Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low

F. Bouchard,[1,2] K. W. Turner,[2,3] L. A. MacDonald,[4] C. Deakin,[2] H. White,[2] N. Farquharson,[2] A. S. Medeiros,[2] B. B. Wolfe,[2] R. I. Hall,[4] R. Pienitz,[1] and T. W. D. Edwards[5]

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[1] Snowmelt is a crucial source of water for many shallow subarctic lakes, but climate models predict that snowfall will decrease in some regions, with profound ecological consequences. Here we use lake water isotope data across gradients of terrestrial vegetation cover (open tundra to closed forest) and topographic relief to identify lakes that are vulnerable to desiccation under conditions of low snowmelt runoff in two subarctic landscapes—Old Crow Flats, Yukon, and Hudson Bay Lowlands, Manitoba (Canada). Lakes located in low-relief, open tundra catchments in both landscapes displayed a systematic, positive offset between directly measured lake water $\delta^{18}O$ over multiple sampling campaigns and lake water $\delta^{18}O$ inferred from cellulose in recently deposited surface sediments. We attribute this offset to a strong evaporative ^{18}O-enrichment response to lower-than-average snowmelt runoff in recent years. Notably, some lakes underwent near-complete desiccation during midsummer 2010 following a winter of very low snowfall. Based on the paleolimnological record of one such lake, the extremely dry conditions in 2010 may be unprecedented in the past ~200 years. Findings fuel concerns that a decrease in snowmelt runoff will lead to widespread desiccation of shallow lakes in these landscapes. **Citation:** Bouchard, F., et al. (2013), Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low, *Geophys. Res. Lett.*, *40*, 6112–6117, doi:10.1002/2013GL058635.

1. Introduction

[2] Northern lake-rich landscapes are vital for wildlife, carbon exchange with the atmosphere, and natural resources utilized by local indigenous communities. Shallow ponds and lakes (typically ≤ 1m depth) are the dominant basin type in these regions. Numerous studies have examined recent changes in the distribution and surface area of these water bodies; some have reported lake expansion (e.g., in the case of thermokarst lakes), while others have documented water level decline [*Smith et al*., 2005; *Carroll et al*., 2011]. An especially acute concern is that longer ice-free seasons and increasing importance of open water evaporation will lead to desiccation of shallow lakes, as observed in Canada's High Arctic [*Smol and Douglas*, 2007]. In these landscapes, snowmelt is important for replenishing shallow lakes and is likely to become even more crucial as evaporative drawdown intensifies with continued warming [*Schindler and Smol*, 2006].

[3] Old Crow Flats (OCF), Yukon, and northwestern Hudson Bay Lowlands (HBL), Manitoba, are two of Canada's largest lake-rich subarctic landscapes. Total surface water areas (including several thousand ponds and lakes; hereafter referred to as "lakes") comprise a significant portion of these landscapes, and both regions have undergone recent warming. In OCF, dendroclimatological records indicate anomalously warm conditions during the twentieth century in the context of the past 300 years [*Porter and Pisaric*, 2011]. Paleolimnological data from the southern HBL indicate that lakes began to respond to climate warming in the 1990s [*Rühland et al*., 2013]. Prior studies of lakes in these landscapes have identified several potential future hydrological consequences in response to continued warming, which will depend upon changes in catchment vegetation, hydrological connectivity, permafrost conditions, seasonal distribution of precipitation, and other factors [*Turner et al*., 2010; 2013; *Wolfe et al*., 2011].

[4] Here we explore the sensitivity of shallow lakes in OCF and HBL to one hydrological outcome: evaporative lake level drawdown following winters of low snow accumulation. We compare multiple measurements of lake water oxygen isotope composition ($\delta^{18}O_{lw}$) with that inferred from the cellulose fraction ($\delta^{18}O_{inf\text{-}lw}$) of surface sediments of 70 lakes spanning a broad gradient of vegetation cover. Winters of very low snow accumulation occurred immediately prior to several of the ice-free seasons when we conducted water isotope sampling, whereas the 5 year intervals prior to the water sampling were characterized by snowfall similar to (HBL) or greater than (OCF) the 1971–2000 climate normals. This provided a unique opportunity to identify the characteristics of shallow lakes in these subarctic landscapes that are most vulnerable to desiccation under conditions of low snowmelt runoff.

