Climate in Southwestern Ontario, Canada, between AD 1610 and 1885 Inferred from Oxygen and Hydrogen Isotopic Measurements of Wood Cellulose from Trees in Different Hydrologic Settings

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Oxygen and hydrogen isotopes were measured in wood cellulose and cellulose-nitrate from trees that grew in different hydrologic settings in southwestern Ontario, Canada. An isotope model that accounts for isotopic fractionations associated with photosynthesis in plants was applied to the stable isotope data to infer past meteoric water isotopic composition and seasonal air moisture variations. The model-inferred climate data was rationalized in terms of the trees' hydrologic environment and weather characteristics of the Great Lakes region. The result is an account of summer and winter conditions in southwestern Ontario for 275 years (1610 to 1885) prior to instrumental climate records. Conditions between 1610 and 1750 are inferred to have been cooler and drier than present. This was followed by a warm-moist climate interval between 1750 and 1885 during which there was an increase in winter precipitation. Cool-dry conditions were recorded instrumentally in this region at the end of the nineteenth century. ©1995 University of Washington.

INTRODUCTION

Stable isotope dendroclimatology involves the reconstruction of past climate conditions from isotope measurements on tree-ring cellulose and cellulose-nitrate. This technique is well suited for paleoclimatic reconstructions because the stable isotope compositions of tree-ring material are often a function of environmental factors related to the local and regional climate. In addition, annual tree rings usually provide a precise chronology in which to place inferred climate changes.

Stable isotope dendroclimatology studies were subdivided into two categories by Edwards (1993). The transfer function category includes all studies in which stable isotope measurements of tree-ring material are directly correlated with meteorologic and climatic variables. Other studies, in which climate parameters were inferred by accounting for isotopic effects on water and CO_2 during photosynthetic assimilation in plants, were categorized as mechanistic.

Correlations between stable isotope data and environmental parameters vary among studies. Tree-ring isotope data have been directly correlated with the isotopic compositions of seasonal precipitation (Epstein and Yapp, 1976; Yapp and Epstein, 1977; 1982), precipitation amounts (Lawrence and White, 1984; Yapp and Epstein, 1985; Ramesh *et al.*, 1986), mean annual and seasonal temperatures (Epstein and Krishnamurthy, 1989; Yapp and Epstein, 1977; 1982; Lipp *et al.*, 1993), and relative humidity and cloud cover (Ramesh *et al.*, 1986). The variation in environmental information provided by tree-ring isotope data can be attributed, in some cases, to the different hydrologic settings of the trees. For instance, the good correspondence between $\delta^2H_{cell\text{-}nitrate}$ values and growing season conditions for the trees from Lawrence and White (1984), Yapp and Epstein (1985), and Ramesh *et al.*, (1986) represent situations where the trees' hydrologic setting restricted the availability of water during the growing season. Relationships between isotopic values and precipitation amounts suggest that, in these cases, water availability had a pronounced effect on the rate of evapotranspiration and, consequently, the isotopic composition of cellulose. Similarly, a good correlation between cellulose-nitrate and winter precipitation δ^2H values from Epstein and Yapp (1976) suggests that the Scots pine investigated was supplied with growing season water that was dominantly recharged by winter precipitation (snowmelt).

Yapp and Epstein (1977, 1982) showed strong relationships between $\delta^2H_{cell\text{-}nitrate}$ values and mean annual temperature. In these cases it is likely that the tree occupied a setting that supplied water with an annual isotopic signal. However, complications in the water supply (a mixture of snowmelt and rain) effectively masked the isotopic signals related to growing season temperature for two of the 23 trees studied by Epstein and Krishnamurthy (1989).

These examples illustrate that the hydrologic setting of a tree can have a significant influence on the relationship between climate and tree-ring isotopic signals. Therefore, isotope dendroclimatological studies that account for the influence of source water on the isotopic compositions of plant water and cellulose have the potential of resolving additional climate related signals.

Burk and Stuiver (1981), who initiated the mechanistic approach, showed how $\delta^{18}O_{cellulose}$ values can vary as a function of the input water isotopic composition, air moisture and

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evapotranspiration and biochemical isotope effects. Similar models developed by Yapp and Epstein (1982) and Edwards and Fritz (1986) accounted for the apparent hydrogen and oxygen fractionations between the plant input water and cellulose. Edwards and Fritz (1986), by solving the equations that account for these apparent fractionations of oxygen and hydrogen, in association with a common link provided by the meteoric water line (MWL), showed that measurements of $\delta^{18}O_{cellulose}$ and $\delta^{2}H_{cellulose\text{-}nitrate}$ from modern trees can give reasonable estimates of $\delta^{18}O_{meteoric\ water}$ and air moisture content. Applications include a Holocene paleoclimate record, based on inferred $\delta^{18}O_{meteoric\ water}$ and air moisture, which favorably compares with climate zones previously delineated by fossil pollen and insect paleoclimatic indicators (Edwards *et al.,* 1985; Edwards and Fritz, 1986). Clague *et al.,* (1992), using the mechanistic approach with trees from different environments, attributed a positive correlation between growing site elevation and inferred $\delta^{18}O_{meteoric\ water}$ and air moisture to differences in air moisture content and the source water available to trees at different elevations during the growing season.

Accounting for hydrologic influences on the isotopic composition of tree-ring cellulose helps to categorize the information obtained from isotope dendroclimatological studies. Further, it is anticipated that the environmental information provided by trees from dissimilar hydrological settings, when combined, will provide some additional information on past climates. To illustrate this we have quantified some climate information inferred from the oxygen and hydrogen isotope data of trees that occupy different hydrological settings in terms of Great Lakes region weather. We infer changes in meteoric water isotopic composition ($\delta^{18}O_{meteoric\ water}$) and air moisture in southwestern Ontario, Canada, for 275 yr (1610 to 1885) prior to instrumental climate records.

