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Influence of Changing Atmospheric Circulation on Precipitation δ^{18}O–Temperature Relations in Canada during the Holocene

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Postglacial precipitation δ^{18}O history has been reconstructed for two regions of Canada. Long-term shifts in the oxygen-isotope composition of annual precipitation ($\delta^{18}O_p$) in southern Ontario appear to have occurred with a consistent isotope–temperature relation throughout the past 11,500 ^{14}C yr. The modern isotope–temperature relation in central Canada near present boreal tree-line evidently became established between 5000 and 4000 years ago, although the relation during the last glacial maximum and deglaciation may also have been similar to present. In the early Holocene, however, unusually high $\delta^{18}O_p$ apparently persisted, in spite of low temperature locally, probably associated with high zonal index. A rudimentary sensitivity analysis suggests that a small reduction in distillation of moisture in Pacific air masses traversing the western Cordillera, perhaps accompanied by a higher summer:winter precipitation ratio, could have been responsible for the observed effect. Equivalent isotope–temperature "anomalies" apparently occurred elsewhere in western North America in response to changing early-Holocene atmospheric circulation patterns, suggesting that a time-slice map of $\delta^{18}O_p$ for North America during this period might provide a useful target for testing and validation of atmospheric general circulation model simulations using isotopic water tracers.

INTRODUCTION

The isotopic composition of past precipitation is commonly considered a proxy for paleotemperature at middle to high latitudes, because of systematic linear relations observed between mean annual air temperature (MAT) and weighted mean oxygen- or hydrogen-isotope composition of annual precipitation ($\delta^{18}O_p$ or δ^2H_p)[1] (Dansgaard, 1964; Rozanski *et al.*, 1992, 1993). Applicability of $\delta^{18}O_p$ or δ^2H_p as a paleotemperature proxy is well-supported by various evidence, including direct archives of past precipitation such as ice cores (e.g., Jouzel *et al.*, 1993; Grootes *et al.*, 1993) and old groundwaters (e.g., Rozanski, 1985), simulations based on atmospheric general circulation model (AGCM) experiments (e.g., Jouzel *et al.*, 1994), and data from various indirect archives such as lake sediments, cave deposits, and tree rings. On the other hand, changing moisture sources and recycling, conditions at the site of evaporation, air mass history, seasonality and amount of precipitation, and other factors can also influence the isotopic composition of local precipitation (e.g., Dansgaard, 1964; Lawrence and White, 1991; Plummer, 1993; Charles *et al.*, 1994). These factors can perhaps confound attempts to reconstruct paleotemperature but can potentially yield other climatically relevant information.

Reconstruction of the weighted mean δ^{18}O of annual precipitation ($\delta^{18}O_p$) for two regions in Canada spanning postglacial time provide contrasting views of the isotopic signals of changing climate. As we discuss below, the $\delta^{18}O_p$ record for southern Ontario seems to be a good indicator of MAT throughout the past 11,500 ^{14}C yr, suggesting a consistent linear isotope–temperature relation. In contrast, a shorter $\delta^{18}O_p$ chronology (ca. 8000 yr) from central Canada offers evidence that a single isotope–temperature relation did not persist, apparently as a consequence of changing atmospheric circulation. Although these results emphasize the uncertainties involved in teasing paleoclimate information out of isotopic archives, they also highlight the value of primary isotopic signals independent of their usefulness as proxies for parameters such as paleotemperature.

Modern Climate of Southern Ontario and Central Canada

The modern climatic settings of the study areas can be readily characterized in terms of seasonally shifting air mass

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[1] δ^{18}O and δ^2H values represent deviations in per mil (‰) from the V-SMOW standard, such that $\delta = ((R_{sample}/R_{VSMOW})-1)1000$, where R is the ^{18}O/^{16}O or ^{2}H/^{1}H ratio.

