Research paper

A Holocene paleoclimate reconstruction for eastern Canada based on $\delta^{18}O$ cellulose of *Sphagnum* mosses from Mer Bleue Bog

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Hafida El Bilali, R Timothy Patterson and Andreas Prokoph

Abstract

We present a ~9200 yr high-resolution oxygen isotope record of plant cellulose ($\delta^{18}O_{cel}$) from the peat deposits of Mer Bleue Bog, Ontario and apply it as a proxy for paleotemperature reconstruction in Eastern Canada. The results show that $\delta^{18}O_{cel}$ of *Sphagnum* follows the general pattern of the Northern Hemisphere reconstructed paleotemperature record for the last 2000 years at a ratio of ~2‰$\delta^{18}O_{cel}$/°C. The $\delta^{18}O_{cel}$ record of ombrotrophic phase of Mer Bleue Bog is also in accordance with major features of the Holocene sunspot number reconstruction. Three distinct time intervals have low $\delta^{18}O_{cel}$ values: 200–800 cal. BP ('Little Ice Age'); 2800–3400 cal. BP synchronous to a cooling period reported elsewhere in North America; and 4200–4600 cal. BP corresponding to a cooling interval in the North Atlantic region. These cooling periods also correlate well with negative excursions in the Holocene sunspot and cosmogenic ^{10}Be records. A fourth period of low $\delta^{18}O_{cel}$ values between AD 1810 and 1820 may be related to the extremely cold summer of 1816 and cooler subsequent years, which occurred in the aftermath of the Tambora volcanic eruption, or possibly cooling associated with the early 19th century Dalton solar minimum. The results also indicate the presence of millennial-scale cycles possibly comparable with the globally recognized Bond cycles that have been correlated to fluctuations in solar irradiance.

Keywords

eastern Canada, cellulose, ombrotrophic bog, oxygen isotopes, paleotemperatures, solar activity

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Introduction

The Earth's climate is controlled by many factors such as water vapor, CO_2, methane, volcanic degassing, solar activity, biological activity, and land use change (Jansen et al., 2007). Since the 1980s there has been a realization that rapid climate change on the scale of the human lifespan was possible (Jansen et al., 2007). Climate change projections for southern Canada through the 21st century predict a 0.5–1.5°C temperature increase, at least partially driven by anthropogenic causes (Zhang et al., 2000).

Long-term trends in regional and global temperatures are interrupted by short-lived events that are difficult to resolve with the short historical records. This is particularly true in eastern Canada where systematic measurement and collection of temperature data only began in the late 19th century. Therefore, a more complete understanding of intermediate and long-term climate oscillations can only be achieved by turning to the geological record. Paleolimnological, dendrochronological, and paleoceanographic studies have revealed cyclic changes in moisture levels in climate records from the NE Pacific (Patterson et al., 2004) and interior of North America at decadal to millennial scales (Dean et al., 2002; Yu and Ito, 1999).

Here we present the first detailed Holocene paleotemperature reconstruction for eastern Canada using the oxygen isotope composition of plant cellulose ($\delta^{18}O_{cel}$). $\delta^{18}O_{cel}$ from *Sphagnum* stems from ombrotrophic Mer Bleue Bog near Ottawa are utilized to reconstruct the paleotemperature variability of the last ~9200 years and are compared with major Northern Hemisphere climate and solar insolation fluctuations (e.g. Bond et al., 2001; Moberg et al., 2005; Solanki et al., 2004). For the last 600 years the paleoclimate record from Mer Bleue Bog can be resolved with a precision of <20 years, which allows comparison with solar activity proxies and short-term climate events.

Previous work

Sphagnum-dominated ombrotrophic bogs as paleoclimate archives

Northern Hemisphere peatlands began developing during the early Holocene, ~9000 cal. BP, and are now widespread across North America and Eurasia (Gajewski et al., 2001). Peatlands are common in cool and moist regions where precipitation exceeds evaporation, but only a few of these systems are ombrotrophic. Ombrotrophic bogs lack groundwater influence and receive water and nutrients solely from precipitation. Anoxic and acidic conditions in ombrotrophic bogs reduce microbial decomposers and prevent the decomposition process (Clymo and Hayward, 1982). As a result, ombrotrophic bogs are considered excellent archives of paleoclimatic variation as shown through isotope-geochemical studies and paleoecological analysis (e.g. Booth and Jackson, 2003; Brenninkmeijer et al., 1982; Elliott et al., 2012).

Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Canada

Corresponding author:
Andreas Prokoph, Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada.
Email: aprokocon@aol.com

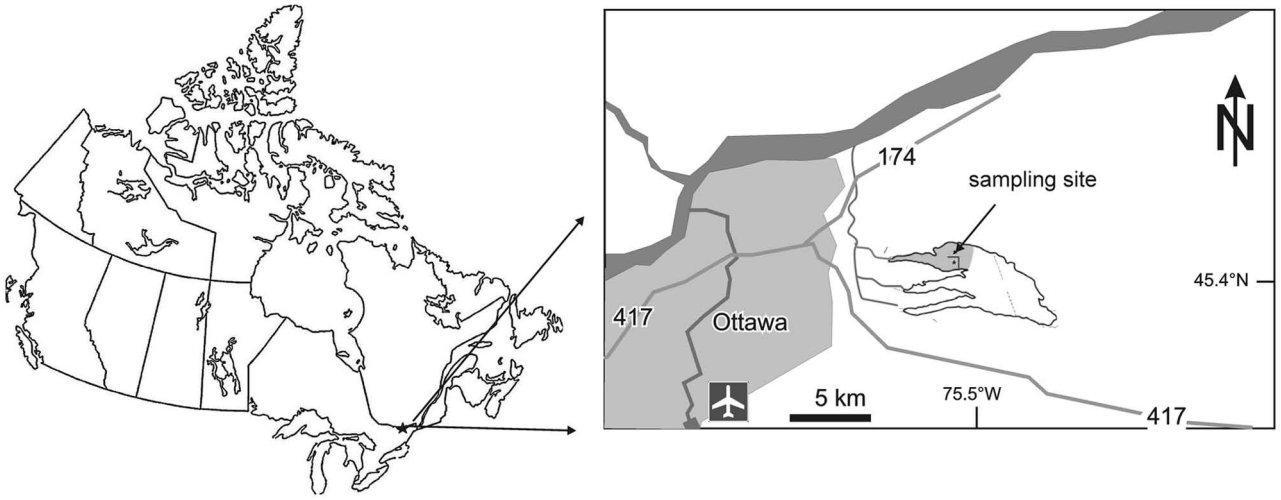

Figure 1. Location map of the Mer Bleue Bog, Ottawa, Ontario in eastern Canada. Asterisk marks the sampling site at the northwestern arm of Mer Bleue.

Previous paleoclimate studies have utilized stable isotope variability obtained from bulk peat (Ménot and Burns, 2001; Skrzypek et al., 2007) or stable isotope variability of the cellulose fraction of bulk peat (Hong et al., 2000, 2001). However, some of these studies have shown that $\delta^{18}O$ of bulk peat is quite variable, likely because of the mixture of non-vascular (*Sphagnum* mosses) and vascular plant remains (Brenninkmeijer et al., 1982; Ménot and Burns, 2001; Ménot-Combes et al., 2002).

Many peatlands in the mid to high latitudes are *Sphagnum*-dominated (Booth and Jackson, 2003; Brenninkmeijer et al., 1982). *Sphagnum* mosses decay very slowly and their structure may be preserved for thousands of years in bog environments. They are restricted to areas of high humidity and have short growth forms relative to other bryophytes (Taylor, 2008). Owing to the absence of stomata and vascular tissues, *Sphagnum* mosses possess limited ability to control water loss and all fractionation of the plant water is environmentally controlled prior to its assimilation and cellulose synthesis (Ménot-Combes et al., 2002). European bogs show significant oxygen isotope ratio differences between different bog plant genera in raised bogs (e.g. Moschen et al., 2009), but no significant differences between different *Sphagnum* species (Daley et al., 2010). A recent study on Mer Bleue Bog by El Bilali and Patterson (2012) showed that $\delta^{18}O_{cel}$ from *Sphagnum* is independent on the species analysed, but other plant matter is highly variable. This confirmed other studies (Daley et al., 2009, 2010; Taylor, 2008) indicating that *Sphagnum* cellulose stable isotope records from ombrotrophic bogs are the most reliable proxies for paleotemperature reconstructions from peat deposits.

