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SOME NEW MATHEMATICAL PROCEDURES IN DENDROCLIMATOLOGY, WITH EXAMPLES FROM SWITZERLAND AND MOROCCO

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ABSTRACT

An original procedure and a new mathematical technique have been developed which allowed us to obtain more reliable climatic reconstructions than with prior methods. They have been tested for different sites in Switzerland and Morocco. First, cores that were too short and cores that were not coherent enough with others were excluded, using cross-spectral analysis. Second, detrending and master chronologies were calculated. Three methods were compared: polynomial, high-pass filter, and spline indexing. An optimal detrending was obtained through comparison with climate, but there seems to be no general rule for it. More reliable and longer climatic reconstructions are made possible. A response functions technique in three steps is presented: regression after extracting principal components on monthly climatic parameters, on seasonal parameters, and on more biological parameters such as potential evapotranspiration, multiple spectral regression introducing frequency domain. This procedure provides a more complete and more dynamic view of tree growth. The transfer function method and its verification are illustrated for different sites in Morocco: three climatic parameters in Tetouan (February, May, and June temperatures) and one in Marrakech (May temperature) have been successfully reconstructed. These reconstructions are confirmed by different verifications.

Une procédure complèt et originale a été mise au point afin d'obtenir des reconstructions climatiques plus fiables que celles obtenues jusqu'à présent à partir de méthodes plus classiques. Elle a été testée en utilisant différents sites en Suisse et au Maroc. Premièrement, on élimine les échantillons trop courts et les échantillons insuffisamment cohérents avec les autres et ce, grâce à l'analyse spectrale croisée. En deuxième lieu, on stationnarise les séries et on calcule les chronologies maîtresses. Trois méthodes sont comparées pour faire cela: polynôme, filtre passe-haut et fonctions splines. La sélection du "detrending" optimal est faite en relation avec le climat, mais il semble impossible de donner une règle générale pour l'obtenir. Cette façon de procéder permet d'obtenir plus de reconstructions climatiques, plus fiables et plus longues. Une nouvelle technique de construction de la fonction de réponse est alors présentée en 3 étapes: régression après extraction des composantes principales sur des paramètres climatiques mensuels, ensuite régression sur les paramètres groupés en saisons et des paramètres plus biologiques tels que l'évapotranspiration potentielle, enfin utilisation de la régression multiple spectrale avec son analyses fréquentielle. Cette procédure permet une analyse de la croissance plus profonde, plus complète et plus dynamique. La fonction de transfert et sa vérification sont illustrées pour le Maroc. La reconstruction fructueuse de 3 paramètres climatiques à Tétouan (tempêtures de févier, mai et juin) et de 1 paramètre à Marrakech (température de Mai) a été possible et confirmée à partir de différentes vérifications.

In das bekannte Verfahren zur Klimarekonstruktion wurde ein neue mathematische Technik eingeführt, die zuverlässigere Rekonstruktionen ermöglicht als mit den bislang üblichen Methoden. Sie wurde für verschiedene Standorte in der Schweiz und in Marokko gestestet. Zuerst werden die zu kurzen Bohrkerne ausgesondert, dann werden mit Hilfe einer Kreuzspektralanalyse die Bohrkerne ausgeschieden, die mit den anderen nicht genügend übereinstimmen. Für die anschließende Elimination des Trends werden drei Methoden verglichen:

Polynomausgleich, Hochpassfilter und Splinefunktionsausgleich. Das optimale Verfahren wir nach Vergleich mit dem Klima ermittelt aber es erscheint unmöglich, eine allgemein gültige Regel hierfür aufzustellen. Nach der Trendbereinigung werden Chronologien gebildet. Diese Art des Vorgehens erlaubt Längere und zuverlässigere Klimarekonstruktionen. Eine neue Technik für die Aufstellung von Responsefunktionen in drei Schritten wird vorgestellt: Regression nach Extraktion der Hauptkomponenten auf Grund der Monatswerte der Klimaparameter, danach Regression auf Grund von nach Jahreszeiten gruppierten Klimaparametern und von mehr biologischen Parametern wie z.B. potentielle Evapotranspiration und schließlich die Verwendung der multiplen spektralen Regression mit Frequenzanalyses. Dieses Vorgehen erlaubt eine tiefergehende, vollständigere und dynamischere Analyse des Baumwachstums. Transferfunktionen und ihre Verifikation werden für verschiedene Standorte in Marokko gezeigt. Die erfolgreiche Rekonstruktion von drei Klimaparametern in Tetuan (Februar-, Mai- und Juni-Temperatur) und eines Parameters in Marrakesch (Mai-Temperatur) war möglich und wurde durch verschiedene Verfahren bestätigt.

INTRODUCTION

The method now most frequently used in dendroclimatology was initiated by Fritts (1976). After crossdating, the cores are detrended with polynomial, negative exponential, or constant slope line. Main information concerning the chronologies is derived from variance and cross-correlation analysis. Master chronologies are obtained from averaging the detrended individual chronologies. Response function based on regression after extracting principal components are calculated on monthly climatic parameters and when a large enough number of sites is available, transfer functions enable reconstruction of climatic patterns in the neighborhood of these sites. This technique has been successfully applied in western North America. Yet many improvements are possible which are quite necessary in Europe and Mediterranean countries where very few reconstructions have been validated up to now.

We propose to improve this method by introducing spectral analysis, cross-spectral analysis, filtering techniques, and spectral multiple regression. This procedure has been tested on Swiss and Moroccan sites. Contrary to prior methods, it enabled one to obtain reliable reconstructions.

