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DENDROCLIMATIC RECONSTRUCTIONS FOR THE SOUTHERN COLORADO PLATEAU

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ABSTRACT

A geographical network of climate sensitive tree-ring chronologies consisting of 25 archaeological sequences and two bristlecone pine series provides the basis for high resolution reconstructions of low and high frequency climatic variability on the southern Colorado Plateau over the last 1,500 years. Qualitative and quantitative dendroclimatic analyses of these data produce annual retrodictions of yearly and seasonal precipitation and summer Palmer Drought Severity Indices for each station and reconstructions of regional scale patterns in climatic variability. These reconstructions provide detailed information on climatic fluctuations that affected biotic and human populations as well as long-term baseline data for evaluating present-day climate and estimating future climatic trends. When integrated with other measures of past environmental variability, these reconstructions specify periods of favorable and unfavorable environmental conditions that would have affected past human populations of the region. The severest degradation, which occurred between A.D. 1250 and 1450, probably was causally related to numerous cultural changes that occurred at the end of the 13th century including the Anasazi abandonment of the Four Corners area. Projecting environmental patterns that characterized the last two millennia into the future indicates potential hazards to long term uranium mill waste disposal and containment and the potential and limitations of environmental restoration.

INTRODUCTION

Dendroclimatic research in general and on the Colorado Plateau in particular began early in the 20th century with the work of Andrew Ellicott Douglass, an astronomer at the Lowell Observatory in Flagstaff, Arizona, who was investigating relationships between solar activity and terrestrial climate. Lacking weather data long enough to establish climatic cycles comparable to the known 22-year sunspot cycle, he turned to the annual rings of trees as possible climatic records and invented the science of dendrochronology (Douglass 1909, 1914, 1919). Dendrochronology (Bannister 1963:161) employs the annual growth rings of trees as measurements of time and a means of dating past events (Dean 1978a) and as proxy records of past environmental conditions and changes (Fritts 1976). The first aspect of dendrochronology endows Southwestern archaeology with the finest prehistoric chronological controls in the world (Dean 1978b, 1986); however, our primary concern here is the second aspect, the reconstruction of past environmental variability.

Douglass first established a quantitative relationship between tree growth and climate in 1914 when he showed a strong positive correlation between ring width and the precipitation of the preceding winter (Douglass 1914). This discovery was developed into the subdiscipline of dendroclimatology, which is concerned with the relationships between tree growth and various external factors and with using variability in ring morphology to estimate past fluctuations in these environmental factors. Douglass' insistence on the uncompromising application of rigorous procedures and standards of tree-ring dating (Douglass 1946) established a firm conceptual and analytical foundation for dendroclimatic reconstruction. Although much of Douglass' subsequent work was focused on the cyclic information in tree-ring series, his colleagues and successors maintained and refined the discipline.

Dendroclimatic research was significantly advanced by Douglass' protégé, Edmund Schulman, who made tremendous strides with comparatively rudimentary analytical techniques. Schulman's scientific vision was enormous, but his efforts were impeded by the inadequacies of the available analytical methods and equipment. He was, for example, forced to analyze vast quantities of data and perform complex statistical operations with hand cranked calculators. His crowning achievement (Schulman 1956) was the publication of Dendroclimatic Changes in Semiarid America, which incorporated many tree-ring chronologies into an analysis of past climatic variability across western North America. Schulman's painstaking work established high standards for dendroclimatic research and set the stage for the great leap in dendroclimatology that occurred only a few years after his untimely death in 1958.

In the 1960s, Harold C. Fritts (1976), his colleagues, and students employed biological expertise, sophisticated multivariate statistical techniques, and computers capable of handling large quantities of data to revolutionize dendroclimatology. They developed and perfected current standards and techniques, which involve the simultaneous analysis of scores of tree-ring and environmental variables over many centuries. These procedures established consistent relationships between tree growth and environmental factors that are used to produce both qualitative and quantitative environmental reconstructions from tree-ring chronologies.

The research covered in this paper applies modern techniques of dendroclimatic analysis to long tree-ring chronologies that combine ring records from both living trees and archaeological samples in the Southwest. The Laboratory of Tree-Ring Research's "Southwest Paleoclimate Project" is a long term dendroclimatic study that grew out of the "Synthesis Project," a National Science Foundation-sponsored reanalysis of the Laboratory's Southwestern archaeological tree-ring collections undertaken between 1962 and 1975 (Robinson et al. 1975:1–2). Among other things, the Synthesis Project produced a large number of measured archaeological tree-ring samples suitable for dendroclimatic analysis. Subsequent grants from the National Park Service, the Southwestern Parks and Monuments Association, and the Department of Defense Advanced Research Projects Agency underwrote the collection and processing of living-tree samples from the region, the construction of 25 climate-sensitive composite ring chronologies composed of archaeological and living-tree samples (Dean and Robinson 1978), and the reconstruction of relative climatic variability in the Southwest from A.D. 680 to 1970 (Dean and Robinson 1977). During the last three years, additional NSF support has allowed the Southwest Paleoclimate Project to produce quantitative reconstructions of annual and seasonal precipitation and temperature, drought, and streamflow for the region.

DENDROCLIMATIC ANALYSIS

Dendroclimatic analysis is extremely complicated. Fortunately, the relevant assumptions, principles, and procedures have been described in detail elsewhere (Fritts 1976; Graybill 1982;

Rose et al. 1981), and they need be only summarized here.

In general, two types of dendroclimatic reconstruction are possible (Dean 1988b). Qualitative reconstructions use tree-ring chronologies as direct measures of relative variability in past climate. In the Southwest, the strong positive correlation between tree growth and precipitation (Fritts 1974) establishes such reconstructions as accurate indicators of relative deviation from average annual rainfall. Quantitative reconstructions, on the other hand, employ mathematical expressions of the relationships between tree growth and specific environmental variables—precipitation, temperature, air pressure, drought, streamflow, crop yields, etc.—to statistically estimate annual and seasonal values for appropriate measures of these variables, such as inches of precipitation, degrees of temperature, millibars of pressure, Palmer Drought Severity Indices (PDSI), acre-feet of runoff, and bushels or pounds per acre of various crops.

Two kinds of data, tree-ring and environmental, are involved in quantitative dendroclimatic reconstruction. Usually, the former consist of long tree-ring chronologies produced by averaging standardized ring-width indices from hundreds of samples from trees that grew in a fairly restricted geographical area. Such chronologies can consist entirely of samples from living trees, from living trees and deadwood remnants, or from living trees and archaeological and/or geological wood. Whatever a chronology's composition, it includes only samples that have been carefully screened against criteria known to characterize great sensitivity to climatic or other environmental factors. These criteria include growth-site characteristics for living trees (Fritts 1976:17–19; Fritts et al. 1965a) and several morphological and statistical characteristics of the individual sample ring series (Fritts 1976:28–34; Fritts and Shatz 1975; Rose et al. 1981:11–15).

The environmental data consist of primary or secondary records of the relevant variables from locations throughout the study region. Most commonly, meteorological records supply primary data on factors such as precipitation, temperature, and frost-free period or data used to calculate derivative measures such as PDSI. Other environmental data, such as records of atmospheric pressure, streamflow, and crop production, are less commonly used.

Both the tree-ring and environmental data sets are rigorously tested for statistical stability, representativeness, and suitability for statistical analysis before they are used in dendroclimatic reconstruction (Fritts 1976:246–311; Rose et al. 1981:11–47). Tree-ring data that do not meet the established criteria are rejected; environmental data that fail to conform are either rejected or, in rare instances, corrected.