SAMPLE SITES

The Victoria Park (VP) elm (*Ulmus americana* L.) and Bleams Road (BR) white pine (*Pinus strobus* L.) are from Kitchener, located in southwestern Ontario, Canada. The Merlau (Ml) maple (*Acer saccharum* M.) is from a woodlot near Wellesley approximately 25 km west of Kitchener (Fig. 1) Victoria Park is a groundwater discharge area in the Schneider Creek catchment and the Merlau farm is a groundwater recharge area for the Nith River catchment. Bleams Road, a corduroy road, was constructed in 1810, which is inferred to be the last growing year of the BR white pine (Buhay, 1994). It is likely that the BR white pine was locally cut from a discharge site.

METHODS

The tree-ring width chronologies provide a composite 380-yr record (1610 to 1990) for southwestern Ontario (Fig. 2). The chronologies are averages of two radii for each tree. The tree-ring wood samples represent 10-yr ring increments which were homogenized from the two radii for each tree. Cellulose was prepared from ground wood samples by solvent extraction, bleaching, and alkaline hydrolysis (Green, 1963). Oxygen isotope analysis was performed on CO_2 gas produced from purified cellulose using a nickel pyrolysis technique (Edwards *et al.,* 1994). Isotopic analysis of nonexchangeable carbon-bound hydrogen was performed on H_2 gas obtained from zinc reduction of H_2O produced by combustion of nitrated cellulose (DeNiro, 1981; Coleman *et al.,* 1982). Oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) isotope ratios (R) are expressed as parts per thousand, or per mil (‰) in delta notation (δ) (δ = (Rsample/RV-SMOW − 1) × 10^3, where V-SMOW is Vienna – standard mean ocean water). The $\delta^{18}O_{cellulose}$ and $\delta H^{2}_{cellulose\text{-}nitrate}$ val-

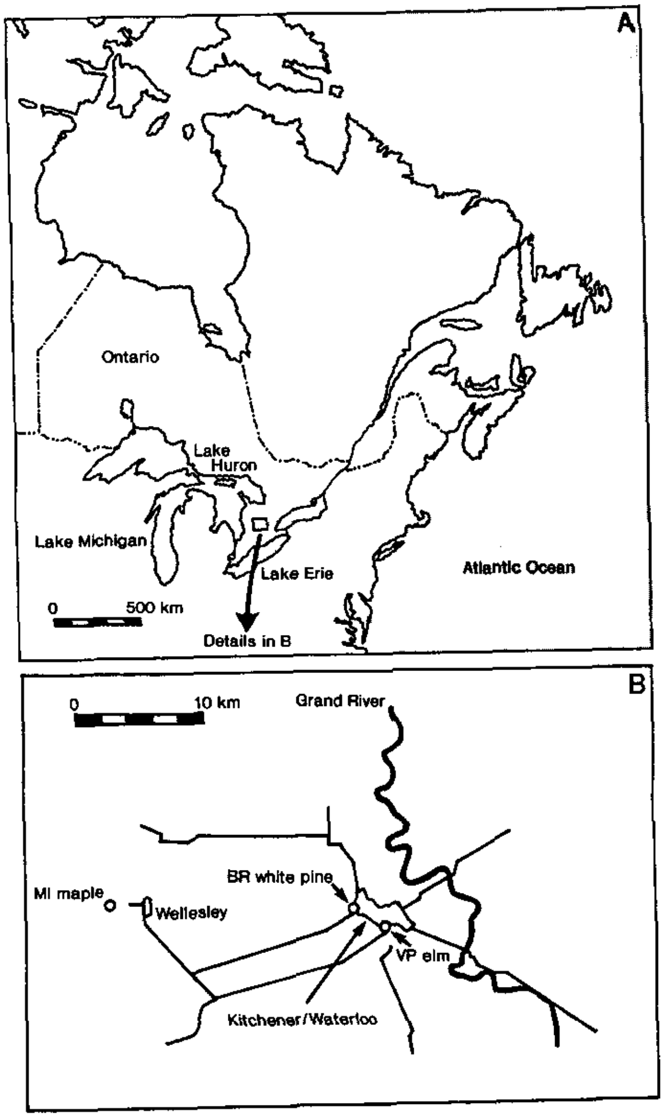

FIG. 1. The location of the study area in southwestern Ontario, Canada, is shown in part A. Locations of the three samples sites, within the study area, are shown in part B.