Cellulose oxygen isotope composition, source water, and paleotemperature

Several studies have demonstrated a direct correlation between the isotopic oxygen composition of cellulose and mean annual temperature (DeNiro and Epstein, 1981; Epstein et al., 1977). Moreover, stable isotope composition of meteoric water at mid to high latitudes is strongly correlated with temperature and relative humidity, and meteoric water is often the source water for plant cellulose (Fricke and O'Neil, 1999; Rozanski et al., 1993). The relationship between cellulose oxygen isotope composition and that of the source water under several environmental conditions has been determined by Yapp and Epstein (1982) and Zanazzi and Mora (2005). For moist environments inhabited by *Sphagnum* where the relative humidity is close to 100% the relationship becomes:

$$\delta_{cell} = \delta_{sw} + \varepsilon_b \quad (1)$$

where δ_{cell} represents isotopic composition of cellulose, δ_{sw} represents the isotopic composition of the source water, and ε_b represents the biochemical enrichment factor (Clymo and Hayward, 1982; Zanazzi and Mora, 2005). Experimental measurements suggest that ε_b is equal to 27 ± 3‰ for oxygen (DeNiro and Epstein, 1981; Epstein et al., 1977).

Previous studies have reported the preservation of this evaporative-enrichment signal in the cellulose of surface *Sphagnum* relative to peat pore waters (Aravena and Warner, 1992; Brenninkmeijer et al., 1982). Whereas Daley (2007) reported that the data yielded a constant cellulose-precipitation fractionation factor (1.0274 ± 0.0010), statistically identical to the biochemical enrichment of oxygen isotopes during photosynthesis as determined by laboratory experiments (Sternberg et al., 1986) suggesting that evaporative enrichment in *Sphagnum* cellulose is minimal. Taylor (2008) also demonstrated that the oxygen isotopic composition of precipitation and in *Sphagnum* cellulose in ombrotrophic bogs at mid to high latitudes is highly correlated with growing-season temperature, providing additional evidence that evaporative fractionation is negligible.

Sampling and methods

Sample location and coring

The Mer Bleue Bog is located 10 km east of Ottawa, Ontario (Figure 1**)** within a now-abandoned postglacial channel of the Ottawa River that was eroded into the floor of the Champlain Sea basin. The peatland formed over the past 8400 years, initially as fen and transitioning to a bog 5000–7000 years ago (Auer, 1930; Roulet et al., 2007). The present-day Mer Bleue Bog is an ombrotrophic bog where plant growth occurs from the end of April to early October. The bog is slightly domed with a hummock–hollow microtopography. Peat thickness varies from 6 m near the center, decreasing to 0.3 m at the margins (Roulet et al., 2007). Sedimentation is entirely composed of autigenic plant matter, which is dominated by *Sphagnum* moss and cotton grasses.

A series of closely spaced Russian cores were collected in March 2008 (N45°24.653′, W75°31.064′) from the center of the Mer Bleue Bog near a previous coring location (Roulet et al., 2007) to a total depth of ~6 m, terminating at the top of Champlain Sea marine clay deposits (Figure 2). The core material consists of relatively fresh *Sphagnum* material through the uppermost

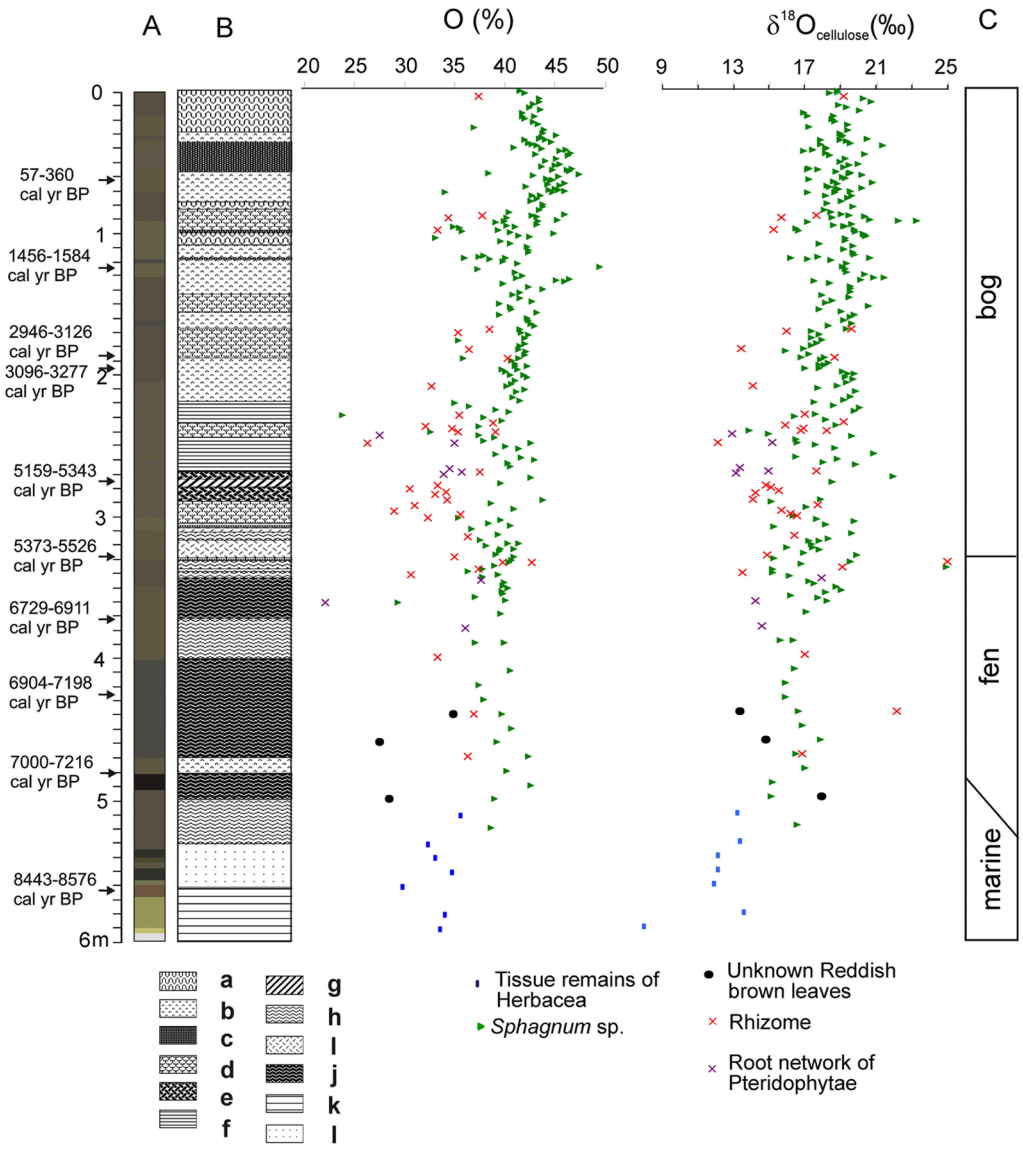

Figure 2. Mer Bleue core sedimentology, oxygen concentration and isotope data of cellulose from different plant material of the Mer Bleue Bog core. (A) Rock color code following Munsell Chart (Munsell, 1975) and calibrated age (Table 1). (B) Lithology, lithotypes: a: coarse-grained *Sphagnum*-dominated peat facies; b: *Sphagnum*-dominant peat facies; c: charcoal-rich peat facies; d: rhizome-dominant peat facies; e: rhizome-dominant peat facies with dark rootlets of pteridophytae; f: alternation of *Sphagnum* and rhizome-dominant peat facies; g: *Sphagnum*-dominant peat facies with dark rootlets of pteridophytae; h: rhizome-dominant peat facies with dark rootlets of pteridophytae and reddish brown leaves; i: *Sphagnum*-dominant peat facies with dark rootlets of pteridophytae and reddish brown leaves; j: dark rootlets of pteridophytae and reddish brown leaves dominant peat facies; k: marine clay dominant facies; l: tissue remains of Herbacea-dominant peat-clay mixed facies. (C) Depositional environments.

25 cm and decomposed *Sphagnum*-dominated peat from 25 cm to 500 cm depth that gradually changed to marine clay to the bottom of the core (Figure 2).

