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For Immediate Release
June 9, 2011 | 094-11

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5,200-year record warns of impending water shortages in western North America

WATERLOO – Researchers from Wilfrid Laurier University and the University of Waterloo are predicting a freshwater shortage in western North America beyond anything experienced in societal memory. The shortage will have implications for many sectors of society, including the Alberta oil sands industry, hydroelectric production and agriculture.

Using a 5,200-year record of water-level variations in Lake Athabasca, researchers show that western Canadian society developed during a rare period of abundant water supply that was ‘subsidized’ by glacier expansion. Now, shrinking glaciers and snowpacks are reducing the discharge in rivers originating in the central Rocky Mountain region that support downstream societies in western North America – a pattern which is expected to continue for many decades.

“We must now prepare for water shortages of duration and magnitude not evident in hydrometric records or our collective awareness,” said Brent Wolfe, principal investigator on the study and associate professor and NSERC Northern Research Chair in Laurier’s Department of Geography and Environmental Studies.

With the anticipated growth in the petroleum sector, along with additional demands on existing freshwater availability, decision-makers will be increasingly challenged to manage freshwater resources appropriately to minimize risks to downstream ecosystems.

“Our findings suggest that predictions made by decision-makers and planners in government and industry – based entirely on inadequate, short instrumental records – will grossly underestimate how rapid and severe the impending water scarcity will be,” said Tom Edwards, professor at the University of Waterloo’s Department of Earth & Environmental Sciences.

This is particularly true for large areas of the arid interior of western North America, where water supplied by rivers originating at high elevation is the life-blood of regional economies.

The Alberta oil sands industry uses more than half of the total water allocation in the Athabasca River Basin. The industry’s water use is expected to increase by 120-165 per cent by 2025.

“As the ‘alpine water tap’ closes, much drier times are ahead,” said Roland Hall, professor at the University of Waterloo’s Department of Biology. “The transition from abundance to scarcity can occur within about a human lifespan. Our findings convey an important message that government and industry must start now to prepare for unprecedented water scarcity.”

Researchers emphasize that recent spring floods in the Prairies should not be misconstrued as an abundance of water. These short-lived floods were driven by snow that accumulated over a single winter at low-elevations. In contrast, sustained high flows occur during summer, fed by high elevation snowpacks and glaciers that grow and shrink over longer time periods. The study identifies that changes in these summer flows are likely to present the greatest challenges.

The study was published June 9, 2011 in *Geophysical Research Letters*.

A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff

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Received 28 March 2011; revised 21 April 2011; accepted 22 April 2011; published 9 June 2011.

[1] Shrinking glaciers and snowpacks are reducing discharge in rivers that drain the central Rocky Mountain region – water that supports downstream societies and ecosystems of western North America. However, a new 5200-year record of Lake Athabasca water-level variations, which serves as a sensitive gauge of past changes in alpine-sourced river discharge, reveals that western Canadian society has developed during a rare period of unusually abundant water 'subsidized' by prior glacier expansion. As the 'alpine water tap' closes, much drier times are ahead. Future water availability is likely to become similar to the mid-Holocene when Lake Athabasca dropped 2–4 m below the twentieth-century mean. Regions dependent on high-elevation runoff (i.e., western North America) must prepare to cope with impending water scarcity of magnitude not yet experienced since European settlement.

Citation: Wolfe, B. B., T. W. D. Edwards, R. I. Hall, and J. W. Johnston (2011), A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff, *Geophys. Res. Lett.*, *38*, L11404, doi:10.1029/2011GL047599.

