A 396-YEAR RECONSTRUCTION OF PRECIPITATION IN SOUTHERN JORDAN

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A 396-YEAR RECONSTRUCTION OF PRECIPITATION IN SOUTHERN JORDAN[1]

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ABSTRACT: Water resources are the lifeblood of the Near East region. Careful planning and management of water resources in dry land regions requires information on the likelihood of extreme events, especially prolonged drought. It is essential to understand the variability of climate on time scales of decades to centuries to assign reasonable probabilities to such events. Tree-ring analysis is one way to increase our knowledge of the climate variability beyond the short period covered by the instrumental data. In this paper, we reconstruct October-May precipitation from a *Juniperus phoenicia* tree-ring chronology in southern Jordan to gain a long-term (A.D. 1600-1995) perspective on runs of dry years and on time series fluctuations in precipitation averaged over several years. The reconstruction equation derived by regression of log-transformed precipitation on tree-ring indices explains 44 percent of the variance of observed precipitation. The longest reconstructed drought, as defined by consecutive years below a threshold of 217.4 mm, was four years, compared with three years for the 1946-95 instrumental data. A Monte Carlo analysis designed to account for uncertainty in the reconstruction indicates a lower than 50 percent chance that the region has experienced drought longer than five years in the past 400 years.

(KEY TERMS: dendrochronology; tree-rings; drought; desertification.)

INTRODUCTION

The quantity and quality of water often constrain agricultural development and plans for future agricultural expansion in the Near East. Problems posed by the limited water resources are exacerbated by a rapidly growing population, which exceeds 200 million people, and is expected to more than double between A.D. 1990 and 2010. Jordan is swiftly approaching the point where it will use all of its available water resources. The Bureau for the Near East (1993) projects that the demand for water in Jordan in the year 2030 will be sixfold that of 1985.

Long term drought in the Near East will greatly affect human beings, animals and soils. Persistent 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 such as Jordan's Badia region, where shortages of water force the Bedu (nomads) along with their animals to migrate, looking for water resources and grasses in four adjacent countries: Syria, Iraq, Jordan, and Saudi Arabia. Such human activities in this dry region cause the degradation of land and water resources, and eventually desertification.

Careful planning, therefore, is critical for the sustainable use of these limiting water resources. Such planning 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.

To understand drought we need to characterize the variability of climate on time scales of decades to centuries. Most high quality instrumental climate records in Jordan start in the 1940s or 1950s, and so contain little information on variability over decades and longer periods. Dendrochronology is one available tool for extending climatic records. Time series of tree-ring growth measurements spanning several centuries may serve as proxy records of past climatic conditions. Such records provide us with knowledge of the past frequency and severity of climatic anomalies such as drought and wet periods, which in turn may be used to help anticipate the future probability of such events.

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Relatively few dendrochronological studies have been performed in the Near East. Some studies have concentrated on using tree ring data to develop paleoclimate records (Liphschitz and Waisel, 1967; Shanan *et al.,* 1967; Chalabi and Martini, 1989; Munaut, 1982; Parsapajouh *et al.,* 1986). Other studies have used tree-ring series to date archeological sites (Bannister, 1970; Kuniholm, 1996; Lev-Yadun, 1992), while others have addressed the cycle of cambial activity in a given species of tree with the aim of determining if a ring represents one year of growth (Liphschitz and Lev-Yadun, 1986; Fahn *et al.,* 1986).

No dendroclimatic reconstruction of precipitation is currently available for Jordan or surrounding countries in the Near East. Some reconstructions are available for other parts of the Mediterranean region (e.g., Stockton, 1985; Meko, 1985; Chbouki, 1992), but the large spatial variability of climate in the region precludes their use for inferring climatic variations in Jordan.

This paper describes the development of a long tree-ring chronology of *Juniperus phoenicia* from Southern Jordan, and application of the chronology to develop the first dendroclimatic precipitation reconstruction in the Near East. The resulting 396-year reconstruction for southern Jordan is analyzed for time series features of variability relevant to water resources planning.

SITE DESCRIPTION

The sampled tree-ring sites are Dana Reserve in the Tafile District (30°38´N, 35°43´E) and Tor-Al Iraq near the Shaubak village, Petra District (30°28´N, longitude 35°30´E) (Figure 1). The two sites separated by about 25 km are part of the Highlands region in southern Jordan. The elevation of the sampled sites ranges between 1100 m and 1400 m above sea level.

The main soil type of the study areas is a poorly structured shallow calcareous loam, with a low bulk density and a very low content of organic materials. On steep slopes the soils are eroded, with sheet, rill, and gully erosion clearly visible (FAO, 1995).

The climate of the study area is characterized as semi-arid Mediterranean. Areas above 1000 meters are characterized by yearly snowfall, and a meter of snow has been reported to cover some areas and last for more than one month (Bensada, 1995). Precipitation occurs only during the fall, winter, and spring (October- May) (Figure 2). Mean annual precipitation for three nearby climate stations (Tafile, Dana, and Shaubak) is 270 mm.

Mean annual temperature at Shaubak is around 13°C (Figure 2). August is the hottest month with a mean daily temperature of 20.7°C. January is the coldest month with a mean daily temperature of 4°C. The highest mean monthly maximum temperature occurs in August (34°C) and the lowest mean monthly minimum temperature is in January (-14°C).