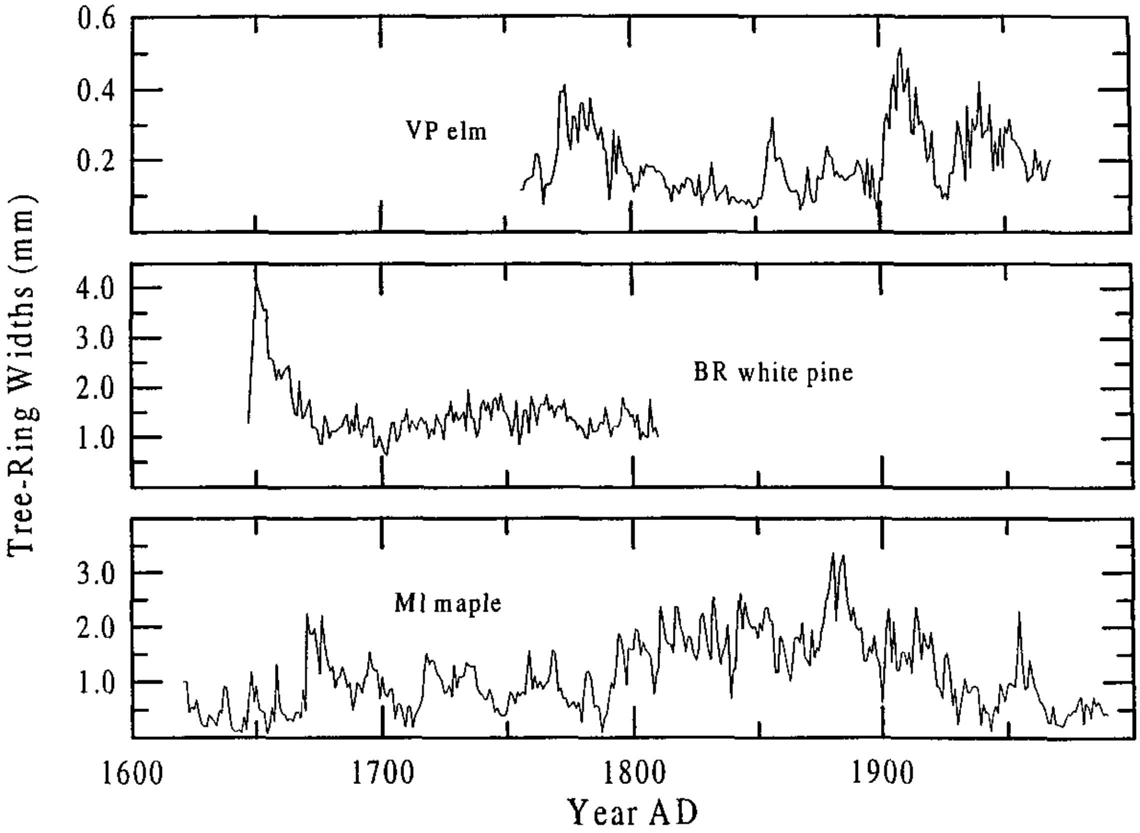

FIG. 2. Tree-ring width chronologies for the VP elm, BR white pine, and MI maple trees.

ues (Table 1) have analytical uncertainties of ±0.2‰ and ±2.0‰, respectively.

A modified version of the Edwards and Fritz (1986) cellulose model (Buhay, 1994) was used in conjunction with the appropriate fractionation factors for equilibrium, kinetic, and biochemical effects to interpret the isotopic data for the three trees. The cellulose model equations are provided below,

$$(1000 + \delta^{18}\mathrm{O}_{\mathrm{cellulose}})/(1000 + \delta^{18}\mathrm{O}_{\mathrm{meteoric\ water}}) = {}^{18}\alpha_{\mathrm{b}} \cdot {}^{18}\alpha_{\epsilon} \cdot {}^{18}\alpha_{\mathrm{k}} - {}^{18}\alpha_{\mathrm{b}} \cdot ({}^{18}\alpha_{\epsilon} \cdot {}^{18}\alpha_{\mathrm{k}} - 1) \cdot h$$

$$(1000 + \delta^{2}\mathrm{H}_{\mathrm{cell\text{-}nitrate}})/(1000 + \delta^{2}\mathrm{H}_{\mathrm{meteoric\ water}}) = {}^{2}\alpha_{\mathrm{b}} \cdot {}^{2}\alpha_{\epsilon} \cdot {}^{2}\alpha_{\mathrm{k}\tau} - {}^{2}\alpha_{\mathrm{b}} \cdot ({}^{2}\alpha_{\epsilon} \cdot {}^{2}\alpha_{\mathrm{k}\tau} - 1) \cdot h$$

$$\delta^{2}\mathrm{H}_{\mathrm{meteoric\ water}} = 8 \cdot \delta^{18}\mathrm{O}_{\mathrm{meteoric\ water}} + 10,$$

where ${}^{18,2}\alpha_{\mathrm{b}}$ accounts for the biochemical isotope effects that occur during cellulose synthesis, and ${}^{18,2}\alpha_{\epsilon}$ and ${}^{18}\alpha_{\mathrm{k}}$, ${}^{2}\alpha_{\mathrm{k}\tau}$ account for the equilibrium and kinetic isotope effects that occur during evapotranspiration, for oxygen and hydrogen, respectively. The biochemical, equilibrium, and kinetic fractionation factors used in the cellulose model for this study are as follows: ${}^{18}\alpha_{\mathrm{b}} = 1.0282$, ${}^{2}\alpha_{\mathrm{b}} = 0.950$; ${}^{18}\alpha_{\epsilon} = 1.0095$, ${}^{2}\alpha_{\epsilon} = 1.0816$; ${}^{18}\alpha_{\mathrm{k}} = 1.014$, ${}^{2}\alpha_{\mathrm{k}\tau} = 1.0254$ for the MI maple and VP elm; and ${}^{18}\alpha_{\mathrm{b}} = 1.0282$, ${}^{2}\alpha_{\mathrm{b}} = 0.950$; ${}^{18}\alpha_{\epsilon} = 1.0095$, ${}^{2}\alpha_{\epsilon} = 1.0816$; ${}^{18}\alpha_{\mathrm{k}} = 1.0285$, ${}^{2}\alpha_{\mathrm{k}\tau} = 1.0382$ for the BR white pine. Air moisture (relative humidity, h) and $\delta_{\mathrm{meteoric\ water}}$ variations are inferred from the model (Fig. 4).

WEATHER AND CLIMATE IN THE GREAT LAKES REGION

Atmospheric circulation, related to westerly flow along the polar front, directs air masses toward the Great Lakes region that convey temperature and air moisture from other areas. Circulation near the Great Lakes draws predominantly from warm/moist, maritime tropical air masses from the Gulf-Atlantic region and cool/dry, continental polar air masses from northwestern North America. The region is occasionally influenced by cool/moist, maritime polar air masses from the North Atlantic and warm/dry, continental tropical air masses from southwestern North America (Bryson and Hare, 1974; Eichenlaub, 1979; Phillips, 1990). The seasonal variation in Great Lakes region weather reflects changes in the dominant air mass influence which is a result of changes in the surface circulation patterns generated by the polar front position and airflow velocity. Therefore, variation in Great Lakes region climate could reflect anomalous seasonal changes in the characteristics of the polar front and its related influence on Great Lakes region weather.

