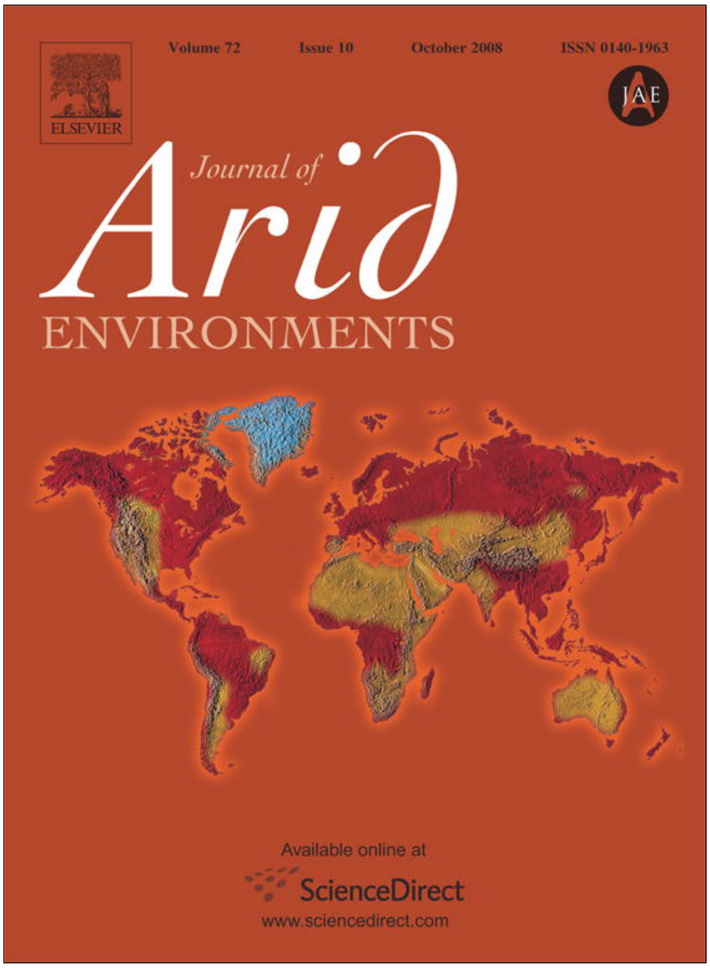
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Precipitation reconstruction for Northwestern Tunisia from tree rings

R. Touchan [a,*], D.M. Meko [a], A. Aloui [b]

[a] Laboratory of Tree-Ring Research, The University of Arizona, P.O. Box 210058, Tucson, AZ 85721-0058, USA
[b] Institute of Sylvo-pastoral of Tabarak, Tabarka, 8110 Tabarka, Tunisia

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ABSTRACT

An October–June precipitation reconstruction was developed from a *Pinus halepensis* regional tree-ring chronology from four sites in northwestern Tunisia for the period of 1771–2002. The reconstruction is based on a reliable and replicable statistical relationship between climate and tree-ring growth and shows climate variability on both interannual and interdecadal time scales. Thresholds (12th and 88th percentiles) based on the empirical cumulative distribution of observed precipitation for the 1902–2002 calibration period were used to delineate dry years and wet years of the long-term reconstruction. The longest reconstructed drought by this classification in the 232-year reconstruction is 2 years, which occurred in the 19th century. Analysis of 500 mb height data for the period 1948–2002 suggests reconstructed extreme dry and wet events can provide information on past atmospheric circulation anomalies over a broad region including the Mediterranean, Europe and eastern Asia.

1. Introduction

Managing water resources requires identifying and characterizing extreme dry and wet periods. High-quality continuous short precipitation time series can be used for this purpose. However, only a limited number of extreme dry and wet events can be identified in a short record, and the information related to probable duration, distribution, and intensity of future extreme events may not be reliable (Meko et al., 1991). Knowledge of local climate variability on time scales of decades to centuries is needed to understand and prepare for dry and wet conditions in the region.

Dendrochronology is a valuable tool for the study of climate variability beyond the short period normally covered by instrumental data (Fritts, 1976). Time series of tree-ring growth measurements spanning several centuries serve as proxy records of past climatic conditions (Cook et al., 1999). Such records provide us with knowledge of the past frequency and severity of climatic anomalies, such as drought and wet periods, and can be used to help anticipate the future probability of such events.

Few dendrochronological studies have been performed in North Africa, with the exception of Morocco. Morocco has a rich history of dendroclimatic research going back nearly 40 years (e.g. Berger et al., 1979; Chbouki et al., 1995; De Corte, 1979; Esper et al., 2007; Glueck and Stockton, 2001; Helleputte, 1976; Meko, 1985; Munaut, 1978; Stockton, 1985; Till, 1987; Till and Guiot, 1990). Dendrochronological studies have also been carried out in Algeria (Messaoudene, 1989; Messaoudene and Tessier, 1997; Safar et al., 1992) and Tunisia (Aloui, 1982; Aloui and Serre-Bachet, 1987; Serre, 1969; Tessier et al., 1994), but previous studies in Tunisia and Algeria were restricted to analysis of the relationship between annual tree-growth and climate. This paper describes the development of regional tree-ring chronology of *Pinus halepensis* from northwestern

* Corresponding author. Tel.: +1 520 621 2992; fax: +1 520 621 8229.
E-mail address: rtouchan@LTRR.arizona.edu (R. Touchan).

