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Reconstruction of Precipitation in Morocco Since 1100 A.D. Based on *Cedrus atlantica* Tree-Ring Widths

CLAUDINE TILL* AND JOËL GUIOT†

**Université Catholique de Louvain, Laboratoire de Palynologie et de Dendrochronologie, Place Croix-du-Sud 4, B-1348 Louvain-la-Neuve, Belgium; and †Université d'Aix-Marseille III, Laboratoire de Botanique historique et Palynologie, CNRS UA 1152, Rue Henri Poincaré, F-13397 Marseille Cedex 13, France*

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Annual (October through September) precipitation from 1100 A.D. to modern times is reconstructed for Morocco, using *Cedrus atlantica* (Endl.) Carrière tree-ring chronologies. Both multiple regression on principal components and the bootstrap method are use to calibrate tree-ring width with precipitation; precipitation variation is reconstructed for three climatically distinct areas: the humid, subhumid, and arid regions of Morocco. A series of successive wet and dry periods is identified for the past 1000 years; the maximum length of the 13 dry periods (during which precipitation was at least 1σ below normal) is 6 years. Twenty-one years are identified during which precipitation fell more than 2σ below normal. We are unable to identify significant correspondence in climatic variation in Morocco, Europe, and the Sahel during this time period. © 1990 University of Washington.

INTRODUCTION

Morocco occupies a distinctive position in the Mediterranean basin, lying between 28° and 36° N latitude, 2° and 12° W longitude. Morocco is limited to the north by the Alboran Sea, to the west by the Atlantic Ocean, and to the east and south by Algeria and the Sahara desert. This situation determines the climate of the country which is also influenced by the topography at a more regional scale. The country falls under Oceanic, Mediterranean, and Saharan influences. The hot and dry summers are dependent on the seasonal shift of the subtropical high-pressure belt, while winter rainfall is determined by the southward displacement of the northwesterly cyclonal activity. Two gradients characterize the climate of Morocco: a north–south gradient and a west–east gradient; along them precipitation decreases and temperature increases.

The Moroccan mountains include, from north to south, the Rif, the Middle Atlas, the High Atlas, and the Anti Atlas. The Rif is oriented E–W, the Atlas NE–SW. Their maximum elevations are 2450 and 4200 m, respectively.

The distribution of cedar forests (*Cedrus atlantica* (Endl.) Carrière) in Morocco is strongly linked to climate (Munaut *et al.*, 1978; Berger *et al.*, 1979; Munaut, 1982; Till, 1985). The cedar forests are located in the Rif, the Middle Atlas, and the Eastern High Atlas between 1300 and 2600 m but the upper and lower limits of the forest vary with the local climatic conditions and with the latitude (Emberger, 1971; Peyre, 1979; Achhal *et al.*, 1980; M'Hirit, 1982; Benabid, 1982). In the schematic altitudinal arrangement of species and vegetation used for the Mediterranean region (Quézel and Barbero, 1982), *C. atlantica* is mainly observed in Morocco at the Mountain-Mediterranean and Oro-Mediterranean levels but it may also be observed at the Upper-Mediterranean and Supra-Mediterranean levels (Benabid, 1982). Its optimum corresponds to the Mountain-Mediterranean level (Achhal *et al.*, 1980; M'Hirit, 1982).

In Emberger's bioclimatic system (Em-

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berger, 1971; Daget, 1977; Daget and David, 1982), *C. atlantica* is observed in the upper semiarid zone to the hyperhumid zone, cold to extremely cold variants. It has its optimum in the subhumid and humid zones, very cold variant (Quézel, 1979; Achhal *et al.*, 1980; M'Hirit, 1982).

The limitation of the extent of cedar forests by climate and the existence of numerous old cedar forests in various environments justified a thorough dendrochronological study of these forests in order to reconstruct climatic events in Morocco for the last thousand years (Munaut, 1982). Such information about precipitation is very useful, because the country is often affected by droughts and long climatic records necessary to evaluate drought frequency are very scarce. This paper presents the spatial and temporal variations of precipitation in Morocco reconstructed from tree-ring chronologies of *C. atlantica* since the beginning of the 12th century.

TREE-RING DATA

Forty-six sites were sampled throughout the whole natural area of the Moroccan cedar forest in order to compute transfer functions (Fig. 1). Site selection and sampling were carried out by Professors A. V. Munaut (Université Catholique de Louvain, Louvain-la-Neuve) and L. Mathieu (Faculté des Sciences Agronomiques de l'Etat de Gembloux) in October of the years 1974 to 1979. At each site, two cores were obtained from each of approximately 20 trees. The ring-widths were measured to the nearest hundredth of a millimeter and the ring-width series was cross-dated. Standardized ring-width indices have been computed using a negative exponential function or a polynomial function (Fritts, 1976). Site chronologies which summarize the common growth variation for each site have then been computed (Till, 1985). The chronologies cover the period 1016–1979 A.D. However, only the period 1100–1979, for which there are at least three site chronologies, has been considered for the paleoclimatic reconstructions. The full description of the cedar forests studied, as well as the methods used to analyze the material and to compute the mean chronologies, is given by Till (1985, 1987a).

The climatic sensitivity of the chronologies varies as a function of the climatic gradients existing in Morocco, the altitude, and the substrate. The less-sensitive sites (mean sensitivity ≤ 0.15) are located in the humid regions of the Rif and along the western edge of the Middle Atlas while the most sensitive sites (mean sensitivity ≥ 0.30) are located in the high continental regions of the Eastern Middle Atlas and the High Atlas. Climatic sensitivity is relatively low on humid dolomitic or basaltic substrates as compared to dry substrates of limestone, marl, and/or shale. There is no obvious relation between the mean sensitivity and aspect or between the mean sensitivity and slope. There are, of course, local variations in the relation between mean sensitivity and ecological factors (Till, 1985, 1987b).

Response function analysis (Fritts, 1976) shows that autumn and winter precipitation play a leading role in *Cedrus* ring-width growth. Above-normal precipitation has a positive effect on ring-width. Temperature has a more complex effect. It has a positive effect in January and in August and a negative effect at the beginning (April) and the end (September) of the growth season. The summary response function of *C. atlantica* has been discussed by Till (1985, 1987b).