influence (Bryson, 1966; Bryson and Hare, 1974). The cool temperate climate of southern Ontario reflects the varying seasonal influence of three distinct air masses: (1) cold, very dry Arctic air arising in northern Canada; (2) warm, moist Maritime-Tropical air from the south, which originates in the subtropical North Atlantic and Gulf of Mexico and traverses northward up the Mississippi and Missouri valleys before being deflected eastward across the Great Lakes basin; and (3) seasonally warm, relatively dry air from the west, which originates over the North Pacific but subsequently loses much of its moisture during passage across the western Cordillera. Summers in southern Ontario are typically warm and humid, reflecting the dominance of Maritime-Tropical air, punctuated by short incursions of dry Pacific air. Southward shifting of frontal zones in winter leads to cold and relatively dry conditions due to strong Arctic air influence. Precipitation, which is mainly derived from Maritime-Tropical air masses, is well-distributed throughout the year.

The arid subarctic to low-arctic climate of central Canada is strongly influenced by Arctic air masses in all seasons. Summer conditions are moderated by Pacific air that also brings most of the limited moisture to the region, but winters are long and severe owing to persistent Arctic air dominance.

PRECIPITATION δ^{18}O HISTORY

Southern Ontario

Precipitation δ^{18}O history in southern Ontario is based on isotopic studies of terrestrial plant matter and organic and inorganic lake sediments. The initial $\delta^{18}O_p$ chronology was developed from oxygen and hydrogen isotopes in fossil wood cellulose, using a semiempirical model to separate humidity-dependent isotopic enrichment of leaf water during evapotranspiration from the primary isotopic signature of water taken up by the trees (Edwards and Fritz, 1986). Calibration of the model using modern trees permitted quantitative reconstruction of both the isotopic composition of local precipitation ($\delta^{18}O_p$) and growth season relative humidity (RH). These preliminary paleo-isotope and paleo-humidity records were supported and supplemented by independent evidence from the oxygen isotope stratigraphy of aquatic cellulose and carbonate in sediment cores from several lakes in the region, using analogous reasoning to separate lake-specific isotopic responses to changing RH from the common signal imposed by the changing isotopic composition of catchment source waters, controlled by $\delta^{18}O_p$ (Edwards, 1987; Edwards and Fritz, 1988; Edwards and McAndrews, 1989). The basis for this approach was addressed in detail by Edwards and McAndrews (1989) and revisited by Edwards (1993). New oxygen isotope data from aquatic cellulose in sediments underlying Hamilton Harbour, a bay at the western end of Lake Ontario, have recently verified and further supplemented the later part of the $\delta^{18}O_p$ record, from about 8000 yr B.P. to present (Duthie *et al.*, 1996). The resulting composite $\delta^{18}O_p$ and RH records derived from these studies are shown in Figure 1.

