Middle Holocene dry climate caused by change in atmospheric circulation patterns: Evidence from lake levels and stable isotopes

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ABSTRACT

Sediment hiatuses, detritus layers, and inwashed terrestrial moss layers in five cores at Crawford Lake, Ontario, Canada, show that the lake level was low between ca. 4.8 and 2 ka (1 ka = 1000 ^{14}C yr B.P.). This low level is attributed to a dry and warm climate, which has also been documented at other sites in southern Ontario, southern Michigan, and southern Wisconsin. Oxygen isotope (δ^{18}O) values from authigenic marl show a negative shift of 2.4‰ from –9‰ to –11.4‰ (Vienna Peedee belemnite) between ca. 5 and 2 ka. Enhanced evaporation under dry and likely closed-basin conditions would lead to more enrichment in ^{18}O, so we suggest that the trend to depleted ^{18}O indicates a significant change in the δ^{18}O value of the source meteoric water. The major moisture source for the Great Lakes region is the Gulf of Mexico, from which the amount and seasonality of precipitation are affected by the interplay of air masses from the Gulf of Mexico and North Pacific, probably controlled by jet stream positions and storm tracks. In the late middle Holocene, the isotopically heavy moisture from the gulf might have contributed less precipitation and/or a higher proportion in winter months, probably caused by more frequent eastward extension of dry Pacific air depleted in ^{18}O. This hypothesis implies that the δ^{18}O values of paleoprecipitation in the middle Holocene reflected moisture-source history more strongly than paleotemperature.

INTRODUCTION

Paleoclimatic studies with multiple proxy data have increasingly improved our understanding of Holocene climate. A dry and warm climate in the early and middle Holocene has been documented by numerous studies in eastern North America (T. Webb et al., 1983, 1993; COHMAP Members, 1988; Baker et al., 1992; R. Webb et al., 1993). Recent studies show that the classic dry and warm prairie period in midwestern North America was time transgressive (Baker et al., 1992; Wright, 1992); it occurred between ca. 8 and 5 ka in Minnesota (McAndrews, 1966; Webb et al., 1983) and from 5.5 to 3 ka in eastern Iowa, southern Wisconsin (Winkler et al., 1986; Baker et al., 1992), and southern Michigan (Manny et al., 1978).

In southern Ontario, several sites show that lake levels were low during the late middle Holocene (ca. 6–2 ka), as interpreted from depositional hiatuses, low sedimentation rates, lithologic changes, and diatom species distribution (see Yu, 1995). The low lake levels reflect decreased effective moisture caused by a dry and warm climate (Yu and McAndrews, 1994; Yu, 1995). In contrast, stable isotopes from fossil wood and marl sediment indicate a dry and warm early middle Holocene climate at 7.4–5.8 ka and a very moist climate at 5.8–1.5 ka (Edwards and Fritz, 1988). Therefore, there is a significant discrepancy in timing for the middle Holocene dry period in southern Ontario, as interpreted from lake levels and stable isotope data.

Here we present multiple proxy evidence for low lake levels from five cores at Crawford Lake, southern Ontario.[1] The combined records of interpreted lake levels and carbonate isotopic data are linked to moisture regime and atmospheric circulation. We show that (1) low lake level was caused by decreased effective moisture, (2) the

[1]GSA Data Repository item 9713, Appendices 1 and 2, Crawford Lake data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