CLIMATIC DATA

Climatic data have been furnished by Métérologie nationale marocaine, Métérologie nationale of Paris, Université d'Aix-Marseille, Archives du Royaume in Brussels, and the Climatic Research Unit of Norwich. These data have been tested and studied by Guiot (1981) and De Corte (1981).

The monthly precipitation records of the 41 weather stations available for the coun-

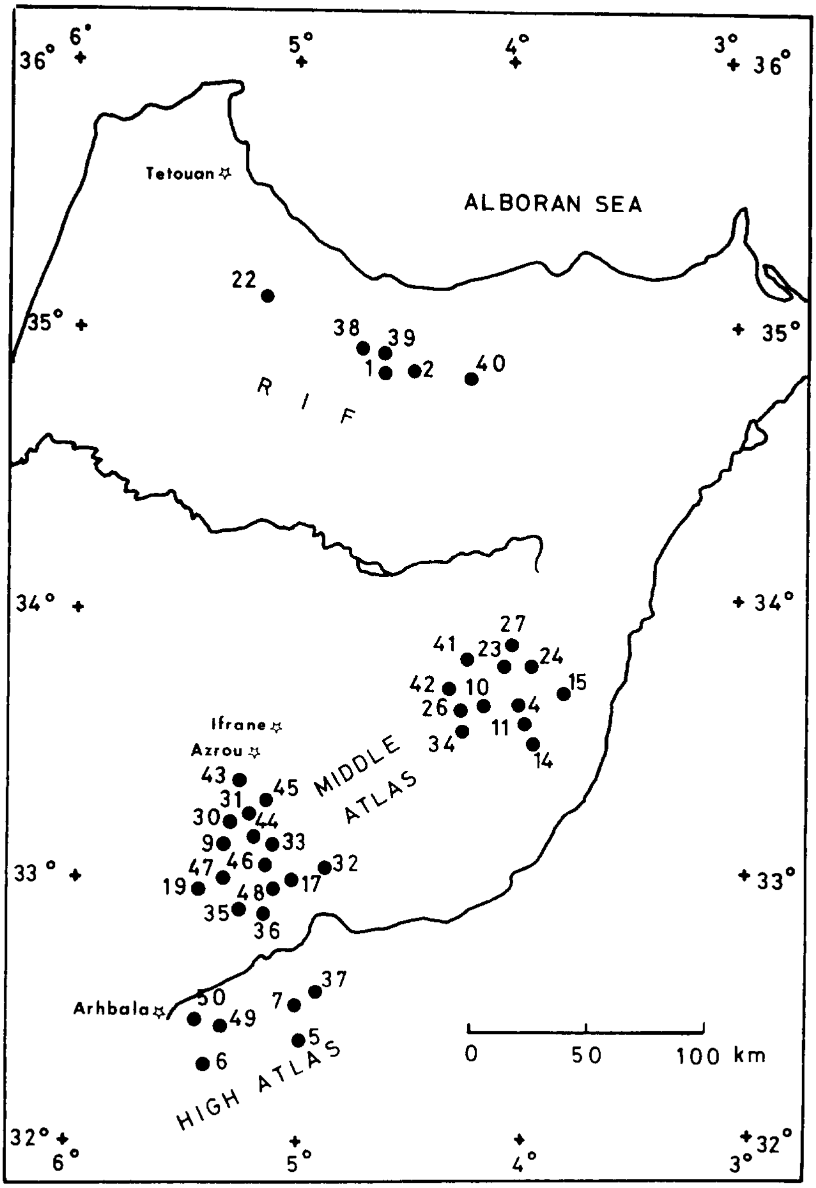

FIG. 1. Morocco, *Cedrus atlantica*. Localization of the stations studied: 1, Tetla de Ketama; 2, Jbel Tidighin (two stations); 4, Agdir Amellal; 5, Afraskou; 6, Hayim Tirhist; 7, Mitkane; 9, Ouiouane; 10, Taffert (two stations); 11, Bouzemmour; 14, Tizi Aït Ali; 15, Gueb er Rehal; 17, Col de Zad (two stations); 19, Aguelman Azigza; 22, Jbel Lakrâa; 23, Tamtroucht; 24, Tankararant (two stations); 26, Tizi Aïni; 27, Adrar bou Mellal; 30, Sidi m'Guid; 31, Aïn Kahla; 32, Tizi n'Tarzeft; 33, Jbel Hayan; 34, Immouzer des Marmoucha (two stations); 35, Talaharine; 36, Jbel Tanourdi; 37, Jaffar (two stations); 38, Ghomara (two stations); 39, Jbel Dahdo; 40, Tizi Ifri; 41, Ich Ramuz; 42, Jbel Serhla; 43, Es Sheb; 44, Ladmer Izem; 45, Izdi Ouareg; 46, Bekrit; 47, Jbel Irhoud; 48, Louta Zad Tafessene; 49, Bou Izane; 50, Amalou'n Moukchab.

try (Fig. 2) have been considered for the years 1924 to 1977. The months have been grouped into seasons and finally the total amount of precipitation has been computed over the biological year defined as October of the previous growth year to September of the current year of growth. The annual amount of precipitation (P) records the pre-