2. Study Areas

[5] Located in the continuous permafrost zone at the northern boreal tree line ~25 km north of the town of Old Crow, OCF encompasses ~2700 shallow lakes, mostly of thermokarst

Additional supporting information may be found in the online version of this article.

[1]Centre d'études nordiques and Département de Géographie, Université Laval, Québec, Québec, Canada.
[2]Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario, Canada.
[3]Department of Geography, Brock University, St. Catharines, Ontario, Canada.
[4]Department of Biology, University of Waterloo, Waterloo, Ontario, Canada.
[5]Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada.

Corresponding author: F. Bouchard, Centre d'études nordiques, Université Laval, 2405 rue de la Terrasse, Québec, QC G1V 0A6, Canada. (frederic.bouchard@cen.ulaval.ca)

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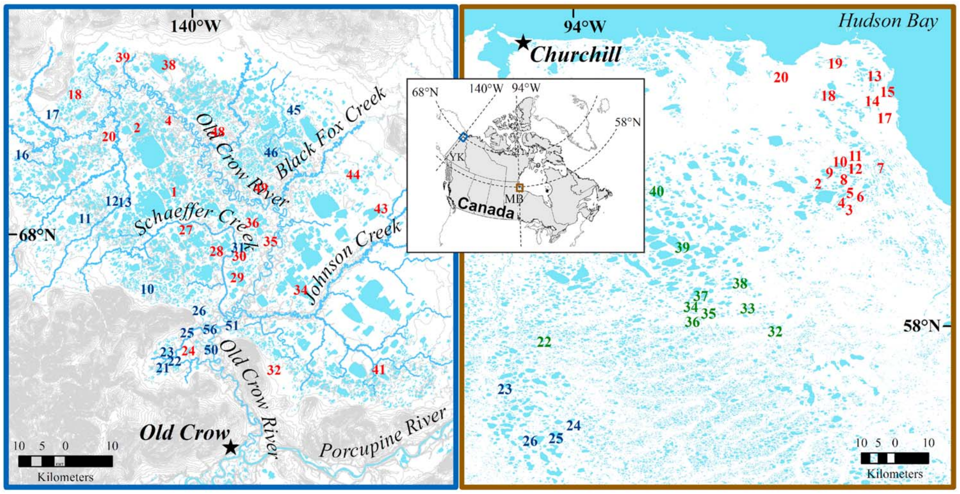

Figure 1. Location of the study areas: (a) Old Crow Flats (OCF), Yukon, (b) northwestern Hudson Bay Lowlands (HBL), Manitoba. The sampled shallow lakes are identified by numbers, color coded based on their classification (i.e., OCF: snowmelt-dominated and rainfall-dominated lakes are labeled in blue and red, respectively; HBL: BSF, IPP, and CF lakes are labeled in blue, green, and red, respectively).

origin (Figure 1). This ~5600 km^2 wetland complex, recognized by the Ramsar Convention for its ecological and cultural importance, provides habitat for abundant wildlife and supports the traditional lifestyle of the Vuntut Gwitchin First Nation. OCF is the former lakebed of Glacial Lake Old Crow [*Zazula et al*., 2004]. The permafrost and fine-grained glaciolacustrine sediments inhibit infiltration of surface water. Thus, lake water level fluctuations are mainly reflective of hydrological processes operating at or near the surface. Lakes have been classified mainly as snowmelt- or rainfall-dominated, reflecting their predominant source waters, and are associated with forest or tundra vegetation in their catchments, respectively [*Turner et al*., 2010, 2013].