Once the tree-ring and environmental data have been evaluated, they are incorporated into the calibration process (Fritts 1976:312–375; Rose et al. 1981:49–78). Calibration involves the derivation of equations that express the relationship between a tree-ring chronology and an environmental record for a purposefully or randomly selected part of the period over which the two records overlap. In climatic calibration, response functions characterize the relationships between ring widths and monthly rainfall and temperature and indicate those climatic variables that are potentially reconstructible. Next, transfer functions are developed from the response functions to estimate values of the reconstructible climatic variables from the ring-width data. Alternatively, in areas (such as the Southwest) where there is a strong relationship between tree growth and climate, regression analysis can be used to directly reconstruct past climate from tree-ring widths.

Completion of the calibration process initiates the verification stage of the analysis (Fritts 1976:376–433; Rose et al. 1981:79–89). The reconstructions derived from the application of the transfer functions are first evaluated with a variety of tests designed to characterize their statistical properties and internal consistency. Second, a battery of statistical tests is used to assess the fit between reconstructed values and those segments of the instrumented climatic data that were withheld from the calibration process. Reconstructions that do not exhibit acceptable statistical properties or that do not correlate sufficiently well with the verification climatic data sets are rejected as suitable for further retrodiction.

The equations for the reconstructions that survived verification are used to retrodict the appropriate environmental values as far back in time as the relevant ring chronologies allow. To give a hypothetical example, this process could produce quantitative estimates of annual values of tree-year (August of the year prior to the growth of a particular ring through July of the current growth year), prior winter, and current spring precipitation, average current summer temperature, current July PDSI, and the annual flow of a particular stream for the last 1000 years. Such reconstructions provide detailed information on past environmental variability that is invaluable for assessing environmental effects on past natural and cultural systems and that provide an empirical baseline for predicting future environmental variations.

Qualitative and quantitative reconstructions of the types outlined above have been made for various localities on the southern Colorado Plateau. Relevant qualitative reconstructions include those of Fritts (1965) for western North America; Fritts, Smith, and Stokes (1965b) for Mesa Verde; and Dean and Robinson (1977) for the Southwest. Quantitative dendroclimatic retrodictions pertinent to the region include Stockton's (1975) reconstruction of Colorado River streamflow, Rose et al's. (1981, 1982) climatic reconstructions for the Santa Fe and Four Corners areas, Burns' (1983) crop yield and Van West's (1990) PDSI and crop yield reconstructions for southwestern Colorado, and Dean's (1986) and Lebo's (1991) precipitation reconstructions for Black Mesa. Several of these retrodictions have been integrated into large scale syntheses that attempt to characterize past climatic variability across the entire region (Dean 1993; Dean et al. 1985; Euler et al. 1979; Plog et al. 1988).

DENDROCLIMATIC RECONSTRUCTION IN THE FOUR CORNERS

The tree-ring data used in the Southwest Paleoclimate study comprise a spatial grid of 27 long tree-ring chronologies that extends from the Grand Canyon on the west to the Pecos River on the east and from central Utah south to the Gila River (Dean 1988b, Figure 5.3). Twenty-five of these chronologies are composed of archaeological and living-tree samples. The other two are multimillennial bristlecone pine series from Mammoth Creek and Wild Horse Ridge, Utah, on the northwestern margin of the grid. The climate data include weather service divisional summaries for Utah, Colorado, Arizona, and New Mexico and records for individual weather stations near the tree-ring chronologies. Variables used include total precipitation for the "tree year" (previous August through current July) and various seasons, annually and seasonally averaged temperatures, Palmer Drought Severity Indices for June and July, total annual streamflow for adequately gauged streams, and crop yield data from southwestern Colorado.

The qualitative reconstructions consist of tree-growth departures (Dean and Robinson 1977; Fritts 1965) in standard deviation units for each of the 27 chronology stations averaged by decade. The departure values indicate relative variability in annual rainfall, with values outside the ±1.1 range considered to be significantly above or below the long term mean with respect to potential favorable or adverse impacts on plant and animal populations and human adaptive behavior (Dean 1988b). Departure sequences for each station represent yearly and decadal fluctuations in annual weather (rainfall and temperature) at the locality represented by that station.

Regional scale behavior of relative climatic variability across the study area is represented by contouring the array of station departure values for each decade. Temporal aspects of regional climatic variability are revealed by arranging the decade maps in order for the period from A.D. 680 to 1970 (Dean and Robinson 1977). The sequence begins at A.D. 680 because too few chronologies extend inside that date to make reliable contouring feasible. The utility of these maps for understanding past climatic behavior in the Southwest is exemplified by Figures 1 through 4, which show the northeast to southwest progression of the "Great Drought" of A.D. 1276–1299 across the region. In the A.D. 1270 to 1279 decade (Figure 1), the beginnings of the drought are evident in the negative departures in the northwestern half of the region, while the rest of the region is characterized mainly by positive values. During the next decade (Figure 2) extremely dry conditions expanded to encompass the entire region except for the area around Flagstaff, Arizona. By the 1290–1299 decade (Figure 3), positive departures in the Rio Grande Valley interrupt the otherwise negative values throughout the region. A decade later (Figure 4), widespread high positive values signal the end of the Great Drought. Long-term changes in regional climatic patterns of the sort seen in the Great Drought example can be traced through the entire 1300-year sequence of departure maps.

Quantitative dendroclimatic reconstructions have been made for a wide range of climatic variables. Tree-year and seasonal precipitation

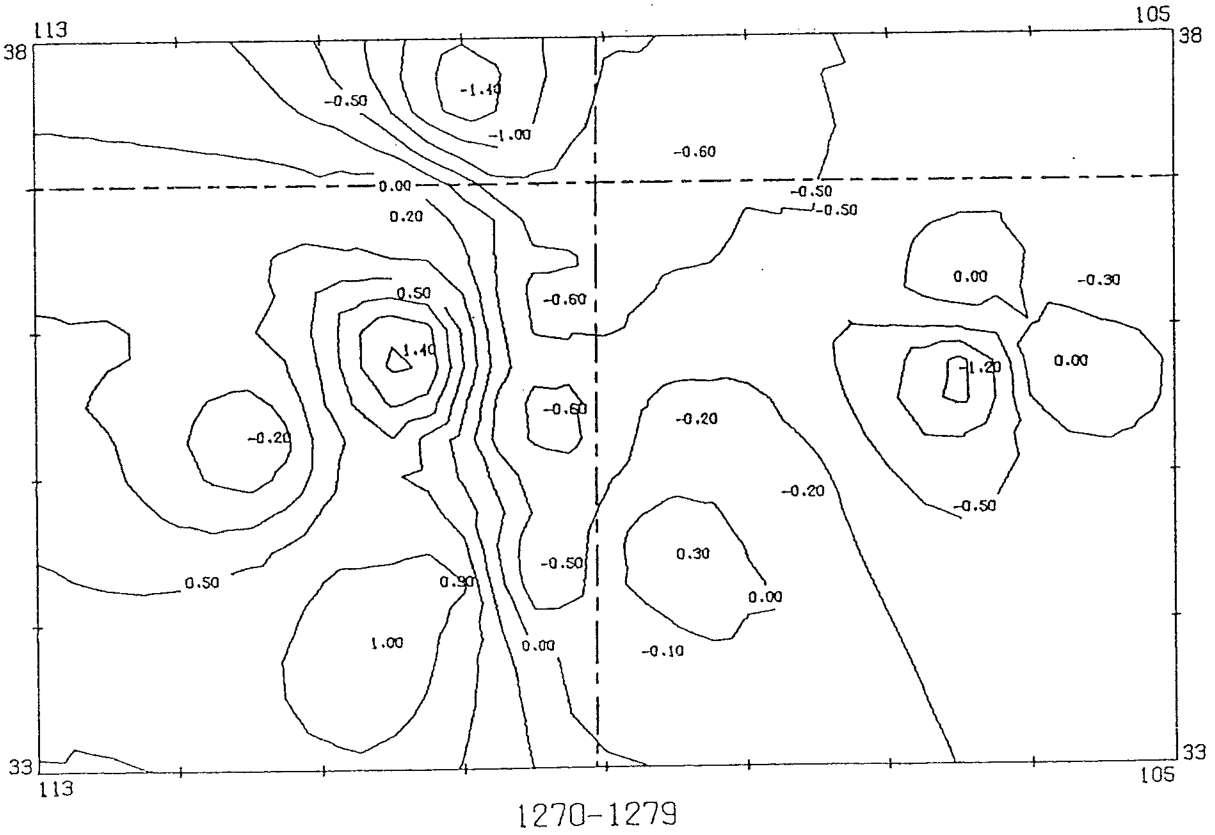

Figure 1. Contour map of Southwestern tree-growth departures for the A.D. 1270–1279 period.

