Géographie physique et Quaternaire

# A Method for Palaeoclimatic Reconstruction in Palynology Based on Multivariate Time-Series Analysis

# Une méthode de reconstitution paléoclimatique en palynologie basée sur l'analyse des séries temporelles multivariées

# Eine Methode zur paläoklimatischen Rekonstruktion in der Palynologie, gestützt auf die Analyse von vielfach variierten Zeit-Sequenzen

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Résumé de l'article

Une méthodologie basée sur la régression multiple, l'analyse canonique et le filtre de Kalman est mise au point pour produire des reconstitutions climatiques fiables à partir de spectres polliniques. Elle est appliquée au sud de la France, région fortement anthropisée et au climat complexe, situations où justement des méthodes plus classiques ne sont pas satisfaisantes. La première étape de la méthodologie est équivalente aux méthodes classiques (régression calibrée sur l'Actuel). Comme la reconstruction qui en découle est souvent perturbée par divers facteurs comme l'action de l'homme ou les particularités des végétations locales, une seconde étape, indépendante, est ajoutée. Elle procède par analyse exclusive du passé en comparant deux sites fossiles. Ceci permet d'obtenir un modèle du forcing du climat régional. Les reconstitutions issues des deux étapes sont mises en commun, fournissant une reconstitution corrigée. Il ressort qu'en 14 000 BP. Ia température annuelle était de 9°C plus basse que l'actuelle; un réchauffement de $4^{o}$C est survenu de 13 500 BP à 11 500 BP, suivi d'un nouveau refroidissement de $2^{o}$C en 15 500 BP. Le maximum de l'Holocène fut situé vers 8000-6000 BP avec une température supérieure de $1^{o}$C à l'actuelle.

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# A METHOD FOR PALAEOCLIMATIC RECONSTRUCTION IN PALYNOLOGY BASED ON MULTIVARIATE TIME-SERIES ANALYSIS

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ABSTRACT A method based on multiple regression, canonical correlation analysis and the Kalman filter is developed with a view to producing a reliable reconstruction of climate from pollen spectra. The study region is the southern France, where traditional analytical techniques are unsatisfactory due to the heavy influence of human activity and the existence of a complex climate. The first stage of the proposed method is the same as the standard techniques in which a spatial network of 36 sites with recent pollen and climate data were analyzed by regression techniques. But since the recent data are frequently subjected to disturbance by such factors as human activity or the particularities of the local vegetations, a second, independent analytical stage was added, in which pairs of fossil sites were compared using ancient data exclusively. In this way a model of the climatic forcing can be obtained, with the above-mentioned factors left out of account. The reconstructions obtained from the first two stages were then compared in the third stage of the method, and the result is a corrected reconstruction, from which it appears that at 14 000 BP annual temperature was 9°C cooler than present, with a 4°C increase between 13 500 and 11 500 BP followed by a 2°C cooling at 10 500 BP. The Holocene temperature maximum occurred between 8000 and 6000 BP, when the temperature was 1°C warmer than present.

RÉSUMÉ *Une méthode de reconstitution paléoclimatique en palynologie basée sur l'analyse des séries temporelles multivariées.* Une méthodologie basée sur la régression multiple, l'analyse canonique et le filtre de Kalman est mise au point pour produire des reconstitutions climatiques fiables à partir de spectres polliniques. Elle est appliquée au sud de la France, région fortement anthropisée et au climat complexe, situations où justement des méthodes plus classiques ne sont pas satisfaisantes. La première étape de la méthodologie est équivalente aux méthodes classiques (régression calibrée sur l'Actuel). Comme la reconstruction qui en découle est souvent perturbée par divers facteurs comme l'action de l'homme ou les particularités des végétations locales, une seconde étape, indépendante, est ajoutée. Elle procède par analyse exclusive du passé en comparant deux sites fossiles. Ceci permet d'obtenir un modèle du *forcing* du climat régional. Les reconstitutions issues des deux étapes sont mises en commun, fournissant une reconstitution corrigée. Il ressort qu'en 14 000 BP, la température annuelle était de 9°C plus basse que l'actuelle; un réchauffement de 4°C est survenu de 13 500 BP à 11 500 BP, suivi d'un nouveau refroidissement de 2°C en 15 500 BP. Le maximum de l'Holocène fut situé vers 8000-6000 BP avec une température supérieure de 1°C à l'actuelle.

ZUSAMMENFASSUNG *Eine Methode zur paläoklimatischen Rekonstruktion in der Palynologie, gestützt auf die Analyse von vielfach variierten Zeit-Sequenzen.* Eine auf multiple Regression, kanonische Korrelationsanalyse und den Kalman-Filter gestützte Methode wird entwickelt, um eine verläßliche Klima-Rekonstruktion aus den Pollen-Spektren zu erhalten. Das Studiengebiet ist Südfrankreich, wo traditionelle analytische Techniken unbefriedigend sing, wegen des beträchtlichen Einflusses menschlicher Aktivitäten und wegen des komplexen Klimas. Die erste Etappe der vorgeschlagenen Methode entspricht den Standard-Techniken, in denen ein Flächen-Netzwerk von 36 Plätzen mit neuen Pollen und Klima-Daten mittels Regressions-Techniken analysiert wurden. Da aber die neueren Daten häufig durch Faktoren wie menschliche Aktivitäten und die Besonderheiten der örtlichen Vegetation gestört werden, wurde eine zweite, unabhängige analytische Etappe hinzugefügt, in welcher Paare von Fossil-Vorkommen verglichen wurden unter ausschließlicher Benutzung alter Daten. Auf diese Weise kann ein Modell der klimatischen Forcierung gewonnen werden, wobei die obengenannten Faktoren nicht miteinbezogen werden. Die aus den zwei ersten Etappen gewonnenen Rekonstruktionen werden dann in der dritten Etappe der Methode verglichen, und das Ergebnis ist eine korrigierte Rekonstruktion, aus der hervorgeht, daß um 14 000 v.u.Z. die jährliche Temperatur um 9°C kälter als heute war, mit einer Zunahme von 4°C zwischen 13 500 und 11 500 v.u.Z., gefolgt von einer Abkühlung um 2°C um 10 500 v.u.Z. die Maximaltemperatur im Holozän wurde zwischen 8 000 und 6 000 v.u.Z. erreicht, mit einer Temperatur, die um 1°C wärmer als heute war.

## INTRODUCTION

Since IMBRIE and KIPP (1971), multivariate techniques have been used for evaluating deep-sea core planktonic foraminifera in terms of temperature, salinity and other oceanographic variables. FRITTS *et al.* (1971) used similar techniques for calibrating tree-rings. The results of studies in those areas have been highly satisfactory. The technique used produces a transfer function, whose application to palynology (WEBB and BRYSON, 1972; BRYSON and KUTZBACH, 1974) has been justified by its successful use in several studies. The method consists in estimating modern relationships between climate and pollen data within a region and using the results to gain estimates of climatic variations from fossil spectra. Frequent reference is made to the technique of canonical correlation analysis. Later studies have been conducted along similar lines. SACHS *et al.* (1977) tried variations on the same theme. ANDREWS *et al.* (1980), MATHEWES and HEUSSER (1981), SHORT AND JACOBS (1981), ANDREWS and DIAZ (1981) and KAY and ANDREWS (1983) applied these methods to Canadian data. The most striking fact about all these studies is that useful results come from data on sparse populations in a stressing climate, such as the Canadian North. Another study was conducted by SWAIN *et al.* (1983) using data from India, another region with a stressful climate. Another remark is that any important mountain chain do not block the meridional movements of the vegetation, such as in Europe.