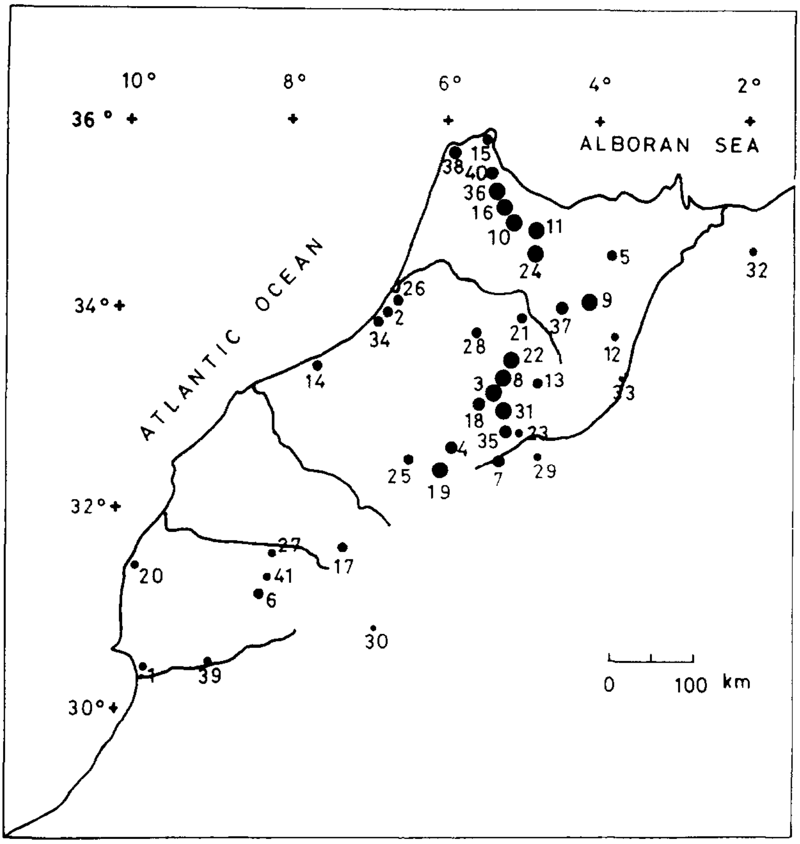

FIG. 2. Morocco, climatic regions according to precipitation (see Table 1 for numerical values): ●, Humid region; ●, subhumid region; ●, semiarid region; •, arid region; ·, hyperarid region.

cipitation of autumn, winter, and spring, as there is no significant precipitation in Morocco in summer.

Climatic regions have been defined (Fig. 2 and Table 1) by averaging values of observed precipitation series for each station as follows:

humid region: P $\geq$ 800 mm/year
subhumid region: 600 $\leq$ P $<$ 800 mm/year
semiarid region: 400 $\leq$ P $<$ 600 mm/year
arid region: 200 $\leq$ P $<$ 400 mm/year
hyperarid region: P $\leq$ 200 mm/year.

STATISTICAL METHOD

Transfer functions estimate values of a predictant (y) when contemporary values of a set of m predictors (x_j) is known. Among the N observations available for the m predictors, we assume that n are common with the predictant. If we have $p > 1$ predictants, the same procedure is repeated p times. The number of observations n can be decomposed into $n = nc + nv$, where nc is the number of observations used for calibration and nv is the number of observations used for an independent verification. Variables are standardized, i.e., replaced by the deviations from the means x_j divided by the standard deviations s_j.

The basic model used to compute a transfer function is the multiple regression

$$y = XB + E \tag{1}$$

where $B = (X'X)^{-1}X'y$ is estimated on the nc observations of the calibration interval. This equation states that the climate is linearly related to the variations of tree-ring width by coefficients b_j, which are an esti-

TABLE 1. MOROCCO, DESCRIPTION OF THE CLIMATIC REGIONS ACCORDING TO ANNUAL PRECIPITATION (P)

Climatic region	Weather station		Precipitation (mm)
	Name	Number	
Humid			
$P \geq 800$ mm/year	Aïn Leuh	3	872
	Azrou	8	838
	Bab bou Idir	9	1416
	Bab Taza	10	1406
	Beni Aros	11	994
	Chaouen	16	1006
	El Ksiba	19	910
	Ifrane	22	1108
	Jbel Outka	24	1748
	Ouiouane	31	1118
	Souk el Arba des Beni Hassan	36	866
Subhumid			
$600 \leq P < 800$ mm/year	Aït Ischak	4	732
	Arhbala	7	615
	El Hamman	18	728
	Sénoual	35	755
	Tahala	37	615
	Tanger	38	738
	Tétouan	40	754
Semiarid			
$400 \leq P < 600$ mm/year	Aïn el Joh	2	495
	Aknoul	5	492
	Amizmiz	6	485
	Boulemane	13	562
	Casablanca	14	423
	Ceuta	15	567
	Demnate	17	555
	Fès	21	552
	Kasba	25	577
	Kenitra	26	536
	Meknès	28	593
	Rabat	34	529
Arid			
$200 \leq P < 400$ mm/year	Agadir	1	230
	Berkine	12	318
	Essaouira	20	274
	Itzer	23	367
	Marrakech	27	259
	Midelt	29	250
	Oujda	32	341
	Taroudannt	39	221
	Zaïoua	41	275
Hyperarid			
$P < 200$ mm/year	Ouarzazate	30	126
	Outat	33	155

mate of the population coefficients. The hypotheses required for the application of such a model are discussed by Fritts (1976).

Correlations among predictor variables can degrade the estimates of the B coefficients and create a problem for the inversion of the matrix $X'X$ in (Eq. 1). We transformed the predictor variables to uncorrelated but equivalent variables, i.e., principal components (PC) or empirical orthogonal functions. The PC are based on the eigenvectors A of the predictors correlation matrix $X'X/n$. We have

$$1/n\ X'X\ A = A\ L \tag{2}$$

where L is the diagonal matrix of the eigenvalues. According to the orthogonality properties of A, we have

$$(X'X)^{-1} = A\ L^{-1}\ A'/n. \tag{3}$$

The correlation between the predictors implies that the last eigenvalues are close to zero within the limits of computational accuracy. Thus L^{-1} has some very large elements. A way to avoid this problem is to use only q ($q < m$) columns of A and a submatrix (q,q) of L determined by the PVP criterion (Guiot, 1981, 1985).

In this problem, the reconstruction of precipitation for the five climatic regions is based on the common period 1924–1977 ($n = 54$) and the extrapolation is made back to 1100 A.D. ($N = 878$). The PVP criterion on the total period leads to keep 23 PC among the 46 tree-ring predictors.