1. Introduction

[2] The Athabasca River provides an important source of water to shallow lakes and wetlands of the Peace-Athabasca Delta (Alberta, Canada), the world's largest freshwater boreal delta, much of which has undergone drying over the past several decades as a result of climate-driven decreases in river discharge [*Wolfe et al.*, 2008a, 2008b]. Concerns over declining freshwater contributions to support this internationally recognized and protected floodplain landscape are heightened by rapidly increasing pressure on the Athabasca River to support societal needs [*Schindler and Donahue*, 2006; *Woynillowicz and Severson-Baker*, 2006; *Lebel et al.*, 2011]. According to the provincial agency responsible for its management, water allocations in the Athabasca River Basin are growing at a rate nine times faster than the provincial average, having increased by 88% since 2000 (see http://environment.alberta.ca/01750.html). The oil and gas sector is the largest water user in the Athabasca River Basin. Water use by this sector has more than doubled since 2000 due to rapid oil sands development in the Fort McMurray region, accounting for ~65% of total allocations in 2008. Use of surface water by the oil and gas sector is forecasted to increase from 2005 to 2025 by 120% under a low to medium growth scenario, and by 165% under a high growth scenario [*Mannix et al.*, 2010]. Although water allocation to support the oil sands industry is regulated by guidelines contained in the Lower Athabasca Water Management Framework [*Alberta Environment/Department of Fisheries and Oceans Canada*, 2007], the anticipated growth of the petroleum sector, coupled with additional demands on existing freshwater availability (e.g., other commercial uses, municipal water supply, agriculture), will increasingly challenge decision-makers to manage this resource appropriately to ensure that impacts to downstream ecosystems are minimized. Development of effective water policy is further complicated by climate warming and declining contributions to river discharge from glacial meltwater and alpine snowmelt runoff [*Schindler and Donahue*, 2006; *Mannix et al.*, 2010]. Other jurisdictions in western North America dependent on runoff generated from high-elevation melting of ice and snow face similar challenges [e.g., *Overpeck and Udall*, 2010].

[3] Characterizing the role of climate on generating river discharge in the Athabasca River Basin is, thus, crucial for establishing appropriate guidelines for water resource allocation. Several studies have employed statistical methods on meteorological and streamflow gauge data to identify climate – discharge relationships and trends for water resource planning in this and other western and northern Canadian watersheds [e.g., *Woo and Thorne*, 2003; *Burn et al.*, 2004; *Déry and Wood*, 2005; *Rood et al.*, 2005, 2008; *Abdul Aziz and Burn*, 2006; *Burn*, 2008]. Although some empirical patterns have emerged, such as evidence for a shift towards an earlier spring discharge peak, the reliability of results can be difficult to assess because of the short operational time span of meteorological and hydrometric stations (i.e., past ~60 years). Indeed, the addition of new years of data to existing instrumental records has often led to conflicting trends of river discharge, and even trend-reversals [e.g., *Déry et al.*, 2009], a feature which suggests instrumental records remain too short to adequately characterize relationships between climatic variability and discharge. Longer hydrological records are needed to evaluate the response of river discharge to a range of natural climatic conditions, knowledge that can better inform water resource management [*Kane*, 2005; *Sear and Arnell*, 2006].

[4] Our previous research has identified that the level of Lake Athabasca, North America's ninth-largest lake, is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains [*Wolfe et al.*, 2008a; *Johnston et al.*, 2010; *Sinnatamby et al.*, 2010]. Paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels

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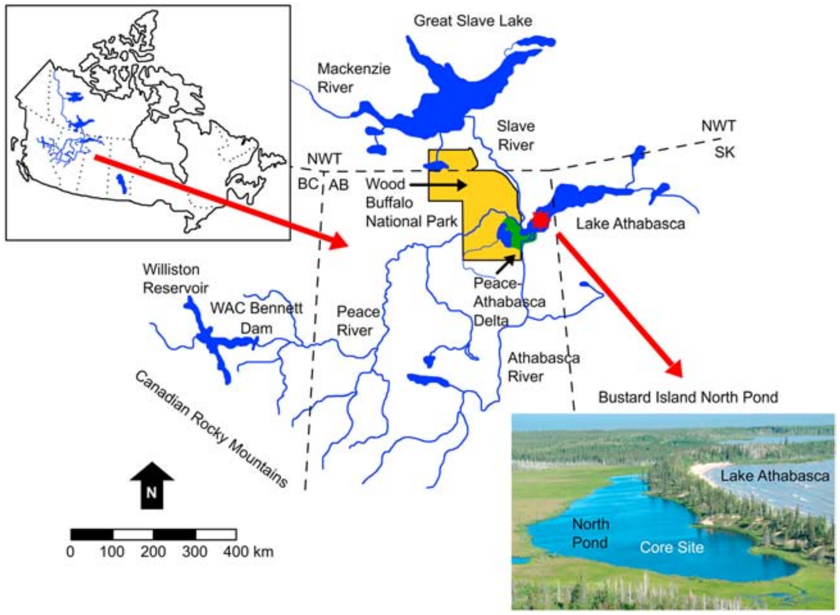

