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Paleoclimatic interpretation of the Elk Lake pollen record

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ABSTRACT

The pollen record from Elk Lake is interpreted in climatic terms by three different numerical approaches. The paleoclimatic record inferred for Elk Lake can be described as a sequence of climatic zones, separated by short transitional intervals: (1) the cold and dry late glacial zone (11,600–11,000 varve yr), (2) the cool and moist early Holocene zone (10,000–8500 varve yr), (3) the warm and dry middle Holocene zone (7800–4500 varve yr), and (4) the warm and moist late Holocene zone (3500 varve yr to present).

Two large-scale controls of this climatic sequence can be inferred from paleoclimatic model experiments. The first is the effect of the Laurentide ice sheet on surface winds and temperatures; this influence was strongest prior to 9 ka. This control was replaced by the amplified seasonal cycle of solar radiation between 12 and 6 ka that increased summer temperature and net radiation and decreased effective moisture. Mesoscale controls on the climate of the Itasca region possibly include a lake effect during the various stages of Lake Agassiz and subtle changes in atmospheric circulation during the prairie period (about 8000 to 4000 varve yr).

INTRODUCTION

In several respects, the paleoecological record of Elk Lake offers a unique opportunity to study climatic variations during the past 11,600 years and their influence on the lake and its watershed. First, the varve chronology provides a temporal resolution not common in late Quaternary lake records, and thus it is possible to document timing and rates of change with considerable precision. Furthermore, the lake is located in a region of steep vegetational gradients controlled by present-day climate; changes in past climate should be evident in the fossil-pollen record and the vegetational changes inferred therein. Finally, the availability of multiple paleoenvironmental indicators at Elk Lake permits a comparison of their relative sensitivities to climate change (Dean and others, 1984).

In Chapter 17, we examined in detail the fossil-pollen record of Elk Lake and emphasized the reconstruction of the past vegetation in the Itasca region. In this chapter we focus on the interpretation of the fossil-pollen data in climatic terms and use the inferred climate to discuss the paleoenvironmental history of the region and its potential causes. Three different numerical approaches—regression, analogue, and response-surface analyses—were used to reconstruct climatic variations. Each method utilizes the relationship between modern climate and pollen abundance in eastern North America to infer past climate from fossil-pollen data. The comparison of the three methods allows us to identify and minimize uncertainty in the reconstructions. The specific climatic history at Elk Lake is compared with simulations of large-scale paleoclimatic patterns (Kutzbach and Guetter, 1986; Webb and others, 1987) to elucidate the potential large-scale and mesoscale controls of regional climatic variations.

DATA

Modern pollen and climate data

The modern pollen data set consisted of 1200 modern spectra, extracted from the data set at Brown University (see Overpeck and others, 1985; Bartlein and Webb, 1985) and supplemented by additional samples from Lichti-Federovich and Ritchie (1965, 1968) and MacDonald and Ritchie (1986) for the central and western interior of Canada. In the analogue and

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response surface approaches, the entire data set was analyzed simultaneously with a pollen sum that included the 44 most abundant pollen types in the modern data set. Some taxa that never appear at Elk Lake were included in this sum to reduce the possibility of obtaining fortuitous analogues (see Whitlock and others, Chapter 17, for the specific list of types). In the regression approach, subsets of the entire data set were used (see below), each with its own pollen sum. The climate values assigned to each modern pollen spectrum were obtained from the closest climatological station to each sample (see Huntley and others, 1989, for discussion of various approaches for assigning modern climate values to individual pollen sampling sites).

Climate-model output

We used output from Kutzbach and Guetter's (1986) experiments with the National Center for Atmospheric Research Community Climate Model (NCAR CCM) to examine how changes in the large-scale controls of regional climates may have influenced the sequence of paleoclimatic variations (see Barnosky and others, 1987; Webb and others, 1987; COHMAP Members, 1988). We used "areal averages" of individual variables obtained by averaging together the simulations for individual model grid points (see Webb and others, 1993, for specific details on the averaging procedure and the specific gridpoints involved).

METHODS

General approach

Whether pollen data are interpreted qualitatively or numerically, their interpretation in climatic terms is a two-step procedure. First, a relationship is constructed between modern pollen and climate, and second, this relationship is applied to the fossil data. In this study, the reconstructed climate variables are mean January temperature, mean July temperature, and mean annual precipitation. These variables were selected to represent the large-scale moisture and temperature controls of plant distribution (see Bartlein and others, 1986).

Individual reconstruction approaches differ mainly in the way in which the relationship between pollen and climate is constructed. For example, the relationship can take the form of a specific prediction equation, as in the regression approach (e.g., Webb, 1980; Bartlein and others, 1984), in which the relative abundance values of particular pollen types acting as predictors are plugged-in to yield predictions of an individual climate variable, acting as the dependent variable or predictand. The relationship can also exist in the form of a tabulation (e.g., Klimanov, 1984) that illustrates the association between particular categories of pollen abundance and ranges of climate variables, or as response surfaces (e.g., Bartlein and others, 1986) that show how the abundance of a particular pollen type varies as a nonlinear function of a small number of climate variables. Most simply, the relationship can take the form of an associated list of pollen spectra and climate values (i.e., the analogue approach).

In this chapter we use the following three specific approaches.

1. In the *regression* approach, regression equations (also referred to as "transfer functions") are established that relate a specific climate variable to a set of pollen predictors (Bartlein and others, 1984). The relationships are then applied to fossil-pollen data to produce estimates of the climate variables.

2. In the *analogue* approach (see Whitlock and others, Chapter 17; Overpeck and others, 1985), a data set of paired observations of modern pollen and climate are searched for the best analogues of a particular fossil spectrum. The modern climate values associated with these analogues are used as the reconstructed values.

3. In the *response-surface* approach (see Bartlein and others, 1986; Webb and others, 1993), response surfaces that describe the relationship between the abundance of a particular pollen type and a small set of climate variables are used as the source of the analogues.

One problem common to all methods, including subjective approaches, is the occasional lack of a modern analogue for a particular fossil spectrum. This situation does not automatically preclude the production of an estimate; however, that estimate may be quite unreliable. A "no-analogue" condition is probably most serious in the regression approach, where it could produce greatly misleading extrapolations (Weisberg, 1985). It is possible to monitor the performance of the reconstruction methods as they proceed and recognize when the problem arises.

A second problem in all reconstruction methods is the potential violation of certain underlying ecological assumptions (Howe and Webb, 1983): (1) that the modern vegetation, as represented by pollen data, is in equilibrium with the modern climate on the temporal and spatial scale of the reconstruction; (2) that variations in the fossil record under consideration are ultimately attributable to climatic changes; and (3) that the vegetation has responded to climatic changes during the course of the record without significant temporal lags (Webb, 1986). Only when the response time of the vegetation is short relative to the time scale of the climatic changes can the vegetation variations be interpreted in climatic terms (Prentice, 1986; Webb, 1986). At Elk Lake, multiple paleoenvironmental indicators are available to test the equilibrium hypothesis by examining the synchroneity of the response of several independent systems to past climatic variations. Another way to minimize violations of these assumptions is to focus attention on longer temporal and larger spatial scales, concentrating, for example, on millenial-scale variations that are coherent across the upper Midwest (Prentice, 1983, 1986; Bartlein and others, 1984).

Specific approaches

The three numerical approaches differ in their relationship-building procedures, and in the measures of goodness of fit, uncertainty in the reconstructed values, and extent of extrapolation in the reconstructed values. Measures of goodness of fit, the extent to which a method can reproduce the observed modern climate from modern pollen data, help judge the overall ability of a procedure to reconstruct past climate. Measures of uncertainty in the reconstructed values and of the extent of extrapolation help to evaluate the reliability of the reconstructed values.

Regression approach. The regression or transfer function approach involves fitting a regression equation that expresses the values of a particular climate variable as a function of the abundances of several pollen types. This equation can then be applied to fossil data in order to interpret the fossil data in climatic terms. The calibration procedure of Bartlein and others (1984) and Bartlein and Webb (1985) was used because it examines explicitly the statistical assumptions that underlie the regression procedure and uses a sequence of steps to minimize any violations of those assumptions.

Bartlein and Webb (1985) defined a number of calibration regions for eastern North America, within which the relationships between a particular climatic variable and most pollen types are linear or monotonic. The reconstruction of climatic variations from the fossil data thus involves first the selection of the appropriate calibration region and second the application of its regression equation to each fossil pollen spectrum. As described by Bartlein and Webb (1985), a criterion for calibration-region selection is the Mahalanobis distance, which provides a measure of the dissimilarity between a particular pollen spectrum and the mean of the pollen spectra within a particular region. The Mahalanobis distance is also an approximate measure of the extent of extrapolation (Weisberg, 1985). In effect, this measure helps to identify the calibration region with pollen analogues for each individual fossil spectrum (and hence the appropriate equation to use), and to assess the extent of extrapolation. Mahalanobis distances are expressed here as probability values, in which values greater than 0.95 indicate little similarity between the fossil spectrum and the modern data set of a calibration region.

Uncertainty in the predicted values generated by a particular regression equation arises from two sources: (1) variations of the values of the dependent (i.e., climatic) variable about the regression line, and (2) uncertainty in the location of the line. Prediction confidence limits that reflect these two components were constructed for the climatic reconstructions in the usual way (Neter and others, 1983, section 7.7). Goodness of fit in the regression approach is measured by the R^2 value for the individual equations.

Analogue approach. Of the three reconstruction approaches used here, the analogue approach is perhaps the most intuitive. The paleoclimatic reconstructions are the modern climate values associated with the best modern pollen analogues of individual fossil spectra. A key assumption of this approach is therefore that the analogue data set (the modern pollen spectra) contains examples of all of the fossil spectra being analyzed. Analogues are identified using the squared-chord distance—a numerical measure of dissimilarity with certain desirable properties for comparing pollen spectra (Whitlock and others, Chapter 17; Anderson and others, 1989; Overpeck and others, 1985). Rather than taking the climate values of the single best modern analogue, we used a weighted average of the climate values of the ten closest modern analogues (see also Guiot, 1987), where the weights were taken as the inverse of the squared-chord distance. This approach has the advantage of providing a degree of interpolation among modern samples that can compensate for the uneven distribution of those samples in geographic as well as climatic space.

In the analogue approach, uncertainty in the reconstructed climatic values was estimated by the standard deviation of the mean of the (weighted) climate values associated with the ten best analogues. This procedure probably results in an underestimate of the true uncertainty because it does not include information on the absolute level of the analogues. In other words, a relatively small prediction interval could result if the closest analogues all had similar associated climate values, even if those closest analogues were relatively poor. Further work is needed to improve the estimates of uncertainty in reconstructed climate values. In this chapter and in Whitlock and others (Chapter 17), the fifth percentile (0.205) of the squared-chord distance values calculated among all modern pollen spectra is adopted as a threshold indicator of a good analogue. When this value is exceeded, the climate reconstructions are considered to be less reliable. Because the reconstructions generated by the analogue approach are limited to those climate values present in the modern data set (or weighted averages of them), the analogue approach is unable to extrapolate when applied to fossil-pollen data.

The overall goodness of fit of the analogue approach is judged by estimating modern climate at individual sites from the modern pollen data (excluding the site itself in the search for analogues). The correlation between the observed and estimated modern climate values can be expressed as an R^2 value to allow comparisons among procedures.

Response-surface approach. Response surfaces describe the abundance of a particular pollen type as a function of a small number of climate variables (Bartlein and others, 1986). In a sense they represent the "inverse" of the functions relating pollen and climate data that are established using regression analysis. Response surfaces are fit to individual pollen types with a weighted-averaging technique. A window is moved within the climate space defined (in this case) by mean January and July temperatures and annual precipitation, and a distance-weighted average of the percentages of a particular pollen type for the observations that fall within the window is determined. The window is moved over a regular grid in the climate space formed by these three variables. Further discussion of the fitting procedure is given by Huntley and others (1989), Webb and others (1993), and Prentice and others (1991).

