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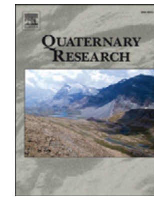

Holocene paleoenvironmental changes inferred from diatom assemblages in sediments of Kusawa Lake, Yukon Territory, Canada

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A B S T R A C T

The southwest Yukon Territory, Canada, is an important region for recovering sensitive records of Holocene paleoclimatic change. More information is needed, however, to constrain the timing of the major Holocene climatic transitions, and to understand associated impacts on different ecosystems. For example, paleolimnological studies have focused on small lakes and ponds, but the history of large lakes has received little study. We analyzed diatom assemblages, species richness, valve concentrations, and biogenic silica, in the sediments of Kusawa Lake (60°16.5'N; 136°10.9'W; 671 m a.s.l.) to reconstruct the responses of this large (surface area = 142 km^2), deep (Z_{max} = 135 m) freshwater ecosystem to Holocene climatic transitions. Diatoms colonized the lake soon after ice retreat, around 11,000 cal yr BP; assemblages throughout the record were dominated by planktonic types. Diatom concentrations and biogenic silica were high during the Holocene Thermal Maximum between 10,700 and 7300 cal yr BP, then began to decrease in response to cooling associated with orbitally driven reductions in insolation. Diatom assemblages shifted towards taxa with lower surface water temperature optima after 8300 cal yr BP, perhaps in response to abrupt and progressive cooling. Our study confirms that diatom assemblages in large lakes are sensitive to regional-scale paleoclimatic changes.

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Introduction

Arctic and subarctic ecosystems are important in the study of climatic change, as increases in temperature in these regions due to greenhouse warming are projected to be two to three times the global average (IPCC, 2007). However, there is uncertainty about the magnitude, the timing and the ecological effects of these climatic changes at the regional and local scales. These uncertainties have led to increased efforts to obtain more accurate paleoclimate records from a variety of types of ecosystems. These records can be used both to calibrate models of the climate system, and to improve predictions of the impacts of climatic change (Edwards et al., 2007).

Owing to mountainous terrain, the presence of glaciers, steep biophysical gradients, diverse microclimates, and a direct connection to changes in maritime conditions of the northeast Pacific Ocean, the southwest Yukon Territory, Canada, is a key region for studies of paleoclimatic change. The general paleoclimate of the southwest Yukon has been reconstructed from a series of paleoecological records (e.g., Denton and Karlen, 1977; Cwynar, 1988; Pienitz et al., 2000; Farnell et al., 2004; Bunbury and Gajewski, 2009). These studies show variability from site to site in the magnitude and timing of Holocene paleoclimatic changes. Thus, more reconstructions are needed to develop an understanding of the effects of particular instances of climatic change on different types of ecosystems in this highly complex environment.

The major supra-millennial feature of post-glacial paleoclimates in the northern hemisphere is the orbitally driven positive insolation anomaly of the early Holocene (Berger and Loutre, 1991) and the resulting relatively warm and dry climate, known as the Holocene Thermal Maximum (HTM), when summer temperatures across the western Arctic were on average 1.6 ± 0.8 °C higher than the 20th century mean (Kaufman et al., 2004). The synthesis study of Kaufman et al. (2004) shows a paucity of sites for constraining the timing of the initiation and termination of the HTM in the southwest Yukon. The data that were available for use in that study indicate that the region is situated transitionally between the zone to the west where the HTM began and ended early (~11,000–9000 cal yr BP) in response to insolation maxima, and the zone to the east, where the HTM began and ended several millennia later, as a result of the cooling effects of the Laurentide Ice Sheet.

The available proxy records from the southwest Yukon confirm that the HTM took place, but indicate variability in terms of the timing of initiation and termination. Pollen records of past vegetation changes have been the primary proxy evidence for the definition of the HTM in the southwest Yukon. Several records (Cwynar, 1988; Lacourse and Gajewski, 2000; Vermaire and Cwynar, 2010) feature major shifts in vegetation composition in response to increasing moisture availability at ~7000–6000 cal yr BP, suggesting a relatively late termination of the HTM, as has been reported for north-central Canada (Kaufman et al., 2004). All of these studies, however, also report plant community

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changes associated with the expansion of Picea at ~9000–8000 cal yr BP; this shift might be interpreted as an earlier termination of the HTM.

Bunbury and Gajewski (2009) provide the first quantitative temperature and precipitation reconstructions derived from pollen data for the region. The record from Upper Fly Lake indicates maximum Holocene temperatures between 10,000 and 7000 cal yr BP, with subsequent gradual cooling, but uncertainties in the radiocarbon chronology of up to 800 yr mean that further work is needed to resolve the timing of the HTM. Also, while pollen data provide information on paleovegetation changes, and can be used to derive quantitative estimates of past climates, in complex mountainous terrain, pollen records integrate information from several ecosystems along elevation gradients (e.g., Lynch, 1996), and also reflect local biogeographic processes such as refugia and dispersal (e.g., Magri et al., 2006). Thus, to determine whether the timing of the termination of the HTM in the southwest Yukon was more similar to regions to the west where the transition took place earlier, or to regions to the east, where the transition took place later, and to understand sensitivities of other ecosystems to climatic changes, records using alternative proxies are needed.

Diatoms (microscopic algae in the Class Bacillariophyceae) preserved in sediment cores provide accurate information on past lake environments as these organisms are sensitive proxies for changes in lake-water temperature, salinity, nutrient status, and pH, factors which can sometimes be linked to climate (e.g., Smol, 1988; Pienitz et al., 2000). For example, diatom growth rates are frequently limited by low temperatures at high latitudes (Raven and Geider, 1988; Weckström et al., 1997). In addition to the direct effect of temperature, changes in ice-cover affect diatom production in cold environments by altering light penetration, the intensity and duration of thermal stratification, and biogeochemical cycles (Douglas and Smol, 1999).