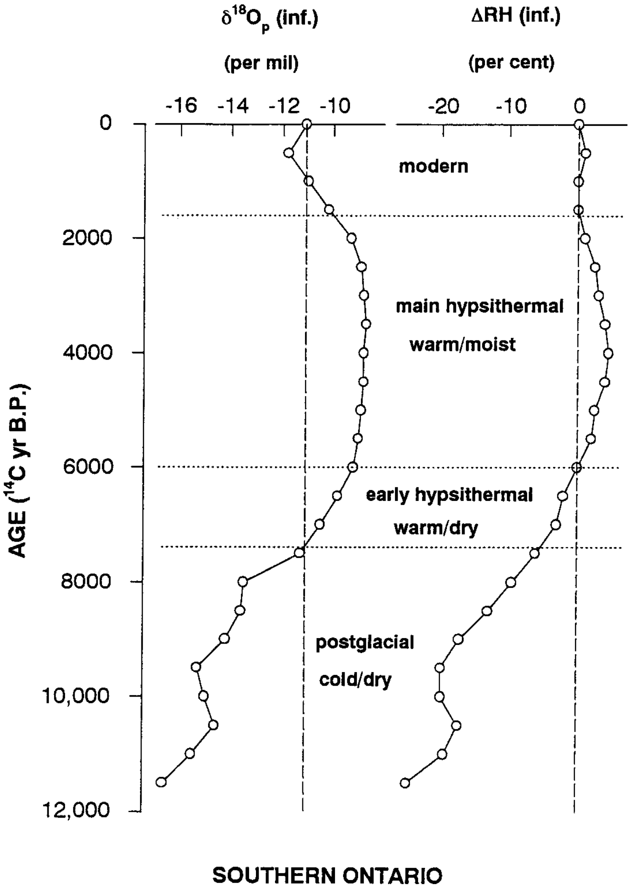


FIG. 1. Reconstructed $\delta^{18}O_p$ and ΔRH for southern Ontario, expressed as 500-yr averages, based on oxygen and hydrogen isotopes in cellulose and inorganic carbonate from lake sediments and fossil wood cellulose (Edwards, 1987; Edwards and Fritz, 1986, 1988; Edwards and McAndrews, 1989; Duthie *et al.*, 1996). ΔRH is scaled to represent difference from present average summer relative humidity. Estimated uncertainties in the reconstructed values are on the order of ±1‰ and ±5%, respectively.

The $\delta^{18}O_p$ history of southern Ontario is characterized by low values during late-glacial and early-Holocene times, rising to a maximum by about 5000 yr B.P., before declining to values approaching those of the past few decades sometime after 4000 yr B.P. Summer RH was evidently closely coupled to changing $\delta^{18}O_p$, also rising from a late-glacial minimum to a maximum in the mid-Holocene, though with a lag centered on about 7000 yr B.P. as $\delta^{18}O_p$ converged on and subsequently exceeded the modern value.

Edwards and Fritz (1986) noted that the systematic shifts in past $\delta^{18}O_p$ (if interpreted as annual temperature) and summer RH are strongly consistent with changing air mass influence in eastern North America inferred from other evidence (e.g., Bryson and Wendland, 1967; Bartlein *et al.*, 1984; Dean *et al.*, 1996). Thus, the long-term coupling between temperature and humidity is in good agreement with progressive postglacial warming and moistening to a mid-Holocene ''climatic optimum,'' as the influence of Arctic air diminished and Atlantic air increased, followed by slight climatic deterioration as the modern intermediate balance became established. Superimposed on this meridional fluctuation in atmospheric circulation is a shorter-term episode of enhanced zonal index in the early Holocene that account for a lag between rising temperature and humidity between about 7500 and 6000 yr B.P., caused by increased incursion of warm, dry Pacific air into the region during the summer months. This general sequence of events is readily visualized through the division of the postglacial climate history of southern Ontario into four climatic intervals, based on qualitative differences between past and present annual temperature and summer humidity (Edwards and Fritz, 1986): (1) a postglacial period of colder and drier conditions culminating around 7400 yr B.P.; (2) a warmer and drier ''early hypsithermal,'' ending about 6000 yr B.P.; (3) a warmer and moister ''main hypsithermal,'' leading to (4) the cool, temperate climate of today sometime within the last two millennia.

As observed by Edwards and Fritz (1986), the $\delta^{18}O_p$ history can be translated quantitatively into a plausible MAT record by assuming a constant linear $\delta^{18}O_p$–MAT relation having a slope of about 0.65‰/°C, approximating the modern spatial isotope–temperature relation in the Great Lakes region. This yields a paleotemperature curve that is remarkably consistent with the regional time-series reconstruction for southeastern Canada reported by Kutzbach (1987, Fig. 13), based on atmospheric general circulation model simulations. Notably, strong qualitative agreement is also evident between inferred RH and modelled precipitation from the same simulations, providing support for both the successful deconvolution of the raw isotopic records and the general validity of the $\delta^{18}O_p$ record as a proxy for paleotemperature. The $\delta^{18}O_p$ curve is also broadly comparable to previous quantitative reconstructions based on pollen data (McAndrews, 1981; Bartlein *et al.*, 1984) and the limited information available from fossil insects and relict permafrost for the earlier part of the record (Edwards *et al.*, 1985). General agreement is evident with mapped representations of inferred changes in temperature and precipitation from the COHMAP project, based on pollen response surfaces (Webb *et al.*, 1993), although direct comparison is hampered by the coarse COHMAP spatial resolution. Lake-level information for southern Ontario in the COHMAP data base is too limited to support an adequate comparison with inferred effective moisture.

