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Reconstruction of Holocene Precipitation Patterns in Europe Using Pollen and Lake-Level Data

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Lake-level data can be used to refine palaeoclimate reconstructions based on pollen data. This approach is illustrated for the European Holocene. Estimates of P−PET (precipitation minus potential evapotranspiration) were first inferred from modern pollen analogues. The pollen-based estimates were then compared with the status of lakes within a 5° radius. Analogues with P−PET anomalies inconsistent with the lake-level changes were rejected. The "constrained" sets of analogues were used to estimate continental-scale patterns of annual mean temperature and annual precipitation at 3000-yr intervals. Estimated temperature anomalies differed only slightly from the unconstrained reconstructions. Estimated precipitation anomalies, however, showed improved spatial coherence and increased regional contrast and were occasionally reversed in sign. The effect of the constraint was to impose a rational selection among almost equally similar modern pollen analogues with similar temperatures but widely varying moisture regimes. The resulting maps showed clear, spatially coherent patterns of change in precipitation as well as temperature, suitable for comparison with climate-model results. Further improvement of these maps will become possible as a more extensive coverage of lake-level data is obtained. ©1993 University of Washington.

INTRODUCTION

Plant distributions respond to changes in summer warmth, winter cold, and moisture balance (Woodward, 1987; Prentice *et al.*, 1992). Climatic changes during the late Quaternary have produced continual changes in the distribution of vegetation types. The patterns of these changes can be reconstructed from continental-scale syntheses of pollen data (e.g., Huntley, 1988, 1990a; Prentice *et al.*, 1991). In long-settled regions the vegetation patterns have been modified by humans, and changes attributed to human impact are widely registered in European pollen diagrams (Behre, 1988). This does not prevent the use of pollen data to reconstruct past climate changes at a continental scale. The importance of climate at this scale is indicated by the fact that the European distributions of major taxa are as spatially coherent as they are in other continents. Furthermore, many European species' distribution limits have been related to specific climatic controls on physiological processes (e.g., Piggott and Huntley, 1981; Woodward, 1988). The abundance patterns of some European taxa can even be predicted from the climatic relationships of their North American equivalents (e.g., *Fagus;* Huntley *et al.*, 1989). This would not be possible unless climate was the major control on both continents. The spatial coherence of past changes in vegetation patterns, reconstructed from pollen data, also strongly argues for the primacy of climatic control in Europe (Huntley, 1988, 1990a,b) as has been demonstrated for eastern North America (Prentice *et al.*, 1991).

Pollen data have been used to map the qualitative patterns of Holocene climatic changes across Europe (Huntley and Prentice, 1988, 1992), and to make quantitative time-series reconstructions of climate at particular sites (Guiot, 1987, 1990; Guiot *et al.*, 1989). Various methods have been employed but all rely ultimately on the use of modern analogues. The range of temperature estimates from modern analogues of Holocene pollen spectra is generally small and the resulting temperature reconstructions are well constrained. In Europe, where growing-season moisture is rarely the main limiting factor on vegetation at a regional scale, modern analogues tend to span a wide range of precipitation values and precipitation reconstructions are less well constrained.

Lakes provide an alternative source of information about precipitation changes. Lakes respond to climatically induced changes in the local hydrological balance (precipitation and runoff versus evaporation and discharge) by changing in area and depth. Records of these changes are preserved as shorelines or in various strati-

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graphic indicators in the lake sediments themselves (Street-Perrott and Harrison, 1985). Runoff-dominated, closed-based lakes in semiarid regions (closed amplifier lakes sensu Street-Perrott and Harrison, 1985) provide the most detailed record of past climate changes, but overflowing lakes in humid regions have also varied on annual to millenial time scales in response to climate changes (e.g., Harrison, 1989; Winkler *et al.*, 1986). Continental-scale syntheses of lake-level data have been widely used to reconstruct past changes in regional water budgets (e.g., Street and Grove, 1979; Street-Perrott and Harrison, 1985; COHMAP Members, 1988; Harrison and Metcalfe, 1989; Street-Perrott *et al.*, 1989) and have recently been used to make preliminary reconstructions of the changing patterns of moisture balance across Europe during the Holocene (Harrison *et al.*, 1991, in press; Saarse and Harrison, in press; Harrison and Digerfeldt, submitted for publication).

Lake levels are influenced by climatic variables affecting evaporation as well as precipitation. However, Harrison *et al.* (in press) have shown that the direct (evaporative) effects of plausible Holocene solar radiation and temperature changes cannot explain the observed patterns of change in lake levels. The Holocene lake-level record of Europe is primarily a precipitation record. The lake-level data alone do not allow a quantitative reconstruction of precipitation, but they can provide a constraint on the choice of pollen analogues used for the quantitative reconstruction of precipitation. We show that this constrained reconstruction approach improves the spatial coherency of the inferred precipitation anomaly patterns while leaving the temperature patterns essentially unchanged. A similar method has been used to refine temperature and precipitation estimates from pollen data during glacial periods in La Grande Pile using organic carbon measurements and clay mineral data, respectively (Seret *et al.*, 1992).

Reconstructions of temperature and precipitation are presented here for 9000, 6000, and 3000 yr B.P. We do not claim that these are definitive. The distribution of sites for which Holocene lake levels have been derived is still spatially clustered and more work is required to provide the necessary evenly distributed network of sites. The pollen site network must also be improved, especially for southern Europe. Nevertheless, the maps demonstrate that a substantial improvement in quantitative palaeoclimate estimation can be achieved by using pollen and lake-level data in combination.

