Pollen-based reconstruction of past millennium temperature in Canada

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Abstract: The climate of the last 1,000 years sets the background for 20th century climate warming. Because of this, temperature records of up to 1,000 years in length are required to better understand natural variability in the climate system. Proxy data in the form of pollen records have been used for reconstructing palaeotemperatures based upon the relationships between vegetation assemblages and historical regional climate patterns. Instrumental records are only available for the last 100 years. Since modern pollen assemblages in Canada have good responses to temperature changes, the relationships between pollen records and modern climate can be used as the basis for estimating the climate of the last 1,000 years. The present study uses the modern analogue technique to estimate temperatures for the last 1,000-year in Canada. It shows that there were four cold phases, with from 0.4° to 1.1°C negative anomalies, in the earlier half of 12th and 15th centuries, most of the 17th century, and in the mid-19th century. Also, one positive anomaly with a temperature increase of up to 1.0°C is identified at the end of 19th century. Results of the study are comparable generally to the patterns of the average temperature of the Northern Hemisphere, and show slightly greater magnitudes in temperature change than that of the Northern Hemisphere as a whole, during the last 1,000 years.

Key words: past climate, pollen data, annual temperature, past 1,000 years, Canada

Introduction

Based upon climate modeling, 41 to 64% of pre-1850 temperature variations in decadal scale are due to changes in insolation and volcanism (Crowley 2000), and more than 60% of land temperature variations in 20th century warming are due to the changes in external forcings (Stott *et al*. 2000). Therefore, there is a requirement for a longer-term perspective and a better understanding of past climate. For northern North America where observed climate records only began in the mid-19th century, a detailed pre-instrumental climate data set is needed in order to meet this requirement. Various proxy climate sources can provide such data, and the pollen record is one of them. So far, most pollen studies from North America have provided reconstructions of climate on century-to-millennium time scales (e.g., COHMAP 1988; Webb *et al*. 1993). Finer-resolution pollen records have been used to estimate climate variability over the past 1,000 years on decade-to-century time scales for north-eastern and central USA, southern Canada and the Arctic regions (e.g., Swain 1978; Bernabo 1981; Gajewski 1987, 1998; Overpeck *et al*. 1997), and to reconstruct the climate changes in time-scales of 10 to 50 year intervals (e.g., McAndrews 1988; Weninger and McAndrews 1989). But there have been few attempts to examine the patterns of regional climate change across the continent, and climate variability throughout the past 1,000 years. Therefore, the objective of this study is to fill this gap by quantitative interpretation and modeling of the existing pollen records at the regional scale for all of Canada.

To transform pollen records into units of temperature, various statistical transfer function methods have been developed (e.g., Webb and Clark 1977; Bernabo 1981; Overpeck *et al.* 1985; Gajewski 1993 *et al*.; Guiot *et al*. 1989, 1993; Yu and Qin 1997). The modern analogue approach, a more robust method with less noise, is such an example (Cheddadi *et al*. 1997). The technique is based on the principal of multiple regressions between climate variables and the pollen taxa, principal component analysis within pollen taxa, and correlation between multiple-year moving averages of the observed climate and the pollen-reconstructed climate. This approach has been successfully applied in East Africa (Bonnefille *et al*. 1990; Peyron *et al.* 2000) and Europe (Guiot *et al.* 1993; Cheddadi *et al*. 1997; Tarasov *et al*. 1999). This study attempts to apply the technique to transfer quantitative pollen data into quantitative paleoclimatic estimates, and to reconstruct the temperatures in Canada over the past millennium.

Data and Methods

Pollen data and the taxa:

Pollen data for this study are taken from the North American Pollen Database (NAPD) (COHMAP 1988; NAPD 1994). The database was compiled by Eric Grimm and John Keltner at the Illinois State Museum, starting with data originally assembled for the COHMAP project (COHMAP 1988). Screening of each NAPD site established that there are 285 fossil pollen sites and 1,050 modern pollen samples in Canada. Most fossil pollen data have radiocarbon-dates. These dates are mostly in the Holocene, and about 14% of the samples have dates within the past 1,000 years. Ages at each sample of pollen sequence have been linear-interpolated according to known radiocarbon dates.