VERIFICATION OF THE RECONSTRUCTION

The reliability of the reconstructions is tested in the following way. Because the climatic series are relatively short, we tested models on overlapping periods. First, the calibration (model I) is done on the most ancient data (1924–1960) and the independent verification is done on the remaining data (1961–1977). Second, the calibration (model II) is done on the period 1941–1977 and the independent verification is done on the period 1924–1940. Last, if the results are relevant, the final reconstruction is based on the total period 1924–1977 (model III). Different statistics were used to evaluate the correspondence between observed and estimated values (Table 2).

Each reconstruction is tested using the correlation R_j ($j = 1, \ldots, p$) between the estimated and the actual values of precipitation but also according to the agreement between estimated ($\hat{\bar{y}}_j$) and actual ($\bar{y}_j$) means and the agreement between estimated ($\hat{S}y_j$) and actual (Sy_j) standard deviations.

TABLE 2. MOROCCO, VERIFICATION STATISTICS OF THE CLIMATIC RECONSTRUCTIONS FOR PRECIPITATION OBTAINED BY MULTIPLE REGRESSION ON PRINCIPAL COMPONENTS

	Calibration period		Verification period	
	Model I	Model II	Model I	Model II
R_1	0.89	0.93	0.72	0.60
R_2	0.88	0.93	0.82	0.66
R_3	0.88	0.90	0.73	0.59
R_4	0.90	0.90	0.66	0.67
R_5	0.80	0.88	0.33	0.80
$\overline{R}$	0.87	0.91	0.65	0.66
RE_1	0.79	0.87	0.38	0.35
RE_2	0.78	0.87	0.59	0.39
RE_3	0.78	0.81	0.37	0.31
RE_4	0.81	0.80	0.23	−0.10
RE_5	0.65	0.77	−0.06	0.64
$\overline{RE}$	0.76	0.82	0.30	0.32
DM	0.0	0.0	−52.1	−20.2
DSD	−6.4	−2.6	−8.6	−51.1

Note. Model I: calibration from 1924 to 1960; verification from 1961 to 1977. Model II: calibration from 1941 to 1977; verification from 1924 to 1940. R_i: correlation coefficient between actual and estimated values of precipitation for region i (i = 1 to 5; 1, humid; 2, subhumid; 3, semiarid; 4, arid; 5, hyperarid). $\overline{R}$: mean correlation. RE_i: reduction of error for the five regions. $\overline{RE}$: mean value of RE_i. DM: mean sum of squares of the difference between actual and reconstructed means. DSD: mean sum of squares of the difference between actual and reconstructed standard deviations.

A classical statistic in dendroclimatology is the reduction of error RE introduced by Lorenz (1956). It measures the ability of the regression model to produce estimates better than the calibration period average. If we assume that the estimated and the actual values are expressed as a function of deviations around the mean calculated on the calibration period, the equation used to calculate RE for each predictant j can be expressed as

$$RE_j = 1.0 - \left(\sum_{i=1}^{nv} (y_{ij} - \hat{y}_{ij})^2 / \sum_{i=1}^{nv} y_{ij}^2 \right), \tag{4}$$

where nv is the number of observations of the verification interval. If the reconstruction produces errors just equivalent to those given by the calibration mean, RE_j =

0, so that the value of zero is often retained as a reliability level. A clearly positive value of RE indicates that the regression model may be accepted. More details are given in Lorenz (1977) and in Kutzbach and Guetter (1980).

The reconstructions are tested separately for each predictant (Table 2). The verification leads us to accept the reconstruction of annual precipitation for the humid, subhumid, and semiarid areas; the reconstructed series are represented by smooth curves in Fig. 3. For the arid and hyperarid regions, the reconstructions are not reliable. This was expected since these regions are not covered by the cedar forest.

In Table 2, the individual correlation R_j and the reduction of error RE_j are averaged over the p predictants ($p = 5$),

$$\overline{R} = \sum_{j=1}^{p} R_j/p \quad \text{and} \quad \overline{RE} = \sum_{j=1}^{p} RE_j/p. \tag{5}$$

Table 2 indicates acceptable values for $\overline{R}$ and $\overline{RE}$. For the calibration intervals, RE is equal to R^2, as indicated by Eq. 4. For the verification intervals, RE is always less than R^2 and always larger than zero. The difference is due to underestimating the means and standard deviations.

The final reconstructions (Fig. 3) are calculated on the total period (1924–1977). The mean correlation $\overline{R}$ between estimated and actual values is 0.87. The mean value for RE is 0.76.

The ability of the reconstruction to reproduce the mean (or the trend for longer series) is tested by DM, the mean sum of squares of the difference between actual and reconstructed means, related to SV, the sum of the variances of the p predictants calculated on the calibration interval

$$DM = \sum_{j=1}^{p} (\bar{y}_j - \hat{\bar{y}})^2/SV, \tag{6}$$

where

$$SV = \sum_{j=1}^{p} S^2y_j. \tag{7}$$

DM is evidently zero over the calibration interval (Table 2) but not over the verification interval, for which an excessively large value reflects a problem of stationarity. The reconstructed mean is underestimated by 20% for the period 1924–1940 and by 50% for the period 1961–1977 (Table 2).

The variance of the series is often underestimated, because of an underfitting of the transfer function. The ability of the reconstruction to reproduce the standard deviation is tested by DSD, the mean sum of squares of the difference between actual and reconstructed standard deviations, related to SV:

$$DSD = \sum_{j=1}^{p} (Sy_j - \hat{S}y_j)^2/SV. \tag{8}$$

In Table 2, the standard deviations are generally well reconstructed except over the verification interval 1924–1940 (underestimate of 51%).

As the period of the available climatic data is short, another method was used which integrates verification and calibration in the same run.

THE BOOTSTRAP METHOD

Bootstrapping is a recent technique (Efron, 1979) for estimating statistics for unknown population distributions by Monte Carlo simulations. The idea is to resample the original observations in a suitable way so as to construct pseudo-data sets on which the estimates are made. In the regression case, it is useful when the residuals are non-normal or autocorrelated or when the data set is small.