Central Canada

Postglacial $\delta^{18}O_p$ and summer RH chronologies for an area in central Canada have been developed from the oxygen-isotope stratigraphies of cellulose in lake sediments (Fig. 2), as part of multiple-proxy investigations of circumpolar treeline fluctuations (MacDonald *et al.*, 1993; Wolfe *et al.*, 1996). Environmental change in this region following local deglaciation around 9000 yr B.P. (Dyke and Prest, 1987) was characterized by the advance and subsequent retreat of boreal treeline, accompanied by profound limnologic and hydrologic changes, in response to shifts in the mean summer position of the Arctic frontal zone. Terrestrial vegetation abruptly shifted from dwarf shrub tundra to *Picea mariana* forest-tundra about 5000 yr B.P., as the frontal zone moved northward. Minor local fluctuations in treeline position or forest density occurred during the subsequent 2000 years, followed by return to the modern dwarf shrub tundra vegetation after 3000 yr B.P.

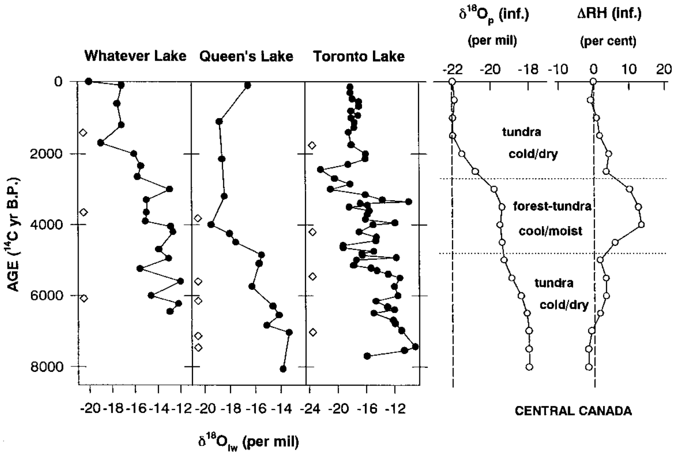


FIG. 2. Reconstruction of $\delta^{18}O_p$ and ΔRH for central Canada, expressed as 500-yr averages, based on oxygen isotopes in lacustrine cellulose from three lakes. Chronologic control for each lake record is provided by ^{14}C-dated samples represented by diamonds (Table 1). $\delta^{18}O_p$ and RH were derived by deconvolution of the inferred lake water $\delta^{18}O$ histories ($\delta^{18}O_{lw}$) for informally named Queen's Lake (64°07′N; 110°34′W), Toronto Lake (63°43′N; 109°21′W), and Whatever Lake (64°41′N; 97°03′W) reported previously by MacDonald *et al.* (1993) and Wolfe *et al.* (1995, 1996). The $\delta^{18}O_p$ history is strongly constrained by the low-frequency $\delta^{18}O_{lw}$ trend from Whatever Lake, which is hydrologically insensitive (Bursey *et al.*, 1991) and thus expected to shift in parallel to long-term changes in $\delta^{18}O_p$, while the ΔRH history is mainly constrained by the residual changes in $\delta^{18}O_{lw}$ independent of changes in $\delta^{18}O_p$ in Queen's Lake, which is believed to have behaved essentially as a closed basin. The long-term evaporative-enrichment response of Toronto Lake is consistent with that of Queen's Lake, but is overprinted by ''noise'' inherited from its hydrologically complex catchment (Wolfe *et al.*, 1996). The tundra and forest-tundra zonation is based on pollen and loss-on-ignition data from Queen's Lake, which lies about 25 km north of the mapped limit of forest-tundra (MacDonald *et al.*, 1993). In order to permit comparison with the southern Ontario reconstruction (Fig. 1), ΔRH has been scaled to approximate deviation from present average summer relative humidity, assuming evaporative enrichment under conditions of long-term hydrologic steady state. Uncertainties in the reconstructed values are somewhat higher than for southern Ontario, on the order of ±1.2‰ and ±6%, respectively.