For the data set from the NAPD sites, there are 633 fossil pollen taxa and 71 modern (surface sample) pollen taxa. To reconcile the pollen taxa, only those taxa that have occurred both in fossils and modern surface samples have been used. In total, there are 62 taxa that have frequencies higher than 95% in the total pollen counts (Table 1). The maximum and minimum percentages of each taxon are listed in Table 1 and show generally similar proportions between the past and the modern pollen percentage values although higher and/or smaller percentage values of fossil pollens do occur in comparison with those of modern pollens. Principal components analysis is used to estimate various contributions within the pollen taxa on all fossil pollen samples from 900 AD to 1900 AD. The first principal component (PC1), showing 22.14% of the total variance, was dominated by broadleaved trees (*Acer, Carya Fraxinus, Quercus, Populus, Tilia* and *Ulmus*) with positive loadings, and needle leaved trees (*Abies, Picea, Pinus* and *Tsuga*) and nonthermophilous broadleaved trees (*Alnus* and *Betula*) with negative loadings. This reflects the main contrast between the northern and the southern regions and between relatively warm and cold climates. The loading of this component (PC1)was used as a distance weighting in the analogue analyses later in the study (Table 1).

Climate data and designation of regions:

The instrument-recorded data set used in reconstructing Canada’s historical air temperature is the result of several years of research at the Climate Research Branch, Meteorological Service of Canada. It is a database of homogenized, long-term time series of monthly mean temperatures and has been specifically designed for climate change studies in Canada (Vincent and Gullett 1999). Annual temperature records from 210 stations with the earliest record in 1895 AD and the latest records in 1998 are used. Most stations have recording lengths greater than 30 years.

The locations of the pollen data and the stations with instrumental records are distributed over most regions of Canada from approximately 54° to 140°W and 40° to 75°N (Figure 1). In order to obtain time slices for applying the modern analogue technique, each pollen sequence is subdivided into 20 time periods, or 50-year intervals beginning in 925±25 and ending in 1875±25 AD. The 50-year interval is arbitrary, but is set in

