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Climate-driven shifts in quantity and seasonality of river discharge over the past 1000 years from the hydrographic apex of North America

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[1] Runoff generated from high elevations is the primary source of freshwater for western North America, yet this critical resource is managed on the basis of short instrumental records that capture an insufficient range of climatic conditions. Here we probe the effects of climate change over the past ~1000 years on river discharge in the upper Mackenzie River system based on paleoenvironmental information from the Peace-Athabasca Delta. The delta landscape responds to hydroclimatic changes with marked variability, while Lake Athabasca level appears to directly monitor overall water availability. The latter fluctuated systematically over the past millennium, with the highest levels occurring in concert with maximum glacier extent during the Little Ice Age, and the lowest during the 11th century, prior to medieval glacier expansion. Recent climate-driven hydrological change appears to be on a trajectory to even lower levels as high-elevation snow and glacier meltwater contributions both continue to decline.
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1. Introduction

[2] Many regions of western North America are experiencing critical water shortages, suggesting we have entered a new hydrological regime that will challenge society to respond effectively [Barnett *et al.*, 2005, 2008; Milly *et al.*, 2008]. Shrinking headwater glaciers, decreasing high-elevation snowmelt runoff, and declining river discharges in the northern Cordillera, the so-called hydrographic apex of North America [Rood *et al.*, 2005], have largely unknown consequences for natural resource development and downstream watersheds [Schindler and Donahue, 2006]. Like other streams that drain this part of the continent and flow across the northern Great Plains, where seasonal and extended intervals of water deficit are a natural element of the landscape, the Peace and Athabasca rivers provide water

that is crucial for societal needs. Climate variability and rapidly increasing industrial development are, however, raising concerns over the future availability of water resources for continued economic growth in these watersheds and to maintain the integrity of aquatic ecosystems, including the Peace-Athabasca Delta (PAD). This is particularly acute for the Athabasca River because the Alberta oil sands industry remains dependent on its water for bitumen extraction. Water consumption at current and projected rates could have undesirable ecological effects on the PAD and other downstream ecosystems [Schindler and Donahue, 2006; Wolfe *et al.*, 2008]. Assessment of contemporary relations between climate and river discharge is limited by the short duration of meteorological and hydrometric records (generally <100 years) [Déry and Wood, 2005; Rood *et al.*, 2005, 2008]. Longer hydrological records are needed to evaluate the responses of river discharge to a range of natural climatic conditions - knowledge that is essential for informed management of water resources.

[3] Here, we assemble high-resolution paleohydrological records from multiple proxies measured in lake sediment cores obtained from an oxbow lake (PAD 15), an upland perched basin (PAD 5), and two lowland basins (PAD 9, PAD 12) in the Peace-Athabasca Delta, as well as from a lagoonal pond on nearby Bustard Island in Lake Athabasca, to examine the effects of changing climate and runoff generation on the quantity and seasonality of river discharge in western Canada (Figure 1). Located in the Boreal Plains ecozone at the convergence of the Peace and Athabasca rivers, the PAD is a large (3900 km²), lake-rich floodplain landscape recognized by international conventions for its ecological significance. Our hydrological reconstructions span the past millennium, a time frame that includes a broad range of climatic conditions during the medieval (~1000 to 1530 CE), Little Ice Age (LIA; ~1530 to 1890) and post-LIA intervals as identified in the Athabasca headwater region [Edwards *et al.*, 2008].

2. Methods

[4] Sediment cores were collected in June 2001 (PAD 5, 9, 12) and July 2004 (Bustard Island North Pond) from a floating platform, and in March 2005 (PAD 15) from lake ice. A gravity corer was used to collect the upper ~30-cm of sediment from all basins. Overlapping 1-m core sequences of lake sediment were retrieved from PAD 5, 9, 12 and Bustard Island North Pond using a Russian peat corer with extension rods. A continuous 5.3-m sediment core was collected from PAD 15 using a vibra-corer system. All