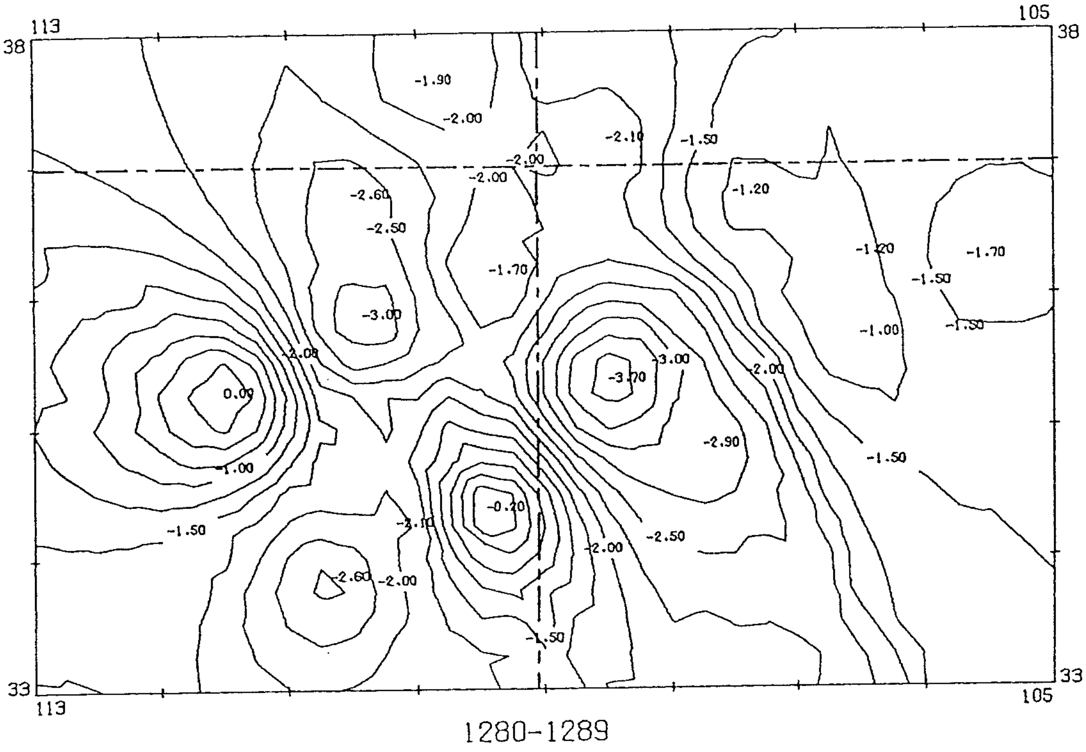

Figure 2. Contour map of Southwestern tree-growth departures for the A.D. 1280–1289 period.

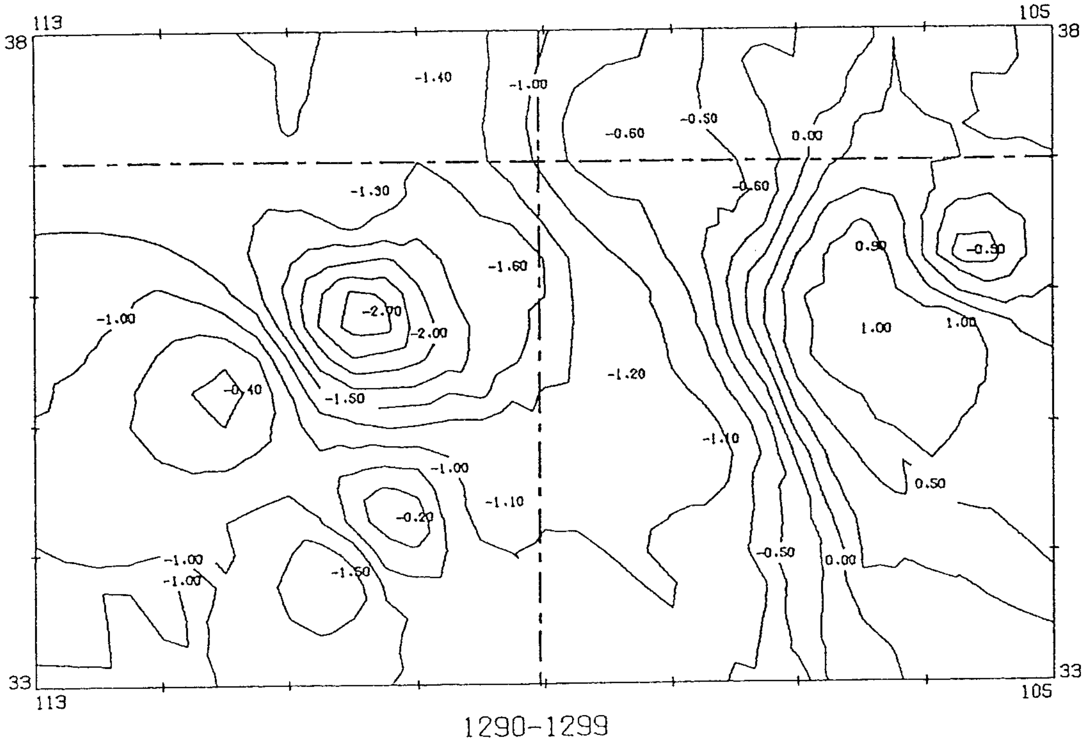

Figure 3. Contour map of Southwestern tree-growth departures for the A.D. 1290–1299 period.

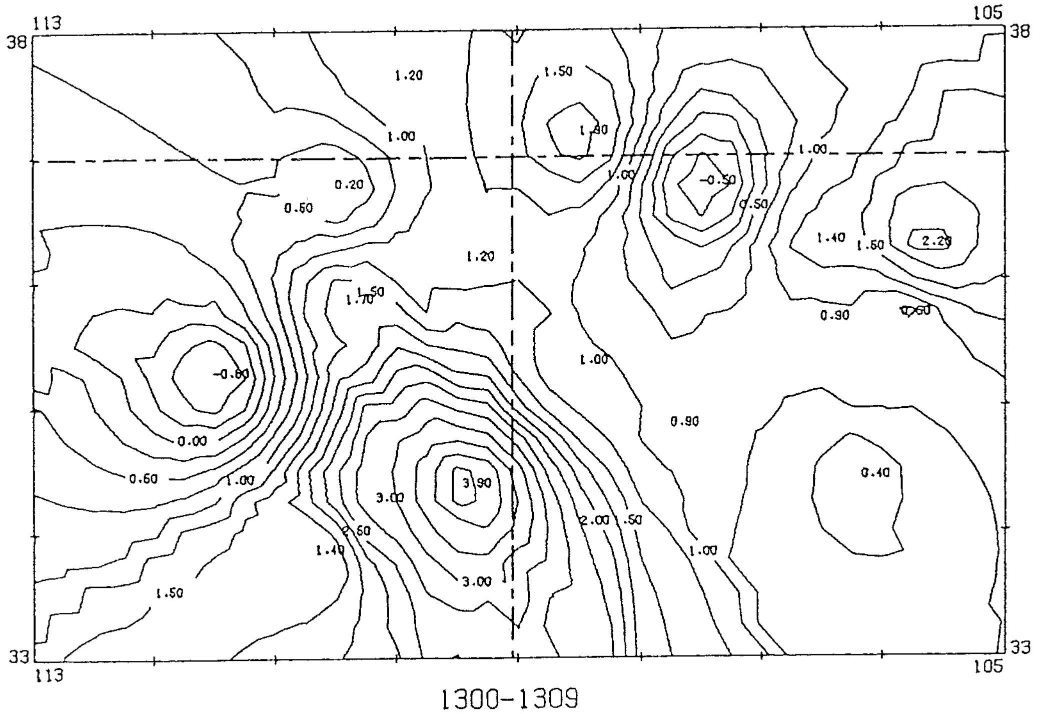

Figure 4. Contour map of Southwestern tree-growth departures for the A.D. 1300-1309 period.

