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# Diatom-inferred wind activity at Lac du Sommet, southern Québec, Canada: A multiproxy paleoclimate reconstruction based on diatoms, chironomids and pollen for the past 9500 years

**Sonja Hausmann,[1,4] Isabelle Larocque-Tobler,[2] Pierre J.H. Richard,[3] Reinhard Pienitz,[4] Guillaume St-Onge[5] and Falko Fye[1]**

**Abstract**
Paleo surface wind for southern Quebec was inferred quantitatively for the past 9500 years from diatom assemblages archived in the sediment of the shallow mountain Lac du Sommet using biweekly sediment trap samples along an elevation gradient in the study area. The wind reconstruction was compared with diatom-inferred dissolved organic carbon concentration, chironomid-inferred mean August air temperature, pollen, grain size and loss-on-ignition. Increased lake circulation, interpreted as indicating stronger surface winds, was inferred from diatoms around 8700, 4500, 3000 to 2000 cal. yr BP and during the past 250 years. Increased lake stratification was diatom-inferred from 7500 to 5000 cal. yr BP and between 1500 and 500 cal. yr BP. Diatom-inferred paleowinds were congruent with the regional fire history. In general, diatom production was significantly correlated with diatom-inferred lake circulation. Diatom-inferred lake circulation and diatom production were not correlated with the pollen assemblage changes, diatom-inferred dissolved organic carbon and chironomid-inferred August air temperature, which were highly intercorrelated. After the disappearance of the meltwater in the St Lawrence River valley, the chironomids reflected a warming trend that lasted until about 5000 cal. yr BP, trees replaced shrubs and diatom-inferred dissolved organic carbon increased from 4 mg/l to 6 mg/l. Diatom-inferred lake circulation exhibited periodicities of 200 and 900 years, whereas chironomid-inferred August air temperatures indicated a distinct (significant) 200 year periodicity.

**Keywords**
chironomid-inferred August temperature, chironomids, diatom-inferred lake circulation, diatoms, grain size, Holocene, LIS, loss-on-ignition, pollen, shallow lake

## Introduction

Human-induced climate change leads to increasing variability of precipitation, temperature rise, and increased storm activity (Intergovernmental Panel on Climate Change (IPCC), 2007). Reconstructions of temperature and wind improve our understanding of climate variation and the long-term dynamics of atmospheric circulation (Kutzbach and Liu, 1997). Wind records derived from marine and ice cores, such as meridional winds inferred from calcium ions archived in Antarctic ice cores (Mayewski et al., 2005) or the productivity responses of marine organisms to changes in trade wind activity in coastal upwelling areas (Holzwarth et al., 2007) are well established. However, in order to improve our understanding of global climate variation, more terrestrial wind records are needed.

Lake sediments can serve as archives of past terrestrial climate and land-use change (Stoermer and Smol, 1999). Surface wind, temperature and lake level are the primary controls of thermal stratification and lake circulation while influencing water chemistry, which, in turn, influences diatom compositions (Anderson 2000; Bradbury and Dieterich-Rurup, 1993; Dean et al., 1996; Stoermer and Smol, 1999). This study attempts to infer past changes in surface wind strength quantitatively from diatoms archived in lake sediments of Lac du Sommet, a small boreal lake in southern Quebec. Hausmann and Pienitz (2007, 2009) have shown in a sediment trap study in shallow boreal lakes along an elevation gradient that the circulation of the water column explains best the diatom differences among the lakes. Diatom communities change composition in response to mixing of the water column when silica ($SiO_2$) from the sediment–water interface becomes redistributed in the water column. Hausmann and Pienitz (2007) have shown that the diatom flux and diatom-inferred summer lake circulation of Lac du Sommet were significantly positively related to recorded wind velocities in June as

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well as to higher August air temperature. The dominant taxon *Fragilaria virescens* is known to be highly competitive and abundant under high Si:P ratios (Tilman et al., 1982), which increased with enhanced lake circulation (Hausmann and Pienitz, 2007). Warm summer winds result in a weakening and deepening of the thermal stratification during summer, and the subsequent disappearance of the hypolimnion in shallow lakes.

Chironomid larval development in lakes is influenced by water and air temperatures (Walker and Mathewes, 1989), and therefore is reflected in fossil assemblages preserved in lake sediments. Various transfer functions have been developed to express these species–environment relationships, and to quantitatively infer past water and air temperatures in different parts of the world (summarized in Brooks, 2006; Walker and Cwynar, 2006). They have been used especially to reconstruct climate change during the Lateglacial and Holocene episodes (e.g. Brooks and Birks, 2000a, b; Larocque and Finsinger, 2008; Potito et al., 2006; Rolland et al., 2008; Thomas et al., 2008). Comparisons between chironomid-inferred temperatures and instrumental data proved that chironomid analysis is a solid technique for reconstructing temperatures over the last 100–150 years in Sweden (Larocque and Hall, 2003) and Switzerland (Larocque et al., 2009a, b).

During the Holocene, changes in diatom assemblage composition were driven by several factors, including catchment vegetation changes and soil development, related water color changes as well as shifts in lake level resulting from hydroclimatic changes and lake aging. Consequently, in order to disentangle long-term soil development and vegetation changes from changes in past surface wind strength, we studied terrestrial and aquatic biological remains archived in lake sediments, each recording different aspects of climate. In addition to diatom-inferred lake circulation patterns based on a sediment trap study in the region (Hausmann and Pienitz, 2007), we reconstructed diatom-inferred dissolved organic carbon concentrations and chironomid-inferred August air temperature using training sets based on surface sediment samples along a north–south gradient in Québec and Labrador (Fallu et al., 2000; Larocque et al., 2006). Past modifications in terrestrial vegetation were inferred from fossil pollen assemblages, whereas fire history data from 31 Québec lakes was used as an independent proxy for conditions favorable for forest fires (Carcaillet and Richard, 2000).

## Study site

The small shallow Lac du Sommet (0.02 km$^2$, 4 m maximum depth, elevation of 830 m a.s.l., 47°43′N, 70°40′W) is located in the boreal forest north of the St Lawrence Estuary (Figure 1). It is of glacial origin and situated on granitic-gneissic bedrock of the Canadian Precambrian Shield in the Laurentian Mountains. The region became ice-free a little before 12 500 cal. yr BP (Dyke et al., 2003). The lake is sheltered to the north and overlooks the south side of the Laurentian Mountain Plateau. In summer, the prevailing winds come from the south (Bryson and Hare, 1974).

In 2002, the lake was ice-free from the end of May until mid-October and showed several periods of isothermic conditions (Hausmann and Pienitz, 2007, 2009). The 30-year average June wind velocity was 7.1 km/h (one standard deviation was 0.93 km/h) and 30-year average August air temperature of 13.7°C (one standard deviation was 1.1°C) was recorded by a meteorological station 50 km south and 260 m lower elevation than the study lake. Vegetation throughout the small catchment (8.13 km$^2$) belongs to the transition zone between *Abies balsamea* (balsam fir) and *Picea mariana* (black spruce) forests. At lower elevations, the vegetation is presently dominated by the mid-successional *Betula papyrifera* (paper birch).

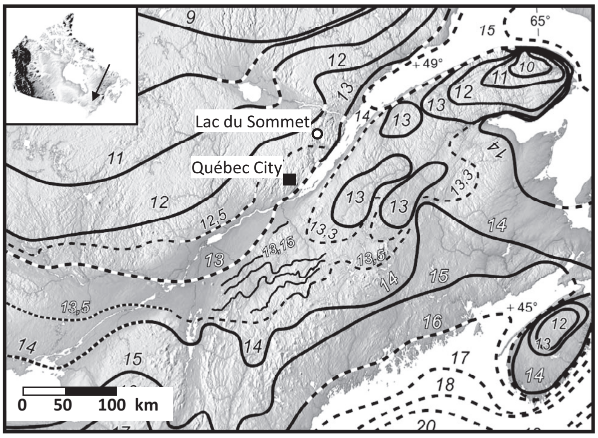

**Figure 1.** Location of Lac du Sommet (830 m a.s.l.; 47°43′N, 70°40′W). Digital elevation map of the study area. Solid contour lines indicate dated isochrones of ice retreat in cal. kyr BP. Dashed lines are interpolated years (Pierre Richard, unpublished data)

## Methods

### Core acquisition and chronology

In order to extend the 30 cm long gravity core previously published by Hausmann and Pienitz (2007), two overlapping parallel cores of 3.14 m length were recovered at the deepest part of the lake with a Livingstone corer in April 2003. The 1 m core segments were extruded in the field into half liners and sliced in the laboratory at 0.5 cm increments. The core segments were correlated by loss-on-ignition (LOI). Using a binocular microscope, wood fragments (one per sample) were picked from seven levels and sent to BETA Analytic (Florida) laboratories for AMS radiocarbon dating (Table 1). The radiocarbon dates were converted into calibrated years BP using the INTCAL98 data base (Stuiver et al., 1998). The depth–age model was developed using a polynomial model between the radiocarbon dates and composite depth (Figure 2). Calibrated radiocarbon years are referred as cal. yr BP throughout the paper.

