, similarly consistent responses between lake isotopic compositions and the North Atlantic Oscillation were also reported from a study of multiple lakes in west Greenland (Kopec et al., 2018), suggesting that lake water isotopes along the western coast of Greenland might be used to produce a record of past air pressure variability over the GrIS. In this manner, placing a greater focus on examining lake isotopic records as regional sets rather than individual records has much underutilized potential for Arctic paleoenvironmental and hydrological research.

Overall, our study displays the high potential value of hydrological insight gained through intensive field isotopic sampling at a landscape scale. The isotopic compositions in our data set encompass a nearly full complement of natural surface water types, and they function as a valuable base of comparison for isotopic studies in other Arctic water systems. The number, diversity, and frequency of lakes sampled in our work is, to our best knowledge, unprecedented for the High Arctic latitude of Pituffik and seldom achieved elsewhere in the Arctic and subarctic. Importantly, the numerous stream, surface flow, and snow/ice samples taken alongside the lake samples provide critical environmental context for understanding the expression and evolution of the lake water isotopes. Finally, our large comprehensive data set can not only aid those investigating past and modern hydrologic systems, but also serve as a foundational isotopic reference point to quantify future environmental changes. Evaporation's role in the Arctic environment will change in a warmer world, but our findings argue that lake water isotopes are primed to capture this hydrological transformation. Isotopic data sets such as in this study will increasingly provide valuable, quantifiable markers of past conditions that can be directly compared with future isotopic samples to track rapid Arctic environmental change in a globally warming Earth.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data and code used in this article's analyses and figure creation, including the full water isotopic data set, are openly available online in an Zenodo repository (Akers et al., 2023a) and also through PANGAEA (Akers et al., 2023c). Geospatial data created for the Pituffik region and used in this article's analyses and figures are also openly available either as part of a new geospatial database available on GitHub (Akers et al., 2023b) or through existing resources also available online (Copernicus, 2019; Howat, 2019; Korsgaard et al., 2016; Porter et al., 2019).

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