GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L13705, doi:10.1029/2008GL034264, 2008

Click Here for Full Article

Long term context for recent drought in northwestern Africa

Ramzi Touchan,[1] Kevin J. Anchukaitis,[2] David M. Meko,[1] Said Attalah,[3]
Christopher Baisan,[1] and Ali Aloui[4]

Received 10 April 2008; revised 31 May 2008; accepted 6 June 2008; published 8 July 2008.

[1] Anthropogenic climate change is projected to exacerbate midlatitude aridity. Here, we analyze newly developed multi-century tree-ring records for a long-term perspective on drought in Tunisia and Algeria. We use a new set of 13 *Cedrus atlantica* and *Pinus halepensis* chronologies with a strong signal for warm-season drought (May–August) to generate a robust, well-validated reconstruction of the Palmer Drought Severity Index (PDSI) for the period AD 1456–2002. Key features of the reconstruction reveal the magnitude of pre-instrumental droughts from the historic record. Remarkably, the most recent drought (1999–2002) appears to be the worst since at least the middle of the 15th century. This drought is consistent with the early signature of a transition to more arid midlatitude conditions, as projected by general circulation models. **Citation:** Touchan, R., K. J. Anchukaitis, D. M. Meko, S. Attalah, C. Baisan, and A. Aloui (2008), Long term context for recent drought in northwestern Africa, *Geophys. Res. Lett.*, *35*, L13705, doi:10.1029/2008GL034264.

1. Introduction

[2] Drought in North Africa is a recurring phenomenon, and prolonged dry periods in this region can have a significant impact on economic and social systems, as well as natural ecosystems. The most recent drought in Algeria and Tunisia began in 1999, part of a widespread pattern of drying throughout the Northern Hemisphere [*Hoerling and Kumar*, 2003]. These conditions are predicted as one potential consequence of anthropogenic climate change [*Seager et al.*, 2007], but currently general circulation models forced by observed sea surface temperatures (SSTs) do not completely capture the magnitude and spatial extent of observed drought conditions over Algeria and Tunisia during the last decade [*Hoerling and Kumar*, 2003; *Seager*, 2007]. To understand modern droughts and evaluate the potential for future spatiotemporal patterns of midlatitude drying, it is necessary to characterise the range of potential natural climate variability over the past few centuries and develop an improved understanding of the links between large-scale climate forcing and regional drought. A few continuous high-quality instrumental data series in North Africa start in the early 1900s, but the majority cover only the later half of the twentieth century. Tree-ring records, however, allow for the development of quantitative and validated paleoclimate drought reconstructions to help understand climate variability on time scales beyond that of the instrumental data.

[3] This study is the first large scale and systematic tree-ring sampling from Algeria and Tunisia aimed at climate reconstruction. Climate-sensitive chronologies were developed for 13 *Cedrus atlantica* and *Pinus halepensis* sites, and were applied to reconstruct the Palmer Drought Severity Index (PDSI) [*Palmer*, 1965] in northern Algeria and Tunisia. The resulting 547 year reconstruction is analyzed for time series features of variability relevant to water resources planning and for possible teleconnections to global modes of climate variability.

2. Data and Methods

2.1. Tree-Ring Width Data

[4] Cores from living *Cedrus atlantica* and *Pinus halepensis* trees and cross-sections from remnant wood were collected between 2003 and 2006 at 13 sites from the region (Table 1, Figure 1 (top), and Table S1[1]). The samples were prepared and crossdated using standard dendrochronological techniques [*Stokes and Smiley*, 1968]. Each series of tree-ring width measurements was fit with a cubic smoothing spline with a 50% frequency response at 67% of the series length to remove non-climatic trends due to 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. The individual indices were combined into a single master chronology for each combination of site and species using a bi-weight robust estimate of the mean [*Cook*, 1985]. Adequacy of sample replication was judged by the expressed population statistic (EPS), computed from pooled interseries correlations and the time-varying sample size [*Wigley et al.*, 1984]. We limited our analysis to the period with an EPS of at least 0.85 (Table S2).