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Tunisia, and application of the chronology to develop the first dendroclimatic reconstruction of precipitation in Tunisia. This reconstruction is analyzed to test the hypothesis that the drought history as given by the short instrumental record for Tunisia adequately represents the conditions of the past few centuries. A 230-year reconstruction for northwestern Tunisia is analyzed for time series features of variability relevant to water resources planning. The association of unusually dry years and wet years in Tunisia with large-scale atmospheric circulation anomalies is summarized by analysis of 500 mb height data.

2. Methods and materials

2.1. Study area

Four *P. halepensis* tree-ring sites were sampled in northwestern Tunisia on the "Dorsale" mountain chain (Fig. 1 and Table 1). They are Dahllia (DHA), Saddine (SAD), Jebnoun (JEB), and Oum Djedour (OUD). Elevation of the sampled sites ranges between 383 and 1100 m a.s.l. The soils at the *P. halepensis* sites are generally derived from the calcareous parent materials. Soil thicknesses are variable following the general ground morphology, and the soils exhibit crusted horizons or contain coarse calcareous elements (Mtimt, 2000).

The climate of the study areas is Mediterranean semi-arid. The rainy season in Tunisia is typically December–March, with secondary wet periods in the spring and fall (Nuttonson, 1961). Mean annual precipitation in the study areas ranges

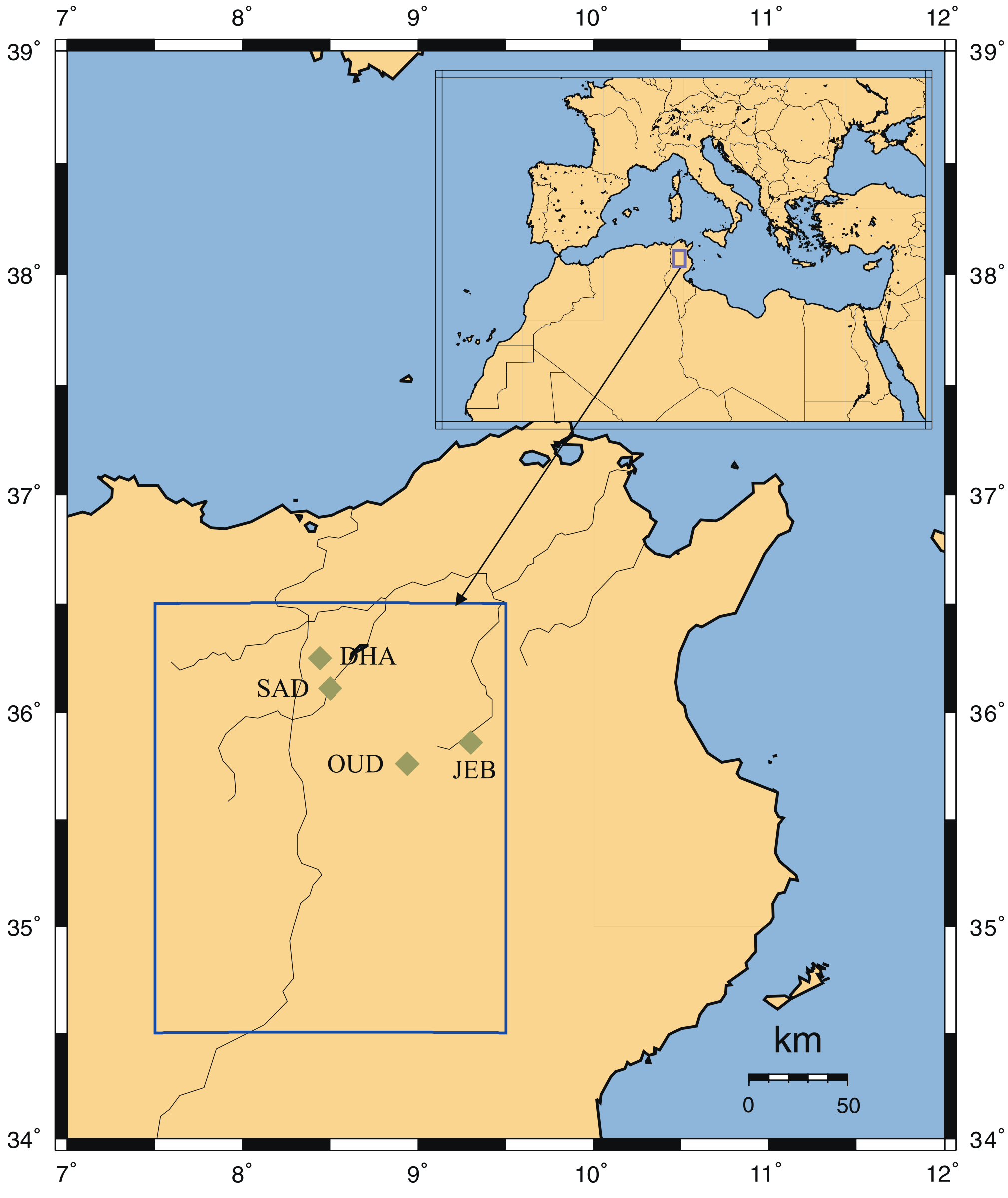

Fig. 1. Locations of tree-ring sites (♦). Solid box represents the range of the gridded precipitation data.