THE DATA

Modern Pollen

The reconstructions presented here were obtained by comparing fossil pollen data with a large set of modern pollen data. The modern pollen data consisted of 675 spectra from Europe, northern Asia, and northern Africa between 10°W and 100°E and 30°N and 80°N, i.e., the surface pollen spectra used in Guiot (1987) with supplementary data from Huntley and Birks (1983) and Peterson (1983). Only the 28 taxa (22 arboreal, 6 nonarboreal; see Guiot, 1990) common to all three sources are used (Table 2). Pollen percentages were calculated relative to the sum of these 28 taxa.

Fossil Pollen

Fossil pollen data for 9000, 6000, and 3000 yr B.P. (Fig. 1) were derived from Huntley and Birks (1983). These data consist of relative pollen counts of major taxa in lake or mire sediment for ca. 400 sites, from the region from 40° to 75°N and 10°W to 45°E and covering part or all of the last 13,000 yr. Sixty-five percent of the sites are ^{14}C-dated. The rest were dated by pollen correlation with nearby ^{14}C-dated sites or by comparison with standard ^{14}C-dated regional pollen stratigraphies. The same 28 taxa retained in the modern pollen data were used, as were all percentages calculated relative to the sum of these 28 taxa.

Lake Levels

The lake-level data (Fig. 2) consisted of 82 sites derived from the European lake-level database. This database consists of records of changes in relative water depth or lake level, derived by analysis of published geologic and biostratigraphic data and covering part or all of the last 30,000 yr. The record for each site is based on the consensus interpretation of multiple lines of evidence, including sediment lithology, aquatic pollen, and other biostratigraphic indicators. Chronologies are provided either by ^{14}C dating or pollen correlation with a well-established, ^{14}C-dated regional pollen stratigraphy. Basins with records that appear to have been influenced by tectonism, changes in the course of a river, changes in the threshold of the lake overflow, or glacier fluctuations are excluded from the data base. The construction of the European lake-level data base is part of an ongoing project. Earlier versions of the data base have been used by Harrison *et al.* (1991), Saarse and Harrison (in press), and Harrison and Digerfeldt (submitted for publication). The current version of the data base is unpublished, but documentation of the primary data and inferred lake-level changes are available from SPH.

Climate

Monthly mean temperature and total precipitation (for 1200 stations: Guiot, 1990) and cloudiness (for 580 stations; Leemans and Cramer, 1991) were smoothly interpolated to the 675 pollen sites. Growing-degree days (GDD) above four threshold values (0, 5, 10, and 15°C) were computed from the monthly temperature data by linear interpolation. Annual actual (E) and potential

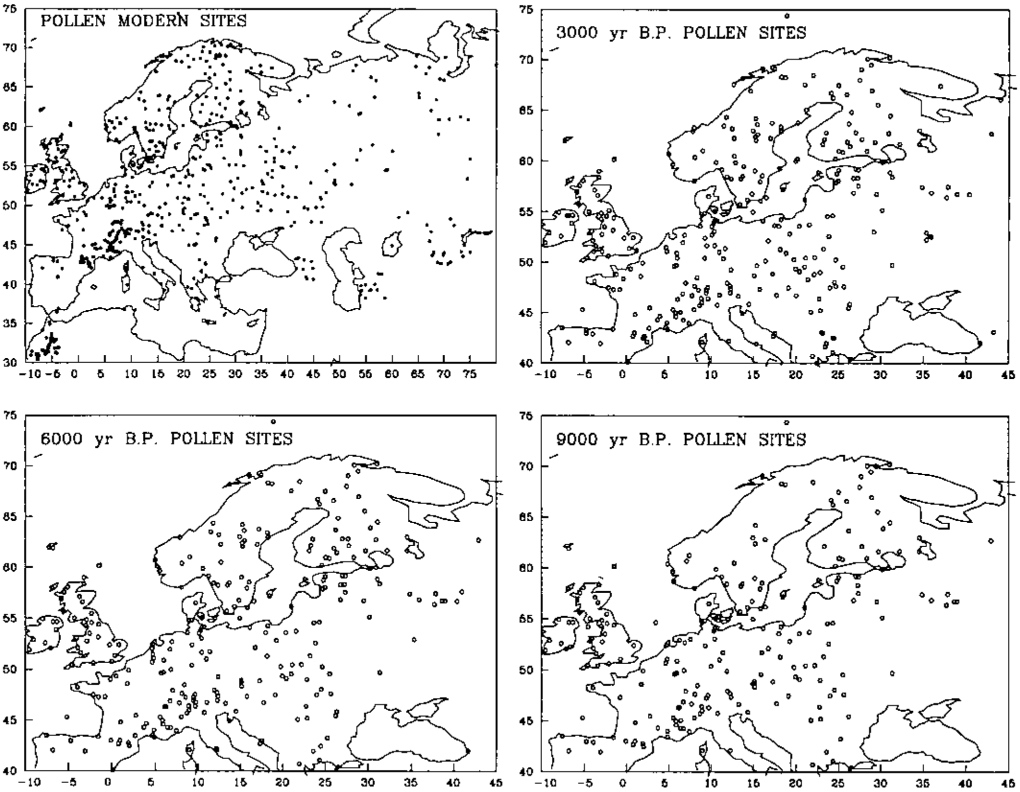

FIG. 1. Distribution of pollen sites at 0, 3000, 6000, and 9000 yr B.P.