2.2. Climate Data

[5] The PDSI for Algeria and Tunisia was computed directly from monthly gridded 0.5° × 0.5° resolution monthly total precipitation and average temperature data [*Mitchell and Jones*, 2005], and was averaged to create a regional mean drought index. Gridded data for 1920–2002 over the spatial domain 1°E to 11°E and 33°N to 37°N were used for the computations (Figure 1 (top)). The sign of significant moisture anomalies over this region is rather uniform during the instrumental period, although the mag-

[1]Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, USA.
[2]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.
[3]Department of Agronomy Faculty of Science, University of Ourgla, Ourgla, Algeria.
[4]Institute of Sylvo-pastoral of Tabarak, Tabarka, Tunisia.

0094-8276/08/2008GL034264$05.00

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034264.

Table 1. Site Information for Algeria and Tunisia

Site[a]	Species[b]	Elevation (m)	Time Span	Trees
1	CEAT	1452	1533–2006	19
2	CEAT	1555	1717–2006	20
3	CEAT	1862	1148–2006	27
4	CEAT	1755	1620–2006	23
5	CEAT	1088	1468–2008	22
6	PIHA	1273	1695–2008	22
7	PIHA	1180	1834–2006	19
8	PIHA	1390	1854–2006	20
9	PIHA	1393	1830–2006	20
10	PIHA	950	1890–2003	11
11	PIHA	424	1751–2003	24
12	PIHA	801	1874–2003	15
13	PIHA	1050	1865–2004	20

[a]Sites numbered as in Figure 1. Sites 1–9 from Algeria. Sites 10–13 from Tunisia.

[b]Species codes are CEAT (*Cedrus atlantica*) and PIHA (*Pinus halepensis*).

nitude may vary. We selected this time period as the most reliable based on our experience with the limited instrumental weather data from these countries and comparison with other gridded drought data sets [*Dai et al.*, 2004].

2.3. PDSI Reconstruction

[6] Response function analysis [*Biondi and Waikul*, 2004] between the tree-ring indices and monthly and seasonal groupings of PDSI (not shown) identified May–August PDSI as the most appropriate predictand for the reconstruction. May–August was found to account for 62% of the tree-ring variance over the period of reliable instrumental climate data, 1920 to 2002. While May through August account for only about 14 percent of the annual precipitation (Figure S1), May–August PDSI reflects the influence of both precipitation and temperature for preceding as well as current months.

[7] Three complementary reconstructions were developed using the tree-ring data described above, in order to objectively assess the potential to accurately capture the long-term drought history of the region. First, we used the individual chronologies as the potential predictors to develop a set of nested multivariate stepwise regression models [*Meko*, 1997; *Cook et al.*, 2002] to estimate the mean May through August PDSI over the study region. In this procedure, an estimate of past drought values is calculated from the stepwise regression model for the period covered by all the individual site chronologies (1893 to 2002). Additional statistical models are subsequently developed for progressively longer periods back in time, with their span corresponding to significant changes in the availability of the underlying predictor tree-ring series. The individual reconstructions in this manner are scaled to have the standard deviation of the best replicated nest (1893 to 2002), and joined into a single long reconstruction such that each time period is represented by the corresponding regression model with the greatest available data. This procedure permits the skill of the drought reconstruction to be estimated as a function of the changing set of available predictor data.

[8] Second, using the same nesting technique we developed an additional reconstruction using as a single predictor for each nest the simple mean of the available tree-ring chronologies for the time period covered by each successive nest. Finally, a third reconstruction was developed by simple linear regression of PDSI on the biweight mean of all individual tree-ring series available in any given year (See Text S1 and Figure S2). This last technique is essentially an averaging over all trees regardless of site location, and is similar to a method previously used to develop drought reconstructions using tree-rings in Morocco [*Esper et al.*, 2007]. The three complementary reconstructions permit an assessment of the accuracy of reconstruction as a function of time, and of sensitivity of reconstruction features to different choices in spatial aggregation of tree-ring data and regression approach.