LOCATION OF THE SITES AND DATA

In Switzerland, four sites were studied in the Grisons; Nos. 401, 402, 403, and 404. Climatic data (Schüepp 1961; Uttinger 1965) recorded in Bivio provided precipitation series from 1901 to now. Although temperature series extend only from 1952 to now, they have been extrapolated back to 1901 using simple regression from Davos data (Wilputte 1977).

In Morocco, the sites are located in the Rif (sites 301, 302) and in the Moyen-Atlas (310, 321, 336, 338, 340). Our reference climatic station is Tetouan in the Rif, where data extend from 1941 to now. Another station has also been studied; Marrakech in western Haut-Atlas (De Corte 1981).

SELECTION OF TREE-RING CHRONOLOGIES AND CALCULATION OF MASTER CHRONOLOGIES; AN EXAMPLE FOR THE GRISONS IN SWITZERLAND

Tree-ring chronologies have not always the same length. Young trees often respond differently to climate; so it is important to distinguish old trees from young ones and to calculate master chronologies from old trees only. This is illustrated here

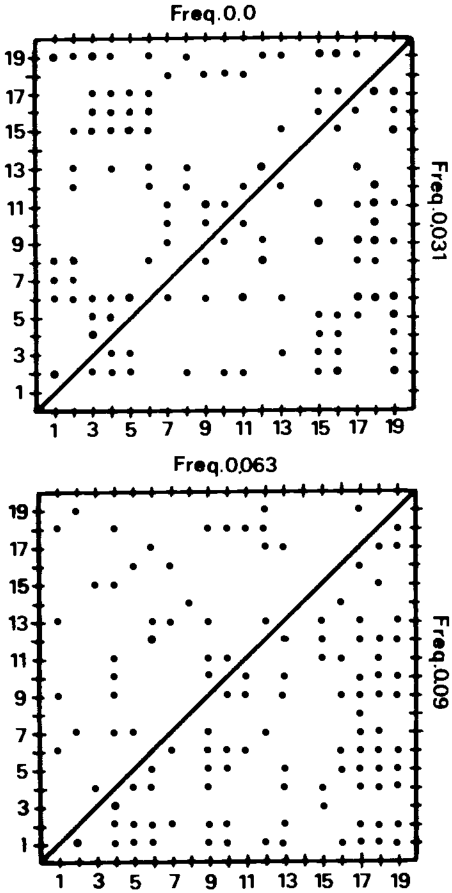
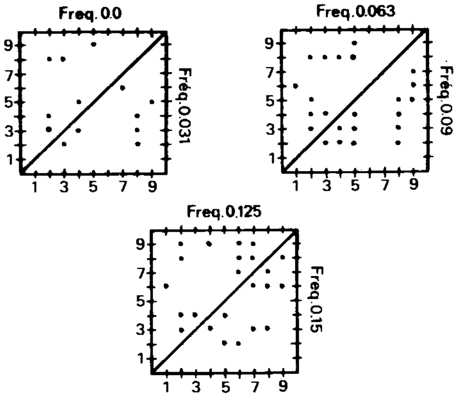


Figure 1. Spectral coherencies higher than 0.5 between different cores of site 401. A point in the intersection of column i and raw j indicates a coherency between core i and core j higher than 0.5 at the frequency indicated along the side of the figure. Each half-diagram is independent and concerned one of the six analyzed frequency bands.



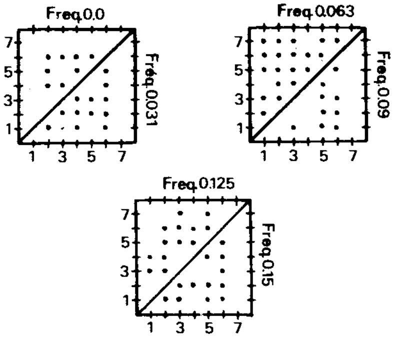


Figure 2. Same as Figure 1 for site 402.

Figure 3. Same as Figure 1 for site 404.

with our four Swiss sites. Cores starting after 1700 have been excluded. So, only 19 cores from site 401, nine from site 402, and seven from site 404 have been kept, all the trees in site 403 being too young to be included.

The second step is the selection of cores containing similar information. This is done using cross-spectral analysis, in order to find the time-scale for which the cores are sufficiently homogeneous. All the series thus selected are then completed by their respective mean so that they all have the same length (1600-1969). Usually this artifice does not modify the characteristic periodicities but it only slightly affects the power of the peaks. Sixteen frequencies have been considered, and coherencies between cores from each site and for each frequency have been analysed. Figures 1, 2 and 3 represent couples of cores with a spectral coherency greater than 0.50 for frequencies of less than 0.156 cycles/year (or periods longer than six years). Null-frequency represents the band of very long periods and must be eliminated in order to make the series stationary. Frequencies for which the cores are not well coherent must also be attenuated. The following remarks can be made (Figures 1, 2 and 3):

Site 401 (Figure 1): the 33-year and 11-year periodicities are sufficiently coherent, but not the 16-year one. Therefore, all the periodicities longer than 15 years have been tentatively eliminated. The corresponding results are then compared with the usual case where only the trend is removed. Unfortunately, even after elimination of these low frequencies, somes cores (3, 8, 14) remain slightly coherent and cannot be used for further calculations.

Sites 402 (Figure 2): cores 1, 6, 7 and 9 are excluded as well as periodicities longer than 33 years.

Site 404 (Figure 3): only the trend is removed as there is a sufficient coherency everywhere.