The Great Lakes can modify the meteorological characteristics of air masses imported into the region (Petterssen and Calabrese, 1959; Richards, 1964; Eichenlaub, 1979; Phillips, 1990). The thermal inertia of the lakes results in stable and unstable seasons when lake water temperatures are cooler and

TABLE 1

Oxygen and Hydrogen Isotope Data for the VP Elm, BR White Pine, and MI Maple

Sample	Interval (AD)	δ180 (SMOW)	δ2H (SMOW)
	Victoria Park elm		
VP23	1960–1968	25.4	–95.0
VP22	1948–1959	26.2	–93.0
VP21	1938–1947	26.4	–102.0
VP20	1928–1937	24.9	–98.0
VP19	1919–1927	26.5	–102.0
VP18	1910–1918	26.4	–98.0
VP17	1902–1909	27.9	–103.0
VP16	1891–1901	28.0	–96.0
VP15	1880–1890	27.0	–108.0
VP14	1869–1879	26.3	–100.0
VP13	1859–1868	25.4	–102.0
VP12	1849–1858	26.5	–84.0
VP11	1840–1848	23.6	–91.0
VP10	1830–1839	23.9	–90.0
VP9	1819–1829	25.1	–88.0
VP8	1809–1818	25.1	–99.0
VP7	1799–1808	26.4	–99.0
VP6	1789–1798	26.0	–97.0
VP5	1779–1788	24.2	–104.0
VP4	1769–1778	24.8	–95.0
VP3	1757–1768	25.4	–99.0
VP2	1747–1756	25.5	–96.0
VP1	1736–1746	25.4	–101.0
	Bleams Road white pine		
BR16	1801–1810	27.3	–106.9
BR15	1791–1800	28.2	–115.7
BR14	1781–1890	27.7	nd
BR13	1771–1780	28.0	–108.1
BR12	1761–1770	28.4	–112.8
BR11	1751–1760	28.1	–123.2
BR10	1741–1750	27.6	–127.8
BR9	1731–1740	27.5	–123.0
BR8	1721–1730	27.1	–123.7
BR7	1711–1720	27.9	–129.4
BR6	1701–1710	27.8	–116.7
BR5	1691–1700	28.0	–124.1
BR4	1681–1690	28.2	–118.3
BR3	1671–1680	27.9	nd
BR2	1661–1670	28.4	–126.0
BR1	1651 ± 1660	27.4	–127.8
	Merlau maple		
MI38	1981–1990	26.4	–100.6
MI37	1971–1980	26.4	–96.7
MI36	1961–1970	25.9	–96.9
MI35	1951–1960	26.4	–103.1
MI34	1941–1950	26.6	–101.1
MI33	1931–1940	26.1	–104.5
MI32	1921–1930	26.4	–106.2
MI31	1911–1920	26.9	–102.1
MI30	1901–1910	27.1	–103.9
MI29	1891–1900	26.8	–107.1
MI28	1881–1890	26.6	–108.2
MI27	1871–1880	27.1	–108.8
MI26	1861–1870	27.0	–112.4
MI25	1851–1860	26.5	–107.2
MI24	1841–1850	26.4	–111.1
MI23	1831–1840	26.5	–116.9
MI22	1821–1830	26.7	–108.3
MI21	1811–1820	26.5	–113.9
MI20	1801–1810	26.9	–111.5
MI19	1791–1800	26.4	–114.5
MI18	1781–1790	26.4	–109.6
MI17	1771–1780	26.1	–110.9
MI16	1761–1770	26.4	–115.7
MI15	1751–1760	26.7	–106.4
MI14	1741–1750	26.2	–104.3
MI13	1731–1740	26.4	–113.1
MI12	1721–1730	25.7	–113.1
MI11	1711–1720	26.1	–112.0
MI10	1701–1710	26.0	–111.4
MI9	1691–1700	26.3	–103.4
MI8	1681–1690	26.8	–112.1
MI7	1671–1780	25.9	–106.5
MI6	1661–1670	25.9	–110.4
MI5	1651–1660	25.6	–103.5
MI4	1641–1650	26.2	–101.7
MI3	1631–1640	25.6	–96.4
MI2	1621–1630	25.5	nd
MI1	1610–1620	25.4	–103.1

warmer than the land, respectively. The temperature difference between the lakes and land modify the weather particularly in winter. Heat released from the warmer lakes during the winter can significantly enhance the temperature (isotopic composition of precipitation), specific humidity, and stability of air masses passing over them. The amount of heat released varies as a result of heating during the preceding summer and the depth, size, and latitude of the lake.

RESULTS AND DISCUSSION

Instrumental versus Inferred Climate Records (1885 to 1990)

The contemporary climate of southwestern Ontario is humid, with adequate precipitation in all months, resulting in cold-snowy winters and warm-moist summers (Dfb Köppen classification) (Geiger, 1971; Eichenlaub, 1979; Egbert, 1990). However, this region was characterized by lower mean annual air temperatures and precipitation amounts during the end of the nineteenth century (Quinn, 1981; Phillips, 1988). Depleted $\delta^2H_{cellulose\text{-}nitrate}$ and enriched $\delta^{18}O_{cellulose}$ values for the VP elm during this time (Fig. 3), are the predictable responses for a discharge site tree that used annually homogenized groundwater, under the influence of cooler/drier air masses (Edwards and Buhay, in press). Accordingly, cellulose-model estimates of $\delta^{18}O_{meteoric\ water}$ (proxy for temperature) and air moisture regimes from the VP elm isotope data (Fig. 4) conform with the cooler and drier climate conditions recorded in the instrumental record at this time.