Table 1
Pinus halepensis tree-ring chronology sites, listed from north to south

Site name	Site code	Elevation (m)	Latitude	Longitude	Time span	Total no. of years	No. of trees	No. of cores	Mean correlation among all radii
Dahllia	DHA	919–981	36°14′N	08°26′E	1890–2003	114	11	19	0.52
Sadine	SAD	383–464	36°06′N	08°29′E	1751–2003	253	24	47	0.72
Jebnoun	JEB	792–810	35°51′N	09°18′E	1874–2003	130	13	25	0.60
Oum Djedour	OUD	1000–1100	35°35′N	08°56′E	1865–2004	140	20	38	0.67

from 473 to 509 mm. Areas at 600–1000 m a.s.l. have snowfall every year that typically lasts for about 3 days. Mean annual temperature ranges from 14.2 to 16.3 °C. July is the hottest month with a mean average of 34 °C; January is the coldest month with a mean average of 1.7 °C (Souleres, 1969).

The dominant trees at all sampled sites are *P. halepensis. Juniperus phoenicia* appears at the Saddine site and *Quercus ilex* at Dahllia.

2.2. Tree-ring data

Increment cores were taken from living trees at all sites and full cross-sections were taken from stumps and logs (Table 1). A total of 129 radii (cores or sections) were taken from 68 trees. Samples were fine-sanded and cross-dated using standard dendrochronological techniques (e.g. Stokes and Smiley, 1968; Swetnam, 1985). The width of each annual ring was measured to the nearest 0.01 mm. Of the collected samples, we used in subsequent chronology development only those with more than 90 rings; the reduced data represented 84 cores or cross-sections from 48 trees.

The samples were originally developed into four site chronologies (DHA, SAD, JEB, OUD) with a mean inter-site correlation of $r = 0.55$ ($N = 113$, $P \leqslant 0.0001$). The inter-site similarities demonstrated by visual cross-dating and computer-based quality control using the COFECHA program (Holmes, 1983) confirmed this strong common signal, and justified combining all 84 series of tree-ring width measurements from the four sites as a single regional chronology. Detrending by a 67% cubic smoothing spline with a 50% cutoff frequency removed the non-climatic trends due to tree age, size, and the effects of stand dynamics (Cook and Briffa, 1990). The detrended series were then prewhitened with low-order autoregressive models to remove persistence not related to climatic variations. Combining of individual indices into the regional chronology was done using a bi-weight robust estimate of the mean (Cook, 1985), designed to minimize the influence of outliers.

We used the subsample signal strength (SSS), calculated from data on sample size and between-tree correlation, to assess the adequacy of replication in the early years of the chronology (Wigley et al., 1984). The SSS is a guide to evaluating the likely loss of reconstruction accuracy that occurs when a chronology made up of a few series is used to reconstruct past climate with a transfer function derived from a chronology with a greater number of series (Wigley et al., 1984). We limited our analysis to the period with an SSS of at least 0.85 to ensure the reliability of the reconstructed precipitation. These thresholds correspond to a sample depth of 5 trees (10 series), and allow for reconstruction for the period AD 1771–2002. The 5 trees for the earliest segment are all derived from site SAD (Table 1 and Fig. 1).

2.3. Climate data

Monthly precipitation and temperature records were obtained from the high-resolution 0.5° gridded climate data set CRU TS 2.1 (Mitchell and Jones, 2005). The historical monthly precipitation and temperature data for the region were defined by grid coordinates 7.5–9.5°E and 34.50–36.50°N for the period 1901–2002 (Fig. 1).

2.4. Precipitation reconstruction

The relationships between the tree-ring chronology and monthly and seasonal groupings of gridded temperature and precipitation were investigated with response function analysis (RFA) (Biondi and Waikul, 2004). This technique, developed by Fritts (1976), applies linear regression of tree-ring indices on orthogonal linear combinations of monthly temperature and precipitation for a set of months leading up to the end of the growing season, and performs the necessary matrix algebra to express the regression coefficients in terms of the original monthly climate variables.

A transfer function analysis (TFA) was conducted between the regional tree-ring chronology and the seasonal climate series identified by RFA. The TFA is a regression with a model that has the regional tree-ring chronology as the predictor and the seasonal climatic time series as the predictand. A regression equation of seasonal precipitation on the regional tree-ring chronology for the calibration period 1902–2002 was developed. The validity of this equation as a transfer model for converting tree-ring values to precipitation values was examined using usual regression and correlation statistics, and the PRESS procedure was used for cross-validation (Fritts et al., 1990; Meko, 1997; Touchan et al., 1999, 2003, 2005a, b;

Weisberg, 1985). A split-sample procedure (Meko and Graybill, 1995; Snee, 1997; Touchan et al., 2003, 2005a, b) that divides the full period (AD 1902–2002) into two subsets (1902–1951 and 1952–2002) was also used to verify model stability. The reduction of error statistic (RE) was calculated to test for skill beyond that possible simply by using the calibration period mean of observed precipitation as the reconstruction. An RE value of greater than 0 is considered positive skill (Fritts, 1976).

The calculated transfer function was then applied to the regional chronology to produce the time series of reconstructed October–June total precipitation for as many years as the adequately replicated portion of the chronology allowed.

