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## Reconstruction of high resolution ground temperature histories combining dendrochronological and geothermal data

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### Abstract

In an attempt to obtain robust records of past climatic variations, geothermal temperature–depth data have been combined with dendrochronological data to yield high resolution ground temperature histories. Since the resolution of the dendrochronological record and the ground temperature history inferred from geothermal data are different, comparison of these records is made possible by multiplying the dendrochronological data by the model resolution matrix for the geothermal data inversion. Under this condition, we find that a simple transformation between tree-ring indices and ground temperature changes allows us to interpret tree-ring widths in terms of ground temperatures, thus yielding a high resolution ground temperature history which explains the observed subsurface temperature regime. The linear transformation relating the ground temperature changes and average variations from the tree-ring chronology was found to be  $\Delta T_g = 9.93 I_{\text{average}}$ .

### 1. Introduction

It is now well established that ground temperature histories (GTHs) can be determined from the analysis of temperature perturbations measured in boreholes [1–7]. For overviews see [8–10] and for a collection of works on the subject see [11]. Several analyses of geothermal data have revealed a marked warming in the last century. However, the warming inferred is not uniform but displays a spatial variability consistent with the predictions of general circula-

tion models (GCMs) for increased concentrations of atmospheric carbon dioxide [12]. For example, the warming during the last 100 years inferred in Alaska is between 2° and 4°C [3], 1–2°C in eastern and central Canada [4,7], and less than 1°C in part of the western U.S. [5,13]. About half of the inferred warming for this century in eastern Canada appears to be due to the recovery from a colder period, which might be associated with the Little Ice Age, also documented from geothermal data.

In all the above analyses, the inferred temperatures are robust and independent of inversion procedures used to interpret the subsurface climatic signal [14]. Reconstructed GTHs have, however, limited time resolution for past thermal events. Studies of

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the resolution of past climatic events from geothermal data [15,16] have shown that the estimated model parameters are obtained as averages over a time interval centered on an event; the averaging interval is at least 60% of the time lapsed since the event. That is, the signal recovered by inversion for a climatic event which occurred 100 years before present (y.B.P.) is spread over 60 yr, and for an event which occurred 500 y.B.P., it is stretched over 300 yr. This relation between time and the temporal spread of the recovered signal varies linearly with the time of occurrence, although it is not generally temporally symmetric.

Thus, although GTHs from geothermal data are a direct record of paleotemperatures and provide a good estimate of the integrated ground surface temperature changes, the resolution of the method decreases rapidly with time as a result of the diffusive character of the heat conduction process.

Proxy records of past climate, such as dendrochronological data, on the other hand, have yearly resolution but their interpretation as a climatic indicator is not always straightforward (see fig. 5.10 in [17], page 236). A complicated interaction of trees with their environment and a host of different factors which may be biotic (tree age, competition, insect defoliations, pathogens, etc.) or abiotic (climate, soil factors, fire, etc.) control the annual tree growth.

For some species of trees, and in some high-latitude regions, temperature is a growth-limiting factor, while in low latitudes precipitation has a dominant control over growth; in these cases the growth-climate relationship is relatively simpler. In general, however, a tree responds in a nonlinear fashion to many factors affecting its growth and a reduced or increased annual ring width may result from different combinations of the same factors (e.g., [17], page 234).

Thus, tree rings represent a high (annual) resolution but proxy measure of climate change, whereas borehole temperatures produce low resolution but a direct record of past ground temperature. In this note we use a simple method for combining geothermal data with a dendrochronological record in order to interpret the dendrochronological record in terms of ground temperature variations, thus yielding a ground temperature history with higher resolution than obtained from geothermal data alone; in other words,

we use the ground temperature history from geothermal data to calibrate the tree-ring data. For the site studied the high resolution GTH resulting from the combination of geothermal and dendrochronological data satisfactorily explains the observed subsurface temperature perturbation observed in a suite of boreholes from the same general region.