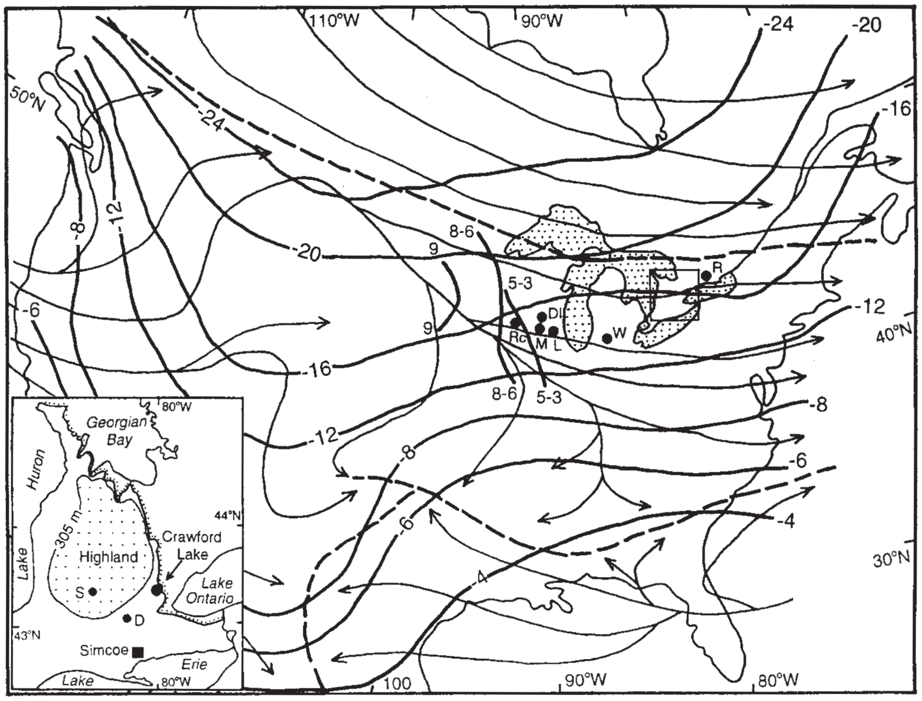

Figure 1. Map showing contours of δ^{18}O values (relative to SMOW, standard mean ocean water) of average precipitation in January (same pattern for July but with gentle gradient; from Lawrence and White, 1991; based on IAEA/WMO database) and surface streamlines (wind directions) for February with dashed lines showing average extent of each circulation path (Bryson and Hare, 1974, Fig. 8) for North America. February (and January) wind patterns represent maximum extension of Pacific flow. Millennial time-transgressive trend of Holocene prairie-forest border is indicated by thick lines (Webb et al., 1983; Baker et al., 1992). Note location of Crawford Lake (large circle), Simcoe isotope station (square; inset) and other sites (small circles) relevant to this study: R—Rice Lake, S—Sunfish Lake, D—Decoy Lake (Yu, 1995), W—Wintergreen Lake (Manny et al., 1978), L—Lima Bog, Dl—Devils Lake, Rc—Roberts Creek (Baker et al., 1992), M—Lake Mendota (Winkler et al., 1986).

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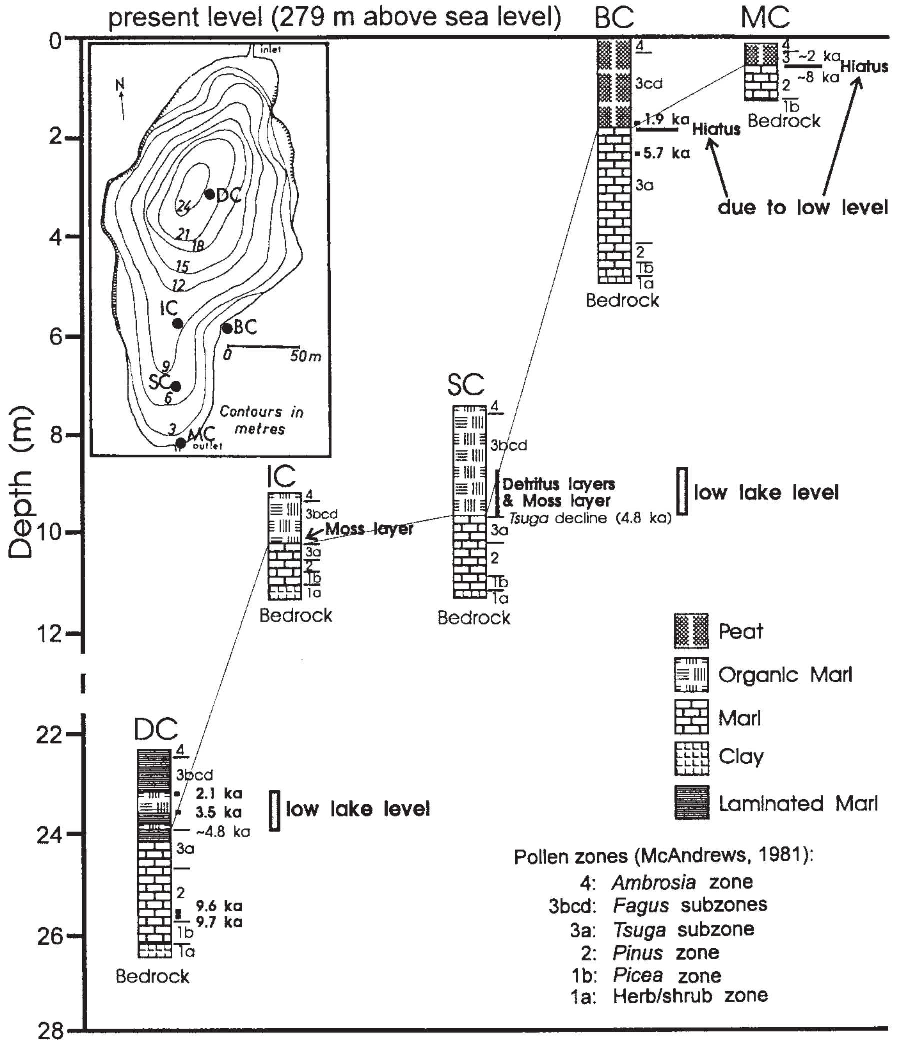