From the interval 1924 to 1977, 1 year is randomly drawn, the corresponding vectors of predictors and predictants being

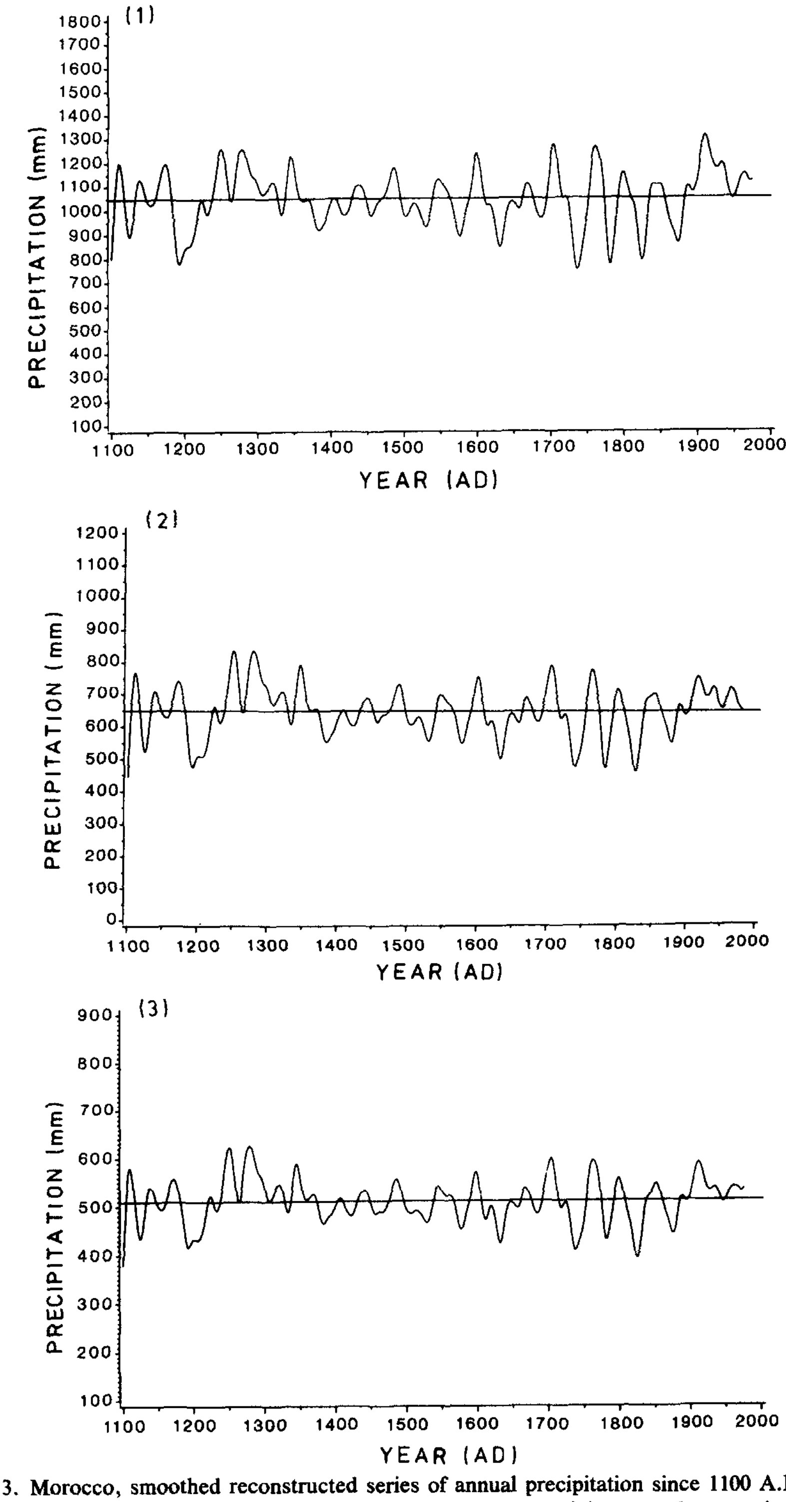

FIG. 3. Morocco, smoothed reconstructed series of annual precipitation since 1100 A.D. for the humid (1), subhumid (2), and semiarid (3) regions, obtained by multiple regression on principal components. Mean values and standard deviation of precipitation are 1047 and 214 mm for the humid region, 649 and 145 mm for the subhumid region, 509 and 86 for the semiarid region.

stacked to a new data matrix. Afterward, another year is randomly drawn and the corresponding data vector is stacked to the same matrix. The same year may be drawn several times. This process is repeated 54 times (i.e., the number of years available) and the matrix so built is called a pseudo-data set. A regression is computed on this pseudo-data set and a reconstruction of the p predictants is obtained back to 1100 A.D. Another pseudo-data set is built in the same way providing another reconstruction back to 1100 A.D. The entire process is repeated an arbitrary number of 50 times (this number has been tested by Guist (in Fritts *et al.*, 1989)).

Fifty sets of regression coefficients and 50 reconstructions are calculated. The means and variances of the 50 pseudo-data sets are different than those of the original data.

The fifty reconstructions of the predictants are summarized in a median series comprised between a lower-limit series (5th percentile) and an upper-limit series (95th percentile) (Fig. 4). This confidence interval gives an idea of the effective confidence we may have in the results. Similar confidence intervals are also computed on the regression coefficients.

For each pseudo-data set, an independent verification is done on the observations which are not included in it. In essence, the goodness of fit is computed in these following steps:

(1) the reconstruction is compared to the actual climatic series both on the retained observation set and on the independent set; verification statistics are so calculated 50 times;

(2) the mean and standard deviations of the verification statistics are obtained dependently on the calibration and independently on the observations not included in the calibration; and

(3) the final reconstruction is the median of the 50 replicated reconstructions and a 90% confidence interval is given by the 5th and 95th percentiles.