The gradual enrichment of MI maple $\delta^2H_{cellulose\text{-}nitrate}$ values (Fig. 3b) could be a result of a reduction in winter precipitation

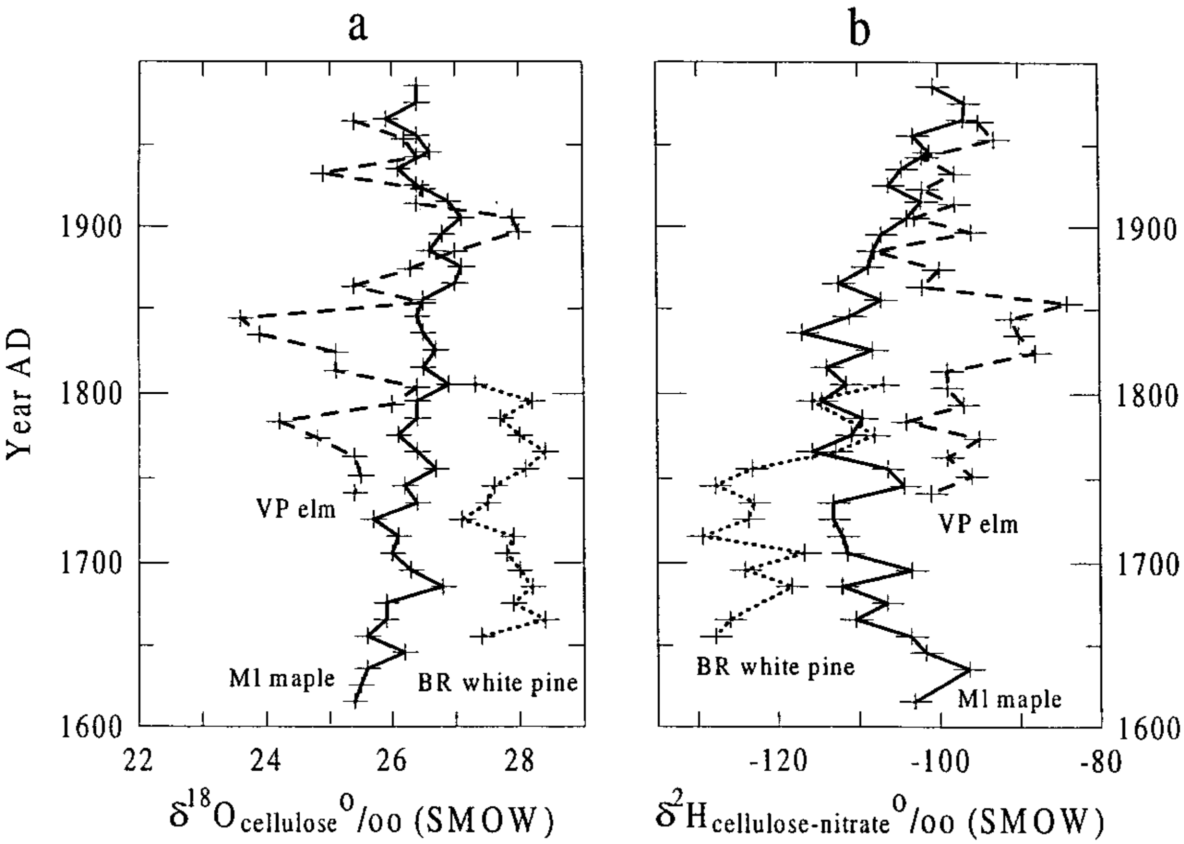

FIG. 3. $\delta^{18}O$ cellulose (a) and δ^2H cellulose-nitrate (b) time series for the Ml maple (solid line), the VP elm (dashed line), and the BR white pine (dotted line). The vertical error bars indicate the 10-yr (ring) sample intervals and the horizontal error bars show the precision of the isotopic measurements.

(snowmelt recharge) and/or drier growing seasons that prevailed during the end of the nineteenth century (Quinn, 1981; Phillips, 1988). In this case, both water-dependent and atmospheric air moisture-dependent isotope effects can result in an enrichment of ^2H in cellulose and, therefore, this enrichment trend could be attributed to a combination of the two effects. However, the corresponding oxygen isotope values, which are more sensitive to atmospheric air moisture-dependent isotopic effects than hydrogen, form a trend of subtle depletion (Fig. 3a). This suggests that the $\delta^2H_{\text{cellulose-nitrate}}$ enrichment is more likely a result of water-dependent isotope effects (Edwards and Buhay, in press) and, therefore, the $\delta^2H_{\text{cellulose-nitrate}}$ enrichment (Fig. 3b) during this period is probably due to reduced snowmelt recharge.

In Figures 3a and b, from about 1900 to present, $\delta^2H_{\text{cellulose-nitrate}}$ becomes enriched while $\delta^{18}O_{\text{cellulose}}$ gradually depletes for both the VP elm and Ml maple. The VP elm inferred increase in $\delta^{18}O_{\text{meteoric water}}$ and atmospheric air moisture content (Fig. 4) agrees with instrumental accounts of an increase in mean annual air temperature and an increase in growing season precipitation that accompanied the predominance of maritime tropical air masses during this time (Quinn, 1981; Phillips, 1988). The enrichment of Ml maple $\delta^2H_{\text{cellulose-nitrate}}$ (Fig. 3b) suggests a continuation of the late nineteenth century reduction in snowmelt recharge for the Ml maple site as winter precipitation steadily decreased. Predominance of drier winters since 1900, however, does not conform to records indicating a steady increase in average annual precipitation, uniformly distributed seasonally, in the Great Lakes region since 1900 (Quinn, 1981; Phillips, 1988). This implies some other source for the Ml maple $\delta^2H_{\text{cellulose-nitrate}}$ enrichment trend in Fig. 3b.