Figure 2. Correlation diagram for sediment stratigraphy in cores DC, IC, SC, BC, and MC from Crawford Lake showing lithology, ^{14}C ages (bold values), regional pollen assemblage zones (PAZ), and age estimates. Inset shows bathymetry of lake and coring locations.

$\delta^{18}O$ record dominantly reflected moisture-source history, and (3) the dry climate resulted from changes in air-mass distribution.

CRAWFORD LAKE

Crawford Lake (lat 43o28'N, long 79o57'W) is situated atop the Niagara escarpment at an altitude of 279 m (Fig. 1). The lake has a surface area of 2.4 ha and a maximum depth of 24 m (Fig. 2). A small inlet drains an isolated catchment of ~80 ha. The lake is in a bedrock basin and is partly surrounded by dolomite cliffs. The deep north part of the lake contains annually laminated sediments because of the absence of both water circulation and bioturbation below 15 m water.

LAKE LEVELS AND MOISTURE CONDITIONS

Postglacial lake levels were reconstructed by using multiple paleoecological data from five cores (Fig. 2). The lake was formed shortly after glacial ice retreat at ca. 13 ka. Chronology was based on six ^{14}C dates from this site and regional pollen zonation. At ca. 13–12 ka, lake level was at least 1.5 m lower than today, as shown by the missing basal herb and shrub pollen zone (1a) and a thin *Picea* zone (1b) in basal clay of the shallowest core (MC). During the *Picea* zone (ca. 12–10 ka), the lake rose to the present level and deposited marl. Marl continued to be deposited during the *Pinus* zone (2) and early *Tsuga* subzone (3a). In the middle of *Tsuga* subzone at ca. 6 ka, laminated marl formed in the deep basin.

The *Tsuga* decline ca. 4.8 ka corresponds with basinwide lithologic changes (Fig. 2): (1) laminated marl in the deep basin (core DC) was replaced by massive organic-rich marl, (2) two shallow cores (SC, IC) contained a layer of inwashed terrestrial mosses *Fissidens grandifrons* and *Fontinalis* sp., and (3) two wetland cores (BC, MC) showed sediment hiatuses from ca. 5 and 8 to 2 ka, indicating nondeposition and/or erosion due to lowered lake levels of at least 2 m (core BC). From 4.8 to 2 ka, detritus layers were deposited in core SC (Figs. 2 and 3), also indicating lowered and fluctuating water level. Laminations in core DC disappeared from 3.5 to 2.1 ka. Rising lake level in the past 2 ka renewed lamina sedimentation (core DC), homogeneous marl deposition (cores SC, IC), and peat accumulation (cores BC, MC). During the low-level phase, the lake likely had no surface outflow, because a bedrock outlet sill is at 1–1.5 m below the present lake level. A water-budget model suggests that the precipitation was probably at least 10% lower than today at this interval, assuming no change in rates of evaporation and seepage discharge.

Lower and fluctuating lake level at 4.8–2 ka was caused by decreased effective moisture under a dry and warm climate. This dry period in the late middle Holocene appears at other sites in southern Ontario, including Rice Lake (Yu and McAndrews, 1994; Yu et al., 1996), Decoy Lake (Szeicz and MacDonald, 1991; Yu, 1995), and Sunfish Lake (Sreenivasa and Duthie, 1973). It correlates in time with the dry period in midwestern North America (Webb et al., 1983; Baker et al., 1992), which shows a time-transgressive trend from 8–5 ka in Minnesota to 5.5–3 ka in southeastern Wisconsin and southern Michigan; the latter is closer to southern Ontario. This pattern contrasts with moisture reconstructions for northeastern North America (R. S. Webb et al., 1993; T. Webb et al., 1993), where dry and warm climates occurred earlier ca. 9–6 ka. This result implies that the Holocene moisture regime in southern Ontario was probably connected with the midwest rather than the northeast.