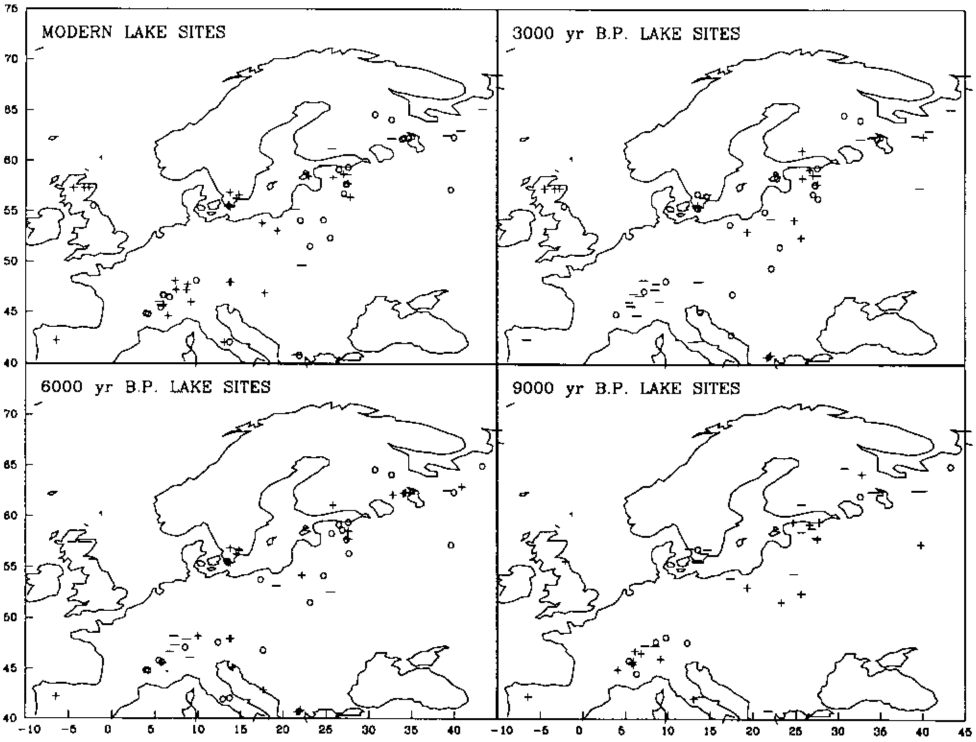

FIG. 2. Distribution of lake sites at 0, 3000, 6000, and 9000 yr B.P.

evapotranspiration (PET) were calculated using the water-balance model of Harrison *et al.* (1993). The model is conceptually similar to but computationally more efficient than that used by Prentice *et al.* (1993) for ecosystem modeling. Actual evapotranspiration in these models is taken as the lesser of a supply function proportional to soil moisture (Federer, 1982) and a demand function calculated from net radiation and temperature (Jarvis and MacNaughton, 1986). Net radiation is obtained as a semiempirical function of insolation, cloudiness, and temperature and varies sinusoidally during the day, allowing daily E and PET to be calculated analytically. We assumed an uniform soil water capacity of 150 mm.

CLIMATE–VEGETATION RELATIONSHIPS

Relationships between modern vegetation and climate were explored by multiple regressions between climate variables and the log-transformed frequencies of the 28 pollen types in the 675 modern pollen spectra (Table 1).

The temperature relationships of the vegetation are adequately represented by the mean January, mean July, and mean annual temperatures (Table 1). None of the GDD variables is more closely correlated with the pollen spectra. GDD (0°C), however, is highly correlated with mean January temperature ($r = 0.94$; $\alpha \ll 0.001$), which can also be considered as a measure of continentality as it is in turn correlated ($r = -0.84$; $\alpha \ll 0.001$) with seasonal amplitude (July temperature minus January temperature). GDD (5°C) is highly correlated with both GDD (0°C) ($r = 0.99$; $\alpha \ll 0.001$) and mean annual temperature ($r = 0.94$; $\alpha \ll 0.001$). GDD (10°C) and GDD (15°C) are highly correlated with July temperature ($r = 0.93$ and 0.96, respectively; $\alpha \ll 0.001$).

TABLE 1
Climate–Vegetation Relationships: Multiple Regression between Climate Variables and Log-Transformed Frequencies of 28 Pollen Types in 675 Modern Pollen Spectra

Variable	r^2
Temperature	
January temperature	0.62
July temperature	0.66
Annual temperature	0.64
Seasonal amplitude	0.66
Growing degree-days (0°C)	0.66
Growing degree-days (5°C)	0.64
Growing degree-days (10°C)	0.64
Growing degree-days (15°C)	0.66
Precipitation	
January precipitation	0.50
July precipitation	0.61
Annual precipitation (P)	0.53
Moisture-balance	
Actual evaporation (E)	0.67
Potential evaporation (PET)	0.81
E/PET	0.79
P-PET	0.66
P-E	0.42

Note. All the determination coefficients (r^2) are highly significant ($\alpha \ll 0.001$).

The moisture relationships proved more complicated. Annual precipitation has a low r^2. P − E, which approximates runoff and is considered to be a good predictor of lake-level changes in humid regions (Harrison *et al.*, 1993), has a still lower r^2. P − PET, which can be considered as a general climatic moisture index, however, achieved a higher r^2, similar to those obtained for the temperature variables. The highest r^2 values were obtained with PET and the ratio E/PET. The relationship with PET may reflect its status as a combined indicator of the effective (growing-season) temperature and light availability. The relationship with E/PET reflects the observation that this ratio is an excellent predictor of moisture-related vegetation boundaries at a global scale (Prentice *et al.*, 1992).

The exploratory analysis illustrates the fact that vegetation and lakes respond to different aspects of the moisture budget. Vegetation is sensitive to the soil-moisture supply/demand ratio (E/PET), whereas lakes in humid regions are sensitive to changes in runoff (P − E). The climatic moisture index P − PET, used in a later section to compare the moisture signal in pollen and lake-level data, represents a compromise between these two quantities.