The response surfaces can be extrapolated to some extent by calculating weighted averages of the fitted values for regions just outside the portion of climate space covered by the data. Such mild extrapolation may be necessary in order to extend the surfaces into regions of climate space not represented in the modern data set (see Prentice and others, 1991, for further discussion).

The pollen spectra synthesized in this way generally do have analogues in the fossil data set for eastern North America, and so it is likely that the extrapolation of the surfaces in this manner does not build artifacts into the climate reconstructions. The result of the response surface analysis is a set of "fitted values" for the different pollen types at specific locations in the climate space defined by the three climatic variables.

The response-surface approach differs from the "straight" analogue approach in the nature of the data set that is searched for modern analogues. In the analogue approach, this data set is the modern pollen and climate data set, whereas in the response-surface approach, the data set consists of the fitted values of the individual pollen types and the associated climate values. The response-surface fitting procedure in effect smooths the modern pollen data and removes much of the spatial variability in the modern pollen data that is unrelated to climate.

The overall goodness of fit of the response-surface approach can be evaluated by estimating the observed modern climate from the modern pollen data, in a similar fashion as for the simple analogue approach. Uncertainties in the predicted values can also be estimated as in the simple analogue approach, and again are probably an underestimate of the true uncertainty. Likewise, a threshold level for the squared-chord distance can be determined by calculating the dissimilarities between all modern pollen spectra and the response-surface fitted values.

RESULTS

Specific results of the different approaches

Regression approach. The regression equations pertinent to the reconstruction of climate from the Elk Lake fossil data appear in Table 1. Individual equations were selected on the basis of Mahalanobis distance values, and the particular time range over which each equation was applied is given in Table 2. Figure 1 displays the climate reconstructions obtained by applying the different regression equations to the Elk Lake fossil data. The Mahalanobis distances for individual fossil spectra, expressed as probability values, appear in Figure 2.

Analogue approach. Figure 3 shows the reconstructed climate values obtained as the weighted average of the ten closest analogues to each fossil spectrum, and Figure 2 shows the squared-chord distances between each fossil spectrum and the closest modern analogue, along with the average of the squared-chord distances for the ten closest analogues. Table 3 contains the R^2 values for the estimation of the observed modern climate values with the modern pollen data.

Response-surface approach. The response surfaces generated in the application of this approach describe the continental-scale relationships between pollen abundance and climate. Figure 4 shows the climate reconstructions obtained with this method, and Figure 2 shows the squared-chord distances between each fossil spectrum and the single best and ten best analogues among the response-surface fitted values. A selection of response surfaces for some major pollen types appears in Figure 5. Table 3 lists the R^2 values for the modern climate values inferred from the modern pollen data.

Modern pollen-climate relationships

The response surfaces display graphically the relationship between modern pollen and climate at the continental scale, and provide some insight into the manner in which the different pollen types may have responded to past climatic variations. Each panel in Figure 5 shows the surface plotted on the July temperature–January temperature plane for a slice through climate space at a particular value of annual precipitation.

The surfaces for individual pollen types are unique, and each have distinct optima or locations in climate space where the maximum abundance of each pollen type is reached. The surfaces are generally unimodal, or bimodal, as for *Betula,* which has two abundance maxima: one in the mixed forest generated by tree birch and one in the boreal forest and tundra generated by shrub birch.

The shapes of the surfaces suggest that a rich variety of changes in pollen abundance could occur in response to a particular change in climate. For example, consider a site with annual precipitation of about 650 mm, mean July temperature of 15 °C, and mean January temperature of –20 °C. An increase in July temperature to 21 °C and January temperature to –10 °C with no change in precipitation would give that site a trajectory in climate space that would (1) move from the abundance maximum (>40%) of spruce to a location with less than 10% spruce; (2) move from a location with around 20% pine, to one with around 40% pine, and then back down to about 30% pine; (3) move from a location with very little oak pollen to one with greater than 10% oak pollen; and (4) result in very little net change in the abundance of birch or prairie forb pollen. The implication of this example for the interpretation of the fossil-pollen data from Elk Lake (and for the interpretation of fossil pollen data in general) is that whereas some climatic changes may produce quite sharp changes in the abundance of particular pollen types, other climatic changes may produce only subtle changes in pollen abundance, and still other changes result in a mixture of responses.

Comparison of reconstruction approaches

The reconstructions are broadly similar among methods. In general, both January and July temperatures increase from the beginning of the record to about 6000 varve yr, and annual precipitation is lowest between about 8000 and 4000 varve yr. The reliability of all three approaches (Fig. 3) is lowest during the *Picea* assemblage, and again during the *Quercus-Ostrya-Carpinus* assemblage, when the fossil spectra do not have good modern analogues (see Whitlock and others, Chapter 17). The general agreement among the approaches becomes evident when the individual reconstructions are superimposed (Fig. 6).

Comparison of the individual reconstructions here in light of

TABLE 1. REGRESSION EQUATIONS

Regression Equations for January Mean Temperature (°C)

Calibration Region: 45–55°N, 95–105°W

Pollen Sum = *Alnus* + *Betula* + Cyperaceae + Forbs + Gramineae + *Picea* + *Pinus* + *Quercus*

Jan. Temp = -13.116 - 0.913 $Alnus^{0.5}$ - 0.304 $Cyperaceae^{0.5}$ + 0.283 $Forbs^{0.5}$ + 0.379 $Gramineae^{0.5}$ - 0.266 $Picea^{0.25}$

R^2 = 0.842; F = 114.21; Pr = 0.000

Calibration Region: 40–50°N, 85–95°W

Pollen Sum = *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + *Fagus* + *Fraxinus* + Herbs + *Juglans* + *Juniperus* + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*
where Herbs = Gramineae + *Artemisia* + Compositeae + (Chenopodiaceae-Amaranthaceae)

Jan. Temp = -11.981 + 0.279 *Acer* - 0.316 $Betula^{0.5}$ + 0.284 *Fagus* + 0.335 Fraxinus - 0.893 $Picea^{0.25}$ - 0.350 $Pinus^{0.5}$ + 2.520 $Quercus^{0.25}$ - 0.194 *Ulmus* + 0.751 $Tsuga^{0.5}$

R^2 = 0.729; F = 29.29; Pr = 0.000

Calibration Region: 45–55°N, 85–105°W

Pollen Sum = *Alnus* + *Betula* + Forbs + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga*
where Forbs = *Artemisia* + Compositeae + (Chenopodiacese-Amaranthaceae)

Jan. Temp = -12.943 - 0.217 *Alnus* + 0.044 *Betula* - 1.039 $Forbs^{0.25}$ - 0.461 $Gramineae^{0.5}$ + 2.581 $Quercus^{0.25}$ - 0.987 $Picea^{0.5}$ + 0.192 Tsuga

R^2 = 0.876; F = 86.43; Pr = 0.000

Calibration Region: 40–55°N, 75–87°W

Pollen Sum = *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + *Fagus* + *Fraxinus* + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*

Jan. Temp = - 5.348 + 0.564 $Acer^{0.5}$ - 0.581 $Alnus^{0.5}$ - 0.256 $Betula^{0.5}$ + 1.042 $Carya^{0.25}$ - 1.282 $Picea^{0.5}$ - 1.740 $Pinus^{0.25}$ + 1.979 $Quercus^{0.25}$ + 0.776 $Tsuga^{0.50}$ - 0.646 $Ulmus^{0.5}$

R^2 = 0.949; F = 236.92; Pr = 0.000

Regression Equations for July Mean Temperature (°C)

Calibration Region: 45–55°N, 95–105°W

Pollen Sum = *Alnus* + *Betula* + Cyperaceae + Forbs + Gramineae + *Picea* + *Pinus* + *Quercus*

July Temp. = 21.796 - 0.272 $Alnus^{0.5}$ - 0.015 Forbs + 0.297 $Gramineae^{0.5}$ - 1.902 $Picea^{0.25}$

R^2 = 0.701; F = 57.33; Pr = 0.000

Calibration Region: 40–50°N, 85–95°W

Pollen Sum - *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + *Fagus* + *Fraxinus* + Herbs + *Juglans* + *Juniperus* + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*
where Herbs = Gramineae + *Artemisia* + Compositeae + (Chenopodiaceae-Amaranthaceae)

July Temp. = 18.686 - 0.334 *Abies* - 0.218 $Betula^{0.5}$ - 0.097 *Fagus* + 0.106 *Fraxinus* + 0.704 $Herbs^{0.25}$ - 0.364 $Picea^{0.25}$ + 1.006 $Quercus^{0.25}$

R^2 = 0.799; F = 56.79; Pr = 0.000

Calibration Region: 45–55°N, 85–105°W

Pollen Sum = *Alnus* + *Betula* + Forbs + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga*
where Forbs = *Artemisia* + Compositeae + (Chenopodiaceae-Amaranthaceae)

July Temp. = 19.199 - 0.384 $Betula^{0.5}$ - 0.285 $Picea^{0.5}$ + 0.079 $Pinus^{0.5}$ + 1.307 $Quercus^{0.25}$ + 0.040 *Tsuga*

R^2 = 0.786; F = 64.13; Pr = 0.000

Calibration Region: 40–55°N, 75–87°W

Pollen Sum = *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + *Fagus* + *Fraxinus* + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*

July Temp. = 20.767 - 0.253 $Alnus^{0.5}$ - 0.160 $Betula^{0.5}$ + 0.372 $Carya^{0.25}$ + 0.170 $Fraxinus^{0.5}$ - 0.294 $Picea^{0.5}$ - 0.811 $Pinus^{0.25}$ +1.097 $Quercus^{0.25}$

R^2 = 0.903; F = 154.92; Pr = 0.000

Regression Equations for Annual Precipitation (cm)

Calibration Region: 45–55°N, 95–105°W

Pollen Sum = *Alnus* + *Betula* + Cyperaceae + Forbs + Gramineae + *Picea* + *Pinus* + *Quercus*

Ann. Precip. = 57.180 - 2.365 $Forbs^{0.5}$ -0.170 Gramineae - 3.580 $Picea^{0.25}$ + 4.941 $Quercus^{0.5}$

R^2 = 0.578; F = 33.18; Pr = 0.000

Calibration Region: 45–55°N, 85–105°W

Pollen Sum = *Alnus* + *Betula* + *Forbs* + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga*
where Forbs = *Artemisia* + Compositeae + (Chenopodiaceae-Amaranthaceae)

Ann. Precip. = 88.283 - 4.208 $Alnus^{0.5}$ + 1.993 $Betula^{0.5}$ - 15.340 $Forbs^{0.25}$ - 1.788 $Gramineae^{0.5}$ + 2.950 $Quercus^{0.5}$ + 0.684 *Tsuga*

R^2 = 0.874; F = 47.29; Pr = 0.000

Calibration Region: 40–55°N, 75–87°W

Pollen Sum = *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + *Fagus* + *Fraxinus* + Gramineae + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*

Ann. Precip. = 65.552 + 1.624 *Abies* + 0.708 *Betula* + 0.589 *Carya* + 0.298 Gramineae + 0.132 *Picea* + 0.402 *Quercus* + 0.865 *Tsuga* -3.693 $Ulmus^{0.5}$

R^2 = 0.680; F = 12.33; Pr = 0.000

Calibration Region: 40–50°N, 85–105°W

Pollen Sum = *Abies* + *Acer* + *Alnus* + *Betula* + *Carya* + Forbs + *Fagus* + *Fraxinus* + Gramineae + *Juniperus* + *Picea* + *Pinus* + *Quercus* + *Tsuga* + *Ulmus*
where Forbs = *Artemisia* + Compositeae + (Chenopodiaceae-Amaranthaceae)

Ann. Precip. = 95.445 + 4.335 $Abies^{0.5}$ - 3.564 $Alnus^{0.25}$ - 2.243 $Betula^{0.25}$ - 2.526 $Fraxinus^{0.25}$ - 6.145 $Forbs^{0.5}$ + 2.07 $Juniperus^{0.5}$ - 1.682 $Pinus^{0.5}$ + 6.108 $Quercus^{0.25}$ + 3.967 $Tsuga^{0.25}$ - 4.206 $Ulmus^{0.25}$

R^2 = 0.940; F = 94.64; Pr = 0.000

*The equations include those reported by Bartlein and Webb (1985) for the reconstruction of mean July temperature, along with additional ones for mean January temperature and annual precipitation not reported, but constructed as part of the same work. Note that the equations for mean July temperature for the calibration region 40–50°N, 85–95°W and for annual precipitation for the calibration region 40–50°N, 85–105°W were also reported in Bartlein and others (1984).

