STANDARDIZED PRECIPITATION INDEX RECONSTRUCTED FROM TURKISH TREE-RING WIDTHS

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Abstract. May–July Standardized Precipitation Index (SPI) for the land area of most of Turkey and some adjoining regions are reconstructed from tree rings for the period 1251–1998. The reconstruction was developed from principal components analysis (PCA) of four *Juniperus excelsa* chronologies from southwestern and south-central Turkey and is based on reliable and replicable statistical relationships between climate and tree ring growth. The SPI reconstruction shows climate variability on both interannual and interdecadal time scales. The longest period of consecutive drought years in the reconstruction (SPI threshold ≤ -1) is 2 yr. These occur in 1607–1608, 1675–1676, and 1907–1908. There are five wet events (SPI threshold $\geq +1$) of two consecutive years each (1330–1331, 1428–1429, 1503–1504, 1629–1630, and 1913–1914). A 5-yr moving average of the reconstructed SPI shows that two sustained drought periods occurred from the mid to late 1300s and the early to mid 1900s. Both episodes are characterized by low variability.

1. Introduction

Drought is a recurring worldwide phenomenon, especially in semiarid and arid regions. Prolonged drought in these regions impacts ecosystems, natural habitats, and economic and social systems. Given the consequences, it is critically important to assess the frequency and severity of drought. However, the exact quantification of drought severity is a difficult task.

Many indices have been developed to measure drought severity (Heim, 2002; Keyantash and Dracup, 2002). Since 1965, the Palmer Drought Severity Index (PDSI) (Palmer, 1965) has been the most used drought index worldwide. Over the past 10 yr, however, the Standardized Precipitation Index (SPI) has come into use as an alternative to the PDSI. SPI provides an objective method for determining drought conditions at multiple time scales for any area that has continuous high quality precipitation records (Edwards and McKee, 1997).

One of the virtues of the SPI, unlike PDSI, is that it can be calculated to represent drought at user-specified time scales. This feature allows meteorological and hydrological drought to be evaluated simultaneously using the same methodology. Another feature of SPI is that it is defined in association with the characteristics of its probability distribution and has been subjected to thorough empirical tests, the results of which allow for well-defined drought levels (e.g., drought is empirically

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designated as SPI ≤ -1.0). In contrast, the PDSI is based on and developed for climate and soil characteristics particular to the central U.S. Calculating Palmer indices requires the use of both temperature and precipitation records. Moreover, Palmer data have been tested and found to be unreliable in many cases (e.g., Alley, 1984; Guttman, 1998). These characteristics make SPI a highly desirable index to use in dendroclimatological studies, particularly in regions for which PDSI data are unavailable.

In order to understand drought, we need to characterize it in the context of past climate variability on multiple time scales. Most drought indices were developed using continuous high quality instrumental climate records. With the exception of Western Europe, portions of North America and a few other regions, the majority of these data do not start until after 1930 and many are less than 50-yr long. Therefore, to understand climate variability over time spans of centuries or millennia, we need to use proxy records. Tree-ring analysis is one of the best sources of proxy data for reconstructing precipitation, temperature, streamflow, and the frequency of extreme drought events on interannual to centennial time scales (Touchan et al., 1999; Hughes et al., 1999; Meko et al., 2001; Chbouki, 1992).

In the Near East, relatively few dendroclimatological studies have been undertaken. Touchan et al. (1999) developed the first climatic reconstruction for southern Jordan. D'Arrigo and Cullen (2001) produced a 350-yr precipitation reconstruction for central Turkey, and in an earlier study, Touchan et al. (2003) reconstructed a 660-yr May–June precipitation record for southwestern Turkey. Other studies in the region have investigated the relationship between climate and tree growth (Gassner and Christiansen-Weniger, 1942; Akkemik, 2000; Hughes et al., 2001).

Many tree-ring studies have successfully reconstructed drought indices such as PDSI (Blasing and Duvick, 1984; Cook and Jacoby, 1977; Cook et al., 1988; Cook et al., 1992; Meko, 1992; Stahle et al., 1985, 1988; Stockton and Meko, 1975, 1983; Cook et al., 1996) and the Palmer Hydrologic Drought Index (PHDI) (Cleaveland and Stahle, 1996). Although SPI has become a widely accepted drought index, to our knowledge no SPI reconstructions have been developed using tree-ring chronologies. In this paper we explore the reconstruction of SPI from Turkish tree rings in order to provide useful information on variability in precipitation over most of the past millennium.