In Figures 3b and 4a, overlapping VP elm and Ml maple $\delta^2H_{\text{cellulose-nitrate}}$ trends and model inferred $\delta^{18}O_{\text{meteoric water}}$ trends suggest that the recharge water supplying the Ml maple was similar, isotopically, to that of the regional precipitation composition during this time. Therefore, for a recharge site receiving evenly distributed precipitation annually, the steady $\delta^2H_{\text{cellulose-nitrate}}$ enrichment for the Ml maple reflects an overall enrichment in both summer and winter precipitation that accompanied an increasing influence of warm/moist maritime tropical air masses. The $\delta^{18}O_{\text{cellulose}}$ depletion for the Ml maple (Fig. 3a) is, as for the VP elm, a result of an increase in air moisture content during the growing season.

The mean position of the polar front was to the north of southwestern Ontario during the summer and south during the winter for the first half of the twentieth century (Lahey *et al.*, 1950). Atmospheric circulation related to the polar front would draw upon warm/moist air masses during the summer and cool/dry air during the winter. Increased lake heat storage, a result

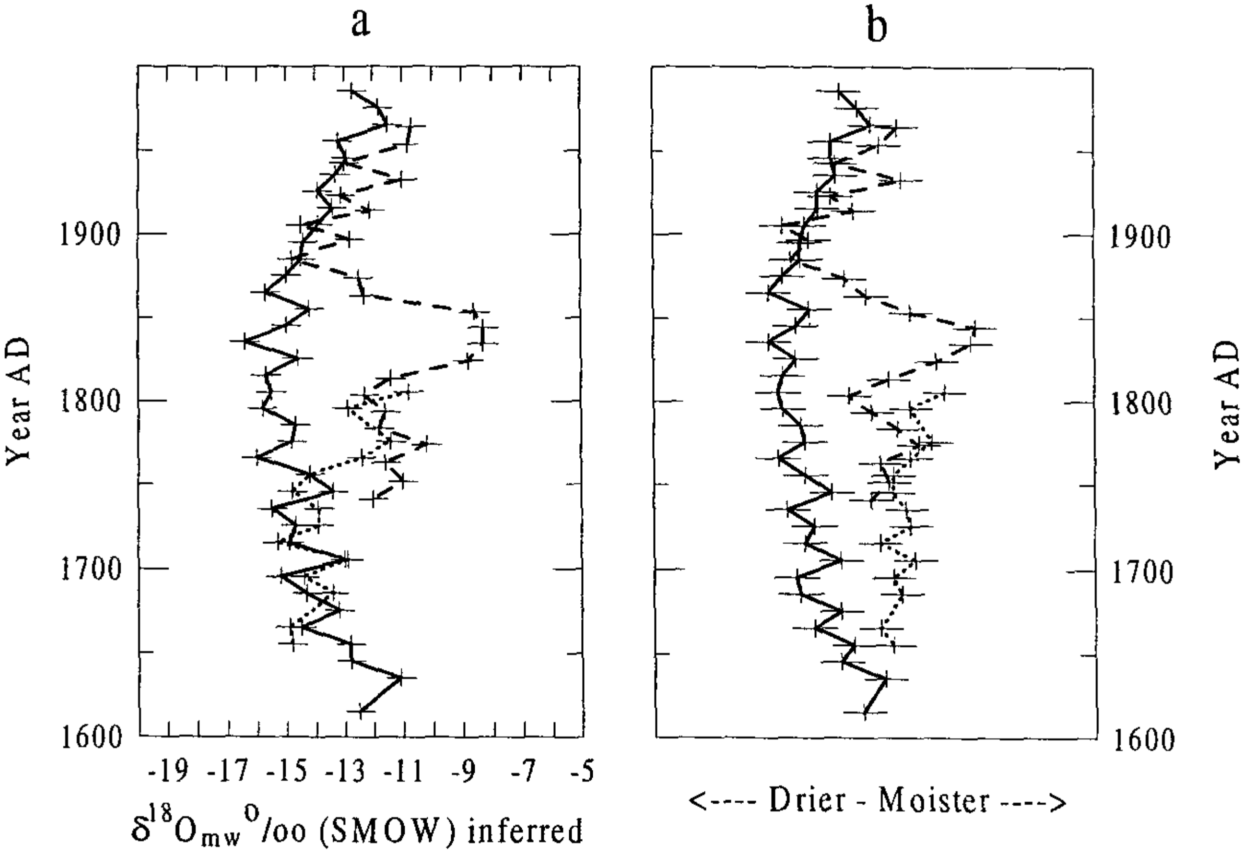

FIG. 4. Inferred $\delta^{18}O_{\text{meteoric water}}$ (a) and air moisture (b) time series for the Ml maple (solid line), the VP elm (dashed line), and the BR white pine (dotted line). The vertical error bars indicate the 10-yr (ring) sample intervals and the horizontal error bars show the variation in cellulose model estimates of $\delta^{18}O_{\text{meteoric water}}$ and air moisture.

of warm summers, would enhance the temperature and air moisture content of air masses passing over the lakes, which could account for elevated winter temperatures and precipitation during this time.

The combination of cooler and drier seasons during the late nineteenth century suggests that, on average, the polar front maintained a mean southerly position which would enhance the annual influence of cool/dry air masses in the area. Reduced winter precipitation probably reflects lower heat storage in the Great Lakes.