TABLE 2. REGRESSION EQUATION APPLICATIONS TO THE ELK LAKE POLLEN DATA

	Calibration Region	Age Range (varve yrs)	R^2
Mean January Temperature	45–55°N, 85–105°W	320–10,084	0.876
	45–55°N, 95–105°W	10,134–11,638	0.842
Mean July Temperature	40–50°N, 85–95°W	320–6,562	0.799
	40–55°N, 85–105°W	6,746–10,084	0.786
	45–55°N, 95–105°W	10,134–11,638	0.701
Annual Precipitation	40–55°N, 85–105°W	320–3,692	0.578
	40–50°N, 85–105°W	3,794–7,662	0.940
	45–55°N, 85–105°W	7,862–11,638	0.578

the assumptions that underlie each approach allows us to make some observations on the relative merits of each approach. In general, when the assumptions that underlie each approach are not violated, and the various measures of extrapolation or unreliability do not signal that such problems exist, there is little difference between reconstructions, as is evident for the past 10,000 varve yr. (The largest difference among reconstructions during this interval is the slightly higher January temperature reconstructed by the response-surface approach in the period prior to 4000 varve yr.) In contrast, prior to 10,000 varve yr, when problems with the reconstructions are apparent (Fig. 2), the amplitude of the variations of the individual reconstructions differ markedly, while the overall patterns of the reconstructions are still generally similar.

The regression approach has the intrinsic merit of being statistically optimal when the assumptions underlying the approach are not violated. Because the prediction confidence intervals arise from a formal statistical model, whenever the uncertainties in the reconstructed values are an issue, the regression approach might be preferred. Because the regression approach is particularly prone to "hidden extrapolations" (Weisberg, 1985), the application of the approach must be carefully monitored.

The analogue approach might be considered to have the distinct advantage of being the least statistical of the three approaches, because it involves the straightforward comparison of individual spectra (which could be done subjectively). In contrast to the regression and response surface approaches, the analogue approach does not involve the construction of a generalized relationship between pollen and climate, and therefore reconstructions derived using the analogue approach may depend overmuch on the nature of the particular spectra in the analogue data set. The analogue reconstructions (Fig. 3) generally show more short-

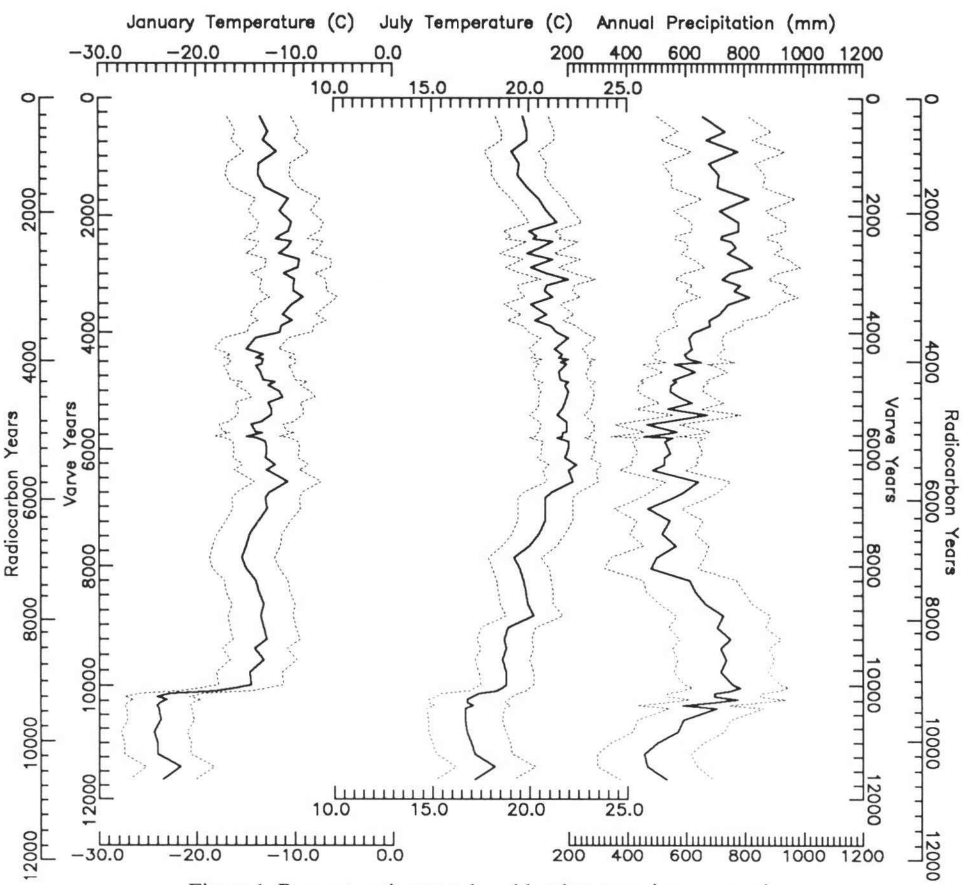


Figure 1. Reconstructions produced by the regression approach.

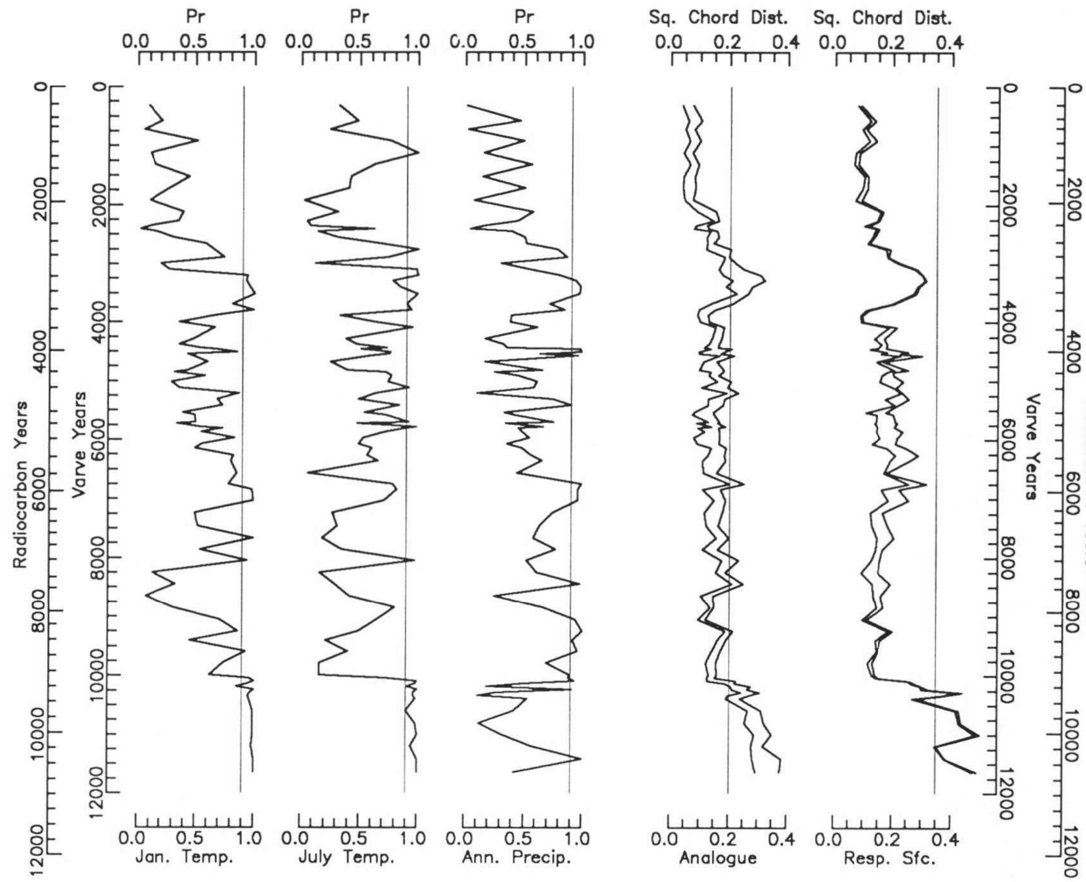


Figure 2. Extrapolation measures. The three series on the left show the series of probability levels of the Mahalanobis distances for the fossil spectra as calculated using the calibration data sets for each climate variable. The fourth series shows the squared-chord distance values for the single closest (on the left), and the average of the ten closest (on the right) modern analogues for each fossil spectrum. The fifth series shows the squared-chord distance values for the single closest (on the left), and the average of the ten closest (on the right) analogues between each fossil spectrum and the response surface fitted values.

term variability than those derived using the other two approaches, particularly during the interval 7000 to 4000 varve yr, which may be a manifestation of that dependence.

The response-surface approach is the only approach that confronts the extrapolation problem in an explicit fashion. In the regression approach, extrapolations are possible but may be unwarranted. Reconstructions produced by the analogue approach are restricted to lie within the domain of the analogue data set. By including an explicit extrapolation procedure, the response-surface approach is arguably the better approach when it is likely that climates prevailed without modern analogues.

Overall, when the assumptions that underlie the individual approaches are not violated, there is little to distinguish among the reconstructions, as for the interval at Elk Lake from 10,000 varve yr to present. Prior to 10,000 varve yr at Elk Lake there are clearly problems with all three approaches (Fig. 2), and there are greater differences among approaches. For this interval, and in consideration of the above, we are therefore inclined to have somewhat greater confidence in the response-surface and analogue reconstructions, and lesser confidence in the regression reconstructions. As noted above, however, the overall pattern of the reconstructions is still quite consistent among approaches for this interval.

General results: Elk Lake climate history

The longer term trends in the climate reconstructions divide the Elk Lake record into the following climate intervals.