The overstory in sampled sites ranges from pure Juniperus phoenicia to areas mixed with *Pistacia atlantica,* and *Quercus calliprinos.* In a relatively small area near Ain Lahda at the Dana Reserve *Juniperus phoenicia* is associated with *Cupressus sempervirens.* The understory is dominated by shrubs and grasses. The shrub layer is dominated by small individuals of oak and juniper associated with species such as *Artemesia herba-alba, Gymnocarpus decandrum, Retama raetum, Helianthemum lipii,* and *Ornopodum ambiguum.* Common grasses and herbs include *Anchusa strigosa, Anthemis melampodina, Globularia arabica, Origanum syriacum, Aegilops cylindrica, Phagnolon rupestre, Psoralea flaccida, Poa bulbosa, Anthemis* spp., *Hirshfeldia* spp., *Hordeum glaucum,* and *Ballota undulata.*

DATA

Seventeen cross-sections of *Juniperus phoenicia* were used from the two sites. In the laboratory, samples were fine-sanded to give a highly polished surface, and crossdated using standard dendrochronological techniques (Stokes and Smiley, 1968) to ensure that each growth layer on every sample was assigned to the exact calendar year. We had great difficulty in crossdating some of the samples because of the high number of locally absent rings (approximately 0.71 percent) and intrannual boundaries (false rings) in some of the samples. Fisher (1994) reported that *Juniperus excelsa* from Oman similarly has a high proportion of missing and false rings.

Each annual ring on the cross-sections was measured to the nearest 0.01 mm. Each time series of ring measurements was then detrended by fitting a cubic smoothing spline with 50 percent cutoff frequency of 200 years to remove the age trend and the effects of stand dynamics (Cook and Kairiukstis, 1990). The detrended index series were prewhitened to remove persistence not related to climatic variation, and combined into a single chronology using a biweight robust estimate of the mean (Cook, 1985). The combined chronology covers 527 years (1469-1995).

The number of samples in the early part of a tree-ring chronology is usually smaller than in the more recent period of overlap with the instrumental data on which transfer functions between tree rings and climate are based. We used the subsample signal strength (SSS) to assess the adequacy of replication in

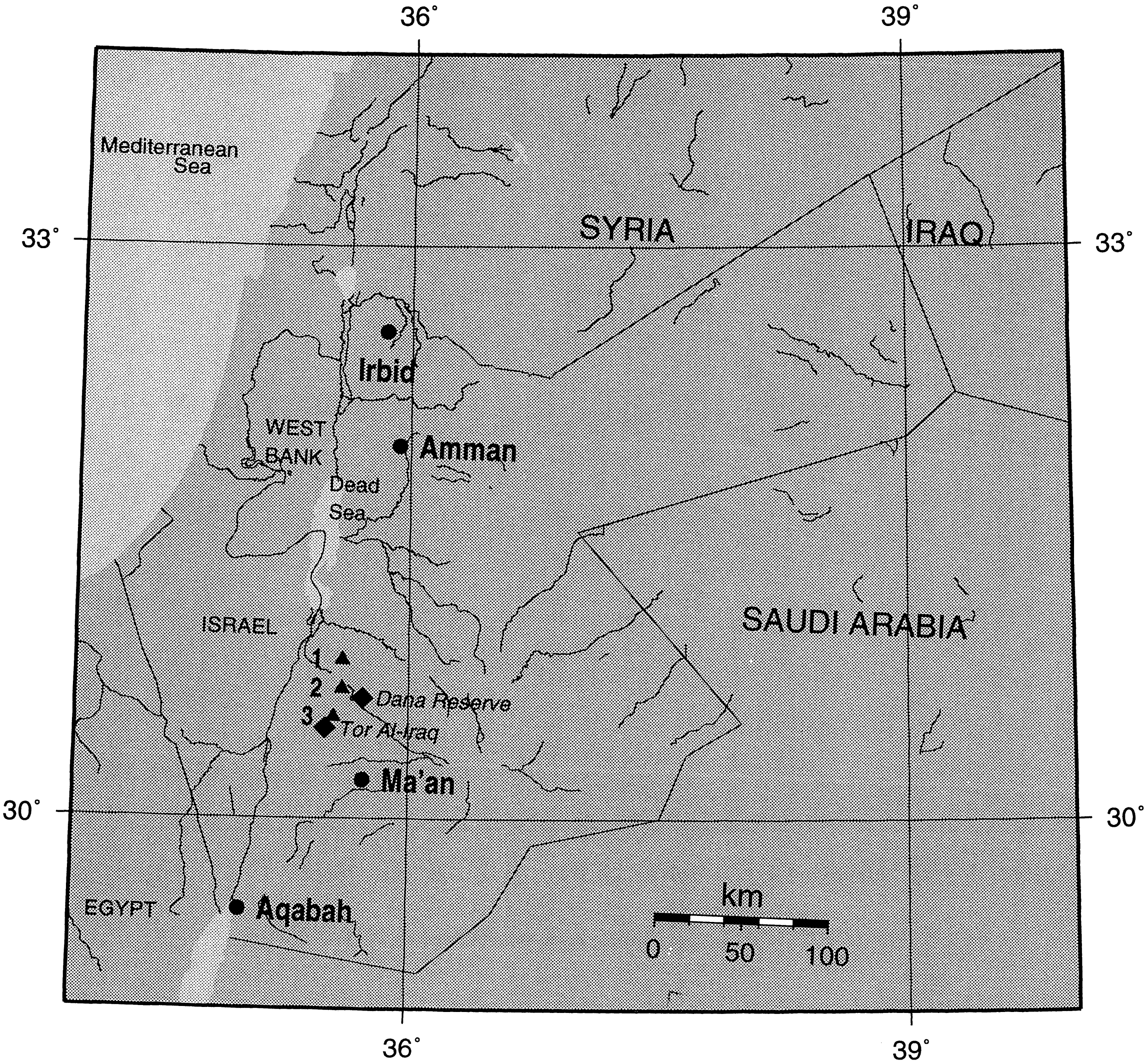

Figure 1. Locations of Tree-Ring Sites (◆) and Three Weather Stations (▲) in Southern Jordan. Station numbering: (1) Tafile, (2) Dana, and (3) Shaubak.

the early years of the chronology (Wigley *et al.*, 1984). The SSS, which is computed from data on sample size and between-tree correlation, is a guide to assessing likely loss of reconstruction accuracy which occurs when a chronology made up of a few series is used to reconstruct past climate with a transfer function derived from a chronology of a greater number of series (Wigley *et al.*, 1984). The average correlation coefficient between trees for our analysis is 0.45 (n = 282), which demonstrates a moderate common growth signal among trees. To ensure the reliability of the reconstructed climate we restricted our analysis to the period with an SSS of at least 0.94. This threshold corresponds to a minimum sample depth of 6 trees, and allows for reconstruction for the period AD 1600 to 1995.