The choice of analytical technique is far from negligeable in importance. WEBB and CLARK (1977) showed that slight methodological difference can produce as much as 2.5°C difference in pre-10 000 BP temperature estimates. Therefore, the use of other methods would seem to be desirable, with a view to scrutinizing how the chosen mathematical technique affects the results. In this connection, the work of ROUX (1979) should be mentioned. He developed a method based on correspondence analysis and tested it on the data of IMBRIE and KIPP (1971). His work has been given a palynological application by SABATIER (1983) and SABATIER and VAN CAMPO (1983), who obtained results for 18 000 BP in Greece from a "principal components analysis on instrumental variables". The major conclusion of that study is the need of modern situations analogous to those that occurred during the last ice age — a conclusion that can be made for numerous similar studies. HUTSON (1977) suggested using the instability of the transfer function in time as an indicator of the no-analogue situation.

The vegetation of Europe is highly complex, owing to the nature of the continent's climate and topography. The correlation of vegetation to climate therefore is quite sensitive to human activities (PONS, 1984). Moreover, the history of mankind in Europe is very long, and human activity has had a particularly great influence in the last several hundred years. For these reasons, the calculation of transfer functions in Europe raises problems that have no counterpart in the Canadian North.

A solution to these problems can be gained in part by a time-series analysis of the data. In the methods previously referred to in this paper, no account is taken of the fact that the climate (and the vegetation) of one epoch is not independent of that of the preceding epoch (the character of time-process of the variables has not been explored). Although GREEN (1982) did use this idea, his purpose was not the study of climate. In dendroclimatology, the techniques of time-series analysis have been applied to the reconstruction of climate from tree-ring data (GUIOT, 1984a), and to the estimation of Quaternary climatic variations due to orbital and insolation variations (BERGER *et al.*, 1981).

The purpose of this article is to apply time-series methods to transfer functions in palynology, with the goal of obtaining results that are as conclusive as can be obtained for regions as complex as the South of France. The transfer function has already been discussed in the literature of multivariate time series (BOX and JENKINS, 1970); calculation depends upon the temporal structure of the series that are correlated. The method presented here is therefore taken from the source literature, although it requires some modification due to the need to carry out the calibrations in the spatial rather than temporal domain. There must be constant interaction of time and space — which is the root of one of the major problems of this work.

Construction of a transfer function requires the use of modern pollen spectra for calculating correlations with climate. The core tops of the period just before the present (before the reforestation of the previous century) used in this study were taken from 36 sites in the South of France (Fig. 1). Thirty-one pollen types (see Table I) were selected from the work of SABATIER (1983), with the addition of *Juniperus*, which proved useful later.

Three sites with fossil spectra were used (Fig. 1). These sites contain records that extend back between 14 000 and

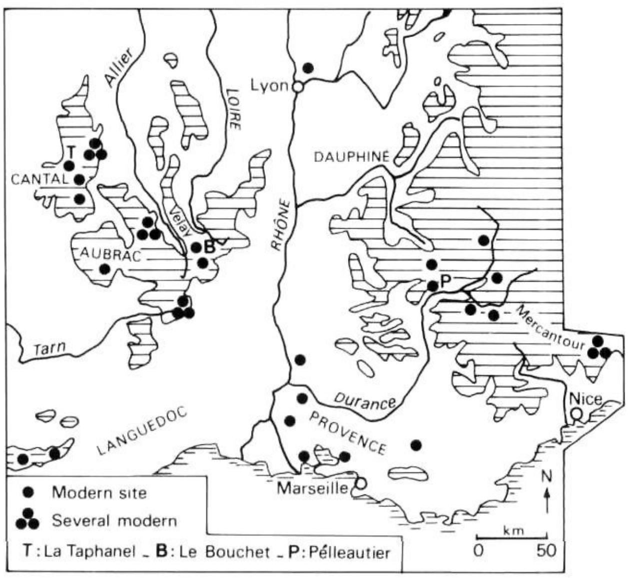

FIGURE 1. Map of Southeastern France, with modern and fossil sites (DE BEAULIEU, 1977; DE BEAULIEU *et al.*, 1982, 1984).

*Carte du Sud-Est de la France et localisation des sites actuels et anciens (voir le texte pour les références concernant les données) (DE BEAULIEU, 1977; DE BEAULIEU* et al., *1972, 1984).*

TABLE I

*Normalized coefficients (independent of the variance of the variables); asterisks indicate the ones that are significant at the 0.05-level*

| Arboreal pollen | | Non-Arboreal pollen | |
|---|---|---|---|
| *Abies* | −0.180* | *Artemisia* | −0.038 |
| *Alnus* | 0.076 | Caryophyllaceae | −0.237* |
| *Betula* | −0.116 | Poaceae (cereale t.) | 0.026 |
| *Carpinus* | −0.065 | Chenopodiaceae | 0.174* |
| *Corylus* | −0.019 | Cicho./Asteraceae | 0.136 |
| *Fagus* | −0.043 | *Ephedra* | 0.009 |
| *Fraxinus* | −0.090 | Ericaceae | −0.035 |
| *Juniperus* | 0.019 | Poaceae | −0.025 |
| *Larix* | −0.187* | Apiaceae | 0.067 |
| *Olea* | 0.056 | *Plantago* | −0.078 |
| *Picea* | −0.038 | *Rumex* | −0.137 |
| *Pinus* | −0.018 | Urticaceae | −0.096* |
| *Pistacia* | 0.154 | *Varia* | 0.064 |
| Decid. *Quercus* | 0.227* | | |
| *Quercus Ilex* | 0.120 | Temp. mean | 7.1°C |
| *Salix* | −0.016 | Temp. variance | 15.3 |
| *Tilia* | −0.076 | Determ. coeff. | 0.909 |
| *Ulmus* | 0.173* | Fisher's value | 6.631* |

18 500 years: Taphanel, in the Massif Central (14 000 years); Pelléautier, in the Hautes Alpes (15 000 years); and Lac du Bouchet, in the Massif Central (18 500 years). One spectrum per 500 years was selected for each of these three sites by De Beaulieu and co-workers (DE BEAULIEU, 1977; DE BEAULIEU *et al.*, 1982, 1984). The corresponding spectra are summarized at Figures 2, 3 and 4.