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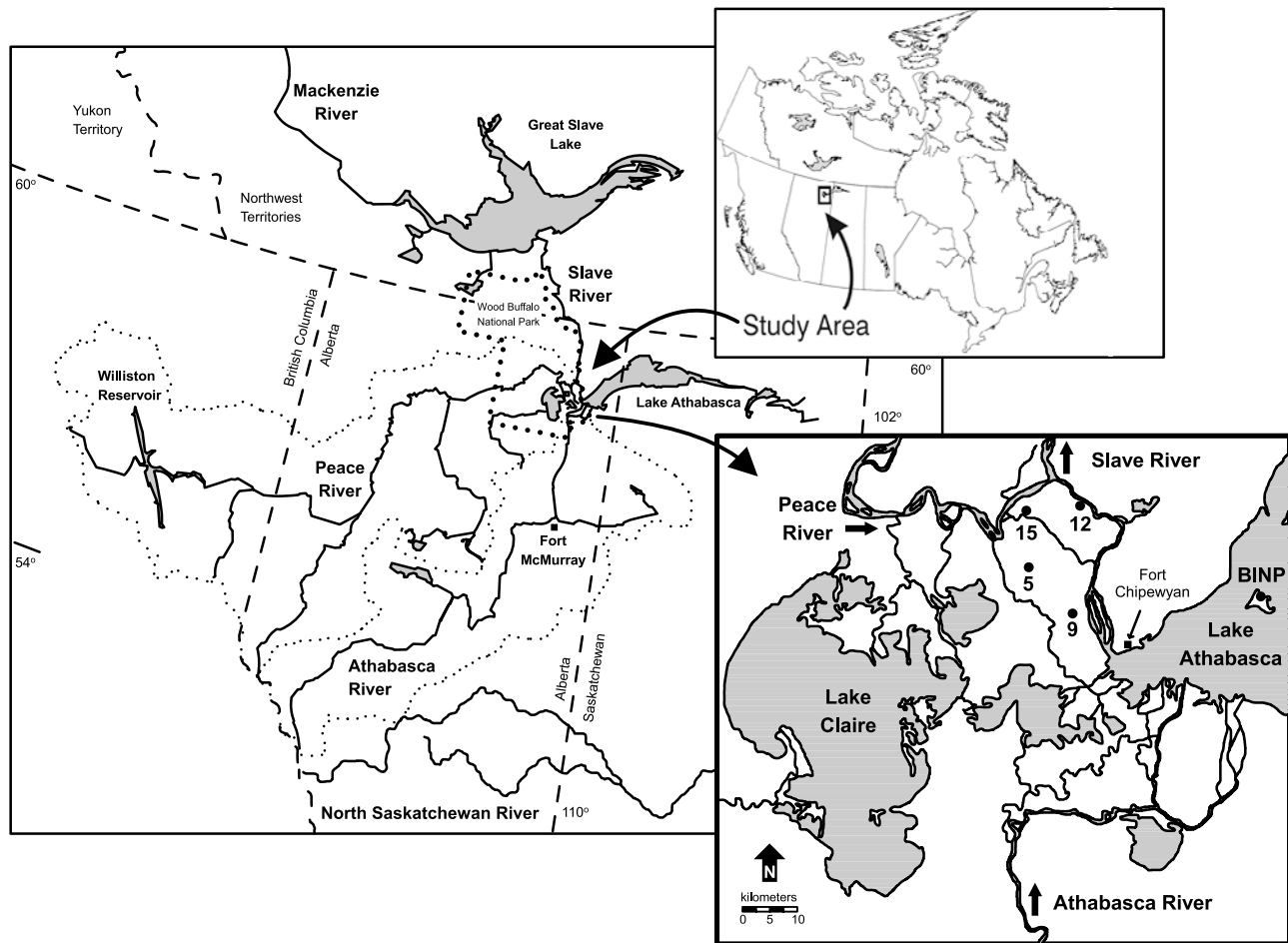


Figure 1. The watersheds of the Peace and Athabasca rivers are located near the hydrographic apex of western North American drainage and are major headwater contributors to the Mackenzie River. Also shown is the adjacent North Saskatchewan River to the south. Identified sites are locations of study basins in the Peace-Athabasca Delta (PAD 5, 9, 12, 15) and on Bustard Island (North Pond, BINP) in western Lake Athabasca, Alberta, Canada.

sediment cores were sectioned at 0.5-cm intervals for chronological and multi-proxy analyses.