### LOI, grain size, pollen, chironomid and diatom analysis

A total of 138 loss-on-ignition (LOI), 37 grain size, 104 diatom, 101 chironomid and 32 pollen samples were analyzed from 0.5 cm slices in the Holocene core. LOI was measured according to standard methods (Dean, 1974). Freeze-dried samples were exposed for 5 h at 550°C and allowed to cool in a desicator prior to weighing immediately after exposure to air.

Grain size was analyzed at visible lithological changes using a Beckman-Coulter LS-13320 (0.04 to 2000 μm) laser diffraction analyzer. Prior to analysis, the sediments were disaggregated in a Calgon electrolytic solution (sodium hexametaphosphate), rotated for at least 3 h using an in-house rotator and then sieved over the instrument (2 mm). All the particle size distributions output were then processed using the Gradistat software (Blott and Pye, 2001). The distribution of the material larger than 2 mm was obtained by

**Table 1.** Radiocarbon dates and lab ID of Lac du Sommet lake sediments

| Uncorrected depth (cm) | Corrected depth (cm)[a] | Lab number | Conventional $^{14}C$ age | Calibrated ages[b] | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|
| 43.75 | 43.75 | Beta-189065 | 1290 | 1225±65 | −26.5 |
| 128.75 | 121.75 | Beta-189066 | 2640 | 2765±25 | −29.4 |
| 189.75 | 183.75 | Beta-189067 | 3890 | 4295±125 | −30.2 |
| 246.25 | 240.25 | Beta-193473 | 6220 | 7125±125 | −26.2 |
| 284.25 | 278.25 | Beta-202755 | 7950 | 8815±185 | −25.9 |
| 293.25 | 281.75 | Beta-197083 | 7790 | 8535±105 | −25.0 |
| 312.25 | 300.75 | Beta-180545 | 8590 | 9545±25 | −26.5 |

[a] Corrected for the rapidly deposited layers (see text for details). All ages were measured from wood samples by the AMS method using Libby's half-life (5568 yr) and corrected for natural and sputtering fractionation ($\delta^{13}C$ = −25‰ VPDB).
[b] The ages represent the average and standard deviation at the 2σ confidence level.

dry sieving and merged with the laser distribution using an in-house algorithm.

For diatom analysis, small aliquots of sediments were placed in 250 ml beakers and heated in 30% $H_2O_2$ to remove the organic matter. The 250 ml beakers were filled with distilled water and placed overnight in the refrigerator to stop the reaction and allow the diatoms to settle. The supernatant was removed and the rinsing was repeated twice. In order to calculate the diatom flux (valves/cm$^2$per yr), the sample was spiked with a known number of microspheres with a 6 µm diameter (Battarbee and Kneen, 1982). The suspension was applied onto cleaned round cover slips and, after overnight air drying, mounted with Naphrax® (refraction index of 1.73). Diatoms were identified to the species level using a DMRB microscope equipped with differential interference (DIC) optics at 1000× magnification with oil immersion. Between 300 and 500 valves were analysed per sample and 104 samples were included in the analysis. The taxonomy followed that of Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Camburn and Charles (2000) and Fallu et al. (2000).

Pollen preparation of 32 samples of 1 ccm followed standard techniques (Faegri and Iversen, 1975). The basic sum used for relative frequency calculations includes all terrestrial plants. At least 500 grains were counted per sample. Pollen concentration (grains/cm$^3$) was determined by the modified method of Benninghoff (1962) and pollen influx was derived from the chronological model (grains/cm$^2$per yr).

Chironomids were extracted from 101 samples. For extraction, 10% KOH was added to the samples overnight, and they were then sieved in a 100-µm mesh sieve and placed in a Bogorov counting tray. Each head capsule found under a stereomicroscope at a magnification of 20× was individually picked and mounted on a microscope slide in a solution of Hydromatrix. Identification was performed using a microscope at a magnification between 400 and 1000×. The identification to genus and sometimes species level followed Wiederholm (1983), Oliver and Roussel (1983) and a taxonomic guide developed for Québec chironomid taxonomy (Larocque and Rolland, 2006). *Tanytarsus* without mandibles were merged into two categories: with spur (when a spur on the antenna pedicel was present) or without spur. When the pores on the head capsules of the *Tanypodinae* were not visible, they were merged into *Pentaneurini* or *Procladius* categories.

### Numerical analyses

The number of statistically significant zones of the pollen, chironomid and diatom biostratigraphies was assessed by the optimal sum of square method implemented in the program 'Zone' (Lotter and Juggins, 1991) in combination with a broken-stick model according to Bennett (1996). The main changes in the diatom, pollen and chironomid assemblages were described by a principal component analysis (PCA) and by detrended correspondence analysis (DCA), respectively. The ordinations were performed using the program 'CANOCO' (version 4.0; ter Braak and Šmilauer, 1998).

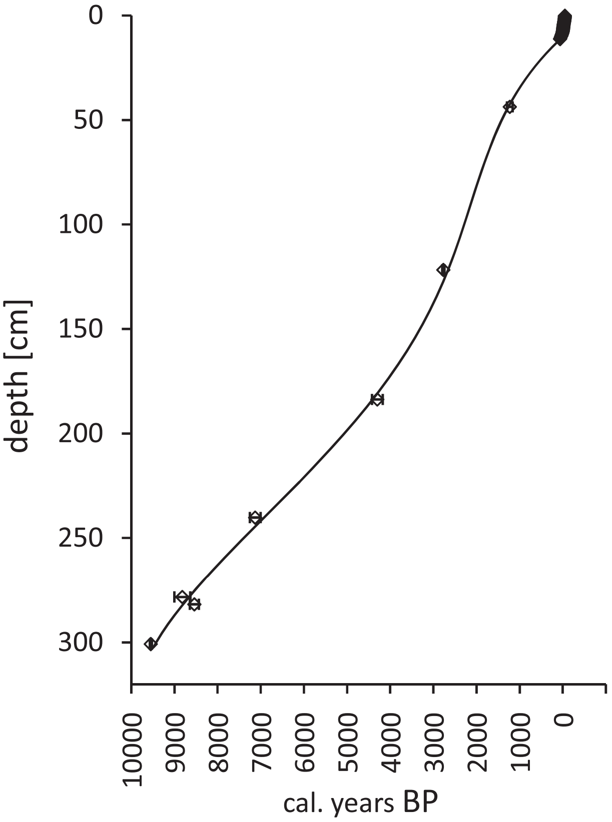

**Figure 2.** Depth–age model for Lac du Sommet lake sediments based on polynomial fit of the fourth order through radiocarbon dates. Error bars indicate 2σ. For details of $^{210}$Pb dating see Hausmann and Pienitz (2007)

The chironomid-inferred mean August air temperature was reconstructed quantitatively with a transfer function modified from Larocque et al. (2006). This modified weighted average partial least squares (WAPLS) model with two components had a coefficient of correlation ($r_{\text{jack}}^2$) of 0.85, the root-mean-square-error of prediction (RMSEP) was 1.1°C, and the maximum bias was 1.5°C (Larocque, 2008).

The circulation of the water column was reconstructed quantitatively using a two component weighted averaging partial least squares (WA-PLS) diatom inference model, using summer sediment trap samples of biweekly resolution in lakes from the study site along an elevation gradient. This previously published model used the ratio of surface- to bottom-water temperature to estimate the strength of water column stratification. It had a coefficient of correlation ($r_{\mathrm{jack}}^2$) of 0.64 for a measured to predicted ratio of top and bottom temperature, and a maximum bias of 1.11 and a root-mean-square-error of prediction (RMSEP) of 0.54 for a ratio of top and bottom temperature (Hausmann and Pienitz, 2007). Hausmann and Pienitz (2007) demonstrated that diatom-inferred circulation of the water column in Lac du Sommet was statistically significantly correlated to measured June wind velocity in the area. Diatom flux and concentration were expressed as anomalies or z-scores, which are the normalized values showing the deviation of the mean as standard deviations (SD) units.