We selected three meteorological stations with precipitation records (Tafile, Dana, and Shaubak) near the sampled tree-ring sites (Figure 1). There were no missing data for any of the three stations during the period 1946-1995. The three stations were screened for inhomogeneity by double-mass analysis, a graphical technique (Kohler, 1949); none exhibited inhomogeneity. Response function analysis (Fritts, 1976) between the chronology and monthly and seasonal temperature and precipitation of Shaubak station indicated that October to May precipitation was the most appropriate predictand for reconstruction.

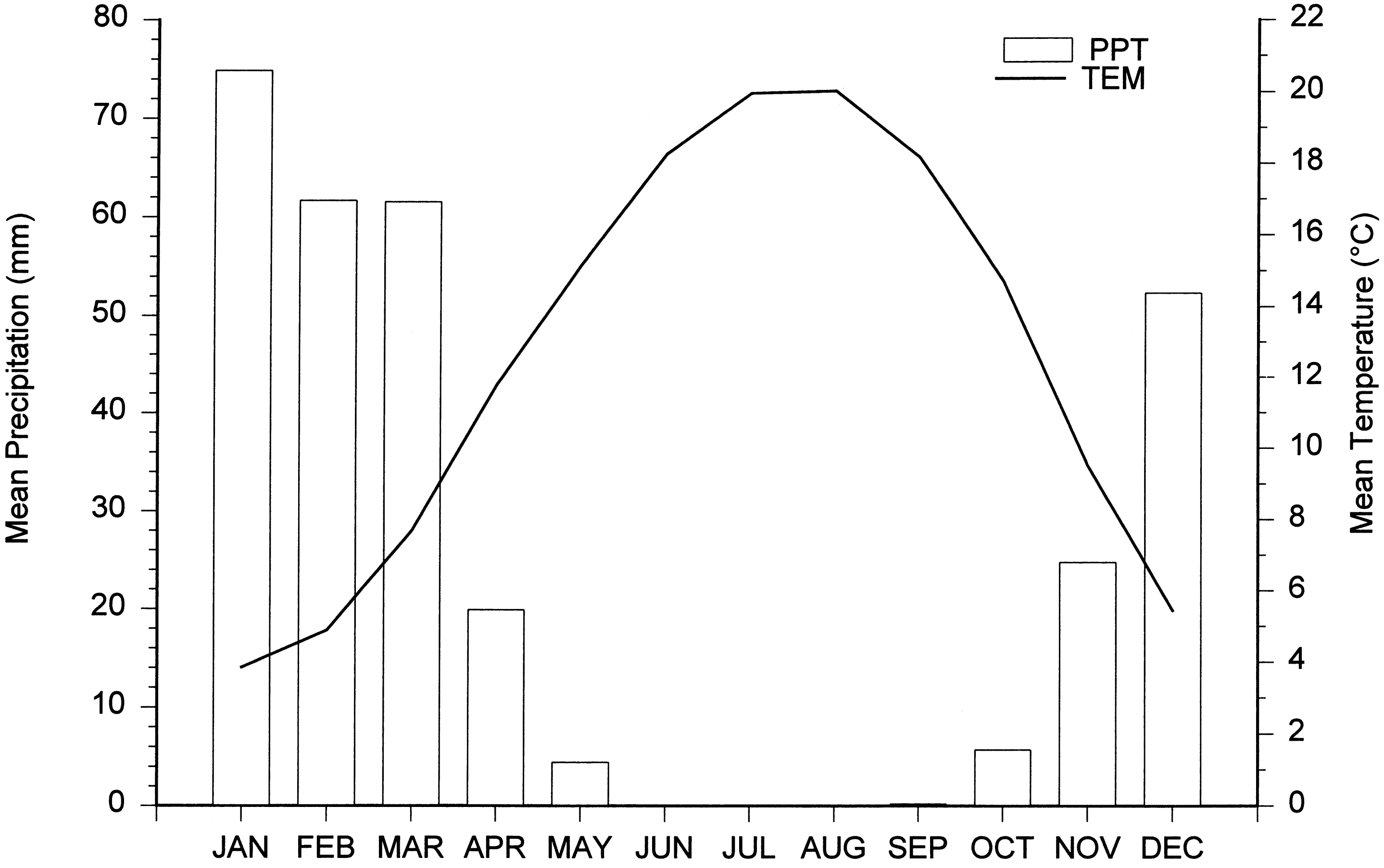

Figure 2. Climagram for Shaubak, Southern Jordan, A.D. 1965-1995.

RECONSTRUCTION MODEL

The interstation correlation of October-May precipitation for the period from 1946 to 1995 exceeds 0.90 indicating a strong regional climate signal. Moreover, The October to May mean precipitation is similar at the three stations (260, 261, and 294 mm). Therefore, we averaged the May-October precipitation over the three stations to develop a regional series for the reconstruction model. The log-transformed regional precipitation series is the predictand for the reconstruction model.