[5] Paleohydrological reconstructions from the lake sediment records are derived from physical, geochemical and biological analytical results, determined using standard methods [Jarvis, 2008; Wolfe et al., 2001, 2007; Hall et al., 2004], and are constrained temporally by radiometric measurements (^{137}Cs , ^{210}Pb , ^{14}C). For PAD 15, magnetic susceptibility measured on laminated sediments is used as a proxy for the frequency and magnitude of detrital input, which is associated with ice-jam flood events on the Peace River [Wolfe et al., 2006]. For PAD 5 and PAD 12, cellulose-inferred lake water oxygen isotope composition ($\delta^{18}\text{O}_{\text{lw}}$) provides a record of lake water balance. For PAD 9 and PAD 12, summary plots of indicator diatom taxa distinguish open- and closed-drainage hydrological conditions, while taxon *Gyrosigma acuminatum* is used to identify intervals of river flooding because *Gyrosigma* is tolerant of river-borne sediment influx [Fore and Grafe, 2002]. For Bustard Island North Pond (BINP), C/N ratios reflect the input of terrestrial organic matter relative to aquatic organic matter, which is interpreted to be inversely

related to pond and Lake Athabasca water level. See auxiliary material¹ for further details.

3. Results

[6] Results (Figure 2) show that during medieval times the upland site (PAD 5) and one of the lowland basins (PAD 12) were persistently influenced by river floodwater as indicated by cellulose-inferred lakewater $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{lw}}$ for PAD 5: ~ -19 to -16 ‰; PAD 12: ~ -22 to -19 ‰) that are similar to modern-day values of local Peace River $\delta^{18}\text{O}$ during spring break-up (-20.1 to -19.0 ‰). Presence of diatom taxon *Gyrosigma acuminatum* (3–40% abundance) at PAD 12 is consistent with frequent flooding. The paleohydrological record for the oxbow lake (PAD 15) only extends to ~ 1418 , but persistently high magnetic susceptibility also indicate that frequent high-magnitude ice-jam floods from the Peace River occurred during this time. In contrast, the other lowland site (PAD 9) did not receive substantial river flooding (<3% abundance

¹Auxiliary materials are available in the HTML. doi:10.1029/2008GL036125.