STABLE ISOTOPES AND INTERPRETATION

Stable isotopes were done on a shallow core (SC) that showed continuous marl deposition. Measurement methods of $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios of authigenic marl (calcite) followed Siegenthaler and Eicher (1986), and results were expressed in delta (δ) notation relative to the Vienna–PDB (Peedee belemnite) standard. The analytical precision is better than 0.02‰ for both $\delta^{18}O$ and $\delta^{13}C$. Isotope results from the late glacial and lower Holocene sediments will be discussed elsewhere in detail. For core SC, $\delta^{18}O$ ranges from –11.77‰ to –8.64‰, and $\delta^{13}C$ ranges from –7.84‰ to –1.77‰ (Fig. 3). From ca. 10 to 5 ka, $\delta^{18}O$ values were relatively constant at about –9‰. The $\delta^{18}O$ values showed a negative shift of 2.4‰ (from –9‰ to –11.4‰) starting ca. 5 ka, but fluctuated between –9.7‰ and –11.8‰ from 3.5 to 0.6 ka, and increased by 2‰ near the surface. The $\delta^{13}C$ values decreased from –1.8‰ to –6.9‰ from >12 to 5 ka, and fluctuated at 4–2 ka. The relatively strong covariance of $\delta^{18}O$ and $\delta^{13}C$ between 4.8 and 2 ka (see Fig. 3) suggests closure of the lake basin (Talbot, 1990; see also Drummond et al., 1995), especially during the late part of this period, which shows stronger covariance and higher $\delta^{18}O$ and $\delta^{13}C$ values.

The $\delta^{18}O$ in carbonate is a function of the $\delta^{18}O$ of the lake water and water temperature, assuming that authigenic calcite precipitated in isotopic

