Glacially mediated impacts of climate warming on alpine lakes of the Canadian Rocky Mountains

Rolf D. Vinebrooke, Patrick L. Thompson, William Hobbs, Brian H. Luckman, Mark D. Graham and Alexander P. Wolfe

Introduction

Climate warming is having a more pronounced impact on temperature change in alpine and polar regions than on a global scale (BENISTON 2006, LEMKE ET AL. 2007). For the Cordillera region of North America, climate models predict that warming will increase with elevation, reaching its maximum at mid-northern latitudes (BRADLEY et al. 2004). Dendrochronological models have already shown that summer temperatures in the Canadian Rockies were anomalously warm during the 20th century (LUCKMAN & WILSON 2005).

Catchment features (e.g., glaciers) strongly influence the impacts of global warming on mountain lakes (THOMPSON et al. 2005, GUILIZZONI et al. 2006). Warmer alpine conditions may cause glacially fed lakes to become more turbid by amplifying the influx of rock flour (LEONARD & REASONER 1999). Alternatively, certain lakes will likely become clearer as climate warming ablates small glaciers (DESLOGES 1994).

Global warming should exert contrasting impacts on primary production in alpine lake ecosystems depending on the presence or absence of glaciers (THOMPSON et al. 2005). Warmer temperatures are expected to suppress primary producers in glacially fed alpine lakes as increased inputs of turbid meltwater reduce underwater light availability and generate colder lake temperatures. In contrast, climate warming can hypothetically stimulate primary production in clear lakes by increasing the extent and duration of stratification (AUSTIN & COLMAN 2007), the number of thermal-degree days (longer and warmer ice-free seasons), and recycling of nutrients (STRECKER et al. 2004).

We tested for the effects of climate warming on total alpine phytoplankton abundance during glacial versus nonglacial periods by reconstructing the 400-yr long histories of 2 lakes located in the Canadian Rocky Mountains. Glacial activity was inferred from estimates of clastic sediment flux based on variations in loss-on-ignition (LOI) organic carbon levels (DESLOGES 1994, LEONARD & REASONER 1999, BEIERLE et al. 2003). Total photoautotrophic abundance was quantified using high performance liquid chromatographic analysis (HPLC) of taxonomically diagnostic sedimentary algal and phototrophic bacterial pigments (VINEBROOKE &

LEAVITT 1999). The relationship between total annual photoautotrophic abundance in each lake and climatic variation was examined by correlating sedimentary microbial pigment concentrations with dendrochronologically inferred summer temperatures (LUCKMAN & WILSON 2005).

Key words: climate warming, glaciers, mountain lakes, microbial pigments, paleolimnology

Materials and methods

Curator Lake (52°48'N; 117°52'W) and McConnell Lake (51°35'N; 115°59'W) are 2 remote fishless alpine lakes located along the eastern Front Ranges of Jasper and Banff National Parks, respectively. Curator Lake is situated at an elevation of 2232 m a.s.l., and has a surface area of 10 ha and maximum depth of 25 m. McConnell Lake is located at 2271 m a.s.l., and is slightly smaller (9.4 ha) and deeper (maximum depth of 31 m). Both lakes are situated in sheltered cirque valleys currently devoid of glaciers and predominated by extensive fields of moraine along with sparse patches of vegetation. Further, short wind fetch (<300 m) and emission of gaseous sulfides upon retrieval of sediment cores suggested the presence of mid-summer thermal stratification and hypolimnetic anoxia in both lakes.

Cores were collected from both lakes during August 2006 using a modified Kajak-Brinkhurst gravity corer to collect a continuous sediment record with an intact sediment-water interface (GLEW et al. 2001). Cores were sectioned at the site in 0.25 cm (0–10 cm), 0.5 cm (10–20 cm), and 1 cm (>20 cm) increments into VWR sample bags (VWR, Mississauga, ON, Canada) using a high-resolution sectioning device. Samples were transported on ice back to the laboratory where they were stored at –20°C until pigment analysis.

Microbial pigment concentrations were quantified using a standard reverse phase high pressure liquid chromatographic technique (VINEBROOKE & LEAVITT 1999). Pigments were first extracted from freeze-dried sediments using an acetone-methanol solution. Extracts were then filtered (0.2-µm pore nylon), dried under N₂, and reconstituted using a precise vol-

ume of injection solution. Chromatographic separation was performed with an Agilent 1100 Series HPLC equipped with a Varian Microsorb-100Å C18 column, and pigment detected using in-line diode array and fluorescence detectors. Pigment concentrations were quantified via calibration equations and an electronic spectral library constructed using standards purchased from DHI Water and Environment (Agerø Alle 5, DK-2970 Hørsholm, Denmark). All concentrations are expressed as mass per gram organic matter ($\text{mg} \cdot \text{g}^{-1} \text{OM}$), which was determined by mass loss on ignition at 550 °C (HEIRI et al. 2001). Chronostratigraphy of the cores was established through analysis of ^{210}Pb (measured as ^{209}Po) by alpha spectroscopy (APPLEBY et al. 2001). Calculation of ages is based on unsupported ^{210}Pb inventories and the constant rate of supply (CRS) model (APPLEBY & OLDFIELD 1978). Having established a constant mass sedimentation rate from the lead inventories, the lower portions of the cores were extrapolated to give an estimated age for the base of each core.