2.5. Identification of dry and wet years

Dry years and wet years were defined as reconstructed precipitation below or above specified thresholds corresponding to percentiles of the observed precipitation for the base period 1902–2002. Percentiles for the thresholds were selected based on exploratory scatterplots of reconstructed precipitation on observed precipitation, with consideration that the threshold must be severe enough to represent a practically significant departure from average conditions. We adopted severe enough percentile thresholds such that dry and wet years are unusual events. Of course, "practical" significance will depend on the user (e.g., farmer, water resources planner) of the data. Multi-year droughts and wet periods were defined by runs of consecutive years below or above the thresholds. A 5-year moving average of reconstructed precipitation was used as an alternative summary measure of drought severity. An 80% confidence interval for the annual reconstruction was computed as $\pm xE$, where E is the cross-validation root-mean-square error of the reconstruction and x is the 0.1 probability point of the cumulative distribution function of the standard normal distribution. For the 5-year moving-average reconstruction, the confidence interval was computed as $\pm xE$ divided by the square root of 5.

2.6. Large-scale circulation analysis

The atmospheric circulation anomalies responsible for occurrence of unusually wet or dry years were evaluated with 500-mb geopotential height anomalies from the National Centers for Environmental Prediction-National Center for Atmospheric Research Reanalysis Project (Kalnay et al., 1996). Composites of October–June geopotential height anomalies from 1968 to 1996 mean were created for the highest and lowest deciles of observed spring precipitation ($n = 6$) in the period 1948–2007.

3. Results

3.1. Chronology

A regional chronology was built using material from four sites in Tunisia (Table 1 and Fig. 1). The tree-ring series of the four sites show strong similarities in terms of visual cross-dating of the wood and computer-based quality control. Individual trees share a high degree of common variation and so are prime candidates as recorders of climate.

The combined chronology is 254 years long (AD 1751–2004), which is slightly longer than the period deemed suitable for climate interpretation (AD 1771–2002). Average series intercorrelation among all radii is 0.5. The mean sample segment length (MSSL) of the regional chronology is 127 years and is adequate to investigate multi-decadal climate variability (Cook and Peters, 1997).

3.2. Precipitation reconstruction

The RFA identified October–June total precipitation as the most appropriate seasonal predictand for reconstruction. The final regression statistics for the 1771–2002 precipitation reconstruction obtained from the relationship between the regional tree-ring chronology (predictor) and precipitation record (predictand) are highly significant (Fig. 2). The predictor variable accounts for 63% of observed precipitation. Cross-validation using the PRESS procedure indicated that the model performs adequately in estimating precipitation data not used to fit the model (prediction $R^2 = 0.61$). The split-sample calibration-validation exercise indicated stability of the relationship over halves of the available instrumental data period. The computed RE statistics indicated skill of reconstruction in the calibration/validation exercises using different sub-periods. On this evidence, the full calibration period (1902–2002) was then used for the final reconstruction model.

3.3. Identification of dry and wet years

A scatterplot of reconstructed and observed precipitation attests to the strength and linearity of the precipitation signal in the tree-ring data over the range of observed precipitation encountered in the calibration period, and indicates that the reconstruction is somewhat more effective in classifying dry years than wet years (Fig. 3). The 12th and 88th percentiles of observed precipitation computed for the base period 1902–2002 were used to delineate dry and wet years, respectively. For the observed precipitation, the 12th percentile corresponds to 294 mm or 72.5% of mean; and the 88th percentile to