Late glacial (11,600–11,000 varve yr). The bottom four samples of the *Picea* assemblage are characterized by high percentages of *Picea,* Gramineae, *Artemisia,* and Cyperaceae pollen. These values imply a cold dry climate (about 5 °C lower in January than present, 2.5 °C lower in July, with precipitation about 200 mm less annually). In general, the individual methods produce similar results, although the response surfaces yield reconstructions of annual precipitation slightly lower than those produced by the other approaches. The climate reconstructions are probably less reliable than later (Fig. 2), because significant

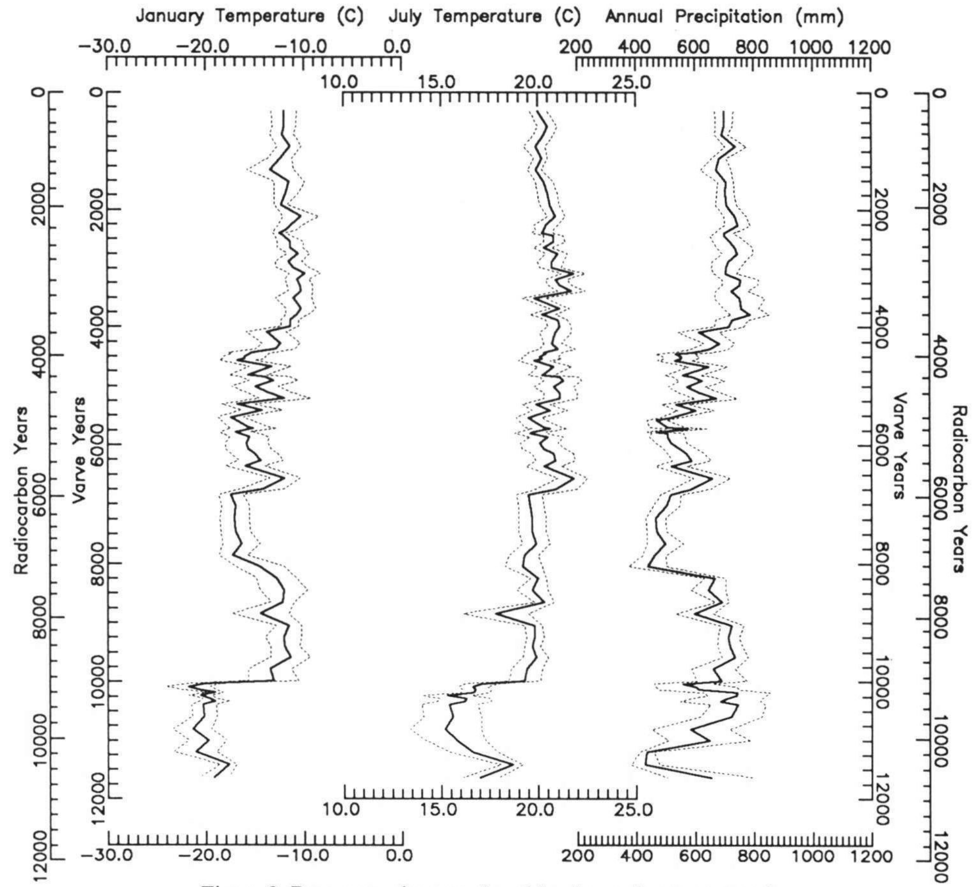


Figure 3. Reconstructions produced by the analogue approach.

TABLE 3. R^2 VALUES FOR ANALOGUE AND RESPONSE SURFACE/ANALOGUE RECONSTRUCTION APPROACHES

	Analogue	Response Surface/Analogue
Mean January temperature	0.928	0.730
Mean July temperature	0.928	0.856
Annual precipitation	0.870	0.751

percentages of indeterminate pollen, which are excluded from the pollen sum, occur in the unvarved portion of the core. The exclusion of the indeterminate pollen may inflate the percentages of *Picea,* thereby producing biased (systematically too cold) reconstructions. The specific values of temperature and precipitation may be in error, owing to extrapolation and bias, but the overall interpretation of conditions colder and drier than present is consistent with the reconstructions of parkland vegetation.

Late glacial–early Holocene transition (11,000–10,000 varve yr). This interval includes the transition from the *Picea* assemblage to the *Pinus banksiana-resinosa–Pteridium* assemblage. The transition begins with high percentages of *Picea, Larix,* and *Betula* percentages, followed by high percentages of *Picea* and *Betula* and various hardwood taxa, including *Fraxinus, Quercus,* and *Ulmus,* and terminates with a dramatic shift from an assemblage dominated by high percentages of *Picea* to one dominated by *Pinus.* Several marked changes in climate values are inferred through the course of this transition. Reconstructed July temperature decreases about 2.5 °C with the increases of *Picea, Larix,* and *Betula* pollen. It subsequently rises with increasing percentages of *Betula* and hardwood taxa, as does annual precipitation. The shift from the *Picea* to *Pinus* assemblage generates equally sharp increases in January and July temperature to values only a few degrees cooler than present. Within the transition, measures of extrapolation decrease from fairly high to insignificant values, and the reconstructions from the three methods are comparable after 10,000 varve yr (Fig. 2).

Early Holocene (10,000–8500 varve yr). This interval encompasses the *Pinus banksiana-resinosa–Pteridium* assemblage and is characterized by relatively cool and moist conditions (warmer than earlier and slightly cooler than present, moister than the late glacial interval, and about as moist as present). A slight warming and drying trend occurs within the interval.

Early Holocene–middle Holocene transition (8500–7800 varve yr). This interval marks the transition from forest to prairie during the early part of the *Quercus*-Gramineae-*Artemisia* as-

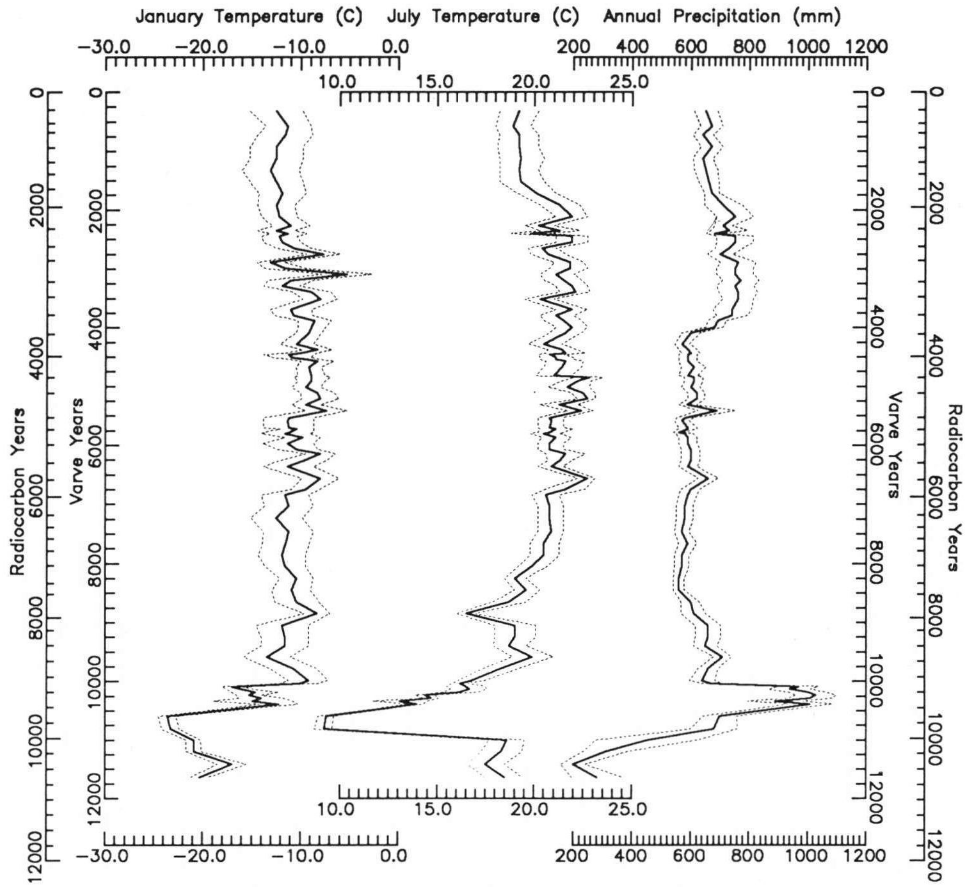


Figure 4. Reconstructions produced by the response surface approach.

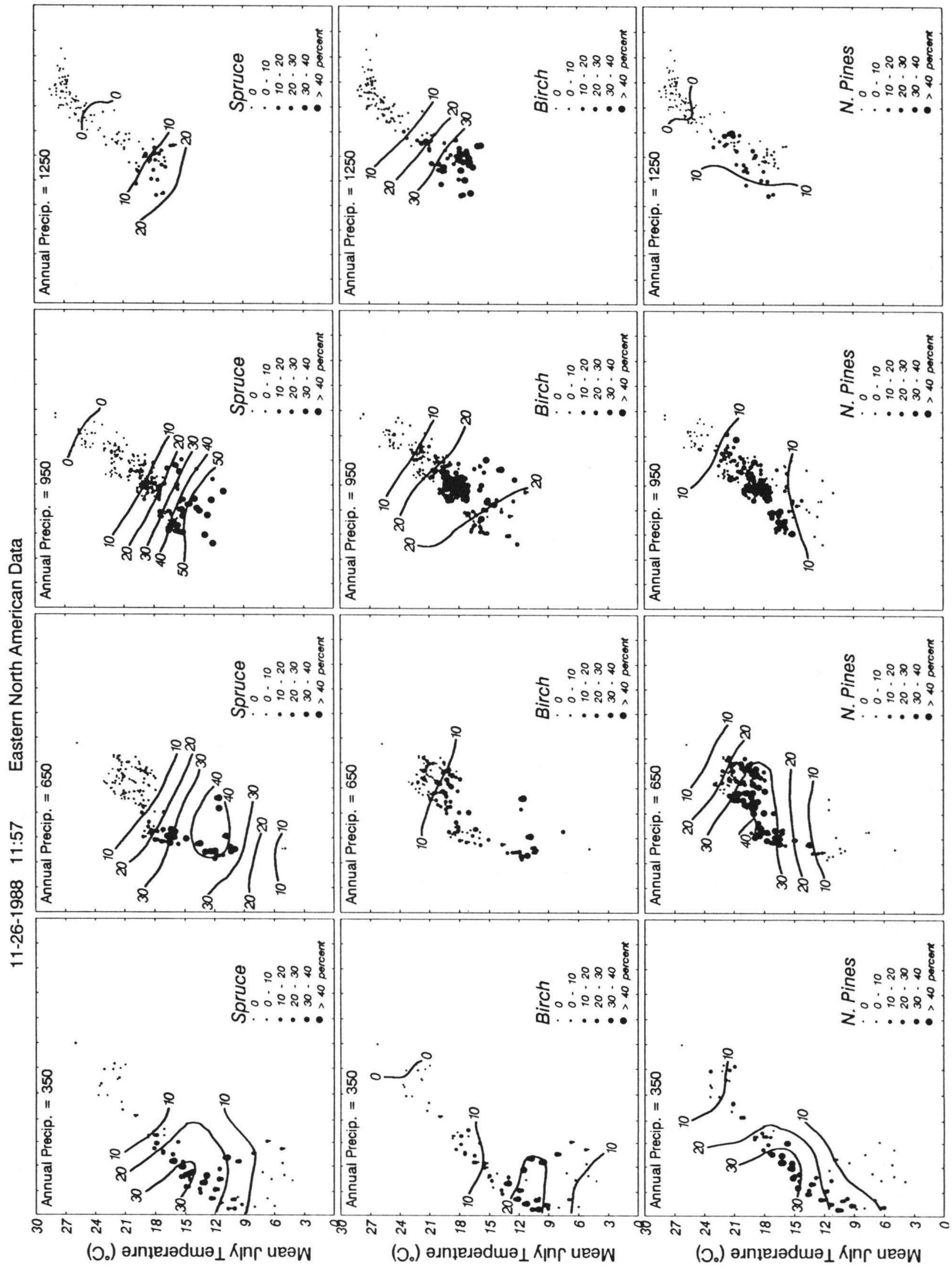
semblage, and is characterized by a continuation and acceleration of the decrease in annual precipitation. January temperature also decreases slightly, while July temperature continues the increasing trend started in the previous interval.

Middle Holocene (7800–4500 varve yr). Most of the prairie period (*Quercus*-Gramineae-*Artemisia* assemblage) is included in this warm, dry interval. Annual precipitation is about 100 mm lower than present, and July temperature is about 2.0 °C warmer near the end of this interval. All three variables show relatively low amplitude short-term variations, including two episodes of warmer, wetter conditions, one between about 6750 and 6250 varve yr, and another, more pronounced one between about 5400 and 4800 varve yr. These fluctuations are inferred from subtle increases in *Quercus* percentages and concomitant decreases in herbaceous taxa. Similar episodes have been identified in other paleoecological and sedimentological records from Elk Lake (see discussion).

Middle Holocene–late Holocene transition (4500–3500 varve yr). This transition embraces the shift from the *Quercus*-Gramineae-*Artemisia* assemblage to the *Quercus–Ostrya-Carpinus* assemblage. Notable are the decreases in herbaceous taxa and *Quercus,* and the increases in *Pinus, Betula,* and *Ostrya-Carpinus.* The reconstructions of annual precipitation increase to values greater than present. January temperature increases, while July temperature remains slightly greater than present.