Figure 1. The Athabasca River originates from alpine snowpack and glacier meltwater in the Columbia Icefield on the eastern slopes of the Canadian Rocky Mountains and discharges into Lake Athabasca. Except for brief periods of ice-jam floods, the Peace River does not flow into Lake Athabasca. During normal flow conditions, it acts as a hydraulic barrier to lake outflow when the river level is higher than lake level. The sediment record was obtained from 'North Pond', a lagoon on Bustard Island located at the western end of Lake Athabasca [*Johnston et al.*, 2010].

relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks [*Wolfe et al.*, 2008a]. The highest levels of the last 1000 years occurred *c.*1600–1900 CE during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies. The magnitude of the LIA Highstand is supported by multiple lines of evidence that Lake Athabasca expanded westward into the central region of the Peace-Athabasca Delta, frequently or perennially inundating shallow floodplain lakes and wetlands [*Sinnatamby et al.*, 2010] and repeatedly re-occupying a paleo-strandline ~2.3 m above the historical average level [*Johnston et al.*, 2010]. Conversely, lowest levels existed at *c.* 970–1080 CE at a time of low glacier volume. Here, we extend the water-level record for Lake Athabasca by four millennia to reveal a mid-Holocene Lowstand of even greater magnitude (2–4 m below 20th century mean) and longer duration (~5200–2500 BP), indicating that ongoing climate-driven decline in high-elevation runoff will markedly intensify freshwater shortages in western Canada.

2. Study Site

[5] Our proxy record for Lake Athabasca water level was obtained from the sediments of 'North Pond', a relict lagoon isolated behind a transgressive barrier-beach complex along the northeastern shore of Bustard Island (Figure 1). North Pond is ~2 m deep and ~7 ha in surface area, and has no surface inlets or outlets. A large wetland (~24 ha) adjacent to the western shore of the pond marks the area flooded at times of high water levels in the past. The barrier consists of waterlain sand deposited as the barrier advanced pondward and is capped by aeolian sand, now stabilized by mature vegetation [*Johnston et al.*, 2010]. Water levels in North Pond closely track changes in the water plane of Lake Athabasca [*Johnston et al.*, 2010], as is commonly the case for lakes, ponds and wetlands that occur behind permeable unconsolidated coastal barriers [*Peterson et al.*, 2007].

3. Methods

[6] Sediment cores were collected from North Pond in July 2004 using a 7.5-cm diameter gravity corer and 10-cm diameter Russian peat corer. Cores were sectioned into 0.5-cm intervals before chronological and geochemical analyses. The core chronology was developed from a combination of ^{210}Pb dating of the uppermost sediments and two ^{14}C dates on organic matter at 68.0 and 229.0 cm depth, reported previously [*Johnston et al.*, 2010]. The age model accounts conservatively for declining sediment compaction with depth up-core using a quadratic polynomial fit between 229.0 cm (5166 cal. BP; 3216 BCE) and 72.8 cm (917 cal. BP; 1033 CE), followed by constant rate of sedimentation to 16.8 cm (89 cal. BP; 1861 CE).

