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Holocene climate change in Newfoundland reconstructed using oxygen isotope analysis of lake sediment cores

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ABSTRACT

Carbonate minerals that precipitate from open-basin lakes can provide archives of past variations in the oxygen isotopic composition of precipitation ($\delta^{18}O_{ppt}$). Holocene $\delta^{18}O_{ppt}$ records from the circum- North Atlantic region exhibit large fluctuations during times of rapid ice sheet deglaciation, followed by more stable conditions when interglacial boundary conditions were achieved. However, the timing, magnitude, and climatic controls on century to millennial-scale variations in $\delta^{18}O_{ppt}$ in northeastern North America are unclear principally because of a dearth of paleo-proxy data. Here we present a lacustrine sediment oxygen isotope ($\delta^{18}O$) record spanning 10,200 to 1200 calendar years before present (cal yr BP) from Cheeseman Lake, a small, alkaline, hydrologically open lake basin located in west-central Newfoundland, Canada. Stable isotope data from regional lakes, rivers, and precipitation indicate that Cheeseman Lake water $\delta^{18}O$ values are consistent with the isotopic composition of inflowing meteoric water. In light of the open-basin hydrology and relatively short water residence time of the lake, we interpret down-core variations in calcite oxygen isotope ($\delta^{18}O_{cal}$) values to primarily reflect changes in $\delta^{18}O_{ppt}$ and atmospheric temperature, although other factors such as changes in the seasonality of precipitation may be a minor influence. We conducted a series of climate sensitivity simulations with a lake hydrologic and isotope mass balance model to investigate theoretical lake water $\delta^{18}O$ responses to climate change. Results from these experiments suggest that Cheeseman Lake $\delta^{18}O$ values are primarily controlled by temperature and to a much lesser extent, the seasonality of precipitation. Increasing and more positive $\delta^{18}O_{cal}$ values between 10,200 and 8000 cal yr BP are interpreted to reflect the waning influence of the Laurentide Ice Sheet on atmospheric circulation, warming temperatures, and rapidly changing surface ocean $\delta^{18}O$ from the input of glacial meltwater into the western North Atlantic Ocean. The increasing trend is interrupted by abrupt negative $\delta^{18}O_{cal}$ anomalies at 9700 cal yr BP, associated with a transition to colder sea surface temperatures (SSTs) in the Labrador Sea and renewed Laurentide Ice Sheet retreat, and at 8500 cal yr BP that coincides with a well-established cooling event in the circum-North Atlantic region. After 8000 cal yr BP, $\delta^{18}O_{cal}$ values gradually decrease until 4300 cal yr BP, which reflects a cooling trend related to declining Boreal summer insolation and lower sea surface temperatures in the western North Atlantic Ocean. $\delta^{18}O_{cal}$ becomes slightly more positive from 4300 to 2500 cal yr BP and thereafter declines to the most negative values of the late Holocene by 1200 cal yr BP. The middle to late-Holocene transition at ~4300 cal yr BP corresponds with a shift to wetter conditions in Newfoundland that is also seen in other paleo-proxy records from the region. The discordance between the Cheeseman Lake $\delta^{18}O_{cal}$ record and declining insolation could in part reflect warmer temperatures or an increase (decrease) in warm (cold) season precipitation. Considering evidence from other paleo-records in Newfoundland, we suggest this transition resulted from a change in synoptic scale atmospheric circulation to a configuration similar to the positive mean state phase of the Pacific-North American pattern. Proxy evidence from Cheeseman Lake therefore supports the idea that a substantial climatic change occurred during the middle to late-Holocene transition (between ~5000 to ~4000 cal yr BP) in northeastern North America.

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1. Introduction

The oxygen isotopic composition of precipitation ($\delta^{18}O_{ppt}$) is an effective tracer of the global hydrologic cycle (Gat, 1995; Araguás-Araguás et al., 2000). $\delta^{18}O_{ppt}$ is controlled by the initial isotopic composition of water vapor at the moisture source and fractionation processes that occur during rainout and subsequent evaporation (Dansgaard, 1964; Rozanski et al., 1992). Reconstructions of paleo $\delta^{18}O_{ppt}$ from ice cores (e.g. Dansgaard et al., 1985; NGRIP, 2004), speleothems (e.g. Ersek et al., 2012), tree rings (e.g. Bale et al., 2010), and lake sediments (e.g. Edwards et al., 1996) can therefore provide valuable information on the paleohydrological and paleoclimatic conditions of the Holocene. For instance, high-resolution $\delta^{18}O_{ppt}$ records from Greenland ice cores reveal substantial changes in atmospheric temperature and snowfall accumulation over the current interglacial (Grootes and Stuiver, 1997), as well as the occurrence of early Holocene abrupt climate events at 9300 and 8200 calendar years before present (cal yr BP) that have been linked to catastrophic drainage of proglacial lakes (Barber et al., 1999) and short-lived cooling events (Alley et al., 1997; Yu et al., 2010; Daley et al., 2011). While highly informative, the Greenland $\delta^{18}O_{ppt}$ records largely provide information on a restricted geographic area (Grootes and Stuiver, 1997; NGRIP, 2004; Vinther et al., 2009), and much less is known about spatial variability in paleo-$\delta^{18}O_{ppt}$ across the greater North Atlantic region over the Holocene, particularly in the underrepresented Atlantic Canadian provinces (Daley et al., 2009).