Since diatom primary production is positively related to temperature, measures of paleoproduction have been used as proxies for Holocene temperature changes (Hu et al., 2003; Podritske and Gajewski, 2007; McKay et al., 2008). Paleoproductivity can be estimated by measuring the concentration of diatom valves per unit sediment volume during diatom enumeration, or by measuring the concentration of biogenic silica (BSi) in sediments. BSi is produced primarily by diatoms, with minor additions of siliceous material from chrysophytes, freshwater sponges and phytoliths. BSi measurements can be done at higher resolution and more quickly than enumerations, and are widely considered to be more accurate estimates of paleoproductivity than valve concentration determinations on the microscope (e.g., McKay et al., 2008).

Pienitz et al. (2000) used fossil diatoms in lake sediments in the southwest Yukon to reconstruct salinity changes, which were linked to regional changes in moisture balance during the Holocene. The diatom assemblages from Lake U60 suggests a freshening around 8100 cal yr BP, associated with greater moisture availability, possibly linked to reduction in aridity with decreases in solar radiation (Pienitz et al., 2000). Modern biogeographic studies of species–environment relations for freshwater diatoms in the Yukon (Pienitz et al., 1995; Wilson and Gajewski, 2002) provide a robust statistical basis for the application of fossil diatoms to quantitative paleolimnological reconstructions in this region. Despite this, few paleolimnological records exist, even from small lakes and ponds. In some cases, this shortage of records is due to poor preservation of diatom valves in the sediments of alkaline lakes that are common in the region. There is even less information available on fossil diatom assemblages in the large lakes of the southwest Yukon, all of which are important landscape features.

Small lakes are often considered more immediately responsive to climatic changes, because small changes in evaporative balance produce biologically significant changes in water chemistry in a smaller water body (Smol and Cumming, 2000). Thus, these systems can provide sensitive paleolimnological records. Large lakes, however, are also important repositories of paleoecological information (e.g., Kumke et al., 2004) yet responses to these systems to paleoclimatic changes are poorly known. Although large lakes may be slower to change in response to climate forcing, these systems are applicable to analysis of large-scale climatic changes such as the HTM. In the southwest Yukon, the proxies used in paleoecological records derived from smaller lakes provide reconstructions centred on paleohydrology (e.g., Pienitz et al., 2000; Anderson et al., 2005). Diatom assemblages in deep lakes are less sensitive to water level fluctuations relative to those in smaller lakes, thus deep lake records may allow for more temperature-focussed reconstructions. Finally, paleolimnological analyses of large lakes provide information on the responses of these hydrologically extensive and ecologically influential systems to climatic changes.

The specific objectives of this study are to use changes in diatom assemblages and paleoproduction proxies, (1) to constrain temporal estimates for the Holocene Thermal Maximum at Kusawa Lake, providing new data for comparisons with reconstructions of the HTM derived from other proxies in the southwest Yukon, and (2), to determine the sensitivity to climatic change of this large subarctic freshwater ecosystem.

Study site

Kusawa Lake (60°16.5'N; 136°10.9'W; 671 m a.s.l), has a maximum depth of 135 m, a surface area of 142 km^2 and, at its outlet, drains 4290-km^2 of the upper Takhini River catchment in the Coast Mountains of Yukon and northern British Columbia, Canada. The measured summer surface water temperature range is 15–17 °C, surface pH is 7.2–7.8, dissolved oxygen in the upper few meters is 8.4–9.0 mg/L, and specific conductivity is 20.8–21.2 μS/cm (Chow, 2009). Kusawa Lake is a dimictic lake that mixes from top to bottom twice per year; the depth to the thermocline is approximately 11 m in a typical summer (Chow, 2009).

The bedrock geology of the upper Takhini watershed consists of coarse-grained, crystalline metamorphic rocks, such as schist, granitic gneiss, marble, and amphibolite, as well as intrusive plutonic rocks including various forms of granite (Johnston and Timmerman, 1994). Surficial deposits in region are characterized by glacial till, glaciofluvial gravels, and glaciolacustrine clays and silts deposited during the McConnell Glaciation, which covered the south and central portions of the Yukon between 26,000 and 10,000 yr ago (Westgate et al., 2001). Key features of the McConnell deglaciation were large ice-dammed lakes, including Glacial Lake Champagne, which occupied parts of the Takhini River valley (Gilbert and Desloges, 2005). The other important surficial deposit in the region is a thin tephra of approximately 2–5 cm in thickness, the White River Ash (WRA). The WRA is found covering stable soils in the region, or can be seen buried under sediments (Clague et al., 1995).

The modern climate in the southwest Yukon region is cool and dry. The 1971–2000 average annual temperature at Whitehorse is −0.7 °C with an average July maximum of 20.5 °C and an average January minimum of −22 °C. The average precipitation at Whitehorse is 267 mm/yr, which includes an average annual rainfall of 163 mm/yr and an average annual snowfall of 145 cm/yr (Environment Canada, 2000). The vegetation of the study region is dominated by open boreal and mixed woodland forests up to the treeline at ~1400 m a.s.l., reflecting the dry rain shadow climate of the region as well as the influence of fire. *Pinus contorta* is the dominant tree species in the region due to its quick regeneration in burned areas. *Picea mariana* forests are abundant on floodplains, sometimes in association with *Populus tremuloides*. *Picea glauca* is found in areas where the water table is higher (Rowe, 1972).

Methodology

Core extraction and chronology

A Rossfelder submersible vibracorer was used to extract 11 cores from Kusawa Lake in July 2004 (Rossfelder Corporation, Poway, California). A single 2.78-m-long core, named KUS324, from the deep

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