Sample preparation and isotope analysis

Samples from 1 cm thick core slices were gently heated in a 5% KOH solution for ~30 min to dissolve humic and fulvic acids. Plant macrofossil samples were then disaggregated using a 125 µm sieve and deionized water. For cellulose isotopic analyses, plant macrofossils, preferentially *Sphagnum* stems, were hand-picked from petri dishes, placed in porcelain crucibles and dried in an oven at about 50°C for 24 h. The samples were then powdered, weighed, labeled, and placed in small plastic vials.

Cellulose isotopic analyses were performed at the University of Saskatchewan isotope laboratories. Cellulose samples were baked at 60°C in a vacuum oven for 2 h to drive off moisture, then immediately transferred and flushed in the zero blank autosampler. Samples were analyzed using a Thermo Finnigan TC/EA coupled to a Conflo III and a Delta Plus XL mass spectrometer. Samples were dropped under helium into a glassy carbon furnace and pyrolyzed at 1450°C to form hydrogen and/or carbon monoxide gases. The gases were carried in a helium stream to a GC column held at 100°C to separate the gases before being diluted in the Conflo III and passed to the mass spectrometer for analysis. Isotope ratios were blank corrected and reported in per mil notation relative to the VSMOW-VSLAP scale.

In-house oxygen standards were calibrated against international standards USGS-34 ($\delta^{18}O = -27.9‰$ VSMOW) and USGS-35 ($\delta^{18}O$ = 57.5‰ VSMOW). An intermediate international standard, IAEA-NO3, gave the result $\delta^{18}O$ = 25.53 ± 0.27‰ VSMOW (n = 23) during calibration of in-house standards and compared with the accepted value of $\delta^{18}O$ = 25.6 ± 0.4‰ VSMOW. For the $\delta^{18}O$ data the accuracy was ±0.11‰ (n = 25) and for %O measurements the accuracy was ±0.5%.

Table 1. Mer Bleue ^{14}C samples.

Sample ID	Depth (cm)	Material	^{14}C age (BP)	pMC	AD/BC	Cal. ages (95.4%)			Cal. ages (95.4%)			Cal. ages (95.4%)		
						min	max	prob	min	max	prob	min	max	prob
MB16	32–33	peat	Post-bomb	125.44± 0.29										
MB22	44–45	peat	Post-bomb	108.4± 0.24										
MB23	46–47	peat	Post-bomb	144.39± 0.41										
MB31	62–63	peat	204 ± 28	97.49± 0.34	AD	1648	1684	0.291	1734	1806	0.554	1930	1951	0.155
MB61	122–123	peat	1566 ± 26	82.29± 0.27	AD	424	552	1.000						
MB93	186–187	peat	2860 ± 22	70.05± 0.19	BC	1118	973	0.939	958	938	0.061			
MB99	198–199	peat	2959 ± 22	69.18± 0.19	BC	1269	1112	0.982	1100	1085	0.013	1064	1058	0.005
MB137	274–275	peat	4449 ± 32	57.47± 0.23	BC	3335	3210	0.418	3192	3151	0.080	3138	3010	0.470
MB163	326–327	peat	4659 ± 31	55.99± 0.22	BC	3518	3365	1.000						
MB185	370–371	peat	5934 ± 33	47.77± 0.2	BC	4903	4864	0.107	4856	4721	0.893			
MB210	420–421	peat	6070± 30	47± 0.17	BC	5190	5185	0.004	5057	4896	0.97	4867	4851	0.025
MB240	480–481	peat	6130± 30	46.62± 0.18	BC	5208	4992	1.000						
MB280	560–561	peat	7640± 30	38.63± 0.14	BC	6568	6544	0.065	6531	6435	0.935			

Radiocarbon dating

Thirteen samples were chosen for radiocarbon AMS dating. Nine samples were analysed at the CHRONOS laboratories at Queens University of Belfast and four samples were analysed at the AMS laboratory at the University of Georgia. Great care was thus taken when subsampling for ^{14}C dating, because ^{14}C dates obtained from bulk peat samples are sometimes affected by the reservoir effect and time-averaging due to sample heterogeneity and contamination from younger plant material (e.g. Goslar et al., 2005). Roots and twigs were also removed from the samples. The ^{14}C dates were calibrated using the computer program CALIB5.0.2 using the Intcal04 ^{14}C calibration data set (Reimer et al., 2004) as shown in Table 1.

Results

Cellulose oxygen isotope composition in depth

Cellulose $\delta^{18}O$ values obtained for plant macrofossils indicate different isotopic signatures between *Sphagnum* species and other plant macrofossils analysed such as rhizomes, red leaves, and root networks of pteridophytae (Table 2, Figure 2) that were studied for isotopic differences between plant types by El Bilali and Patterson (2012). A new set of *Sphagnum* $\delta^{18}O$ values was added (Table 2) to increase sampling resolution and improve confidence by repeated analysis for detection of extreme paleotemperature intervals.

The cellulose $\delta^{18}O$ values of plant macrofossils analysed ranged from ~8‰ for tissue remains of herbacae at 590 cm depth to ~26‰ for rhizomes at 334 cm depth. $\delta^{18}O_{cel}$ values of *Sphagnum* vary from ~ 25‰ at 338 cm depth to ~14‰ at 242 cm depth with a general decreasing trend from ~19‰ at 20 cm depth to ~16‰ at ~520 cm depth (Figure 2). Plant cellulose oxygen concentrations range from ~20% to 50% through the 6 m section. As observed with the isotopic values, the oxygen concentrations decreased with core depth and were generally higher in *Sphagnum* compared with other plant macrofossils (Figure 2).

Mer Bleue Bog age–depth model

The age–depth model of the Mer Bleue Bog core was constructed using exponential, linear and polynomial regression functions that reflect different stages of peat decomposition, and gradual to abrupt changes in the depositional environment through the last ~ 9200 years (Figure 3). The age model utilized the ten calibrated mean ages, an estimated palynological age of ~AD 1860 for first *Ambrosia* appearance in this area (Talbot et al., 2010) detected in sample interval of 52–53 cm (S Elliott, personal communication, 2010) and the 0 yr BP (=AD 1950) intercept at the top. The obtained ^{14}C dates for three samples from near the top of the core (Table 1) were not used for the model because they have nuclear bomb testing signatures. The 2-sigma confidence interval of the age model was determined from error propagation from age uncertainty of the individual calibrated radiocarbon samples and the uncertainty of the best-fit function.

As suggested by Frolking et al. (2010) for this bog, an exponential decay model is applied until a depth of 73.5 cm, were the peat is fully compacted. Below 73.5 cm a linear-polynominal age model was constructed in two parts separated at 327 cm where the abrupt change from fen to bog deposition occurred (Figure 3). The age of 9112 ± 70 cal. BP at the peat/clay transition at ~590 cm is in accordance with the model age obtained by Frolking et al. (2010).

Cellulose oxygen isotope composition in time

The transformation of the isotope record from a depth to time scale results in an average sampling interval of ~50 years from ~80 to 7300 cal. BP, a much higher sampling resolution through the most recent 80 years, and a less frequent ~200 years sampling interval through the interval of the core deposited from ~7300 to 9200 cal. BP (Figure 4B). The oxygen isotope record reveals a general trend toward heavier isotopic compositions from ~7300 cal. BP to present as well as several multicentennial to millennial fluctuations with >1‰ amplitude (Figure 4B). The record appears relatively constant with only a few >1‰ deviations from the average through the last 2800 years. The cellulose $\delta^{18}O$ record contains low-value excursions with minima at ~4200, 2800, and 1300 cal. BP that are verified by high-resolution and/or repeated sampling (Table 2). Relatively low cellulose $\delta^{18}O$ values at Mer Bleue through these intervals were found to coincide with global and North Atlantic climate cooling intervals (Bond et al., 1997; Viau et al., 2006), glacier advances and high ice-rafted sediment indices (Bond et al., 2001) (Figure 4C–E).

The Mer Bleue Bog $\delta^{18}O_{cel}$ record deposited through the last 2000 years shows a good correlation with the Northern Hemisphere temperature reconstruction of Moberg et al. (2005). There is a particularly good correlation between the record at Mer Bleue Bog and the timing of most major warming and cooling events (Figure 5). The record for the modern warm period and 'Little Ice Age' present an exception though as the amplitude of the modern warming maximum and the signature of 'Little Ice Age' are weaker in the Mer Bleue Bog

Table 2. Oxygen isotope ratio and oxygen concentration of plant cellulose from Mer Bleue Bog, Ottawa, Ontario.

Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	#	Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	#
1yss	2	41.4	18.81	*S. capillifolium*	1	93bss	186	42.0	15.86	*S. fuscum*	1
2yss	4	42.0	18.32	*S. capillifolium*	1	94bss	188	41.9	17.18	*S. fuscum*	1
3r	6	37.3	19.14	Rhizome	1	95yss	190	41.3	18.09	*S. capillifolium*	1
4yss	8	43.3	20.22	*S. capillifolium*	1	95bss	190	35.8	16.74	*S. fuscum*	1
5yss	10	43.4	20.64	*S. capillifolium*	1	95r	190	40.2	18.66	Rhizome	1
6yss	12	42.7	18.88	*S. capillifolium*	1	96bss	192	40.6	17.82	*S. fuscum*	1
7yss	14	42.4	19.28	*S. capillifolium*	1	97bss	194	41.0	18.29	*S. fuscum*	1
8yss	16	43.4	20.05	*S. capillifolium*	1	98bss	196	42.2	18.06	*S. fuscum*	1
9yss	18	41.7	16.91	*S. capillifolium*	1	98yss	196	41.0	17.74	*S. capillifolium*	1
10yss	20	41.7	17.13	*S. capillifolium*	1	99bss	198	41.2	17.80	*S. fuscum*	1
10bss	20	42.9	18.58	*S. fuscum*	1	99yss	198	39.7	16.94	*S. capillifolium*	1
11yss	22	41.9	18.48	*S. capillifolium*	1	100	200	40.0	19.11	*S. fuscum*	1
12yss	24	42.8	18.64	*S. capillifolium*	1	101dbss	202	41.8	19.36	*S. magellanicum*	1
13yss	26	43.2	19.34	*S. capillifolium*	1	101 dbss repeat	202	40.5	19.72	*S. magellanicum*	1
14yss	28	36.8	17.17	*S. capillifolium*	1	102bss	204	42.1	19.18	*S. fuscum*	1
15yss	30	43.8	19.36	*S. capillifolium*	1	103dbss	206	40.9	19.68	*S. magellanicum*	1
16yss	32	43.7	18.95	*S. capillifolium*	1	104bss	208	40.6	19.26	*S. fuscum*	1
17yss	34	45.1	19.08	*S. capillifolium*	1	105bss	210	40.1	18.79	*S. fuscum*	1
Sb1yss	35	43.6	18.99	*S. capillifolium*	1	105r	210	32.7	14.05	Rhizome	1
18yss	36	43.4	20.43	*S. capillifolium*	1	106bss	212	41.9	17.72	*S. fuscum*	1
Sb2yss	37	44.0	17.82	*S. capillifolium*	1	107dbss	214	41.1	19.81	*S. magellanicum*	1
Sb2bss	37	41.9	18.94	*S. fuscum*	1	109bss	218	40.7	19.53	*S. angustifolium*	1
19yss	38	44.5	19.32	*S. capillifolium*	1	110bss	220	41.4	19.11	*S. fuscum*	1
Sb3bss	39	42.3	19.49	*S. fuscum*	1	111bss	222	35.0	17.49	*S. fuscum*	1
20bss	40	42.6	17.88	*S. fuscum*	1	112bss	224	36.4	18.56	*S. fuscum*	1
Sb4yss	41	43.1	21.32	*S. capillifolium*	1	113Lbss	226	39.1	20.00	*S. angustifolium*	1
21yss	42	40.8	18.13	*S. capillifolium*	1	114bss	228	40.3	19.74	*S. fuscum*	1
Sb5yss	43	43.6	18.15	*S. capillifolium*	1	115bss	230	23.7	17.55	*S. fuscum*	1
22yss	44	46.0	17.41	*S. capillifolium*	1	115r	230	35.4	16.95	Rhizome	1
Sb6yss	45	45.4	16.89	*S. capillifolium*	1	116bss	232	37.9	16.43	*S. fuscum*	1
23yss	46	46.6	18.13	*S. capillifolium*	1	117bss	234	39.6	18.16	*S. fuscum*	1
Sb7yss	47	43.0	20.28	*S. capillifolium*	1	118r	236	38.7	19.14	Rhizome	1
24yss	48	46.2	18.36	*S. capillifolium*	1	119r	238	32.0	15.86	Rhizome	1
25yss	50	45.1	19.18	*S. capillifolium*	1	119bss	238	37.3	18.70	*S. fuscum*	1
26yss	52	44.0	18.92	*S. capillifolium*	1	120r	240	34.7	16.88	Rhizome	1
27yss	54	45.4	19.97	*S. capillifolium*	1	121r	242	35.3	16.77	Rhizome	1
27.5yss	55	44.9	19.40	*S. capillifolium*	1	121r repeat	242	39.1	18.18	Rhizome	1
28yss	56	43.6	19.15	*S. capillifolium*	1	121dbss	242	32.5	13.89	*S. magellanicum*	1
28.5yss	57	46.6	17.21	*S. capillifolium*	1	122DS	244	27.5	12.92	Root networks of Pteridophytae	1
29yssRE	58	46.2	17.71	*S. capillifolium*	1	122dbss	244	37.3	14.92	*S. magellanicum*	1
29yss	58	44.7	17.09	*S. capillifolium*	1	123dbss	246	39.0	19.54	*S. magellanicum*	1
29.5yss	59	46.3	18.68	*S. capillifolium*	1	124dbss	248	37.9	16.46	*S. magellanicum*	1
30yss	60	38.3	19.47	*S. capillifolium*	1	125r	250	34.9	15.19	Rhizome	1
30.5yss	61	47.3	19.43	*S. capillifolium*	1	125DS	250	26.3	12.11	Root networks of Pteridophytae	1
31yss	62	42.8	20.15	*S. capillifolium*	1	125bss	250	42.5	16.56	*S. fuscum*	1
31.5yss	63	45.4	19.06	*S. capillifolium*	1	126dbss	252	40.0	17.58	*S. magellanicum*	1
32bss	64	44.1	19.23	*S. fuscum*	1	127dbss	254	41.3	18.67	*S. magellanicum*	1
32.5yss	65	44.8	17.17	*S. capillifolium*	1	129dbss	258	39.0	20.83	*S. magellanicum*	1
33bss	66	44.5	18.57	*S. fuscum*	1	130dbss	260	41.6	16.47	*S. magellanicum*	1
33.5yss	67	45.9	20.75	*S. capillifolium*	1	131dbss	262	42.9	18.82	*S. magellanicum*	1
34bss	68	44.3	18.78	*S. fuscum*	1	132dbss	264	40.2	17.98	*S. magellanicum*	1
34ayss	69	45.5	18.24	*S. capillifolium*	1	133dbss	266	40.5	19.78	*S. magellanicum*	1
35bss	70	42.0	18.34	*S. fuscum*	1	134DS	268	34.5	13.33	Root networks of Pteridophytae	1
35ayss	71	45.0	20.17	*S. capillifolium*	1	135DS	270	35.6	14.95	Root networks of Pteridophytae	1
36bss	72	45.3	18.74	*S. fuscum*	1	135r	270	37.4	17.63	Rhizome	1
36dbss	72	44.3	18.86	*S. magellanicum*	1	136DS	272	33.9	13.11	Root networks of Pteridophytae	1

(Continued)

Table 2. (Continued)

Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	#	Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	
36ayss	73	45.9	19.52	*S. capillifolium*	1	137dbss	274	42.5	21.92	*S. magellanicum*	1
37dbss	74	44.7	18.61	*S. magellanicum*	1	139dbss	278	39.6	18.46	*S. magellanicum*	1
37bss	74	34.0	17.11	*S. fuscum*	1	139r	278	lost	lost	Rhizome	1
38dbss	76	42.7	19.57	*S. magellanicum*	1	140r	280	33.3	14.80	Rhizome	1
38bss	76	43.5	18.16	*S. fuscum*	1	141r	282	30.5	15.08	Rhizome	1
39bss	78	43.1	19.36	*S. fuscum*	1	142r	284	34.1	15.54	Rhizome	1
40bss	80	42.5	18.97	*S. fuscum*	1	143r	286	33.0	14.26	Rhizome	1
41bss	82	43.8	18.21	*S. fuscum*	1	145r	290	34.2	14.06	Rhizome	1
42bss	84	43.7	19.68	*S. fuscum*	1	145bss	290	43.7	17.82	*S. fuscum*	1
43bss	86	43.3	18.09	*S. fuscum*	1	146dbss	292	38.6	15.11	*S. magellanicum*	1
44bss	88	40.4	18.45	*S. fuscum*	1	147r	294	30.9	17.71	Rhizome	1
44.5yss	89	45.9	19.31	*S. capillifolium*	2	148dbss	296	40.8	17.03	*S. magellanicum*	1
45r	90	37.7	17.60	Rhizome	1	149r	298	28.9	15.67	Rhizome	1
45Lbss	90	42.7	19.43	*S. angustifolium*	1	150r	300	35.6	16.20	Rhizome	1
45.5yss	91	43.1	20.27	*S. capillifolium*	2	151r	302	32.3	16.56	Rhizome	1
46bss	92	40.1	18.49	*S. fuscum*	1	151dbss	302	35.3	16.34	*S. magellanicum*	1
46r	92	34.3	15.65	Rhizome	1	152dbss	304	39.5	17.63	*S. magellanicum*	1
46.5yss	93	45.2	20.56	*S. capillifolium*	2	153dbss	306	38.3	19.71	*S. magellanicum*	1
47bss	94	39.9	23.21	*S. fuscum*	1	154dbss	308	40.5	18.16	*S. magellanicum*	1
47yss	94	43.3	22.25	*S. capillifolium*	2	155dbss	310	36.6	15.27	*S. magellanicum*	1
47.5yss	95	39.0	17.14	*S. capillifolium*	2	157dbss	314	39.2	19.54	*S. magellanicum*	1
48yss	96	43.1	19.56	*S. capillifolium*	1	158r	316	36.2	16.40	Rhizome	1
48.5yss	97	40.1	18.61	*S. capillifolium*	2	159dbss	318	37.4	18.25	*S. magellanicum*	1
49bss	98	34.8	19.18	*S. fuscum*	1	160bss	320	40.2	17.75	*S. fuscum*	1
49yss	98	41.0	19.23	*S. capillifolium*	1	160dbss	320	41.3	17.21	*S. magellanicum*	1
49.5yss	99	35.4	16.54	*S. capillifolium*	2	161dbss	322	38.1	17.34	*S. magellanicum*	1
50r	100	33.3	15.22	Rhizome	1	162dbss	324	40.9	15.97	*S. magellanicum*	1
50yss	100	39.3	19.73	*S. capillifolium*	1	162bss	324	39.6	17.38	*S. fuscum*	1
50.5yss	101	35.7	16.58	*S. capillifolium*	2	163dbss	326	39.4	17.76	*S. magellanicum*	1
51bss	102	40.5	19.80	*S. fuscum*	1	164bss	328	39.0	16.89	*S. fuscum*	1
51.5yss	103	44.8	20.16	*S. capillifolium*	2	165r	330	35.0	14.89	Rhizome	1
52bss	104	41.4	20.27	*S. fuscum*	1	165bss	330	40.8	19.89	*S. fuscum*	1
52.5yss	105	42.4	20.42	*S. capillifolium*	2	166bss	332	40.6	15.26	*S. fuscum*	1
53dbss	106	33.0	19.21	*S. magellanicum*	1	167r	334	42.6	24.96	Rhizome	1
54dbss	108	39.5	19.22	*S. magellanicum*	1	167 r repeat	334	39.8	25.18	Rhizome	1
55Lbss	110	40.5	17.76	*S. angustifolium*	1	167bss	334	40.4	19.51	*S. fuscum*	1
56yss	112	42.1	19.65	*S. capillifolium*	1	168bss	336	38.9	16.79	*S. fuscum*	1
57bss	114	42.3	19.12	*S. fuscum*	1	169r	338	37.4	19.06	Rhizome	1
58yss	116	42.2	19.68	*S. capillifolium*	1	169bss	338	37.7	24.82	*S. fuscum*	1
59bss	118	37.8	19.70	*S. fuscum*	1	170syss	340	36.3	15.13	*S. papillosum*	1
59.5yss	119	37.4	17.66	*S. capillifolium*	2	171r	342	30.6	13.53	Rhizome	1
60bss	120	35.9	16.20	*S. fuscum*	1	171syss	342	39.3	15.17	*S. papillosum*	1
60yss	120	40.0	20.62	*S. capillifolium*	2	172syss	344	37.7	16.08	*S. papillosum*	1
60.5yss	121	38.4	17.15	*S. capillifolium*	2	173DS	346	37.5	17.88	Root networks of Pteridophytae	1
61bss	122	39.8	18.44	*S. fuscum*	1	174dbss	348	39.9	17.23	*S. magellanicum*	1
62bss	124	41.2	19.32	*S. fuscum*	1	175bss	350	39.8	17.51	*S. fuscum*	1
63bss	126	49.3	19.06	*S. fuscum*	1	176dbss	352	40.3	18.71	*S. magellanicum*	1
64yss	128	37.2	19.23	*S. capillifolium*	1	177dbss	354	39.7	18.99	*S. magellanicum*	1
65Lbss	130	40.9	19.31	*S. angustifolium*	1	178dbss	356	39.8	18.14	*S. magellanicum*	1
66yss	132	41.7	20.29	*S. capillifolium*	1	179dbss	358	37.0	16.21	*S. magellanicum*	1
67yss	134	41.1	21.42	*S. capillifolium*	1	180dbss	360	40.0	17.69	*S. magellanicum*	1
67.2yss	134.4	46.4	20.83	*S. capillifolium*	2	181DS	362	22.1	14.24	Root networks of Pteridophytae	1
67.8yss	135.6	45.1	20.08	*S. capillifolium*	2	181dbss	362	29.3	18.18	*S. magellanicum*	1
68yss	136	45.9	17.47	*S. capillifolium*	1	185bss	370	39.5	17.08	*S. fuscum*	1
69yss	138	39.8	18.37	*S. capillifolium*	1	190DS	380	36.1	14.59	Root networks of Pteridophytae	1
70yss	140	42.3	19.49	*S. capillifolium*	1	195bss	390	39.9	16.33	*S. fuscum*	1
71bss	142	43.7	19.50	*S. fuscum*	1	195dbss	390	37.0	15.63	*S. magellanicum*	1
72yss	144	41.5	19.50	*S. capillifolium*	1	200r	400	33.3	16.97	Rhizome	1
73bss	146	40.7	17.95	*S. fuscum*	1	205dbss	410	40.5	16.39	*S. magellanicum*	1
74bss	148	41.4	19.42	*S. fuscum*	1	210bss	420	37.4	15.88	*S. fuscum*	1
75bss	150	42.6	18.50	*S. fuscum*	1	215bss	430	37.8	15.91	*S. fuscum*	1

Table 2. (Continued)

Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	#	Sample ID	Depth (cm)	%O	$\delta^{18}O$ (‰,VSMOW)	Macrofossils taxa	#
76bss	152	39.5	18.16	*S. fuscum*	1	220 r	440	36.9	22.08	Rhizome	1
77bss	154	40.5	20.52	*S. fuscum*	1	220rbl	440	34.8	13.38	Unknown Reddish-brown leaves	1
78bss	156	40.6	17.80	*S. fuscum*	1	220dbss	440	39.7	16.65	*S. magellanicum*	1
79bss	158	43.1	19.02	*S. fuscum*	1	225bss	450	40.6	16.85	*S. fuscum*	1
80bss	160	39.4	19.69	*S. fuscum*	1	230bss	460	39.2	17.85	*S. fuscum*	1
81yss	162	42.1	19.50	*S. capillifolium*	1	230rbl	460	27.4	14.77	Unknown Reddish-brown leaves	1
82bss	164	42.2	19.15	*S. fuscum*	1	235dbss	470	42.3	16.49	*S. magellanicum*	1
83bss	166	42.5	19.56	*S. fuscum*	1	235r	470	36.3	16.83	Rhizome	1
84bss	168	43.0	18.30	*S. fuscum*	1	240bss	480	40.2	16.99	*S. fuscum*	1
85yss	170	41.5	19.28	*S. capillifolium*	1	245bss	490	42.5	15.17	*S. fuscum*	1
85r	170	38.4	19.61	Rhizome	1	250rbl	500	28.4	17.88	Unknown Reddish-brown leaves	1
86r	172	35.3	15.93	Rhizome	1	250dbss	500	39.0	15.08	*S. magellanicum*	1
86yss	172	41.6	17.34	*S. capillifolium*	1	255trh	510	35.5	13.19	Tissue remains of Herbacea	1
87yss	174	42.3	17.78	*S. capillifolium*	1	260bss	520	38.6	16.56	*S. fuscum*	1
88yss	176	42.0	17.37	*S. capillifolium*	1	265trh	530	32.2	13.37	Tissue remains of Herbacea	1
89bss	178	35.3	17.94	*S. fuscum*	1	270trh	540	33.0	12.15	Tissue remains of Herbacea	1
90bss	180	41.9	17.61	*S. fuscum*	1	275trh	550	34.7	12.10	Tissue remains of Herbacea	1
91bss	182	41.4	17.36	*S. fuscum*	1	280trh	560	29.8	11.94	Tissue remains of Herbacea	1
92bss	184	41.4	16.90	*S. fuscum*	1	290trh	580	34.0	13.55	Tissue remains of Herbacea	1
92r	184	36.4	13.47	Rhizome	1	295trh	590	33.5	7.99	Tissue remains of Herbacea	1

