Dendrochronological Evidence for Long-Term Hydroclimatic Variability

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THREE

THE ROLE OF PALEOCLIMATOLOGY IN REGIONAL ASSESSMENTS

It is important to place twentieth-century climate events, such as the Dust Bowl drought of the 1930s, into perspective so that their relative severity can be assessed. This can be done to an extent with the existing instrumental record. For example, although the southern Great Plains drought in 1998 had a severe effect on the economies of Texas and Oklahoma, costing $6 billion in Texas alone, the physical characteristics of that drought (spatial extent and duration) pale in comparison to the 1950s drought (Plate 8). The Dust Bowl drought of the 1930s was even more severe in terms of coverage and duration; it encompassed almost 70 percent of the country in its worst year and lasted seven to eight years (Riebsame et al. 1991). How unusual were the droughts of the 1930s and 1950s? Records for instruments that measure indicators of drought (primarily rain gauges) exist for less than 100 years in much of the central and western United States. This is a period of insufficient length for answering questions about the frequency of unusual droughts.

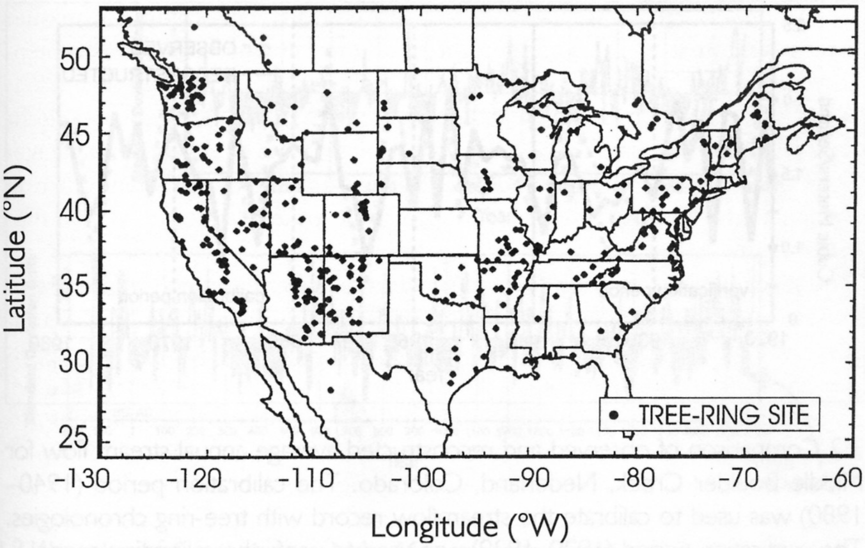
Along with placing extreme twentieth-century events into a broader temporal context, it is also important to determine whether the instrumental record of climate variability, which includes these extreme events, is representative of long-term natural climatic variability. Because twentieth-century records are used as the basis for water-resource planning and management, this is an important question and can be answered only with information about climate for an extended period of time prior to the use of weather instruments.

Paleoclimatic data from a number of kinds of environmental proxies or indicators of climate can provide information about past climates. Variations in climatic conditions can be reflected in tree-ring widths and densities, the chemical characteristics of layers of ice in glaciers and ice caps, fossil material in lake and ocean sediments, or other natural physical records. Once the relationship between climate and an environmental indicator is determined, it is possible to use the record as a proxy for climate variability in the past. The proxy record may be calibrated with climate data to generate a model that can be used in reconstructing a record of past climate.

DENDROCHRONOLOGY: THE STUDY OF TREE RINGS

Tree rings are the best source of terrestrial temperate-region paleoclimatic data on timescales of hundreds to several thousands of years, although a limited number of even longer (up to 12,000 years) tree-ring records exist. The National Oceanographic and Atmospheric Administration World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo) houses the International Tree-Ring Data Bank, which contains contributions of tree-ring data from dendrochronologists around the world (Grissino-Mayer and Fritts 1997). In the United States alone, more than 400 tree-ring collections exist for the time period 1700–1979 (Figure 3.1). The spatial coverage of tree-ring data is quite good for the western United States, although there are several areas of deficiency. In some regions, such as western Colorado, most tree-ring collections were last made in the 1970s and are now out of date. In other areas, such as the western Great Plains, the scarcity of trees has inhibited the collection of tree-ring samples, although work now in progress will improve coverage.

The basic unit of a tree-ring study is a tree-ring chronology. A tree-ring chronology is generated by averaging tree-ring measurements (usually widths or densities) of dated rings from a number of tree-ring samples, usually in the form of cores about 5 mm in diameter, from one location. The sampling site is selected according to the climate variable of interest. In studies that focus on drought, a site is selected where trees are typically stressed by drought. If temperature variations are of interest, trees at high elevation or high latitude are sampled because growth of trees in these locations is sensitive to