The transfer function method is based on two standard assumptions: (i) the relationship between climate and vegetation is stationary over the time period of analysis and (ii) the modern observations contain all the information necessary for interpreting the fossil spectra. But these assumptions are affected by three difficulties: (i) at any moment, the response of vegetation to climate is partly function of the persistence of this climate; (ii) at one time, the recording of the regional climate in the vegetation variations, for different sites, depends partly, on the one hand, of the previous local structure of this vegetation, and, on the other hand, of the natural particularities of each site (elevation, exposure, micro-climate, human disturbance eventually, ...); (iii) no modern analogue has been found for some fossil spectra (around 18 000 BP for example) and human activity has often distorted the climatic signal of the modern spectra. Some of these problems are discussed by HOWE and WEBB (1983), but this paper proposes another solution.

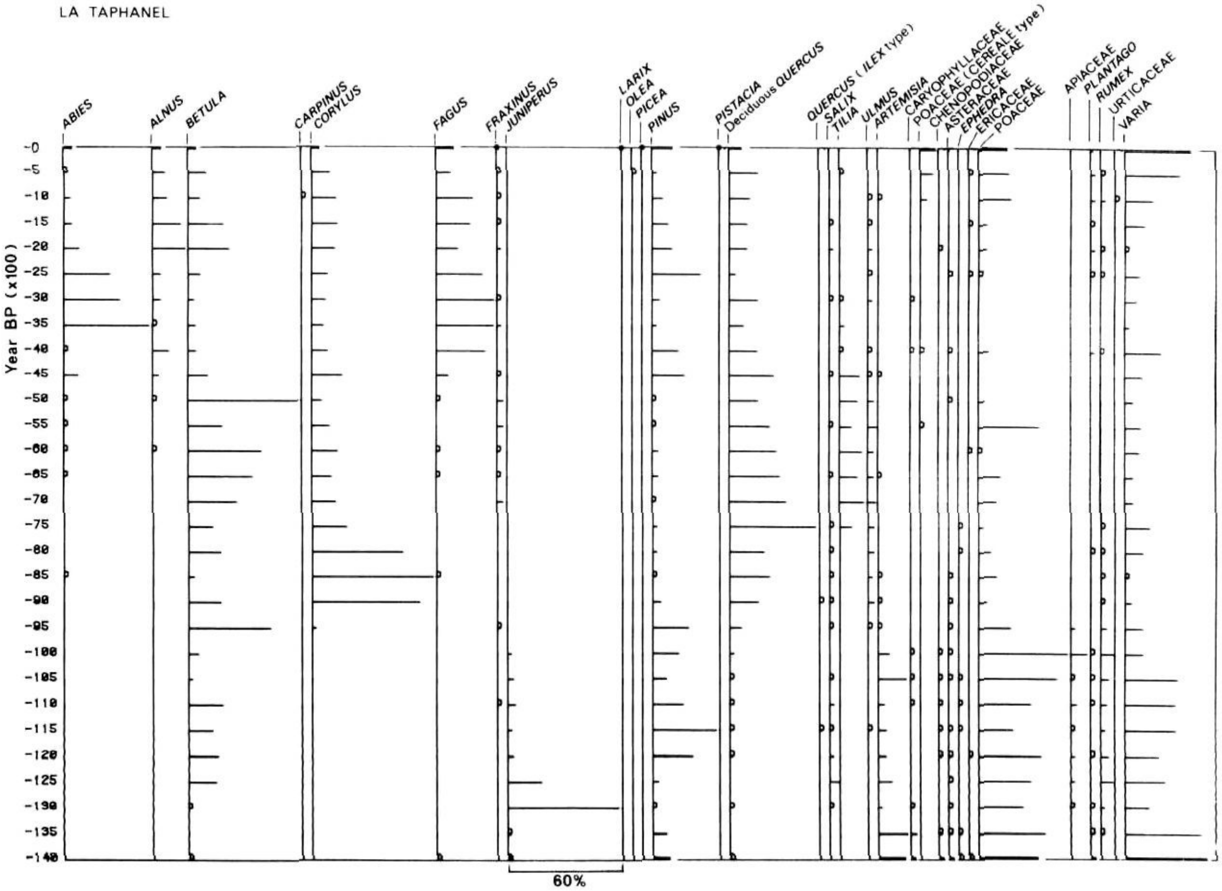

FIGURE 2. Summarized pollen diagram of La Taphanel: a dot indicates a frequency less than 1% (DE BEAULIEU *et al.*, 1982).

*Résumé du diagramme pollinique de la Taphanel: un point indique une fréquence inférieure à 1% (DE BEAULIEU* et al.*, 1982).*