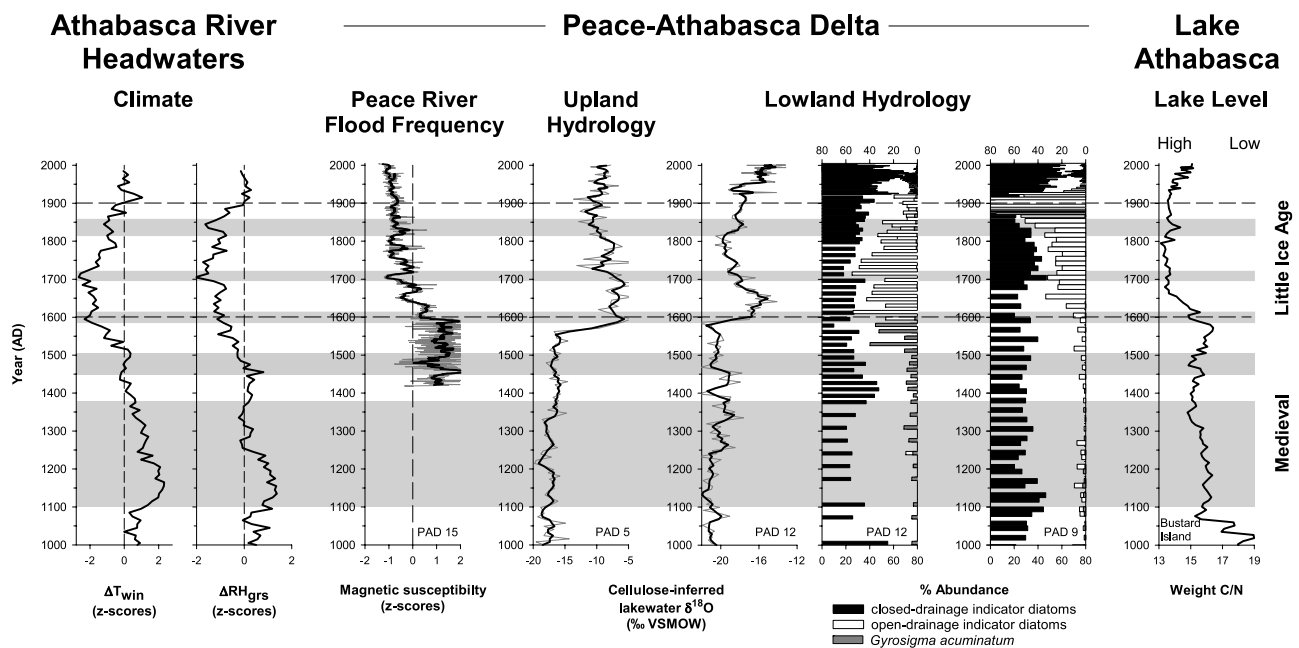


Figure 2. Multi-centennial records of Athabasca River headwaters climate (winter temperature [ΔT_{win}] and growth season relative humidity [ΔRH_{grs}]) [Edwards *et al.*, 2008], Peace River flood frequency and magnitude (PAD 15 magnetic susceptibility), Peace-Athabasca Delta upland (PAD 5 cellulose-inferred lakewater $\delta^{18}O$) and lowland hydrology (PAD 12 cellulose-inferred lakewater $\delta^{18}O$; PAD 9, PAD 12 closed- and open-drainage indicator diatoms, and diatom taxon *Gyrosigma acuminatum*), and Lake Athabasca water level (Bustard Island North Pond weight C/N ratios). Athabasca headwater climate and PAD 15 magnetic susceptibility records are plotted using z-scores, a dimensionless quantity that indicates the number of standard deviations relative to the mean value. Shaded time intervals identify known periods of glacier expansion in the eastern Rocky Mountains [Edwards *et al.*, 2008]. Hatched lines mark approximate paleohydrological transitions from the Medieval - Little Ice Age (LIA) and LIA - post-LIA intervals, which are closely aligned with the climate history described by Edwards *et al.* [2008].

of *Gyrosigma acuminatum*) and diatom assemblages are reflective of persistent closed-drainage hydrological conditions. Likewise, Lake Athabasca water levels were low, especially during the 11th century, based on high C/N ratios at BINP.

[7] Pronounced corresponding changes in Peace River flood frequency and magnitude and upland lake hydrology occurred during the transition into the LIA (Figure 2). Peace River flood frequency and magnitude, recorded by magnetic susceptibility at PAD 15, declined precipitously at ~ 1600 and remained variable until ~ 1850 . At PAD 5, $\delta^{18}O_{lw}$ values rose correspondingly by ~ 10 ‰ between ~ 1550 and ~ 1600 , attaining values that may reflect periodic to seasonal desiccation of the basin between ~ 1600 and ~ 1700 . Between ~ 1700 and ~ 1900 , $\delta^{18}O_{lw}$ values at PAD 5 fluctuated between ~ -12 and -7 ‰, which are typical of closed-drainage conditions in this ecosystem and are similar to those measured from lakewater samples obtained directly from PAD 5 (-13.4 to -3.4 ‰) over the course of several years of recent monitoring.

[8] Marked changes in lowland hydrology at PAD 9 and Lake Athabasca water levels also occurred between ~ 1600 and ~ 1900 , but proxy indicators reflect higher, rather than lower, water levels (Figure 2). These data, supported by evidence from historical maps, indicate that Lake Athabasca expanded westward into low-lying areas of the delta and generated elevated discharge along some outflow channels leading to the frequent flooding of PAD 9 [Sinnatamby,

2006]. At the other lowland site, PAD 12, stratigraphic changes at ~ 1600 are similar to both PAD 5 and PAD 9. Like PAD 5, PAD 12 $\delta^{18}O_{lw}$ values rapidly increased ~ 1600 and remained high until ~ 1650 (~ -15 ‰), although not as high as at PAD 5, indicating the lake did not approach desiccation. Instead, PAD 12 received Lake Athabasca outflow waters at this time based on the rise in the abundance of open-drainage diatoms, similar to PAD 9.