Late Holocene (3500 varve yr to present). The last parts of the *Quercus–Ostrya-Carpinus* assemblage and all the *Pinus strobus* assemblage are characterized by a warm, moist climate. At the beginning of this interval, July temperature was about 1.5 °C higher than present, January temperature about 2.0 °C higher, and annual precipitation was about 100 mm greater. All three climate variables gradually decrease toward their modern value, with a slight acceleration toward cooler, drier conditions after 1750 varve yr. These reconstructed trends can be inferred from the increased abundances of *Pinus* at the expense of *Betula, Quercus,* and *Ostrya-Carpinus.*

To summarize, the sequence of climatic changes at Elk Lake reconstructed from the pollen evidence shows a transition from relatively cold and dry conditions during the first 1000 yr of the record to relatively cool and moist conditions during the early Holocene. The vegetation changed from parkland to spruce forest and finally to pine forest. In the middle Holocene, prairie became established, with the introduction of warm and dry conditions. Modern vegetation and climate prevailed after 3500 varve yr. Superimposed on these broad climatic trends were low-amplitude short-term fluctuations.


11-26-1988 11:57 Eastern North American Data
Annual Precip. = 350
Annual Precip. = 650
Annual Precip. = 950
Annual Precip. = 1250
Mean July Temperature (°C)
Spruce
Birch
N. Pines
0
0 - 10
10 - 20
20 - 30
30 - 40
> 40 percent

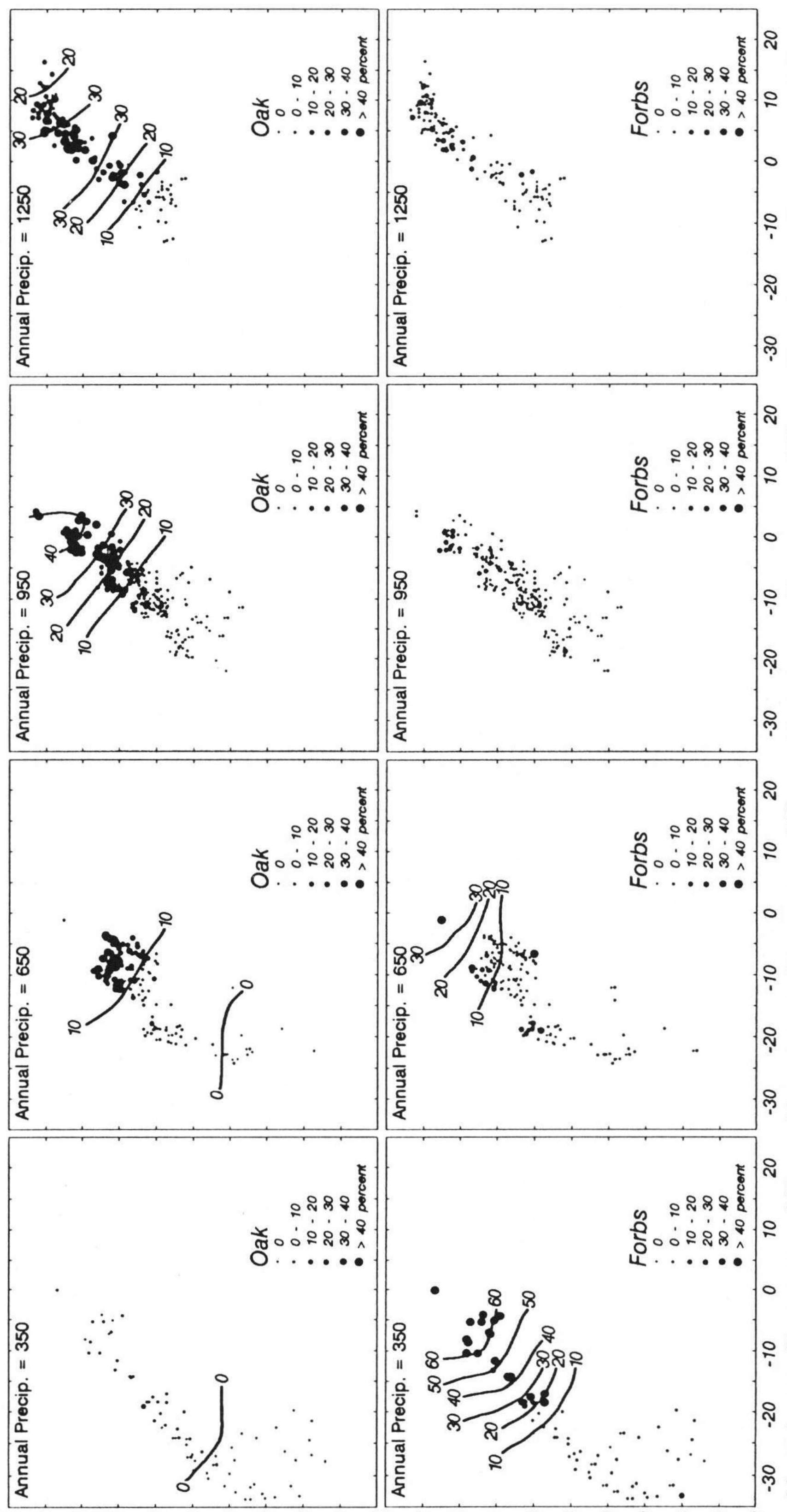


Figure 5. Response surfaces for some of the major pollen types.

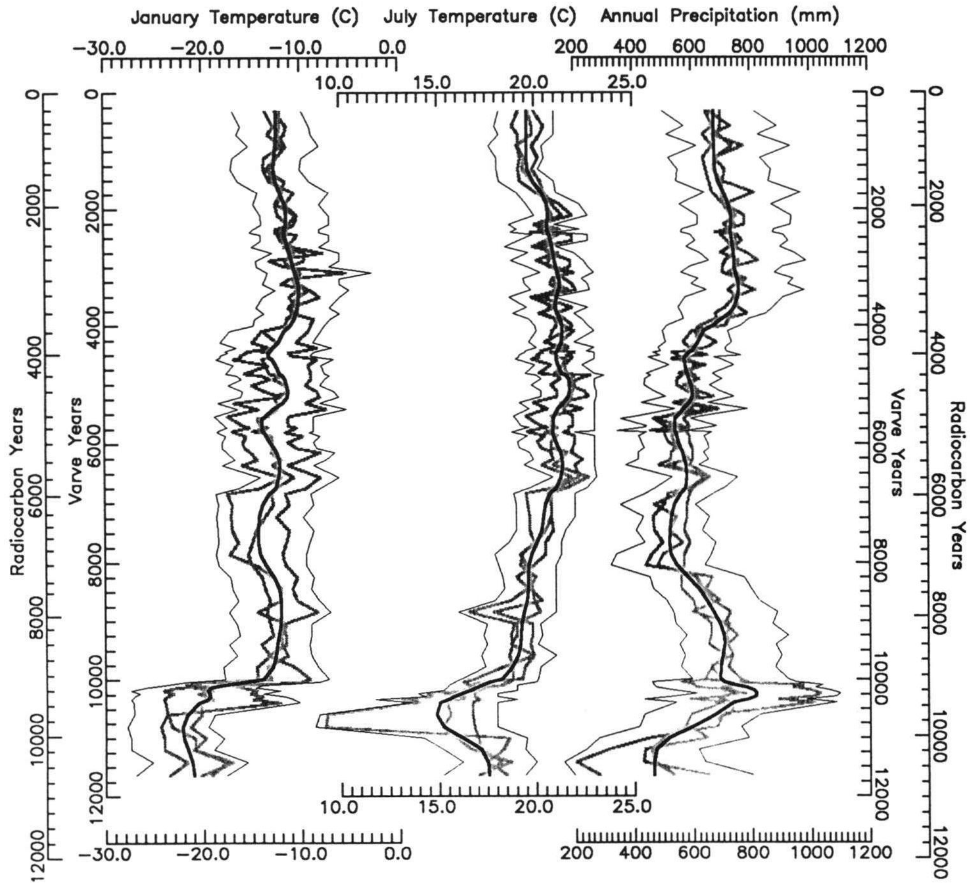


Figure 6. Elk Lake climate reconstruction summary. The three series plotted with stippled lines show the reconstructions produced by the individual approaches, the series plotted with the thin line show the envelope of the prediction intervals, and the series plotted with a thick black line represents the stacked and smoothed reconstruction of each variable (constructed by simple averaging of the individual reconstructions for each level, followed by smoothing [Velleman, 1980]). The modern observed values (1978–1984) for Itasca Park are also shown.

Comparisons with other paleoenvironmental indicators

Every paleoenvironmental indicator responds to environmental changes in a unique way. Each has its own, usually nonlinear, multivariate response function of the kind typified for pollen types (Fig. 5). The multivariate nature of most response functions thus implies that the record of an individual indicator contains the influence of several controls, and, moreover, different indicators will respond independently to a given change in controls. Where multiple paleoenvironmental indicators are available, as they are at Elk Lake, there is no reason to expect that the indicators would all produce identical paleoenvironmental reconstructions. On the contrary, different reconstructions from various indicators are a natural result of the different response functions. Where multiple and diverse paleoenvironmental indicators yield similar results, the reconstructions are probably relatively robust.

Overall, the various indicators at Elk Lake suggest similar millenial-scale variations in the environment. The most extensive agreement occurs for the dry middle Holocene climate interval (7800–4500 varve yr), and the transition into and out of it. Diatom evidence for the interval between 8200 and 4000 varve yr registers a greater influx of diatoms than before or after, and dominance by taxa that imply generally dry conditions and lower lake level (Bradbury and Dieterich-Rurup, Chapter 15). The ostracode record has a similar interpretation (Forester and others, 1987): the interval from 7800 to 4000 varve yr is interpreted as a time of generally drier conditions and increasing temperature. The influx of detrital clastic material to the lake was higher from 8200 to 4000 varve yr (Dean, Chapter 10), again an indication of drier conditions during that interval. A similar level of general agreement exists for middle Holocene temperature changes at Elk Lake, as inferred from different paleoenvironmental indicators.

What is more remarkable, however, is the consistent evidence among the different records for an interval of generally wetter conditions between 5400 and 4800 varve yr that occurred within the dry middle Holocene climate interval (Dean and others, 1984). This interval of wetter conditions has been inferred independently from a number of indicators, including pollen, diatoms, ostracodes, and the physical and chemical characteristics of the sediments. The varve chronology of Elk Lake permits the timing of its occurrence to be closely dated. That the different indicators register the climatic interval synchronously implies that little lag (i.e., <200 yr) occurs in their response to climatic change.

DISCUSSION

The sequence of climatic variations recorded in the paleoecological record of a particular location reflects the superimposition of several different controlling factors that operate at different scales. At the global or hemispheric scale the boundary conditions of the climate system include the seasonal and latitudinal distribution of solar radiation; the area, height, and reflectivity of the ice sheets; the temperature of the oceans; and the composition of the atmosphere. Together these factors act to control the nature of the large-scale circulation of the atmosphere. Atmospheric circulation governs the location and activity of storm tracks and the duration at which different air masses dominate particular regions. Solar radiation has an additional direct effect by controlling in part the net radiation at a particular location, which in turn governs both sensible heating and evapotranspiration. At the regional scale or mesoscale, local geography exerts some control on climate. The influence of the North American Great Lakes on the climate of adjacent regions is an example. As the spatial scale decreases to the size of the local region that contributed fossils to the record (e.g., the "pollen catchment"), landscape factors assume increasing importance. All three scales of control must be considered with respect to the paleoclimatic record at Elk Lake, even though it is difficult to treat each scale independently.