The method is applied to the three best reconstructed series obtained by the standard regression: humid, subhumid, and semiarid regions. Twenty-three PC are selected to represent the 46 tree-ring series (PVP criterion). The observations are randomly drawn from the 54 observations of the 1924–1977 A.D. period. Table 3 shows that the means and standard deviations are only weakly underestimated. It proves that the underestimates found in Table 2 are mainly due to the large difference between the calibration and the verification periods; when the two sets are well mixed, like with the bootstrap method, better results are obtained. The standard deviations of R are small even for the verification data. The verification correlations are thus significant. The loss of precision on the verification data compared to the calibration data appears in a lower R and mainly in a higher standard deviation.

The reconstructions themselves are represented by smooth curves in Fig. 4 which shows a good correlation with Fig. 3. The 90% confidence intervals are useful to assess whether the variations are significant.

The bootstrap method is not, by itself, an improvement of the calibration methods, but rather an improvement of our ability to interpret the verification statistics. This verification may be done without making assumptions regarding the distribution of the residuals and without eliminating data. Indeed, the data which are lost in one given pseudo-data set (and kept for the independent verification) are recovered in the other ones. This advantage is particularly important when climatic series are short, as in the present study. Another advantage is that the reliability of the reconstructions can be assessed by confidence intervals.

VARIATION OF PRECIPITATION IN MOROCCO SINCE 1100 A.D.

According to Fairbridge (1976) and Nicholson (1980) the present-day arid climate of the tropical and temperate margins of the Sahara, the Sahara itself, and North Africa and East Africa began around 5000–

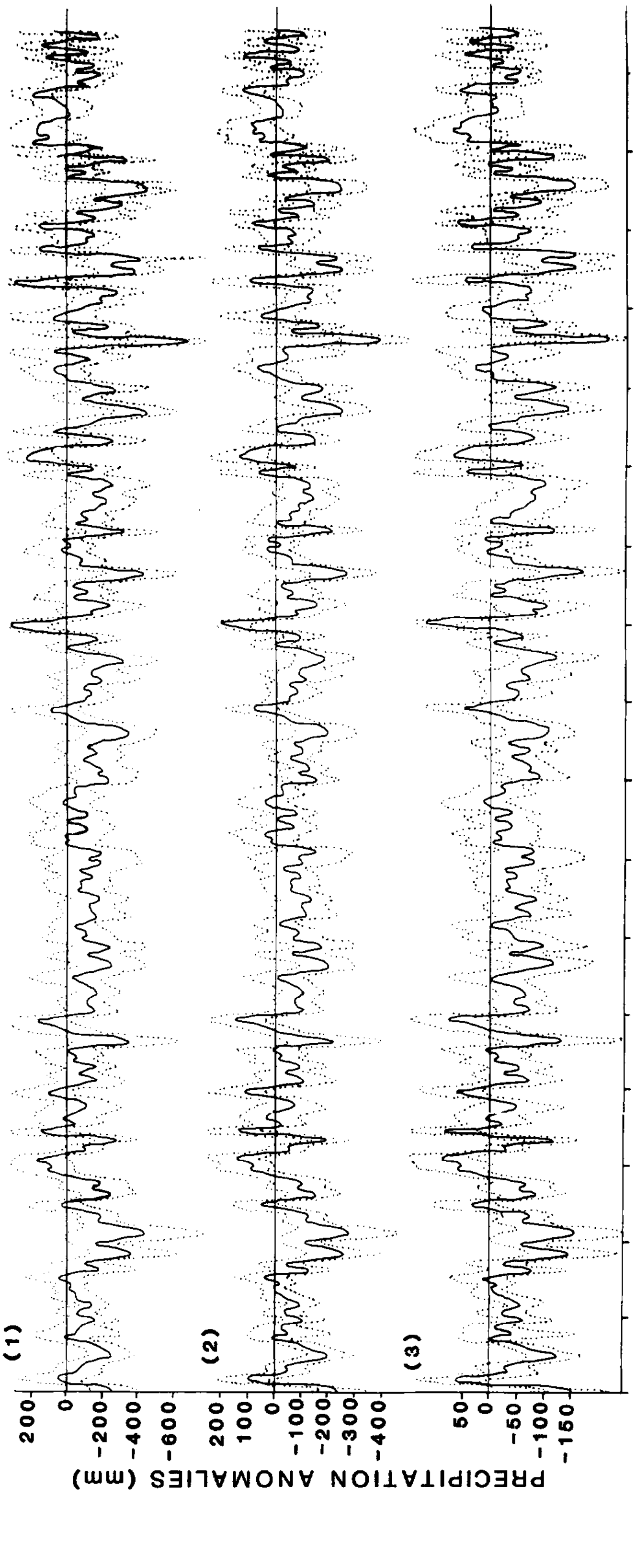

FIG. 4. Morocco, smoothed reconstructed series of annual precipitation since 1100 A.D. for the humid (1), subhumid (2), and semiarid (3) regions, obtained by the bootstrap method. Precipitation values are expressed as deviation from the calibration period mean in millimeters (1120 mm for the humid region, 689 mm for the subhumid region, 524 mm for the semiarid region).

TABLE 3. MOROCCO, VERIFICATION STATISTICS OF THE CLIMATIC RECONSTRUCTIONS FOR PRECIPITATION OBTAINED BY THE BOOTSTRAP METHOD

	Calibration period	Verification period
DM %	0.00	2.00
DSD %	−16.00	−15.00
R ± standard deviation		
humid	0.88 ± 0.03	0.67 ± 0.12
subhumid	0.88 ± 0.03	0.69 ± 0.10
semiarid	0.85 ± 0.04	0.62 ± 0.14

4000 yr B.P. During Neolithic time, 6000–5000 years ago, the climates of these regions were considerably wetter than at present. During the past two millennia, which were relatively stable climatically, several episodes of alternately wetter and drier character occurred. This climatic variation is well confirmed in this study. Successive wet and dry periods occurred in Morocco during the last thousand years (Figs. 3 and 4).[1]

A high correlation exists between the reconstructed series of precipitation for the three regions: the correlation coefficients between the three series range between 0.96 and 0.97 and are significant at the 0.0001 significance level. This phenomenon was expected as the observed series are also well correlated: the correlation coefficients between the three series are equal to 0.94 (same significance level). The reconstructions thus reproduce accurately the slight differences existing between the three climatic regions. This is corroborated by the quite similar regression coefficients of the 23 principal components (Table 4).