[6] HBL is a low-relief landscape that spans continuous and discontinuous permafrost and traverses the northern boreal tree line. HBL developed following the end of the Wisconsinan glaciation and the retreat of the Laurentide Ice Sheet and is underlain by impermeable silts and clays deposited by the Tyrrell Sea [*Dredge and Nixon*, 1992]. Consequently, water pools on the surface creating thousands of lakes; many of which are formed by thermokarst processes. Near the Hudson Bay coast, isostatic rebound has produced a series of raised beaches, and the topographic depressions between them are also often occupied by lakes. Three major ecological zones can be identified in Wapusk National Park in northwestern HBL: coastal fen (CF) dominated by tundra vegetation, interior peat plateau-palsa bog (IPP) that contains small shrubs, and boreal spruce forest (BSF) (Figure 1) [*Parks Canada*, 2013].

3. Methods

[7] Lake water and surface sediment samples were retrieved from 38 snowmelt- ($n=17$) and rainfall-dominated ($n=21$) lakes in OCF (as defined by *Turner et al.* [2010]) and from 32 lakes spanning the three major ecozones in Wapusk National Park, HBL (CF: $n=18$; IPP: $n=10$; BSF: $n=4$; Figure 1). Water samples were collected in 30 ml high-density polyethylene bottles at ~10 cm depth three times (June, July, and September) during the ice-free season in OCF (2007–2008) and HBL (2010–2012). Surface sediments (upper 1–2 cm) were collected in September 2008 in OCF and September 2012 in HBL using a coring tube (38mm internal diameter). Cellulose was isolated from the sediments following several steps designed to remove noncellulose organic and inorganic fractions [*Wolfe et al*., 2001, 2007]. Water and surface sediment cellulose oxygen isotope compositions were determined at the University of Waterloo-Environmental Isotope Laboratory (UW-EIL) using conventional techniques [*Epstein and Mayeda*, 1953; *Wolfe et al*., 2007]. Results are expressed as δ values, representing deviations (‰) from Vienna Standard Mean Ocean Water (VSMOW) such that $\delta_{sample}=[(R_{sample}/R_{VSMOW}) - 1]\times 10^3$, where R is the $^{18}O/^{16}O$ ratio in sample and VSMOW. The δ values are normalized to −55.5‰ for Standard Light Antarctic Precipitation [*Coplen*, 1996]. Surface sediment $\delta^{18}O_{inf\text{-}lw}$ was calculated using a cellulose-water fractionation factor of 1.028 [*DeNiro and Epstein*, 1981; *Wolfe et al*., 2001].

4. Results

[8] Comparison of $\delta^{18}O_{inf\text{-}lw}$ with $\delta^{18}O_{lw}$ showed good agreement for several lakes in OCF (Figure 2a). These results were obtained mainly for the snowmelt-dominated lakes, whereas rainfall-dominated lakes on average possessed $\delta^{18}O_{inf\text{-}lw}$ values ~7‰ lower than $\delta^{18}O_{lw}$. Closer inspection of the relation between $\delta^{18}O_{inf\text{-}lw}$ and $\delta^{18}O_{lw}$ revealed that $\delta^{18}O_{inf\text{-}lw}$ best aligned with early ice-free season (mean June) $\delta^{18}O_{lw}$ for the snowmelt-dominated lakes (Figure 2b). In contrast, all but one of the rainfall-dominated lakes plotted systematically above the 1:1 line. Time series plots of $\delta^{18}O_{lw}$ for selected lakes of the snowmelt- (OCF13) and rainfall-dominated (OCF24) categories further demonstrate good agreement between $\delta^{18}O_{inf\text{-}lw}$ and early ice-free season $\delta^{18}O_{lw}$ for OCF13. Yet a much lower $\delta^{18}O_{inf\text{-}lw}$ was obtained from OCF24 compared to all $\delta^{18}O_{lw}$ values (Figure 2c).