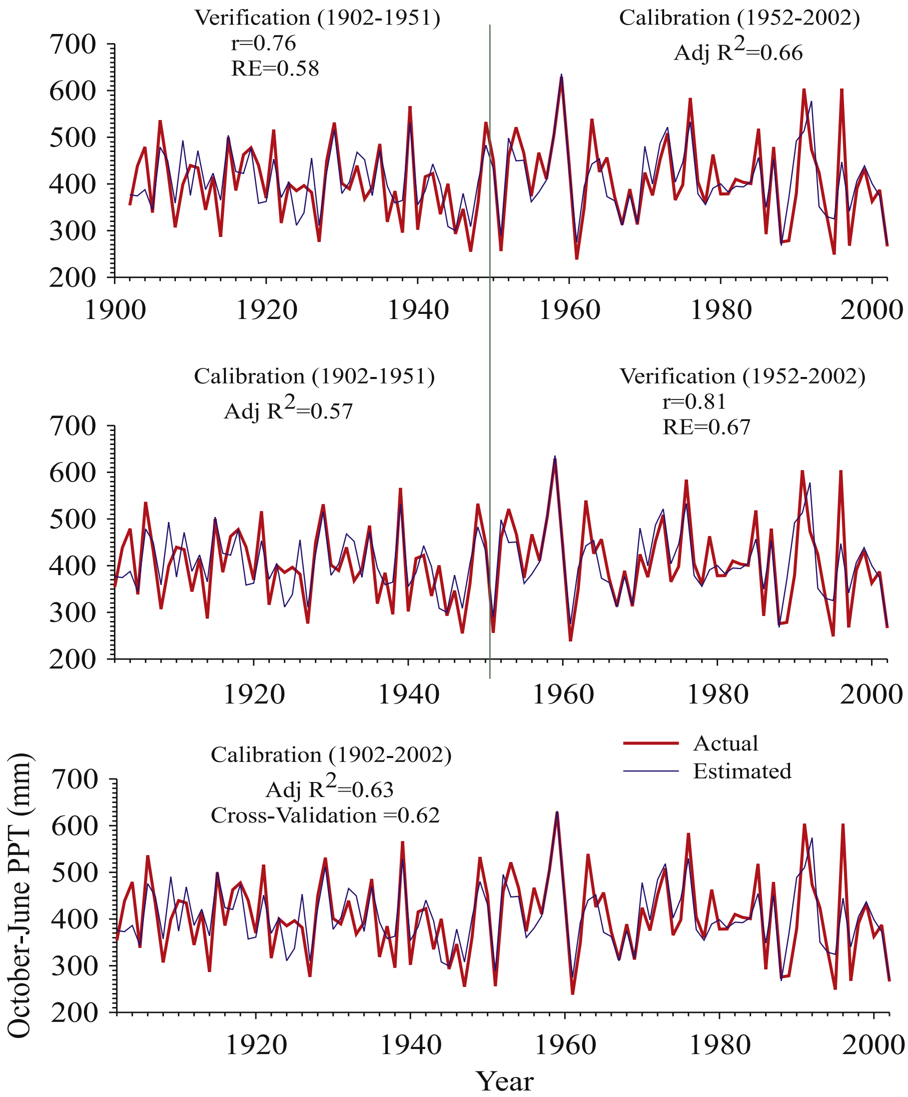

Fig. 2. Time-series plots of actual and reconstructed October–June precipitation for the calibration and verification periods of the split sample procedure.

512 mm, or 126.5% of the mean. For the reconstructed precipitation, the same percentiles (12th and 88th) for the 1902–2002 base period are 326 and 486 mm. That the same percentiles correspond to different thresholds for observed and reconstructed precipitation is a consequence of compression of variance in the reconstruction process. The correlation between the reconstructed and observed precipitation is $r = 0.79$, $n = 101$. The counts of dry and wet years discussed in subsequent sections are based on the 294 and 512 mm thresholds defined from the observed precipitation. As is evident from the scatterplot (Fig. 3), the tree-ring data are more effective at classifying dry years than wet years. Eight of the 12 driest observed years in the period 1902–2002 were also among the 12 driest reconstructed years, while only 5 of the 12 wettest observed years were among the 12 wettest reconstructed years.

By the 294 mm threshold, the long-term reconstruction for the period 1771–2002 contains 17 dry years, marked by dots on the time-series plots in Fig. 4. The maximum interval between October–June drought events is 63 years (1888–1951). The 19th century contains the highest number of dry years (9 events), and the longest period of consecutive dry years in the reconstruction is 2 years. Only one 2-year drought (1876–1877) occurs in the record, and that is before the start of the instrumental record. The single driest year in the reconstruction was 1789 (173 mm).

By the 512 mm threshold, the reconstruction contains 20 wet events, with a maximum interval between events of 47 years (1882–1929). Single wet years are evenly distributed throughout the 19th and the 20th centuries, but multi-year wet events are restricted to the period prior the 20th century. The longest wet period, defined by consecutive wet years, is 2 years. One such event occurs in the 18th century (1791–1792) and two in the 19th century (1833–1834 and 1848–1849). The single wettest year in the reconstruction was 1868 (653 mm).

It should be emphasized that the reconstruction likely underestimates the true frequency of droughts and wet periods when these events are defined by a specified level of observed precipitation as done here. This bias arises from the compression of regression estimates towards the calibration-period mean, as evident in the time-series plots of observed and reconstructed precipitation (Fig. 2).