2. Data

2.1. TREE-RING DATA

Six tree-ring sites were sampled in the Antalya, Burdur, and Mersin Districts of southwestern and south-central Turkey near the eastern end of the Mediterranean Sea. The dominant tree species in the region is *Juniperus excelsa* (Table I, Figure 1). Sites range in elevation from 1002–2022 m a.s.l. and are characterized by

TABLE I
Site information for Antalya, Burdur, and Mersin districts in Turkey

Site name	District	Elevation (m)	Latitude	Longitude	Time span (A.D. unless indicated) Earliest	Latest	Total no. of years	Number of trees	No. of cores
Su Batan	Burdur	1808–1916	37°25′ N	30°18′ E	1246	2000	755	24	34
Göller	Antalya	1002–1093	37°05′ N	30°31′ E	1152	2000	849	17	31
Elmali	Antalya	1853–2022	36°36′ N	30°01′ E	1032	2001	970	44	63
Neşeli	Mersin	1708–1741	37°12′ N	34°28′ E	1235	2001	767	24	29
Ananardiç	Mersin	1762–1868	37°16′ N	34°33′ E	1330	2001	672	18	23
Silpişli	Mersin	1727–1851	37°16′ N	34°33′ E	1525	2001	477	17	22

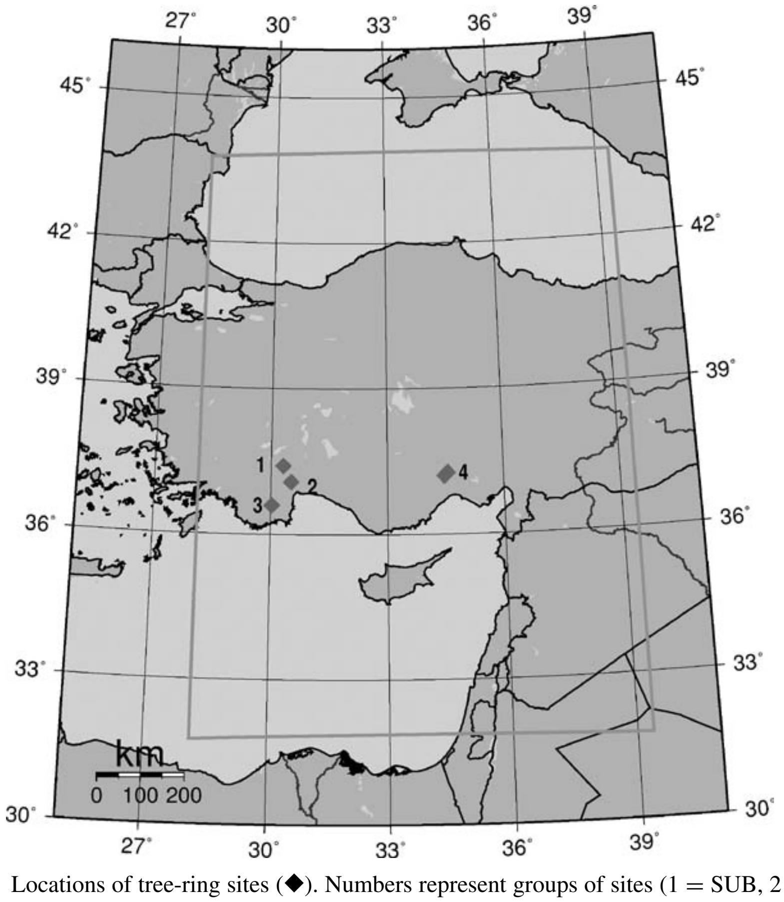

Figure 1. Locations of tree-ring sites (◆). Numbers represent groups of sites (1 = SUB, 2 = GOL, 3 = ELM, and 4 = NES, ANA, and SIL). Solid box represents the range of the gridded precipitation data.

Mediterranean subhumid to humid climates. Climate at the Göller site is considered intermediate between Mediterranean and Continental regimes with dry summers and wet winters. The Burdur district site, in the Mediterranean Mountainous Region, is characterized by cooler and wetter conditions than the other sites.