[9] Similar patterns were evident when comparing $\delta^{18}O_{inf\text{-}lw}$ with $\delta^{18}O_{lw}$ for lakes in HBL (Figures 2d–2f). For lakes in the BSF and most lakes in the IPP, $\delta^{18}O_{inf\text{-}lw}$ was in good agreement with $\delta^{18}O_{lw}$ (Figure 2d). In contrast, eight of the 18 lakes in the CF had $\delta^{18}O_{inf\text{-}lw}$ that averaged ~6.5‰ lower than $\delta^{18}O_{lw}$. Similar to the OCF lakes, $\delta^{18}O_{inf\text{-}lw}$ agreed best with

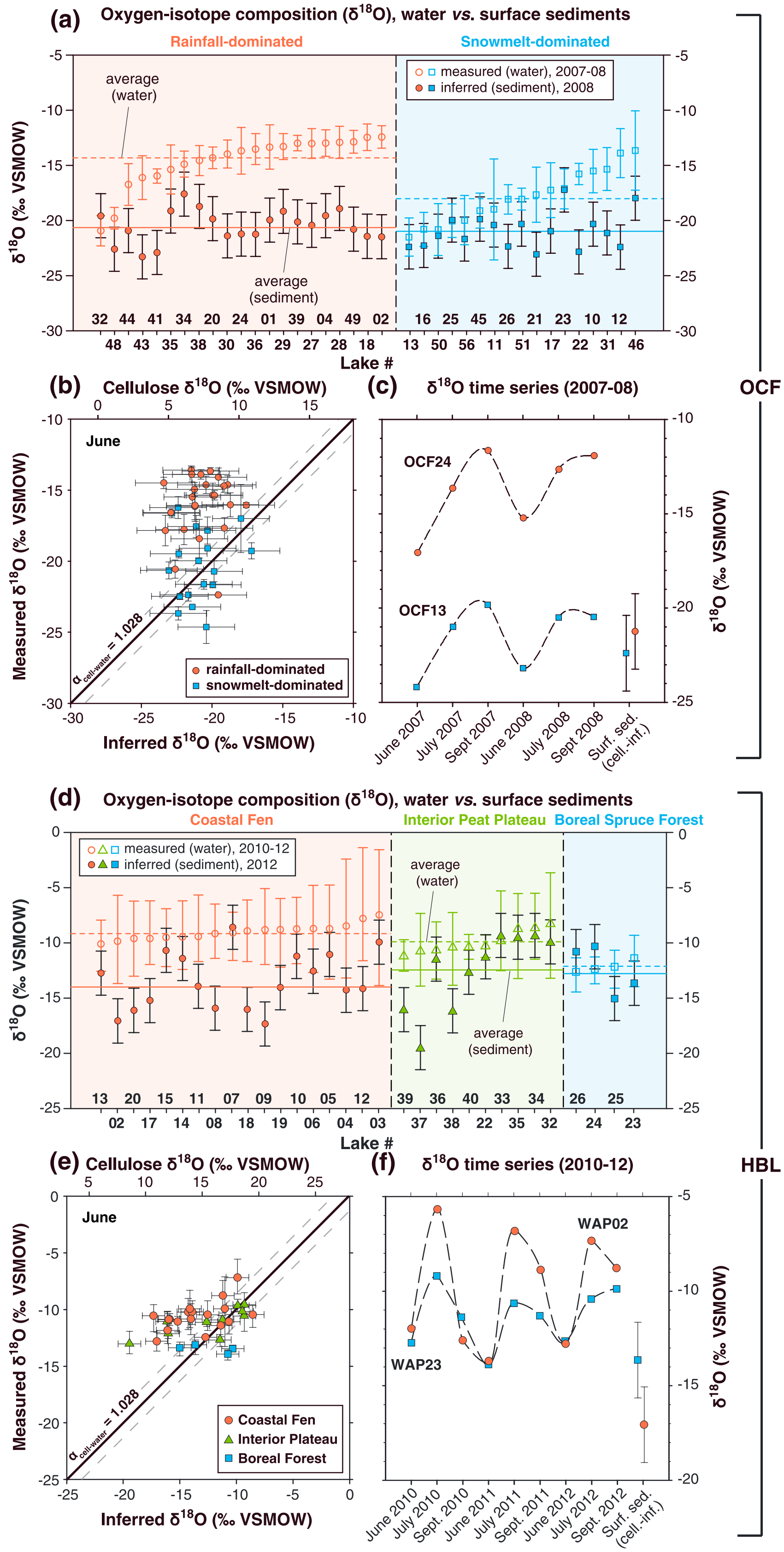
(a) Oxygen-isotope composition (δ18O), water vs. surface sediments
Rainfall-dominated
Snowmelt-dominated
measured (water), 2007-08
inferred (sediment), 2008
average (water)
average (sediment)
δ18O (‰ VSMOW)
Lake #
(b) Cellulose δ18O (‰ VSMOW)
June
Measured δ18O (‰ VSMOW)
Inferred δ18O (‰ VSMOW)
α cell-water = 1.028
rainfall-dominated
snowmelt-dominated
(c) δ18O time series (2007-08)
OCF24
OCF13
June 2007
July 2007
Sept 2007
June 2008
July 2008
Sept 2008
Surf. sed. (cell.-inf.)
OCF
(d) Oxygen-isotope composition (δ18O), water vs. surface sediments
Coastal Fen
Interior Peat Plateau
Boreal Spruce Forest
measured (water), 2010-12
inferred (sediment), 2012
average (water)
average (sediment)
(e) Cellulose δ18O (‰ VSMOW)
June
Coastal Fen
Interior Plateau
Boreal Forest
(f) δ18O time series (2010-12)
WAP02
WAP23
June 2010
July 2010
Sept. 2010
June 2011
July 2011
Sept. 2011
June 2012
July 2012
Sept. 2012
Surf. sed. (cell.-inf.)
HBL