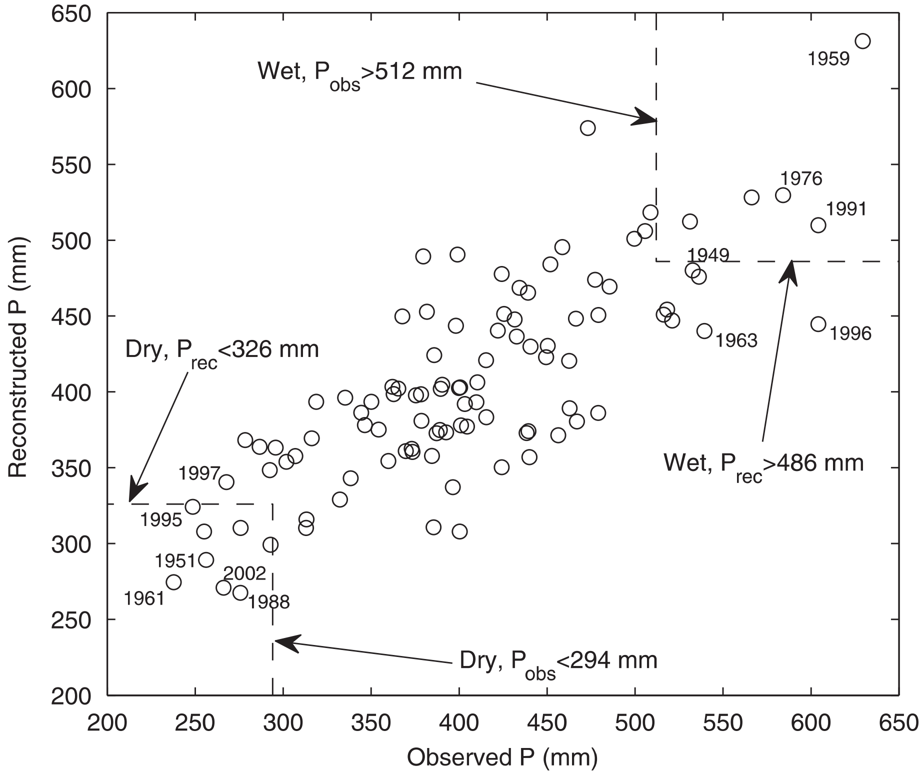

Fig. 3. Scatteplot of reconstructed on observed precipitation for calibration period 1902–2002. Dashed lines mark thresholds used to define dry events and wet events (see text). Annotated years are the 6 driest years and 6 wettest years of observed precipitation after the start of the Reanalysis Data (Palmen and Newton, 1969). These annotated years were used to form the composites of 500 mb anomaly patterns in Fig. 6A and B.

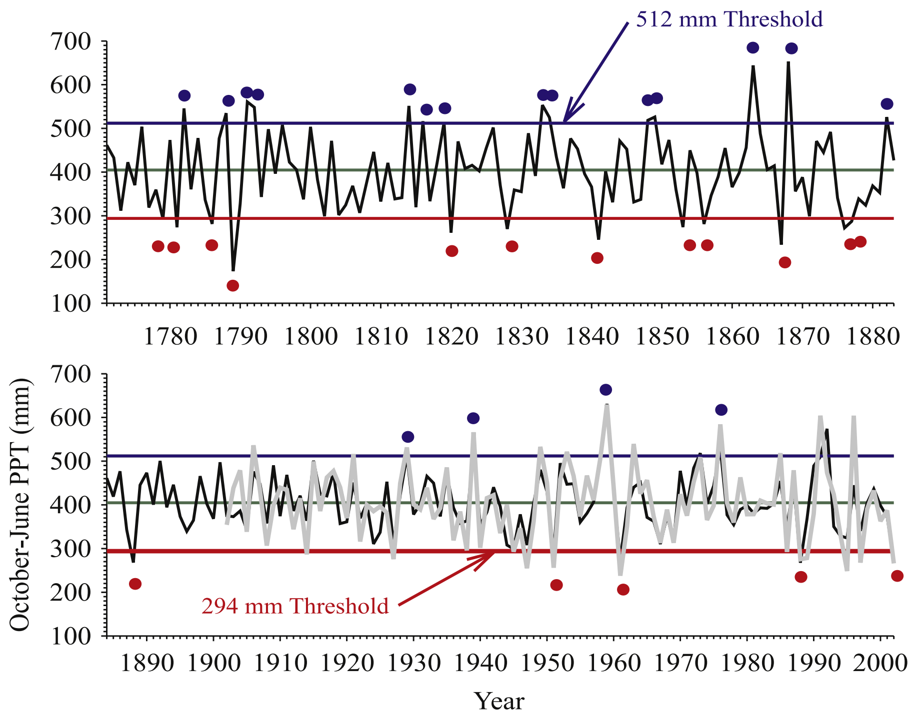

Fig. 4. Time-series plot of reconstructed October–June precipitation, AD 1771–2002. Solid line is the mean of the observed data.

The threshold-based tally of dry and wet periods is sensitive to the choice of threshold, and is also poorly suited for summarizing droughts that might be characterized by intervals of very dry years interspersed with year of slightly above-normal precipitation. As an alternative, droughts (and wet periods) were also summarized by a 5-year moving average of reconstructed October–June precipitation (Fig. 5). This smoothed series emphasizes multi-year and decadal variations.

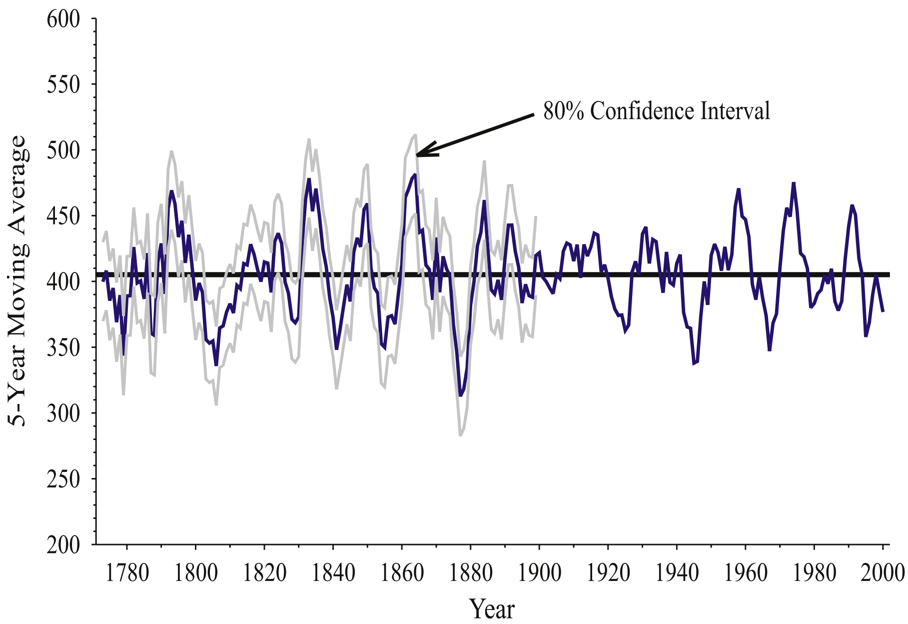

Fig. 5. Five-year running mean of reconstructed October–June precipitation for the period AD 1771–2002.