[9] Hydrological conditions during the 20th century are characterized by a complacent magnetic susceptibility record at PAD 15, suggesting relatively low frequency and magnitude of floods; increasing but moderate $\delta^{18}O_{lw}$ values at PAD 5, indicating increasing importance of evaporation; and closed-drainage conditions at PAD 9 and PAD 12 with the lowering of Lake Athabasca water levels.

4. Discussion

[10] Multi-centennial records of Peace River flood frequency and magnitude, perched basin upland and lowland hydrology in the PAD, and Lake Athabasca water level closely align with the three-phase climate history at the headwaters of the Athabasca River outlined by Edwards *et al.* [2008] (Figure 2). As we discuss below, the site-specific paleohydrological trajectories, which are complex at the landscape scale, can be reconciled by considering the quantity and seasonality of river discharge originating in

the eastern Rocky Mountains in the context of climate and glacier mass balance variability over the past ~1000 years.

[11] Glaciers expanded in the Rocky Mountains during the early millennium (mainly between ~1100–1380 and ~1450–1505; Figure 2) because of increased snowfall at high elevations [Edwards *et al.*, 2008]. The earlier time interval includes the “Medieval Megadrought” (~900–1300) when widespread hydrological drought occurred throughout western North America [Cook *et al.*, 2004; Meko *et al.*, 2007], although our results indicate that lakes in the northern portion of the PAD were frequently flooded. Lowland areas in the central part of the delta did not receive floodwater because of low levels in Lake Athabasca. The latter is supported by high C/N ratios at BINP and agrees with low mean annual streamflow reconstructed for the adjacent North Saskatchewan River watershed (Figure 1) [Case and MacDonald, 2003]. These results suggest that warmer conditions during the Medieval Megadrought, and for perhaps two centuries thereafter, continued to cause early and rapid melt of the alpine snowpack in the headwater region of rivers draining the eastern Rocky Mountains. These are hydroclimatic conditions that are likely to contribute to frequent, severe ice-jam flooding downstream [Prowse and Conly, 1998; Beltaos, 2003] but are less favourable for sustaining river discharge, and Lake Athabasca water levels, beyond the spring melt period [Rood *et al.*, 2008]. In the past millennium, our results indicate lowest levels of Lake Athabasca existed in the 11th century because rapid depletion of snowmelt was accompanied by reduced glacier meltwater contributions to river discharge.

[12] Several documented glacier expansions also occurred during the LIA in the Rocky Mountains, including ~1585–1615, ~1695–1720 and ~1815–1860 (Figure 2), in response to colder conditions between the 16th and 19th centuries [Edwards *et al.*, 2008]. Two of these expansions (~1585–1615 and ~1695–1720) correlate with decreases in flood frequency and magnitude recorded in the magnetic susceptibility from PAD 15, consistent with attenuation of the spring freshet because of increased glacial storage of water. Another glacier expansion may have occurred ~1650 based on the corresponding decrease in magnetic susceptibility. General decline in flood frequency and magnitude over this time interval is consistent with the transition to colder conditions during the LIA because slow melting during the spring thaw tends to suppress dynamic ice break-up downstream in the vicinity of the PAD [Prowse and Conly, 1998; Beltaos, 2003]. Reduction in flood frequency and magnitude caused the water balance of PAD 5 to switch rapidly from being controlled by river flooding to local climate. Under drier hydroclimatic conditions of the LIA, PAD 5 underwent extreme evaporation. While locally arid conditions created low water levels at PAD 5, rising Lake Athabasca water levels (as documented at lowland sites PAD 9, PAD 12 and BINP) clearly reflect a different hydrological response to prevailing climatic conditions. Based on these reconstructions, we suggest that delayed generation of snowmelt runoff in the Peace and Athabasca river headwaters reduced the frequency and magnitude of ice-jams downstream but sustained higher annual river discharge and higher water levels in Lake Athabasca during the LIA. In contrast, upland areas in the northern Peace sector of the delta beyond the reach of low-magnitude floods and rising