The diatom-inferred dissolved organic carbon (DOC) concentration was reconstructed using a previously published training set incorporating 59 surface sediment samples from lakes along a latitudinal gradient in northern Quebec (Fallu and Pienitz, 1999). The WA-PLS model with three components had a coefficient of correlation ($r_{\mathrm{jack}}^2$) of 0.81. The root-mean-square-error of prediction (RMSEP) was 1.2 mg/l DOC.

Diatom flux, chironomid-inferred temperature and PCA axis 1 of the pollen were assessed for periodicities with Morlet wavelet analysis (Torrence and Compo, 1998). Prior to wavelet analysis, the data of each proxy were interpolated to equal time intervals of 191 years for pollen, 63 years for chironomids and 68 years for diatoms using the smoothing function LOESS in S-Plus (TIBCO Software Inc.).

## Results

### LOI, grain size and chronology

Apart from the rapidly deposited layers (RDLs) around 8500 and 1700 cal. yr BP, the core is composed mostly of organic-rich postglacial lake sediments with high concentrations of diatoms, chironomids and pollen. No sediments of glacial origin were recovered. In general, LOI increased from 10% to 40% from 9500 cal. yr BP to 8000 cal. yr BP and remained around 40% through the rest of the Holocene (Figure 3). RDL were identified by LOI and grain-size analysis (Figure 3). A double peak of coarser grain size (gravel; 2–64 mm) occurred between 293 and 287.5 cm (*c.* 8500 cal. yr BP) and between 67 and 73 cm (*c.* 1750 cal. yr BP). In order to model sedimentation rates unaffected by mass wasting events, the RDLs were subtracted from the composite depth (314 cm total depth minus RDL = 302.5 cm) and then used for the core chronology (depth–age model), using a fourth order polynomial model between the seven radiocarbon dates based on wood fragments ($r^2 = 0.998$; Figure 2). Each sample of the Holocene core (0.5 cm slices) encompassed *c.* 16 years, and the average sedimentation rate was calculated at 0.32 mm/yr. The third lowest radiocarbon date, just above the RDL, at 284.25 cm (uncorrected depth) is around 300 years older than the radiocarbon date from just below the RDL (Figure 2). The dated material might have been redeposited by the RDL (Figure 3). However, the date was not removed as an outlier and remained in the depth–age model because error bars overlapped and it did not affect the depth–age model.

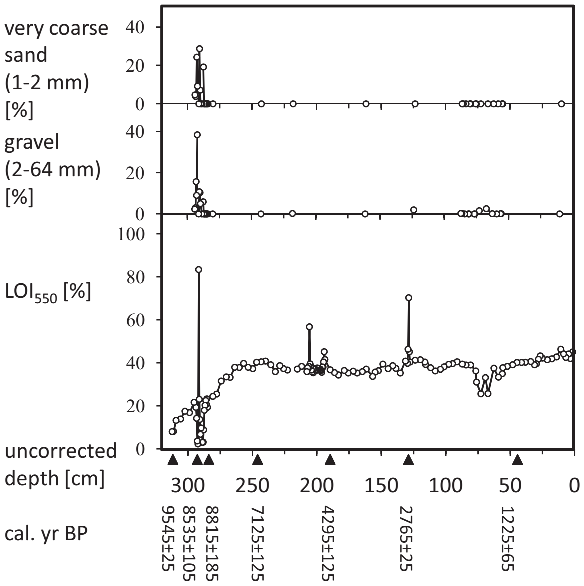

**Figure 3.** Grain size and loss-on-ignition at 550°C of the lake sediment core of Lac du Sommet. The triangles indicate the depths where the wood fragments were taken for radiocarbon dating

Changes in the sedimentation rate have an influence on the calculation of diatom fluxes, which were highly correlated with the changes of diatom composition as expressed by PCA axis 1 (Table 2, $r = 0.82$, $n = 104$, $p < 0.0005$). This is noteworthy since the calculation of diatom fluxes depends on the core chronology, whereas the PCA axis is based on relative diatom abundances independent of the chronology. This strong correlation increased our confidence in the depth–age model constructed for the Lac du Sommet sediment core.

### Diatoms

A total of 105 diatom species (with relative abundance of > 1%) were identified in 104 out of 600 samples. The average interval between sample was 80 years between 6000 and 0 cal. yr BP and 154 years between 9500 and 6000 cal. yr BP. The diatom flux ranged between $3.5\times10^6$ and $1.4\times10^8$ valves/cm$^2$ per yr. Elevated diatom production, exceeding 1 SD, occurred between 9000 and 8200 cal. yr BP, between 3100 and 2000 cal. yr BP and from 200 cal. yr BP to the present (Figure 5d). Five statistically significant diatom assemblage zones (DAZ) were identified (Figure 4a). DAZ 1 (9500–9200 cal. yr BP) encompassed only two samples and was dominated by *Fragilaria pinnata* with a relative abundance of 25%, *Fragilaria brevistriata* (15%) and *Fragilaria virescens* var. *exigua* (10%). DAZ 2 spanned from 9200 to 7800 cal. yr BP and showed a clear dominance of *Aulacoseira distans* var. *nivalis* (50%) together with *Cyclotella stelligera* (20%) and *Achnanthes minutissima* (10%). *A. distans* var. *nivalis* dropped from 50% at 8535±105 cal. yr BP (293.25 cm uncorrected depth) to 20% after the landslide event at 284.75 cm (uncorrected depth). DAZ 3 (7800–2900 cal. yr BP) is a 4500 year long period of *Pinnularia microstauron* (40%) dominance; followed by DAZ 4 (2900–20 cal. yr BP), which is characterized by *Cymbella hebridica* (10%), an increase of *Fragilaria virescens* var. *exigua* and increased *Frustulia rhomboides* around 100 cal. yr BP. The most striking changes in the biostratigraphy occurred in DAZ 5 which covers the past 70 years of the record. DAZ 5 was dominated by

**Table 2.** Correlation coefficients between diatom flux (valves/cm$^2$ per yr), PCA axis one of diatoms, relative abundance of *Fragilaria virescens* var. *exigua*, diatom-inferred circulation of the water column, diatom-inferred dissolved organic carbon concentration, PCA axis one of pollen, chironomid-inferred air temperature and sum of littoral chironomids. Significant correlations are shown in bold

| | Diatom flux | Diatom PCA I | % Frag. vir. | Diatom-inf circ. | DI-DOC | Pollen PCA I | CI-temp. | Σ of littoral taxa |
|---|---|---|---|---|---|---|---|---|
| Diatom PCA I | **0.82** | | | | | | | |
| % Frag. vir. | **0.70** | **0.82** | | | | | | |
| Diatom-inf. circ. | **0.49** | **0.49** | **0.63** | | | | | |
| DI-DOC | −0.16 | −0.30 | 0.04 | −0.14 | | | | |
| Pollen PCA I | 0.31 | **0.44** | 0.31 | 0.30 | **0.81** | | | |
| CI-temp. | −0.07 | −0.36 | 0.24 | 0.16 | **0.70** | **−0.76** | | |
| Σ of littoral taxa | −0.16 | −0.31 | 0.22 | −0.07 | **0.68** | **−0.80** | **0.73** | |
| Chiro DCA I | 0.10 | 0.30 | −0.27 | −0.02 | **−0.78** | **0.76** | **−0.84** | **−0.83** |

*Fragilaria virescens* var. *exigua* (40%) and *Aulacoseira distans* var. *nivalis* (30%). *F. virescens* abundances were elevated during the following time intervals: at the beginning of the Holocene, from 2600 to 1500 cal. yr BP, and during the past 250 years.

### Chironomids

Four chironomid assemblage zones (CAZ) were identified as being significant (Figure 4b). All taxa with a relative abundance of 5% in at least two samples are shown in Figure 4b. CAZ 1 (9500–8800 cal. yr BP) was dominated by *Sergentia* with up to 45% relative abundance and *Psectrocladius sordidellus*-group. CAZ 2 (8800–6400 cal. yr BP) was dominated by *Chironomus plumosus*-group and *Tanytarsus* without spur. From 9500 to 4000 cal. yr BP, the sum of littoral taxa increased from around 30 to about 80%, suggesting a shallowing of the lake. During CAZ 3 (*c*. 6400–2000 cal. yr BP), *Tanytarsus* without spur dominated and increases in *Polypedilum* and *Tanytarsus* sp. B were seen. *Procladius* remained high while *Chironomus plumosus*-group decreased. In zone CAZ 4 (*c*. 2000 cal. yr BP to present), *Tanytarsus* without spur decreased to 10% and *Polypedilum* decreased to 5%. *Psectrocladius septentrionalis*-group and *Psectrocladius sordidellus*-group increased. *Chironomus plumosus*-group further decreased.