Then each core is detrended. Several trials have been made by Hughes et al. (1978). A new program is presented here (Lefebure 1980; Berger 1980) which allows one to use different detrending functions: negative exponential, polynomial, spline, constant slope line, high-pass filter, and stochastic detrending. Three different options have been retained for the three sites: a third degree polynomial, a spline function, and a high-pass filter. Only the first option is independent of the preceding cross-spectral analysis and therefore may be used as a reference for comparing the results. The spline-function is fitted to averaged tree rings over intervvals fixed on the basis of the cross-spectral analysis: seven years for site 401, 15 years for site 402 and 20 years for site 404, that is to say half of the cut-off periods determined through Figures 1, 2, 3. The cut-off period of the high-pass filter is also based on the cross-spectral analysis: 15 years for site 401, 30 years for site 402 and 40 years for site 404. Thus, nine master chronologies are obtained whose characteristics are presented in Table 1. The variance analysis (ANOVA) shows that the filter method maximizes the part of variance attributed to the chronology. However, the best master chronology — with a maximized signal to noise ratio — cannot be selected only on the basis of this information; so further analyses are necessary.

SELECTION OF A MASTER CHRONOLOGY

We propose to select the best master chronology from the response functions themselves. However, as the response function using regression after extracting principal components is mainly sensitive to interannual climatic variations — because they

Table 1. Characteristics of the master chronologies of three Swiss sites.

	Site 401			Site 402			Site 404		
	Polynomial	Filter	Spline	Polynomial	Filter	Spline	Polynomial	Filter	Spline
Total Period	1600-1972	1600-1972	1607-1972	1600-1972	1600-1972	1615-1972	1600-1972	1600-1972	1620-1972
number of trees	8	8	8	2	2	2	5	5	5
number of cores	16	16	16	5	5	5	7	7	7
missing rings	0.0	0.0	0.0	0.12%	0.12%	0.12%	0.53%	0.53%	0.53%
mean ring (mm)	0.87	0.87	0.87	0.68	0.68	0.68	0.67	0.67	0.67
serial — R	0.64	0.01	0.39	0.31	0.04	0.34	0.63	0.51	0.34
mean sensitivity	0.12	2.87	0.11	0.26	4.3	0.26	0.25	1.48	0.25
mean index	1.02	0.13	1.0	1.01	0.20	0.98	1.0	0.01	1.0
standard deviation	0.18	12.28	0.13	0.30	18.85	0.33	0.37	20.8	0.28
Reference Period (1871-1970)									
number of trees	8	8	8	2	2	2	5	5	5
number of cores	16	16	16	5	5	5	7	7	7
mean ring (mm)	0.51	0.51	0.51	0.38	0.38	0.38	0.71	0.71	0.71
ANOVA (% variance)									
cores	80	62	74	58	40	40	38	29	36
years	20	38	26	42	60	60	62	71	64

Table 2. Percentages of variance remaining in the spectral bands.

Sites	Spectral Band Normally Removed	Polynomial	Filter	Splines
401	∞ - 15 years	69%	7%	40%
402	∞ - 33 years	25%	14%	29%
404	∞ - 40 years	35%	1%	12%

Table 3. (1) Maximum value of the correlation coefficients between the nine master chronologies and the monthly total precipitation and mean temperature series, after filtering with a low-pass filter (cut-off period = 6 yrs.). (2) Number of coefficents larger than 0.5 (in absolute value).

Sites	Polynomial		Filter		Splines	
401	−0.36	0	−0.24	0	−0.50	1
402	−0.78	7	+0.23	0	+0.45	0
404	+0.42	0	+0.68	5	+0.46	0
	(1)	(2)	(1)	(2)	(1)	(2)

contain a larger part of the climatic variance — this technique does not make it possible to test the master chronologies whose differences lie in very low frequencies. Moreover, nine response functions have been calculated which did not prove to be significantly different for a same site (Guiot 1981a).

A spectral analysis of the nine master chronologies gave the percentage of the total variance remaining in the low frequencies band normally eliminated in the previous section (Table 2). It shows that the filtering technique is the most efficient whereas polynomial detrending is the least efficient.

Correlation coefficients with climatic variables have been calculated in order to verify whether the spectral band removed is the most adequate. As it is not possible to reconstruct high frequencies on only three sites, only the long-term variations of climate will be analysed. The 24 climatic parameters (monthly mean temperatures and total precipitation) of Bivio and the nine master chronologies have been filtered with a low-pass filter before computing correlation coefficients. The cut-off period of the low-pass filter used has been fixed to six years, a period which seems to divide the spectra in two equivalent parts. The maximum correlation coefficients between each master chronology and the 24 climatic parameters are presented in Table 3. These coefficients are very sensitive to the detrending method; so, the following selection is proposed:

Site 401: all the correlations are weak. The highest coefficient is obtained for spline detrending with June precipitation (-0.50). The spline chronology is selected accordingly.

Site 402: as the correlation of polynomial detrending with December precipitation is high (-0.78), the polynomial chronology is selected.

Site 404: the filtered chronology is adopted, because its correlation with November precipitation is 0.68 and with July -0.67.

This procedure as a whole clearly shows that an adequate detrending technique can provide better results and that the selection of this detrending technique must be based on climatic data and not on variance analysis considerations alone. In only one site, more traditional techniques, such as the polynomial detrending, maximize the signal to noise ratio. In most cases, a deeper and more appropriate approach is provided by the new technique described here. Correlations are improved for the nine master chronologies by using cross-spectral analysis and excluding uncoherent cores (13 correlation coefficients instead of three are higher than 0.50 when no selection is made). As, in some master chronologies (402), only two trees have been included, this also demonstrates that it is much more important to carefully select a few trees with a similar good response to climate than to generate a master chronology from as many trees as possible.