PALAEOCLIMATE RECONSTRUCTION METHODS

Pollen-Based Reconstruction

Three methods are currently in use to reconstruct climatic variables from pollen data (Guiot, 1991): the response surface method (Bartlein *et al.*, 1986; Prentice *et al.*, 1991), Klimanov's (1984) information method, and the palaeobioclimatic analogues method (Guiot, 1985, 1987, 1990; modified in Guiot *et al.*, 1989). These methods are conceptually similar in that they all use modern analogues to assign climate values to past vegetation. Multiple regression ("transfer function") methods, applied in two earlier studies in Europe (Guiot, 1987; Huntley and Prentice, 1988), have proved less robust because of their ability to make spurious extrapolations beyond the climatic range represented in the modern pollen data set (Guiot, 1991). The current, analogue-based methods differ from one another in the way in which the modern pollen data are smoothed and in the relative significance assigned to individual taxa in the calculation of distances between fossil pollen spectra and modern analogues. Nevertheless, work currently undertaken by J. Guiot and B. Huntley suggests that these methods yield consistent results, especially during nonglacial periods.

The palaeobioclimatic analogues method used here begins with a principle components analysis of the between-taxon correlation matrix based on the fossil data. The taxon loadings on the dominant principal component(s) are used to weight the taxa in the calculation of the distances between pollen spectra. The use of these weights reduces the influence of high-frequency and other nonclimatic variability on the assessment of similarity. The weights are calculated using only the fossil data; they are therefore free from bias due to human impact on the modern spectra. The closest analogues found using the weighted distance measure are used to reconstruct the climate as an average of the associated modern climate values, weighted by the inverse of the distances. Confidence intervals for the reconstruction are calculated using a bootstrap method (Efron, 1979).

Principal components analysis was performed on all fossil pollen spectra at 1000-yr intervals from 13,000 to 1000 yr B.P. (3331 spectra) after logarithmic transformation to minimize the dominance of overrepresented pollen types. The first principal component explained 16% of the total variance and was dominated by thermophilous trees (e.g., *Corylus, Quercus*) with positive loadings and nonthermophilous trees and shrubs (*Juniperus, Betula, Salix*) and herbs with negative loadings. The second and the third components together explained a further 17% of the variance. The first component reflects the main contrast between high and low latitudes and between lateglacial and Holocene climates. The loadings of this component were used as weights w_j (Table 2) in the distance operator

$$d_{it}^2 = \sum_{j=0}^{m} w_j^2 (f_{ij}^{k_i} - f_{tj}^{k_t})^2, \tag{1}$$

where f_{ij} and f_{tj} are the relative frequencies of pollen taxon j (out of m taxa) in modern pollen spectrum i and fossil pollen spectrum t, respectively. The exponents k_i and k_t are given by

$$\begin{aligned} k_i &= 0.3 && \text{if } m_i/m \leqslant 0.3 \\ k_i &= m_i/m && \text{if } 0.3 < m_i/m < 0.5 \\ k_i &= 0.5 && \text{if } m_i/m \geqslant 0.5, \end{aligned}$$

(and similarly for k_t) where m_i/m is the proportion of the 28 taxa present in the spectrum i, i.e., an index of taxonomic diversity. In Europe during nonglacial periods generally, $m_i/m > 0.5$, so Eq. (1) gives the chord distance of Overpeck *et al.* (1985).

Equation (1) is used to find a set of closest modern analogues of the fossil spectra. Variability among the climates represented by this set of analogues is estimated by bootstrapping. Bootstrapping is a resampling procedure used to derive the prediction error for reconstruction (Efron, 1979) and has previously been used with transfer function methods (Guiot, 1989; Till and Guiot, 1990; Birks *et al.*, 1990). A large number of estimates is made, each based on different subsamples of the modern pollen data. Subsampling is performed randomly and with replacement. The size of each subsample is the same as that of the original data set (n) to avoid bias (Efron, 1983). The closest analogue of the fossil spectrum obtained from each subsampling is the modern pollen spectrum giving the smallest value of Eq. (1); this is called the bootstrapped best analogue. We repeated the procedure 50 times and obtained 50 bootstrapped best analogues. Although more replications have been recommended in the literature, our use of only the minimum distance at each replication appears to increase the robustness of the procedure (Guiot, 1989) and we found 50 replications sufficient to yield a stable estimate.

The reconstructed climate value for each fossil spectrum t is the distance-weighted mean of the climate values C_i associated with the s bootstrapped best analogues:

$${}^0R_t = \frac{\sum_{i=1}^{s} C_i \big/ d_{it}^2}{\sum_{i=1}^{s} d_{it}^{-2}}. \tag{2}$$

Instead of a unique standard deviation around ${}^0R_t$, the lower and upper limits of this mean estimate were computed. The lower limit LL_t is given by the distance-weighted mean of the analogues (out of the total $s = 50$) with $C_i < {}^0R_t$; the upper limit UL_t is given by the distance-weighted mean of these analogues with $C_i > {}^0R_t$. These confidence limits implicitly include errors in the modern climate observations (usually small, <0.5°C of a

TABLE 2
The Pollen Taxa and Their Weights as Used in the Palaeoclimate Reconstruction

Abies	0.20	*Alnus*	0.32
Betula	−0.18	*Buxus*	0.03
Carpinus	0.20	*Cedrus*	0.00
Corylus	0.36	*Fagus*	0.24
Fraxinus	0.27	Hippophae	−0.11
Ilex	0.03	*Juniperus*	−0.20
Larix	−0.05	*Olea*	0.00
Picea	0.13	*Pinus*	−0.05
Pistacia	0.04	Deciduous *Quercus*	0.35
Evergreen *Quercus*	0.07	*Salix*	−0.20
Tilia	0.32	*Ulmus*	0.34
Ephedra	−0.06	Ericaceae	−0.03
Hedera	0.12	*Artemisia*	−0.15
Chenopodiaceae	−0.06	Poaceae	−0.13

few mm/month), the natural variability of the assemblages for a given value of the climatic variable, and the influence of nonclimatic factors such as soil variations.