The regression equation between the tree-ring indices (predictors) and log10 precipitation (predictand) for the 1946-1995 calibration period is highly significant ($F = 39.7$, $p < 0.0001$). The regression model for the calibration period is:

$$Y = 1.9958 + 0.4012X$$

where Y= Log_{10} Precipitation (precipitation in mm) and X = Tree-Ring Indices. The predictor variable accounts for 44 percent (adjusted for loss of degrees of freedom) of the variance in the $\log_{10}$ precipitation (Figure 3). Cross-validation using the PRESS procedure (Weisberg, 1985) indicated that the model performs well in estimating precipitation data not used to fit the model (R^2 of 0.41). The regression equation was therefore deemed appropriate for reconstruction back to AD 1600.

As shown in Figure 3, tree growth responded extremely poorly to the two wet years 1964 and 1965. In December 1963 a single storm accounted for 62 percent (352mm/567mm) of the total October-May rainfall. In January 1965, another storm produced 66 percent (350mm/527mm) of the total rainfall. Large surface runoff from these two events likely resulted in little increase in the soil moisture available for tree growth. We tested an alternative model treating the years 1964 and 1965 as outliers and omitting them from development of the regression equation. Doing so raises the adjusted R^2 to 0.58. However, we included 1964 and 1965 in the calibration of our reconstruction model because we cannot discount the possibility that similar events have happened in the past.

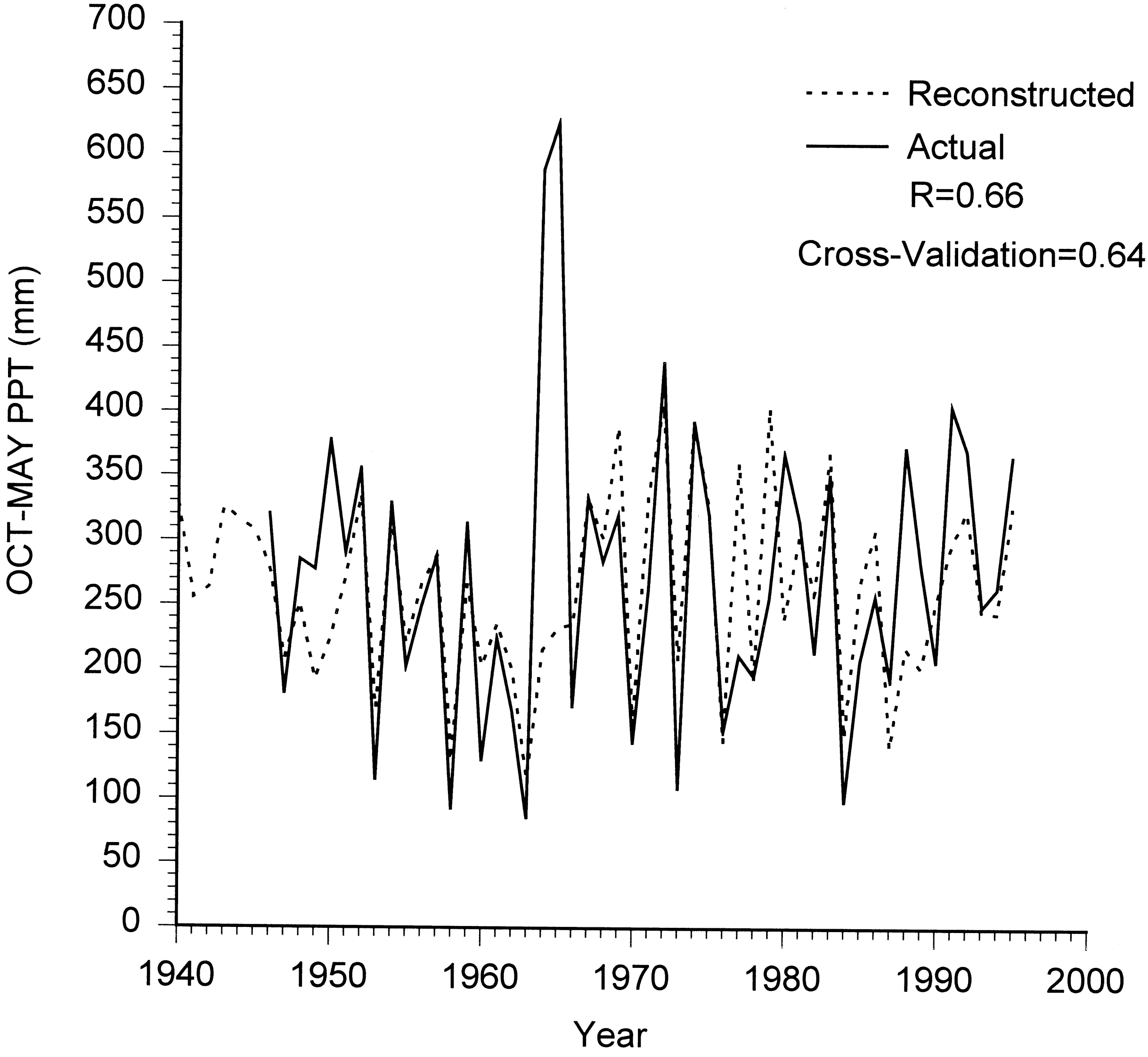

Figure 3. Comparison of Actual and Estimated October Through May Precipitation for Southern Jordan, A.D. 1946-1995.

ANALYSIS OF RECONSTRUCTION

The annual reconstructed time series of May-October precipitation is plotted in Figure 4. We summarized the short-term drought properties in this series by runs analysis (Sadeghipour and Dracup, 1985) using an arbitrary threshold of 217.4 mm to define a "drought year." This threshold is approximately 80 percent of the 1946-1995 mean observed October-May precipitation. By this method of tabulation, the long-term reconstruction contains 93 drought years with an average interval between droughts of 4.2 years and a maximum interval of 16 years (1664-1680). Fifty-five drought events had a duration of 1 year, seven a duration of 2 years, four a duration of 3 years, and three a duration of 4 years.