HOW TO BUILD A RESPONSE FUNCTION; AN EXAMPLE FOR MOROCCO

The concept of response functions in dendroclimatology was analysed by Fritts (1976). It gave rise to many further researches. Different ways to compute it are compared in Guiot et al. (1982) and in Guiot (1981a). These comparisons lead to a global procedure which is a compromise between biological and statistical constraints. It must help to understand biological mechanisms and enable one to get more reliable regressions. An illustration of this is given by a site with cedars in the Moroccan Rif (site 301) (Berger et al. 1979).

The first step is the computation of the response of tree-ring indices (master chronology I(t)) to monthly precipitation and temperatures (P_{oct} (t-1) . . . P_{sept} (t), T_{oct} (t-1), . . . T_{sept} (t)). These 24 predicators are selected because the cedar growth seems to stop in September. The calibration period is 1941-1971. The technique used is regression after extracting principal components. The general method is the same as was used in Berger et al. (1979), but here no selection of climatic parameters is done. It differs from the method used in Munaut et al. (1978) by using PVP criterion, leading to include in the regression 18 principal components for which the cumulative product of eigenvalues exceeds 1. Nine of these components, which are significantly correlated with I (t) at the 0.5- level (median), are definitively introduced in the response function, leading to:

$$\hat{I}(t) = \sum_{j=1}^{24} a_j x_j(t) \tag{1}$$

where $\hat{I}$ (t) is an estimation of I (t) from the 24 predictors x_j (t). The coefficients a_j are drawn in Figure 4. All the variables are standardized.

However, persistence may play an important role in tree growth. So, a test of first order serial correlations (first order Markov process) of I (t) is performed and, as it is significant at the 0.05-level, a regression between I (t) and I (t-1) is computed:

$$I(t) = 0.63 + 0.38\, I(t) + I^*(t)$$

$I^*(t)$ is the residual at time t and is not significantly autocorrelated. Thus $I^*(t)$, which is tree growth after prewhitening, presumably represents the influence of climate.

A relationship between $I^*(t)$ and the 24 predictors can then be established using the already mentioned regression after extracting principal components:

$$I^*(t) = \sum_{J=1}^{24} b_j x_j(t) + e_1(t) \tag{2}$$

The coefficients b_j (standardized) are displayed in Figure 5. From the biological point of view it is proper to test whether climatic variables of the previous years are correlated with the residuals $e_1(t)$ given in (2). In fact, here, no partial correlation coefficients between $e_1(t)$ and the predictors $x_j(t\text{-}1)$ are significantly different from zero. Thus, equation 2 represents sufficiently well the tree-response to climate, and as coefficients a_j (1) are not significantly different from coefficients b_j (2), it seems possible to represent the persistance effect by the climate of the previous year and to estimate I (t) from the following equation:

$$\hat{I}(t) = \sum_{j=1}^{24} b_j x_j(t) + \sum_{j=1}^{24} c_j x_j(t\text{-}1) \tag{3a}$$

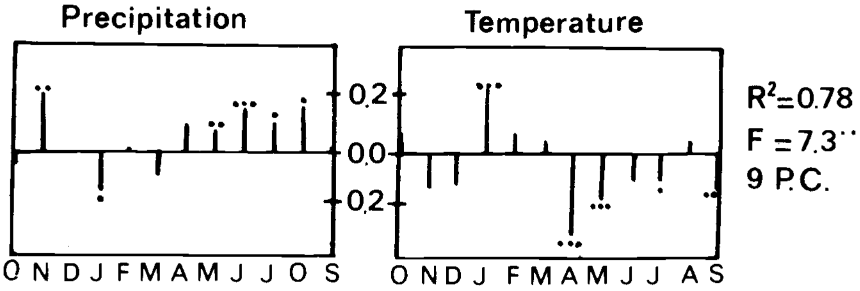


Figure 4. Response function of the master chronology I(t) (site 301, Morocco) on 24 monthly climatic parameters. The vertical axis represent the standardized regression coefficients after extracting principal components. 1 dot (2 or 3) indicates a 0.10 significance level (0.05 or 0.01). R² is the coefficient of determination, F the Fisher-ratio, and p is the serial correlation of the residuals.

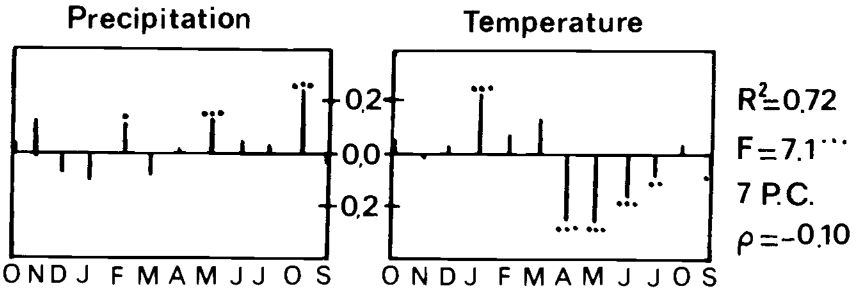


Figure 5. Response function of I* (t) (=I(t) after prewhitening; refer to Figure 4.