## 2. Theory

Superposition of a background temperature  $T_b(z)$  and  $T_1(z,t)$  the temperature perturbation arising from the time-varying surface temperature can be written as:

$$T(z,t) = T_b(z) + T_1(z,t) \quad (1)$$

where  $T(z,t)$  is the observed temperature at depth  $z$ .  $T_b(z)$ , does depend on time but, if evaluated in a deep enough region of the temperature log, its rate of change is small for our time of interest. In a layered media, the background temperature is conveniently expressed as:

$$T_b(z) = T_0 + q_0 \Sigma \left( \frac{\delta z}{\lambda} \right) \quad (2)$$

where  $T_0$  is a reference (quasi-steady state) surface temperature;  $q_0$  is the surface heat flow;  $\lambda$  is the thermal conductivity; and the quotient  $\left( \frac{\delta z}{\lambda} \right)$  is the thermal resistance of individual layers [18]. In practice, a subsurface temperature anomaly  $T_1(z,t)$ , caused by changing temperature at the Earth's surface, can be identified as departures to the quasi-steady state by (Fig. 2):

$$T_1(z,t) = T(z,t) - \left\{ T_0 + q_0 \Sigma \left( \frac{\delta z}{\lambda} \right) \right\} \quad (3)$$

A surface temperature history,  $T_1(0,t)$ , can be approximated by the average surface temperature over a series of  $K$  time intervals of duration  $\Delta$ :

$$T_1(t) = T_k, \quad (k-1)\Delta \leq t < k\Delta \quad (4)$$

and  $k = 1, \dots, K$ .

Eq. (3) can then be written as [16]:

$$\Theta_j = A_{jl} X_l \quad (5)$$

where  $\Theta_j$  is the measured temperature anomaly at depth  $z_j$ , corrected for thermal conductivity variations and the heat production from the surface to that

depth if necessary.  $X_i$  is a vector containing the unknowns  $\{T_1, \dots, T_K\}$ , and  $A_{ji}$  is a matrix, each row of which contains the  $K$  elements formed by evaluating the difference between complementary error functions at depth  $z_j$  and times  $t_{k-1}$  and  $t_k$ :

$$A_{jk} = \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_k}}\right\} - \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_{k-1}}}\right\} \quad (6)$$

where  $\kappa$  is the thermal diffusivity.

This yields an overdetermined system of linear equations which can be solved by singular value decomposition (SVD) [13,16,19–22].

The model resolution matrix is defined as [21]:

$$\mathbf{R} = \mathbf{V}\mathbf{V}^T \quad (7)$$

where  $\mathbf{V}$  is an orthonormal matrix of normalized eigenvectors spanning model space, resulting from the singular value decomposition.  $\mathbf{R}$  depends only on the data kernel of  $\mathbf{A}$ ; that is, the experimental geometry and the initial assumptions applied to the problem.  $\mathbf{R}$  is independent of the values of the data themselves. The physical interpretation of  $\mathbf{R}$  can be understood by writing (e.g., [21])  $\mathbf{T}^{est} = \mathbf{R}\mathbf{T}^{true}$ ; that is, the model parameters are perfectly resolved if  $\mathbf{R} = \mathbf{I}$ , where  $\mathbf{I}$  is an identity matrix; if  $\mathbf{R}$  does not equal an identity matrix, the estimated model parameters are recovered as *averages* of the neighbouring true model parameters. In other words, a multiplication of a time series by the model resolution matrix is equivalent to filtering the time series. This is the model resolution matrix property used in the present work.

A forward approach has been attempted as well, but it has been found that the factor relating ground temperature and proxy data is dominated by shallow depths and the most recent times, such that the transfer functions obtained are not robust unless a ‘weighting’ function is introduced for compensation [23,24]. This will be reported elsewhere (Beltrami, 1995. manuscript in preparation).

### 3. Data

#### 3.1. Tree-ring data description

An 802 yr dendrochronological series developed by Archambault and Bergeron [25] near Rouyn

(Québec) was used in this work. The chronology was built from 38 specimens of the *Thuja occidentalis* L. (Northern white cedar) growing in 16 different homogeneous sites spread over an area of approximately 25 km<sup>2</sup>. The use of isolated trees ensures that they do not share growth anomalies caused by stand dynamics effects or site-specific factors and that common growth patterns, most probably caused by the common climatic forcing, will be maximized in the averaging process.