Most of the sites are covered with snow from December to April. Precipitation occurs predominantly during the fall, winter, and spring. Summers are typically fairly dry. Mean annual precipitation ranges from 700 to 1200 mm (Turkish Ministry of Forestry, 1997; Turkish General Directorate of Meteorology, 2001). Mean annual temperature ranges from 6 °C to 17 °C. July is the warmest month, with an average mean temperature of between 18 °C and 29 °C. January is the coldest month, with an average mean temperature ranging from –2.5 °C to 6 °C (Turkish Ministry of Forestry, 1997; Turkish General Directorate of Meteorology, 2001).

2.2. CLIMATE DATA

We used the 2.5° by 3.75° gridded land-only precipitation data set developed by Hulme (1992) and obtained from http://www.cru.uea.ac.uk/∼mikeh/datasets/global/, as updated June 2, 2000, to calculate the SPI. The historical monthly precipitation data for the region defined by grid coordinates 28.125°–39.375°E and 31.250°–43.750°N for the period 1924–1998 were selected for analysis because this maximized the number of station records available for analyses while optimizing stability in sample depth.

We tested many subsets of this gridded climate data against the tree-ring data. A split sample procedure that divided the full period into two subsets of equal length (1924–1960 and 1961–1998) was used to test the stability of potential regression models for reconstructing SPI. Calibration and verification statistics were calculated for the periods 1924–1960 and 1961–1998, and vice versa, respectively. In all cases, both the calibration and verification R^2 values were smaller for the post-1960 period than for the 1924–1960 period. Therefore, we present here the reconstruction for the total area defined by the full grid as shown by the box in Figure 1. This is generally consistent with the findings of Hughes et al. (2001) that drought, as recorded in tree rings, in the eastern Mediterranean region can be characterized as a large-scale phenomenon.

3. Methods

3.1. TREE-RING DATA

During 2000 and 2001 we developed four chronologies from samples collected at six sites in the Antalya, Burdur, and Mersin districts in Turkey (Table I, Figure 1).

Increment cores were taken at all sites and 24 full cross sections were taken from stumps and logs of juniper at selected sites. Samples were fine-sanded and cross-dated at the Laboratory of Tree-Ring Research, The University of Arizona, using standard dendrochronological techniques (Swetnam, 1985; Stokes and Smiley, 1996). The widths of each annual ring on the cores and cross-sections were measured to the nearest 0.01 mm.

A cubic smoothing spline with a 50% cutoff frequency of 200 yr was fit to each ring-width measurement series to remove non-climatic growth trends related to age, size, and the effects of stand dynamics (Cook and Briffa, 1990) (Table II). The application of the cubic smoothing spline in dendroclimatology has been described by Cook and Peters (1981). It "... can be thought of as a concatenation of cubic polynomial segments that are joined together at their ends. ..." They point out that "Splines are inherently superior to polynomials for approximating functions that are disjointed or episodic in nature," because they are calculated piecewise.

The index series for each sample were prewhitened with low-order autoregressive models to remove any residual persistence not related to climatic variation that remained after standardization. The indices from individual cores were then averaged into a master chronology for each combination of site and species using a biweight robust estimate of the mean (Cook, 1985). Because visual crossdating and computer-based quality control showed a strong similarity among the Neşeli, Ananardiç, and Silpişli sites, these *Juniperus excelsa* ring-width series were combined to form a single chronology.

3.2. SPI CALCULATION

SPI is a dimensionless drought measure calculated by fitting precipitation data to an incomplete gamma probability density function and standardizing the transformed data so that they are normally distributed with a mean of zero and a variance equal to one. The outcome is a drought index where values below zero represent dry conditions and values greater than zero represent wet conditions. The SPI calculation is fully described in McKee et al. (1997). McKee et al. (1993) and Hayes (2003) used the normal cumulative probability of the SPI to develop a table that categorizes various degrees of drought. From this table, McKee et al. (1993) defined a SPI value of -1 or less as the general indicator of a drought event. We empirically defined a drought threshold as 80% of the observed data (1924–1998) mean of all SPI negative values (Touchan et al., 1999). This drought threshold is -1.0, which is one standard deviation below the SPI mean. Similarly, we used 120% of the mean of the observed positive values as the wet period threshold, which represents $+1.0$ standard deviation above the SPI mean.