Figure 2

Table 1. Winter (October to April) Precipitation (mm) for Old Crow (Yukon; Station 2100800) and Churchill (Manitoba; Average of Stations 5060600, 5060606, and 5060608)[a]

Period	Old Crow	Churchill
2001–2002	99.7[b]	
2002–2003	99.3[b]	
2003–2004	135.3[b]	
2004–2005	151.2[b]	185.6[b]
2005–2006	>61.9[c]	165.2[b]
2006–2007	148.0[d]	180.2[b]
2007–2008	35.0[d]	151.9[b]
2008–2009		133.5[b]
2009–2010		62.9[d]
2010–2011		46.0[d]
2011–2012		164.9[d]
Climate normal, 1971–2000	104.3	167.7
Average, years prior to water sampling	121.4	163.3
Average, years of water sampling	91.5	91.3

[a]*Environment Canada* [2013].
[b]Years prior to water sampling.
[c]Incomplete record (not included in average calculation).
[d]Years of water sampling.

early ice-free season (mean June) $\delta^{18}O_{lw}$ (Figures 2e and 2f). For the lakes that did not display agreement between $\delta^{18}O_{inf\text{-}lw}$ and $\delta^{18}O_{lw}$ (mainly in the CF), results were positioned systematically above the 1:1 line (Figure 2e) and $\delta^{18}O_{inf\text{-}lw}$ was lower than the seasonal range of $\delta^{18}O_{lw}$ (Figure 2f).

5. Discussion and Conclusions

[10] Agreement between $\delta^{18}O_{inf\text{-}lw}$ and mean June $\delta^{18}O_{lw}$ for most of the snowmelt-dominated lakes in OCF, as well as all BSF and most IPP lakes in HBL, can be explained by high aquatic production during the early part of the ice-free season. At this time, lake waters are supplied by isotopically depleted snowmelt runoff that is rich in dissolved nutrients from interactions with soil and plant organic matter. In OCF, snowmelt-dominated lakes have higher concentrations of nutrients including dissolved phosphorus, silica, and organic carbon compared to rainfall-dominated lakes [*Balasubramaniam*, 2012]. Furthermore, incorporation of isotopic signatures from the early ice-free season by aquatic cellulose has been identified in paired analyses of seasonal $\delta^{18}O_{lw}$ and surface sediment $\delta^{18}O_{inf\text{-}lw}$ from other shallow boreal lakes [e.g., *Wolfe et al*., 2012].