$\delta^{18}O_p$ was apparently higher than present, when organic

TABLE 1
Radiocarbon Dates from Lake Sediment Cores

Depth (cm)	Material	Age (^{14}C yr B.P.)	Laboratory number
	Whatever Lake		
20–22	Organic sediment	1410 ± 110	TO-4526
89.0–91.5	Organic sediment	3650 ± 130	TO-4527
172.5–175	Organic sediment	6080 ± 80	TO-4528
	Queen's Lake		
15–20	Organic sediment	3820 ± 60	WAT-1770
45–50	Organic sediment	5600 ± 60	WAT-1771
60–65	Organic sediment	6150 ± 60	WAT-1772
100–105	Organic sediment	7150 ± 70	WAT-1773
105	Twig	7470 ± 80	TO-827
	Toronto Lake		
35–40	Organic sediment	1760 ± 90	Beta-49705
80–85	Organic sediment and moss	4200 ± 80	Beta-53129
125–130	Organic sediment and moss	5460 ± 90	Beta-53130
155–160	Organic sediment	7040 ± 120	Beta-49708

lake-sediment accumulation began shortly before 8000 yr B.P., and decreased progressively to about 4500 yr B.P. Values subsequently increased slightly to a localized maximum around 4000 yr B.P. before declining to near modern values by about 1500 yr B.P., followed by a small rise to the modern level, which has persisted for the past 1000 years. Summer RH during this 8000-yr period shows a simpler pattern of change, oscillating between low values prior to and following a pronounced maximum during the forest-tundra event. Correspondence between RH and forest expansion even occurred on the scale of centuries, as shown by high-resolution sampling of one core (Wolfe *et al.*, 1996).

The post-5000 yr B.P. part of the $\delta^{18}O_p$ record reveals evidence of a straightforward isotope–climate linkage, with higher values than present corresponding to maximum forest-tundra development between 5000 and 3000 yr B.P., followed by a decline as treeline receded. This is consistent with the expected temperature shift as the strong Pacific air mass influence in summer that triggered the treeline advance was reduced by southward movement of the Arctic frontal zone. However, reconstructed $\delta^{18}O_p$ values about 4‰ higher than present during the earlier tundra period, when temperatures must have been at least as cold as present, are clearly not in harmony with the isotope–temperature relation that became established after 5000 yr B.P.

DISCUSSION

Isotope–Temperature Relations in Precipitation

Calibration of isotope–temperature relations using modern data is inherently limited by the short temporal range of observational records at individual sites. As a result, calibrations of paleotemperature are commonly based on empirical $\delta^{18}O_p$–MAT or $\delta^{2}H_p$–MAT relations derived using data from several scattered sites within a region. This approach has been applied extensively to interpret isotopic records from various archives.

The $\delta^{18}O_p$–MAT relation used by Edwards and Fritz (1986), based on a survey of limited modern data available from sites in the Great Lakes region, is described by

$$\delta^{18}O_p = 0.65\text{MAT} - 15.5, \tag{1}$$

which has essentially the same slope as, but more negative intercept than, the ''global'' empirical $\delta^{18}O_p$–MAT relation for sites having MAT less than 15°C (Jouzel *et al.*, 1994) given by

$$\delta^{18}O_p = 0.64\text{MAT} - 12.8. \tag{2}$$

Although the modern spatial and temporal $\delta^{18}O_p$–MAT relations in the study area in central Canada are less-well defined than in eastern Ontario, local $\delta^{18}O_p$ and MAT (ca. −22‰ and −10°C) are also in good agreement with (1). The occurrence of more depleted modern $\delta^{18}O_p$ values for a given temperature in both areas compared to the ''global'' relation probably reflects continental effects due to rain-out from long-distance transport of moisture, perhaps reinforced in the Great Lakes region by recycling of isotopically depleted vapor from the lakes (Gat *et al.*, 1994).