Climate in the Great Lakes Region between 1610 and 1885

The discharge site trees (VP elm and BR white pine) provide reliable information on the isotopic composition of annual precipitation and growing season air moisture. The recharge site tree (Ml maple) provides information on the isotopic composition of precipitation recharging meteoric water locally. Therefore, merging of discharge and recharge site-inferred $\delta^{18}O_{\text{meteoric water}}$ signals corresponds to intervals when the isotopic composition of precipitation at the recharge site was similar to that of the mean annual isotopic signal. At these times, signals from recharge site trees also reveal annual precipitation and growing season air moisture variations. At other times a decoupling of inferred climate signals reveal useful information on local seasonal precipitation variations in addition to the annual variation estimates provided by the discharge site trees.

Between 1650 and 1750, inferred climate trends for the BR white pine (Fig. 4) suggest that the regional meteoric water was recharged by precipitation with an average isotopic composition that was 2 to 3‰ depleted with respect to the present average composition of −11.0‰ (Edwards and Fritz, 1986). The alliance of inferred $\delta^{18}O_{\text{meteoric water}}$ and air moisture characteristics for the Ml maple and BR white pine (Fig. 4a) is likely due to a similarity in the seasonal distribution of annual precipitation at both sites. However, the gradual decrease in Ml maple inferred air moisture after 1650 (Fig. 4b) is probably not a product of drier growing conditions at the recharge site, but rather, an increasing local influence of snowmelt at the recharge site.

In Figure 4 the inferred climate trends, for the trees from different hydrological settings, separate between 1750 and 1850. Both the VP elm and the BR white pine suggest a steady increase in the characteristics related to an influence of warm/moist air masses. The constancy in the Ml maple inferred $\delta^{18}O_{\text{meteoric water}}$ and air moisture regimes during this time may be related to greater winter precipitation accumulations and an increase in snowmelt recharge at the Ml maple site. This is likely due to the proximity of the higher elevation Ml maple site to the southwestern Ontario snowbelt region, which could enhance the accumulation of snow locally during certain conditions. For example, atmospheric circulation that enhances the fetch of air masses across Lake Huron and Georgian Bay (to the northwest) could significantly increase the specific humidity of the air mass, especially during an unstable period with more evaporation from warmer lakes that remained ice-free longer. Orographic lifting of unstable air masses encroaching from the north could result in higher snow accumulations in the northwest. Therefore, the main difference in inferred $\delta^{18}O_{\text{meteoric water}}$ values (Fig. 4a), between the two sites, is perhaps a result of differential snow accumulation.

Evidence to test the climate changes inferred for southwestern Ontario over the last 400 yr is rare. Local comparisons can be made between a tree-ring index of *Thuja occidentalis* that grew on the nearby Niagara Escarpment in southern Ontario (Kelly *et al.*, 1994) and climate inferred from the VP elm and BR white pine trees. The positive correlation between tree-ring indices and inferred $\delta^{18}O_{\text{meteoric water}}$ in Figure 5 suggests that the high late-summer temperatures, which negatively influence the growth potential of these *Thuja occidentalis* trees in the next season (Kelly *et al.*, 1994), occur during years when the bulk of the precipitation that recharged groundwater for the VP elm and BR white pine was delivered during the cooler months. Generally, very warm late summer conditions were absent during overall warmer years with the exception of some summers between 1830 and 1850 (Fig. 5).

Another local comparison can be made between historical accounts of water levels in Lakes Erie, Huron, and Michigan (Bishop, 1992) and the inferred moister air conditions. The inference of moister air conditions in southwestern Ontario between 1750 and 1850 followed by a 50-yr drier period correlates with the historical accounts of a similar rise and fall of water levels in these Great Lakes.

Verification of these inferred climate changes can also be made from comparisons with areas peripheral to southwestern Ontario. For a temperature coefficient between 0.65 and 0.70‰/°C (Fritz and Fontes, 1980), the inferred 2 to 3‰ depletion in $\delta^{18}O_{\text{meteoric water}}$ between 1650 and 1750 (Fig. 4a) partially coincides with a recent palynological account that suggests mean annual air temperatures were 2°C cooler in southeastern Ontario between 1200 and 1850 (Campbell and McAndrews, 1991;1993). Also, the inferred ameleoration of climate commencing around 1750 would accompany changes in atmospheric circulation associated with a northward retreat of the polar front. Daily weather observations in Hudson's Bay Company journals (Ball, 1985) and tree-ring time-series (Scott *et al.*, 1988) from sites in northern Manitoba suggest that the polar front occupied a more northerly position between 1760 and 1820. A northerly position of the polar front during this time could also account for a peak period of fire frequency in the boreal forest of Quebec (1750 to 1860) (Bergeron and Archambault, 1993) by an increase in thunderstorm activity that would accompany an influx of unstable southerly air during the summer. Movement of warm/moist air masses into southwestern Ontario, due to the north positioning of the polar front, would correspond with accounts of increased mean annual air temperature in New England during the 1820s and 1830s (Baron and Gordon, 1985). Finally, the renewal of the inferred 1750 initiated climate amelioration during the early nineteenth century, following a brief interruption between 1775 and 1810 (Fig. 4), corresponds to a predominance of cyclone tracking north of the Great Lakes in response to a shift from low to high zonal index of upper westerly flow (Wilson,