Unfortunately, considering the number of observations (30), the number of predictors (48) is too large to obtain a reliable regression. However, the month entity is not really biologically representative: a division into seasons is quite appropriate and allows reduction of the predictors number in (3a). These seasons must be defined on a biological ground, for example in relation with the sign of the regression coefficients in (1). Therefore, the following biological seasons are tentatively defined here:

$$\mathrm{Au}\,(t\text{-}1) = \mathrm{Oct}\,(t\text{-}1) + \mathrm{Nov}\,(t\text{-}1) + \mathrm{Dec}\,(t\text{-}1)$$
$$\mathrm{Wi}\,(t) = \mathrm{Jan}\,(t) + \mathrm{Feb}\,(t) + \mathrm{Mar}\,(t)$$
$$\mathrm{Sp}\,(t) = \mathrm{Apr}\,(t) + \mathrm{May}\,(t)$$
$$\mathrm{Su}\,(t) = \mathrm{Jun}\,(t) + \mathrm{Jul}\,(t) + \mathrm{Aug}\,(t) + \mathrm{Sep}\,(t)$$

So, the following equation can be computed:

$$\hat{I}\,(t) = \sum_{j=1}^{8} c_j\, x_j\,(t) + \sum_{j=1}^{8} d_j\, x_j\,(t\text{-}1) \qquad (3b)$$

where the x_j's represent the four seasonal temperatures and the four seasonal precipitations. The coefficients c_j and d_j are drawn in Figure 6. The influence of precipitations seems to be negligible and the serial correlation of the residuals of (3b) is

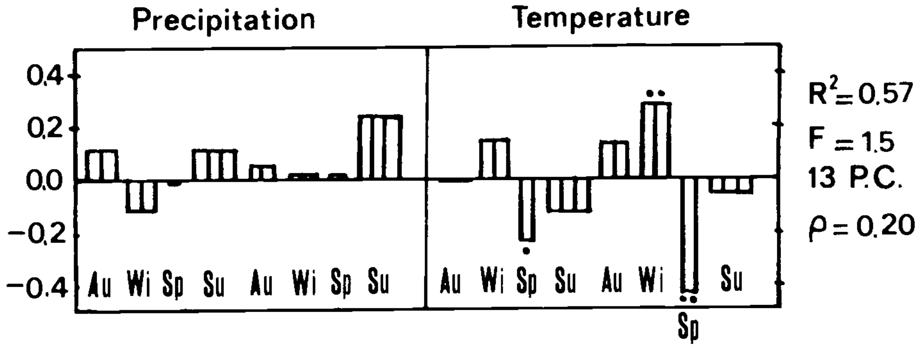


Figure 6. Response function of I(t) on 16 seasonal climatic parameters; refer to Figure 4.

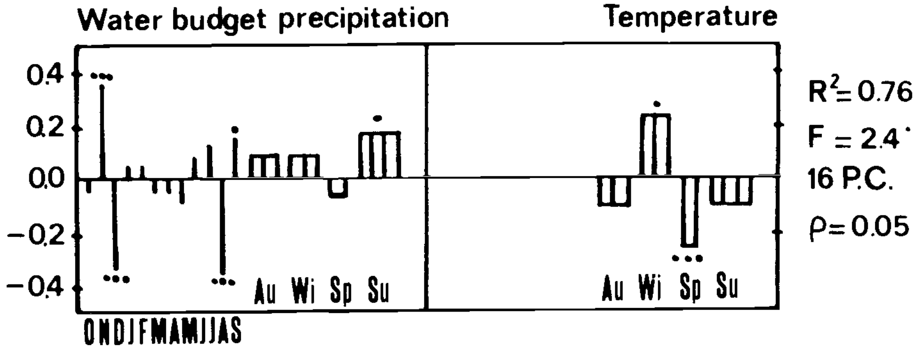


Figure 7. Response function of I(t) on 8 seasonal climatic parameters and 12 monthly water budget parameters; refer to Figure 4.

rather strong. Consequently, this model does not seem to be adapted for representing the persistence effect and it is thus necessary to look for other relationships which could give better results.

As site 301 is in a warm and dry environment during half of the year, a simple concept of potential evapotranspiration and water budget has been used, following Thornthwaite method. This is certainly incomplete, but it presents two advantages. It allows to include predictors with a more physical meaning into the response function and to bring non-linearity in the regression, so going a step further than the linearity imposed by the usual descriptive techniques. It is also easy to compute and only needs monthly temperatures and precipitation, the most accessible climatic parameters in many countries such as Morocco. Different trials have shown that monthly water budget (W_j = monthly precipitation minus monthly potential evapotranspiration) from Oct (t-2) to Sept (t-1), precipitation and temperatures of the 4 seasons preceedingly defined are an optimum selection to better explain the growth with a minimum of predictors. The coefficients of the equation:

$$\hat{I}\,(t) = \sum_{j=1}^{8} c_j\, x_j\,(t) + \sum_{j=1}^{12} d_j\, W_j\,(t\text{-}1) \tag{4}$$

are presented in Figure 7. The skill is improved and the autocorrelation of the residuals is not significantly different from zero. As a conclusion, this seems to be a satisfactory model. The fact that the response to some water budget parameters is different from one month to the other shows that a seasonal grouping would not be adequate here.

If this way of introducing some non-linear parameters is already an improvement, an other great improvement is given by the regression in the frequency domain (Guiot 1979, 1981b). This method enables one to distinguish long term variations (effect of interannual climatic pattern) from short-term variations (effect of interannual climatic variations). When applied to eight seasonal parameters as above, it gives the following relationships (L indicates low-frequencies and H indicates high-frequencies) between tree-ring indices and climate:

$$\hat{I}^{L}\,(t) = \sum_{j=1}^{8} C_j^{L}\, x_j^{L}\,(t) \tag{5}$$

$$\hat{I}^{H}\,(t) = \sum_{J=1}^{8} C_j^{H}\, x_j^{H}\,(t) \tag{6}$$

The coefficients C_j^L and C_j^H are presented in Figure 8. The weights (w_0, w_{-1}) of the low-pass filter are defined by (1/2, -1/2) and those of the high-pass filter are (1/2, -1/2). The high-frequency model (6) shows that a cold winter and a warm spring produce a tree ring smaller than expected by persistence alone. The low-frequency one (5) shows that a persistent cold winter is less damaging than a warm spring. If spring is exceptionnally warm during two years or more, it seriously handicaps growth.