Tree-ring series often show an age-related decrease in ring width after the early years of a tree’s life, or growth anomalies related to, for instance, growth enhancement after a forest fire. This unwanted noise specific to a single tree is routinely extracted by fitting a more or less flexible growth curve to the series and dividing each yearly ring width by the corresponding value of the growth curve [17]. The resulting indices are most often stationary and can then be statistically compared to yearly fluctuations of climatic variables. However, the standardizing procedure has the obvious drawback that, if it is performed with a very flexible growth curve, it filters out a large proportion of the chronology’s long term climatic information [26]. Furthermore, elimination of growth curves from *each individual tree-ring series* involves the fitting of different arbitrary functions to the raw data; thus the filtering is not homogeneous from tree to tree. Most important, the individual tree-ring series are not of the same duration, such that information on frequency variation varies irregularly through time (Luckman, 1995, pers. commun.). To bypass these problems, an absolute tree-ring chronology was obtained by simply dividing each ring width series by its mean, thus giving each tree the same weight, prior to averaging the different sites into a site chronology. Great care was taken to delete from the series the accelerated growth periods related to any growth anomaly that could be confidently associated with a known forest fire. The absolute chronology which retains most of the common long-term growth variations is shown in Fig. 1a.

#### 3.2. Geothermal data description

Analysis of a large set of geothermal data have shown that ground temperature histories for a large

area of central and eastern Canada are remarkably similar [27,28], both in terms of the magnitude of modern warming and the timing of the cold period known as the Little Ice Age. Whereas short-term changes represented in meteorological data are correlated over a scale of 1200 km [29], climatic changes inferred from geothermal data appear correlated over larger scales [28]. It is to be expected that inter-annual variability in meteorological data would dominate the record over short time scales; in the case of ground temperatures, the Earth filters out the high frequency variation and records only the long-term climatic trends. Accordingly, the geothermal data considered for this work can be taken from practically any part of eastern Canada. Thus, the quality of the data was the most important factor for the selection of the site for this preliminary study.

Temperature–depth logs measured by Nielsen and Beck in 1989 [30] include a continuous temperature

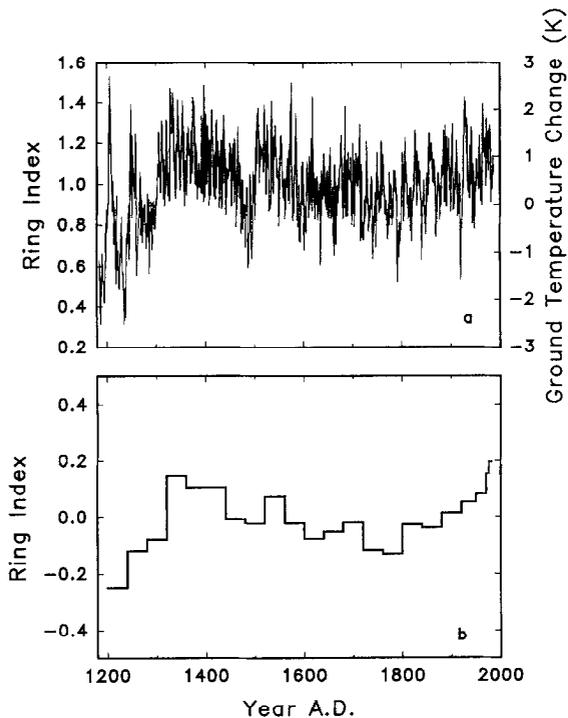


Fig. 1. (a) Absolute 802 yr tree-ring chronology (1186–1987) for *Thuja occidentalis* L. from Lake Duparquet in Québec [24]. The right-hand axis indicates the ground temperature change after the calibration (see text). (b) Tree-ring index averages of the series in a.