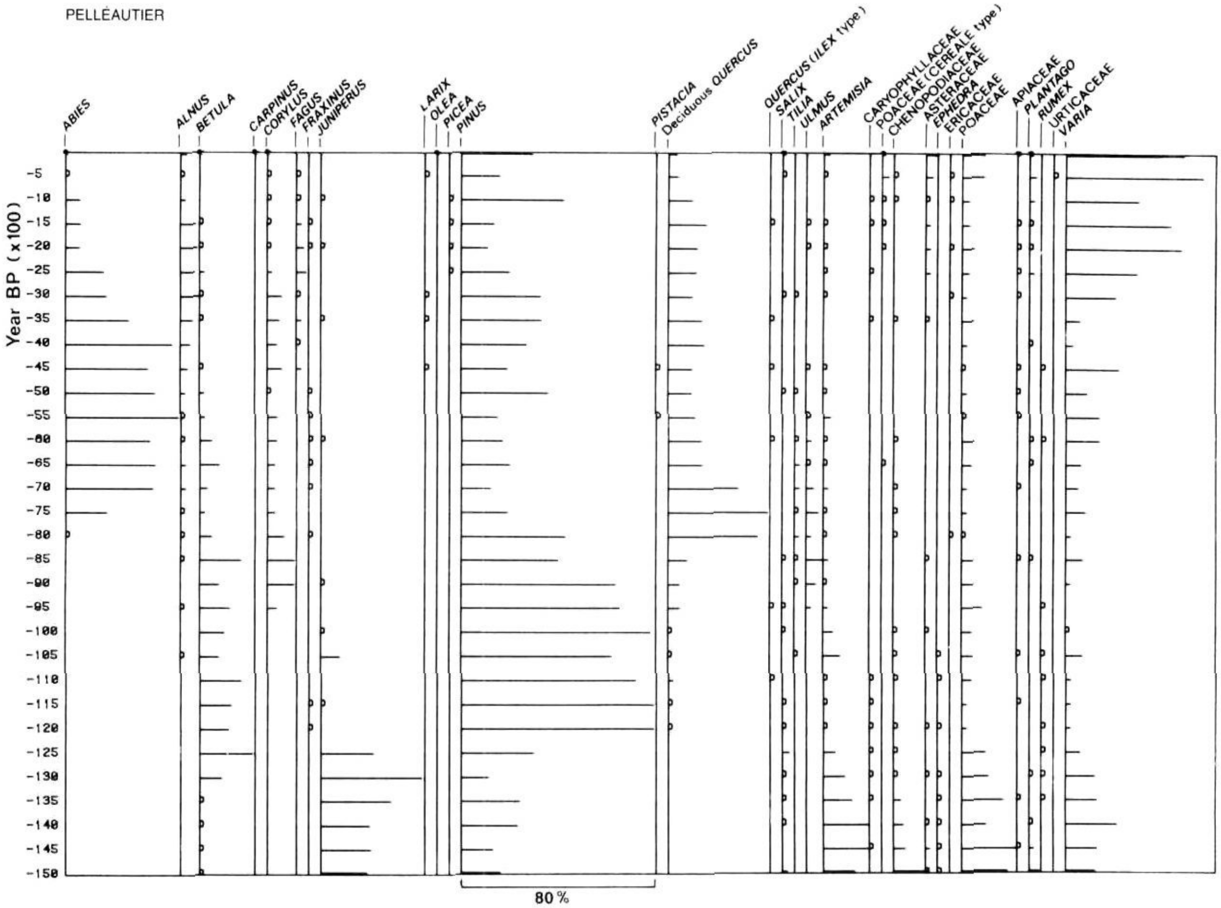

FIGURE 3. Summarized pollen diagram of Pelléautier (DE BEAULIEU, 1977).

*Résumé du diagramme pollinique de Pelléautier (DE BEAULIEU, 1977).*

Comparison of synchronous pollen spectra from two nearby sites with fossil data can provide a solution to the second difficulty. This solution requires a third assumption (fairly natural) that the climatic environment of two sites (at an intermediate distance) had changed in a similar way during the past. This fact allows us to separate the common information, mostly macroclimatic, from the effects of the local vegetation dynamics and from all factors that distinguish both sites.

A three-stage method will be used. The first stage closely resembles the standard methods for calculating transfer functions. I will refer to it as spatial analysis (S treatment), and it involved an extrapolation to the past of an equation established from modern spatial observations. The second stage consisted of finding information that is shared in the temporal variations in two cores (T treatment). The third stage involved use of the Kalman filter to correct imperfections resulting from the first stage by the use of the series from the second one.

## MODERN CLIMATE-SPECTRA RELATIONSHIPS (TYPE S)

The point of departure is a (s, t) — matrix composed of s modern sites (= s rows) and t types (= t columns). The $i^{th}$ row of S is the logarithm of the pollen frequencies of the modern site i, and the $j^{th}$ column contains the logarithm of the frequencies of the $j^{th}$ pollen type in the study region. The logarithm is used in order to attenuate the large variations of the most frequent taxa.

At the same time, a (s, p) — matrix Q was established for these sites by interpolation of the existing meteorological network. This type of work raised a number of problems, often due to the low density of the network. That problem will not be explored here, however (see GUIOT, 1984b). The starting point was a matrix Q whose $i^{th}$ row gives the p climatic parameters of site i and the $j^{th}$ column gives the profile of the $j^{th}$ climatic parameter in the study region. The relation between the two matrices can be written as:

$$Q = S\,\beta + \epsilon \qquad (1)$$

where $\beta$ is a matrix (t, p) giving the coefficients of linear combinations that fit the best (least squares method) to the climatic variables and $\epsilon$ is a residual matrix (s, p) that contains the noise in the system (non-linearity, errors, climatic variations that do not affect the pollen composition of the site, etc.). When p is equal to unity, the relation is estimated by regression on principal components, a former standard method of paleoclimatology. When $p > 1$, canonical regression techniques can be applied (*e.g.* SACHS *et al.*, 1977). Here, Q will be indentified with annual temperature ($p = 1$). Table I shows the coefficients obtained; botanical and ecological interpre-

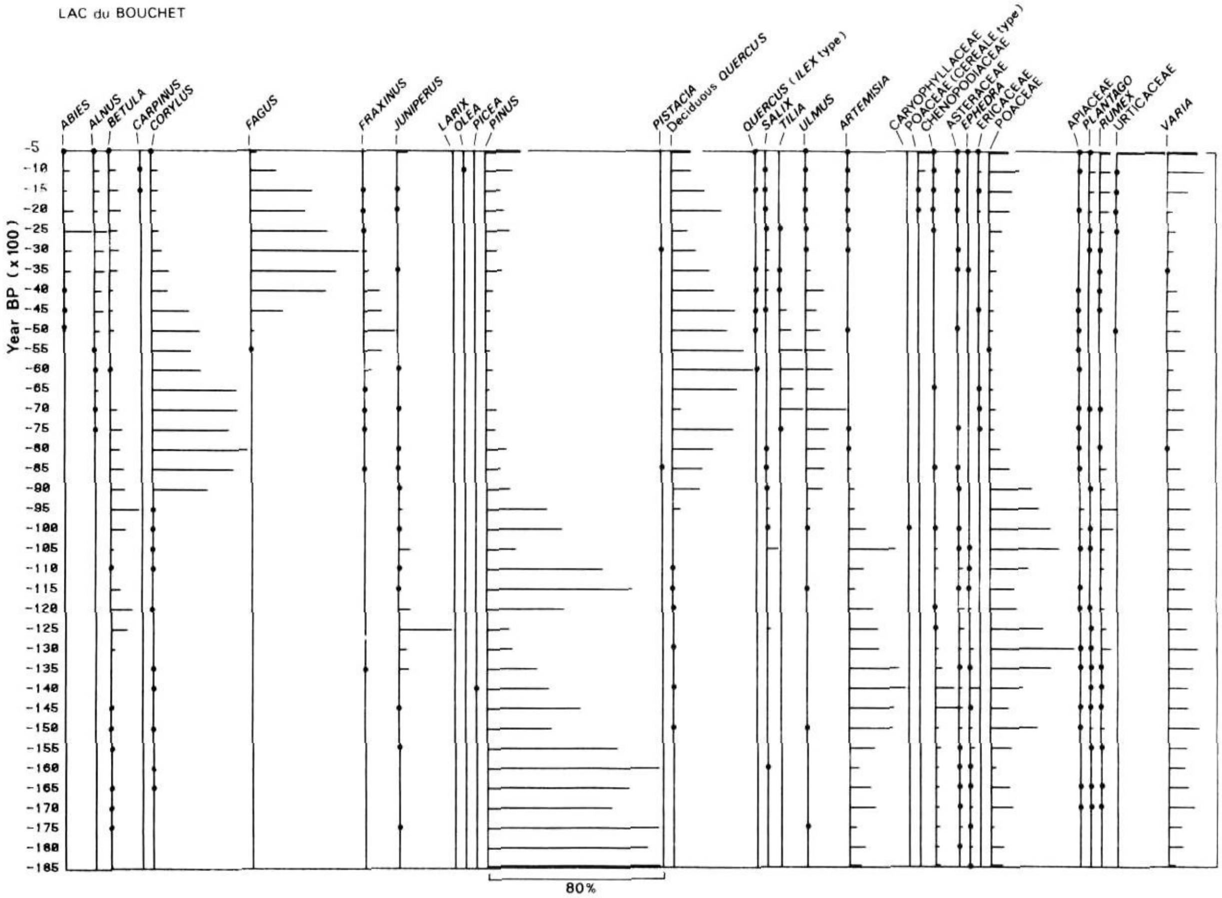

FIGURE 4. Summarized pollen diagram of Lac du Bouchet (DE BEAULIEU *et al*., 1984).