[9] Models for all three reconstruction techniques were validated with a split-sample procedure that divides the full period (1920–2002) into two subsets (1920–1961 and 1962–2002) alternately exchanged for calibration and validation. Calibration accuracy was measured by the adjusted R^2, and validation skill by the Pearson product-moment correlation coefficient (*r*), the reduction of error (*RE*) and the coefficient of efficiency (*CE*) [*Cook et al.*, 1994]. Models for the final reconstructions were calibrated on the full, combined, period, and were further validated by a leave-one-out jacknife procedure [*Meko*, 1997].

3. Results and Discussion

3.1. PDSI Reconstructions

[10] The reconstructed May–August PDSI for the nested reconstructions is plotted in Figure 2. Using either the individual chronologies or epochal means yields nearly identical long-term drought timeseries ($r = 0.94$, $p < 0.0001$) with similar variance. Split-sample calibration/val-

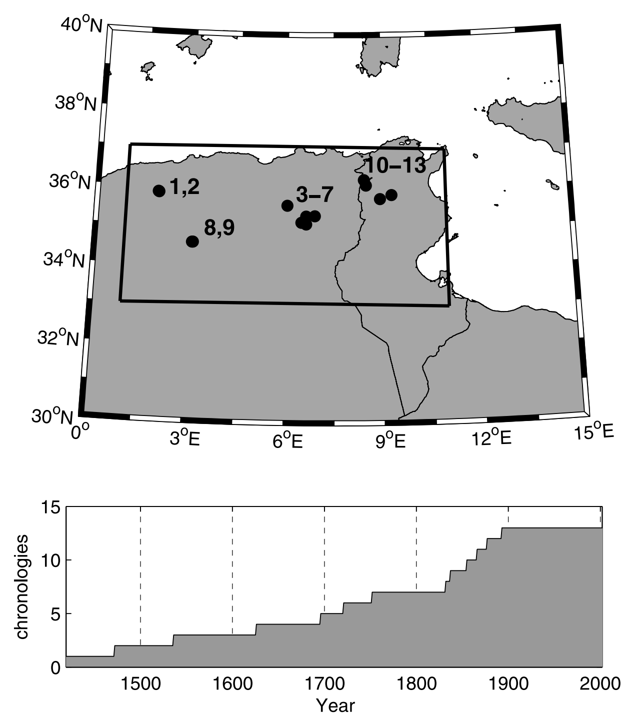

Figure 1. (top) Tree-ring sampling sites and (bottom) temporal sample depth for Algeria and Tunisia. The grid cells used for the PDSI reconstruction are shown by the box in Figure 1 (top).