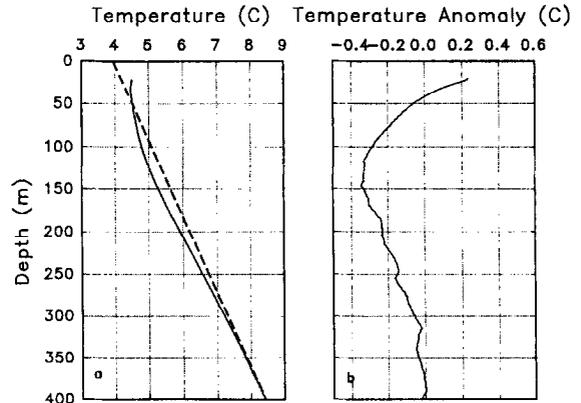


Fig. 2. (a) Temperature–depth log for Minchin Lake (solid line) measured by Nielsen and Beck [28]. The dashed line indicates the extrapolated reference gradient from the deepest part of the temperature log. The intersection of this line at the surface represents the long-term mean ground temperature. (b) Reduced temperature resulting from the removal of the reference profile from the measured temperature log. Comparison of a and b reveal a discrepancy in the magnitudes of the temperature perturbation with depth. This arises because a shows the temperature log without the thermal conductivity corrections (Bullard plot; [18]) required to evaluate correctly the magnitude of the temperature perturbation.

log at Minchin Lake (Ontario). This temperature–depth log has been analyzed many times by different groups as a test for different inversion schemes and yields similar results for the inferred surface temperature history [6,14]. Furthermore, the subsurface thermal properties at this site are rather well characterized by 77 thermal conductivity measurements. Finally, the GTH inferred from this single log does not deviate significantly from the average solution for southern Canada given by Beltrami and Mareschal in 1992 [28]. Fig. 2a shows the full temperature–depth log, and Fig. 2b shows the subsurface temperature anomaly resulting after the removal of the steady-state gradient evaluated in the deepest part of the temperature profile by the Bullard technique [18] or, as in this case, determined directly from the inversion [16].

#### 4. Analysis

A GTH for Minchin lake has been determined by several investigators as part of a benchmark test of

procedures [14]. Our GTH was obtained by inverting 400 m of the temperature–depth profile (Fig. 2) using singular value decomposition (SVD) for a model consisting of a series of 22 step temperature changes set at 5, 10, 30, 60, and then every 40 yr to 780 y.B.P., with the singular value cut-off set at 0.025 of the maximum singular value. The values for the reference or initial surface temperature (4.15°C) and the quasi-equilibrium heat flow density (32.33 mW/m<sup>2</sup>) were evaluated simultaneously. This type of inversion has been described in detail in [16] and [22].

To make the tree-ring series (from 1980 to 1200 A.D.) compatible with our model for inversion of geothermal data, a series of average departures from the mean was constructed from the original yearly ring-index series for the same time intervals as for the GTH model. This series is shown in Fig. 1b. To be able to compare the averaged tree-ring series with a GTH from geothermal data, it is further necessary that the ring series be filtered through the same process, because heat diffusion affects the details of the GTH. That is, the series must be averaged in the same fashion as the loss of resolution of the GTH indicates. This procedure can be accomplished simply by multiplying the averaged tree-ring series by the model resolution matrix from the geothermal data inversion. Smoothing the time series using running averages does not yield appropriate results since running averages have no physical significance.

The model resolution matrix relates the estimated parameters to the true parameters in a way that incorporates the physics of heat diffusion; thus, a multiplication of the averages tree-ring series by the resolution matrix is equivalent to inverting the tree-ring series (assuming that the tree-ring width is a representation of ground temperature changes).

The averaged tree ring time series was first expressed as a series of departures from the overall mean, normalized by its range, and then multiplied by the model resolution matrix to yield the filtered series.

The ‘filtered’ or ‘diffused’ tree-ring series can now be directly compared with the GTH derived from geothermal data. The filtered series and the GTH are shown in Fig. 3.