The runs summary is sensitive to the choice of drought threshold, such that raising or lowering the threshold slightly can appreciably affect the drought tally. For example, raising the threshold can cause two short droughts separated by a year with precipitation slightly above 217 mm to merge into a longer drought. Moreover, the loss of variance in regression ($R^2 < 1.0$) forces the reconstructed values to be conservative (closer to the calibration-period mean) relative to the observed data. This compression of range lowers the frequency of occurrence of events of extremely high or low precipitation below that indicated by the observed data. Because the tree-ring estimates themselves contain error, the tree-ring reconstruction plotted in Figure 4 is best interpreted in a probabilistic sense.

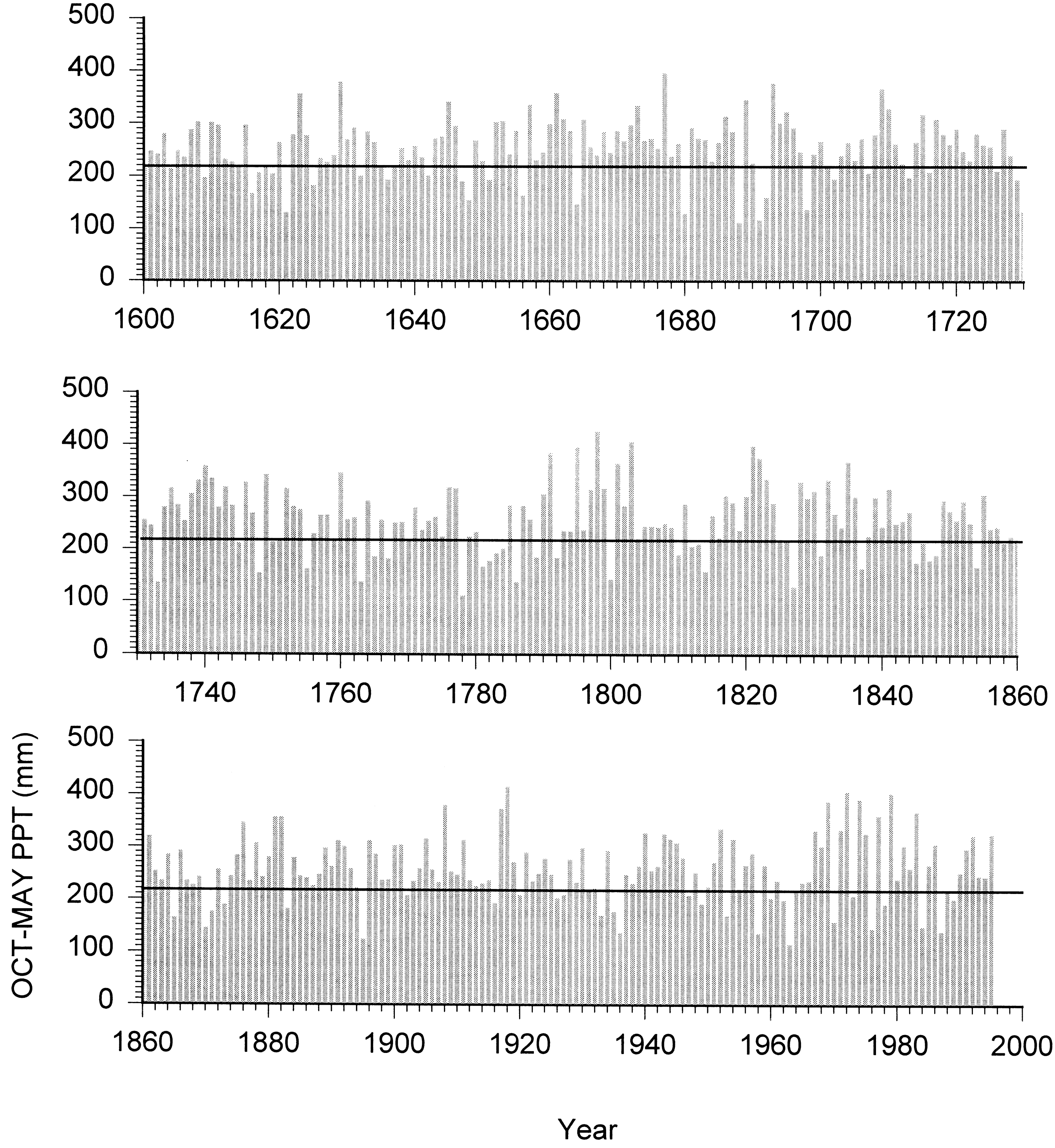

Figure 4. Time Series Plot of Reconstructed October through May Precipitation, A.D. 1600-1995. Horizontal line is an arbitrary drought threshold of 217.4 mm.

We have done this by a Monte Carlo approach that yields empirical confidence intervals for statistics (e.g., runs properties, running means) of the annual reconstruction. The steps in the procedure are as follows: (1) draw 1000 random sequences of length 346 years (1600-1945) from a normal distribution with mean zero and variance equal to the error variance of the reconstruction equation, (2) add these noise sequences to the 1600-1945 reconstruction, in log10 units, to get 1000 noise-added reconstructions, (3) back-transform the noise-added reconstructions to millimeter units, (4) compute the desired summary statistic separately on each of the 1000 noise-added series, and (5) extract confidence intervals for the statistic from its empirical cumulative probability function.