in inches per year has been calculated for each of the 27 chronology stations. Similarly, annual June and July PDSI values have been estimated for each station. Streamflow reconstructions in millions of acre-feet per year, similar to that done by Graybill (1989) for the Salt and Verde Rivers in southern Arizona, have been done for the Colorado River (Stockton 1975) and are contemplated for other Plateau streams with acceptable gauge records. Annual crop yield values for corn and beans have been estimated for southwestern Colorado, the only area on the southern Colorado Plateau with usable modern crop production records (Burns 1983; Van West 1990). All these reconstructions are statistically significant estimates of past amplitude fluctuations in the relevant climate measures. These estimates can be presented as annual values, averaged over longer periods, or smoothed to show longer trends.

Both the qualitative and quantitative reconstructions portray important aspects of past climatic variability in addition to simple amplitude (wet vs. dry) fluctuations. Temporal variability, the rate of change from high to low values, varies systematically through time. During some periods, fluctuations from maximum to minimum values are rapid, often occurring from one decade to the next. At other times the transition is more gradual with the change occurring over several decades. The hatched zones in Figure 10D indicate periods of high temporal variability interspersed among intervals characterized by more temporal persistence (low temporal variability).

Related to temporal variability is the recurrence interval of high or low extreme values. There appear to be fairly regular periodicities in the incidence of extremes in many local reconstructions. This phenomenon, however, has yet to be systematically investigated and its amplitude range, spatial characteristics, and periodic structure are not well known (Graybill 1991). Other poorly understood variables are the variance structure of the regional network (Dean 1988b, Table 5.1) and subdivisions of the regional array (Dean, in press), although both these attributes fluctuate during the last 1300 years.

Finally, there is considerable climatic variability across space. Some periods are characterized by high spatial variability (Figure 5), while in others a great deal of spatial uniformity prevailed (Figure 6). Figure 10E, a plot of the standard deviations of the station departures for each decade, shows that spatial variability was low (that is, conditions were similar throughout the region) in the A.D. 700 to 1000, 1150 to 1300, and 1650 to 1900 intervals and high (conditions varied across the region) during the A.D. 100 to 1150, 1300 to 1650, and 1900 to 1970 periods.

Additional aspects of the spatial behavior of climate across the Southwest during the last 1500 years are indicated by recent multivariate analyses. In order to illuminate the spatial structure of Southwestern climate, principal components analysis (PCA) was employed to investigate the geographic patterning of covariation among the tree-ring chronologies. Principal components analysis partitions the chronologies into statistically independent subgroups that exhibit similar patterns of variation (the principal components). Drawing boundaries around the chronologies that contribute heavily to individual principal components produces fairly coherent and logical patterns.

Analysis of the entire study period, A.D. 966 to 1988, revealed two spatially discrete principal components (Figure 7). The first component includes stations in the northwestern part of the region and accounts for approximately 60% of the total variance in the network. Principal Component 2 includes stations in the southeastern part of the region and accounts for about 10% of the variance. This general configuration bears an uncanny resemblance to the modern spatial distribution of seasonal precipitation in the Southwest during the last 70 years (Dean 1988b, Figure 5.1). In the south and east, precipitation exhibits a unimodal, summer dominant pattern, while to the north and west, a bimodal distribution with both summer and winter maxima prevails. These areas are separated by a sinuous boundary zone that runs eastward from the southwestern corner of Arizona, turns northward at the New Mexico border, loops back into Arizona on the Colorado Plateau, curves back to parallel the Colorado—New Mexico border, and ends in the mountains north of Santa Fe. Given the striking resemblance between the climatic configuration and the PCA pattern, the PCA dichotomy probably reflects the long-term persistence of the geographic division between summer-dominant rainfall in the southeast and summer-winter precipitation pattern in the northwest.

Temporal aspects of this regional spatial pattern are revealed by principal components analyses of each 100-year period from 539 to 1988 overlapped by fifty years. By and large, the bimodal PCA pattern persists throughout the period of record. The A.D. 739–838 period (Figure 8) exemplifies the general pattern. A couple of things are evident when this map is compared to the 966–1988 map (Figure 7). The most obvious is that different combinations of stations are included in each component, a reflection of the fact that the boundary between the two zones moves back and forth in space over time. Examination of the entire series of maps shows that while the boundary does indeed fluctuate in time, it always maintains its general position and configuration.

The PCA also revealed that the general pattern was not uninterrupted. During a 200-year period, the long-term pattern breaks down completely. The A.D. 1339–1438 interval (Figure 9) typifies the period from about 1250 to 1450 when a totally aberrant pattern prevailed. The A.D. 1339–1438 interval exhibits four rather than two major principal components, and some 100-year segments of the two century period have as many as six

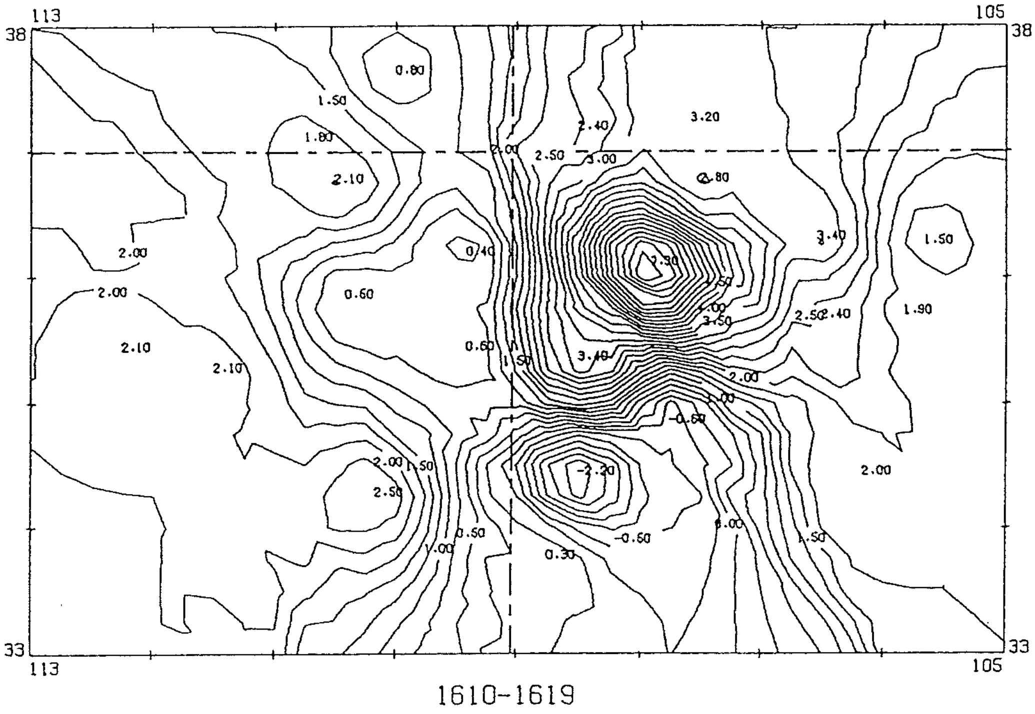

Figure 5. Contour map of Southwestern tree-growth departures for the A.D. 1610–1619 decade showing high spatial variability in climate.