The two time series in Fig. 3, have both similarities and marked differences. Both series reach their

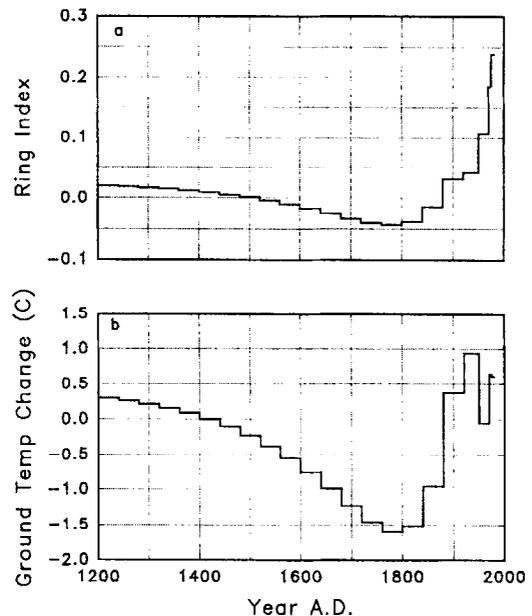


Fig. 3. (a) ‘Filtered’ tree-ring chronology resulting from the product of the tree-ring index averages series of departures from the overall mean (Fig. 1b) by the model resolution matrix. (b) GTH obtained from inversion of the geothermal data. Values of the temperature and tree-ring indices are given as averages according to the model described in the text.

maximum values this century, have local minima centered around 1800 A.D., and return to values less than those of the present day at about 1500 A.D.

It must be pointed out that a given subsurface temperature profile generated, as a forward problem, from a yearly record, is different than the equivalent temperature profile obtained from an average of the same series. Thus, when we attempt to recover a calibration factor from the observed temperature profile in a borehole for a proxy series of averages, a correction must be carried out to eliminate this problem. This error, inherent to the averaging procedure and as inferred from synthetic data tests, can produce on the order of 5% uncertainty on recovering a known factor relating ground temperature and a proxy data series (Beltrami, 1995, manuscript in preparation).

A second step in our analysis involves the direct comparison of the GTH with the filtered ring time series. This relation is shown in Fig. 4, where the GTH from geothermal data and the filtered series have been plotted against each other. Evaluation of

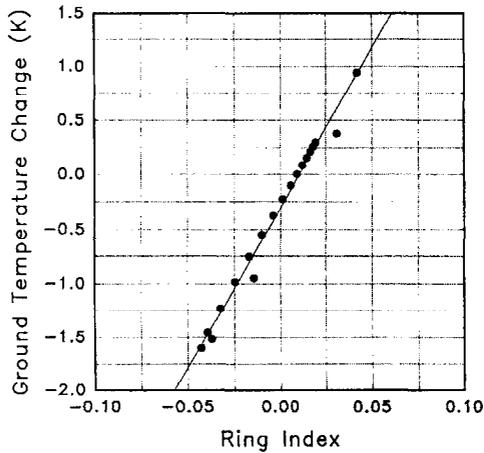


Fig. 4. Relation between tree-ring indices and ground temperature changes. The most recent 30 yr have been removed to determine this relation (see text).

the GTH–tree ring relation was carried out after deleting the first 30 yr, because we do not have complete information on the ground temperature for this period, since the temperature–depth log lacks data for the first 20 m.

The relation between these quantities appears to be not only regular but, indeed, linear and is given by:

$$\Delta T_g = 29.47I^f - 0.31 \quad (8)$$

where  $\Delta T_g$  is the temperature change from the initial or reference mean temperature ( $^{\circ}\text{K}$ ) and  $I^f$  is the — filtered and normalized — average ring index from the absolute chronology.