Here we present a lacustrine oxygen isotope ($\delta^{18}O$) record from a small, alkaline lake (Cheeseman Lake) located in west-central Newfoundland, Canada spanning the period 10,200 to 1200 cal yr BP. We analyzed the stable isotope composition (δD and $\delta^{18}O$) of surface water samples, instrumental climate data from a proximal weather station, and monthly precipitation δD and $\delta^{18}O$ data from a Canadian Network of Isotopes in Precipitation (CNIP) station to investigate modern lake-catchment hydrologic and water isotope relationships. To provide a framework for interpreting the Cheeseman Lake $\delta^{18}O$ record, we employed a coupled hydrologic and water isotope mass balance model (Steinman et al., 2010) to assess the sensitivity of the lake to hydroclimate forcing (Steinman and Abbott, 2013). We interpret the Cheeseman Lake $\delta^{18}O$ record in the context of Greenland ice core $\delta^{18}O$ data, near shore marine records, and several terrestrial hydroclimate records from Newfoundland to evaluate the underlying causes of centennial to orbital scale climate variability in the North Atlantic region during the Holocene.

2. Site location and regional setting

Cheeseman Lake (informal name; 49.351° N, 57.603° W, 180 m asl) is a small (0.2 km^2), alkaline, open-basin lake located near the coast of west-central Newfoundland (Fig. 1). The lake is elliptical in shape, and the small (1.9 km^2) surrounding watershed (Supplemental Fig. 1) is characterized by moderately steep slopes along much of the shoreline. The lake receives inflow from a stream on the southwest shore and drains to Lomond River through an outlet stream on the northeast side. The maximum water depth is 4.1 m near the geometric center of the basin. The catchment contains second-growth forests that are characterized by a Dryopteris-Hylocomium-Balsam Fir forest type (South, 1983).

The lake and surrounding area is located in the West Coast Calcareous Uplands physiographic province, characterized by hilly terrain and irregular topography (South, 1983). Alkaline ponds that precipitate carbonate minerals, similar to Cheeseman Lake, are a common feature of the province. Bedrock geology in the catchment consists of Cambrian to Ordovician age limestone, dolostone, and shale (Colman-Sadd et al., 2000). Surficial geology in the immediate area is till veneer, which is composed of a thin (< 1.5 m) discontinuous sheet of lodgment till (Liverman and Taylor, 1990). The Island of Newfoundland was covered by the Laurentide Ice Sheet during the last glacial period (Dyke and Prest, 1987). Humber River Gorge and the lower Deer Lake valley, located ~30 km southeast of Cheeseman Lake, was deglaciated by 14,100 cal yr BP (median age; 13,800 to 14,600 cal yr BP 2σ uncertainty) (12,220 ± 90 ^{14}C yr BP) (Batterson and Catto, 2001). Post-glacial isostatic depression resulted in higher relative sea level in west-central Newfoundland in the latest Pleistocene (Batterson and Catto, 2001) and presumably an unstable land surface. Cheeseman Lake was not inundated by higher sea levels during deglaciation; however, the lake and catchment were presumably influenced by general landscape instability during the rapid isostatic adjustment that followed deglaciation.

The climate of Newfoundland is principally controlled by the marine influence of the Gulf of St. Lawrence and Atlantic Ocean along with the North Atlantic Oscillation (NAO) (Ullah, 1992), a hemisphere-wide

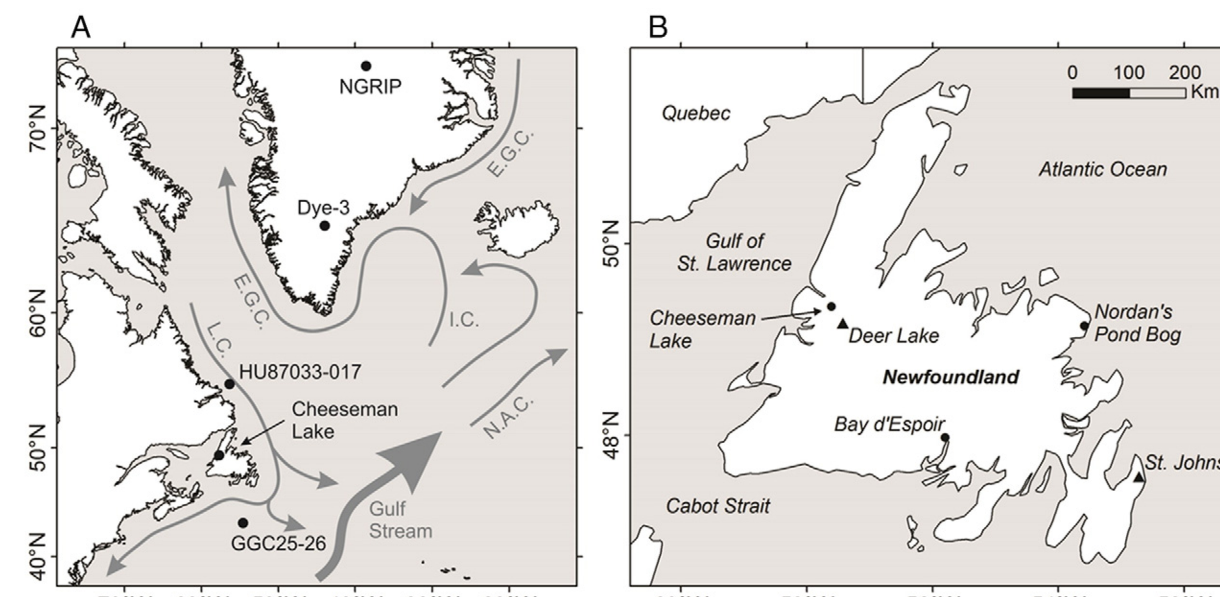

Fig. 1. a) Map of the western North Atlantic region showing modern surface ocean currents and sites mentioned in the text. Ocean currents include, N.A.C. – North Atlantic Current, E.G.C. – East Greenland Current, I.C. – Irminger Current, and L.C. – Labrador Current. b) Map of Newfoundland with Cheeseman Lake (informal name) and other sites mentioned in the text.