### Terrestrial vegetation

Three distinct pollen assemblage zones (PAZ) could be identified (Figure 4c). PAZ 1 (9500–7600 cal. yr BP) was characterized by a dominance of *Alnus crispa* type pollen. PAZ 2 (7600–4750 cal. yr BP) was dominated by *Betula* and increased abundance of *Pinus strobus* pollen. PAZ 3 (4750–present) showed an increase of pollen representation of *Alnus incana* and was dominated by *Betula* (30%), *Abies balsamea* (20%) and *Picea* (20%) pollen. Taking into account the differential pollen representation of the taxa, and comparing with the pollen assemblages produced by modern vegetation (Richard, 1976), the vegetation represented by the successive pollen zones was dominated by balsam fir (*Abies balsamea*) with some black spruce (*Picea mariana* type) since 9500 cal. yr BP, with an open canopy admitting green alder (*Alnus crispa* type) during PAZ 1, and a denser character during PAZ 3. White birch (*Betula*) was a very secondary companion except during PAZ 2 where it was locally abundant. Most if not all the other tree taxa represented by their pollen were not present in the catchment around Lac du Sommet. Variations in the pollen representation of white pine (*Pinus strobus*) and hemlock (*Tsuga canadensis*) reflect changes in distant, southern populations.

### Climate inferences

A comparison of modern diatom and chironomid assemblages from training sets in northwestern Quebec developed for DOC and for August air temperature models with the fossil assemblages from our high elevation lake in southern Quebec showed that on average 83% (SD 7.4%) of the fossil diatom taxa from Lac du Sommet were represented in the DOC training set from northwestern Quebec. Between 7500 and 5000 cal. yr BP, only 75% of the fossil taxa were represented in the training set, during which time the analog situation is weaker compared with the rest of the record. As tested by a detrended correspondence analysis (figure not shown), all fossil diatom samples are within the training set assemblages.

Concerning the chironomids, only five sample depths (55.75; 59.25; 243.25; 256.75; 298.75 cm) had fossil taxa which were represented at 80–90% in the calibration set. All other samples had fossil taxa represented at more than 99%. These results suggest that the chironomid transfer function for August air temperature is applicable on this lake record located a few hundred kilometers east from the training set transect, and that most samples (98%) have good modern analogues. Chironomid-based transfer functions from other countries have been applied to lake sediment samples in various countries (e.g. Brooks and Birks, 2000a, b; Ilyashuk et al., 2005; Langdon et al., 2004) and the applicability of external transfer functions was recently tested (Larocque-Tobler, 2010). As tested by a correspondence analysis (figure not shown), all fossil chironomid samples are within the training set assemblages. Only two sample depths (194.25 and 178.75 cm) are outside the 95% confidence interval and could be considered has having lower modern analogues.

In Lac du Sommet, during the past 9500 years the diatom-inferred surface-water temperature was on average 1.3 times warmer than the bottom-water temperature (see dashed line in Figure 5c). At 8800 cal. yr BP, 4500 cal. yr BP, from 3000 to 2000 cal. yr BP and during the last 250 years diatom-inferred ratio of surface- to bottom-water temperature was around 1.1, which is 1 SD below the average, while from 7500 to 5000 cal. yr BP the lake was more stratified (Figure 5c). Diatom flux was significantly higher when the lake circulation was higher ($r = 0.49$, $n = 105$, $p < 0.005$). Diatom-inferred lake circulation was correlated to the dominant taxon *F. virescens* var. *exigua* ($r = 0.63$, $n = 105$, $p < 0.0005$) and PCA axis one (Figure 4a) of the diatom assemblages ($r = 0.49$, $n = 105$, $p < 0.0005$), which expressed 22% of the overall diatom changes, but not to diatom-inferred DOC ($r = -0.14$, $n = 105$, $p > 0.05$; Table 2). The diatom-inferred DOC concentrations indicated elevated lake transparency from 9250 to 7500 cal.

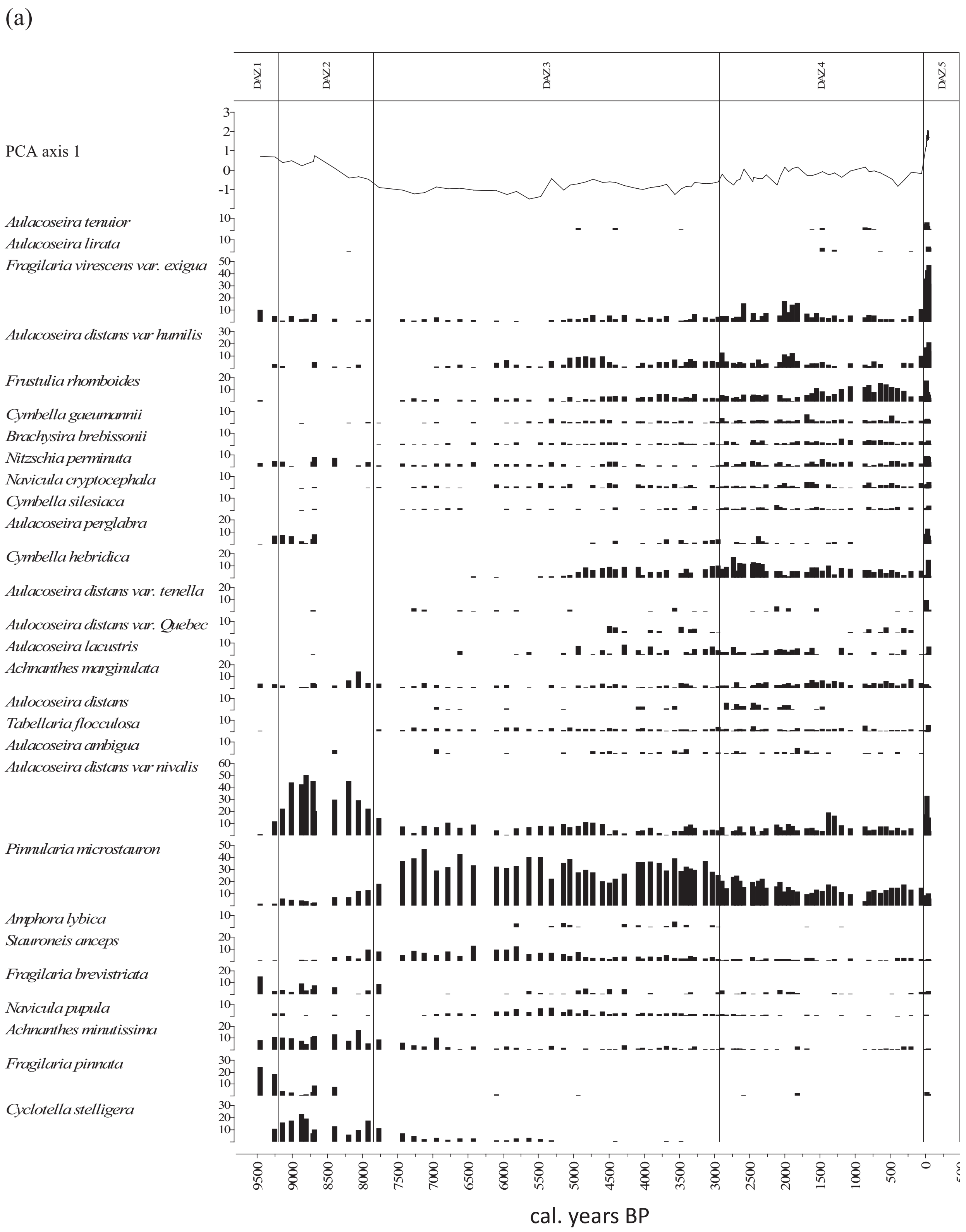
(a)
DAZ 1
DAZ 2
DAZ 3
DAZ 4
DAZ 5
PCA axis 1
*Aulacoseira tenuior*
*Aulacoseira lirata*
*Fragilaria virescens var. exigua*
*Aulacoseira distans var humilis*
*Frustulia rhomboides*
*Cymbella gaeumannii*
*Brachysira brebissonii*
*Nitzschia perminuta*
*Navicula cryptocephala*
*Cymbella silesiaca*
*Aulacoseira perglabra*
*Cymbella hebridica*
*Aulacoseira distans var. tenella*
*Aulocoseira distans var. Quebec*
*Aulacoseira lacustris*
*Achnanthes marginulata*
*Aulocoseira distans*
*Tabellaria flocculosa*
*Aulacoseira ambigua*
*Aulacoseira distans var nivalis*
*Pinnularia microstauron*
*Amphora lybica*
*Stauroneis anceps*
*Fragilaria brevistriata*
*Navicula pupula*
*Achnanthes minutissima*
*Fragilaria pinnata*
*Cyclotella stelligera*
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
cal. years BP