The following dry periods are recognized: 1186–1234, 1379–1428, 1455–1481, 1499–1542, 1572–1596, 1607–1663, 1680–1694, 1714–1759, 1779–1798, 1805–1835, 1858–1887, 1895–1899, and 1903–1905.

Figure 5 shows the frequency of years with precipitation below and above normal

[1] The reconstructed values of precipitation for Morocco are available to interested parties by writing to the authors.

TABLE 4. MOROCCO, STANDARDIZED REGRESSION COEFFICIENTS OF THE 23 PRINCIPAL COMPONENTS USED FOR THE RECONSTRUCTION OF ANNUAL PRECIPITATION FOR THE HUMID, SUBHUMID, AND SEMIARID REGIONS

CP No.	Humid region	Subhumid region	Semiarid region
CP 1	−0.22	−0.24	−0.23
	(0.10)	(0.09)	(0.10)
CP 2	−0.15	−0.19	−0.19
	(0.06)	(0.06)	(0.06)
CP 3	−0.29	−0.30	−0.32
	(0.07)	(0.06)	(0.08)
CP 4	−0.20	−0.12	−0.12
	(0.08)	(0.07)	(0.08)
CP 5	0.34	0.30	0.31
	(0.07)	(0.07)	(0.07)
CP 6	−0.13	−0.17	−0.17
	(0.09)	(0.09)	(0.10)
CP 7	−0.07	−0.07	−0.01
	(0.08)	(0.07)	(0.07)
CP 8	0.11	0.02	0.06
	(0.08)	(0.08)	(0.08)
CP 9	−0.07	−0.05	−0.08
	(0.07)	(0.06)	(0.07)
CP10	0.04	0.04	0.06
	(0.08)	(0.08)	(0.07)
CP11	−0.10	−0.07	−0.05
	(0.09)	(0.09)	(0.10)
CP12	0.09	0.11	0.10
	(0.08)	(0.08)	(0.09)
CP13	0.09	0.11	0.06
	(0.09)	(0.08)	(0.09)
CP14	−0.06	−0.02	−0.05
	(0.09)	(0.08)	(0.09)
CP15	0.09	0.10	0.09
	(0.07)	(0.07)	(0.08)
CP16	0.15	0.14	0.18
	(0.08)	(0.08)	(0.08)
CP17	0.06	0.09	0.05
	(0.11)	(0.11)	(0.11)
CP18	−0.10	−0.08	−0.13
	(0.11)	(0.11)	(0.10)
CP19	0.04	−0.03	0.00
	(0.07)	(0.07)	(0.07)
CP20	0.24	0.26	0.18
	(0.08)	(0.07)	(0.09)
CP21	0.01	0.02	−0.05
	(0.10)	(0.10)	(0.09)
CP22	−0.19	−0.20	−0.16
	(0.08)	(0.09)	(0.08)
CP23	−0.09	−0.06	−0.05
	(0.10)	(0.10)	(0.10)

The values in parentheses are standard deviations.

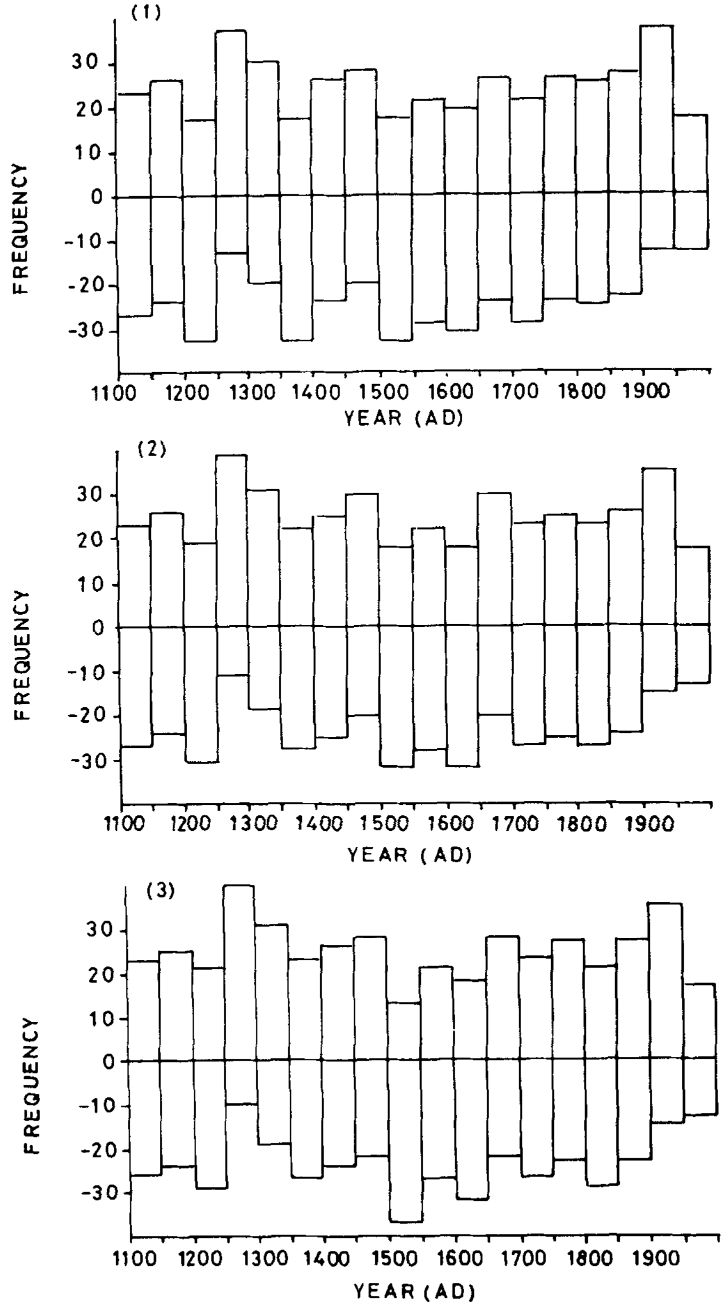

FIG. 5. Morocco, frequency (n) of years characterized by precipitation below and above normal per half century for the humid (1), subhumid (2), and semiarid (3) regions. The frequency of years with below-normal precipitation are drawn below the x-axis as negative numbers. The frequency of years with above-normal precipitation are drawn above the x-axis as positive integers.

by half century for the three regions. It indicates clearly that during the Little Ice Age (16th, 17th, and 18th centuries) of northern Europe, the average climate of Morocco was drier than at present. Average reconstructed precipitation between 1500 and 1650 was 1014, 622, and 493 mm for the humid, the subhumid, and the semiarid regions, respectively. This result is not in agreement with Nicholson (1980). For arid Africa, she concluded that during the Little Ice Age the climates of the margins of the Sahara and possibly also North Africa were wetter than today, with the 18th century being characterized by several droughts and famines.