Table 1: *Pollen taxa used in the palaeoclimate reconstruction.*

No	Pollen taxa	Surface pollen Max. (%)	Surface pollen Min. (%)	Fossil pollen Max. (%)	Fossil pollen Min. (%)	Weight (PC1)
1	*Ulmus*	12.74	0.29	20.14	0.12	0.36
2	*Acer*	9.62	0.37	23.58	0.10	0.34
3	*Carya*	4.27	0.05	6.30	0.10	0.32
4	*Fagus*	16.41	0.53	33.94	0.13	0.31
5	*Quercus*	34.88	0.83	42.52	0.12	0.30
6	*Tilia*	2.63	0.02	9.66	0.10	0.29
7	*Fraxinus*	9.28	0.23	16.18	0.10	0.26
8	*Juglans*	2.47	0.03	5.29	0.10	0.24
9	*Platanus*	1.44	0.01	6.14	0.10	0.22
10	*Tsuga canadensis*	12.84	0.06	39.00	0.10	0.20
11	*Ambrosia-type*	47.69	1.42	52.02	0.10	0.09
12	*Castanea*	0.98	0.01	1.24	0.10	0.08
13	*Ostrya-type*	9.17	0.16	9.03	0.16	0.07
14	*Liquidambar*	0.46	0	0.81	0.10	0.06
15	*Pinus undiff.*	86.86	12.75	87.89	0.13	0.05
16	*Cerealia*	1.10	0	39.56	0.10	0.04
17	*Iva*	1.04	0	2.58	0.13	0.04
18	*Populus*	34.43	0.24	37.67	0.10	0.04
19	*Rumex*	13.14	0.15	2.68	0.10	0.04
20	*Celtis*	0.53	0	1.63	0.16	0.02
21	*Cephalanthus*	1.56	0	2.88	0.10	0.02
22	*Nyssa*	0.19	0	2.60	0.10	0.02
23	*Tsuga heterophylla*	52.36	0.18	34.00	0.13	0.02
24	*Ephedra*	0.25	0	0.75	0.11	0.01
25	*Pinus subg. Strobus*	46.30	1.45	49.87	0.16	0.01
26	*Poaceae undiff.*	95.00	5.87	90.54	0.10	0.01
27	*Brassicaceae*	75.00	0.13	2.58	0.10	0
28	*Corylus*	6.48	0.10	2.31	0.10	0
29	*Cupressaceae/Taxaceae* undiff.	50.60	0.41	0	0	0
30	*Larix/Pseudotsuga*	10.38	0.16	8.54	0.10	0
31	*Myricaceae*	15.57	0.55	0.99	0.18	0
32	*Aquifoliaceae*	8.86	0.03	2.06	0.15	-0.01
33	*Chenopodiaceae/Amaranthaceae* undiff.	37.93	0.59	5.03	0.10	-0.01
34	*Empetrum-type*	3.04	0	15.78	0.18	-0.01
35	*Rubiaceae undiff.*	63.66	0.20	0.82	0.30	-0.01
36	*Shepherdia canadensis*	1.54	0.01	73.51	0.10	-0.01
37	*Sphaeralcea*	5.56	0.01	7.69	5.61	-0.01
38	*Asteraceae subf.*	14.73	0.27	18.10	0.10	-0.02
39	*Fabaceae*	65.63	0.16	63.57	0.10	-0.02
40	*Rumex/Oxyria digyna* undiff.	2.86	0.01	9.66	0.10	-0.02
41	*Selaginella*	15.56	0.06	1.54	0.10	-0.02
42	*Apiaceae*	0.57	0	4.53	0.10	-0.03
43	*Asteraceae undiff.*	13.21	0.17	10.71	0.11	-0.03
44	*Sarcobatus vermiculatus*	10.00	0.05	6.14	0.10	-0.03
45	*Saxifragaceae*	13.73	0.11	9.73	0.16	-0.03
46	*Thalictrum*	3.81	0.04	16.81	0.10	-0.03
47	*Tsuga undiff.*	25.44	0.54	14.12	0.13	-0.03
48	*Caryophyllaceae*	50.91	0.35	1.61	0.10	-0.04
49	*Ericales undiff.*	5.08	0.06	11.59	0.10	-0.04
50	*Oxyria digyna*	25.66	0.14	20.28	0.10	-0.04
51	*Ranunculaceae undiff.*	53.77	0.09	16.67	0.10	-0.04
52	*Artemisia*	90.74	1.09	77.87	0.10	-0.05
53	*Pinus subg. Pinus*	79.48	1.81	79.48	0.18	-0.05
54	*Rosaceae undiff.*	92.68	1.55	8.16	0.10	-0.06
55	*Tsuga mertensiana*	13.25	0.03	57.41	0.48	-0.06
56	*Ericaceae*	92.70	5.86	75.61	0.11	-0.07
57	*Salix*	97.34	3.79	1.94	0.11	-0.07
58	*Betula*	91.00	19.09	87.44	0.13	-0.08
59	*Abies*	20.27	1.15	32.32	0.10	-0.11
60	*Cyperaceae*	95.18	6.24	66.67	0.10	-0.11
61	*Alnus*	83.17	9.31	87.76	0.12	-0.18
62	*Picea*	90.98	20.58	86.29	0.11	-0.20

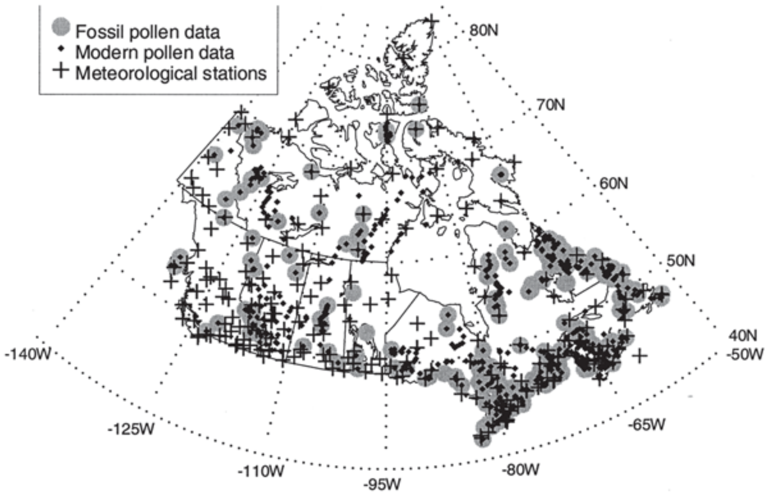

Figure 1: *Location of fossil and modern pollen data sites and meteorological stations used in the study*

consideration of the need to fit the pollen sample resolution with the current database and the numbers of statistical samples. Additionally, samples dated between 850 AD and 900 AD are also analyzed in the same manner to give the time slice of 875±25 (or pre-1000), and samples after 1900 AD at the top of the cores of the pollen sites are all grouped into the last time slice of 1925±25.