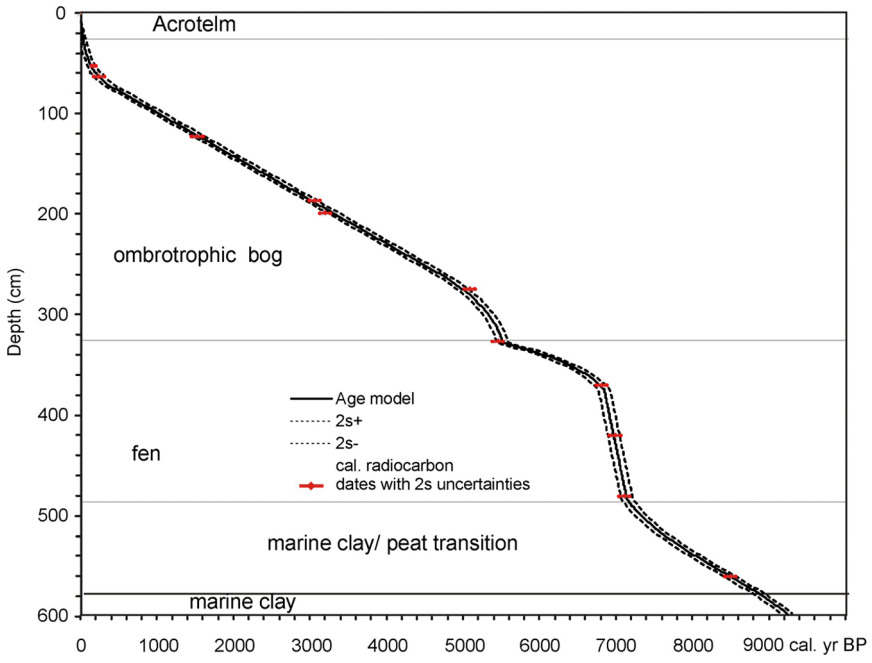

Figure 3. Mer Bleue core age–depth model and main depositional stages, based on ten AMS radiocarbon ages, first occurrence of Ambrosia pollen (AD 1860 at 52–53 cm sample depth), and an intercept with 0 m depth at October 2007. The top 25 cm consisted of poorly decayed and weakly compacted *Sphagnum*-dominated plant material in the oxic zone (Acrotelm).

record when compared against the entire Northern Hemisphere record suggesting, as has been observed, that 20th-century warming was not as great as some other areas (Prokoph and Patterson, 2004). In contrast the $\delta^{18}O_{cel}$ values obtained from the Mer Bleue Bog record that correspond to the 'Medieval Warm Period' are higher than recorded through most of the

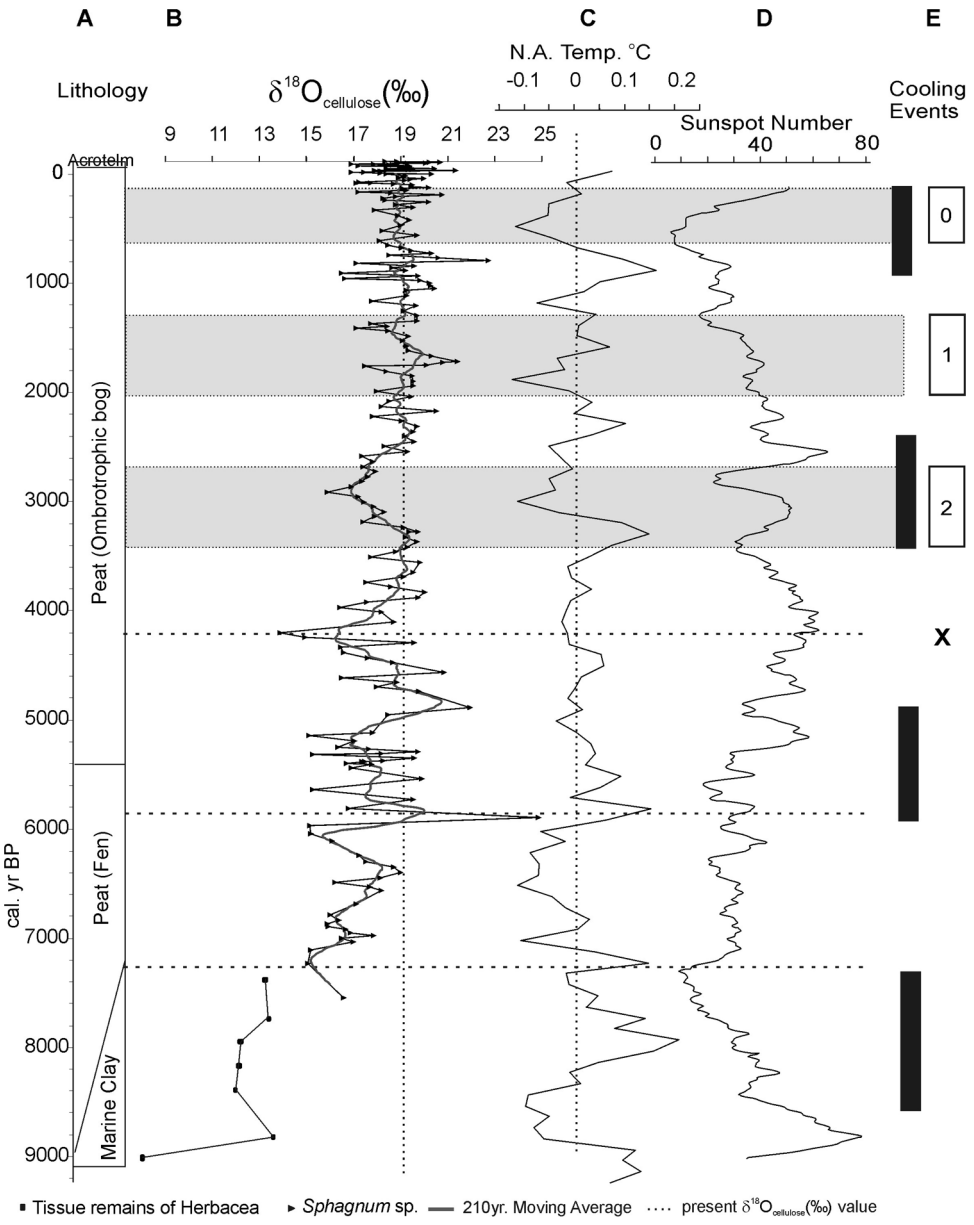

Figure 4. Oxygen isotope record of cellulose from Mer Bleue Bog through the last 9200 years. (A) Depositional environment, (B) oxygen isotope record of cellulose with mean and 210 yr moving average, (C) Reconstructed North American July temperature from pollen record (Viau et al., 2006), (D) reconstructed sunspot record (Solanki et al., 2004) at 210 yr moving average, (E) global glacier advances (black bars) and high drift ice indices (0, 1, 2) after Bond et al. (2001). X: ~4200 cal. BP cooling in North Atlantic (Bond et al., 1997).

modern maximum, suggesting that the climate in eastern Ontario was on average warmer during the 'Medieval Warm Period' (~1000 cal. BP) than at present. The Mer Bleue Bog temporal $\delta^{18}O_{cel}$ record generally correlates with the Beryllium (^{10}Be) isotope anomaly, sunspot number, and solar variation events records. The Maunder minima and maximum cooling is less pronounced in the $\delta^{18}O_{cel}$ data than in the Northern Hemisphere reconstructed paleotemperature record (Moberg et al., 2005), which may be due to less pronounced cooling in eastern Ontario. The $\delta^{18}O_{cel}$ record from Mer Bleue Bog shows a good correlation with the smoothed ^{10}Be-record (Figure 6a, b). The low $\delta^{18}O_{cel}$ values at ~AD 1810–1820 are verified by repeated and high-resolution sampling (Table 2) and may be related to the lower solar activity during the Dalton Minimum (Figure 6), to the cooling influence of the Tambora volcanic eruption for the summer of AD 1816 and subsequent years, or both.