The method can be validated by estimating the modern climate from the modern pollen data. The correlations obtained between estimated and actual values were 0.80 ($\alpha \ll 0.001$) for temperature and 0.67 ($\alpha \ll 0.001$) for precipitation. The mean error (the average of $UL_t - LL_t$) was 1.6°C for temperature and 136 mm for precipitation. The lower correlation and relatively wide error margin for precipitation indicate that only part of the precipitation signal is registered in the pollen data, as previously noted.

Selection of Analogues Using Lake-Level Data

The lake-level data were interpolated to locations with fossil pollen data as follows. A moisture anomaly index δM_t was defined for each fossil pollen site *i* at each time period,

$$\delta M_t = \frac{\sum_{h=1}^{z_t} S_h/D_{th}^2}{\sum_{h=1}^{z_t} D_{th}^{-2}}, \qquad (3)$$

where S_h is the lake-status anomaly for lake site *h* (1 if higher than present, 0 if as present, -1 if lower than present); $D_{th}{}^2$ is the geographic distance between lake site *h* and pollen site *t;* and z_t is the number of lake sites within a 5° radius of pollen site *t*. Then for each fossil pollen spectrum, analogues were selected from the modern pollen spectra subject to a broad consistency requirement,

$$[\delta(\mathrm{P-PET})_{ti} < -200 \text{ mm} \quad \textit{and}\ \delta M_t < -0.3]$$

or

$$[\delta(\mathrm{P-PET})_{ti} > 200 \text{ mm} \quad \textit{and}\ \delta M_t > 0.3]$$

or

$$[-200 \text{ mm} \leq \delta(\mathrm{P-PET})_{ti} \leq 200 \text{ mm} \quad \textit{and}\ -0.3 \leq \delta M_t \leq 0.3]$$

where $\delta(\mathrm{P-PET})_{ti}$ is the difference between the P – PET associated with fossil pollen spectrum *t* and the P – PET at modern pollen site *i*. The thresholds of ±200 mm for $\delta(\mathrm{P-PET})_{ti}$ and ±0.3 for δM_t were chosen by trial and error and the results are not sensitive to their exact values. The consistency requirement was waived for fossil pollen sites that had no lake sites within 5°. The use of a 5° radius ensures that major, climatically related regional patterns in the lake-level data are used.

The bootstrap method was applied to the set of 10 closest analogues that satisfied the consistency requirement, where applicable. Potential "analogues" were disregarded if their distance was <50% of the mean distance between randomly chosen pairs of modern pollen spectra. This 50% cutoff is arbitrary, but its exact value is unimportant for the analysis because the analogues are in any case weighted by distance according to Eq. (2).

RESULTS AND DISCUSSION

Pollen- and Lake-Derived Moisture Anomaly Patterns at 6000 Yr B.P.

Figure 3 shows the differences between reconstructed (6000 yr B.P.) and modern P – PET, with their upper and lower limits. These reconstructions were made by the palaeobioclimatic analogues method with no lake-level constraint. Regions with negative upper limits are significantly drier than present and regions with positive lower limits are significantly wetter than present, according to this reconstruction. Large error bars cloud the emergence of clear spatial patterns.

Figure 4a gives the mean distance of the three closest analogues used in the reconstruction. The distances are expressed as "relative distances," i.e., percentages of the mean distance between randomly chosen pairs of modern pollen spectra. A comparable map by Huntley (1990b), showing the minimum chord distance between 6000 yr B.P. and modern pollen spectra, shows a similar pattern. Minimum chord distances >0.3 in Huntley's 6000-yr B.P. map correspond to relative distances of >20% in Figure 3. Huntley (1990) noted that chord distances of <0.3 are typical within modern vegetation units (e.g., boreal forest, Mediterranean vegetation, tundra). A small number (<6) of sites were excluded from the reconstruction because they had no analogues at <50% relative distance. All of these were in high mountain areas (one in the Alps, one in the Pyrenees, and several in the Carpathians).

The lake-derived moisture index map for 6000 yr B.P. (Fig. 5a) shows clear similarities with the (mean) pollen-based reconstruction of P – PET anomalies (Fig. 3). However, there is a region of disagreement extending from southern Sweden to the northern Balkans. Here, the mean pollen-based reconstruction shows conditions wetter than present while the lakes were lower than present. The pollen analogues in this region were poor (relative distances >20%) and the reconstructed P – PET anomalies are found not to be significant when variation among the possible alternative modern analogues is taken into account (Fig. 3). This suggests that the lake-level data could provide a useful constraint.

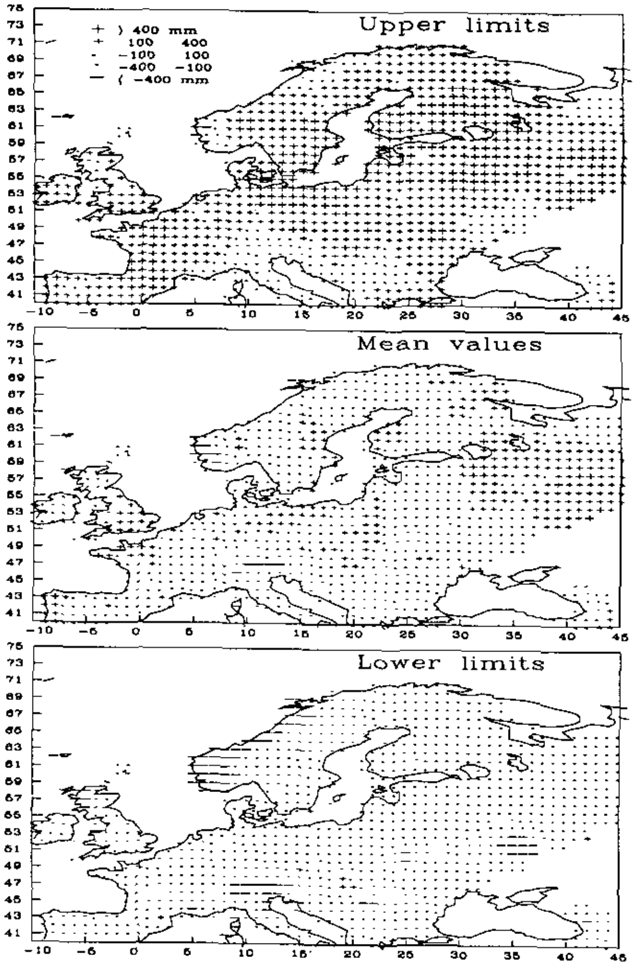

FIG. 3. P − PET anomalies (mm), 6000 yr B.P. minus present, reconstructed from pollen data alone: upper limits, mean values, and lower limits.