TABLE II
Summary statistics for the four chronologies from computer program ARSTAN

	Total chronology					Common intervals		
Chronology name	Standard deviation	Skewness	Kurtosis	1st year SSS[1] > 0.85 A.D.	Time span A.D.	Total no. of years	Mean correlation among radii	Variance in first principal component (%)
Su Batan	0.18	0.09	0.11	1338	1673–1950	278	0.44	50
Göller	0.16	0.14	0.46	1567	1759–2000	242	0.33	37
Elmali	0.19	0.36	0.26	1375	1820–2001	182	0.37	40
South-Central[2]	0.20	0.19	0.14	1351	1823–1998	176	0.41	44

[1]SSS is Subsample signal strength (Wigley et al., 1984).
[2]South Central combines Neşeli, Anamdiç, and Silpişli into one chronology (see text).

3.3. DROUGHT RECONSTRUCTION

The relationships between the tree-ring chronologies and monthly and seasonal groupings of gridded temperature, precipitation, and SPI were investigated with response function analysis (Fritts, 1976, 1991). These analyses identified May–July SPI as the most appropriate seasonal predictand for reconstruction. This is consistent with the results of Hughes et al. (2001) for a much larger region .The four tree-ring chronologies were transformed into uncorrelated predictors through principal component analysis (PCA) prior to developing a regression equation to emphasize the common variance among the original chronologies (Fritts, 1976; Kutzbach and Guetter, 1980; D'Arrigo and Jacoby, 1991). Predictors for the final reconstruction models were selected by a forward stepwise regression procedure. The first and second PCs, accounting for 46% of the tree-ring variance, entered as significant predictors for the first reconstruction.

Calibration equations used SPI data for the period of 1924–1998. The PRESS (prediction error sum of squares) procedure was used for cross-validation (Weisberg, 1985; Fritts et al., 1990; Meko, 1997; Touchan et al., 1999) to maximize the number of observations and the degrees of freedom used to calculate model significance in the final regression equation. This measure is calculated by sequentially removing single observations from the calibration period and caculating a new regression equation over the remaining $n - 1$ observations and using it to estimate the observation that was removed. This is repeated for each observation in the calibration period. A split-sample procedure (Snee, 1977; Meko and Graybill, 1995; Touchan et al., 2003) that divided the full period into two subsets of equal length (1924–1960 and 1961–1998) was used to verify model stability.

4. Results and Discussion

4.1. TREE-RING DATA

The lengths of the four chronologies range from 755 (Su Batan) to 970 (Elmali) years (Table I). Statistical analyses of each chronology are summarized in Table II. The mean correlation among individual radii at each site represents the strength of the common signal and ranges from 0.33 to 0.44. Some difficulty in the analysis was encountered in crossdating the juniper due to relatively high incidences of locally absent rings. Locally absent rings also have been reported for *Juniperus phoenicia* in southern Jordan (Touchan et al., 1999) and *Juniperus excelsa* in Oman (Fisher, 1994).

The average correlation of all pairs of the chronologies is significant ($r = 0.41$, $n = 750$, $P \leq 0.01$). PCA was used in order to capture the regional dendroclimatic signal and to determine how the chronologies filter their respective climatic signals.

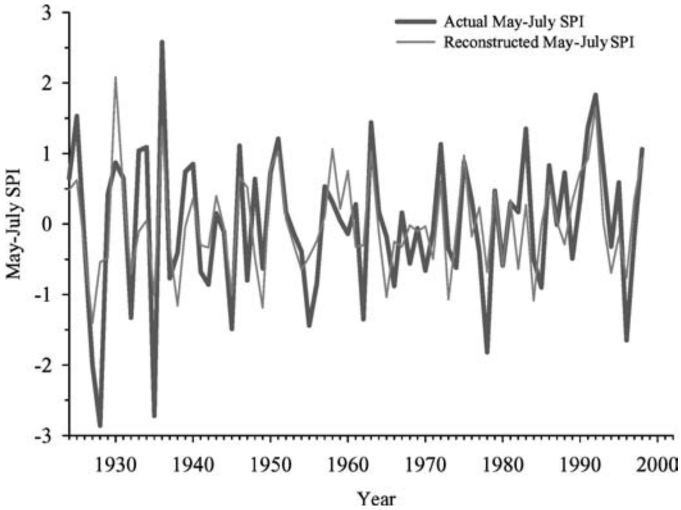

Figure 2. Comparison of actual and estimated May–July SPI for the 1924–1998 period.