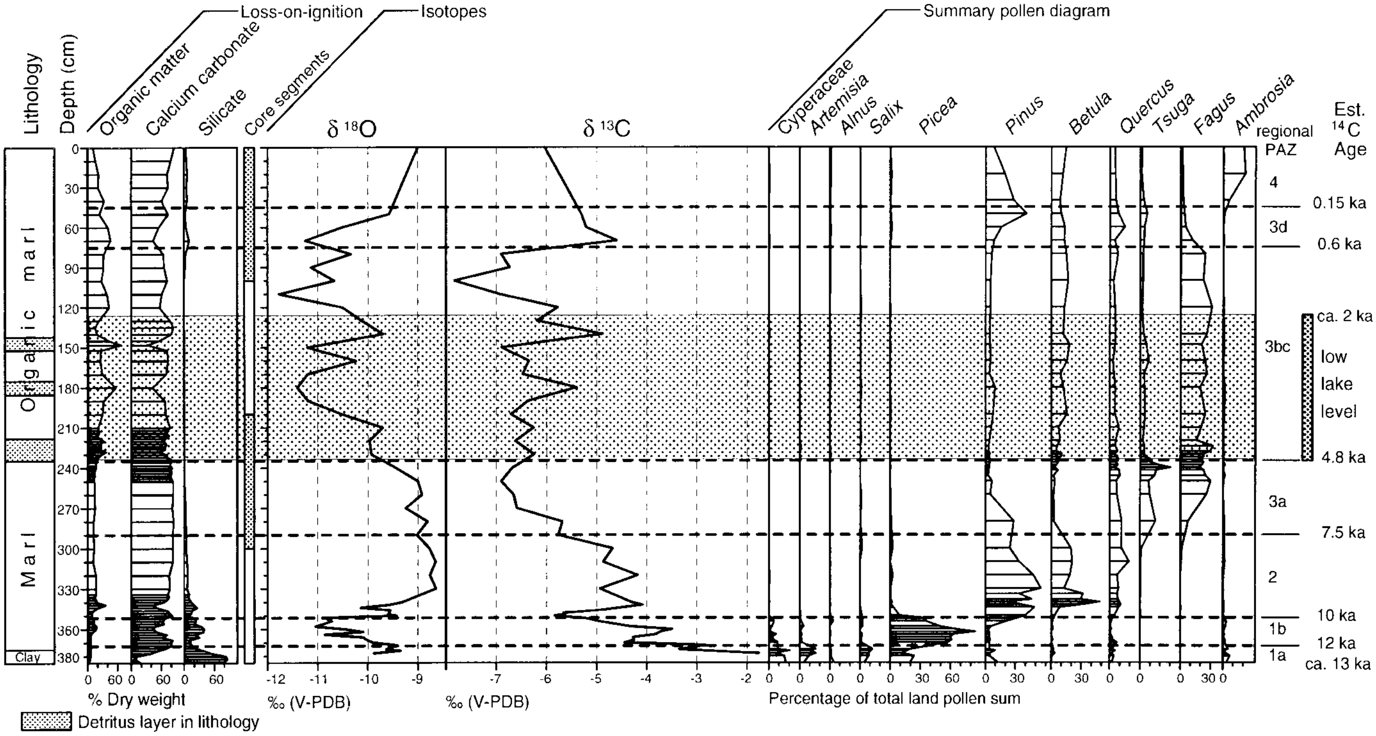

Figure 3. Lithology, isotope, and summary pollen diagrams of core SC at Crawford Lake. Chronology was based on ^{14}C dates from this site and pollen correlation with nearby dated pollen sequences. Isotopic covariance of $\delta^{18}O$ and $\delta^{13}C$ shows Spearman correlation coefficients of 0.15 for interval from 378 to 240 cm (ca. 12 to 5 ka), 0.40 for that from 230 to 130 cm (5 to 2 ka), and –0.30 for that from 120 to 0 cm (2 to 0 ka). V-PDB = Vienna Peedee belemnite.

equilibrium. The $\delta^{18}O$ of lake water is controlled by the isotopic composition of inflowing water (temperature-dependent $\delta^{18}O$ values in precipitation and continental effects related to moisture-source history) and hydrological effects including evaporative enrichment. The mechanisms that could cause the 2.4‰ depletion in $\delta^{18}O$ at ca. 5–3.5 ka include changes in air and/or water temperatures, disequilibrium of marl precipitation, hydrological change, and change in moisture sources. A positive correlation occurs between $\delta^{18}O$ in precipitation and air temperature at high and middle latitudes (Dansgaard, 1964); in the Great Lakes region it is 0.65‰ per degree Celsius (Edwards and Fritz, 1988). However, a decrease of 3.7 °C in mean annual temperature is required to account for the observed isotopic depletion, which is unlikely and not supported by any proxy records from this region. The temperature-dependent fractionation between calcite and water has a negative coefficient of –0.24‰ per degree Celsius (see Edwards and Fritz, 1988). However, enhanced evaporation caused by increased water temperature could neutralize this temperature-dependent effect (cf. McKenzie and Hollander, 1993). Therefore, the 2.4‰ decrease in $\delta^{18}O$ was unlikely to be caused by changes in air and water temperatures. Disequilibrium precipitation of calcite could exist in eutrophic conditions, which could cause depletion in $\delta^{18}O$, as proposed by Fronval et al. (1995). However, it is unlikely that the presently alkaline, oligotrophic Crawford Lake became eutrophic enough in the Holocene to account for this isotopic depletion. An increase in organic matter and diatoms from core DC suggests only a slight increase in trophic state during the *Tsuga* decline (J. P. Smol, Queen's University, 1995, written commun.). Moisture derived from evaporation of the Great Lakes could contribute to the atmospheric vapor load in the region that is downwind (Gat et al., 1994), but our site would not be greatly affected owing to the orographic effect of the highland westward (see inset in Fig. 1) and to its distant location from snow belts (Bryson and Hare, 1974). If this lake effect played a role in the isotopic depletion, it would likely be superimposed on change in distribution of air masses (see below). If all these other effects are minor, then the depleted ^{18}O during the dry period most likely reflected a change in the $\delta^{18}O$ of inflowing water. Changes in the seasonal distribution of precipitation would change the isotopic composition of lake water because snow and rainfall in cold months is isotopically lighter (Fig. 4).

The $\delta^{13}C$ in carbonate is primarily controlled by that of the dissolved inorganic carbon (DIC) of lake water. The $\delta^{13}C$ in DIC can mainly be explained by exchange with the atmospheric CO_2 reservoir, the inflowing ground water containing dissolved carbonate, photosynthesis of aquatic plants (lake productivity), and decomposition of organic matter (for which $\delta^{13}C$ is <–20‰) (Stuiver, 1970). The decrease in $\delta^{13}C$ from before 12 ka to 5 ka at our site suggests that decomposition of organic matter was mainly responsible, which was probably controlled by change in the catchment's organic supply from tundra, evergreen *Picea* and *Pinus* forests, to mixed *Tsuga*-deciduous hardwood forests. The slight increase and fluctuation in $\delta^{13}C$ after 5 ka suggest changes in evaporative enrichment and/or lake productivity, because there was little vegetation change then. Exchange with atmospheric CO_2 was unlikely to be an important factor, considering that this small and deep lake is in a cliff-sheltered setting.