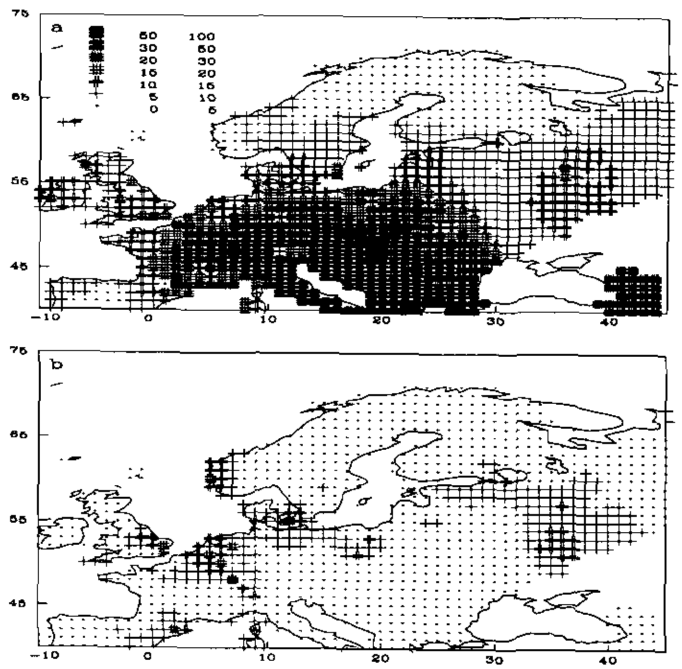

FIG. 4. (a) Average distance between the 6000 yr B.P. pollen spectra and their three closest modern analogues, as percentages of the mean distance between randomly chosen pairs of modern pollen spectra. (b) Increases in this distance when lake-level data were used to constrain the selection of analogues.

Pollen-Based Climate Reconstructions Constrained by Lake Levels

The use of the lake-derived moisture index to constrain the selection of modern pollen analogues accentuated the large-scale regional contrasts in reconstructed P − PET (Fig. 5b). The constraint generally increased the distances between fossil pollen spectra and their analogues by less than 15% (Fig. 4b). This result implies that almost equally close analogues are associated with a wide range of P − PET values, leading to ambiguity in the reconstructions based on pollen data alone. The lake-level constraint reduced this ambiguity, producing a more spatially coherent map (Fig. 5b).

The reconstructed precipitation maps for 6000 yr B.P., with and without the lake-level constraint (Fig. 6), closely resemble the corresponding P − PET maps (Figs. 3 and 5b). The changes brought about by the constraint were similar for precipitation and P − PET. In contrast, reconstructions of annual mean temperature anomalies were hardly altered by the constraint (Fig. 7).This reflects the fact that the modern analogues for a given pollen spectrum usually span only a narrow range of mean annual temperature, in contrast with the situation for annual precipitation and P − PET.

Similar results (not shown) were obtained from comparisons of constrained and unconstrained palaeoclimate reconstructions for 9000 and 3000 yr B.P. At 9000 yr B.P., a region including southern Scandinavia, northern Germany, and Poland was shown as wet in the (mean) unconstrained reconstruction but became dry in the constrained reconstruction due to the widespread occurrence of low lake levels (Harrison *et al.,* 1991). The constraint eliminated modern analogue pollen spectra from northwest Europe and substituted almost equally close analogues with similar mean annual temperatures from farther east. At 3000 yr B.P. the constraint removed similar though smaller discrepancies. The temperature reconstructions were essentially unaffected by these changes.

Constrained Reconstructions of Holocene Climate Changes (Fig. 8)

Reconstructed temperatures at 6000 yr B.P. show broadly similar patterns to the July temperature reconstruction by Huntley and Prentice (1988), with anomalies ≥2°C (especially in northern Europe and in mountain regions), contrasting with zero or even negative anomalies in some (especially coastal) regions. Northeastern Eu-

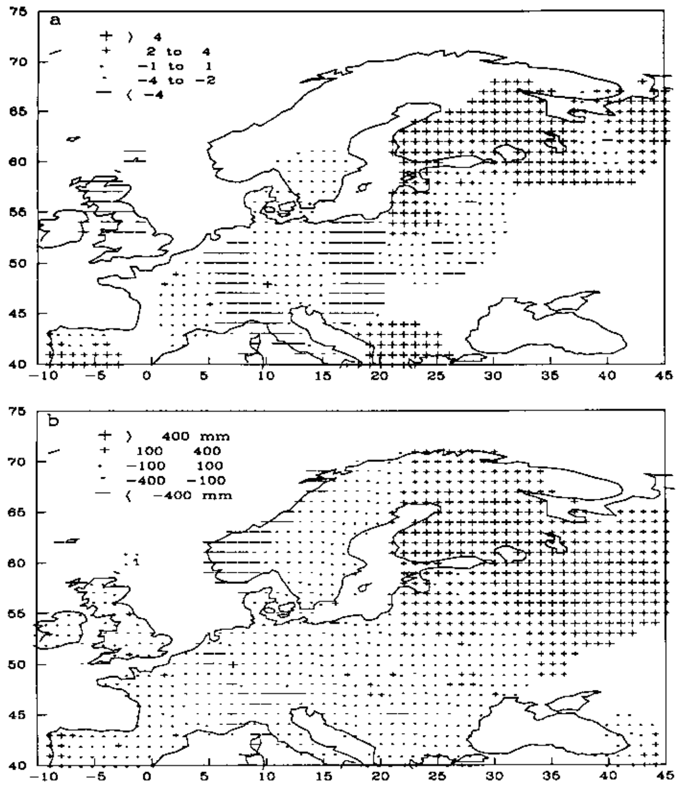

FIG. 5. (a) Moisture index deduced from the lake data at 6000 yr B.P. (positive values mean wet climate); (b) Reconstructed P−PET anomalies (mm) at 6000 yr B.P. when the analogues are constrained.