4.2. SPI RECONSTRUCTION

The final regression statistics of the May–July SPI reconstruction obtained from the relationship between the transformed tree-ring data (predictors) and precipitation (predictand) are highly significant ($F = 32.73$, $P \leq 0.01$) (Figure 2). The regression equation for the calibration period is:

$$\text{May–July SPI} = 0.0072 - 0.458\ \text{PC1} - 0.277\ \text{PC2}$$

The predictor variables account for 46% (adjusted for the degrees of freedom) of the variance in the precipitation data. Cross-validation using the PRESS procedure indicated that the model performs adequately in estimating precipitation data not used to fit the model ($R^2 = 0.43$). The similarity and strength of the derived calibration equations and verification tests of the two subset periods (Figure 3) justified using the full calibration period (1924–1998) for developing the final reconstruction.

As shown in Figure 2, the tree ring indices underestimate the observed SPI (e.g., 1928 and 1935). All regression-based reconstructions tend to underestimate extreme values and it is also possible that the seasonal distribution of the total precipitation can add to this. For example, above average winter precipitation might have effects on May–July tree growth. Nevertheless, the interannual course of variability in tree growth can resemble that of the climatic variability during these 2 yr.

A time series plot of reconstructed May–July SPI is shown in Figure 4. The long-term reconstruction contained 57 drought events. Fifty-one events have a duration of 1 yr and three events have a duration of 2 yr. The average interval between

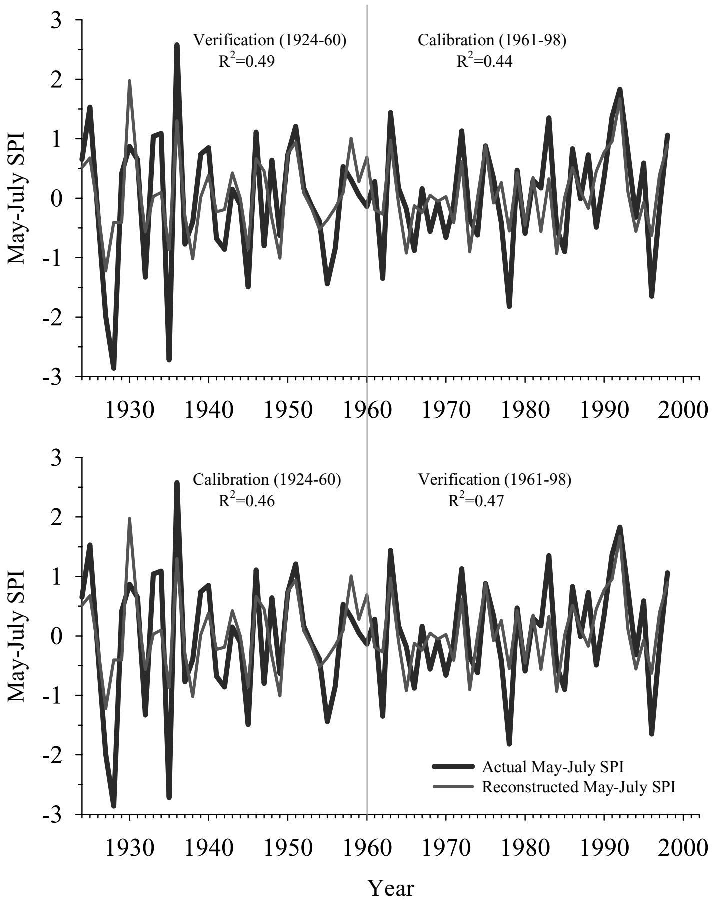

Figure 3. Time series plots of calibration and verification using the split sample procedure.

drought events was 12.6 yr with a maximum interval of 59 yr (1375–1434). The single driest year (−1.8) in the reconstruction was 1440 and the single driest year (−1.4) in the instrumental data is 1927.

One-year dry periods are evenly distributed throughout the reconstruction with the exception of the 1500s (two events) and the early to mid-1800s (four events). Two consecutive years of May–July drought are evident in two centuries. The 17th century contains two 2-yr dry periods (1607–1608 and 1675–1676) and the 20th century has one 2-yr dry period (1907–1908). Drought events in the long-term reconstruction most likely underestimate rather than overestimate drought severity, as they do during the calibration period (Figure 2).