Results and discussion

Temporal variation in sedimentary organic content differed substantially between the 2 alpine study lakes (Fig. 1). Little variation in the relatively low organic content of the core from Curator Lake indicated that clastic input was constant and heavy for approximately 200 years prior to the mid-1800s (Fig. 1a). Thereafter, a steady rise in organic content occurred during the early 1900s as witnessed by a sharp transition from light gray to brown sediments at the 4-cm depth interval. We interpret these results as evidence of the ablation of a small glacier within the catchment of Curator Lake during the early 20th century. In contrast, organic content was higher and more variable in the core from the deeper McConnell Lake (Fig. 1b). The rapid decline and subsequent increase in organic content between the late 1800s and mid-1900s corresponded with a sharp transition from dark grayish to black sediments at 8 cm below the water-sediment interface. We infer that glacial activity was more variable in the catchment of McConnell Lake and involved complete ablation by the mid-1900s. These results agree with declines in sediment yield in other lakes of the southern Canadian Cordillera where sediment flux was exhausted following glacier retreat from Little Ice Age maxima during the late 1800s (DESLOGES 1994).

Sedimentary pigment-inferred total photoautotrophic abundance increased substantially in both lakes during the 20th century (Fig. 2). Whole-lake primary production in Curator Lake was attributable to algae, consisting primarily of chlorophyll *a*-containing cyanobacteria and

Fig. 1. Percentage organic content of accumulated sediment in (A) Curator Lake and (B) McConnell Lake as related to the ^{210}Pb -dated chronology.

chromophytes, such as chrysophytes, diatoms, and dinoflagellates (Fig. 2a). In contrast, the dramatic increase in total chlorophyll in a deeper McConnell Lake consisted primarily of bacteriochlorophylls (Fig. 2b) derived from planktonic, and also possibly benthic, green and purple sulfur bacteria (HURLEY & WATRAS 1991). These microbes thrive in anoxic deepwater habitats if underwater spectral irradiance is sufficient to sustain positive net photosynthesis. Therefore, we interpret these results as evidence of improved underwater light availability in both lakes following the decline of small local glaciers and their turbid inputs and longer ice-free growing seasons during a warmer 20th century.

A warmer climate would also reduce vertical mixing (AUSTIN & COLMAN 2007) and promote deepwater anoxic conditions for phototrophic bacteria by increasing the thermal stability and stratification of McConnell Lake. Minimal variation by the pigment degradation index (total pheophytin-*a* and pheophorbide-*a*:total chlo-

Fig. 2. Preserved sedimentary chlorophyll concentrations in (A) Curator Lake and (B) McConnell Lake as related to the ^{210}Pb -dated chronology.

rophyll-*a*) throughout both cores refutes the alternate explanation of these pigment profiles as being produced by diagenesis. In fact, our pigment-based inferences of increased pelagic primary production are supported by evidence from other measured paleo-proxies (i.e., stable isotopic carbon, diatoms) for both lakes (W. Hobbs, unpubl.).

Pigment-based estimates of whole-lake primary production were correlated positively with dendrochronologically inferred summer temperature anomalies (Fig. 3). The predictive relationship between annual summer temperature and total sedimentary chlorophyll content was significant ($r = 0.48$, $p < 0.001$) for Curator Lake, but not McConnell Lake ($r = 0.18$, $p = 0.18$). The more variable history of glacial activity in the McConnell catchment was a potential factor affecting the weak correlation between temperature and pigment concentration in the core. Specifically, periods of warmer temperature may have stimulated glacial melting, which would have actu-

Fig. 3. Preserved sedimentary chlorophyll concentrations in (A) Curator Lake (significant regression line shown) and (B) McConnell Lake as functions of dendrochronologically inferred anomalies in summer air temperatures relative to the average for the 20th century.

ally resulted in more turbid, colder, and less productive ice-free seasons in McConnell Lake. In Curator Lake, the impact of a warmer 20th century on primary production would have been less confounded by the negative effect of cold, turbid meltwater given the possible earlier complete ablation of the small local glacier.

Our findings highlight the context dependency of the impacts of global warming on small alpine lakes. Local glaciers may dampen or even reverse the short-term decadal effects of warmer air temperatures on alpine lakes. However, the eventual complete ablation of small glaciers can amplify the impact of global warming on these ecosystems as they shift from a turbid coldwater condition to a clear and warmer state. For example, THOMPSON et al. (2005) reported that the epilimnetic temperature of ultra-sensitive alpine lakes can rise by 12 °C with an increase in air temperature of 6 °C. Such a dramatic state change in alpine lakes would likely have a

devastating effect on biodiversity as stenothermic species are eliminated, while immigration by tolerant species from warmer montane lakes is severely dispersal-limited (HOLZAPFEL & VINEBROOKE 2005). Conversely, warming may increase certain alpine ecosystem functions (e.g., nitrogen fixation and phosphorus recycling) by enhancing enzymatic rates. Therefore, global warming could hypothetically shift alpine lakes toward a state for which there exists no post-glacial analogues.

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Authors' addresses: R. Vinebrooke, Freshwater Biodiversity Laboratory, Biosciences Centre, University of Alberta, Edmonton, Alberta, Canada T6G 2E9. E-mail: rolf@ualberta.ca

P.L. Thompson, M.D. Graham, Freshwater Biodiversity Laboratory, Biosciences Centre, University of Alberta, Edmonton, Alberta, Canada T6G 2E9.

W. Hobbs, A. Wolfe, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2E3.

B. Luckman, Department of Geography, University of Western Ontario, London, Ontario, Canada N6A 5C2