*Résumé du diagramme pollinique du Lac du Bouchet (DE BEAULIEU* et al., *1984).*

tations seem to bear out certain values. The sites used for the calculation are distributed over a temperature range of 0 to 14°C, providing an upper and a lower limit for the extrapolations. Since the modern temperatures of the fossil sites are on the order of 8°C, it seems rather difficult, at this point, to show negative anomalies (compared with present observations) greater than 8°C, or positive anomalies greater than 6°C.

By applying the coefficients in Table I to the ancient spectra from Taphanel and Pelléautier, the estimates in Figure 5 were obtained. In the figure, the points for Pelleautier were connected between 10 000 BP and the present, while the points for Taphanel were connected for the period before 10 000 BP. The two curves are fairly consistent through the Holocene (80% parallel variations) but there is less consistency during the Late Glacial when the estimates for Taphanel are more likely to be accurate (see later discussion). The major defect of curves like these is immediately apparent — too much variability in temperature over the last several millenia (impact of man) and the temperatures before 14 000 BP that were too high. This is a clear illustration of the limitations of the traditional approach to paleoclimatic reconstruction, which is why this model will be considered only as the first stage of a more general approach.

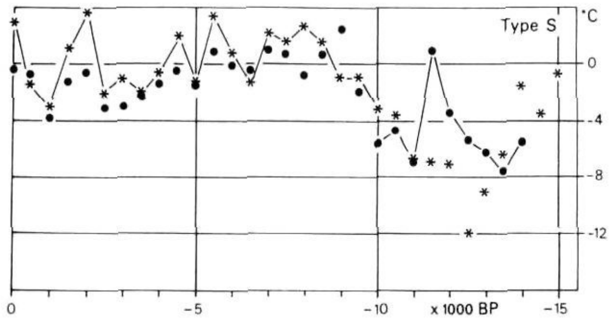

FIGURE 5. Annual temperature reconstruction by regression (S treatment) at Pelléautier and La Taphanel.

*Température annuelle reconstituée par régression (traitement de type S) à Pelléautier et la Taphanel.*

## CLIMATE-POLLEN RELATIONSHIPS OVER TIME (T-TREATMENT)

If it is assumed that the common information in the sequences of the contemporary states of the vegetation for two sites comes from climate, the need for an exclusive analysis of the fossil spectra in their temporal environment emerges fairly naturally. Canonical correlation analysis is an excellent method for this work. The method however, is not used with the same intent as it is when used to calculate standard *transfer functions*.

The pollen data from the Pelleautier and Taphanel cores were used for the canonical correlation analysis. The variables are the 31 taxa at the levels of the analysis, one every 500 years. This gives two (nx, t) and (ny, t) — matrices, where nx = 29 (Taphanel) and ny = 31 (Pelleautier). The matrices will be constructed, as for S, from the logarithm of the pollen frequencies.

Canonical correlation analysis finds linear relationships between two sets of the 31 taxa variables (one in each two sites). The regression equation in stage 1 also involved calculating a linear combination of the 31 taxa, but the criterion for a best fit was the multiple correlation of the linear combination of taxa with the spatial variations in temperature. In this second stage the criterion for a best fit is the canonical correlation between linear combinations among taxa given their temporal variations. Thirty-one progressively less well correlated pairs of linear combinations of these taxa were identified on the basis of the 29 common levels. For additional detail on canonical correlation analysis, refer to CLARK (1975).

In this case, ten canonical pairs were significant at the 0.05-level (using a chi-square test). The first is approximatively constant over time and positive except for level 0 (present) where it is null: it probably takes into account the increase in human activity over the last few centuries. The second axis (see Fig. 6) is fairly close in appearance to the reconstruction of Figure 5. The strong correlation here of Pelleautier and Taphanel is due to the calculation criterion. The time profile is negative for years before 9000 BP and positive after that time.

The distribution of the taxa about the axis is also important. In order to be climatically significant, there must be similarity between the two sites. Such similarity is not always obtained through canonical correlation analysis. Lack of homogeneity indicates the presence of noise, but in this case the distribution is similar and it is characterised by the following pollen types:

(+) deciduous Quercus, Corylus, Alnus
(−) Artemisia, Cichoroideae-Asteraceae, Ephedra, Juniperus, Chenopodiaceae

The presence of vegetation dominated by deciduous *Quercus, Corylus, Alnus* and other minor taxa in these sites is an indication of a warm, humid climate. *Artemisia* and other herbaceous taxa are characteristic of cool, dry climates. *Juniperus* is associated with the period 11 000 − 13 500 BP.

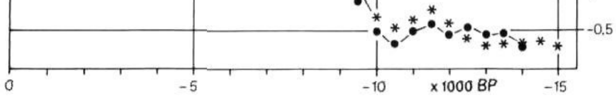

FIGURE 6. Curve calculated by canonical analysis (T treatment) giving the profile of the annual temperature (standardized scale).

*Courbe calculée par régression canonique (traitement de type T) du profil de la température annuelle (échelle standardisée).*

The curve in Figure 6 was obtained without reference to the present. It exibits a clearer demarcation betwen the warm Holocene period and the preceding cooler one than the one in Figure 5, based on modern data and standard methods. It, however, cannot be calibrated in terms of temperature, but this problem will be resolved in stage 3 of the method.

## SYNTHESIZING S AND T TREATMENTS BY MEANS OF THE KALMAN FILTER

The synthesis of the S and T treatments is achieved by a Kalman filter (simplified here) which can be used for representing a time series dynamically as a function of its past. Only order 1 will be considered here, so that the climatic variable will be expressed as:

$$z_k = \phi z_{k-1} + d_k e_k + u_k \tag{2}$$

where $z_k$ is temperature (unknown) at time k, $\phi$ is a coefficient of persistency, $e_k$ is a determined function that, weighted by the nonstationary coefficient $d_k$, governs the system, and $u_k$ is tied to a white noise that can distort the climatic signal. The curve T will used for determining the parameter of this "theoretical" model (2) for the climatic forcing.

Equation (2) is a dynamic equation with the following limitation: the random term $u_k$ has a mean zero and is not autocorrelated. An empirical equation is introduced. The temperature $z_k$ has been estimated by a variable $w_k$ (S treatment), but the estimate is distorted by white noise $v_k$, such that

$$w_k = c_k z_k + v_k \tag{3}$$

where $v_k$ has a mean of zero and is not autocorrelated or not correlated with $u_k$. The time-dependent coefficient $c_k$ will be used for compensating for human activity in the estimates. The set of equations (2) and (3) is called a Kalman filter. More information on that subject can be found in DUBUISSON and SCHWARTZ (1973) in terms of applications to time-series forecasting, and in EYKHOFF (1974) or LIFERMAN (1981) in terms of general information. In this case, we have a simple, order 1 model that is quite characteristic from the point of view of the assumptions made on random terms $u_k$ and $v_k$. A priori temperature persistence should be of order 2 or higher: it would be necessary to introduce the concept of state representation.