This method undoubtedly gives information about the dynamics of these biological mechanisms, and a better global response function:

$$\hat{I}(t) = \hat{I}^L(t) + \hat{I}^H(t)$$

$$= 1/2 \sum_{j=1}^{8} (C_j^L + C_j^H)\, x_j(t) + 1/2 \sum_{j=1}^{8} (C_j^L - C_j^H)\, x_j(t\text{-}1) \qquad (7)$$

The coefficients $1/2\,(C_j^L + C_j^H)$ and $1/2\,(C_j^H - C_j^H)$ are drawn in Figure 9. So this spectral method provides a long-term a short-term and a global relationship, this last being, in fact, a different way to compute a response function as (3). In Figure 9 the coefficients are more contrasted than in Figure 6. As in Figure 8, 3 coefficients are ob-

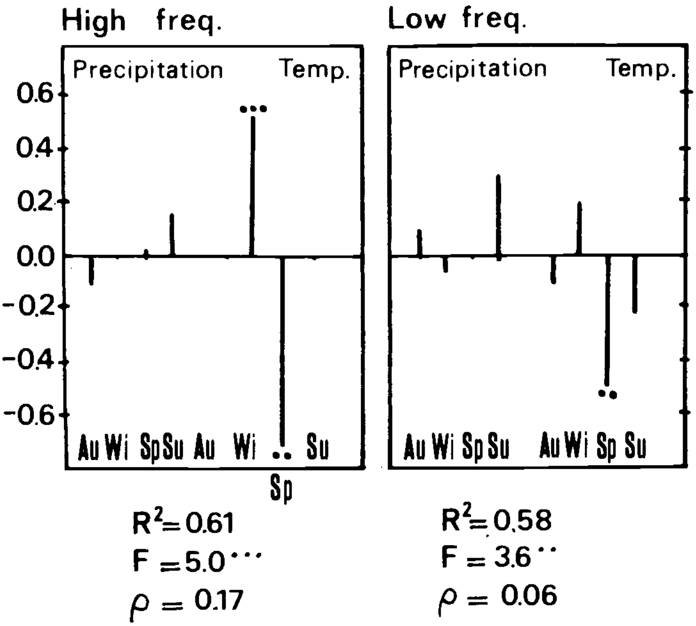


Figure 8. Response function of the high frequencies and low frequencies of I (t) on corresponding frequency bands of 8 seasonal climatic parameters; refer to Figure 4.

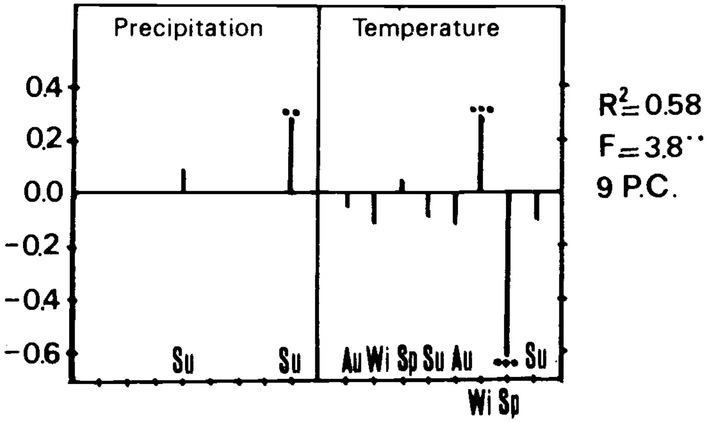


Figure 9. Response function of I (t) derived from the recombination of the response functions of Figure 8.

viously null (for P_{Au} (t-1), P_{Wi} (t) and P_{Sp} (t), therefore they could be removed in the computation of (7).

To conclude, this response function procedure certainly leads to a deeper knowledge of the relationship between tree growth and climate. One should remember that Fritts' method (Fritts 1976) represents the first step of this new procedure.

METHODS USED FOR CLIMATIC RECONSTRUCTIONS: EXAMPLES FOR THE SWISS GRISONS AND FOR MOROCCO

Swiss Grisons

The selection of cores in three Swiss sites has made it possible to reconstruct three climatic parameters: August temperature, November and December precipitation. This reconstruction is presented in details in Guiot et al. (1981) and is summarised here to illustrate the new techniques that have been developed. Low frequencies of indices, chronologies and climate chronologies have been isolated (high frequencies variations cannot be reconstructed from such a small number of sites) and climate parameters have been extrapolated through regressions on dendrochronological variables. Low frequencies (periodicities larger than six years) of August temperature, December and November precipitation have been reconstructed from the three sites and tested with corresponding series observed at Grand-St-Bernard, Bever, Basel, and in central England. So, mainly December precipitation and August temperature have been validated in numerous intervals between 1620 and now.

Morocco

A more general and efficient method has also been developed; it will be illustrated here by the study of seven sites.

The most appropriate climatic station with respect to the proximity of the sites and the length of the series is Tetouan. The maximum calibration interval available is 1941-1974. Its short length explains why an other station (Marrakech) has also been considered over the interval 1924-1975. Because the seven sites are located in different parts of Morocco, it seems difficult to reconstruct precipitation whose characteristic scale is mostly local. Only temperatures will be analysed.