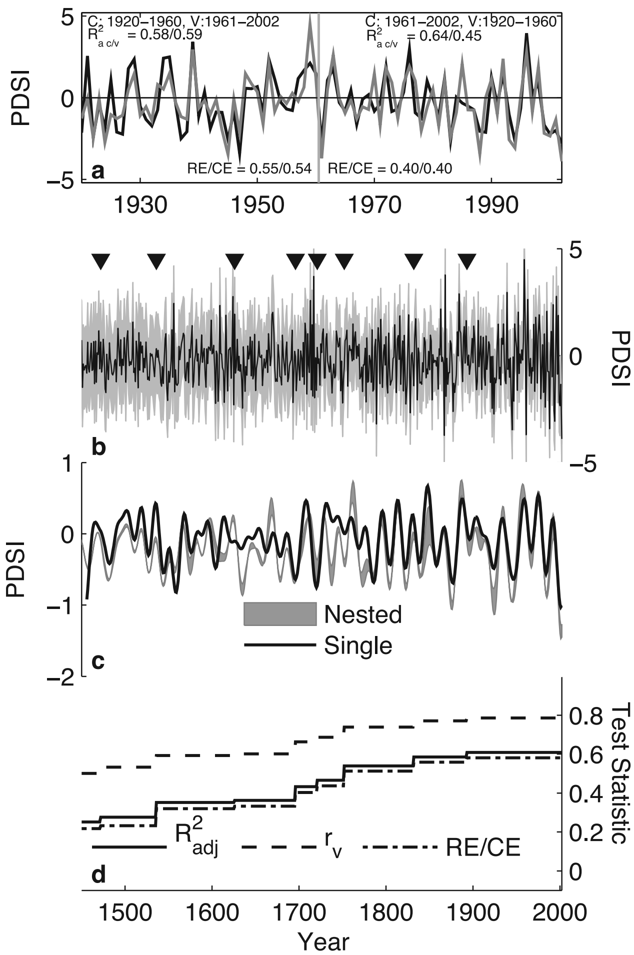

Figure 2. Reconstruction of May–August PDSI. (a) Calibration and validation skill over the reliable period of instrumental data (black line). Numbers at the top and bottom of each plot show the split-sample calibration and validation statistics for R^2, *RE*, and *CE* (see text for details). (b) Full length long-term reconstruction and confidence intervals shown by the standard error of prediction in grey [*Wilks*, 2006]. Splice points for the nested reconstructions are indicated by the arrows. (c) Low frequency drought variability (15-year low pass filter) for reconstructions based on the three different techniques described in the text. The two nested reconstruction are virtually identical. (d) Temporal variability in the nested reconstruction using the full 1920 to 2002 period for calibration and a leave-one-out jacknife procedure for validation. Full calibration and validation statistics for the reconstructions, including split-sample models, are available in the auxiliary material.

idation shows that the nested reconstructions are skillful as a function of time and the underlying tree-ring data (Figure 2a), and account for a significant portion of the observed variance (25 to 61%) irrespective of which period is used to develop or verify the regression model (see Figures S3–S6). The split-sample validation also supports our use of the reconstructions based on the full period of reliable observational data (1920–2002) in the following discussions (Figures 2b and 2d). None of the regression models showed any trend or first-order autocorrelation in the residuals.

[11] While the single regional chronology reconstruction is similar at interannual time scales to those using nested regression models, and significantly correlated (individual chronologies, r = 0.76, p < 0.0001; nested mean, r = 0.88, p < 0.0001), there are some notable discrepancies in decadal-scale drought variability (Figure 2c). The largest differences are in the middle of the 17th and 18th centuries. The conflicting estimates almost certainly arise because, in contrast to the nested reconstructions, the regression model coefficients are invariant over time and cannot realistically represent the changes in the predictor tree-ring data as chronology sites become progressively sparse back in time. Caution is therefore necessary when interpreting low-frequency drought variability in reconstructions based on a single mean regional tree-ring series over a large region with temporally-varying sample depth [e.g., *Esper et al.*, 2007]. For these reasons, we consider the nested reconstructions to be the most accurate and use them here to describe the long-term drought history of the region.

3.2. Drought History in North Africa

[12] If dry years are arbitrarily defined as reconstructed PDSI below its 25th percentile based on the 1920–2002 instrumental period (PDSI ≤ -1.05), the longest period of consecutive drought years in the long-term reconstruction for the period AD 1456–2002 is 4 years. This drought extreme occurred in 1999–2002, and in fact is exceptional during the last five centuries by either the simple regional mean reconstruction or nested reconstructions. Single drought years as defined here typically occur between 12 and 16 times per century, although the number rose to 19 in the 20th century. The driest single years over the full length of the reconstruction are 1867 (−3.74) and 2002 (−3.90).

[13] The reconstructions also demonstrate substantial variation on multi-annual and decadal time scales, with several significant events in the last five centuries (Figure 2c), although there is no long-term linear trend. In addition to the most recent severe drought, substantial and sustained dry conditions occurred in the 1540s, the 1860s, the 1870s, the 1920s, and the 1940s. Interestingly, none of these events are coincident with the large 19th (the 'Civil War droughts') and 20th century ('Dustbowl' and 1950s) droughts in North America [*Seager et al.*, 2005]. Four times in the last five centuries there are six year periods where every consecutive year was below the long-term reconstructed index mean: 1548–1553, 1737–1742, 1770–1775, 1876–1881. The last of these events had an average six-year average May–August PDSI of −1.25 in our reconstruction and for that averaging interval is the worst of the sustained droughts in the pre-instrumental record. Historical sources also point to drought, famine, cholera, and plagues of locust during this period [*Taithe*, 2006], and in particular to a persistent drought at Belezma (Batna) that caused massive damage to the cedar forests [*Boudy*, 1955]. The middle of the 1940s is also known from documentary sources as a time of particularly severe dry conditions. The year 1945 was known as a 'year of hunger', and drought and famine in Algeria were described by the philosopher Albert Camus in articles from that era [*Kassoul and Maougal*, 2006].