Equation (2) is identified with time series T corrected by a high-frequency signal capable of compensating for the excessively stepwise configuration in Figure 2. Thus, $z_k$ is the unknown climatic variable to be calculated using series T. A reference (S) to the modern data, $w_k$, has been calculated: it is perturbed by a noise $v_k$. Thus the two equations (2) and (3) are an expression of time series S and T.

The estimation (noted $z'_k$) of $z_k$ using the theoretical model (2) and empirical model (3) is given by:

$$z'_k = \phi z'_{k-1} + d_k e_k + g_{k-1} (w_k - \phi c_k z'_{k-1}) \tag{4}$$

where $g_{k-1}$ is called filter gain, Equation (4) expresses the estimate of temperature as a function of the past, of a known random function $e_k$ and an adaptation of the S treatment.

On the basis of the foregoing, the following selection was made:

— $\phi$ is an autogression coefficient of the first order in time series T: 0.98 for Taphanel and 0.91 for Pelleautier.

— $e_k$ is the residual at time k, after application of $\phi$ to time series T. The variance of curve T gives values of 0.20 for Taphanel and 0.21 for Pelleautier, the corresponding residual variances are 0.04 and 0.05.

— The last two terms in (4) have been made complementary by adapting $d_k = 1 - g_{k-1}$; calculation of $g_{k-1}$ is given later.

— The large variations in temperature over the last four millenia in Figure 5 are supposedly the result of human interference, so the vector $c_k$ was selected to nullify the effect of this reconstruction during these last millenia: $c_k = \exp(8 - k)$ for $k < 8$ (k denotes levels from 0 by 500-years periods) and $c_k = 1$ for $k > 8$.

— The variance of $w_k$ gives 7.3 for Taphanel and 13.4 for Pelleautier. The variance of the time series T are reduced to the variance of the series S.

The iterative gain formula is:

$$g_k = p_{k-1} c_k / (p_{k-1} c^2_k + V_v) \qquad (5)$$

where V is the symbol for variance and $p_{k-1}$ the projection of $z'_k$ namely a measure of the difference between the estimation and the parameter to be estimated. The equation can be written as:

$$p_k = \phi^2 (1 - p_{k-1} c^2_k / (p_{k-1} c_k + V_v)) p_{k-1} + V_u \qquad (6)$$

The following initial values are selected (because the temperatures are calculated with the reference to their present values)

$$z_o = 0 \text{ and } p_o = V_w \phi^2 + V_u$$

$$V_v = V_w (1 - r^2_S) \text{ and } V_u = V_w (1 - r^2_T)$$

where $r_T$ is the correlation of the Taphanel and the Pelléautier time series T; $r_S$ is the correlation of the S series. These initial values are important; they are based on the fact that anything not common to two time series of the same type is considered noise. Thus, the S curves for Taphanel and Pelleautier are compared (Fig. 5). Their common variance ($r^2_S$) is supposed to be climatic. This reasoning is valid for the T curves. On the basis of that assumption, respectively for Taphanel and Pelléautier, $p_o = 7.3$ and 11.7, $V_v = 3.9$ and 7.2, $V_u = 0.29$ and 0.54. The following four steps can be taken:

1) calculate $g_k$ by (5) and $d_k = 1 - g_k$
2) calculate $z'_k$ by (4)
3) calculate $p_k$ by (6)
4 $k = k + 1$, then go back to (1)

The accuracy of the estimate can evaluated by calculating the mean error given by:

$$E_k = [(1 - g_{k-1} c_k) p_{k-1}]^{1/2} \qquad (7)$$

Table II shows values for $p_k$, $d_k$ and $E_k$. The gain diminishes the error, which should be equal to $p^{1/2}_o$ using a traditional method. Moreover, $c_k$ is selected as close to zero in the recent sample (level 0), thereby nullifying the effect of the gain. Therefore, for Taphanel, the error is reduced from 2.7°C (3.4°C for Pelléautier) to the value of 0.9°C for Taphanel (1.2°C for Pelléautier). Figure 7 shows the curve — the period 13 000 BP to 10 500 BP is not rendered in the same manner for Taphanel as for Pelléautier; this is due to the dissimilarity of S time series (Fig. 5).

## OTHER APPLICATIONS

The same method were also applied to another pair: Pelléautier and Lac du Bouchet. It proved important to have the two sites located at intermediate distance to filter out common influences not due to climate. As before, an S series and a T series are obtained for each site. The correlations between the time-series of the two sites are 0.78 (S) and 0.92 (T).

TABLE II

*Listing of $c_k$, $p_k$, $g_k$ and $E_k$ in function of time for Taphanel and Pelléautier*

| k | time BP | Taphanel | | | | Pelleautier | | |
|---|---|---|---|---|---|---|---|---|
| | | $c_k$ | $p_k$ | $g_k$ | $E_k$ | $p_k$ | $g_k$ | $E_k$ |
| 1 | 0 | 0 | 7.30 | 0.00 | 2.70 | 10.18 | 0.00 | 3.41 |
| 2 | 500 | 0 | 7.30 | 0.00 | 2.70 | 8.97 | 0.00 | 3.19 |
| 3 | 1000 | 0 | 7.30 | 0.00 | 2.70 | 7.97 | 0.00 | 2.99 |
| 4 | 1500 | 0 | 7.30 | 0.00 | 2.70 | 7.14 | 0.00 | 2.82 |
| 5 | 2000 | 0.01 | 7.30 | 0.02 | 2.70 | 6.45 | 0.01 | 2.67 |
| 6 | 2500 | 0.05 | 7.30 | 0.09 | 2.70 | 5.88 | 0.05 | 2.54 |
| 7 | 3000 | 0.30 | 7.08 | 0.48 | 2.66 | 5.32 | 0.23 | 2.41 |
| 8 | 3500 | 0.70 | 5.22 | 0.67 | 2.17 | 4.21 | 0.38 | 2.11 |
| 9 | 4000 | 1.00 | 2.44 | 0.57 | 1.31 | 2.74 | 0.37 | 1.62 |
| 10 | 4500 | 1.00 | 1.73 | 0.38 | 1.02 | 2.18 | 0.28 | 1.32 |
| 11 | 5000 | 1.00 | 1.44 | 0.31 | 1.03 | 1.93 | 0.23 | 1.26 |
| 12 | 5500 | 1.00 | 1.30 | 0.27 | 1.00 | 1.80 | 0.21 | 1.22 |
| 13 | 6000 | 1.00 | 1.23 | 0.25 | 0.97 | 1.73 | 0.20 | 1.19 |
| 14 | 6500 | 1.00 | 1.19 | 0.24 | 0.96 | 1.70 | 0.19 | 1.18 |
| 15 | 7000 | 1.00 | 1.16 | 0.23 | 0.95 | 1.68 | 0.19 | 1.17 |
| 16 | 7500 | 1.00 | 1.15 | 0.23 | 0.94 | 1.67 | 0.19 | 1.16 |
| 17 | 8000 | 1.00 | 1.14 | 0.23 | 0.94 | 1.66 | 0.19 | 1.16 |
| 18 | 8500 | 1.00 | 1.14 | 0.23 | 0.94 | 1.66 | 0.19 | 1.16 |
| 19 | 9000 | 1.00 | 1.14 | 0.23 | 0.94 | 1.66 | 0.19 | 1.16 |
| 20 to 31 | | 1.00 | 1.13 | 0.23 | 0.94 | 1.65 | 0.19 | 1.16 |