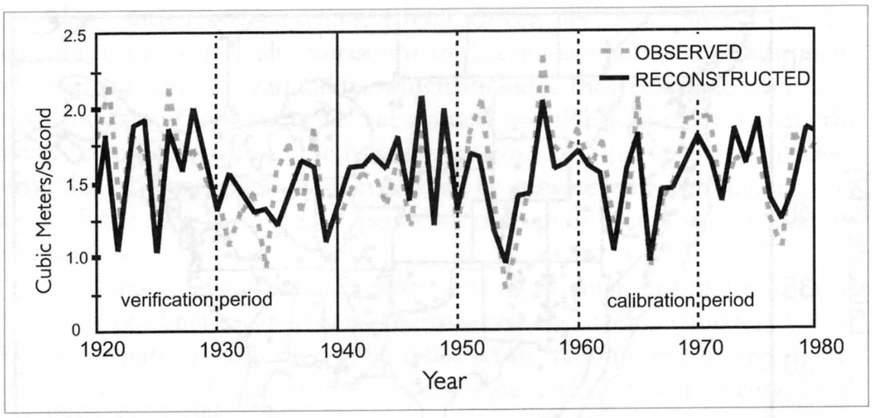
3.1 Distribution of tree-ring chronology sites that fall within the period 1700–1979 (modified from Cook et al. 1999).

temperature, which dictates the length of the growing season. Usually twenty or more trees are sampled so that the variations unique to individual trees do not have excessive influence (Fritts 1976; Cook and Kairiukstis 1990).

In reconstructing climate from tree rings, variations in year-to-year growth as represented by one or more tree-ring chronologies are calibrated with an instrumental climate record by use of regression analysis. The analysis results in a transfer function (a function that uses climate as a dependent variable and tree-ring data as an independent variable), which is then used to reconstruct the climate variable for the length of the tree-ring record. The skill of the reconstruction is evaluated by comparison of the instrumental climate values and values produced by the regression (Figure 3.2). Climate conditions most limiting to tree growth (such as dry conditions) tend to be duplicated more accurately than extremes of the opposite sign (such as wet conditions). In general, the effects of extreme conditions are muted by regression analysis. Consequently, reconstructions are usually a conservative estimate of climate variability.

DENDROCHRONOLOGICAL EVIDENCE OF HYDROCLIMATIC VARIABILITY

The network of chronologies shown in Figure 3.1 was used to reconstruct drought, as measured by the Palmer Drought Severity Index (PDSI, a widely

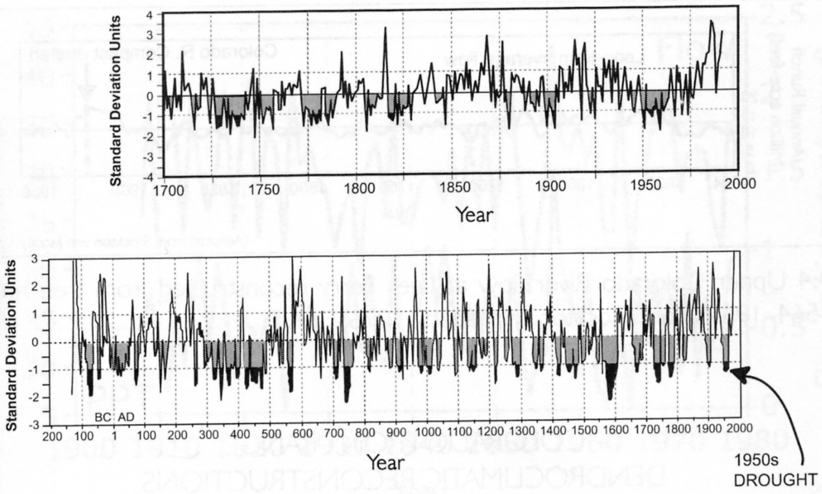


3.2 Comparison of observed and reconstructed average annual stream flow for Middle Boulder Creek, Nederland, Colorado. The calibration period (1940–1980) was used to calibrate the streamflow record with tree-ring chronologies. The verification period (1920–1939) was used to verify the calibration model.

used measure of drought that incorporates precipitation, air temperature, and soil moisture) from 1700 to 1979 for a set of grid points that covered the conterminous United States (Cook et al. 1999). Maps were generated of the spatial patterns of drought for each year of this time period (http://www.ngdc.noaa.gov/paleo/pdsi.html). In Plate 9, the observed instrumental and reconstructed patterns of drought for the worst year of droughts in the 1930s (1934) and the 1950s (1956) can be compared. The tree rings accurately duplicate the general spatial patterns and duration of drought but do not fully capture the severity of drought. Thus, as mentioned previously, they are conservative estimators of drought.

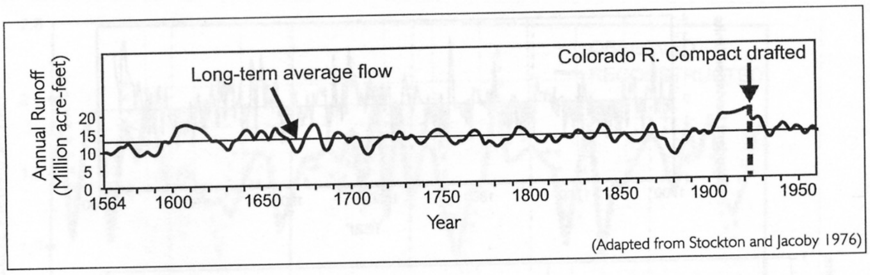
With the PDSI maps it is possible to assess the probability of the 1930s and 1950s droughts. Over the past three centuries, four droughts—each lasting two to six years—appear to have been comparable to the 1950s drought. The worst years of these four droughts are shown in Plate 10. Although the spatial extent of drought in 1934 is not equaled in any of the reconstructions, the effect of the 1930s drought on specific regions in the intermountain West was probably matched by several droughts in the past 300 years.