**Figure 4.**

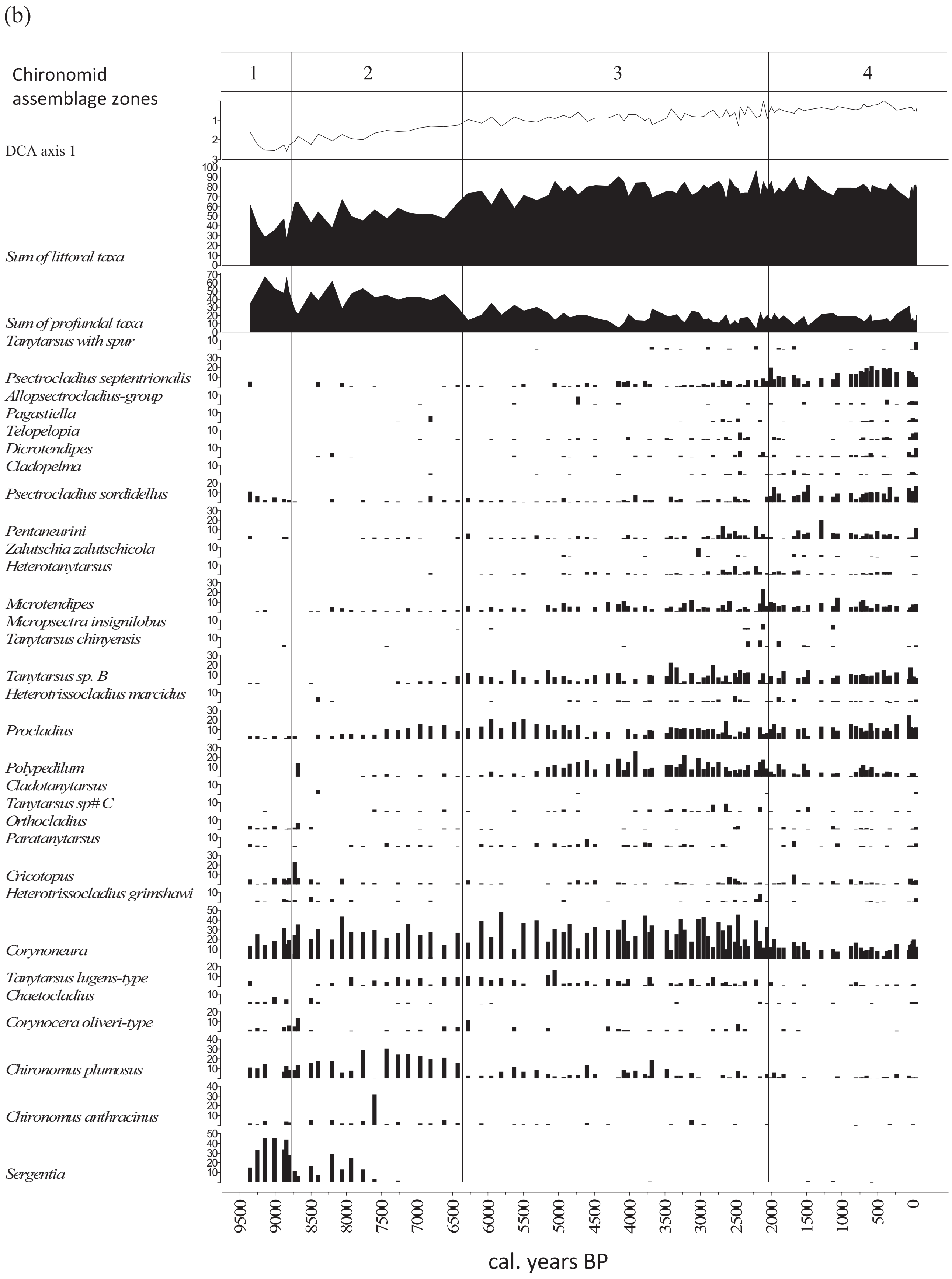
(b)
Chironomid assemblage zones
1
2
3
4
DCA axis 1
Sum of littoral taxa
Sum of profundal taxa
Tanytarsus with spur
Psectrocladius septentrionalis
Allopsectrocladius-group
Pagastiella
Telopelopia
Dicrotendipes
Cladopelma
Psectrocladius sordidellus
Pentaneurini
Zalutschia zalutschicola
Heterotanytarsus
Microtendipes
Micropsectra insignilobus
Tanytarsus chinyensis
Tanytarsus sp. B
Heterotrissocladius marcidus
Procladius
Polypedilum
Cladotanytarsus
Tanytarsus sp# C
Orthocladius
Paratanytarsus
Cricotopus
Heterotrissocladius grimshawi
Corynoneura
Tanytarsus lugens-type
Chaetocladius
Corynocera oliveri-type
Chironomus plumosus
Chironomus anthracinus
Sergentia
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
cal. years BP

**Figure 4.**

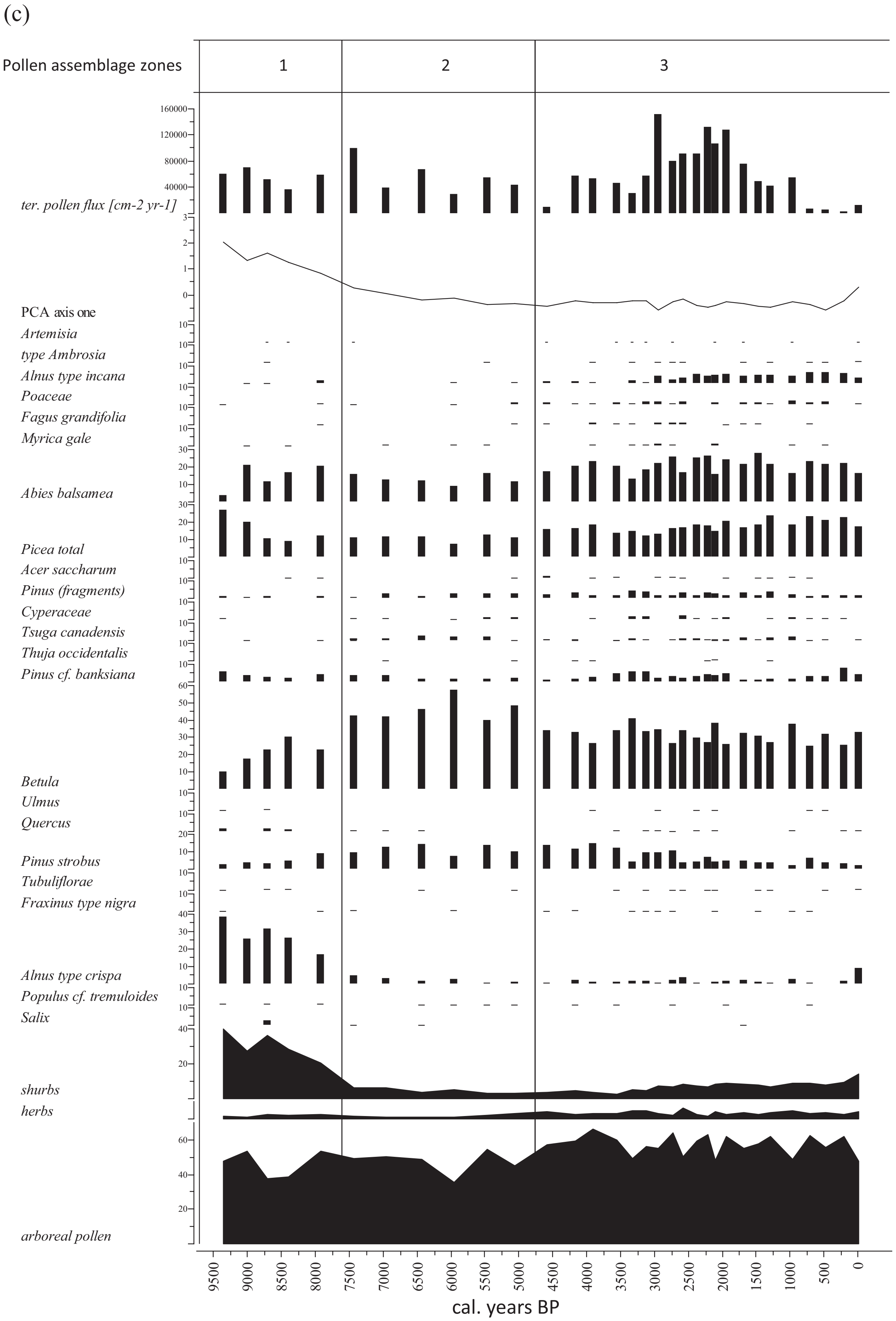

**Figure 4.** Biostratigraphy of Lac du Sommet for the past 9500 years. Significant assemblage zones are indicated. The x-axes represent cal. yr BP: (a) Diatoms of Lac du Sommet for the past 9500 years with a maximum relative abundances of > 4% and PCA axis 1, (b) subfossil chironomid assemblages with a maximum relative abundances of > 5%, sum of profundal and littoral taxa and DCA axis 1 and (c) terrestrial pollen of Lac du Sommet for the past 9500 years with a maximum relative abundances of > 1%