Considering that Canadian climate varies from region to region, this study presents information on climate change on a regional basis. Site-by-site correlation technique is applied to find similarities between meteorological stations and to define spatial patterns with coherent temperature records (Yu 1996; Harrison *et al.* in press). As a result, Canada is subdivided into four core-groups composed of 170 stations using the 30-year mean monthly temperature of 210 stations and a cut-off values of correlation coefficient (*r*) e”0.98. They are the west coast (Region 1), the western mountains (Region 2), central areas (Region 3) and eastern areas (Region 4). These regions are consistent with modern climate patterns in Canada based on temperature (e.g., Philips 1990). Fossil pollen sites in 21 groups (850AD to 1900AD) were then assigned to each region for purposes of plotting the regional temperature curves (i.e., 6, 25, 23, and 169 pollen sites for Regions 1, 2, 3 and 4, respectively).

Analogue method for reconstruction of climate:

The analogue method uses pollen assemblages from the past and systematically compares these with a large set of modern assemblages derived from, as wide as possible, a range of climates within the same biogeographic zones. Climate variables are then estimated from the present climate associated with those assemblages that are selected as analogues (Guiot *et al.* 1993).

First, to find a set of closest modern analogues of the fossil sample, the Euclidean distance between the pollen assemblages after square-root transformation of the pollen percentages are calculated as follows:

$$D_{it}^{2} = \sum_{j=0}^{m} W_{j}^{2} (M_{ij}^{1/2} - F_{tj}^{1/2})^{2} \qquad (1)$$

Where $\mathbf{D_{it}}$ is the distance between pollen samples, $\mathbf{W_j}$ is the weight in pollen taxon **j** (out of **m** taxa), $\mathbf{M_{ij}}$ and $\mathbf{F_{tj}}$ are the relative frequencies of pollen taxon **j** in the modern pollen sample **I,** and fossil pollen sample **t**, respectively. The taxon loading on the dominant principal components listed in Table 1 are used to weight the taxa in the calculation of the distances between pollen samples (W_j).

The reconstructed climate value for each fossil sample is the weighted distance mean of climate values:

$$R_{t} = (\sum_{i=1}^{s} C_{i} / D_{it}^{2}) / (\sum_{i=1}^{s} D_{it}^{-2}) \qquad (2)$$

Where $\mathbf{R_t}$ is the reconstructed climate variable at pollen site **t**, $\mathbf{C_i}$ is the observed climate variable (out of **s** stations), $\mathbf{D_{it}}$ is the distance calculated using Equation (1). **s** is numbers of observed climate sites surrounding the pollen site **t** in a certain radius range. After several tests of different ranges, we found 9-degrees in latitude or longitude is a good radius range as it showed the best analogue.

All pollen samples at the 237 sites in 22 groups (ages falling into the periods 850AD to 1950AD) are calculated to provide palaeotemperature estimates following the above processes. Finally, if more than one sample occurs within a group at each site during the 50-year period, an average of the calculated temperature is taken.

Results

Relationship between modern pollen assemblages and instrument-recorded temperature:

The relationship between pollen taxa and climate was explored by multiple regressions between 30-year means of monthly temperature and the log-transformed frequencies of the pollen taxa in the modern pollen sites, as measured by the correlation coefficients between the climate variables and the pollen taxa at 1,050 modern pollen samples. The best fit of the pollen data is annual temperature ($r = 0.82$). The fit is relatively high for January, July, summer (June, July and August) and winter (December, January and February) (with r from 0.69 to 0.65) in the same samples of the series. The good correlation of the 1,050 surface samples suggests that pollen data do reflect the regional vegetation and climate for a catchment size ranging from 10^2 km^2 to 10^3 km^2.