[7] Bulk organic carbon and nitrogen elemental content were measured on most 0.5-cm intervals in the Russian core sequence. Subsamples were acid-washed (10% HCl), rinsed with de-ionized water and freeze-dried. The fine fraction (<0.5 mm) was measured using an elemental analyzer at the University of Waterloo – Environmental Isotope Laboratory. We interpret the carbon to nitrogen (C/N) weight ratio in North Pond sediments to reflect changes in the source of accumulating organic matter (aquatic plants versus peat) [*Meyers and Teranes*, 2001], as the relict lagoon expanded and contracted in response to changes in Lake Athabasca water levels. The C/N ratio record of the past millennium corresponds with the pattern of variability in the tree-ring-based reconstruction of North Saskatchewan River streamflow

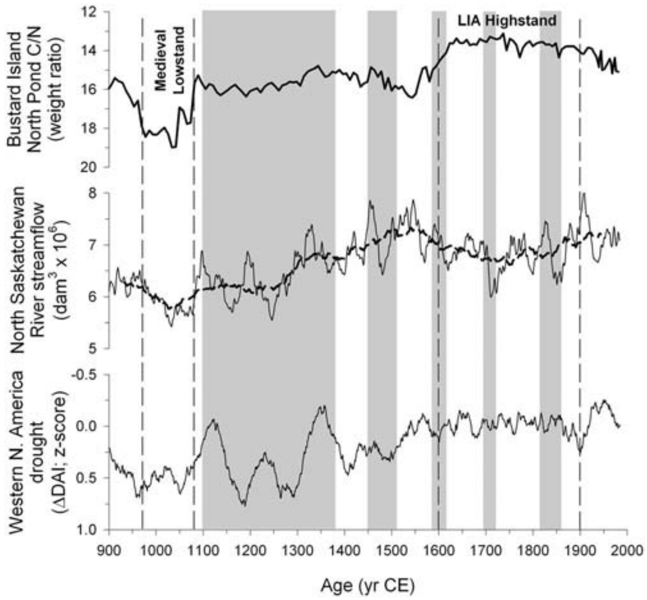

Figure 2. Past millennium C/N ratio record from Bustard Island 'North Pond' [*Johnston et al.*, 2010], a proxy for Lake Athabasca water level (upper graph), North Saskatchewan River streamflow (20-yr and 100-yr means shown, middle graph) [*Case and MacDonald*, 2003] and western North America Drought Area Index (DAI; lower graph) where positive values reflect drier conditions [*Cook et al.*, 2004]. Note that scales are reversed for the upper and lower graphs. Dashed lines mark intervals of the Lake Athabasca Medieval Lowstand and Little Ice Age (LIA) Highstand derived from the C/N ratio profile, which closely align with the other paleohydrological reconstructions as well as multiple paleolimnological records from the Peace-Athabasca Delta [*Wolfe et al.*, 2008a]. Shaded time intervals identify known periods of glacier expansion in the eastern Canadian Rocky Mountains [*Edwards et al.*, 2008], which sustained river discharge during the summer and raised Lake Athabasca water levels following the Medieval Lowstand and again during the LIA [*Wolfe et al.*, 2008a].

[*Case and MacDonald*, 2003], whose headwaters lie near those of the Athabasca River (Figure 2). In particular, both records indicate low water supply during the 11th century Medieval Lowstand as well as generally higher water levels and greater discharge during the LIA, linked to runoff characteristics associated with naturally-occurring fluctuations in glacier mass balance at the headwater region. Early millennium drought also has been widely recognized throughout the western United States [*Cook et al.*, 2004] (see Figure 2).

4. Results

[8] The 229-cm core consists of interbedded units of peat and peat with sandy laminations (Figure 3a). A 94-cm basal sequence of peat (P1 (fibrous: 229 to 175 cm); P2 (175 to 135 cm)) is followed by three alternating intervals of sandy laminations in peat (S1 (135 to 110 cm), S2 (85 to 70 cm) and S3 (32 to 17 cm)) and dispersed sand in peat (P3 (110 to 85 cm), P4 (70 to 32 cm) and P5 (17 to 5 cm)).