Although the five driest and wettest moving averages were distributed evenly between the 19th and 20th centuries, the extremes occurred before the 20th century. The driest 5-year period is 1875–1879 (313 mm) and the wettest is 1862–1866 (482 mm).

3.4. Large-scale circulation analysis

Investigation of upper-air circulation patterns associated with dry and wet years was restricted to the period of overlap of reconstructed and observed precipitation with reanalysis data, which begins in 1948. The driest 6 years and wettest 6 years in this period were used to form the composites of 500 mb height data (years annotated in Fig. 6A and B). Five of the 6 years for the dry-year composite are also dry-event years in the reconstruction (Fig. 3), but only 3 of the 6 years for the wet-year composite are wet years in the reconstruction. This is consistent with results from other tree-ring studies that show increased uncertainty of reconstruction in very wet years (e.g. Touchan et al., 1999). The dry-year composite is characterized by strengthened westerlies over Europe associated with a negative height-anomaly center north of Scandinavia and a positive center over northern Algeria and Tunisia. In the composite, this positive center is connected with a much stronger positive center in Eurasia at about 60°N, 65°E (Fig. 6A). This pattern probably represents a blocking of cyclone activity, as the Eurasian center is located directly in a region of principally high activity of the polar-front jet stream (Palmen and Newton, 1969). The dry-year composite is moderately representative of its 6-year sample. Four years exhibit the anomalous high over Eurasia. It should be noted, however, that 1997 and 2002 depart considerably from this pattern. In 2002, for example, a strong positive anomaly of 500 mb height was centered directly over southern Europe at about the longitude of Tunisia, and a strong negative anomaly was located in Eurasia at 55°E, 55°N.

The wet-year composite of 500-mb height anomaly is the reverse of the dry-year composite in that the positive anomaly over Algeria and Tunisia is replaced by a negative anomaly (Fig. 6B). This negative anomaly combined with an anomalous high over the North Sea suggests weakened westerlies over much of Europe and perhaps an enhanced subtropical jet across northern Africa. Positive height anomalies with an east–west axis through the British Isles or Scandinavia was typical of all years of the composite, but the structure of the negative height anomaly near Tunisia differed considerably from year to year.

4. Discussion and conclusions

Long-term drought in North Africa will greatly affect human beings, animals, and soils. Constant drought can cause human suffering where agricultural production and food supplies are marginal, and diminished forage will reduce animal production. Drought can also exacerbate the deterioration of marginal lands.

The effects of severe drought in North Africa are difficult to manage without careful planning. This requires the ability to anticipate climatic variability, especially drought. Skilled management of water and other natural resources requires sufficient information about the probable duration, distribution, and intensity of future drought.

Tree-ring data from this study help supply this information in the form of natural records to study past climate variation in Tunisia. This paper presents the first quantitative tree-ring reconstruction of precipitation in Tunisia. The reconstruction