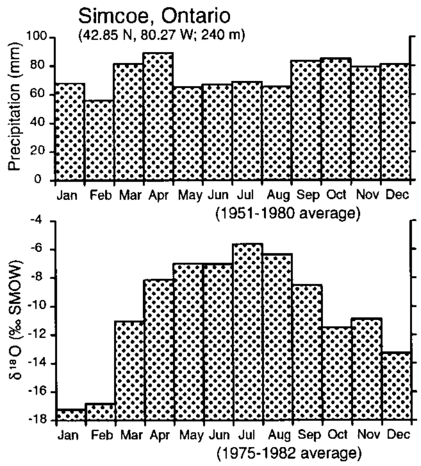

Figure 4. Seasonal changes of precipitation and $\delta^{18}O$ in precipitation at Simcoe climate station, closest isotope station to Crawford Lake. Simcoe has annual mean precipitation of 941 mm and weighted mean $\delta^{18}O$ of –9.27‰ relative to SMOW.

CHANGING AIR-MASS DISTRIBUTIONS AND DRY CLIMATE

The most likely mechanism that could alter the $\delta^{18}O$ values of inflowing water is change in atmospheric circulation patterns. Circulation changes affect the relative importance of different moisture sources and thus the isotopic composition of local precipitation. Two major air masses (moist and warm maritime tropical air from the Gulf of Mexico and dry and mild North Pacific air from the continental west) predominantly control moisture conditions in the Great Lakes region (Fig. 1; Bryson and Hare, 1974; Gat et al., 1994). Moisture from the North Pacific source arrives in this region with a much lower $\delta^{18}O$ value than that of moisture from the Gulf of Mexico (Fig. 1; Charles et al., 1994). An isotope study of present precipitation in central Iowa shows that the $\delta^{18}O$ values from the Gulf of Mexico–Pacific mixed moisture source (–10.80‰) are more depleted than those ascribed solely to a gulf moisture source (–7.24‰) (Simpkins, 1995).

Change in circulation patterns has been used to interpret a similar depletion of $\delta^{18}O$ in a Swiss lake (McKenzie and Hollander, 1993), and its importance has been emphasized in the interpretation of Greenland ice-core isotope records (Charles et al., 1994). During the late middle Holocene, the gulf air mass, as the major moisture source for this region, might have contributed less precipitation enriched in ^{18}O. Greater contribution might derive from winter and spring storms, the summer precipitation being limited to major storms having a strong effect. At the same time, Pacific air might have extended eastward more frequently, possibly as far as eastern Ontario, and blocked the gulf air and contributed isotopically lighter precipitation, although the amount was limited. Changes in air-mass distributions and precipitation seasonality were likely controlled by latitudinal shifts of the jet stream and storm tracks in the upper atmosphere (Rodionov, 1994). This hypothesis explains the timing and magnitude of the middle Holocene dry period in the midwest and southern Ontario, which shows that the prairie-forest border moved eastward in Minnesota from ca. 8 to 5 ka and in southern Wisconsin from 5.5 to 3 ka (Baker et al., 1992); in southern Ontario, the lower lake levels lacked obvious upland vegetation responses from 5 to 3 ka (McAndrews, 1981; Yu, 1995). Recent paleoclimate investigations in the northern Great Plains also show a time-transgressive dry period from 7.3–4.4 ka in southern Alberta to 4–2.7 ka in southern Saskatchewan (Vance et al., 1992, 1995). This pattern suggests that there could be a teleconnection between these regions linked by changing air-mass distributions controlled by atmospheric circulation.

CONCLUSIONS AND IMPLICATION

1. Stratigraphic data from five cores at Crawford Lake show that lake levels were low in the late middle Holocene, and the regional correlation with other sites indicates that the low levels were caused by decreased effective moisture under a dry climate.

2. The $\delta^{18}O$ in the middle Holocene lake sediments recorded mostly moisture-source history, probably linked with changing distributions of air masses controlled by atmospheric circulation.

3. Because warm climate is probably linked with the continental hydrological cycle and regional drought in middle latitudes (Overpeck, 1996), paleoclimate studies are important for understanding future climate warming and potential responses of natural systems.

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