The SPI reconstruction contains 66 wet periods. There are 56 single year and five 2-yr wet episodes. The average interval between wet periods is 11.4 yr with a maximum interval of 44 yr (1459–1503). With the exception of the 1400s and

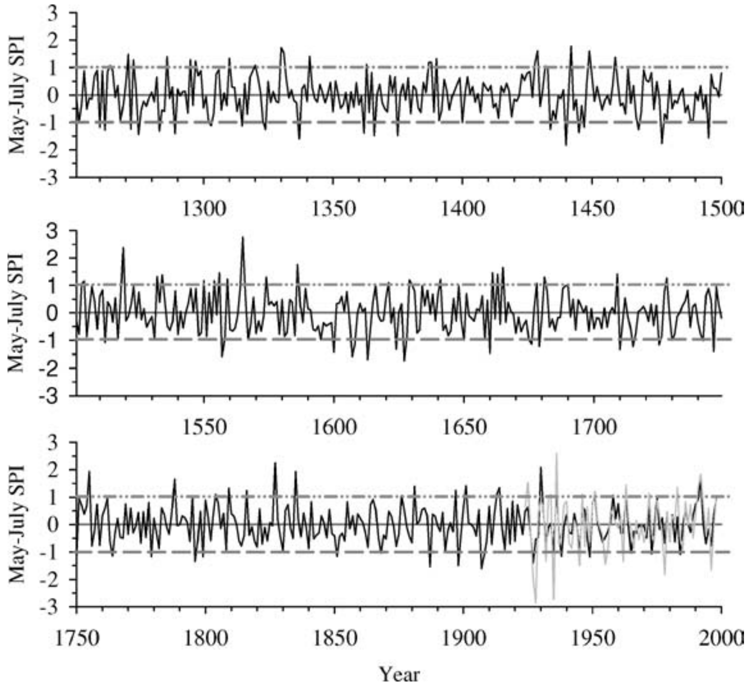

Figure 4. Time series plot of reconstructed May–July SPI, AD 1251–1998. Solid line is the mean of the observed data. Dash-dot line is the SPI wet threshold (SPI $\geq +1$). Dashed line is the SPI drought threshold (SPI ≤ -1). The observed record is in grey.

1700s, the 1-yr wet periods were relatively evenly distributed throughout the record. The greatest number of wet periods and the fewest number of drought events were recorded in the 1500s. However, the reconstruction shows that there were many consecutive years of negative values between 0 and -1 during this century (e.g. 1592–1599). Two-year wet periods were evident in the 1300s, 1400s, 1500s, 1600s, and 1900s. The wettest single year in the reconstruction was 1565 (2.76), while the wettest year in the observed data was 1930 (2.1).

Fitting a low pass filter with a 50% response over 5 yr to the reconstruction (Figure 5) shows multi-year and decadal variation and reveals several prolonged dry and wet periods. For example, drought periods occurred during late 1200s, mid to late 1300s, late 1400s, early 1700s, and early to mid-1900s. The only continuous multi-decadal wet period was from late the 1400s to early 1500s. Unusually high variability is shown from the mid 1500s to early 1600s. Two of the sustained drought periods (mid to late 1300s and early to mid 1900s) both show similar patterns of low variability. The driest 5 yr in the reconstruction are 1443–1447 (-0.7). By comparison, the driest 5 yr in the observed data are 1925–1929 (-0.4). The wettest reconstructed 5 yr period was 1751–1755 (0.93), while the wettest 5 yr in the observed data was 1989–1993 (0.73).