There are on average 48 years per century for which precipitation is below normal and 12 years per century for which precipitation is below normal minus one standard deviation. Except for a dry interval of 7 years between 1121 and 1127 in the subhumid and the semiarid regions, the maximum length of a dry period (for which precipitation is below normal minus one standard deviation) is 6 years for the three considered regions.

Defining severe drought years as years in which precipitation falls below normal minus two standard deviations, the following years are recognized as severe drought years for the three regions: 1189, 1190, 1613, 1631, 1635, 1661, 1734, 1738, 1739, 1779, 1781, 1782, 1783, 1824, 1825, 1828, 1834, 1874, 1878, 1882, and 1905.

Very wet years characterized by precipitation above normal plus two standard deviations are, for the three regions, 1108, 1255, 1272, 1602, 1705, and 1711.

Variations of precipitation in Morocco have been compared to climatic variations in Europe and the Sahel (Lamb, 1972; Maley, 1981; Nicholson, 1980, 1983; Table 5). It appears that long-term trends and single-year extreme events in European temperature history are not uniformly correlated with the Moroccan precipitation variation. The very cold European winters of 1143, 1150, 1173, 1253, 1276, 1323, 1326, 1354, 1361, 1364, and 1408 reconstructed by Alexandre (1987) correspond to wet years in Morocco for all three regions under study. The European cold winters of 1126, 1210, 1219, 1234, 1303, 1317, and 1339 coincide with dry winters in Morocco. Among the five very mild winters also reported by Alexandre (1987) for the Middle Ages in Europe, three of them (1279, 1357, and 1362) were wet in Morocco and two were dry (1304 and 1332).

Drought in the Sahel is not correlated with drought for the regions studied in Mo-

TABLE 5. REGIONAL COMPARISON OF CLIMATIC VARIATION BETWEEN EUROPE, MOROCCO, AND SAHEL

Century	Sahel	Morocco	Europe
12th		Drought 1186–1234	Little
13th			Optimum
14th		Drought 1379–1428	
15th		Drought 1455–1481	
		Drought 1499–1542	
16th	Rainfall 1550–1680	Drought 1572–1596	L I
17th		Drought 1607–1663	I C
	Drought 1681–1687	Drought 1680–1694	T E
18th	Algerian drought	Drought 1714–1759	T
	1710–1720		L A
	Drought 1730–1760		E G
	Rainfall 1780–1800	Drought 1779–1798	E
19th	Maximum drought	Drought 1805–1835	
	1828–1839		
	Rainfall 1870–1900	Drought 1858–1887	
		Short drought	
		1895–1899	
20th	Drought 1910–1920	Short drought	
		1903–1905	
	Rainfall 1920–1960		
	Drought since 1968		

rocco. Similarly, observed data are not correlated between the two regions. The extreme drought affecting the Sahel since 1968 was characterized in Morocco by 1968, 1969, 1970, and 1971 having precipitation above normal, 1968 having moderate rainfall, 1969 being a humid year, 1970 and 1971 being also moderately wet years, 1972 being a normal year for precipitation, 1973 to 1977 being characterized by rainfall below normal, and 1973 being a moderately dry year. Fairbridge (1976) showed also that during the years 1970–1972 a wet anomaly was centered on Morocco when the Sahelian zone and East Africa were dry. Therefore, it seems that no drought occurred in Morocco from 1968 to 1979 as in the Sahel, except perhaps in the regions close to the desert. The climatic data of the hyperarid region indeed show a drought in 1969 and 1970.

The maximum droughts which occurred in 1913, 1941, and 1975 in the Sahel were also noted by Faure and Gac (1981) but do not correspond to droughts in Morocco. Certainly, the year 1913 was a very dry year in the semiarid region of Morocco, but 1941 was a very wet year in the whole country. Finally, 1975 was a moderately dry year in the humid, subhumid, semiarid, and arid regions; it was a very dry year in the hyperarid region.

The years of maximum wetness in the Sahel were 1925, 1933, 1956, and 1964 according to Faure and Gac (1981), but 1925 was a moderately dry year over all Morocco (there are no data for the subhumid and hyperarid regions); 1933 was a normal year for all regions (no data for the subhumid region); 1956 was also a year of maximum wetness in all regions; and 1964 was a normal year. In fact, the maximum wetness in Morocco occurred 1 year before, in 1963, over all regions.

This interregional comparison between Europe, Morocco, and the Sahel shows no significant correspondence. Three hypotheses may be advanced to explain this lack of correlation:

(1) the sources of paleoclimatic data are too heterogeneous to allow valuable comparisons;

(2) the climatic variables limiting tree growth in the three areas are different and the climatic variables reconstructed by proxy data are therefore different. In Europe, winter and summer temperatures are generally reconstructed because these are the most limiting factors for tree growth. In North Africa, the most important limiting factors are winter and spring precipitation. The Sahelian climate is characterized by summer rainfall. Therefore, paleoclimatic comparisons between these areas are very difficult;

(3) climatic variations are geographically independent; a climatic variation occurring in one area does not necessarily involve a simultaneous variation in another one, especially when the climates of the regions compared are different, as in the case for Europe, Morocco and the Sahel. Futher studies and discussions are needed to clarify these three hypotheses.

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