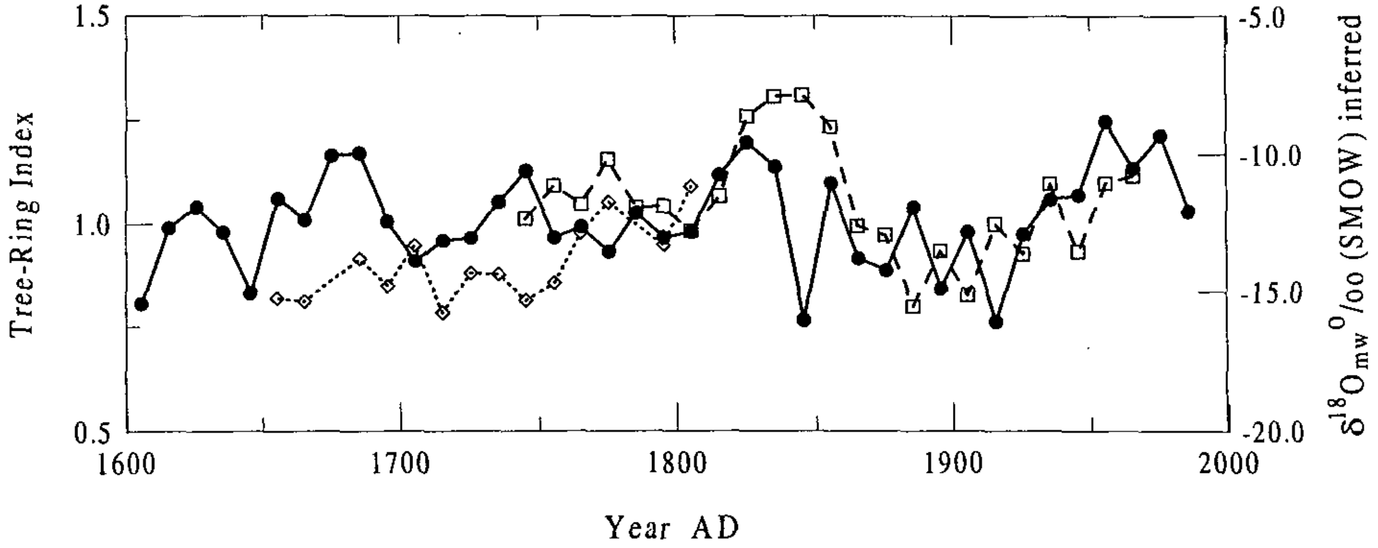

FIG. 5. Inferred $\delta^{18}O_{\text{meteoric water}}$ for the VP elm (open squares and dashed line) and BR white pine (open diamonds and dotted line) superimposed on tree-ring indexes (solid circles and heavy line; 10-yr averages) from Niagara Escarpment *Thuja occidentalis* (Kelly *et al.*, 1994).

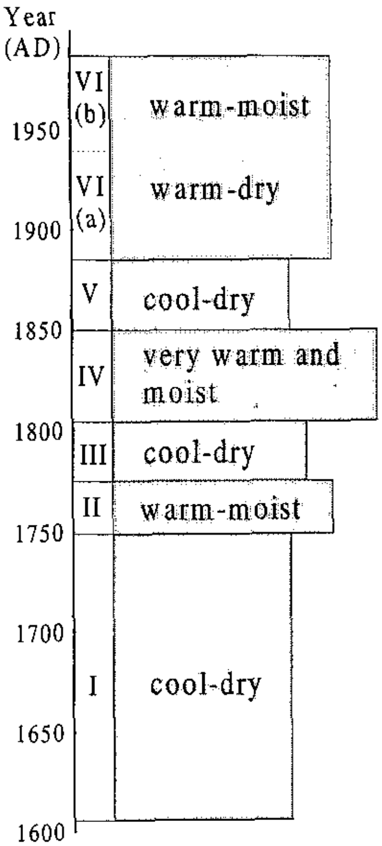

FIG. 6. Inferred paleoclimate for southwestern Ontario, Canada, between 1610 and 1990.

1985; 1992; Catchpole, 1992; Ball, 1992; Lamb, 1992; Newell, 1992).

CONCLUDING REMARKS

This study illustrates the integrated influence of a tree's hydrologic, physiographic, and climatologic setting on the information inferred from tree-ring isotope data. Here, the oxygen and hydrogen isotope data, from trees that grew in different settings, were used to infer the annual isotopic compositions of precipitation and seasonal air moisture information for southwestern Ontario, Canada. This study extends the current knowledge on southwestern Ontario climate by 275 years and helps corroborate and augment the findings of other studies indicating noticeable variations in regional climate during the recent past.

For instance, the inferred cool-dry climate conditions between 1660 and 1750 corresponds to the palynological evidence of Little Ice Age conditions in southeastern Ontario (Campbell and McAndrews, 1991; 1993); the inferred warm-moist conditions (accompanied by an increase in winter precipitation) between 1750 and 1885 correspond to historical high water levels in Lakes Erie and Michigan-Huron (Bishop, 1990); the inferred cool-dry interval during the end of the nineteenth century is supported by regional records of climate that indicate conditions deteriorated during the same time. Also, the inferred climate information from the discharge site trees suggest that periods of high late summer temperatures, responsible for reduced growth of Niagara Escarpment *Thuja occidentalis* (Kelly *et al.,* 1994), are more characteristic of years in which temperatures tend to be cooler. An inferred paleoclimatic summary for southwestern Ontario, Canada, between 1610 and 1885 (including the recorded interval between 1885 and 1990), is shown in Fig. 6.

Knowledge of the factors controlling isotopic signals in plants remains incomplete (DeNiro and Cooper, 1989; Edwards, 1990; Yakir, 1992; Buhay, 1994). However, plausible accounts of climate change, based on the current knowledge, are possible as this and other studies illustrate (Edwards *et al.,* 1985; Edwards and Fritz, 1986; Clague *et al.,* 1992). Continued work in the field of isotope dendroclimatology is warranted by the fact that improved knowledge of environment/plant isotope systematics can only result in refined paleoclimatic interpretations with new and previous data.

In the future, groundwater isotopic compositions inferred from geographically distributed trees could provide information on the spatial and temporal variability of precipitation. Isotopic information from catchments, displayed on geographic grids, could provide a means of identifying spatial and temporal changes in precipitation patterns. On a larger scale, isotopic time-series from trees across continental areas should reveal variations in the position of the polar front associated with atmospheric circulation patterns.

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