Each noise-added reconstruction can be considered a possible historical sequence of the unknown precipitation given the reconstructed values and the uncertainty in the reconstruction. The effect of addition of noise can be seen when the above procedure is repeated for the short (1946-95) period for which both reconstructed and observed precipitation are available. Box plots of distributions based on 50-year samples of data are shown in Figure 5. The two boxes at far left show that the distribution of the reconstructed values for 1946-95 is indeed compressed relative to that of the observed data. The remaining boxes (only the first 8 of 1000 are shown) indicate that the addition of noise spreads out the distribution of the reconstructed data such that the low extremes of the various noise-added reconstructions fluctuate around the low extreme of the observed data.

The Monte Carlo results for the long-term reconstruction were used to derive an empirical probability distribution for the maximum severity of 1-yr, 2-yr, etc., drought. The median, 5th and 95th percentile of the maximum severity as a function of drought duration are plotted in Figure 6. Annotated above the 95th percentile bar is the total number of simulations (maximum possible is 1000) with at least one drought of the indicated duration. For example, only 128 of 1000 simulations have any droughts lasting seven years.

Droughts longer than five years appear unlikely, occurring in fewer than half the noise-added series.

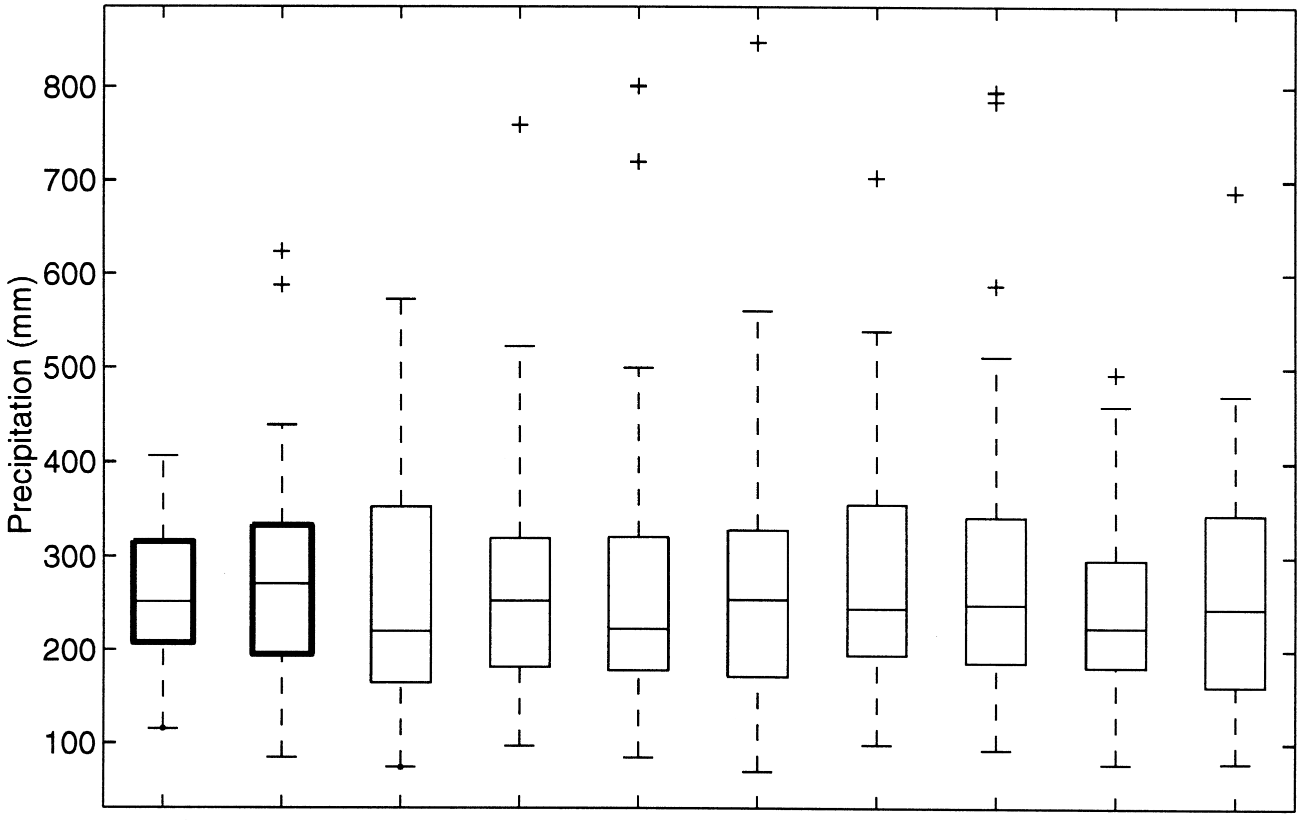

Figure 5. Box Plots Comparing the Distributions of Reconstructed and Observed Precipitation for the 1946-95 Calibration Period and Illustrating Effect of Adding Random Normal Noise to Reconstruction. From left: boxes for reconstructed data, observed data, and the first 8 of 1000 noise-added reconstructions. Sample size is 50 for each box. Box elements are median (central horizontal line), range (whiskers), interquartile range (box limits), and outliers (plus signs) any values at a distance of more than 1.5 times the interquartile range from the mean. Noise-added reconstructions defined in text.

In contrast, all 1000 noise-added series have at least one 3-year drought. As shown in Figure 6, the maximum severity of 3-year drought in the instrumental period is unrepresentative of the most severe 3-year droughts in the long-term reconstruction. The most severe 3-year instrumental drought has a cumulative deficit of 93 mm below the drought threshold. In contrast, the median deficit for the most severe 3-year droughts in the noise-added reconstructions is 230 mm.

The ranges on the maximum severity values in Figure 6 can be used as a guide for posing extreme scenarios. For example, the upper bar for the 3-year duration indicates a 5 percent probability that the maximum severity of 3-year drought was greater than 309 mm. The corresponding average annual deficit is 103 mm per year. For the specified threshold of 217.4 mm, this average deficit could result from three years of October-May precipitation averaging 114 mm/yr. For a perspective, the observed October-May precipitation has been less than 114 mm only four times in the 1946-95 instrumental record.