Large-scale controls: The ice sheet and insolation

During the past 18,000 yr, the regional climatic variations during the transition from glacial to interglacial conditions have been controlled by the size of the Laurentide ice sheet and the latitudinal and seasonal distribution of solar radiation (COHMAP Members, 1988). The ice sheet exerted control over regional climates by acting both globally (on atmospheric circulation) and locally, through proximal or periglacial influences (Wright, 1987). At the global scale, the ice sheet at its largest extent had a major influence on atmospheric circulation in the Northern Hemisphere: it split the jet stream and created a glacial anticyclone over eastern North America (COHMAP Members, 1988). The great elevation and high reflectivity of the ice sheet also contributed to the great cooling of the mid-latitude regions. The areas along the southern ice margin experienced both these global influences, as well as the more direct influence of the glacial anticyclone. When the ice sheet was large, the anticyclone was probably well developed, and adiabatic warming of the winds descending from the broad dome of the ice sheet resulted in climates that were milder and drier than might be anticipated along the southern margin of the ice sheet (Bryson and Wendland, 1967). As the ice sheet decreased in size, this effect probably became attenuated.

During the interval spanned by the Elk Lake record, considerable changes in the size of the ice sheet occurred (Dyke and Prest, 1987; Fig. 7). In terms of the oxygen isotope changes from glacial to interglacial conditions, 60% of the full-glacial isotopic level remained at 12 ka, decreasing to 25% at 9 ka, to 10% at 6 ka, and to approximately present values by 3 ka (Mix, 1987). The ice sheet probably exerted considerable influence on the Elk Lake record before 6 ka, both locally, due to its periglacial influence, and globally, through its influence on atmospheric circulation.

Insolation, the second major control at the global scale, also varied considerably during the interval spanned by the Elk Lake record (Berger, 1978). At 12 ka, summer (July) insolation at 47°N was greater than present by 7.7%, and winter insolation was less than present by 9.8%. This difference was caused by the slightly greater tilt of the Earth's axis then and the occurrence of perihelion in summer, rather than winter, as at present. By 9 ka, the insolation anomaly had increased to 8.6% greater than present in July, and 10.6% less in January. From 9 ka to present the amplification of the seasonal cycle of insolation attenuated gradually, but it was still important at 6 ka. As for the ice sheet, insolation probably had both global and local effects. On a global scale, the greater summer insolation about 10,000 yr ago probably produced heating of the centers of the continents relative to coastal areas, consequently modifying atmospheric circulation (Kutzbach, 1987). On a local scale, the greater summer insolation probably increased net radiation. The additional net radiation potentially served to increase both sensible heating (heating of the ground surface and the air above it) and latent heating (evapotranspiration).

The specific influence of these large-scale controls on the Itasca region can be evaluated with the help of paleoclimatic model simulations. Kutzbach and Guetter (1986) and Kutzbach (1987) described a series of experiments with the NCAR CCM wherein they simulated past climates at 3000 yr intervals from 18 ka to present. For eastern North America, the main responses of the simulated climate to the changing controls included (Webb and others, 1987) (1) strong control of atmospheric circulation by the large ice sheet at 18 and 15 ka in both summer and winter; (2) diminished control of atmospheric circulation by the smaller ice sheet at 12 and 9 ka, the main influence being confined to summer; and (3) earlier response to the increasing summer insolation in regions farther from the ice sheet, and delayed response in regions close to the ice. Several secondary responses of the simulated climate are also important, including a shift in the location of the largest temperature differences in July (relative to present) toward the center of the continent from 9 to 6 ka and consequent shift in the surface wind patterns, and a tendency for January temperatures in the simulations to remain lower than the model's control (modern) simulations until 6 ka, while July temperatures increased to values higher than the modern values by 9 ka.

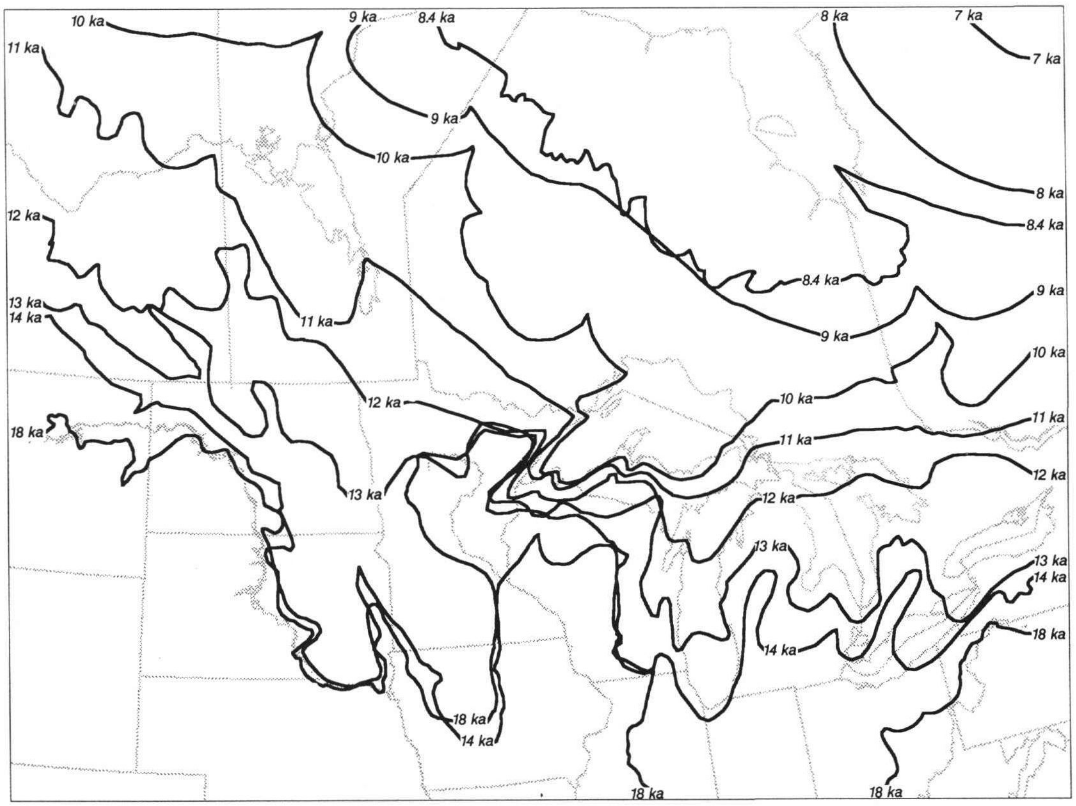


Figure 7. Retreat of the Laurentide ice sheet. Contours are in ka. Redrawn from Dyke and Prest (1987).

The detailed results of these simulations that are relevant to the Elk Lake record are obtained by examining areal averages of specific climate variables. Several limitations of the simulation results, however, must be kept in mind when interpreting such information. The resolution of the model is coarse (4.4° of latitude by 7.5° of longitude), and mesoscale features that have important influences on climate, such as the Great Lakes and the Appalachians, are not represented in the model. Similarly, the western Cordillera is crudely represented in the model, and its downstream influences on the climate of eastern North America may also be crudely represented. The simulations of precipitation and precipitation minus evaporation by the model are also poor. Simulations are described as "snapshots" of climate taken at different specific times, but in reality the boundary conditions change slowly and individual simulations therefore represent fairly broad intervals within which the controls were at generally similar levels.

The glacial anticyclone in the model simulations creates stronger (than present) northerly and northeasterly winds in the Itasca region from 18 to 12 ka (Fig. 8). During the interval from 9 to 3 ka, the shift in the heat low and its attendant circulation toward the center of the continent is evident in the simulation of stronger westerlies (than present) in July. Although both July and annual net radiation were greater than present at 12 ka (Fig. 9), July and January temperatures remained lower than present in the simulations. At 9 ka in the simulations, July temperature increased to levels greater than present and January temperature remained close to modern values in response to the seasonal distribution of insolation. The difference in the temperature response to similar radiation anomalies at 12 and 9 ka can be ascribed to the stronger influence of the ice sheet at 12 ka.

In summary, the modeling results suggest that as the northeasterly winds generated by the glacial anticyclone weakened (they were still quite strong at 12 ka), westerly winds strengthened as a result of a shift in the "heat low" generated by the stronger summer insolation (Kutzbach, 1987). The westerlies reached a maximum around 6 ka in both seasons, and decreased thereafter. The proximal or periglacial effects of the ice, still large at 12 ka, also decreased, probably becoming insignificant by 7.5 ka. As the influence of the ice was waning, the influence of the insolation anomaly increased (see also Wright, 1992).

This sequence of changes in the large-scale controls has several implications for the Itasca region. When the ice sheet was large, generally cool conditions should have prevailed, consistent with the generally cool conditions inferred from the pollen data from Elk Lake for the interval 11,600–6000 varve yr. With the replacement of the glacial anticyclonic wind regime by stronger westerlies during the interval between 9000 and 6000 varve yr,

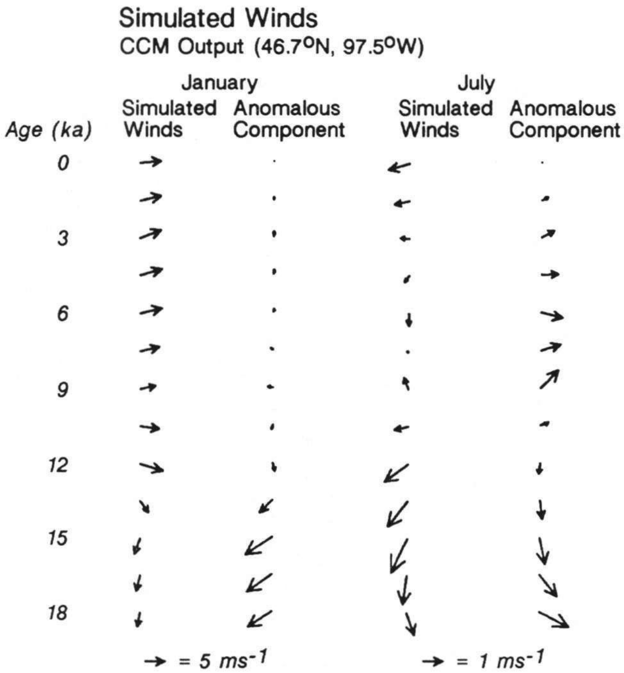


Figure 8. Winds simulated by the CCM. Simulated winds are displayed as vectors, where the length and orientation of the vectors represent the strength and direction of winds. The vectors were constructed by taking a distance-weighted average of the wind components at the model's grid points surrounding the grid point at 46.7°N, 97.5°W (the closest one to Elk Lake), and including that point. The anomalous components show the sense in which the simulated winds differ from those simulated for the model's control experiments.

precipitation should have decreased to its lowest levels during the Holocene, again consistent with the Elk Lake evidence. Finally, during the past 6000 yr, modern conditions should have developed as the seasonal distribution of insolation gradually approached present-day levels.

Mesoscale controls: Lake Agassiz

During the early part of the Elk Lake record, the presence of Lake Agassiz (Teller, 1985, 1987) probably modified the regional climate, much the same way that the North American Great Lakes generate a lake effect today (cooler summers, warmer winters, greater annual precipitation on the leeward shore). The record from Elk Lake provides an opportunity to examine the significance of Lake Agassiz on the regional climate. This discussion of the Lake Agassiz chronology follows Teller (1985, 1987; Fig. 10), but the ages cited there have been adjusted to calendar years with the relationship described by Stuiver and others (1986) (Fig. 11).

Lake Agassiz formed around 12,800 yr ago as the Laurentide ice retreated (Figs. 6 and 10). For the first 1000 yr of its existence (the Cass and Lockhart phases), the lake occupied much of the Red River Valley to the west of Elk Lake. The size of this lake suggests that the lake effect was large. As the ice retreated, outlets to the east opened and Lake Agassiz receded into Canada during the Moorhead phase (between about 11,900 and 10,750 yr ago). During this interval the lake effect in the Itasca region was probably diminished. During the Emerson phase, between 10,750 and about 10,250 yr ago, ice readvanced into the Lake Superior basin, closing the eastern outlets and allowing the lake to reoccupy its former position south of the International Boundary. The lake effect on the Itasca region thus probably increased. After 10,000 yr ago, during the Nipigon, Ojibway, and Terrell Sea phases, the ice retreat again caused the lake to recede into Canada and the local lake effect to diminish (Fig. 10).