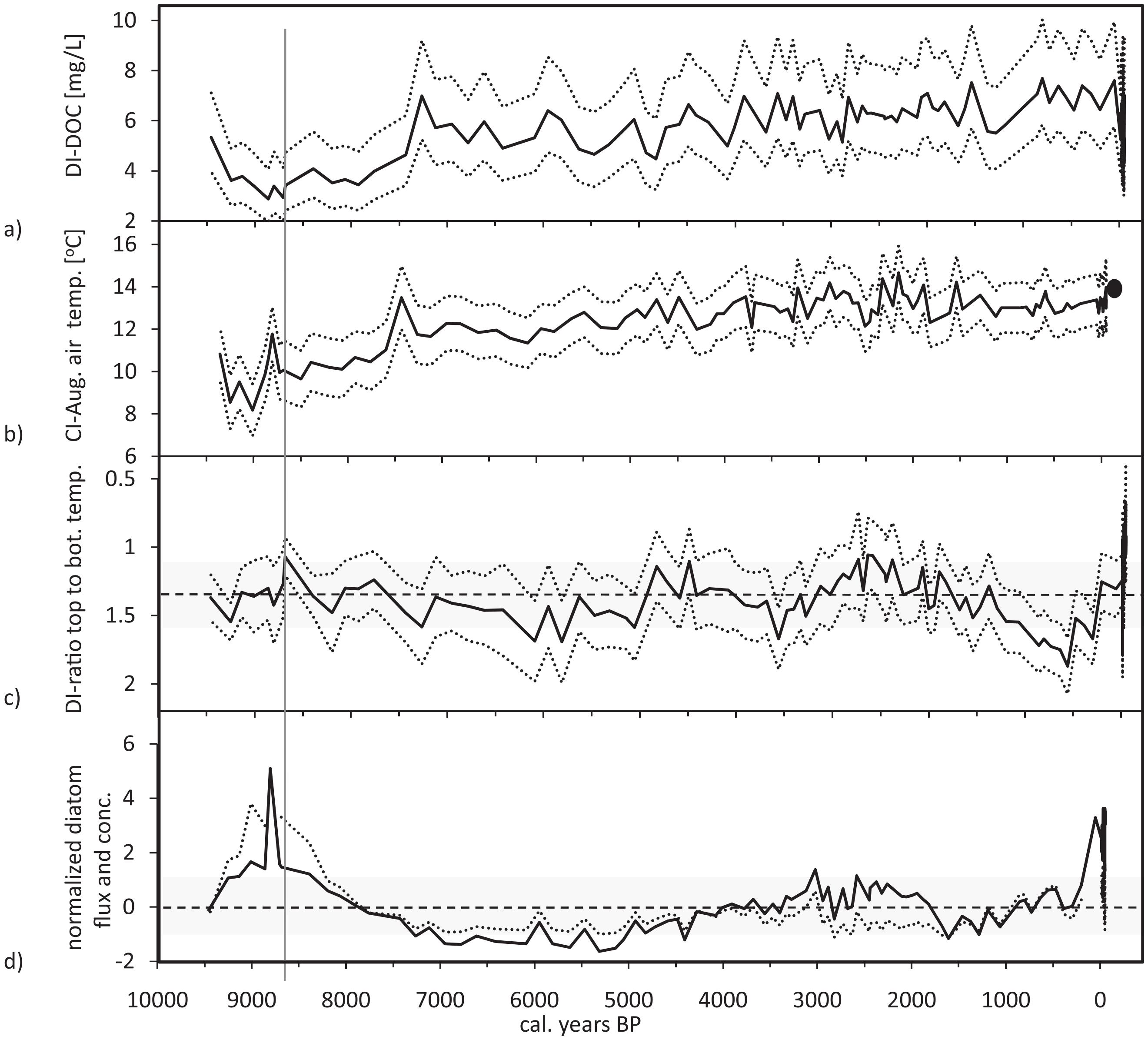

**Figure 5.** Quantitatively diatom- and chironomid-inferred environments of Lac du Sommet for the past 9500 years BP. The sample-specific error (SEB) as assessed by bootstrapping is indicated by dotted lines (a–c). The dashed lines indicate the mean and the gray area represents 1 ±SD (c, d). The rapidly deposited layer around 8535 ± 105 cal. yr BP is indicated as a gray line: (a) diatom-inferred DOC (mg/l), (b) chironomid-inferred August air temperature; note 30 year average of the observed August air temperature is indicated as filled circle and (c) diatom-inferred ratio of top to bottom temperature (note inverse y-axis), interpreted as lake stratification and (d) normalized diatom flux and diatom concentration (dotted line)

yr BP with values around 4 mg/l increasing up to 5 mg/l until about 7250 cal. yr BP, then slowly increasing to 7 mg/l DOC at present (Figure 5a). Chironomid-inferred August air temperature was significantly correlated to diatom-inferred DOC ($r$ = 70; $n$ = 80, $p <$ 0.0005; Table 2) and changes in pollen assemblages ($r = -0.76$; $n$ = 32; $p < 0.0005$), but not to the diatom-inferred lake circulation ($r$ = 0.16, $n$ = 80, $p > 0.05$). Diatom-inferred DOC concentrations were highly correlated with changes in PCA axis 1 of pollen assemblages (Figure 4c), which reflects changes in terrestrial vegetation ($r = 0.81$; $n = 32$; $p < 0.0005$), suggesting that DOC might have terrestrial origin. Pollen changes were also significantly correlated to chironomid-inferred August air temperature ($r = -0.76$, $n = 32$; $p < 0.0005$) and the relative abundance of littoral chironomid taxa ($r = -0.80$, $n = 32$; $p < 0.0005$; Table 2).

During CAZ 1 (from 9400 to 8800 cal. yr BP) the chironomid-inferred mean August air temperature was around 9°C. Prior to the RDL, at 8535±105 cal. yr BP (293.25 cm uncorrected depth, Table 1), the chironomid-inferred mean August air temperature showed a temperature peak (Figure 5b). Between 8000 and 4000 cal. yr BP, the chironomid-inferred air temperature increased up to 13°C. The chironomid-inferred temperature during the past 2000 years was stable around 12°C. The modern August air temperature recorded at the closest meteorological station (260 m lower altitude) had a 30-year average of 13.7°C, while the chironomid-based temperature inferred for the surface sediment was 13.4°C, thereby suggesting that chironomids yield reliable (below the RMSEP) estimates of mean-August air temperature at this site, at least during the past 30 years.

**Table 3.** Statistically significant periodicities of terrestrial pollen, chironomid-inferred August air temperature and diatom-inferred lake circulation. Significance was tested by comparison with a white noise (higher frequency) and red noise (lower frequency) Monte Carlo Permutation Model (compare Figure 6)

| | Time frame BP | Sample interval | White noise cycles | Red noise cycles |
|---|---|---|---|---|
| Pollen PCA axis 1 | 0–9500 | 191 | | |
| Chironomid-inferred temperature | 0–9500 | 63 | | 200 |
| Diatom-inferred lake circulation | 0–9500 | 68 | 900 | 200 900 |