To find a relation between the ground temperature changes and the *unfiltered* 40 yr tree-ring series ( $I_d$ ), it is necessary that this relation be transformed, by multiplying the slope of the series by the ratio of the unfiltered and filtered ranges, that is:  $I_u^f = \frac{\alpha_f}{\alpha_u} RI_d$ , where the subscripts f and u refer to filtered and unnormalized series and  $\alpha$  is the respective data range. This yields:

$$\Delta T_g = 9.93I_d - 0.31 \quad (9)$$

If we assume that this linear relation between tree rings and ground temperature holds throughout the time interval used to derive Eq. (9), we can attempt to use such a relation to convert the averaged unfiltered values of the complete tree-ring series into

equivalent ground temperature changes. This yields a reconstructed ground temperature history with significantly higher resolution than that obtained from geothermal data alone. As well, the tree rings have now been calibrated against ground temperature changes. Fig. 5 shows the GTH from geothermal data alone and the high-resolution GTH obtained from the combination of geothermal and tree-ring data.

A fundamental requirement for the acceptance or rejection of such a reconstructed GTH is that this thermal history must explain the observed subsurface thermal regime. This can be easily verified by using the reconstructed ground temperature series as a forcing function at the Earth's surface and solving the forward problem.

The subsurface profile generated from the corrected tree-ring ground temperature reconstruction appears similar to the observed temperature anomaly profile and it is shown in Fig. 6. Shown in this figure are the subsurface profiles generated for the full averaged proxy data and for the same series without the first 30 years. The agreement between observation and the latter of these profiles is better because the most recent temperature changes are not well represented in the measured temperature logs, because data is generally taken only below the water table and below the depth for which seasonal variations of ground surface temperature affect the temperature–depth profile.

There is, however, part of the subsurface profile

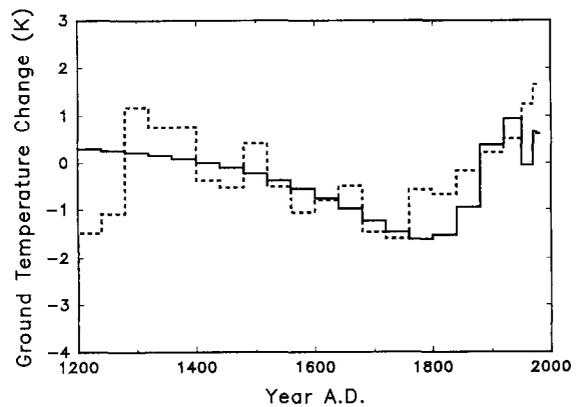


Fig. 5. Comparison of the ring-index average series (Fig. 1b) in terms of ground temperature changes (dashed line) and ground temperature history from geothermal data used here (solid line).

remaining unexplained. The assumption that ground temperatures determine the average growth of tree rings is certainly valid, as shown in Fig. 4, but there are in the tree-ring series, non-climatic factors (e.g., growth trend or climatic effects such as June temperature and precipitation, as found by Archambault and Bergeron in 1992 [25]), which might be affecting the tree-ring ground temperature reconstruction.

In an attempt to find out whether the ground temperature–tree ring relation can be used to reconstruct the ground temperature history from the tree-ring series at several resolutions, the 20 yr averages and yearly variation of ground temperature, were transformed by Eq. (8), after scaling by the normalizing factors, to obtain their respective tree-ring ground temperature reconstructions.

It would be expected that the subsurface temperature profile from these reconstruction would fit the lower part of the profile but disagree on its shallow part, because of the filtering carried out by the Earth on high-frequency temperature variations [31] and because of the different averaging intervals in the

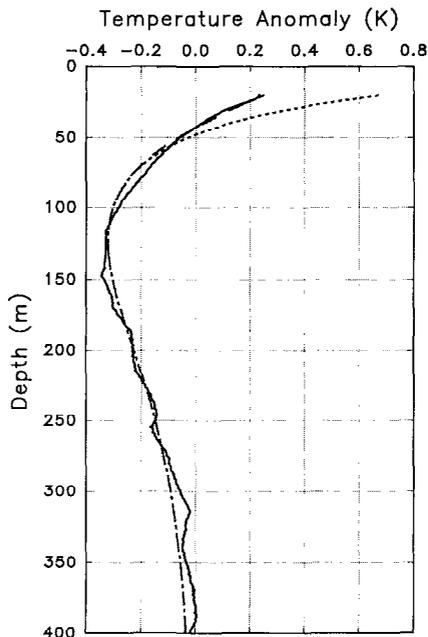


Fig. 6. Subsurface temperature perturbation from observations (solid line), subsurface anomaly generated from the full 40 yr average tree-ring ground temperature reconstruction (short dashes) and subsurface anomaly for the previous with the first 30 years removed (long dash).