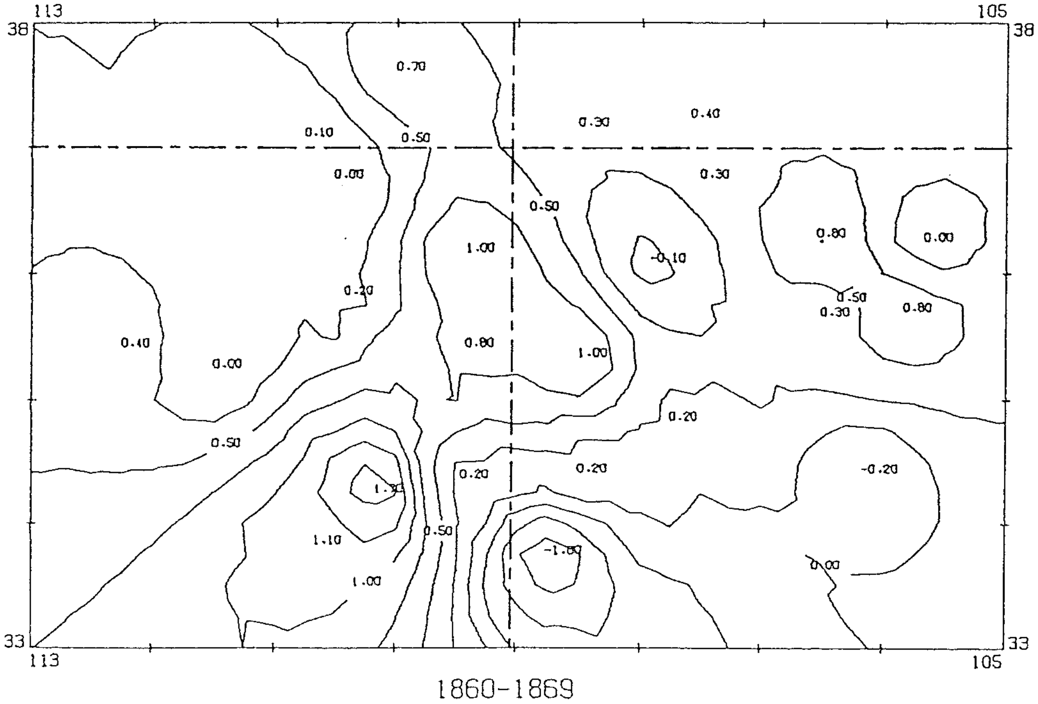

Figure 6. Contour map of Southwestern tree-growth departures for the A.D. 1860–1869 decade showing low spatial variability in climate.

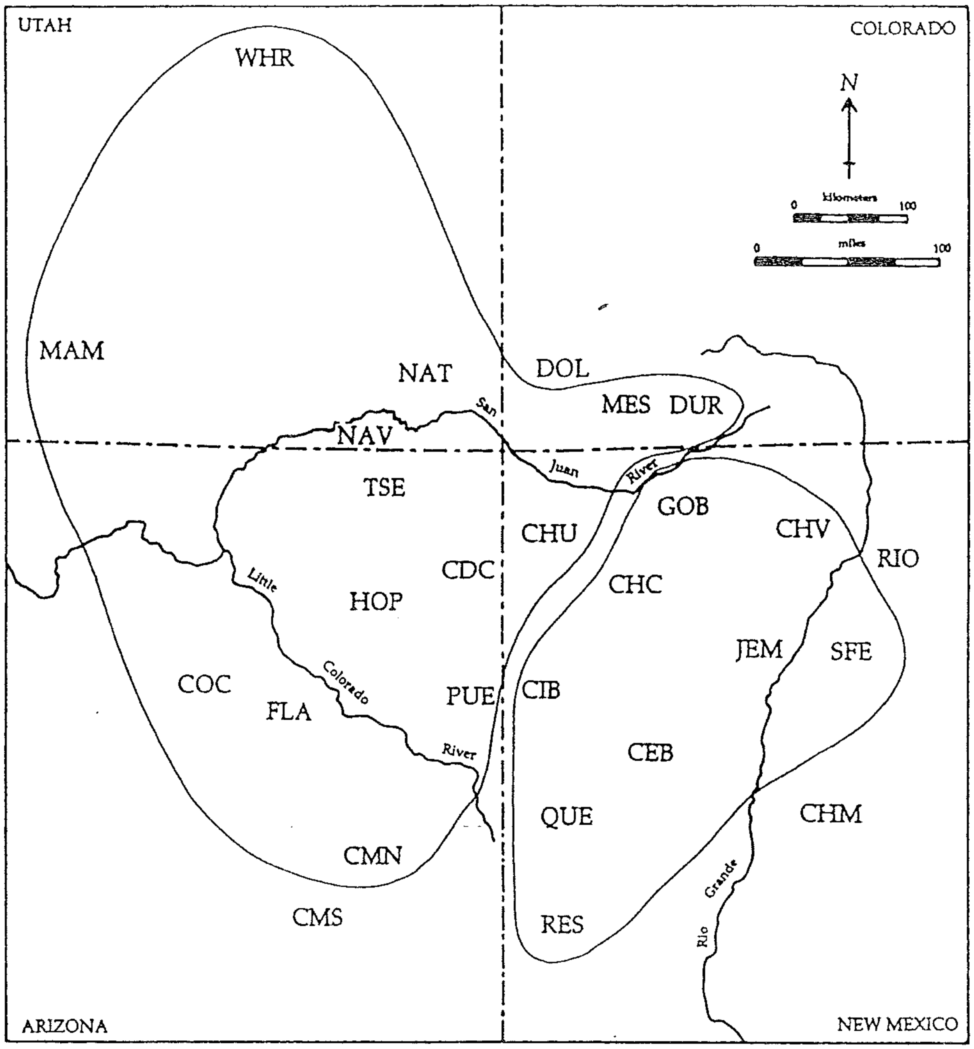

Figure 7. Principal components of Southwestern tree growth (climate) for the A.D. 966–1988 period.

components. Unlike the patterns of other periods, this chaotic configuration makes little sense in terms of modern climate. The only stable characteristic of this period is the persistence of the southeastern component, which indicates that most of the disruption of the long term pattern occurred in the northwestern area.

These results specify a major climatic disruption that would have had major impact on the Colorado Plateau. For two centuries a fairly simple, long-term, stable pattern was interrupted by a complex, chaotic configuration that represents an unprecedented change in conditions to which the human and biotic populations of the region had become accustomed. The effects of this disruption obviously were greatest in the northwestern part of the region, basically, the Colorado Plateau. Just the change from a persistent stable pattern to an unstable one would have had important adaptive repercussions. The probable breakdown of the bimodal seasonal distribution of precipitation would have had even more specific consequences for the farming populations of the region, especially when