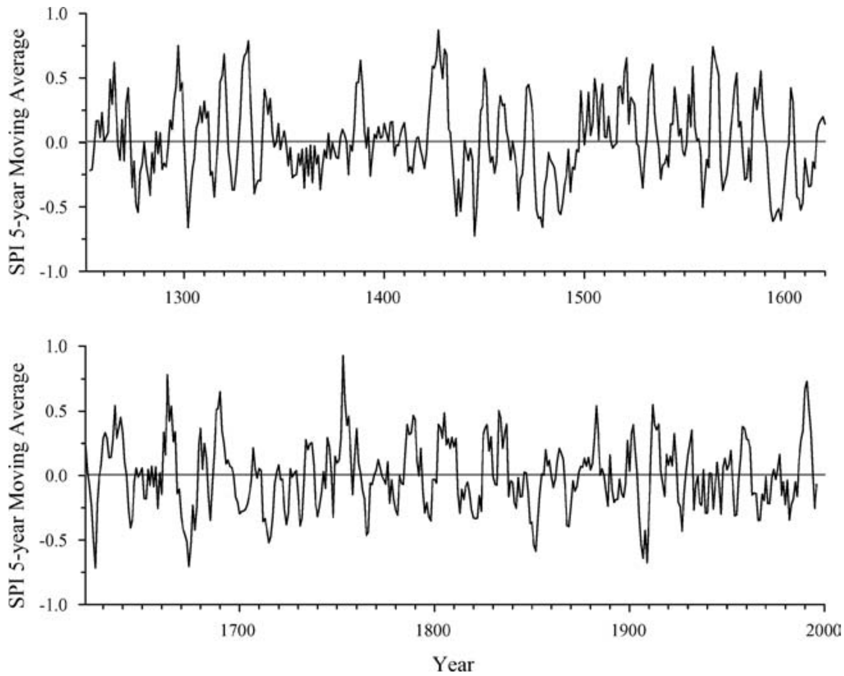

Figure 5. Time series plot of low-pass filtered (50% response) reconstructed May–July SPI, AD 1251–1998.

This much longer and more heavily replicated SPI reconstruction is significantly correlated with the February–August precipitation reconstruction of D'Arrigo and Cullen (2001) ($r = 0.69$, $n = 353$, $P < 0.01$). This correlation is not surprising as their reconstruction was for a station within the large gridded area used in this study and two of the five tree-ring series they used were from the subregion where our sampling effort was concentrated. Furthermore, spectral analysis of our reconstruction (Spectral density, smoothed by 9-weight Hamming filter, a finite impulse response filter which is commonly used in spectral analysis because it provides a good frequency response) resembles the spectrum of their reconstruction for the same period, with, among others, evidence of concentration of spectral power close to periods of 2.2, 8–10, and 27 yr over a 352-yr period. As D'Arrigo and Cullen (2001) pointed out, these periods also exist in the North Atlantic Oscillation instrumental record and in the Cook et al. (1998) NAO reconstruction. Similarly, we have not been able, as yet, to establish a strong, direct, statistical relationship between the SPI reconstruction and the NAO.

The temporal specificity of the SPI reconstruction render it suitable for comparison with historical records that have been subject to rigorous climatic analysis (Grove and Contario, 1995; Xoplaki et al., 2001). For example, several major historical events (Kuniholm, 1990; Purgstall, 1983) coincide with extreme dry periods seen in the 1251–1998 reconstruction. For example, Kuniholm (1990, p. 253) relays historical evidence (communicated to him by Professors H. Inalcik and W. Griswold) for widespread famine and food shortages across Turkey, Syria, and Italy during the late 16th century. This is coincident with the period of extended extreme drought in the reconstruction (1592–1596) (see Figure 5). Purgstall (1983) reported catastrophic fires and famine in Anatolia in 1660. The reconstruction shows that 1660 was an extremely dry summer. In addition, the preceding year was wetter than average. This is a common pattern where, during wet years, there is a build up of fine fuels which become an important pre-condition for fire spread after ignition when conditions become drier. Purgstall (1983) reported a sustained famine in Anatolia from 1925–1928. The reconstruction shows that 1926–1929 is a sustained dry period with 1927 exceeding the drought threshold with an SPI of -1.4. We intend to follow up on this in future studies as we expand our network of tree-ring sites.

5. Conclusions

This paper presents the first SPI reconstruction (1251–1998) developed using tree-ring data. Our reconstruction will provide essential information concerning hydroclimatic variability in the southwestern and south-central Turkish regions. Understanding drought characteristics for several centuries will help natural resource managers apply low risk and long-term plans to conserve and sustain water and other natural resources that are the foundations of social, political, and economic systems in the region. It also provides an additional dimension in the study of environmental history and its relationship to human social and population dynamics.

The longest identified period of consecutive May–July drought during the past seven centuries was 2 yr. Two drought events of two consecutive years occurred in the seventeenth century (1607–08 and 1675–1676) and one 2-yr dry period occurred in the twentieth century (1907–1908). The 1-yr dry periods were evenly distributed throughout the seven centuries, with the exception of the sixteenth century that has only two events. The sixteenth century, however, recorded the highest number of wet periods.

Notable periods of multi-year and decadal variation were observed in the reconstruction. The mid to late 1300s and early to mid 1900s reveal similar patterns of extended drought accompanied by low variability. An extended period of high variability was recorded from the mid 1500s to the early 1600s. The reconstruction shows spectral peaks similar to those of the North Atlantic Oscillation, although a direct statistical relationship between them has not been established.

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