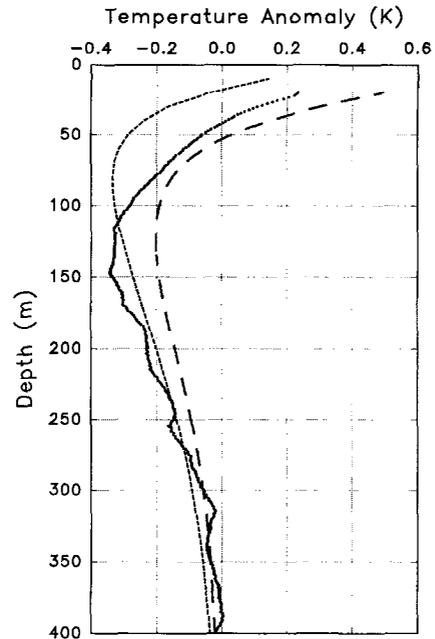


Fig. 7. Subsurface anomalies observed (dots) and generated from the yearly (short dash) and 20 yr average (long dash) series. It is apparent that the subsurface anomalies generated from these reconstructions do not fit the observed profile.

series. Fig. 7 shows the observed temperature anomaly and the subsurface perturbation generated from the 20 yr averages and yearly records of reconstructed ground temperature. The profiles show some qualitative similarity but do not fit the subsurface anomaly near the surface, where the larger variability of the 20 yr and yearly series have an influence, as expected. We think that increased resolution using this methodology can be achieved only up to the size of the average temperature interval allowed by the geothermal data.

## 5. Discussion and conclusions

Our basic result is that a simple linear transform between tree-ring indices and ground temperatures changes yields a high-resolution ground temperature history capable of reproducing subsurface temperature anomalies in eastern Canada. The linear transformation between tree-ring indices and a single climatic variable is not unusual in tree-ring tempera-

ture reconstructions; for example, the reconstruction developed by Jacoby and D'Arrigo in 1989 [32] is a linear transformation between the standardized tree-ring indices and air temperatures. It is reasonable to assume that tree-ring growth is partially dependent on ground temperature, particularly since this variable integrates the effects of air temperature and precipitation [33].

It would not be correct however, to assume that ring growth is completely determined by ground temperatures. Archambault and Bergeron [25] have found significant positive correlations between ring width and June precipitation, as well as negative correlations with the temperature for the April of the year prior to growth, and they report a strong negative correlation with the summer maximum of the Drought Code of the Canadian Forest Fire Behaviour System. It may be possible that different tree species or trees from sensitive areas respond preferentially to different single climatic variables [17], or to a combination of these variables. Perhaps this analysis, in order to be applicable, might need to be combined with 'classical' principal components analysis so as to be sure the ring series is sensitive to ground temperatures. We are not aware of any tree-ring climatic reconstruction for which soil temperatures have been taken into account and included in the analysis. We suggest that, in the light of the results presented here, such analysis should be carried out when possible, even if soil temperature records are scarce and usually span no more than 30 yr.

We have attempted to increase the resolution of the GTH from geothermal data by combining a GTH with a tree-ring width series and, at the same time, we have provided a method for the comparison of proxy data time series with the integrated values of ground temperature from geothermal data for the last 780 years. The tree-ring ground temperature reconstruction reproduces the subsurface temperature anomaly regime well. We hope that this work stimulates research into the integration of several paleoclimatological records in order to obtain a single robust history of climate.

Other attempts to integrate different climatic indicators have been carried out to calibrate oxygen isotope with temperature–depth profiles in ice cores [23,24]. The method applied in this study has been successfully used to combine geothermal data and

ice core oxygen isotope data in the Canadian Arctic [34].

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