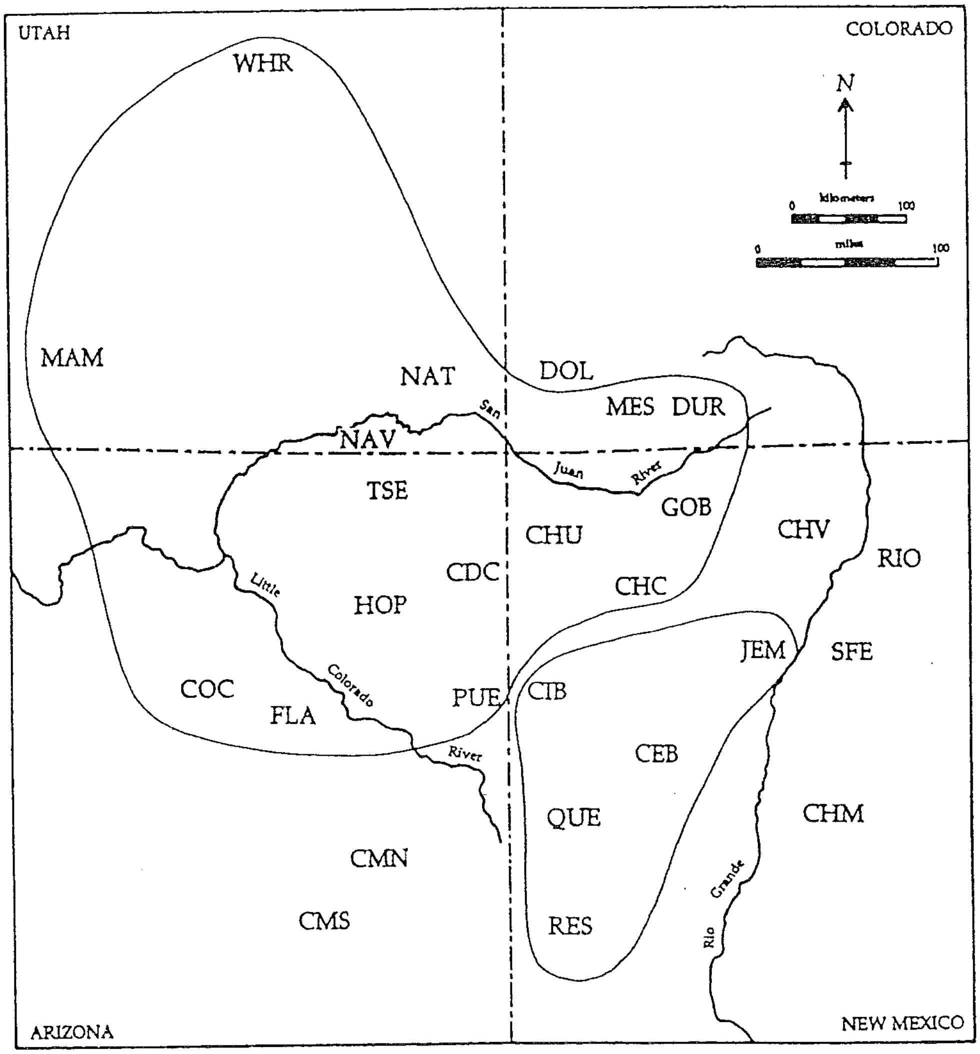

Figure 8. Principal components of Southwestern tree growth (climate) for the A.D. 739–838 period.

combined with other environmental changes that characterized this period.

Recently, dendrochronology has allowed the reconstruction of another environmental variable that, though not climatic, is closely related to both climate and human activity. Trees that were damaged but not killed by wildfires often preserve in the scars associated with their rings records of fires that occurred in their lifetimes. Dating of these scars provides detailed histories of the timing and extent of fires in affected areas (Swetnam and Dieterich 1985). Obviously, forest fires could have influenced the plant and animal communities and the human inhabitants of the affected localities. As forest managers well know, forest fires are related to the weather, and a relationship between fire frequencies in the western U.S. and the El Niño-Southern Oscillation (ENSO) has been established (Swetnam and Betancourt 1990). Equally pertinent are relationships with human behavior. There is evidence that prehistoric and historic populations of the Colorado Plateau intentionally started fires either to clear land (Kohler and Matthews 1988) or to eliminate underbrush (Sullivan 1982). Alternatively, livestock

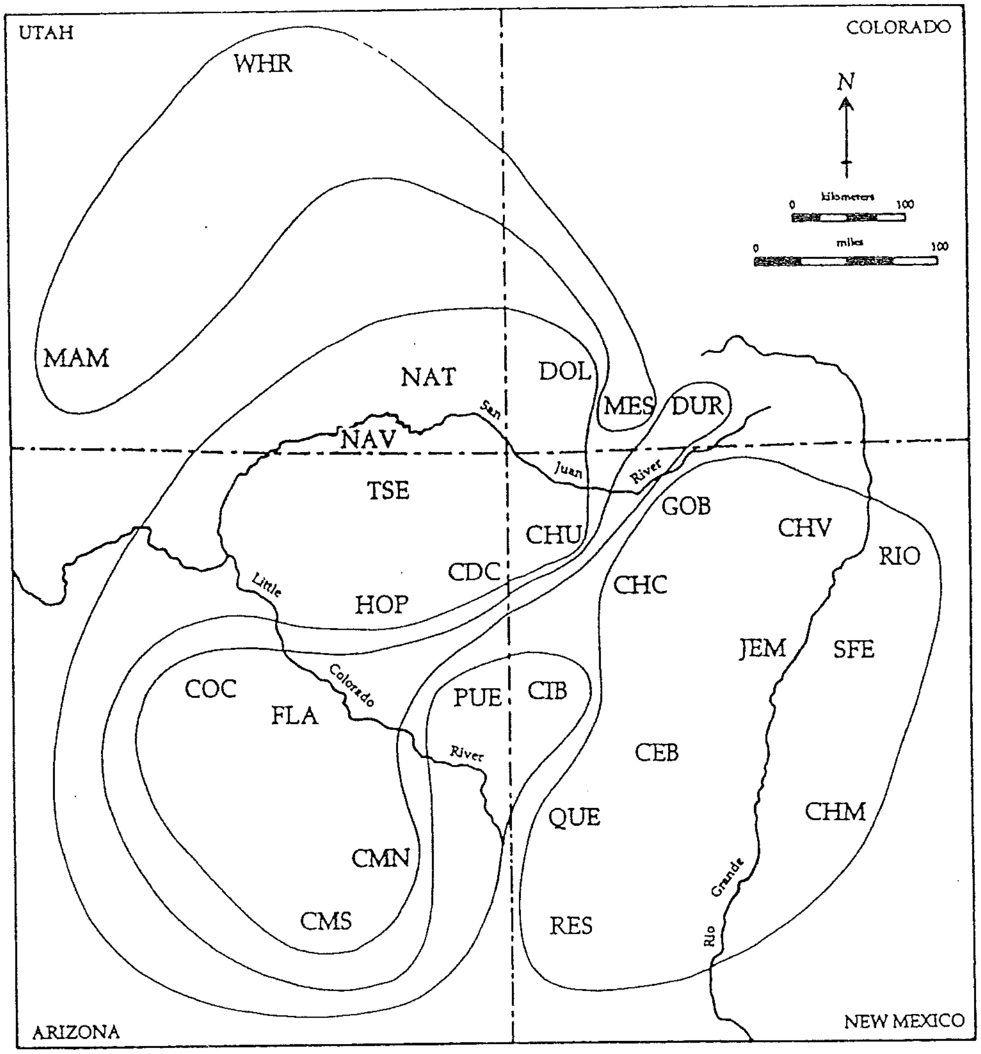

Figure 9. Principal components of Southwestern tree growth (climate) for the A.D. 1339–1438 period.

grazing and fire suppression during the historic period substantially reduced the frequency and increased the severity of forest fires. As yet, no Southwestern fire history reaches far enough into the past to illuminate the relationships of forest fires with prehistoric populations. Ongoing research, however, holds considerable promise for extending these records farther back in time.

COMPARISON WITH OTHER PALEOENVIRONMENTAL RECONSTRUCTIONS

Before the various aspects of climatic variability indicated by tree rings can be related to human behavior, they must be integrated with information derived from other paleoenvironmental indicators (Dean 1988b). Because different environmental factors present different adaptive opportunities and problems for human groups and because the effects of each factor are mitigated or amplified by the others, it is necessary to relate the dendroclimatic reconstructions to paleoenvironmental measures that record other environmental conditions and are sensitive to different spatial and temporal parameters. Other relevant indicators of past environmental variability include stratigraphic and geomorphological analysis of alluvial and colluvial deposits, palynological analyses of geological and archaeological contexts, packrat midden analysis, and archaeobotanical and zooarchaeological studies. On the southern Colorado Plateau, these disparate paleoenvironmental reconstructions are integrated through independent, high-resolution chronological control based on ceramic, radiocarbon, and tree-ring dating of stratigraphic sequences, packrat middens, and archaeological sites and on the intrinsic chronological accuracy of the dendroclimatic reconstructions (Dean 1988b). Figure 10 allows the visual comparison of fluvial, pollen, and tree-ring reconstructions on the southern Colorado Plateau.