An alternative summary of the severity of hydrologic drought is given by low values in precipitation averaged over several years. Such a summary for 5-year periods of the reconstruction is given by the plot of 5-year moving average reconstructed precipitation (Figure 7). The adjacent periods 1959-63 and 1964-68 mark the low and high 5-year running means for the instrumental period; these periods represent a swing in mean precipitation from 184 mm to 400 mm. The reconstruction includes no comparable swings from

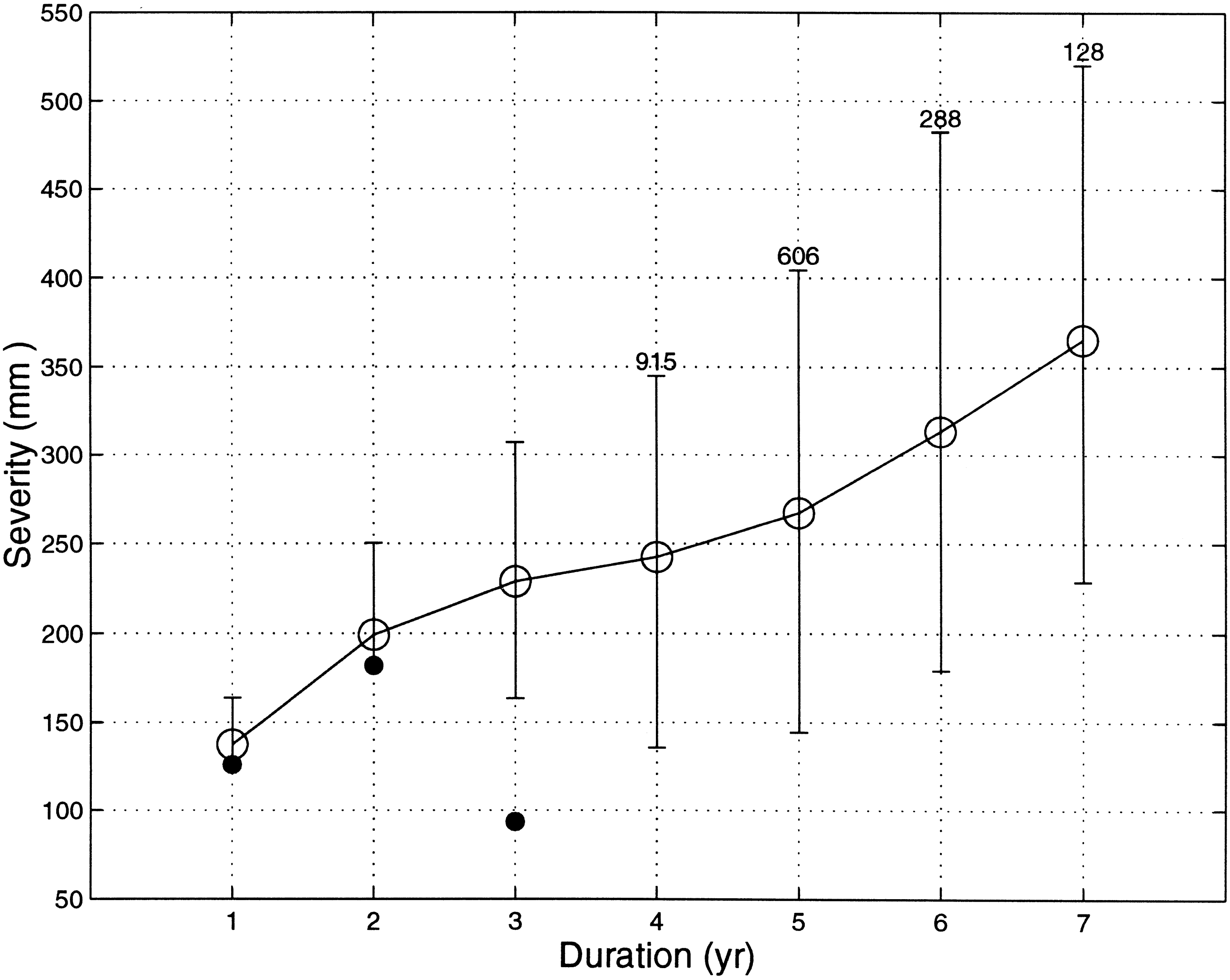

Figure 6. Median, 5th, and 95th Percentiles of Severity of Most Severe n-Year Droughts in Noise-Added Reconstructions, 1600-1995. Black dots mark most severe n-year droughts in the observed precipitation series, 1946-95. Severity defined as run-sum below an arbitrary drought threshold of 217.4 mm. Results based on 1000 simulations. Number of simulations having at least one n-year drought annotated unless all simulations have a n-year drought.