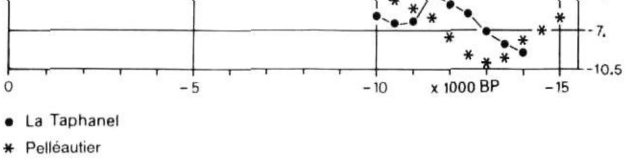

FIGURE 7. Reconstruction of the annual temperature by synthesis of the curves of Figures 1 and 2 (Kalman filter).

*Reconstitution de la température annuelle par synthèse des courbes des figures 1 et 2 (Filtre de Kalman).*

The Kalman filter was used for obtaining the curves in Figure 8. Some defects can be observed: there is a hump around 3500 BP for Le Bouchet, which is too large in comparison to the other variations, and there is a questionable curve as in Figure 3. The mean errors are 1.3°C for Le Bouchet and 1.1°C for Pelléautier.

A curve synthesizing Figures 7 and 8 is presented in Figure 9. To obtain it, the relative variations (increases and decreases) of the four reconstructions were compared. It was noticed that from 0 to 12 500 BP, Taphanel matched constantly with the most frequent profile among the four curves. Whereas Pelléautier gave the best representation for the period 13 000 – 14 500 BP; for 15 000 – 18 500 BP, only Lac du Bouchet was old enough (the method is less powerful when only one site is available).

Other climatic parameters were also tested. Summer temperature, the most commonly analysed parameter in the literature due to its ecological importance, was quite close to annual temperature, because measurements were done using a sample of highly correlated annual and summer temperatures (r = 0.97).

As regards total summer precipitation, the same observation can be made, since the correlation of temperature and summer precipitation in the modern data is −0.88. The correlation of annual precipitation and annual temperature is not significant, but the regression equation was found to be hard to interpret.

A reconstruction of a bioclimatic indicator, P-3T was presented (Fig. 9). This was developed by ecologists to explain vegetation distribution. It is therefore related to the data treated in this paper, although its usefulness for purely climatic purposes is questionable. P-3T is an effort to integrate two parameters which are simultaneously important for vegetation, by taking into account the difference between rainfall accumulation in summer and evaporation due to high temperatures. The factor 3 is chosen for the wettest Mediterranean regions so that 3 mm evaporation can be made to correspond to 1°C (see DAGET, 1977). When P-3T is negative, the climate is of Mediterranean type with dry summers; when it is positive, the climate is more continental. The region studied includes both climate types. During the last glaciation the climate was more continental, *i.e.* cool and dry (Fig. 9). At the beginning of the Holocene, the warming trend was accompanied by an increase in precipitation. Finally, only variations greater than 33 mm (the mean error) must be taken into consideration.

## DISCUSSION

Five time-series (Fig. 10) were chosen to test the results shown in Figure 9. The reconstruction of Alpine forest limit (MARKGRAF, 1974) is very similar to the reconstruction of Tyrolean summer temperature (PATZELT and BORTENSCHLAGER, 1976). A first warming period occurred at the beginning of Bølling between 13 500 BP and 13 000 BP, reaching a maximum (after the slight temporary cooling of the Older Dryas) about 11 500 BP in the Allerød. The August temperature for the Bay of Biscay as reconstructed by DUPLESSY *et al.* (1981) varies somewhat from the Alpine reconstruction — the Bølling-Allerød maximum is at about 12 000 BP, a few centuries before the Alpine one. When the polar water invaded the Bay between 11 000 BP and 10 000 BP, the ocean temperature dropped by almost 10°C. On the other hand, the cooling trend in the Alpine reconstruction was much weaker (of the order of 1 – 2°C) but also delayed (it started some few centuries after the input of cold waters) because vegetation may have taken some time to reflect climatic change.

Curve 5 (Fig. 10: $^{18}O$ / $^{16}O$ ratio from EICHER *et al.*, 1981) seems to agree with the results obtained (4) by DUPLESSY *et al.* (1981). These two reconstructions concern water temperature, not the temperature that actually affects alpine vegetation, since the $^{18}O$ / $^{16}O$ ratio is linked with rainwater

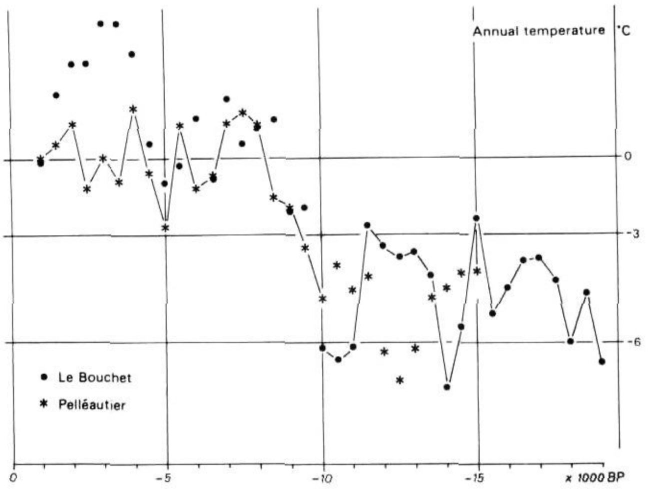

FIGURE 8. Reconstruction of the annual temperature similar to this of Figure 7 but based on the site of Pelléautier and Lac du Bouchet.

*Reconstitution de la température annuelle à partir des sites de Pelléautier et du lac du Bouchet, comme à la figure 7.*

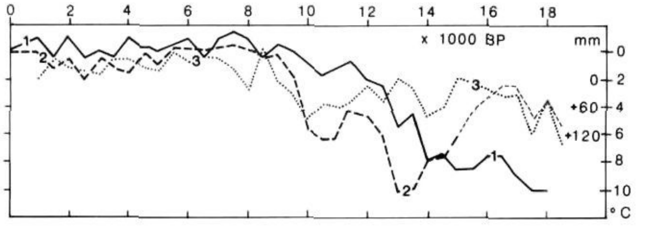

FIGURE 9. (1) Reconstruction of the tyrolean summer temperature from data about alpine glaciers (PATZELT and BORTENSCHLAGER, 1976). (2) Reconstruction of the annual temperature: synthesis of the 4 reconstructions of Figures 7 and 8. 18 500 – 15 500 BP = Bouchet (Fig. 8); 15 000 – 13 000 BP = Pelléautier (Fig. 7); 12 500 – 0 BP = Taphanel (Fig. 8). (3) Reconstruction of the bioclimatic index P-3T (see text): 18 500 – 15 500 BP = Bouchet; 15 000 – 500 BP = Pelleautier.