Validation of pollen-based reconstruction is accomplished by comparison with the instrumental temperature records of the past 100 years. Two pollen sites, namely No. 102 (Humber Pond 3, Ontario (Weninger and McAndrews 1989)) and No. 48 (Crawford Lake, Ontario, data provided by McAndrews (NAPD 1994)), have broad-scale records at 10 to 30-year intervals covering the past 100 years (Figure 2a and 2b). Pollen site No. 185 (Pasqua Lake, Saskatchewan (McAndrews 1988)) is a unique site with high-resolution records for every 2 years in the last 100 years (Figure 2c). Three meteorological stations (a. M-6137287: 43.02N, 79.17W, 98 m asl., b. M-6139445: 43.00N, 79.27W, 175 m asl. and c. M-4016560: 50.43N, 104.67W, 577 m asl.) with annual temperature data are selected to compare the reconstructed temperatures. Station locations have a maximum distance of 0.7° (ca 80 km) radius range around the pollen sites. The relationships between actual temperatures and estimated temperatures are measured by correlation between the two series (Figure 2). Correlation coefficients (r) for the three sites are 0.77, 0.50 and 0.53, respectively, and are significant at the 0.95 confidence level. The good statistical fit of multiple-year moving averages suggests that the multiple-annual reconstruction is more reliable than a single-annual reconstruction in using pollen data to reconstruct temperature.

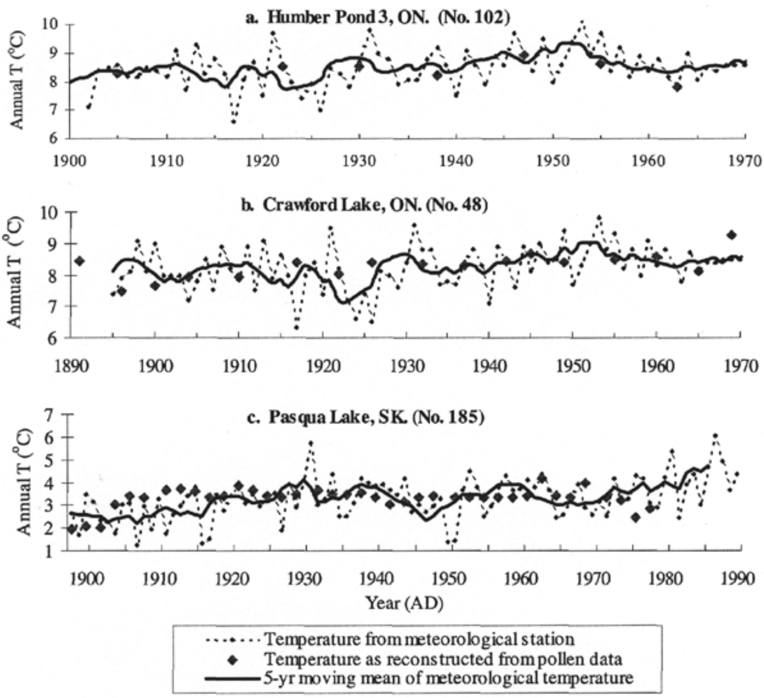

Figure 2: *Comparison of pollen-based temperature estimates and instrumental temperature data.*

Although the pollen records of the three sites have 2 to 30-year intervals, they are still low resolutions compared with 1-year intervals of instrumental records. Therefore, even if the correlations are significant at the 95% confidence level, they are still rather low as some temperatures may be inversely proportional to the pollen records. It is possible that a lower pollen resolution record may give a higher correlation with recorded temperature just because there are fewer chances of being ‘wrong’. These problems can be solved by the adoption of a high-resolution sampling scheme in future pollen studies

Temporal sequence of reconstructed climate during the past 1,000 years:

Reconstructed temperatures during the past 1,000 years are plotted in time sequence curves (Figure 3). Using each 50-year interval, the temperature anomalies are expressed by the reconstructed temperature