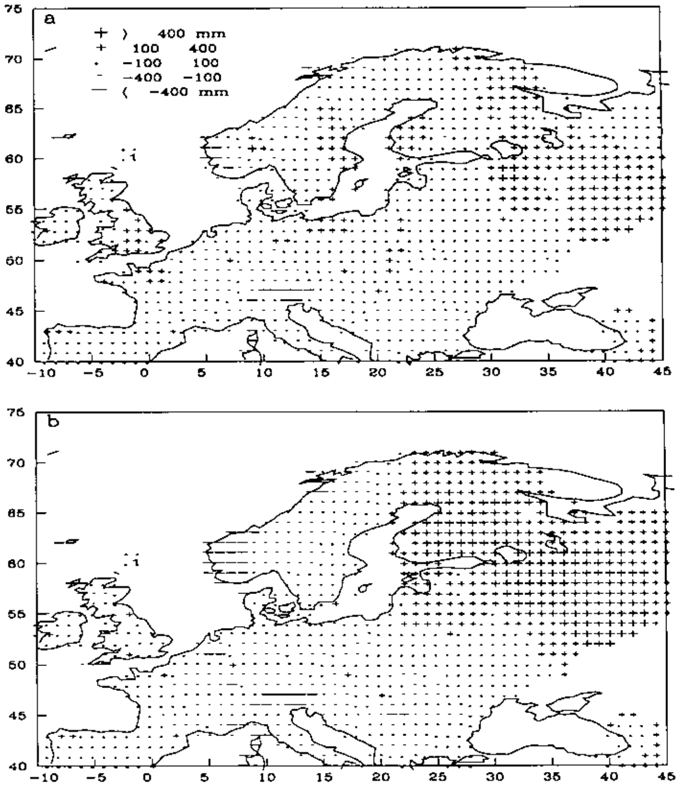

FIG. 6. (a) Unconstrained reconstruction (from pollen alone) of annual precipitation at 6000 yr B.P.; (b) same reconstruction constrained by lakes.

rope is shown wetter than present at this time, while much of central and western Europe is shown drier than present. The reconstructions for 9000 yr B.P. show the continent on average ≈2°C cooler than at 6000 yr B.P. and much cooler (up to 10°C cooler) than present along the western seaboard. The continent is also shown drier overall at 9000 yr B.P. than at 6000 yr B.P., except for a region of higher-than-present precipitation in western France. The reconstructions for 3000 yr B.P. show temperature anomalies similar to, but weaker (in most areas), than those at 6000 yr B.P. while the continent is shown generally drier than present.

One advantage of such continental-scale summaries, focusing on well-separated time intervals, is the possibility of comparison with the results of climate model experiments (e.g., Kutzbach and Guetter, 1986; Mitchell *et al.*, 1988). This, in turn, may allow the patterns to be interpreted in terms of changes in the long-term controls on climate such as orbital and ice-sheet variations (COHMAP Members, 1988). During the Holocene, summer and annual insolation in the high northern latitudes (both maximal around 9000 yr B.P. due to a coincidence of the precession and tilt cycles) steadily declined toward their present values. In the mid-latitudes, high summer insolation was opposed by low winter insolation, so annual insolation changed little while seasonal amplitude declined. Superimposed on these insolation changes were the effects of the Laurentide ice sheet, which was still present as a large residual ice mass in Labrador at 9000 yr B.P. but was gone by 6000 yr B.P. Harrison *et al.* (1992) reviewed the likely consequences of these changes for the climate of Europe, based on published climate model results.

Many of the features shown in Figure 8 can be explained with reference to these model results (Huntley and Prentice, 1992; Harrison and Digerfeldt, in press). Briefly, the ≥2°C warming of high latitudes at 6000 yr B.P. reflects high annual insolation (warming both ocean and land) whereas in the mid-latitudes, zero to negative temperature anomalies reflect the sum of high summer and low winter insolation effects. Warm high-latitude sea-surface temperatures in the North Atlantic and a strong poleward-shifted subtropical anticyclone could account for high precipitation in northern Europe (Harrison and Digerfeldt, in press). Temperature anomalies at 3000 yr B.P. could be explained as for 6000 yr B.P., but they should be weaker.