*(1) Reconstitution de la température estivale au Tyrol à partir de données concernant les glaciers alpins (PATZELT et BORTENSCHLAGER, 1976). (2) Reconstitution de la température annuelle: synthèse des figures 7 et 8. 18 500 – 15 500 BP = Bouchet (fig. 8), 15 500 – 13 000 BP = Pelléautier (fig. 7), 12 500 – 0 BP = Taphanel (fig. 8). (3) Reconstitution de l'indice bioclimatique P-3T (voir texte): 18 500 – 15 500 BP = Bouchet; 15 000 – 500 BP = Pelléautier.*

temperature, the source of which is, of course, the Atlantic Ocean. Around 10 500 BP, the warming trend that occurred in the Atlantic caused an almost simultaneous warming in the Alps.

Another summer temperature reconstruction was proposed by LAMB (1982) from pollen in central England, and one reconstruction of winter temperature. THUNELL (1979) applied a transfer function to micropaleontological data in the Eastern Mediterranean for the last glacial maximum (18 000 BP). Table III summarizes the essential characteristics of these data.

Table III shows that there is relatively good agreement in the literature in estimating temperature difference from present in the last glaciation in sites dominated by Atlantic air masses; the difference is about 10°C (summer) to about 14°C in England. THUNELL (1979) shows that in a predominately Mediterranean type of climate, the difference would be much less marked (4°C or less in the centre). There is nothing extraordinary about a finding of an intermediate value for Southern France with a climate that is influenced by both the Atlantic and the Mediterranean. The value of −6°C, calculated for 18 000 BP in this article's reconstruction of annual temperature, should be treated with caution because there was only one core (Lac du Bouchet) old enough to cover the period in question. Because the method is based essentially on a comparison of two sites, the reconstruction of the climate between 15 000 BP ans 18 500 BP is doubtful. On the other hand, the value identified for 14 000 BP (−9°C) is useful because (with the exception of England) summer temperature did not fluctuate greatly from 18 000 BP to 14 000 BP in the reference reconstructions. The annual temperature of the period 18 000 to 14 000 BP in the South of France could reasonably be assumed to have been 9°C lower than at present.

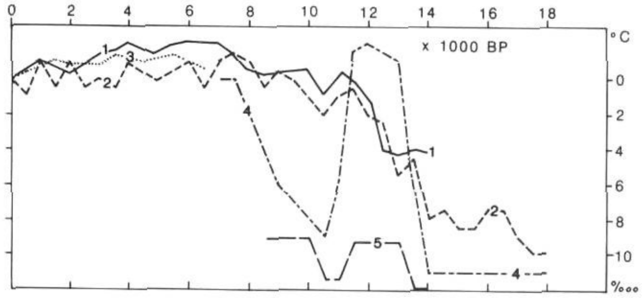

FIGURE 10. Reference paleotemperature. (1) Reconstruction of the July temperature from the treeline in the Alps, after MARKGRAF (1974). (2) Figure 9 (1). (3) Mean of 11 reconstructions of the July temperature in the Canadian North by palynological transfer functions (ANDREWS and DIAZ, 1981). (4) Reconstruction of the August temperature in the Bay of Biscay (CH72101) by micropaleontological transfer function after DUPLESSY *et al.* (1981). (5) Curve of the $^{18}O$ / $^{16}O$ ratio (in %...): mean by chronozones in the Dauphiné (France) after EICHER *et al.* (1981).

*Paléotempératures de référence: (1) Reconstitution de la température de juillet à partir de la limite forestière dans les Alpes, d'après MARKGRAF (1974). (2) Figure 9 (1). (3) Moyenne de 11 reconstitutions de la température de juillet dans le Nord canadien (ANDREWS et DIAZ, 1981). (4) Reconstitution de la température d'août dans le golfe de Gascogne (CH72101) par une fonction de transfert micropaléontologique d'après DUPLESSY* et al. *(1981). (5) Rapport $^{18}O$ / $^{16}O$ (en %...): moyenne par chronozones dans le Dauphiné (France) d'après EICHER* et al. *(1981).*

The warming during the Bølling and Allerød periods was probably substantial in summer (equivalent to modern temperature) but very modest in winter (LAMB, 1982). Thus the finding of a midpoint in this reconstruction of yearly temperature (4°C lower than present) comes as no surprise. For the period 14 000 BP to present, there is good correlation between the reconstruction in this paper and the results obtained by PATZELT and BORTENSCHLAGER (1976) or MARKGRAF (1974), because 80% of the relative variations in the two curves (in comparison with the values at the immediately preceding level) show the same trends.

## CONCLUSIONS

A three stage method for calculating and applying transfer functions can filter out a large amount of noise in climatic reconstructions for regions in which the impact of human activity has been considerable. A climatic reconstruction, which is an empirical model of the climate, was first obtained by standard techniques, and it provided a point of reference that could be used for calculating climatic variations. Some aspects

TABLE III

*Some characteristic temperature and $^{18}O/^{16}O$ data for the period since 18 000 BP; the $^{18}O/^{16}O$ ratios are given in real values and the temperatures in deviations from present values (°C)*

| Author | parameter | −18K | −13K/−14K | −11.5K/−12K | −10.5K | −8K/−6K |
|---|---|---|---|---|---|---|
| Markgraf, 1974 | July T | − | −4 | 0 | −1 | +2 |
| Patzelt *et al.*, 1976 | summer T | −10 | −8 | −.5 | −2 | +1/1.5 |
| Andrews *et al.*, 1981 | July T | − | − | − | − | +1 |
| Duplessy *et al.*, 1981 | August T | −11 | −11 | +2 | −9 | +2 |
| Eicher *et al.*, 1981 | $^{18}O/^{16}O$ (‰) | − | −11.9 | −9.3 | −11.4 | −9.1 |
| Lamb, 1982 | summer T | −10 | −3 | +1 | −4 | +1.5 |
| Lamb, 1982 | winter T | −14 | −12 | −11 | −12 | +1 |
| Thunell, 1979 | summer T | −4 (max) | | | | |
| Thunell, 1979 | winter T | −6 (max) | | | | |
| this paper | annual T | (−6) | −9 | −4 | −6 | +1 |
| this paper | P-3T | +140 | +80 | 0 | +80 | 0 mm |

*of climatic forcing were clearly indicated in the fossil data,* but others were affected by noise. For that reason a second stage was added to the method. It consisted of a canonical correlation analysis of fossil data by paired observations from two sites with no reference to modern data. The analysis yielded a model of climatic forcing, disassociated from the gradual impact of human activity in the last several millenia and from particularities of local vegetation. Finally, the data obtained from the two stages were put together. Although some refinements are in order, the method used here has yielded a reconstruction of annual temperature that is in line with the results obtained in the literature. This method is promising for regions where palynological reconstructions have been disappointing, but results will be improved by input of more diversified modern pollen data and by data covering a longer period of the past.

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