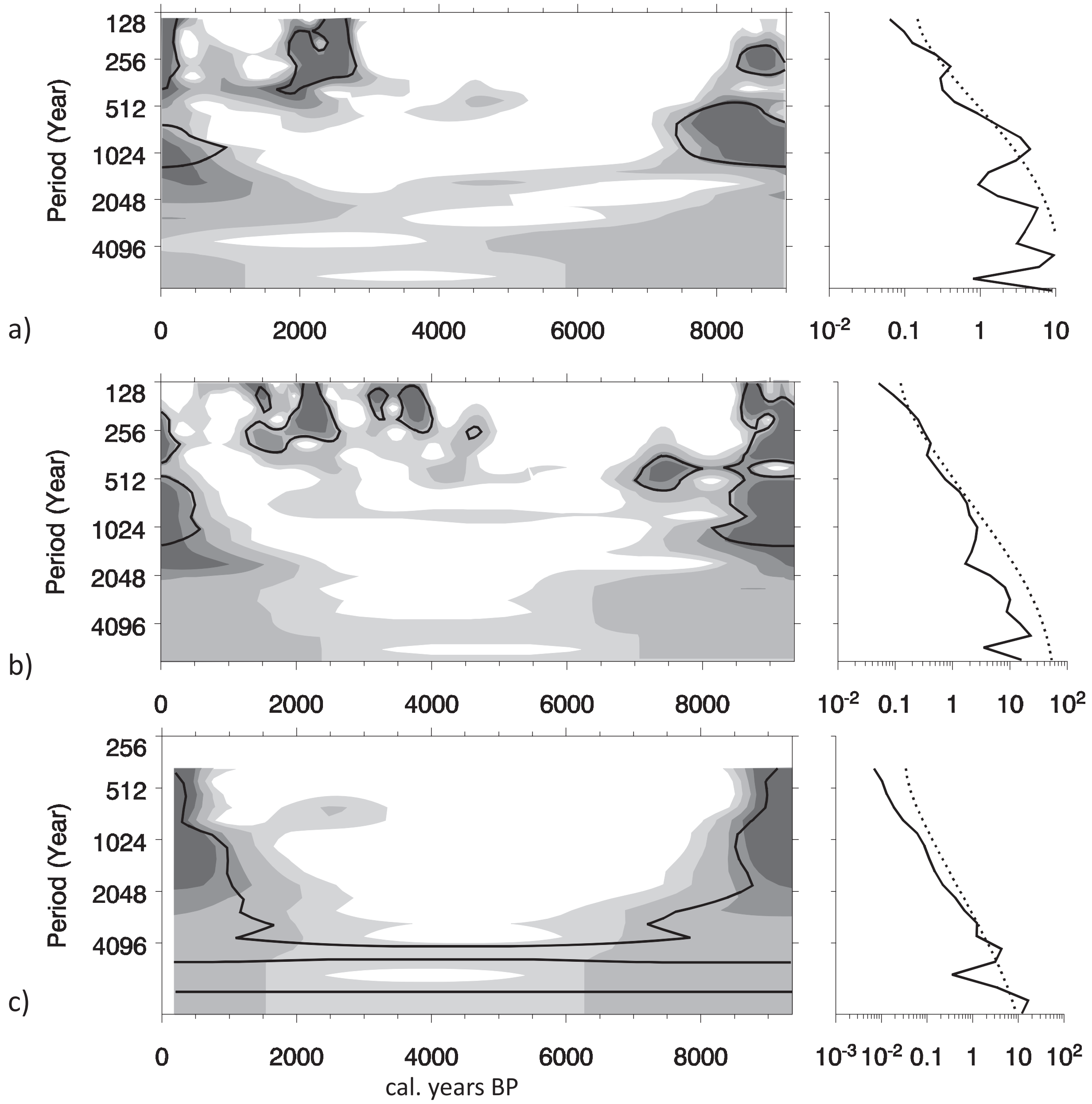

**Figure 6.** The wavelet power spectrum (Torrence and Compo, 1998) of (a) diatom-inferred lake circulation, (b) chironomid-inferred temperature and (c) PCA axis 1 of pollen. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. The contour levels are chosen so that 75%, 50%, 25% and 5% of the wavelet power is above each level. On the right the global wavelet power spectrum (black line) is in comparison with the 10% significance (dashed line)

Diatom-inferred lake circulation and chironomid-inferred August air temperature showed statistically significant 200 year cycles, starting around 4000 cal. yr BP, whereas diatom-inferred lake circulation also revealed a significant 900 year cycle when tested with low frequency noise (Table 3, Figure 6a, b). The 900 year cycles are only found at the surface and at the bottom of the record. The pollen record shows no cyclicity (Figure 6c).

## Discussion

### Environmental change from Lateglacial to 5000 cal. yr BP

Deglaciation in Québec started via ice calving in the Gulf of St Lawrence, opening a bay in the St Lawrence estuary that extended south to the present-day location of Québec City between 14 000 and 13 000 cal. yr BP (Richard, 2007). In contrast to other nearby lakes to the south and west, Lac du Sommet (meaning summit in French) did not accumulate sediments right after regional ice retreat *c*. 12 500 years ago, possibly because this high-elevation basin had a later meltout compared with its surroundings at sea level (Figure 1). Other sites in the vicinity, at lower elevations, present complete Lateglacial sequences (Labelle and Richard, 1981), including evidence of the Younger Dryas cold spell (12 700–11 500 cal. yr BP) and a delayed colonization by trees. Lac du Sommet began to accumulate sediments around 9500 cal. yr BP which corresponds with the end of the afforestation stage. For the first 250 years, LOI remained below 20% and diatom assemblages were dominated by *Fragilaria pinnata* indicating that early Lac du Sommet was similar to an Arctic lake (Smol, 1988). At the time, the ice margin of the Laurentian Ice Sheet (LIS) was positioned near Lake St John, some 100 km to the northwest (Richard, 2007). According to the chironomid-inferred August air temperatures (9–10°C) and the terrestrial vegetation, consisting mainly of shrubs and herbs, the local climate at the study site must have been cold during the first 1000 years of the record. The strong influence of the nearby meltwater stream of the LIS in the St Lawrence River valley is evident (Teller, 1990).

Dune studies by Filion (1987) revealed strong winds which led to eolian deposits with NE–SW orientation in the Lower St Lawrence River valley south of the ice sheet until *c*. 7500 cal. yr BP. Similarly, Carcaillet and Richard (2000) inferred conditions suitable for fire activity (strong winds, dry climate) from the beginning of the Holocene until *c*. 8000 cal. yr BP, speculating that during the early Holocene, dry katabatic winds from the Laurentide Ice Sheet might be related to positive fire anomalies. Above-average diatom flux, diatom concentration, dominance of *Aulacoseira distans* var. *nivalis* between 9300 and 8000 cal. yr BP and elevated lake circulation around 8700 cal. yr BP, seems to reflect northerly katabatic winds and low DOC concentrations. *Aulacoseira* taxa are typical for high water column turbulence (Bradbury and Dieterich-Rurup, 1993). One reason that a dominance of *A. nivalis* did not yield a higher inferred lake circulation signal might be that this taxon was mainly dominant in the fall sediment trap samples of the highest elevation lake, whereas the training set for lake circulation is based on summer sediment trap samples only. According to the diatom-inferred DOC concentrations, the early lake was clearer between 9000 and 8000 cal. yr BP.

The dominance of profundal chironomids *Sergentia* and *Chironomus plumosus* from 9250 to 6000 cal. yr BP and planktonic diatoms are typical for a lake that was deeper than the present lake (Brooks et al., 2007). Both taxa have cold temperature optima in the training set (Larocque et al., 2006). As in our study, chironomid assemblages were dominated by *Sergentia* and/or *Chironomus plumosus* in many temperate and high latitudinal lakes (e.g. Kurek et al., 2009; Rolland et al., 2008; Velle et al., 2005). Bigler et al. (2002) found that in various parts of the Northern Hemisphere these profundal and also mesotrophic chironomid taxa are typical following deglaciation. Mesotrophic conditions might have been present in the early Holocene, possibly associated with less tree coverage (based on the higher percentages of shrubs and lower percentages of trees) resulting in higher nutrient runoff to the lake (Hausmann and Pientiz, 2009).

Several proxies indicate an abrupt warming in the early Holocene followed by a rapidly deposited layer (RDL) at around 8500 cal. yr BP (uncorrected depth 293 cm; Table 1). Immediately before the RDL, at 295.25–293.25 cm uncorrected depth, the chironomid cold indicator *Sergentia* decreased from 44 to 12%, and the cold climate proxy *Picea* decreased from 21 to below 11%. In addition, the cold indicator diatom *Aulacoseira distans* var. *nivalis* decreased from 46 to 21%, from 296.75 to 285.25 cm uncorrected depth, and returned to 46% around 8200 cal. yr BP. In addition to evidence of warming events by diatoms, pollen and chironomids, fire activity peaked between 9500 and 8500 cal. yr BP as indicated by the charcoal record in Lake Yamaska, 300 km west of our study area (Carcaillet and Richard, 2000) suggesting that the climate was also drier. This multiproxy evidence for warmer and drier climate was followed by two RDL events recorded by two gravel layers dated at *c*. 8500 cal. yr BP (Figures 3 and 4; Table 1). Following the RDL event, the LOI of the sediments increased from 20% at 8500 cal. yr BP to 40% at 7430 cal. yr BP. The terrestrial vegetation also changed from an open-canopy forest including *Abies* (fir), *Picea* (spruce) and *Alnus crispa* (green alder) to an *Abies*-dominated closed-canopy forest with *Betula* (birch) around 7500 cal. yr BP, indicating further climate warming. In addition, chironomid-inferred August air temperatures showed a temperature peak of 13.4°C at 7430 cal. yr BP. Major sedimentological changes in the nearby St Lawrence Estuary after *c*. 8500 cal. yr BP were also observed by St-Onge et al. (2003) and St-Onge and Long (2009) who observed a drastic decrease in sedimentation rates after c. 8500 cal. yr. BP in these marine cores. The authors attributed this drastic change to the catastrophic drainage of proglacial Lake Agassiz-Ojibway at *c*. 8500 cal. yr BP (e.g. Barber et al., 1999; Lajeunesse and St-Onge, 2008) and the subsequent rerouting of the cold Laurentide Ice Sheet meltwaters from the St Lawrence River to the Hudson Bay and Strait (Teller, 1990). This rerouting of cold meltwaters could explain the inferred higher temperatures observed in the presented proxies after *c*. 8500 cal. yr BP.