To understand the relationships among the various paleoenvironmental reconstructions and their relevance to human behavior, environmental variability is categorized by the frequency ranges to which the different natural processes respond and to which various paleoenvironmental techniques are sensitive. One human generation, 25 years, is arbitrarily chosen as the reference for partitioning the range of variability into three categories (Dean 1984, 1988a).

Stable aspects of the past environment are those that have not changed appreciably over the length of the study period, in the case of dendroclimatic reconstruction the last 2,000 years. An important attribute of stable elements is that their present states are valid indicators of past conditions during the last two millennia. Among these features of the Colorado Plateau are climate type, bedrock geology, topography, and the elevational zonation of vegetation communities.

Low frequency environmental variability is that due to natural processes with periodicities greater than or equal to 25 years. Because these factors vary at rates shorter than the study period, they must be reconstructed. Important low frequency factors are the rise and fall of alluvial water tables (Figure 10B) and the deposition and erosion of sediments along drainages (Figure 10A), which are crucial to floodplain farming (Cooley 1962; Eddy 1964; Hack 1942; Hall 1977; Karlstrom 1988; Lipe and Matson 1975). Other low frequency variations involve elevational changes in the boundaries of vegetation zones and in the composition of plant communities (Hevly 1988; Petersen 1988). Palynological reconstructions of these variables reveal fluctuations in the effective moisture available to plants (Figure 10C). Climatic variations with frequencies longer than 25 years generally are not reconstructible by dendroclimatology, which is relatively insensitive to low frequency fluctuations. Recent progress along these lines, however, has been made through the analysis of a chronology from the El Malpais National Monument constructed of extremely long individual sample components. This preliminary reconstruction of low frequency climatic variability over the last 2,000 years (Grissino-Mayer, in press) bears an uncanny resemblance to Karlstrom's (1988) hydrologic curve (Figure 10B).

High frequency environmental variability is caused by natural processes with periods less than 25 years long. Basically, this is climate, which varies hourly, daily, seasonally, annually, and at a nearly continuous range of longer wavelengths. High frequency variability must be reconstructed. The most obvious reconstructive technique is dendroclimatology, which is sensitive to seasonal, annual, and longer variations up to about a century (Dean 1988b). High resolution pollen studies also reflect high frequency variability (Hevly 1988) with results quite similar to the tree-ring reconstructions.

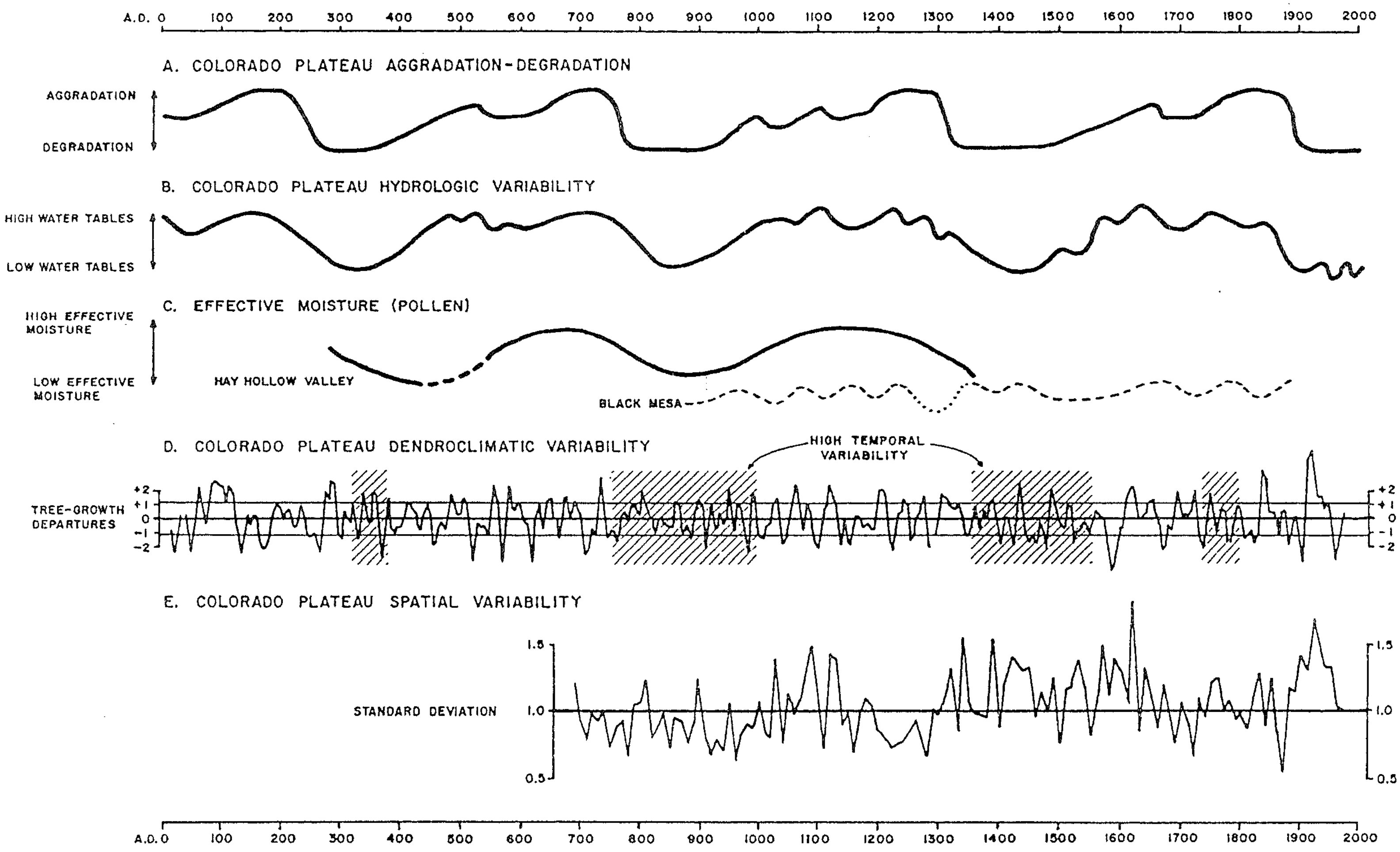

Figure 10. Low and high frequency environmental variability on the Colorado Plateau: A, deposition and erosion of alluvium; B, primary and secondary variations in alluvial groundwater levels; C, fluctuations in effective moisture; D, decadal variability in relative dendroclimate expressed as standard deviations from the long term mean (hatching indicates periods of high temporal variability); E, spatial variability in dendroclimate measured by the standard deviations of chronology station values for each decade.

Comparison of the various environmental records discussed above reveals periods of time in which environmental deterioration is likely to have exerted a major influence on human adaptive behavior on the Colorado Plateau. But even extreme external conditions probably would have had minimal effect until regional populations reached absolute levels and/or local densities that inhibited simple responses such as moving to an unaffected locality or altering local mobility patterns (Plog et al. 1988). Thus, major adaptive behavioral responses to environmental adversity should not be expected until after A.D. 1000 when regional population reached a critical level (Dean et al. 1994).