In order to express climate as a function of the tree ring, the first step is the analysis of the stability (Gray 1980) of tree response to climate. Two relationships between each chronology of indices and the 12 monthly temperatures are computed, one in the high-frequency band and the other in the low-frequency band, using the spectral multiple regression (Guiot 1981b). A cut-off period of these bands was fixed to 3.5 years in order to divide the chronologies spectra in a dominant low-frequency band and a high-frequency band with a weak variance. Then, the calibration period has been arbitrarily divided into three parts for Tetouan: the stability is verified by comparing the results of a calibration on the 1951-1974 interval and a calibration on the 1941-1950/1961-1974 interval. Usually, two independent intervals are defined, but here the total number of observations is too weak: therefore we have defined two semi-independant periods: 1951-1974 and 1941-1950/1960-1974. The tests have shown a significant stability for low frequencies, whereas for high frequencies some unstabilities are noticed, which are probably due to the fact that the high-frequency band contains random variations. The unstabilities are not sufficient to hinder climatic reconstructions: as the determination coefficients of February to June in

Tetouan are all higher than 0.60, a reconstruction of the high and low-frequencies of the temperature of these months is attempted.

For each climatic parameter, two estimations are made, one over the 1951 to 1974 interval and the other over the 1941 to 1950/1961 to 1974 interval. The first is verified over the independent 1941-1950 period and the second over the independent 1951-1960 period. The verification is made through the test of the reduction of (RE)

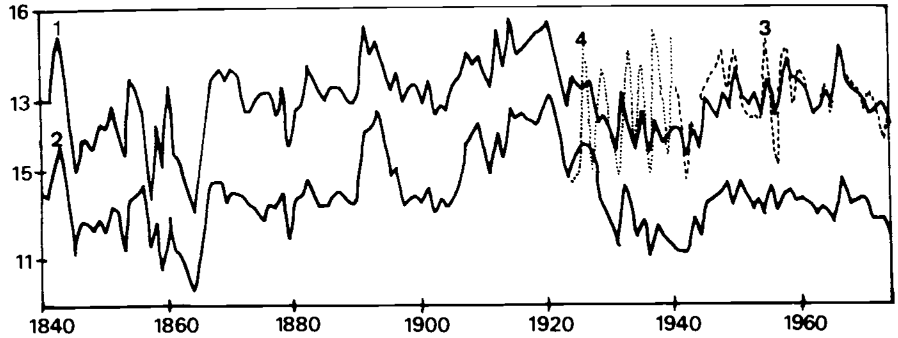


Figure 10. Temperature of February at Tetouan (Morocco). (1) Reconstruction from 7 sites calibrated over 1951-1974; (2) Reconstruction from 7 sites calibrated over 1941-1950/1961-1974; (3) Corresponding series observed at Tetouan; (4) Corresponding series observed at Marrakech.

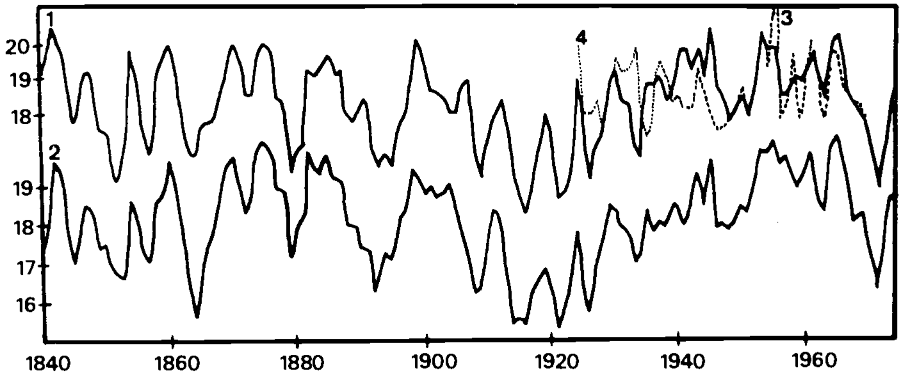


Figure 11. Temperature of May in Tetouan (Morocco); see Figure 10.

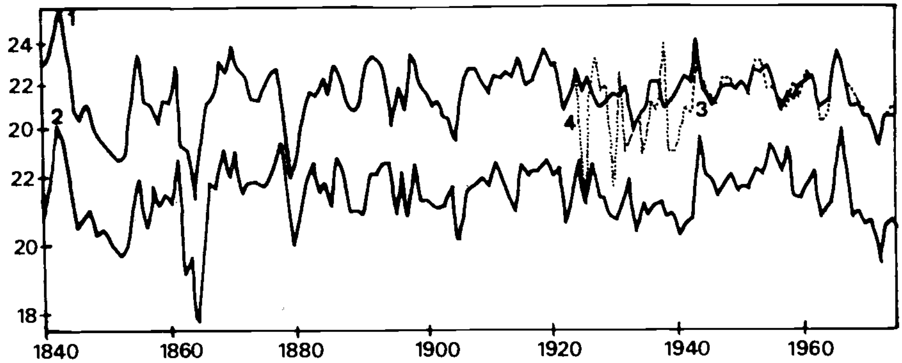


Figure 12. Temperature of June in Tetouan (Morocco); see Figure 10.

Table 4. Statistics of verification of both calibrations 1 and 2 of temperature series at Tetouan: R_T = correlation over 1941-1974; R_I = correlation over independent interval 1941-1950 or 1951-1960; RE = reduction of error (Gordon 1980) decomposed in T_1 (error risk with ideal value of − 1.), T_2 (coherency between observed mean and estimated mean over independent interval) and T_3 (covariance factor between estimations and observations over independent interval).