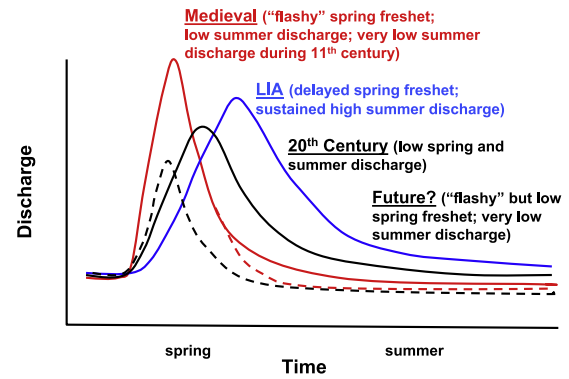


Figure 3. Evolution of hydrographs for rivers draining the hydrographic apex of North America over the past millennium and anticipated future. Schematic profiles for the Medieval Period (solid red line) including the 11th century (dashed red line), Little Ice Age (LIA; solid blue line) and 20th century (solid black line) are based on paleohydrological records in Figure 2; the future hydrograph (dashed black line) is based on expected trends [Barnett *et al.*, 2005; Wolfe *et al.*, 2008; Rood *et al.*, 2008]. Analysis of hydrometric data indicates transition to the future scenario, characterized by reduced river discharge during the spring freshet (which will continue to discourage ecologically important ice-jam flooding) and low summer discharge (which is important to sustain economically important industrial activities such as the Alberta oil sands development), is well underway [Rood *et al.*, 2008].

Lake Athabasca waters experienced net evaporative draw-down as a result of locally arid conditions and reduced contributions from local precipitation.

[13] The assemblage of 20th century hydrological conditions recorded at these sites in the PAD, which includes low flood frequency and magnitude, and closed-drainage conditions at both upland and lowland basins, are unlike any other time interval during the past 1000 years (Figure 2). These reconstructions indicate that the combined influence of the Peace and Athabasca rivers has contributed less to maintaining the hydrological status of lakes in some parts of the PAD during this century than during any other over the past millennium - a probable outcome of shrinking headwater glaciers and decreasing high-elevation snowmelt runoff since the conclusion of the LIA [Schindler and Donahue, 2006]. Consequently, drying trends at the lowland basins of the past 100 years reflect declining fluvial input, consistent with gauged records of the Athabasca River (May–August [Schindler and Donahue, 2006]), but are likely also a response to locally decreasing relative humidity over this same time period [Wolfe *et al.*, 2008]. The latter is mainly responsible for the corresponding drying trend at PAD 5 [Wolfe *et al.*, 2005, 2008]. While continued warming might be expected to generate hydrological conditions experienced during the early millennium, a comparable return of elevated flood frequency and magnitude is unlikely because of diminishing meltwater sources needed to trigger dynamic break-up events downstream [Beltaos *et al.*, 2006]. Thus, the ecological integrity of the PAD may well be at a crossroads. Further drying appears inevitable because declining high-elevation snowpack and

river discharge trends are expected to continue [Barnett *et al.*, 2005; Lapp *et al.*, 2005; Rood *et al.*, 2005, 2008; Rauscher *et al.*, 2008].

[14] The temporal perspective offered by these paleohydrological reconstructions indicates that climatic changes over the past millennium have led to characteristic responses in the quantity and seasonality of streamflow generated from the hydrographic apex of North America (Figure 3). For water resource managers, a key feature that emerges from these results is that the hydrograph of the 21st century may be evolving towards conditions unprecedented over the past ~1000 years, extending beyond the 11th century when reduced glacier meltwater contributions were partly compensated by abundant snowmelt runoff. Continuing reduction in both peak and total discharge clearly underscores the need for stringent allocation of freshwater resources in these watersheds, and in others reliant on high-elevation snowmelt runoff [Barnett *et al.*, 2005].

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