Discussion

Influences on $\delta^{18}O_{cel}$ signature in ombrotrophic bogs

The present-day global mean $\delta^{18}O_{cel}$ value for *Sphagnum* is 19‰ (Daley et al., 2010), which corresponds to our results from this study. In addition, there is a good correlation between our paleotemperature reconstruction for eastern Ontario through the last 2000 years and the Northern Hemisphere reconstructed paleotemperature record (Moberg et al., 2005). Such correlations have been more difficult to establish in other areas owing to a lack of long records or as a result of different climate settings.

In the maritime realm of northwest Europe, precipitation plays a much more important role than temperature on bog surface wetness (BSW) (Charman et al., 2004; Daley et al., 2010), because shifts in air mass trajectories during the growing season strongly influence BSW, which drives stable isotope variations in

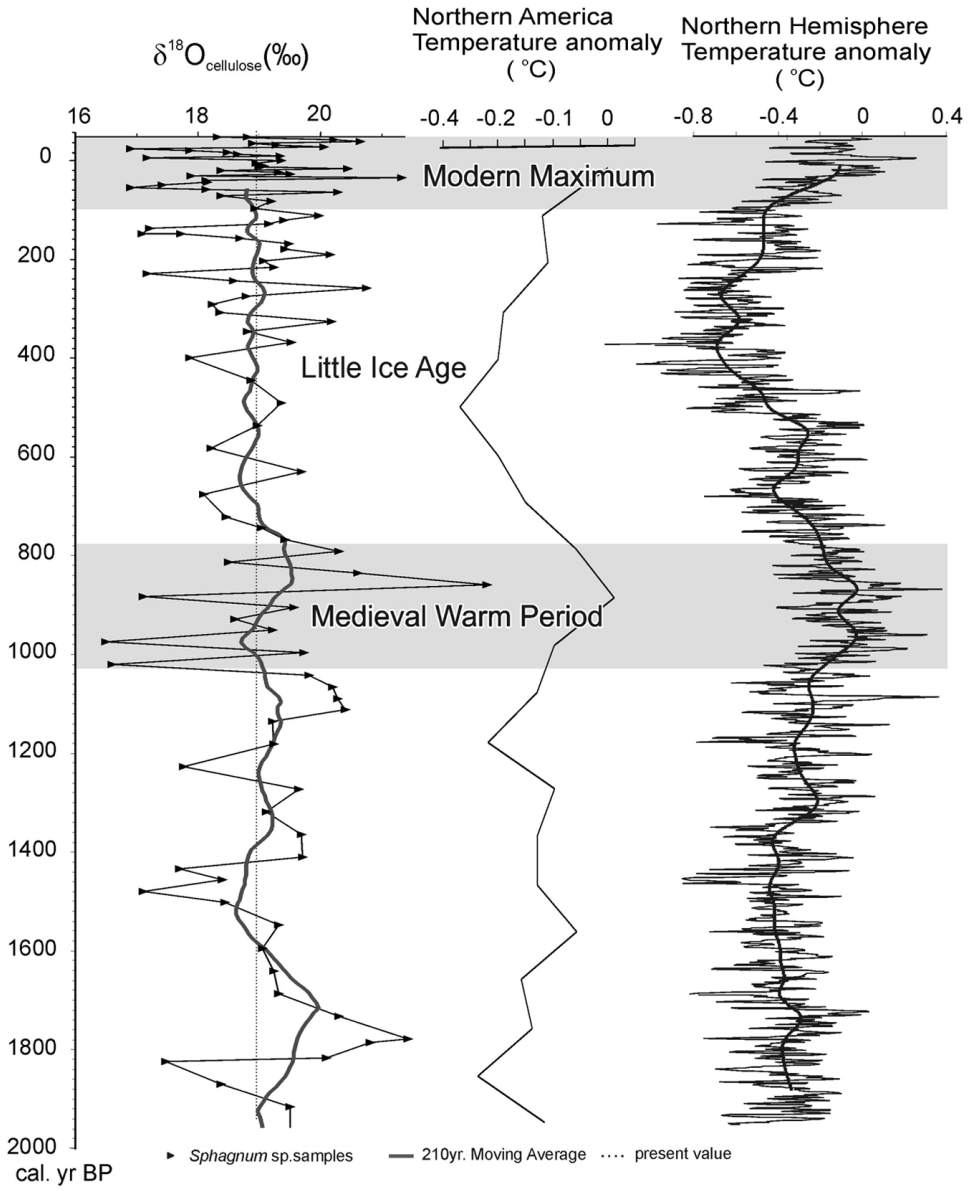

Figure 5. Comparison of isotope record of cellulose from Mer Bleue Bog with the North American and Northern Hemisphere temperature difference to present (in °C) by Viau et al. (2006) and Moberg et al. (2005) through last 2000 years. Gray-shaded area marks the 'Medieval Warm Period'.

Sphagnum peat in these areas (Daley et al., 2010). The effects of high summer temperature, variable precipitation (including periodic droughts) and related water-table height are preserved in eastern Canadian ombrotrophic bogs by a lateral variation in the peat types across bog surfaces.

Mer Bleue Bog shows a much higher variability in both *Sphagnum* accumulation and decomposition rates because of significant year-over-year variability in summer conditions, characteristic for continental climatic zones (see Figure 7, and Roulet et al., 2007) than in the raised bogs in northwest Europe (Charman et al., 2004; Daley et al., 2010). However, observed stratigraphic variation in *Sphagnum* cellulose $\delta^{18}O$ are not significantly influenced by accumulation rate changes (Figures 3 and 4) supporting the hypothesis that the $\delta^{18}O_{cel}$ record at Mer Bleue Bog predominantly represents temporal paleotemperature variation as opposed to geographic, plant physiological or hydrological variations related to precipitation.

$\delta^{18}O_{cel}$ as a paleotemperature proxy

Based on recent paleotemperature reconstructions it has been estimated that there was an ~1°C difference in the mean decadal temperature between the temperature minimum during the coldest part of the 'Little Ice Age', which occurred in the early 17th century and the 'Medieval Warm Period' temperature maximum at ~AD 1000 (e.g. Mann et al., 2008; Moberg et al., 2005). When compared with the range of $\delta^{18}O_{cel}$ values in this study through the same intervals (Figure 6) there is a calibration ratio of ~2‰/°C for temperature reconstructions using *Sphagnum* cellulose. Furthermore comparison of instrumental temperature and $\delta^{18}O_{preciptiation}$ records from Ottawa Airport weather station from ~1938 to 2007 with the $\delta^{18}O_{cel}$ values from Mer Bleue Bog suggest that there is a strong relationship between air temperature and $\delta^{18}O$ (Figure 7). The $\delta^{18}O_{cel}$ values through this interval correlate better with growing season temperatures than with mean annual air temperature, demonstrating that there is a strong empirical foundation for application of the $\delta^{18}O_{cel}$ proxy (Figure 7) at a calibration ratio of ~2‰/°C as also found in the long-term record (Figure 6).