At 9000 yr B.P., however, any warming effects due to high insolation were opposed by the ice sheet, thereby reducing temperatures by ≥2°C (Mitchell *et al.*, 1988), especially on the western seaboard. A very strong poleward shift of the subtropical anticyclone may have re-

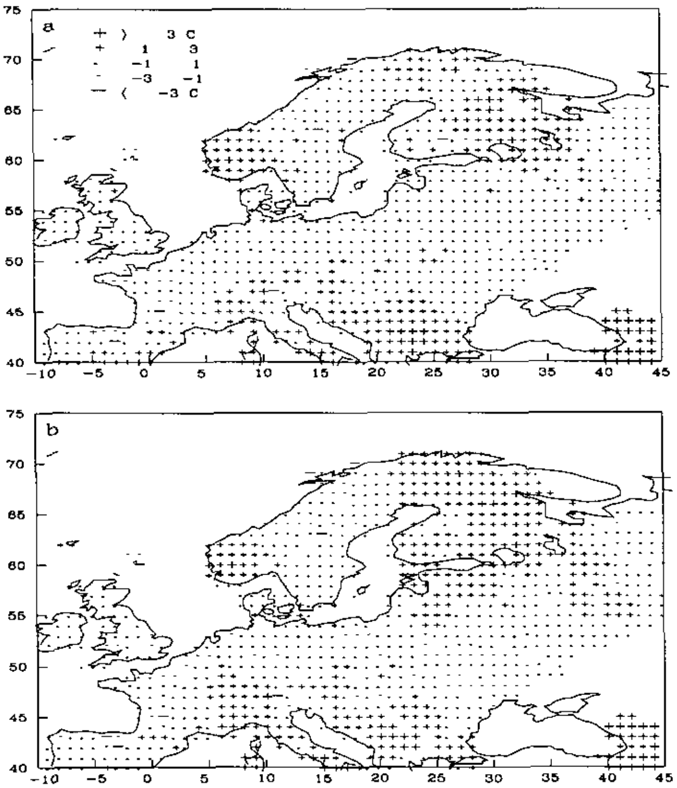

FIG. 7. As Figure 6 but for mean annual temperature.

duced precipitation in northern Europe at 9000 yr B.P. (Harrison and Digerfeldt, in press) while a poleward shift of the winter jet stream (Harrison *et al.*, 1992) may have produced excess precipitation in western France.

CONCLUSION

The inclusion of the lake-level constraint in pollen-based precipitation reconstructions improves spatial coherence and increases regional contrast by allowing a rational selection among almost equally close analogues with fairly similar mean annual temperatures but different precipitation and P – PET values. The constraint has only a mild effect on the reconstructed mean annual temperature patterns, but an important effect on the total annual precipitation patterns. Thus, the combined use of pollen and lake-level data will strengthen the basis for comparison between palaeoclimatic data and climate model simulations. Results obtained thus far with this approach are plausible, but we do not claim that they are definitive. Refinement of these estimates will be possible after the European lake-level data base has been extended to give more even spatial coverage.

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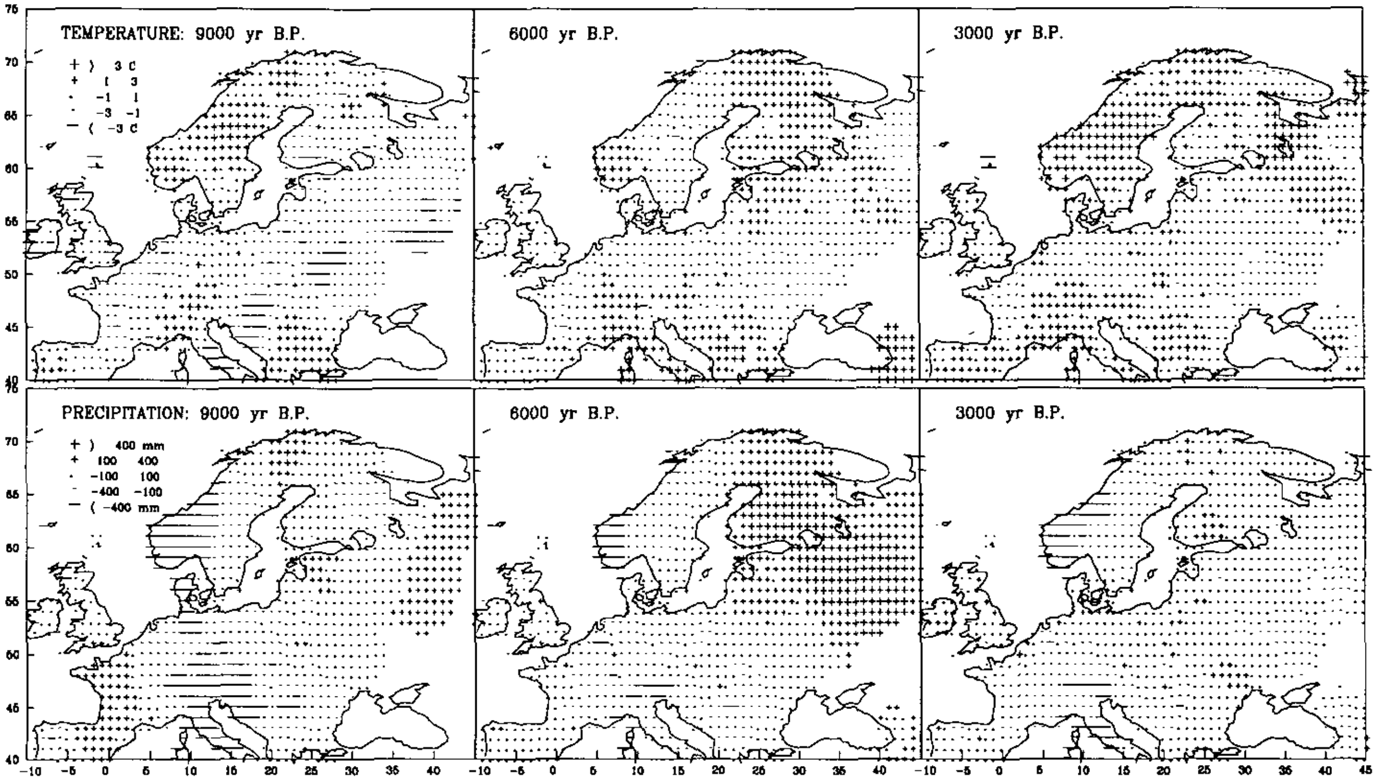

FIG. 8. Constrained reconstructions of mean annual temperature (above) and precipitation (below) at 9000, 6000, and 3000 yr B.P.

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