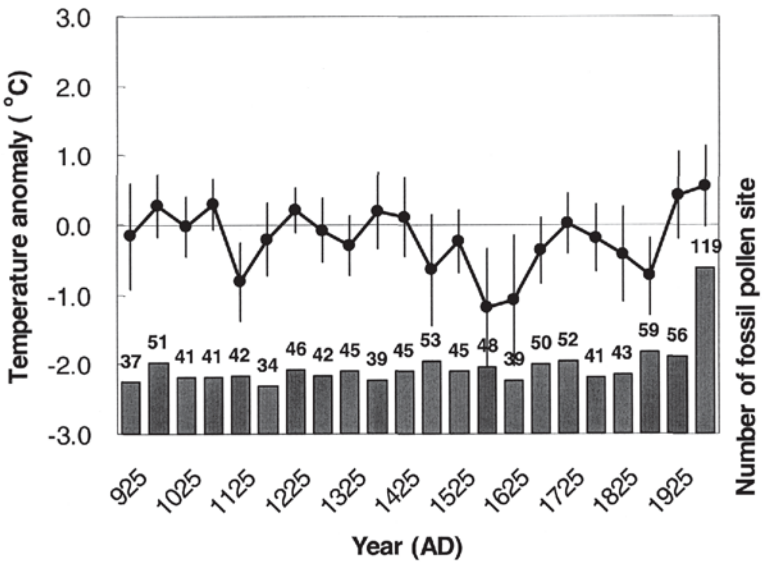

Figure 3: *Reconstruction of average annual temperature (°C) anomaly in Canada during the past 1,000 years.*

means minus that of the 1,000-year mean. The year at the X-axis is the central age of each 50-year group. The bars in the lower part represent the number of pollen sites in each interval. Vertical lines are error bars computed at the 0.95 confidence level of the data spatial series.

Figure 3 shows that the reconstructed temperature during 925-1075 AD was about 0.3-0.5°C warmer than normal. The temperature anomaly decreased 0.3°C around 1125 AD. A warm phase occurred during 1175-1425 AD with a slightly small fluctuation around 1325 AD. Afterwards, a few cold phases occurred in 1475 AD, 1575-1675 AD and 1775-1875 AD, with temperatures 0.5°C, 1.1°C and 0.5 colder than normal, respectively. The temperature increased and became much warmer after 1875 AD. This curve suggests four cold phases during the past 1,000 years with the coldest period during the 17th century and three secondary cold phases during the earlier half of the 12th and 15th centuries and the mid-19th century, and an increase in temperature at the end of the 19th century until present.

Figure 4 shows the four regional temperature anomaly curves for Canada. Vertical lines are error bars computed at the 0.95 confidence level of the data spatial series. Dash lines are for the cases with samples less than 2 and could be unreliable reconstructions. The maximum and minimum of the temperature anomalies in each region are shown in 4e. The sample sizes in each region are not equal, particularly in Region 1 (with only 6 sites, not analyzed). Three common cold phases occurred in the three regions of Canada (Figure 4b, 4c and 4d). The first was centred in the period 1075-1225 AD in Region 2, 1075-1275 AD in Region 3, and about 1125 AD in Region 4. The second occurred during 1425-1675 AD in Region 2, 1475-1575 AD in Region 3 and 1475-1674 AD in Region 4. The third cold phase was more synchronous and occurred in the three regions around 1825-1875 AD.

Discussion and Conclusions

The reconstructed temperature curve of the present study can be compared with the curve of Northern Hemisphere average surface temperature (Mann *et al.* 1999) showing a general decreasing temperature from about 1200 AD to 1900 AD. A few cold phases with negative temperature anomalies of less than -0.2°C occurred around 1340 AD, 1460 AD, 1590 AD, 1660-1700 AD and 1820-1900 AD. These have been captured by the present study with slight discrepancies in timing. The anomalies are also slightly larger (-0.4 to -1.1°C) than those for Northern Hemisphere average (-0.2 to -0.4°C). This can be explained by the fact that the hemispheric average is the result of inter-regional averages around the hemisphere. Therefore it can be expected to be much smoother than that of a region of Canada.

The regional sequences between 900 AD and 1900 AD show different temperature amplitudes (Figure 4e), with positive temperature anomaly ranges between +0.51°C and +1.79°C, and negative temperature anomaly between –1.22°C and –1.46°C. A pollen-based reconstruction of the temperature sequences (Gajewski 1988) indicated a similar timing in the eastern North America where this warm phase occurred pre-10th century and a cold phase occurred afterwards. For the regions of eastern North America (Gajewski 1998) and Canada (the present study), temperatures at the end of the 19th century are higher than at any previous time within the last millennium; this shows clearly the start of the global warming event. In comparison, however, the European Mediaeval Warm Period ca. 1000-1300 AD was not found in all regions of Canada based upon the present study, although Region 3 shows a strong warming signal pre-1000 AD.