[9] Systematic variations in the organic carbon to nitrogen (C/N) ratio correspond with the stratigraphic zonation of alternating peat and peat with sandy laminations (Figure 3b). The lowermost zones, P1 and P2, contain high and variable C/N ratios with values mainly ranging from 15.9 to 25.4. C/N ratios decrease at the top of zone P2 from ~17 to ~13.5. Conversely, C/N ratios in zone S1 are low and less variable, ranging from 13.2 to 14.7, and increase towards the top of the interval. In zone P3, C/N ratios range from 13.9 to 17.0 and exhibit oscillations of high and low values. C/N ratios in zone S2 are high and defined by a peak in values of ~18–19. In zone P4, C/N ratios are moderate, ranging from 13.4 to 16.4. C/N ratios in zone S3 are low and within a narrow range (13.1 to 14.4). In zone P5, C/N ratios increase from ~14 to 15. Generally, peat zones (P1–P5) have relatively high C/N ratios, whereas zones containing peat with sandy laminations (S1, S3) have relatively low C/N ratios, with the exception of zone S2.

5. Discussion

[10] Close correspondence between the C/N ratio profile and the physical stratigraphy of the sediment core suggests that this geochemical parameter is tightly coupled to the prevailing hydrological conditions in North Pond. As discussed by *Johnston et al.* [2010] for the upper P4-S3-P5 stratigraphic sequence, oscillation in the trend of C/N ratios can be explained by changes in lake level, which is supported by other multi-proxy paleolimnological data. Low lake levels during zones P4 and P5 are associated with the deposition of peat and high C/N ratios, the latter reflecting an increase in terrestrial and peat organic matter reaching the coring site. Conversely, high lake level during zone S3 is inferred from the deposition of sandy laminations in peat and low C/N ratios, the latter due to reduced influx of terrestrial and peat organic matter reaching the coring site. The sandy laminations of zone S3 contain grain size characteristics consistent with deposition by overwash processes likely caused by periodic waves on a corresponding high-water plane of Lake Athabasca that overtopped the barrier [*Johnston et al.*, 2010]. A similar interpretation of the physical stratigraphy and C/N ratios can be readily applied to most of the remainder of the stratigraphic record. Thus, low lake levels characterize the high C/N ratio zones P1, P2 and P3 and high lake level defines the low C/N ratio zone S1. Zone S2, which contains high C/N ratios and corresponds to the Medieval Lowstand (Figure 2), is an exception to this pattern. Here, sandy laminations are well-defined and have sharp contacts (Figure 3a), consistent with aeolian deposition directly onto a dry or near-dry lake bed.

[11] Given the apparent straightforward relation between C/N ratios and lake level, we transformed the C/N ratio record into a quantitative expression of Lake Athabasca water level relative to the 20th century mean using the following approach: (1) the average C/N ratio for the 20th century was assigned a baseline lake level of "zero"; (2) the average C/N ratio for the LIA (1600–1900 CE) was used to represent a rise in lake level of 2.3 m, based on the findings of *Johnston et al.* [2010]; and (3) the average C/N ratio for the Medieval Lowstand interval (970–1080 CE) was used to estimate the maximum pond-level decline (−2.1 m), which was determined from the water depth at the time of coring (1.36 m) plus the mid-point depth in the sediment core for this interval (73.25 cm). Linear regression through these control points provides a C/N ratio – lake level relation (R^2 = 0.9) from