As expected, (1) yields highly reasonable MAT values for the past 5000 yr from the central Canada $\delta^{18}O_p$ history, suggesting cooling of about 3°C since the time of maximum treeline advance. However, isotope-inferred MAT values of 6°C or more above present for the older part of the record are clearly incompatible with pollen and diatom evidence suggesting that MAT was no higher than present during this time (Moser and MacDonald, 1990; MacDonald *et al.*, 1993; MacDonald, 1995; Pienitz, R.; J. P. Smol, personal communication, 1995). This discrepancy is shown schematically on a plot of MAT versus $\delta^{18}O_p$ (Fig. 3). The entire southern Ontario record and the later part of the central Canada record apparently lie near the continental line defined by (1), whereas the earlier part of the central Canada record is distinctly offset, plotting above the global line defined by (2). AGCM simulations (Jouzel *et al.*, 1994) and the isotopic composition of late-glacial groundwater (Remenda *et al.*, 1994) suggest that (1) also approximates isotope–temperature relations in central and south-central Canada during the last glacial maximum and the early stages of deglaciation. Thus, the ''anomalous'' isotope–temperature relation in central Canada appears to have been limited to a discrete time interval during the early Holocene, beginning sometime after 11,000 yr B.P. and culminating shortly after 5000 yr B.P.

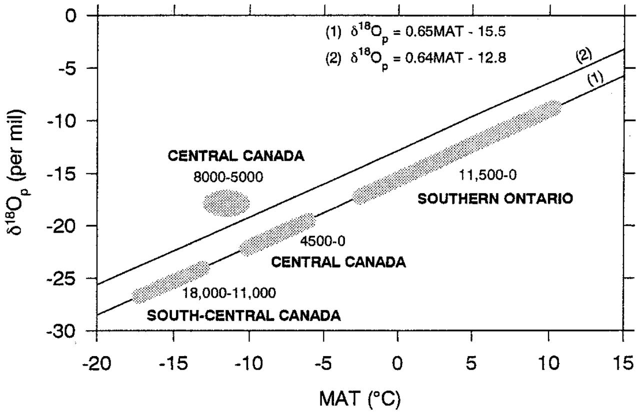


FIG. 3. Schematic diagram showing apparent $\delta^{18}O_p$–MAT relations for central Canada and southern Ontario. Isotope–temperature relations in both areas seem to lie close to the ''continental'' line defined by (1), except for the earlier part of the central Canada record, which plots above the ''global'' line defined by (2) (Jouzel *et al.*, 1994). $\delta^{18}O_p$–MAT in the area of the Laurentide Ice Sheet during deglaciation of southwestern and central Canada probably also lay near the continental line.

Possible Origin of ''Anomalous'' $\delta^{18}O_p$–MAT Relation in Central Canada

Two likely mechanisms can be invoked to explain elevated $\delta^{18}O_p$ in central Canada during the early Holocene, both linked to the high zonal index that is believed to have persisted at this time (Bryson and Wendland, 1967; Bryson *et al.*, 1970; Bartlein *et al.*, 1984; Vance *et al.*, 1995; Dean *et al.*, 1996). Abundant evidence supports the existence of elevated alpine treeline in the western Cordillera from prior to 9000 until at least 6000 yr B.P., accompanied by pronounced dryness at lower altitudes (Clague *et al.*, 1992 and references therein) and drought in western Canada (e.g., MacDonald, 1989; Schweger and Hickman, 1989; Vance *et al.*, 1995). As noted by Clague *et al.*, (1992), a higher cloud base enhanced the efficiency of moisture transport through the mountains. This should have led to decreased rain-out effects on the isotopic composition of residual vapor (and ultimately precipitation derived from it), which can be simulated assuming a simple Rayleigh distillation process, described by the equation