After the disappearance of the meltwater in the St Lawrence River valley around 8000 cal. yr BP climatic amelioration inferred from pollen and chironomids lasted until around 5000 cal. yr BP. The *Betula* pollen zone from 7500 to 5000 cal. yr BP indicates a generally warm climate. From 8000 to 5000 cal. yr BP the chironomids indicate a period of warming of August air temperatures (Figure 5b) as well as steady increases of littoral chironomid taxa until around 5000 cal. yr BP (Figure 4b). The latter seems to reflect continuous sediment infilling of the lake basin over time.

The mid Holocene seemed to have been a calmer period in southern Quebec according to the below-average diatom-inferred lake circulation record between around 7500 and 5000 cal. yr BP, the below-average diatom production between 8000 and 4000 cal. yr BP, and the low fire activity 7000 to 3000 cal. yr BP (Carcaillet and Richard, 2000). Interestingly, farther southwest in Minnesota (350 km south and 1700 km west) varved sediments of Elk Lake, and other lake sediments throughout the Great Plains, recorded higher eolian activity (Dean et al., 1996), and also a dune field developed (Grigal et al., 1976) during the mid Holocene. We believe that the diatom-inferred lake circulation reflects wind rather than temperature, because it was not correlated to chironomid-inferred August air temperature, but was similar to the regional fire history. That might also explain why the zones of the diatom and chironomid assemblages were different. Chironomid changes are highly correlated to the terrestrial vegetation changes which do not reflect wind and respond slower to climate change as diatoms because of slower generation cycles.

### *Evidence for paleowinds from 4500 cal. yr BP to the present*

Diatom-inferred lake circulation as estimation for paleowind is supported by the strong positive correlation with diatom flux, which was highly correlated with observed June wind velocity (Hausmann and Pienitz, 2007). Upper air movement affects the surface winds, influencing lake circulation and the redistribution of nutrients which favor diatom growth (Hausmann and Pienitz, 2007). Coherence of several proxies showed that, despite the small sample size of the sediment trap samples, the diatom-inferred lake circulation patterns seem to provide a reliable estimate for local surface wind activity. In contrast to dunes (Schmeisser et al., 2010), diatoms do not preserve the wind direction. The diatom-inferred lake circulation patterns in Lac du Sommet suggest that stronger surface winds prevailed around 4500 cal. yr BP, between 3000 and 2000 cal. yr BP and during the past 250 years, preceded by a 1000 year calmer period. The periods of increased diatom-inferred lake water circulation seem to correspond with the history of forest fires (Carcaillet and Richard, 2000), with increased fire activity during the recent 3000 years indicating more frequent drought events, and increased surface winds. This pattern is not unique to our study site. Increased eolian activity indicated with 400–700 yr cycles, possibly related to solar activity, was found by Schwalb et al. (2010) in Pickerel Lake in the Great Plains after 4000 cal. yr BP. Interestingly, during the wind maxima at Lac du Sommet around 2500 cal. yr BP, eolian input was less farther southwest at Elk Lake in Minnesota (Dean, 1997) and at Lake Pickerel in South Dakota southwest of our study site (Schwalb et al., 2010). During a period of increased diatom-inferred lake stratification in southern Quebec between 1000 to 500 cal. yr BP, eolian activity, indicated by *A. granulata*, quartz and Al, was increased in the varved Elk Lake sediment record (Bradbury and Dietrich-Rurup, 1993; Dean, 1997) and in Pickerel Lake (Schwalb et al., 2010). Northeast of Lac du Sommet, in a diatom record from glacial lake Hvítárvatn (Iceland), Black (2007) found higher diatom variability around 5000 cal. yr BP indicating a change of boundary conditions. The increase in wind activity during the past 250 years was also recorded at Pickerel Lake (Schwalb et al., 2010) and corresponded with records along the coast of Maine (Buynevich et al., 2007), which show increased wind intensity, inferred from OSL dated paleoscarps, during the past 500 years, preceded by a 1000-year long calm period. Furthermore, Hubeny et al. (2006) interpreted post-‘Little Ice Age’ Pettaquamscutt River varves, three times thicker than the ‘Medieval Warm Period’ varves in New England, to reflect intensification of NAO and northward heat flux.

Wavelet analysis indicated a 900 year periodicity of diatom-inferred lake circulation, around 8000 cal. yr BP, and a 200 year periodicity of diatom-inferred lake circulation and chironomid-inferred August air temperature starting around 4500 cal. yr BP (Figure 6a, b). An absence of the 200 year cycles prior to 4500 cal. yr BP might be related to a lower sample resolution compared with 4500 cal. yr BP to present. As in our study site, reconstructed wind activity in Pickerel Lake showed centennial cycles possibly related to solar activity (Schwalb et al., 2010). A 200 year cycle was also present in the varve thickness of Elk Lake, which is reflected in eolian inputs that might be related to solar activity (Anderson, 1993). Quasi-millennium cycles and 200 year cycles are found in radiocarbon production in tree rings (Stuiver et al., 1991) and also in many lake records (Anderson, 1992; Hu et al., 2003; Schwalb et al., 2010). A high resolution CAT scan record from sediment cores from the St Lawrence River Estuary, in close proximity to our study site, revealed 1000, 400 and 200 year cycles (St-Onge and Long, 2009). Potential mechanisms are geomagnetic changes (Dean et al., 1996) or warming of the subtropics which influence atmospheric circulation (Cubasch et al., 1997). Atmospheric circulation is one way to explain simultaneous wind regime changes spatially. Climate models and spatial palynological data showed that during the last glacial maximum, Hadley cells were reduced in extent and the Jet Stream zone (Westerlies) was displaced southward (Bartlein et al., 1998). Archer and Caldeira (2008) found that, under current climate warming, the Hadley cells are expanding and the Jet Stream is showing a poleward displacement and an increase in intensity. The Jet Stream is a large-scale meandering current of stronger winds within the global Westerlies. The latitudinal position of the jet stream is a region of sharp thermal contrast between cold polar air and warm tropical air influenced by the size of the Hadley cells (Bluestein, 1993; Holton, 1992). The onset of Lac du Sommet lake circulation periodicities after the mid Holocene and the anti-correlation to the Elk Lake paleowind record (Dean et al., 1996) could be interpreted as being the result of increasing surface wind strength related to increased exposure to the Jet Stream, when central Québec became ice-free after around 6000 cal. yr BP (Dyke, 2004). The climate record from southern Quebec might have been influenced by several atmospheric circulation systems. A comparison of a high-resolution lake record with gridded atmospheric pressure data should provide more insights into climate patterns and paleo-wind archives in southern Quebec lakes sediments.

## Conclusions

The multiproxy study of Lac du Sommet allowed a regional climate reconstruction of the past 9500 years in southern Quebec. Chironomids and pollen indicated regional warming prior to the deposition of the RDLs around 8500 cal. yr BP, the time interval corresponding to the disappearance of the Laurentian Ice sheet meltwater in the St Lawrence River valley. Diatom-inferred lake circulation and diatom production was enhanced around 8700 cal. yr BP reflecting katabatic winds. A *c*. 4000 year long calmer period followed. During this calmer period the shift from *Abies* to *Betula* and the gradual increase of chironomid-inferred August air temperature by 3°C indicated a warm mid Holocene.

From 4500 cal. yr BP onwards diatom production and diatom-inferred lake circulation increased. We propose that increased wind activity starting around 4500 BP reflects exposure of Lac du Sommet in southern Quebec to the Jet Stream, which shifted northward following the retreat of the LIS. Diatom-inferred lake circulation showed 900 and 200 periodicities over short periods, which were interpreted as periodically increasing surface winds.

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