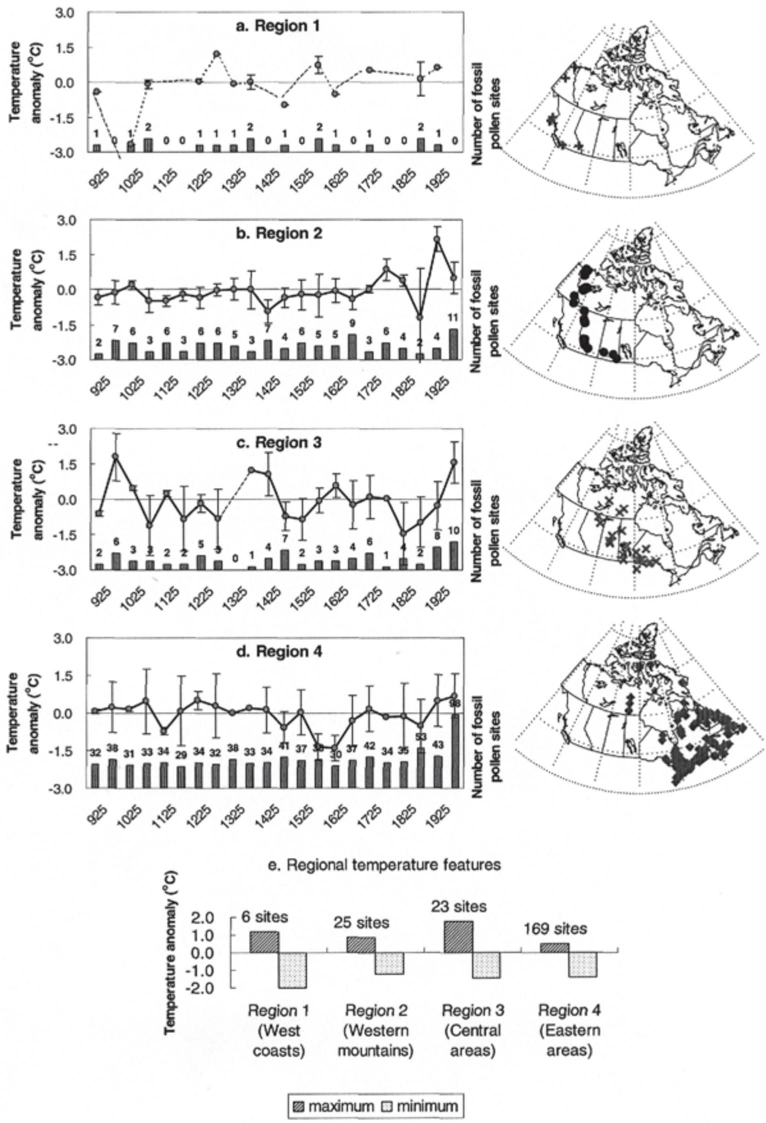

***Figure 4:** Reconstruction of regional annual temperature (°C) anomalies in Canada during the last 1,000 years.*

Studies of regional temperature reconstruction based on pollen data can provide independent regional records for inter-regional comparison. The general temperature anomaly sequence from the 16th to 19th century in Region 2 (Figure 4c) is consistent with a reconstruction of ground surface temperature based upon borehole data from Northwest Territories, Alberta, Saskatchewan and Manitoba (Majorowicz and Skinner 2001), and both show a trend of decreasing temperature pre-1600 AD, slightly higher temperatures at about 1650 AD, lower temperatures during 1750-1850 AD, and higher than normal temperature after 1900 AD. However, the two curves have discrepancies in magnitudes; this could be due to the fact that the work of Majorowicz and Skinner (2001) was based on groundwater temperature records.

Monitoring of the climate system for evidence of change has a fundamental requirement of long-term homogeneous data sets. Instrumental records in Canada are only about 100 years in length. Therefore, long-term data sets will largely rely on the proxy data from sediments. This study has presented a palaeotemperature reconstruction back to 900 AD based on a pollen data set. There are still geographical gaps in the reconstruction, for example in northern Canada. The NAPD database only provided 71 modern pollen taxa; this limits the analogue to the fossil pollen taxa. Moreover, refinement of the climate reconstruction will be possible only after improvement of fine-palynological analysis and high-resolution pollen data sets, and multiple proxy data synthesis across the whole Canada.

Acknowledgements

The research was supported by the CCRM, Environment Canada (No. KM040-0-2233) and Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (CXNIGLAS-A02-06). The authors are very grateful to Mr. Walter Skinner (Environment Canada) for his constructive discussion and comments on the project, to two anonymous referees for their critical comments, and to Dr. Bernie Thraves (University of Regina) for polishing the English of the paper.

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