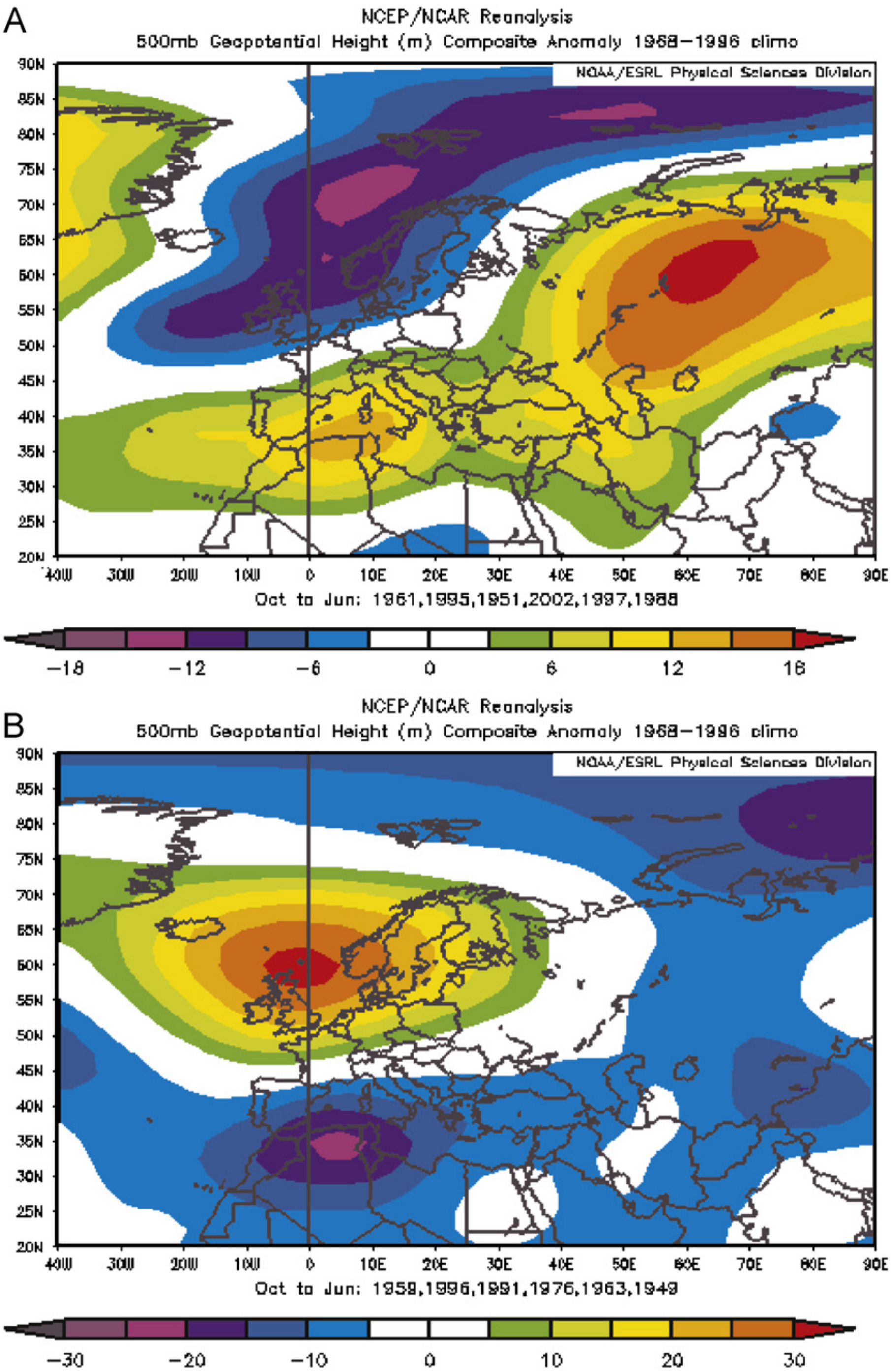

Fig. 6. The 500 hPa geotpotential height composite anomalies for (A) extremely dry and (B) extremely wet years. Heights are expressed as anomalies from 1968 to 1996 mean. NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at (http://www.cdc.noaa.gov/).

accuracy as measured by regression and calibration statistics is comparable to that achieved in high-quality climatic reconstructions for North America (e.g. Cook et al., 1999; Meko and Graybill, 1995). The time period of reconstruction (1771–2002) is a vast improvement over the instrumental period as a basis for investigating drought characteristics in the region.

The tallies of consecutive dry years and wet years are perhaps surprising for the absence of droughts or wet periods longer in duration than 2 years. Multi-year sequences of anomalous moisture conditions therefore appear not to be characteristic of this region, at least in the more than two centuries of extended record provided by this tree-ring study. This assessment must of course be accompanied by the caveat that we have used fairly severe levels of precipitation anomaly (12th and 88th percentiles) to define individual dry years and wet years.

The alternative summary in terms of 5-year moving average of reconstructed precipitation does reveal some prolonged periods of generally dry and wet conditions. These results suggest the short instrumental period is not representative of extreme dry conditions, as illustrated by the lowest 5-year running mean in the 1870s. Therefore, we must reject the null hypothesis that the short instrumental record for Tunisia adequately represents the drought conditions of the past few centuries.

This reconstruction of October–June Tunisia precipitation is not significantly correlated with May–August precipitation reconstruction of Touchan et al. (2005b) for the eastern Mediterranean region. This reconstruction is also not significantly correlated with Touchan et al. (in preparation) and Esper et al. (2007) November–March precipitation and February–June Palmer Drought Index reconstruction for Morocco, respectively. The lack of the correlation is probably due to different atmospheric circulation influences on precipitation in the two regions. The authors also note that the seasonal precipitation signal as filtered by the tree-ring records differs from one region to another—cool season for this study and Morocco, and warm season for the eastern Mediterranean. Such differences in seasonal response require further study, but may be due to site-specific factors such as species, topography, soil depth, and slope. In particular, different tree species were used in this study and in the eastern Mediterranean region. Fritts (1976) has documented species differences in seasonal climate response for tree species in North America, but little is yet known about such species dependence for tree species in North Africa to the Eastern Mediterranean. Improved understanding depends on future collections from multiple species and sites in North Africa.

In order to establish whether our October–June precipitation reconstruction exhibited links with large-scale atmospheric circulation, we analyzed correlation between our reconstruction and the North Atlantic Oscillation (NAO), but did not find a significant correlation. The NAO has been shown to be strongly related to cool-season precipitation variations on the Iberian Peninsula (Goodess and Jones, 2002) and the western Mediterranean region (Glueck and Stockton, 2001; Xoplaki et al., 2004), but no studies have as yet demonstrated a strong influence on Tunisia precipitation patterns.

The analysis of 500-mb heights does however support large-scale atmospheric teleconnections to dry years and wet years in Tunisia. Notably, the dry-year composite of 500-mb height anomaly is characterized by strengthened westerlies over Europe associated with a negative anomaly center north of Scandinavia and positive center over northern Algeria and Tunisia. The wet-year composite is the reverse of the dry-year composite, with the positive anomaly over Algeria and Tunisia replaced by a negative anomaly. These results suggest that inferences of past occurrence of blocking patterns in the westerlies can be made from tree-ring chronologies in the Mediterranean region. Stronger inferences could probably be made with augmented tree-ring networks sampling adjacent areas, especially eastern Asia.

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