	Months	R_T	R_I	T_1	T_2	T_3	RE
	February	0.71	0.84	−0.74	0.04	1.13	0.43
	March	0.72	0.40	−2.29	0.63	0.70	−0.96
1	April	0.69	−0.08	−0.92	0.12	−0.11	−0.91
	May	0.85	0.68	−1.42	−0.29	1.40	−0.31
	June	0.88	0.65	−1.40	0.54	1.17	0.31
	February	0.73	0.64	−0.27	0.07	0.52	0.32
	March	0.75	−0.26	−0.84	1.13	−0.17	0.12
2	April	0.71	−0.14	−1.48	0.75	−0.17	−0.90
	May	0.85	0.61	−0.83	0.82	0.46	0.45
	June	0.85	−0.12	−0.95	1.04	−0.10	−0.01

Table 5. Statistics of verifications of both calibrations 1 and 2 of temperature series at Marrakech. The symbols are defined such as in Table 4, but total interval is 1924-1975 and the independent intervals are 1924-1933 and 1934-1943.

	Months	R_T	R_I	T_1	T_2	T_3	RE
	April	0.76	−0.06	−8.34	1.18	−0.20	−7.36
1	May	0.79	0.67	−2.92	−0.99	1.59	−2.32
	June	0.74	−0.08	−6.14	1.35	−0.22	−5.01
	April	0.46	0.14	−0.08	−0.34	0.03	−0.39
2	May	0.84	0.75	−0.80	−0.20	1.14	0.14
	June	0.57	0.36	−0.11	−0.04	0.17	0.02

decomposed in three terms as suggested by Gordon (1980). Table 4 shows results which seem to indicate that extropolation for February, May and June temperatures is sufficiently stable to be considered as reliable. The curves obtained from both the estimated high and the estimated low frequencies are reported on Figures 10, 11 and 12.

Concerning Marrakech, only the low-frequencies of April, May and June temperatures have a determination coefficient high enough ($R > 0.60$) to permit such a reconstruction, probably because the town is far-distant from most sites. For these monthly temperatures, two estimations are made, one over the 1934-1975 interval and the other over the 1924 to 1933 — 1944 to 1975 interval. The corresponding independent periods are 1924-1933 and 1934-1943. The verification statistics are reproduced in Table 5. Only May temperature seems to be stable. Although the first calibration has a negative RE (because of the term T_2 which is largely negative in

Table 5 for May) the covariance term T_3 is very high and we suggest not to reject. These reconstructions (only low frequencies) are shown in Figure 13.

In this case, another verification is possible, as reconstructed May temperature is available both in Tetouan and in Marrakech. In fact, the calibrations are relatively independent: intervals are very different and their interdistance leads to different relationships between tree-rings and climate. However, from Figures 11 and 13 it is obvious that the climatic curves have the same trend as well over the calibration period (1941-1974) as over the total period, this being an argument for the reliability of the reconstructions.

It is important to stress that the stability of the regression and the subsequent reliability of the reconstruction are due to the use of a spectral multiple regression which makes possible a distinction between frequency bands. Similar reconstructions performed with regression after extracting principal components were not stable over the extrapolation period, though the skills were high over the calibration period. The spectral method has its main efficiency in extrapolation rather than in calibration (Guiot 1981b).

CONCLUSIONS

This method as a whole has made possible more reliable climatic reconstructions than could be obtained with previous methods. Different comparisons have shown that it was better to remove from the master chronology cores that are too short or too individual: the signal-to-noise ration is increased when the master chronology is computed from only a few coherent cores. The field experience of the scientist who selects the most appropriate cores is as useful as adequate statistical laws. Concerning the detrending, it is not possible to give a general rule, but different detrendings must be made and the optimum one must be selected in relation with the climatic parameters.

Response function is a very complex problem. A suitable analysis must be based on different considerations and the introduction of non-linear parameters. Multiple spectral regression can do that. Fritts' method is a first, very useful step which has opened a wide range of possible and necessary improvements, particularly in countries

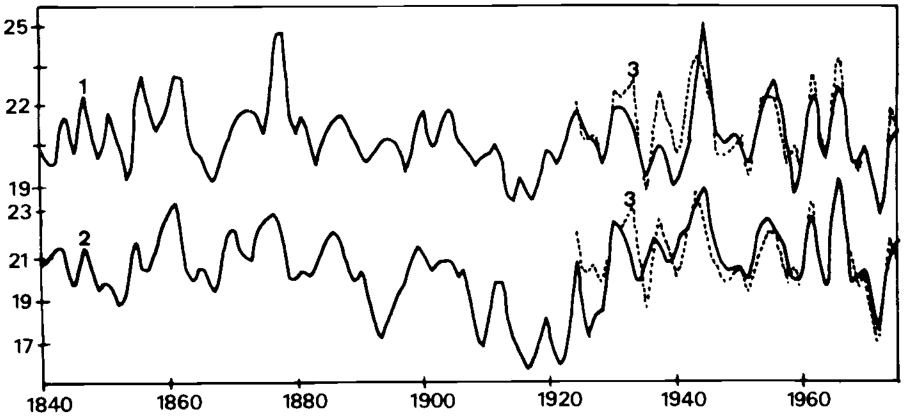


Figure 13. Temperature of May in Marrakech (Morocco) (1) Reconstruction from 7 sites calibrated over 1934-1975; (2) Reconstruction from 7 sites calibrated over 1924-1933/1944-1975; and (3) corresponding observed series for Marrakech.

where climate is not as strong a limiting factor as it is in North America.

The transfer functions are also improved with spectral methods. Several stable reconstructions from 1840 up to now have been made possible: temperature of February, May and June in Tetouan and of May in Marrakech. Different ways to verify them exist and demonstration of their reliability has been made.

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