$$R_{Vr}/R_{Vo} = f^{(\alpha-1)}, \tag{3}$$

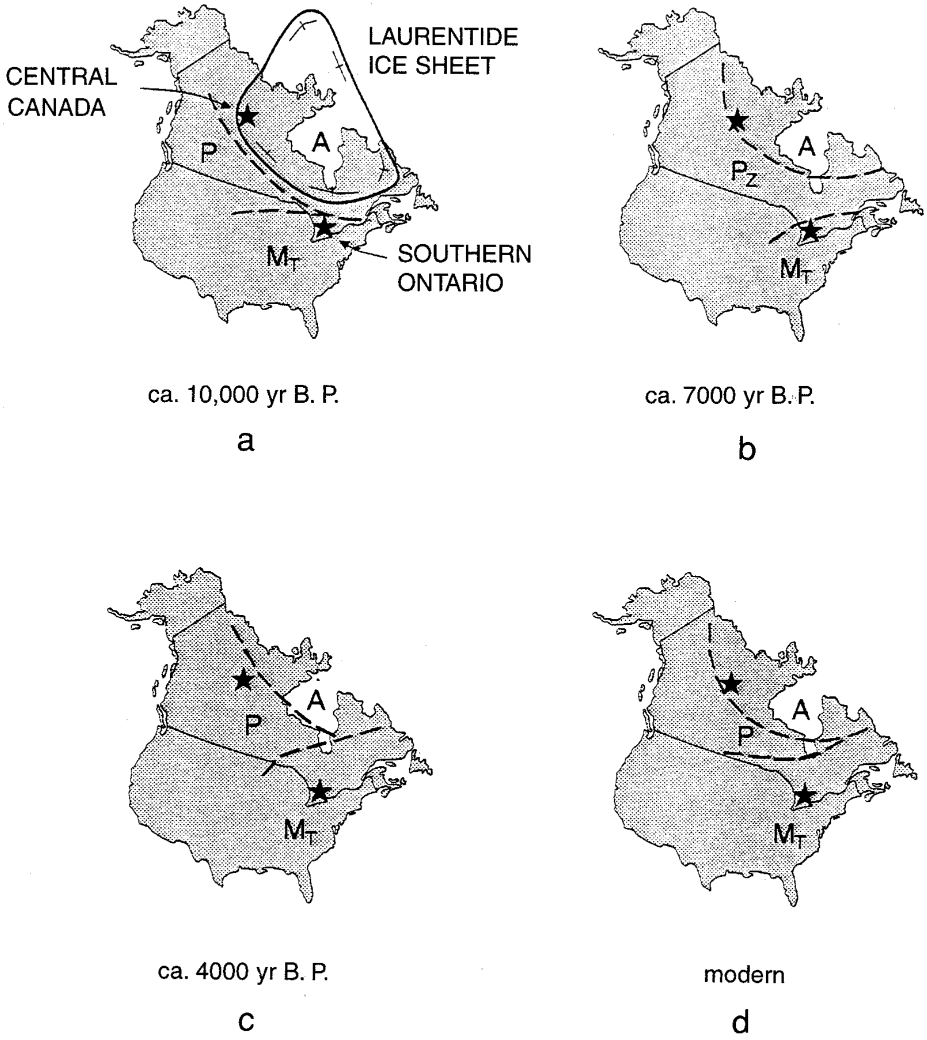
where R is the $^{18}O/^{16}O$ ratio in residual (Vr) and initial (Vo) vapor, f is the fraction of residual vapor remaining at any time, and α is the liquid–vapour equilibrium isotopic fractionation occurring during condensation ($=R_L/R_V$). Manipulation of (3) using a plausible value of $-15‰$ for the $\delta^{18}O$ of original vapor and α of 1.010 suggests that the present $\delta^{18}O_p$ of $-22‰$ represents an f of about 0.18. Assuming all else remained constant, a relatively moderate increase in moisture transport efficiency (from an f of 0.18 to 0.28) would be sufficient to generate the observed 4‰ increase in $\delta^{18}O_p$.

Moreover, any isotopic enrichment generated in this way is likely to have been reinforced by an increase in the summer:winter precipitation ratio, because the effect of higher cloud base would be more pronounced in summer. Sensitivity to this effect can also be readily simulated. Based on isotope hydrology studies in the region (Gibson *et al.*, 1993, 1994) and meteorological records (Environment Canada, 1982), the modern $\delta^{18}O_p$ value of $-22‰$ represents roughly a 55:45 mixture of summer rain and winter snow (water equivalent) having average $\delta^{18}O$ values of about -17 and $-28‰$, respectively. Mass balance considerations show that a modest shift to a 65:35 mixture in the annual budget would cause an increase in $\delta^{18}O_p$ of over 1‰, in the absence of changes in other factors.