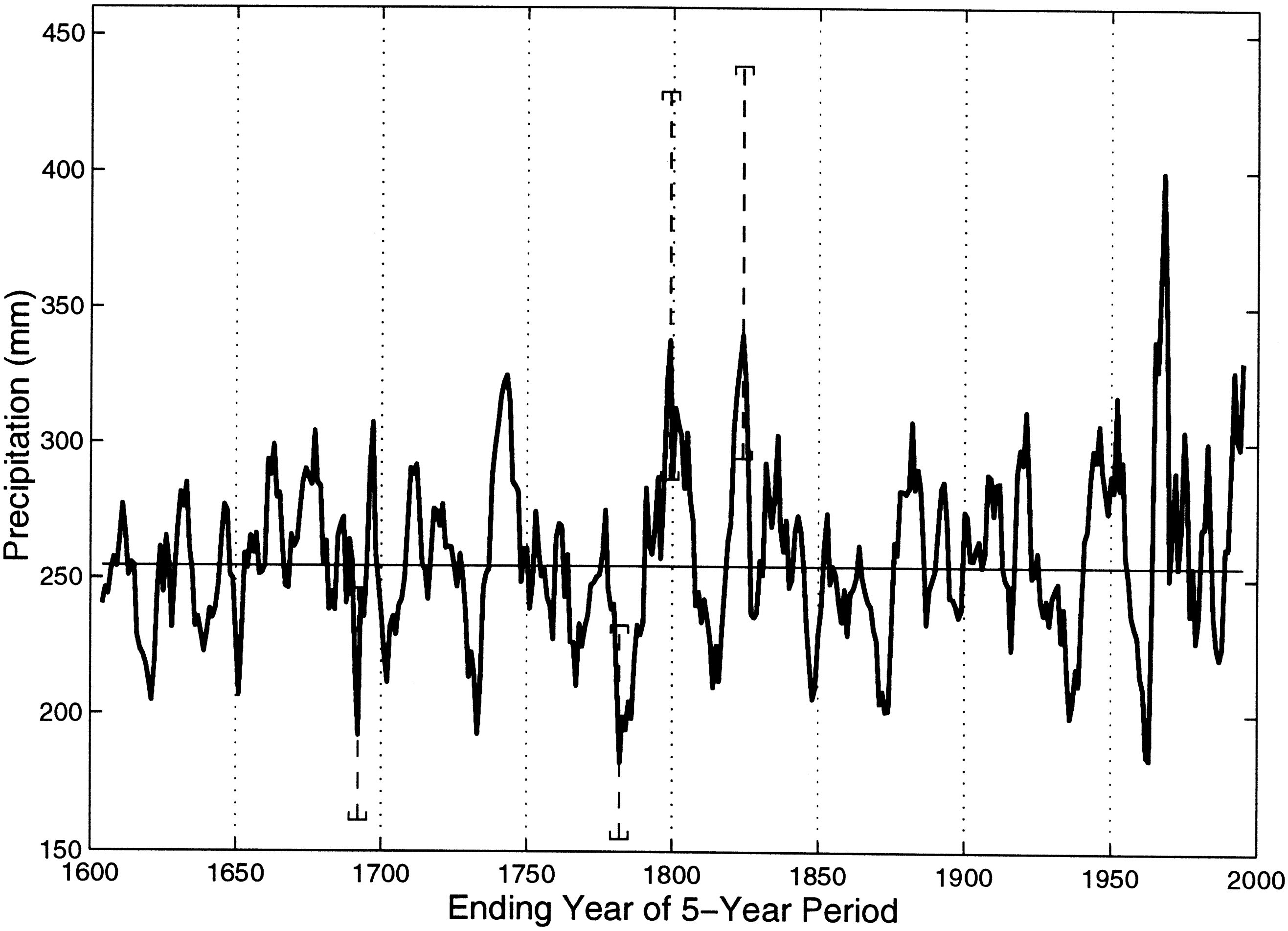

Figure 7. Five-Year Running Mean of Reconstructed October-May Precipitation for Southern Jordan, 1600-1995. Error bars indicate 10th and 90th percentile of values for 1000 noise-added reconstructions, as described in text. Series before smoothing made up of annual reconstructed data 1600-1945 and actual data 1946-95.

dry to wet conditions. The 5-year reconstructed mean for 1778-82 (182 mm) is however slightly lower than the lowest 5-year mean in the instrumental record.

As with the runs properties described previously, the reconstructed running means are uncertain to a degree depending on the variance not accounted for by the regression model. The same Monte Carlo procedure used in the runs analysis was applied to derive confidence bands for the reconstructed running means. In this case, the 1000 noise-added reconstructed precipitation series were filtered into 5-year running means. For any given five-year period (e.g., 1778-1782), this procedure yields a set of 1000 possible values of mean precipitation. The empirical cumulative frequency distribution for these 1000 values can be used to attach confidence bands around the reconstructed 5-year mean. An 80 percent confidence band (defined by the 10 percent and 90 percent exceedance probabilities) derived in this way has been marked for selected periods in the time series in Figure 7. These confidence bands allow assessment of the probability of large departures. For example the probability is 10 percent that the 1778-82 mean (reconstructed at 182 mm) was as low as 155 mm.

Because the reconstruction equation was derived for log-transformed precipitation, the error bars are asymmetrical about the estimates and are wider for wet periods than for dry periods. Thus the magnitude of peaks such as those in the 1790s and 1820s is highly uncertain. The difficulty in reconstructing extremely wet years is probably due to the fact that tree growth at the sampled sites does not respond positively beyond a certain level of soil moisture. It may be possible to estimate precipitation in extreme wet years using $\delta^{13}C$ from tree-ring cellulose (Leavitt, 1994).

CONCLUSION

Tree-ring reconstruction provides a baseline for studying past climate variability in southern Jordan. Understanding the effects of this variability is important for managers of water, agriculture, and other resources because it will help them to implement low-risk, long-term plans to achieve conservation and sustainable use of water and other natural resources.

Calibration and verification statistics indicate moderate accuracy for this tree-ring reconstruction of precipitation for southern Jordan. The longest period of reconstructed drought during the past four centuries is four years. Monte Carlo analysis indicates that drought periods longer than five years are unlikely, and that the maximum severity of three-year drought is considerably greater in a long-term context than suggested by the short instrumental record. A swing from very dry to very wet conditions in the 1960s appears to be unprecedented in severity in the past 400 years.

More sampling is needed from southern Jordan to increase the length of the reconstruction and to improve the accuracy of the reconstruction. Moreover, tree-ring sampling needs to be extended to the neighboring countries in order to gain a better understanding of past climate variability for the whole region.

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