[11] We considered several hypotheses to explain the positive offset in $\delta^{18}O_{lw}$ relative to $\delta^{18}O_{inf\text{-}lw}$ that is evident for most of the rainfall-dominated lakes in OCF and some of the CF and IPP ecozone lakes of HBL. Potential incorporation of nonaquatic cellulose from terrestrial sources always poses concern when using sediment cellulose as a lake water oxygen isotope archive [*Sauer et al*., 2001], yet this would not yield a positive offset, since terrestrial cellulose should be more enriched under the same climatic conditions [*Edwards and McAndrews*, 1989]. Organic carbon and nitrogen elemental and isotope data for the surface sediments of these lakes (see Table S1 in the supporting information) also supports a fully aquatic origin for sedimentary organic matter, and hence the validity of the inferred positive $\delta^{18}O_{lw}$-$\delta^{18}O_{inf\text{-}lw}$ offset. On the other hand, meteorological records reveal that three of our water-sampling campaigns were performed following winters of substantially lower snowfall (i.e., winter 2007–2008 for OCF and 2009–2010, 2010–2011 for HBL) compared to climate normals (Table 1). Furthermore, average snowfall was 25% and 44% less during the water-sampling years in Old Crow and Churchill, respectively, compared to the average of the 5 years immediately prior. Although we recognize that precipitation can be spatially heterogeneous, a meteorological station deployed in central OCF during our water-sampling years showed good agreement with the Environment Canada meteorological station records from the hamlet of Old Crow [*Turner et al*., 2013]. Thus, less snow generated less snowmelt runoff to several lakes during the water-sampling years, which resulted in more pronounced isotopic enrichment by evaporation compared to the time intervals captured by the surface sediments (which span ~5–10 years based on paleolimnological studies) [e.g., *Wolfe et al*., 2011; *MacDonald et al*., 2012]. *Turner et al*. [2013] identified strong evaporative isotopic enrichment in OCF lake waters during 2008, following a winter of low snow accumulation. Our results suggest that a similar evaporative response explains the positive offset in $\delta^{18}O_{lw}$ relative to $\delta^{18}O_{inf\text{-}lw}$, albeit over longer time scales. These hydrologically sensitive or "flashy" lakes are mostly situated in catchments characterized by low-relief terrain and sparse tundra vegetation where snow cover is vigorously redistributed by wind.

[12] Shallow subarctic lakes that undergo pronounced evaporation when snowmelt runoff is low may desiccate. In fact, this was observed in midsummer 2010 in HBL (Figure 3a), which may reflect an extreme hydrological consequence of recent climate warming in this region—warming that has led to shifts in algal communities in deeper lakes in the southern HBL [*Rühland et al*., 2013]. Additional paleolimnological data suggest that shallow subarctic lakes in northwestern HBL, like their high-arctic counterparts, may indeed be approaching the "final ecological threshold" [cf. *Smol and Douglas*, 2007]. Lake water $\delta^{18}O$ reconstructed from cellulose $\delta^{18}O$ measurements along a 24.5 cm long sediment core retrieved from CF lake WAP12, which almost completely desiccated during midsummer 2010, indicate remarkably stable hydrological conditions over most of the past ~200 years (Figure 3b). Although desiccation horizons in lacustrine strata can be difficult to identify, the WAP12 record appears to contain no evidence of comparably dry intervals in the past.

[13] Low snowmelt runoff and lake desiccation during midsummer 2010 may be a sign of things to come for the HBL and other regions with shallow lakes in catchments having low-relief and sparse tundra vegetation. Based on

Figure 2. Comparison of measured lake water oxygen isotope composition ($\delta^{18}O_{lw}$) with surface sediment cellulose-inferred lake water oxygen isotope composition ($\delta^{18}O_{inf\text{-}lw}$) for (a–c) Old Crow Flats (OCF) and (d–f) northwestern Hudson Bay Lowlands (HBL) lakes: $\delta^{18}O_{lw}$ range versus $\delta^{18}O_{inf\text{-}lw}$ (Figures 2a and 2d), mean and range for June $\delta^{18}O_{lw}$ versus $\delta^{18}O_{inf\text{-}lw}$ (Figures 2b and 2e), time series of $\delta^{18}O_{lw}$ for lakes OCF13 (snowmelt dominated) and OCF24 (rainfall dominated), WAP02 (coastal fen) and WAP23 (boreal spruce forest), and $\delta^{18}O_{inf\text{-}lw}$ (Figures 2c and 2f). Lake categories and ecological zones as defined by *Turner et al*. [2010] and *Parks Canada* [2013], respectively. Error bars for $\delta^{18}O_{inf\text{-}lw}$ represent estimated uncertainties of ±2.0‰.