Major depositional and hydrologic stress would have occurred during periods characterized by floodplain erosion (Figure 10A) and falling or low water tables (Figure 10B). Primary degradation of this sort characterized the A.D. 750 to 925, 1275 to 1450, and 1875 to the present intervals. Secondary fluvial minima were centered on A.D. 1150 and 1700. Effective moisture fluctuations paralleled hydrologic variability and would have exacerbated major crises due to the latter in the A.D. 800 to 1000 and 1250 to 1400 intervals and would have reinforced favorable conditions between 1000 and 1250. Low frequency aspects of climatic variability would have modified the hydrologic and vegetational fluctuations. High temporal variability would have provided enough decade-to-decade variability to moderate adverse fluvial and effective moisture conditions during the A.D. 750 to 1000, 1350 to 1550, and 1730 to 1800 intervals. Greater climatic persistence would have reinforced the favorable hydrologic conditions of the intervening periods. Low spatial variability, on the other hand, would have exacerbated inimical hydrological and effective moisture conditions between A.D. 700 and 1000 and between 1150 and 1300 and tempered the favorable conditions between 1700 and 1900. The climatic instability and changes in seasonal precipitation patterns caused by the disruption of the long-term regional configuration between A.D. 1250 and 1450 would have significantly aggravated the other major low and high frequency environmental degradations of this period. High frequency amplitude variability in dendroclimate would have (1) reinforced unfavorable low frequency conditions in the middle 1100s, late 1200s, middle 1400s, and early 1900s, (2) moderated unfavorable conditions in the early and late 1400s, around 1700, and in the early 1900s, (3) reinforced favorable conditions in late 1000s, early 1100s, early 1200s, early 1600s, and middle 1800s, and (4) moderated favorable conditions in the middle and late 1000s, late 1500s, early 1700s, and early 1800s.

Comparison of various paleoenvironmental records reveals several periods of seriously decreased environmental potential. The severest of these undoubtedly was that between 1250 and 1450 when hydrologic conditions, effective moisture conditions, temporal and spatial climatic behavior, the breakdown in the seasonal patterning of precipitation, and a prolonged drought combined to depress environmental potential across a wide spectrum of variation. Secondary environmental depressions, involving both hydrologic and climatic factors, occurred around A.D. 1150 and 1700. Lesser stress periods occurred in the 1500s and early 1900s. These are intervals in which major, regional scale adaptive culture changes should be expected across the Colorado Plateau. On the other hand, the A.D. 925 to 1130 and 1750 to 1850 periods were characterized by especially favorable low and high frequency conditions.

BEHAVIORAL IMPLICATIONS OF THE PALEOENVIRONMENTAL RECONSTRUCTIONS

Obviously, the potential for comparing past environmental variability with human activities on the Colorado Plateau is virtually limitless and is an exercise that has captivated archaeologists and natural scientists throughout the history of scientific endeavor in the Southwest. While this is not the place to go into this topic in detail, a few observations illustrating the potential of these reconstructions for better understanding the prehistory, and perhaps the future, of the region are warranted.

As has been noted before, the expansion of the most complex manifestation of Anasazi culture, the Chacoan regional interaction system, took place during a period of particularly salubrious environmental conditions (Dean 1993). The Chacoan expression reached its cultural apogee and maximum geographical extent during the favorable A.D. 925 to 1130 period and began to contract during the 1130–1180 interval of environmental stress. It seems quite likely that the advantageous conditions of the 11th century at least facilitated, if not impelled, the Chacoan expansion and that the rather sudden environmental deterioration in the middle 1100s helped trigger the Chacoan decline.

The coincidence of the worst environmental degradation of the last two millennia with one of the greatest cultural upheavals in the span of human occupation of the Plateau virtually demands consideration. The A.D. 1250–1450 interval was a period of great human change throughout the Plateau and the Southwest. Major population dislocations occurred, including local rearrangements, the abandonment of the San Juan drainage, and major population movements into the Little Colorado River drainage, the Mogollon Highlands, and the Rio Grande Valley. Agricultural intensification, involving increased irrigation and more sophisticated dry farming, occurred throughout the region. Important settlement transformations included greater site diversification, extremely large towns, hierarchical settlement systems, and the rise of new occupation centers. Interareal interaction and exchange increased. Socioreligious ideas and organizational principles were elaborated. Widespread cultural stability was not reestablished until the environmental situation ameliorated after A.D. 1450. While it would be foolish to attribute the changes that occurred after 1250 solely to environmental disruption, it would be equally unwise to ignore this potent source of cultural and demographic upset as an important contributing factor in the social transformations that characterized this interval.

Although relating past human behavior to paleoenvironmental variability is a daunting task, hindsight makes it an easier job than trying to extrapolate environment-behavior relationships into the future. Nevertheless, it is possible to suggest some possible future environmental effects on uranium mill tailings disposal and environmental restoration activities on the southern Colorado Plateau.

Given the mandated multicentury longevity for uranium mill tailings repositories, the possibility that even natural processes that have been "stable" during the last two millennia may transgress periodic thresholds and initiate environmental changes must be acknowledged. Earthquakes and/or volcanic eruptions could rupture waste containment facilities or alter the topography of disposal sites. Natural or anthropogenic climatic transformations (due, for example, to changes in ENSO behavior, global warming, or CO_2 enrichment) could alter the ambient weather and biotic environments of the containment sites. Changes in such "stable" factors also would affect efforts to restore damaged environments.

Low frequency climatic and hydrologic fluctuations also could impact waste disposal and habitat restoration efforts. Climatic amplitude changes involving increasing or decreasing precipitation or temperature would alter both the climatic and biotic parameters of waste disposal sites and either inhibit environmental damage mitigation or steer it in unexpected directions. Resumption of high temporal variability will elevate the occurrence frequency of climatic extremes, which would increase disturbance, alter the biota of waste containment facilities, and change the environmental boundaries of both pristine and disturbed habitats. The return of low spatial climatic variability will reduce between-locality environmental differences, which would have little impact on radioactive waste disposal but would tend to limit habitat diversity and the scope of environmental regeneration. The resumption of regional deposition and alluvial water table accretion could directly impact some waste containment sites through burial, groundwater saturation, and even inundation, and it will alter the local environments of some of these facilities and the nature of the biotic threats to their stability. Through their effects on the boundary conditions that regulate valley floor environments, the hydrologic changes will alter floodplain habitats and the nature and possibilities of riparian restoration.

Finally, high frequency climatic fluctuations should have little direct impact on waste disposal and environmental restoration as long as variability remains within the boundaries established by prevailing stable conditions and low frequency processes. When such thresholds are breached, however, high frequency variability could impact waste containment facilities directly or through effects on local flora and fauna. Variations that exceed the "normal" range of high frequency variability could have adverse effects as well. For example, severe storms could damage waste storage facilities either directly or through runoff, while drought could adversely affect the local biota. Positive or negative extremes also would constrain habitat restoration.

CONCLUSIONS

Dendroclimatic retrodictions of past environmental variability are characterized by unusually high sensitivity and chronological resolution. Nevertheless, they are most informative when used in conjunction with other paleoenvironmental indicators because the variables and the reconstruction methods are sensitive to different environmental phenomena and to different wavelengths of variability. Integrated reconstructions illuminate the full range of potential variability and identify periods characterized by unusually detrimental or favorable environmental conditions. These indications can then be used to refine investigations of human adaptive behavior across the region. These reconstructions also provide baseline data for assessing likely environmental impacts on future activities such as the containment of uranium mill tailings and the repair of human environmental damage.

An indisputable outcome of paleoenvironmental research on the Colorado Plateau is the demonstration that modern records do not capture the full range of environmental variability. Therefore, these records cannot be used to estimate potential environmental impacts on future activities in the region. Only detailed, high resolution paleoenvironmental reconstructions provide an adequate empirical basis for long-term environmental planning. The work done so far provides only a glimpse of the possibilities along these lines. Much more environmental, archaeological, ethnographic, and historical research is necessary to enhance knowledge of human and natural phenomena in the region, to elucidate the interactions among human and natural systems, and to provide a sound theoretical and empirical foundation for planning future activities on the Colorado Plateau.

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