The readvance of the lake into the Red River Valley and probable reestablishment of the lake effect on surrounding areas provide a possible explanation for variations in the reconstructed climate between 11,000 and 10,000 varve yr. Between 11,000 and 10,250 varve yr, inferred July temperatures were low. Annual precipitation increased, reaching levels greater than present near the end of the interval. Both cooler and wetter conditions implied by these reconstructions are consistent with a lake effect that would occur as the shore of Lake Agassiz moved within 75 km of Elk Lake during the Emerson phase.

This explanation has some weaknesses. First, the increased precipitation about 10,250 varve yr is inferred from elevated abundances of hardwood taxa in a few fossil spectra. Throughout the Midwest there is an episode of higher hardwood abundances between 12,000 and 10,000 varve yr ago (Amundson and Wright, 1979; Webb and others, 1983), and it is within this broader interval that the hardwood peak at Elk Lake occurs. If this minor hardwood oscillation was fostered by the lake effect during the Emerson phase, its expression should have become attenuated with increasing distance from Lake Agassiz. Unfortunately most fossil records from the Midwest are not analyzed in sufficient detail to identify this oscillation nor are they adequately dated to make site to site comparisons. Second, there may be some uncertainties in dating. The beginning of the oscillation lies in the unvarved part of the core, and is thus poorly dated. The chronology of Lake Agassiz comes from radiocarbon dating of material within the terraces and deposits of the lake, and indirectly by radiocarbon dating of glacial deposits in the Midwest. The chronology is therefore subject to the uncertainties attached to such a heterogeneous suite of dates. The Elk Lake record does not include the older Cass and Lockhart phases, when the lake effect should have been equally as pronounced. The tentative correlation between the reconstructed climate and Lake Agassiz stages is based on but a single example, the Emerson phase, and it could be fortuitous. Some of these problems could be resolved with additional detailed regional analyses of the late glacial–Holocene transition (see Webb and others, 1983).

The Elk Lake record provides an interesting perspective on the Younger Dryas climatic fluctuation. The drainage of Lake Agassiz to the east during the Moorhead phase redirected meltwater flow from the Mississippi drainage into the North Atlantic. The introduction of this meltwater has been implicated as a trig-

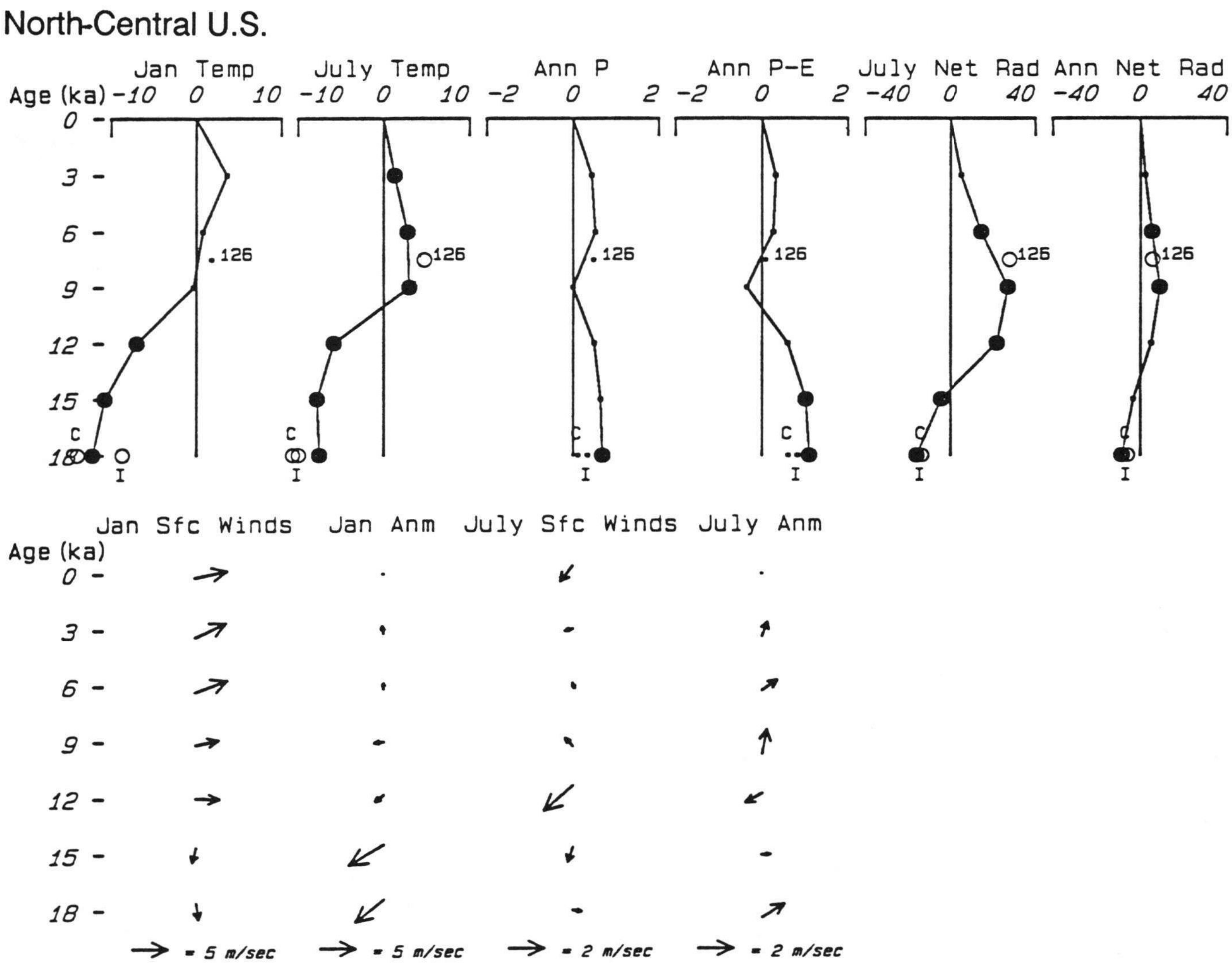


Figure 9. Averages of selected climate variables for a region centered on the upper Midwest. See Webb and others (1993) for details. The variables are all expressed as anomalies, or differences from the model's control simulations. Large dots indicate differences that are "significant," i.e., that exceed the model's natural variability.

gering mechanism for the Younger Dryas-age cooling in the North Atlantic region (see Wright, 1987, for discussion), but whether this climatic event is hemispheric or global in extent is controversial (Rind and others, 1986). At Elk Lake, reconstructions of July temperature and annual precipitation do show a pronounced change at the *end* of Younger Dryas time (10,600 to 10,000 ^{14}C yr; Cwynar and Watts, 1989), or 11,600 to 11,000 calendar years before present (applying the calibration of Stuiver and others, 1986). The change in temperature, however, is toward cooling with the increased lake effect, rather than the warming observed elsewhere. Even though the change at Elk Lake has the same ultimate cause and is contemporaneous with the end of the Younger Dryas reversal elsewhere, its proximal cause is something quite different.

Whereas Lake Agassiz may thus have been the ultimate cause of the Younger Dryas cooling, the mesoscale climatic changes in the Itasca region were in an opposite direction. Should the Elk Lake record then be cited as evidence of a global Younger Dryas-age cilmatic event? On one hand, it is contemporaneous with and related to the same ultimate cause as the Younger Dryas reversal in other parts of the world. On the other hand, the climate interval at Elk Lake was not controlled by changes in the North Atlantic region that might have driven the climate system on a global scale.

Short-term paleoclimatic variations

A striking feature of the Elk Lake record is the similarity in registration by different paleoenvironmental indicators of shorter term (i.e., century scale) climatic variations, such as those that occurred within the dry middle Holocene interval. The ultimate controls of these short-term climatic variations cannot be as easily identified as those that caused the millenial-scale variations. There are a number of potential controls that may operate on the century scale, and their individual effects may be impossible to separate in a single record. These controls include solar variability, volcanism, and internal variations in the climate system (Bartlein, 1988). In order to identify the specific controls responsible for a particular short-term climatic fluctuation (such as that at Elk Lake between 5400 and 4800 varve yr) it will be necessary to develop spatial networks of paleoecological data that have the appropriate temporal resolution (e.g., Gajewski, 1988).

SUMMARY AND CONCLUSIONS

The past climatic variations inferred from the Elk Lake pollen record disclose a sequence of changes that are consistent with what is known about the large-scale controls of climate over the past 12,000 yr, and the record inferred from other paleoenvironmental indicators. The results of three different numerical approaches used to reconstruct climate differ only in detail.

The late glacial climate interval (11,600–11,000 varve yr) was characterized by conditions much colder and drier than present, when *Picea* dominated the pollen record. This interval was followed by a transitional interval, lasting about 1000 yr, characterized by marked increases in temperature and precipitation. The early Holocene interval (10,000–8500 varve yr) is characterized by relatively cool and moist conditions when *Pinus* dominated (warmer and moister than earlier, and a little cooler than and about as moist as present). Another transition at the time of change from forest to prairie led to the middle Holocene interval (7800–4500 varve yr), when the reconstructions show low annual precipitation, and a general increase in July temperatures. The warm dry prairie interval terminated with a transition in

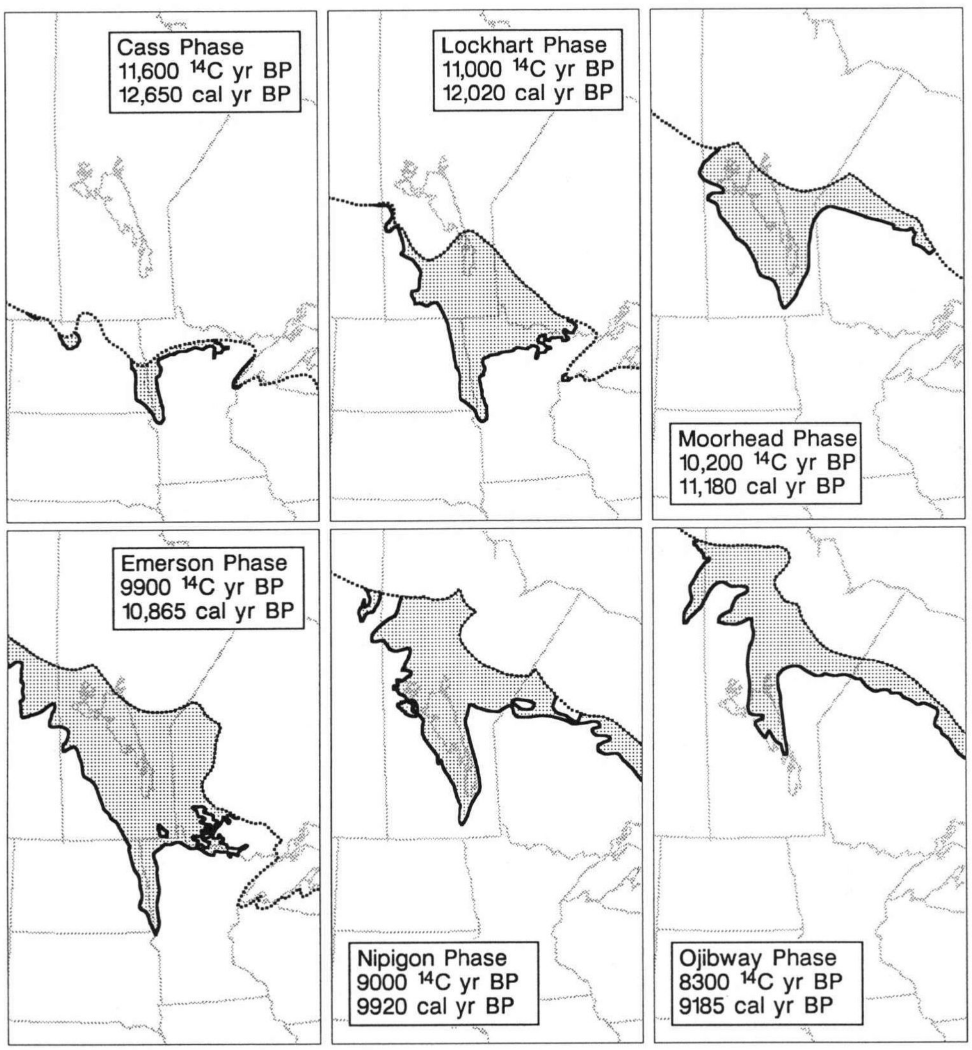


Figure 10. Lake Agassiz stages. Redrawn from Teller (1985), except for Nipigon Phase, from Dyke and Prest (1987). The dotted line shows the ice margin at different times, and the heavy line indicates proglacial lake shorelines.