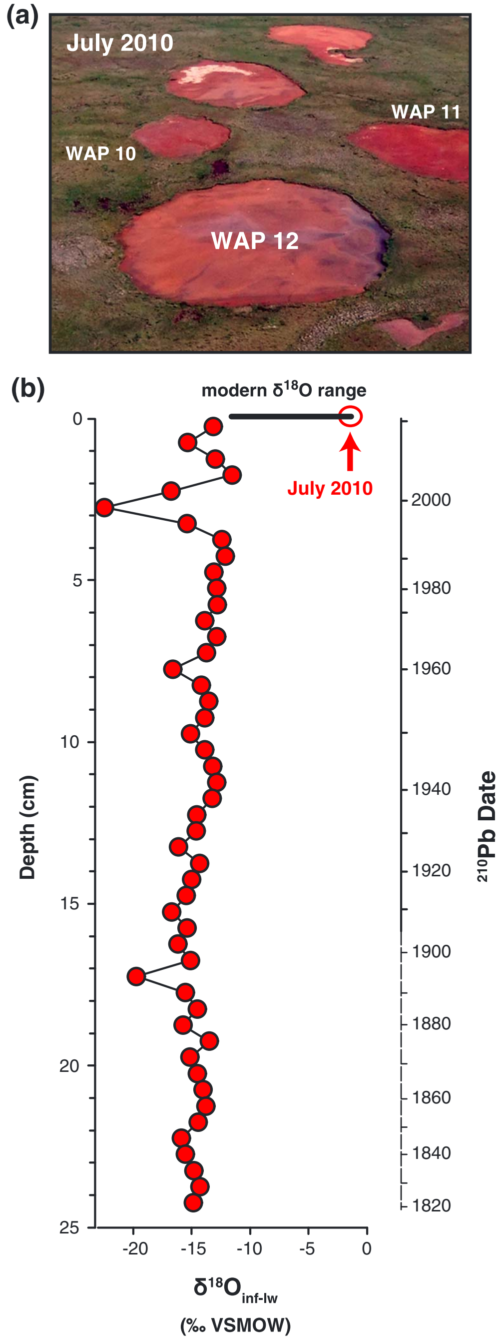

Figure 3. (a) Near-complete desiccation of WAP12 (and other nearby lakes) during midsummer of 2010. Note that despite lower snowfall in 2010–2011, substantial late summer rainfall in 2010 prevented desiccation of WAP12 in 2011, (b) cellulose-inferred lake water oxygen isotope composition ($\delta^{18}O_{inf\text{-}lw}$) record from lake WAP12 (coastal fen ecozone). The depth-age model was determined using ^{210}Pb (see supporting information).

satellite data spanning the past 4 decades, *Derksen and Brown* [2012] reported marked reductions in spring (April to June) snow cover extent over the Northern Hemisphere and indicated that the rate of snow cover loss from 1979 to 2011 (−17.8% per decade) was almost double the rate of September sea ice loss during the same period (−10.8% per decade). Moreover, the lowest spring snow cover extent for both North America and Eurasia has occurred during the 2008–2012 period; the year 2010 set a record low for North America. Trends toward declining snow cover are expected to continue [*Derksen and Brown*, 2012], although significant spatial and seasonal differences are projected to occur [*Arctic Monitoring and Assessment Programme*, 2011; *Krasting et al.*, 2013].

[14] For regions that experience a decline in snow cover extent and reduction in snowmelt runoff with continued warming, our isotope data coupled with field observations from two of Canada's largest lake-rich subarctic landscapes indicate that shallow lakes located in low-relief, open tundra terrain are particularly susceptible to desiccation by evaporation. Such hydrological changes will have profound effects on wildlife habitat, carbon cycling, and other aquatic ecosystem services [e.g., *van der Molen et al.*, 2007; *Abnizova et al.*, 2012].

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