A ~4‰ variation in *Sphagnum*-derived $\delta^{18}O_{cel}$ values through the last 4000 years and ~2‰ variation through the last 2000 years has also been confirmed by analysis of European ombrotrophic bog sections (Daley et al., 2010). A higher amplitude $\delta^{18}O_{cel}$ flux

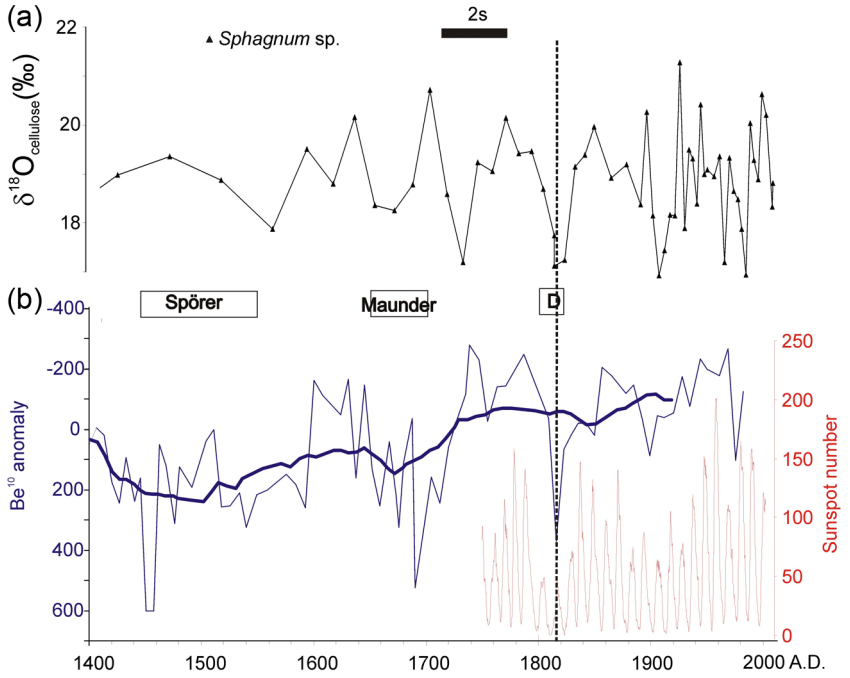

Figure 6. Comparison of isotope record of cellulose of Mer Bleue Bog through the last 600 years with (a) solar activity events Spörer, Maunder and Dalton minima and (b) Beryllium isotope anomaly (Bard et al., 2000) and measured sunspot numbers from the last 250 years. The vertical dashed line marks AD 1816.

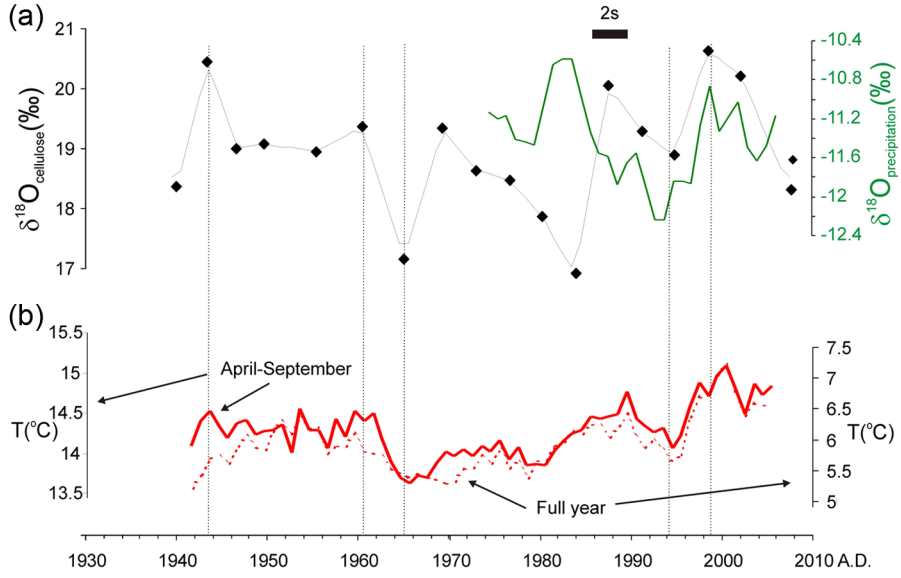

Figure 7. Comparison of instrumental air temperature and $\delta^{18}O_{precipitation}$ records from Ottawa Airport Weather station from ~1938 to 2007 with the $\delta^{18}O_{cel}$ values from the Mer Bleue Bog (Environment Canada, 2010; Global Network of Isotopes in Precipitation (GNIP/ISOHIS), 2001).

was also reported in paleotemperature reconstructions based on Chinese peat bogs, but these studies employed cellulose derived from a variety of plant types (Hong et al., 2000, 2001).

The $\delta^{18}O_{cel}$ fluctuations within the Mer Bleue Bog core are much higher in the uppermost ~60 cm of the section than below. Obtaining a reliable $\delta^{18}O_{cel}$ record through the top of the core was difficult as the uncompressed samples from the upper part of the core often correspond to monthly growth records, or short-lived weather fluctuations, which get averaged out in the more homogenized sections of the core lower down. The youngest relatively consistent low $\delta^{18}O_{cel}$ interval is recognizable through the 1970s (Figure 7), which corresponds to an interval of lower temperatures in eastern Ontario (Prokoph and Patterson, 2004).

The paleotemperature reconstruction based on *Sphagnum* $\delta^{18}O_{cel}$ from the ombrotrophic section of the Mer Bleue Bog could be considered more reliable than from the fen part of the bog below 320 cm. In the fen, plants receive their water not only from precipitation but also from groundwater and surface runoff. However, *Sphagnum* does not have roots and therefore its growth is upward from the apex only (Goslar et al., 2005). This means that there is less opportunity for the *Sphagnum* in the center of the bog to derive water from groundwater or surface runoff. Indeed, most paleoclimate reconstructions seem to interpret their *Sphagnum* $\delta^{18}O_{cel}$ record irrespective of the depositional environment (fen or ombrotrophic section) (Daley et al., 2009, 2010; Taylor, 2008). In addition the *Sphagnum* $\delta^{18}O_{cel}$ record from Mer Bleue Bog shows good correlation with

the sunspot number reconstruction by Solanki et al., (2004) from present to ~7400 cal. BP (Figure 4).

Most of the observed $\delta^{18}O_{cel}$ record obtained from Mer Bleue Bog core correlates well with Northern Hemisphere paleotemperature (e.g. Moberg et al., 2005) as well as solar activity reconstructions (Bard et al., 2000, 2003; Solanki et al., 2004). In addition, a good correlation between the Mer Bleue Bog core $\delta^{18}O_{cel}$ record and the ice-rafted sediment record from the Atlantic Ocean (Bond et al., 2001) and European records (e.g. Bond et al., 1997) indicate that eastern Canada experienced a similar ~1300 yr climate cycle as recognized in those areas. The low $\delta^{18}O_{cel}$ values through the 4200–4600 cal. BP interval coincide with the North Atlantic Cooling event (Bond et al., 1997) and provide further evidence of a strong paleoclimate link to the North Atlantic region during the mid Holocene.

Low $\delta^{18}O_{cel}$ values characterizing the ~3000–3300 cal. BP interval in the Mer Bleue Bog record document a cool interval that has been recognized in other parts of North America (Daley et al., 2009; Patterson et al., 2004; Taylor, 2008). Also notable in the $\delta^{18}O_{cel}$ record at Mer Bleue Bog is an excursion that correlates well with pronounced cooling during the ~AD 1810–1820 interval in eastern Canada. This cooling was brought on by climatic change triggered by the Dalton solar minimum and amplified by the Mount Tambora, Indonesia eruption of 1815 (Rampino et al., 1988; Usoskin and Kovaltsov, 2004). The ensuing global cooling beginning in AD 1816, which became known as the 'Year Without a Summer', was particularly devastating in eastern North America with frosts in July and August as far south as Pennsylvania (Oppenheimer, 2003).

Conclusions

The results indicate that $\delta^{18}O$ of *Sphagnum* cellulose from Mer Bleue Bog can provide a reliable proxy for growing-season paleotemperature for eastern Canada.

The $\delta^{18}O_{cel}$ record obtained from the Mer Bleue Bog core is in accordance with Northern Hemisphere paleotemperature (e.g. Moberg et al., 2005) and solar activity reconstructions (Solanki et al., 2004).

A good correlation between the Mer Bleue Bog $\delta^{18}O_{cel}$ record, and records based on ice-rafted debris from the Atlantic Ocean and Europe indicate that eastern Canada experienced a similar ~1300 yr climate cyclicity as well as a cooling event at ~4200–4300 cal. BP (e.g. Bond et al., 1997, 2001).

Low $\delta^{18}O_{cel}$ values at ~3000–3300 cal. BP document a cool interval that has been recognized in other parts of North America (Daley et al., 2009, 2010; Patterson et al., 2004).

Low $\delta^{18}O_{cel}$ values at Mer Bleue Bog indicate a pronounced cooling during the AD 1810–1820 interval in eastern Canada that may have been triggered by the Dalton solar minimum and amplified by the Mount Tambora eruption of AD 1815. There is, however, no indication for a significant regional warming trend since AD 1850 as detected globally (e.g. Jansen et al., 2007).

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