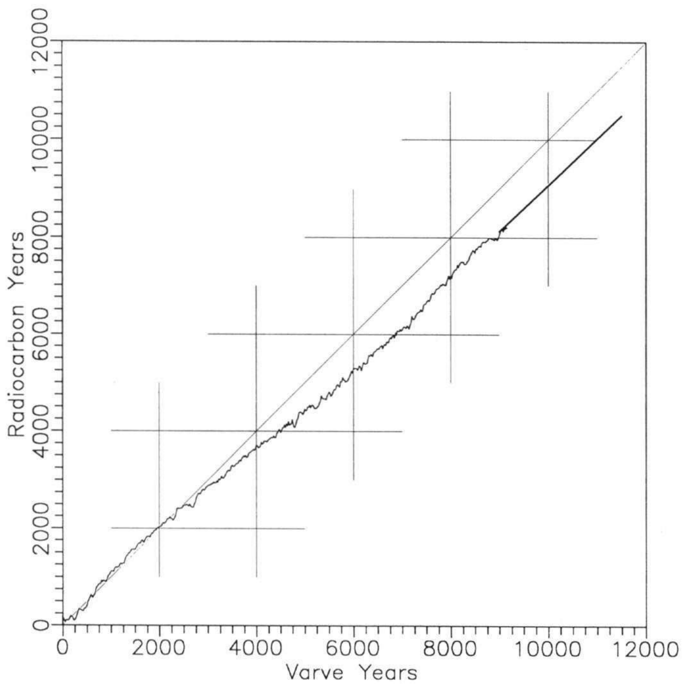


Figure 11. Radiocarbon years/varve years relationship. The curve plotted here illustrates the relationship between absolute ages expressed in calendar or varve years and those derived from radiocarbon analyses. The data were obtained from the file "atm20.14c" that accompanies the program of Stuiver and Reimer (1986). The straight line segment plotted between 9000 and 11,500 varve yr is that given by Stuiver and others (1986).

which the pollen of forest taxa increased. The late Holocene interval (3500 varve yr to present) is characterized by modern vegetation and climate.

Superimposed on these millenial-scale variations are shorter term variations in climate, such as those related to Lake Agassiz and those that occurred within the middle Holocene interval. The synchroneity among the different indicators for the latter implies that the pollen record, and hence the vegetation, is able to respond rapidly to environmental changes.

The ultimate cause of all of these climatic variations is difficult to determine precisely, because the pollen record reflects the combination of climatic changes that have taken place on a hierarchy of spatial scales, ranging from global to local. Nevertheless, the particular sequence of climatic changes at Elk Lake seems to be consistent with the effects of a gradually diminishing Laurentide ice sheet, superimposed on the amplification of the seasonal cycle of insolation as produced by orbital variations. In particular, as long as the proximal effects of the ice sheet on circulation and temperature prevailed, the response to the higher summer insolation during the early Holocene was attenuated.

ACKNOWLEDGMENTS

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REFERENCES CITED

Amundson, D. C., and Wright, H. E., Jr., 1979, Forest changes in Minnesota at the end of the Pleistocene: Ecological Monographs, v. 49, p. 1–16.

Anderson, P. M., Bartlein, P. J., Brubaker, L. B., Gajewski, K., Ritchie, J. C., 1989, Modern analogues of late-Quaternary pollen spectra from the western interior of North America: Journal of Biogeography, v. 16, p. 573–596.

Barnosky, C. W., Anderson, P. M., and Bartlein, P. J., 1987, The Northwestern U.S. during deglaciation: Vegetational history and paleoclimatic interpretations, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 289–321.

Bartlein, P. J., 1988, Late-Tertiary and Quaternary paleoenvironments, *in* Huntley, B., and Webb, T., III, eds., Vegetation history: Dordrecht, Kluwer, p. 113–152.

Bartlein, P. J., and Webb, T., III, 1985, Mean July temperature at 6000 yr B.P. in Eastern North America: Regression equations for estimates from fossil-pollen data, *in* Harrington, C. R., ed., Climatic change in Canada 5: Critical periods in the Quaternary climatic history of northern North America: Syllogeus, v. 55, p. 301–342.

Bartlein, P. J., Webb, T., III, and Fleri, E. C., 1984, Holocene climatic change in the northern Midwest: Pollen-derived estimates: Quaternary Research, v. 22, p. 361–374.

Bartlein, P. J., Prentice, I. C., and Webb, T., III, 1986, Climatic response surfaces from pollen data for some eastern North American taxa: Journal of Biogeography, v. 13, p. 35–57.

Berger, A., 1978, Long-term variation of caloric insolation resulting from the Earth's orbital elements: Quaternary Research, v. 9, p. 139–167.

Bryson, R. A., and Wendland, W. M., 1967, Tentative climatic patterns for some late-glacial and postglacial episodes in central North America, *in* Mayer-Oakes, W. J., ed., Life, land, and water: Winnipeg, University of Manitoba Press, p. 271–298.

COHMAP Members, 1988, Climatic changes of the last 18,000 years: Observations and model simulations: Science, v. 241, p. 1043–1052.

Cwynar, L. C., and Watts, W. A., 1989, Accelerator-mass spectrometer ages for late-glacial events at Balybetagh, Ireland: Quaternary Research, v. 31, p. 377–380.

Dean, W. E., Bradbury, J. P., Anderson, R. Y., and Barnosky, C. W., 1984, The variability of Holocene climate change: Evidence from varved lake sediments: Science, v. 226, p. 1191–1194.

Dyke, A. S., and Prest, V. K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: Geographie Physique et Quaternaire, v. 41, p. 237–263.

Forester, R. M., Delorme, L. D., and Bradbury, J. P., 1987, Mid-Holocene climate in northern Minnesota: Quaternary Research, v. 28, p. 263–273.

Gajewski, K., 1988, Late Holocene climatic changes in eastern North America estimated from pollen data: Quaternary Research, v. 29, p. 255–262.

Guiot, J., 1987, Late Quaternary climatic change in France estimated from multivariate pollen time series: Quaternary Research, v. 28, p. 100–118.

Howe, S., and Webb, T., III, 1983, Calibrating pollen data in climatic terms: Improving the methods: Quaternary Science Reviews, v. 2, p. 17–51.

Huntley, B., Bartlein, P. J., and Prentice, I. C., 1989, Climatic control of the distribution and abundance of beech (Fagus L.) in Europe and North America: Journal of Biogeography, v. 16, p. 551–560.

Klimanov, V. A., 1984, Paleoclimatic reconstructions based on the information statistic method, *in* Velichko, A. A., ed., Late Quaternary environments of the Soviet Union: Minneapolis, University Minnesota Press, p. 297–303.

Kutzbach, J. E., 1987, Model simulations of the climatic patterns during the deglaciation of North America, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 425–446.

Kutzbach, J. E., and Guetter, P. J., 1986, The influence of changing orbital patterns and surface boundary conditions on climate simulations for the past 18,000 years: Journal of the Atmospheric Sciences, v. 43, p. 1726–1759.

Lichti-Federovich, S., and Ritchie, J. C., 1965, Contemporary pollen spectra in central Canada, II. The forest-grassland transition in Manitoba: Pollen et Spores, v. 7, p. 63–87.

—— , 1968, Recent pollen assemblages from the western interior of Canada: Review of Paleobotany and Palynology, v. 7, p. 297–344.

Macdonald, G. M., and Ritchie, J. C., 1986, Modern pollen spectra from the western interior of Canada and the interpretation of late Quaternary vegetation development: New Phytologist, v. 103, p. 245–268.

Mix, A. C., 1987, The oxygen-isotope record of glaciation, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 111–135.

Neter, J., Wasserman, W., and Kutner, M. H., 1983, Applied linear regression models: Homewood, Illinois, R. D. Irwin, Inc., 547 p.

Overpeck, J. T., Prentice, I. C., and Webb, T., III, 1985, Quantitative interpretation of fossil pollen spectra: Dissimilarity coefficients and the method of modern analogs: Quaternary Research, v. 23, p. 87–108.

Prentice, I. C., 1983, Postglacial climatic change: Vegetation dynamics and the pollen record: Progress in Physical Geography, v. 7, p. 273–286.

—— , 1986, Vegetation responses to past climatic changes: Vegetatio, v. 67, p. 131–141.

Prentice, I. C., Bartlein, P. J., and Webb, T., III, 1991, Vegetation and climate change in eastern North America since the Last Glacial Maximum: Ecology, v. 72, p. 2038–2056.

Rind, D., Peteet, D., Broecker, W., McIntyre, A., and Ruddiman, W., 1986, The impact of cold North Atlantic sea surface temperatures on climate: Implications for the Younger Dryas cooling (11–10k): Climate Dynamics, v. 1, p. 3–33.

Stuiver, M., and Reimer, P. J., 1986, A computer program for radiocarbon age calibration: Radiocarbon, v. 29, p. 1022–1030.

Stuiver, M., Kromer, B., Becker, B., and Ferguson, C. W., 1986, Radiocarbon age calibration back to 13,300 years BP and the ^{14}C age matching of the German oak and US bristlecone pine chronologies: Radiocarbon, v. 29, p. 969–979.

Teller, J. T., 1985, Glacial Lake Agassiz and its influence on the Great Lakes, *in* Karrow, P. F., and Calkin, P. E., eds., Quaternary evolution of the Great Lakes: Geological Association of Canada Special Paper 30, p. 1–16.

—— , 1987, Proglacial lakes and the southern margin of the Laurentide Ice Sheet, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 39–69.

Velleman, P., 1980, Definition and comparison of robust nonlinear data smoothers: Journal of the American Statistical Association, v. 75, p. 609–615.

Webb, T., III, 1980, The reconstruction of climatic sequences from pollen data: Journal of Interdisciplinary History, v. 10, p. 749–772.

—— , 1986, Is the vegetation in equilibrium with climate? How to interpret late-Quaternary pollen data: Vegetatio, v. 67, p. 75–91.

—— , 1993, Vegetation, lake levels, and climate in eastern North America since 18,000 yr B.P., *in* Wright, H. E., Jr., Kutzbach, J. E., Webb, T., III, Ruddiman, W. F., Street-Perrott, F. A., and Bartlein, P. J., eds., Global climates since the Last Glacial Maximum: Minneapolis, Minnesota, University of Minnesota Press (in press).

Webb, T., III, Cushing, E. J., and Wright, H. E., Jr., 1983, Holocene changes in the vegetation of the Midwest, *in* Wright, H. E., Jr., ed., Late-Quaternary environments of the United States, Volume 2: The Holocene: Minneapolis, University of Minnesota Press, p. 142–165.

Webb, T., III, Bartlein, P. J., and Kutzbach, J. E., 1987, Post-glacial climatic and vegetational changes in eastern North America since 18 ka: Comparison of the pollen record and climate model simulations, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 447–462.

Weisberg, S., 1985, Applied linear regression: New York, Wiley, 324 p.

Wright, H. E., Jr., 1987, Synthesis; the land south of the ice sheets, *in* Ruddiman, W. F., and Wright, H. E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 479–488.

—— , Jr., 1992, Patterns of Holocene climatic change in the Midwestern United States: Quaternary Research, v. 38, p. 129–134.

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