These simple calculations demonstrate that the magnitude of the early-Holocene $\delta^{18}O_p$ ''anomaly'' in central Canada can be reasonably explained by small changes in rain-out effects and seasonality of precipitation, independent of change in MAT. Although there are certainly other factors that might influence spatial and temporal isotope–temperature relations, such as changing sea-surface conditions where vapor originates or changing moisture sources, we speculate that the above mechanisms may be the major ones operating at the coarse resolution of our existing $\delta^{18}O_p$ time-series. Most importantly, this provides the basis for a unified model that reconciles inferred climate and isotope–climate histories readily within the established framework of shifting postglacial atmospheric circulation (shown schematically in Fig. 4).

''Anomalous'' $\delta^{18}O_p$–MAT Relations Elsewhere in North America

Several examples of unusually high $\delta^{18}O_p$ (or δ^2H_p) in relation to MAT have been identified previously in North America. These include pre-Holocene episodes revealed by isotope study of fossil wood cellulose at several U.S. sites (Yapp and Epstein, 1977), groundwater along the southeastern Atlantic coastal plain (Plummer, 1993), and soil carbonate in Wyoming (Amundson *et al.*, 1996). Possible early-Holocene examples that may correspond in time with high $\delta^{18}O_p$ in central Canada have been inferred from isotopes in tree-ring cellulose from the White Mountains of California (Feng and Epstein, 1994) and the San Juan Mountains of Colorado (Friedman *et al.*, 1988), lake sediment kerogen from western Michigan (Krishnamurthy *et al.*, 1995), and fossil hackberry endocarp carbonate in the midwestern U.S. (Jahren *et al.*, 1995). Although detailed analysis would be required to verify teleconnection to events in central Canada, it is likely that these episodes are also a manifestation of the same atmospheric circulation changes outlined in Figure



ca. 10,000 yr B. P.
a

ca. 7000 yr B. P.
b

ca. 4000 yr B. P.
c

modern
d

FIG. 4. Schematic representation of mean summer frontal zone positions at selected times during the Holocene in relation to southern Ontario and central Canada (cf. Bryson and Wendland, 1967) (A = Arctic; M_T = Maritime-Tropical; P = Pacific; P_Z = high-zonal Pacific). (a) Earliest Holocene (ca. 10,000 yr B.P.): central Canada ice-covered; southern Ontario strongly influenced by Arctic air interacting with Maritime-Tropical air. (b) High Zonal Index (ca. 7000 yr B.P.): central Canada strongly influenced by Arctic air interacting with high-zonal Pacific air; southern Ontario strongly influenced by Maritime-Tropical air with subsidiary high-zonal Pacific air influence. (c) ''Climatic Optimum'' (ca. 4000 yr B.P.): central Canada strongly influenced by Pacific air; southern Ontario strongly influenced by Maritime-Tropical air. (d) Modern: central Canada strongly influenced by Arctic air with subsidiary Pacific air influence; southern Ontario strongly influenced by Maritime-Tropical air.

4, and that ''anomalous'' $\delta^{18}O_p$-MAT relations along the Arctic frontal zone in the north may have been mirrored by analogous effects along the Pacific frontal zone in the south.

CONCLUDING COMMENTS

Our results are strongly consistent with the notion that ''the $\delta^{18}O$ values of precipitation in North America are controlled by a complex array of processes that occasionally shows a strong dependence on MAT'' (Amundson *et al.*, 1996, p. 26). Further investigation and analysis of isotopic data from precipitation, both past and present, are clearly needed to document isotope–climate relations better. We view our compilation and interpretation of $\delta^{18}O_p$ histories for two areas in Canada as a preliminary step toward preparation of continental-scale paleo-isotope maps that can be used to gain deeper understanding of climate dynamics through synoptic–climatological analysis. As well, such time-slice maps will have obvious value for validation of AGCM simulations incorporating isotopic tracers and may indeed provide isotopic boundary conditions necessary for future-generation AGCMs to explore other aspects of global paleoclimate. Growing evidence for ''anomalous'' isotopic distribution in parts of North America during the early Holocene, in concert with differing circulation than present, suggests that a mapped time-slice within this interval might be a particularly fruitful target for a climate modeling experiment.

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