[14] Neither SST nor sea level pressure show a clear relationship with interannual anomalies in May–August PDSI. Other studies of the limited instrumental data have

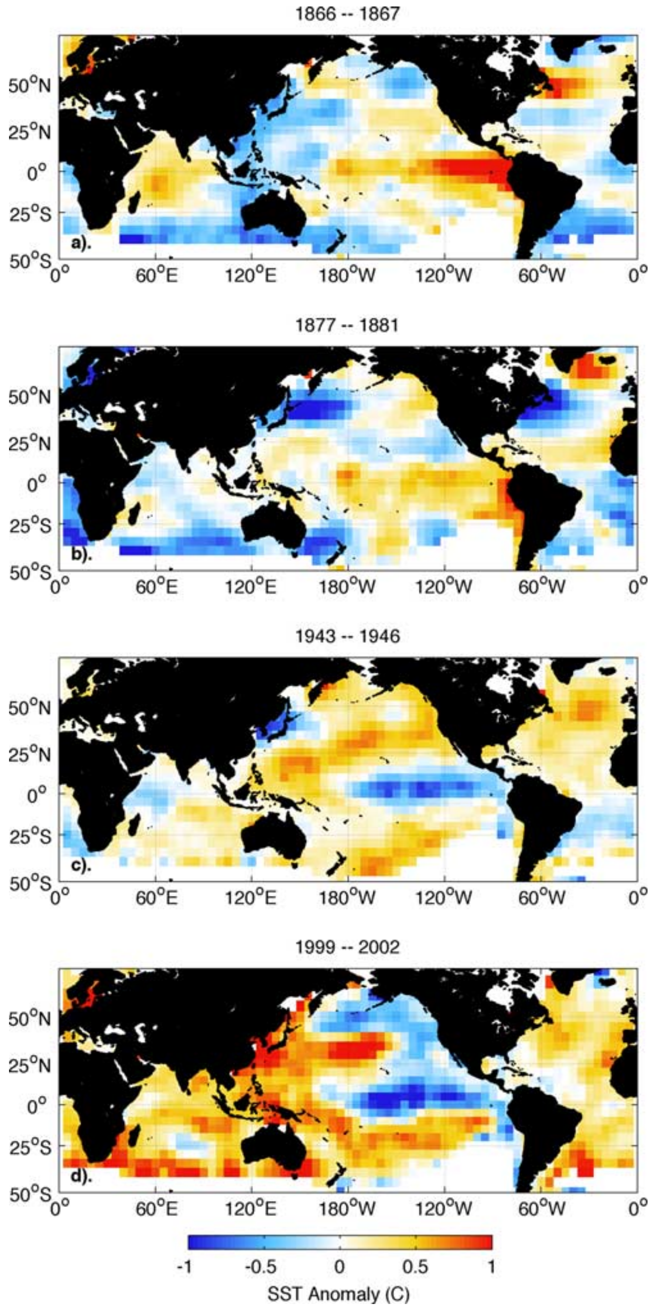

Figure 3. Composite mean sea surface temperature anomalies [*Kaplan et al.*, 1998] for significant drought periods 1856 to 2002.