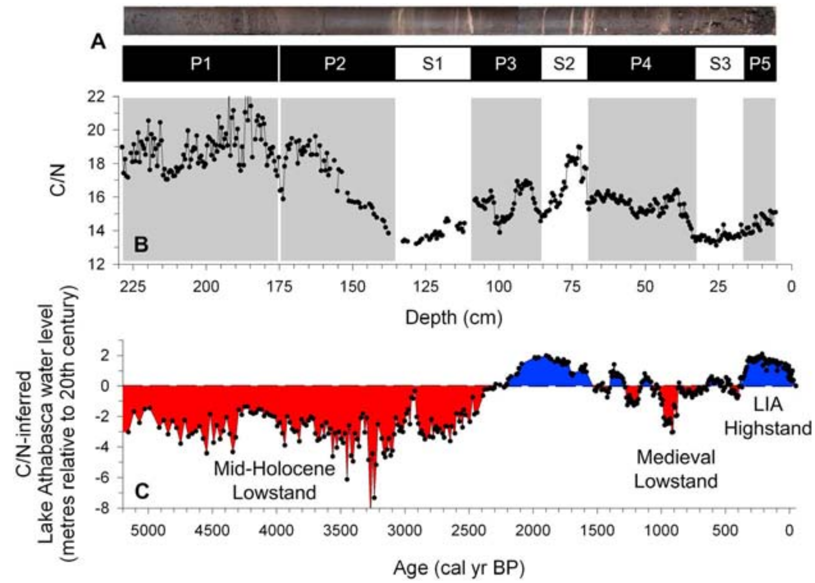

Figure 3. (a) Stratigraphic units of the sediment record from 'North Pond'. (b) C/N weight ratio versus sediment depth. (c) C/N-inferred Lake Athabasca water-level record relative to the 20th century average.

which a first-order approximation of Lake Athabasca water level history was derived for the past 5200 years (Figure 3c). Based on correspondence between inferred changes in lake level and glacier mass balance during the past millennium (Figure 2), we propose a similar relation for the earlier 4000-year portion of the record. Thus, extremely low lake levels from 5200–2500 BP were likely caused by naturally low glacier volume and snowpack in the alpine headwater region, an interpretation consistent with absence of known regional glacier advances in western Canada during 5000–3000 BP [*Clague et al.*, 2009].

[12] The lake-level reconstruction reveals that modern society in western Canada developed during a rare interval of relatively abundant freshwater supply – a now rapidly diminishing by-product of the LIA glacier expansion, which is in agreement with late 20th century decline in Athabasca River discharge identified in hydrometric records [*Burn et al.*, 2004; *Schindler and Donahue*, 2006]. Freshwater has only been in similar plentiful supply during one other multi-centennial interval (2000–1500 BP) of the past ~5200 years. Notably, the data reveal that the transition from water abundance to scarcity can occur within a human lifespan, which is a very short amount of time for societies to adapt. These findings have important implications for management of freshwater resources. If water allocation guidelines are derived solely on the basis of the brief instrumental hydrometric record (e.g., to support the Alberta oil sands industry, agriculture), the magnitude and rate of decline in freshwater supply due to climate warming will be grossly underestimated because continued reduction in glacier volume and high-elevation snow accumulation is expected [*Lapp et al.*, 2005; *Sauchyn and Kulshreshtha*, 2008].

[13] Although too brief to be captured in our sediment record, a short-lived decline in Lake Athabasca water level during 1969–1971 offers insight into potential downstream consequences of reduced river discharge. At this time, combined effects of hydrological drought in western Canada and hydroelectric reservoir filling at the Peace River headwaters caused Lake Athabasca to decline 1.5 m below the historic average. This led to temporary disappearance of nearly 40% of surface water and shorelines in the Peace-Athabasca Delta, and sparked >30 years of controversy and conflict at a national scale over utilization of water resources [*Prowse and Conly*, 2002]. Development of future conditions similar to the mid-Holocene Lowstand, a ~2–4 m lake-level drop relative to the 20th century, would impose even more severe hydro-ecological consequences and water-related conflicts. While other independent data are required to verify our quantitative lake-level reconstruction, we note that marked aridity also persisted in the Rocky Mountain headwaters of the Snake-Columbia, Missouri-Mississippi and Green-Colorado rivers from ~9000–3000 BP [*Shuman et al.*, 2010], indicating that the magnitude and duration of the mid-Holocene Lowstand is a likely sign of things to come for substantial regions of western North America that are dependent on freshwater generated from alpine ice and snow. As consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory.

[14] **Acknowledgments.** This research was supported by the NSERC Northern Research Chair, Discovery, and Collaborative and Research Development Grant Programs, the British Columbia Hydro and Power Authority, and the Polar Continental Shelf Program. Logistical support was provided by Wood Buffalo National Park. E. Dobson, P. Harms, C. Light, N. Sinnatamby, N. St. Amour, J. Wiklund, and Y. Yi contributed to field work and laboratory analyses.

[15] The Editor thanks Stephen Dery and an anonymous reviewer.

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