shown that the coherent influence of large-scale Atlantic ocean-atmosphere modes of variability on the seasonal mean climate of northwestern Africa is largely confined to Morocco in the west [*Knippertz et al.*, 2003; *Li et al.*, 2003]. Climate model simulations have shown the North American drought can be caused by cold sea surface temperatures and La Nina-type conditions in the eastern tropical Pacific [*Seager et al.*, 2005; *Seager*, 2007], and a recent study suggested that Pacific teleconnections could also be responsible for Medieval drought conditions in Morocco [*Esper et al.*, 2007]. Our comparison of periods of persistent drought in Algeria and Tunisia with SST anomalies (Figure 3), however, suggests that for this region the climate dynamics responsible for drier and warmer conditions are more complicated. While the strongest droughts during the historical period are indeed associated with anomalous temperatures in the Pacific, the sign of these anomalies is different between the earlier and latter portions of the instrumental SST record. Such associations are therefore either coincidental, or both El Nino and La Nina can influence North African drought through different mechanisms (perhaps associated with drought seasonality, the balance between rainfall and temperature, or the mediating influence of the Atlantic). Indeed, the most consistent SST anomalies associated with drought appear to be warmer than normal conditions in the Atlantic, especially the tropical Atlantic. A testable hypothesis is that the association between drought, remote teleconnections, and atmospheric circulation has changed over the last 150 years. Models do not currently capture the spatial extent and severity of the modern and historic drought periods in Algeria and Tunisia [*Seager et al.*, 2007], although recent analyses of long HadCM3 control simulations suggest that our study region sits at the margin of modelled ENSO-influenced teleconnections to geopotential heights and zonal winds over Europe and the western Mediterranean [*Busby et al.*, 2007]. If this is the case, than relatively small differences in the nature of the ENSO teleconnections, or the additional influence of the Indian [*Hoerling and Kumar*, 2003] or Atlantic Ocean or radiative forcing, might influence the position of circulation patterns and the sign of the local precipitation or temperature anomaly, leading to drought. Given the importance and potential impact of drought in the region, further study of the mechanisms associated with drier conditions in northern Africa should be included in future general circulation model analyses, as has been done for North America [e.g., *Seager*, 2007].

4. Summary and Conclusions

[15] In this paper, we present the first long-term drought reconstruction for Algeria and Tunisia. The 547-year reconstruction can now provide a baseline for studying past climate variability in the region, and provides a simulation target for general circulation modeling. The relationship between global SST anomalies and the strongest droughts in Algeria and Tunisia (Figure 3) indicate that further climate model studies are necessary to determine how both internal climate variability and global anthropogenic climatic change may influence drought conditions in this already arid region. The 1999–2002 drought appears to be the worst since the middle of the 15th century and is potentially ominous due to the possible link to anthropogenic climate change [*Hoerling and Kumar*, 2003; *Seager et al.*, 2007]. Our May–August PDSI drought reconstruction also now provides essential information concerning hydroclimatic variability in northern Algeria and Tunisia, including the long-term return period of severe and multiyear dry periods. The placement of modern drought characteristics in the context of several centuries of climate variability can help natural resource managers apply low-risk and long-term plans to use, conserve, and sustain water and other natural resources that are the foundations of social, political, and economic systems in the region. The information from our

reconstruction will also provide an additional dimension in the study of environmental history and its relationship to human social and population dynamics in North Africa. The strong drought signal in our *Cedrus atlantica* and *Pinus halepensis* chronologies indicates that further development of the North African tree-ring network will provide the necessary proxy data for robust, fine scale regional paleoclimate field reconstructions.

[16] **Acknowledgments.** We wish to thank our colleagues from Algeria (Mohamed Azzedine Idder, Belkitir Dadamoussa, Mohamed Seghir Mellouhi, Hocine Medjedoub, Abdallatif Guasmi, and Chabane Cheriet, and the Directors of Forest of Khenchela, Djelfa, and Tissemssilt) and from Tunisia (Toumi Lamjed) for their great support in making this study possible. We thank Jeffrey Balmat, Nesat Erkan, Jim Burns, Jeremy Goral, Julie Wong, and Salah Eddine Sadine for their valuable assistance in the field and laboratory. LDEO Contribution (KJA) #7172. Funding was provided by the US National Science Foundation, Earth System History (ESH 0317288).

References

Biondi, F., and K. Waikul (2004), DENDROCLIM 2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies, *Comput. Geosci.*, *30*, 303–311.

Boudy, P. (1955), *Economie Forestière Nord-Africaine*, vol IV, *Description Forestière de l'Algérie et de la Tunisie*, 483 pp., LaRose, Paris.

Busby, S. J., K. R. Briffa, and T. J. Osborn (2007), Simulation of ENSO forcings on US drought by the HadCM3 coupled climate model, *J. Geophys. Res.*, *112*, D18112, doi:10.1029/2007JD008705.

Cook, E. R. (1985), A time-series analysis approach to tree-ring standardization, Ph.D. dissertation. Dep Geosci., Univ. of Arizona, Tucson.

Cook, E. R., and K. R. Briffa (1990), A comparison of some tree-ring standardization methods, in *Methods of Dendrochronology*, edited by E. R. Cook and L. A. Kairiukstis, pp. 104–123, Kluwer, Dordrecht.

Cook, E. R., K. R. Briffa, and P. D. Jones (1994), Spatial regression methods in dendroclimatology: A review and comparison of two techniques, *Int. J. Climatol.*, *14*, 379–402.

Cook, E. R., R. D. D'Arrigo, and M. E. Mann (2002), A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since AD 1400, *J. Clim.*, *15*, 1754–1764.

Dai, A., K. E. Trenberth, and T. Qian (2004), A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, *5*, 1117–1130.

Esper, J., D. Frank, U. Büntgen, A. Verstege, J. Luterbacher, and E. Xoplaki (2007), Long-term drought severity variations in Morocco, *Geophys. Res. Lett.*, *34*, L17702, doi:10.1029/2007GL030844.

Hoerling, M., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*, 691–694, doi:10.1126/science.1079053.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan (1998), Analyses of global sea surface temperature 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589.

Kassoul, A., and M.-L. Maougal (2006), *The Algerian Destiny of Albert Camus*, Academica, Palo Alto, Calif.

Knippertz, P., M. Christoph, and P. Speth (2003), Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates, *Meteorol. Atmos. Phys.*, *83*, 67–88.

Li, S., W. Robinson, and S. Peng (2003), Influence of the North Atlantic SST tripole on northwest African rainfall, *J. Geophys. Res.*, *108*(D19), 4594, doi:10.1029/2002JD003130.

Meko, D. M. (1997), Dendroclimatic reconstruction with time varying subsets of tree indices, *J. Clim.*, *10*, 687–696.

Mitchell, T., and P. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*, 693–712.

Palmer, W. C. (1965), Meteorological drought, *Res. Pap. 45*, 58 pp., U.S. Dep. of Comm., Washington, D. C.

Seager, R. (2007), The turn of the century North American drought: Global context, dynamics, and past analogs, *J. Clim.*, *20*, 5527–5552.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik, and J. Velez (2005), Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000, *J. Clim.*, *18*, 4065–4088.

Seager, R., et al. (2007), Model projections of an imminent transition to a more arid climate in southwestern North America, *Science*, *316*, 1181–1184.

Stokes, M. A., and T. L. Smiley (1968), *An Introduction to Tree-Ring Dating*, Univ. of Chicago Press, Chicago.

Taithe, B. (2006), Algerian orphans and colonial Christianity in Algeria, 1866–1939, *Fr. Hist.*, *20*, 240–259, doi:10.1093/fh/cr1019.

Wigley, T., K. Briffa, and P. Jones (1984), On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*, 201–213.

Wilks, D. S. (2006), *Statistical Methods in the Atmospheric Sciences*, Academic, San Diego, Calif.

A. Aloui, Institute of Sylvo-pastoral of Tabarak, 8110 Tabarka, Tunisia.

K. J. Anchukaitis, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA.

S. Attalah, Department of Agronomy, Faculty of Science, University of Ourgla, Bp 54 Sidi-Khouiled, 30100 Ourgla, Algeria.

C. Baisan, D. M. Meko, and R. Touchan, Laboratory of Tree-Ring Research, University of Arizona, P.O. Box 210058 Tucson, AZ 85721-0058, USA. (rtouchan@ltrr.arizona.edu)