Prior to 1700, spatial coverage of tree-ring records is more limited, but a number of longer chronologies do exist that make possible longer reconstructions. One long reconstruction is of annual rainfall for north-central



3.3 Annual rainfall for western New Mexico, as reconstructed from tree rings. The top graph shows these reconstructions for A.D. 1700–1992, whereas the bottom shows the entire period (136 B.C. to A.D. 1992). Data are from Grissino-Mayer 1996.

New Mexico (Grissino-Mayer 1996). This reconstruction, which extends to 136 B.C., allows comparison of the 1950s drought—which was quite severe in New Mexico—with droughts of the past two millennia. Although several droughts of a magnitude similar to the 1950s drought have occurred in the past three centuries, none has been conspicuously more severe (Figure 3.3). When the 1950s drought is assessed in the context of the last 2,000 years, however, it becomes evident that much more severe droughts have occurred in the past (Figure 3.3). A drought in the late sixteenth century is especially notable for its severity and relatively recent occurrence. It is found in a large number of proxy records besides the one for New Mexico. Multiple records help to chronicle its length, severity, and spatial extent. For example, this drought can be seen in the upper Colorado River flow reconstruction of Stockton and Jacoby (1976; Figure 3.4); it corresponds to one of the lowest periods of flow in 500 years. This drought illustrates the problem of basing resource management solely on the instrumental record. The 1922 Colorado River Compact was based on a flow record that began in the early twentieth century, the first two decades of which were the most anomalously wet in the entire 500-year time span.



(Adapted from Stockton and Jacoby 1976)

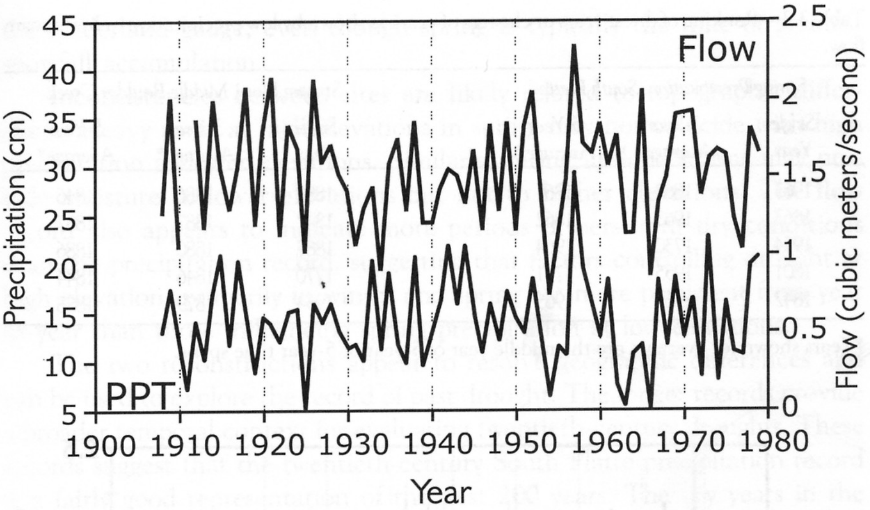
3.4 Upper Colorado River flow at Lees Ferry reconstructed from tree rings, 1564–1961 (from Stockton and Jacoby 1976).

COLORADO FRONT RANGE DENDROCLIMATIC RECONSTRUCTIONS

Two reconstructions of hydroclimatic variability have been generated for the Colorado Front Range. Reconstructions of average annual stream flow for Middle Boulder Creek at Nederland, Colorado, and regional spring (March–May) precipitation for ten stations in the South Platte basin (Woodhouse 1999) demonstrate the ability of tree rings to provide information on fine temporal and spatial scales. Because Middle Boulder Creek is mostly unregulated, its flow reflects climatic influences on flow for the entire water year. Annual discharge is mainly related to the amount of winter and spring snowpack, but the annual hydrographs reflect summer precipitation as well. The gauging station and 93 km^2 basin lie above 2,500 m elevation. In contrast, the South Platte spring precipitation record reflects precipitation falling during the time of year of maximum precipitation for the South Platte River basin. Most of the weather stations from which data were averaged to create the record for spring precipitation are located at elevations less than 1,800 m. Thus the record represents conditions at a lower elevation and over a larger region than the streamflow record for Middle Boulder Creek.

The Middle Boulder Creek stream flow and South Platte precipitation show some similarities as well as marked differences. For example, the 1960s drought—the longest and most extreme period of drought in the precipitation record—is less notable in the flow record. In the flow record the 1950s show the most extreme low flow, and the 1930s show the most persistent period of low flow (Figure 3.5).

The reconstructions of South Platte spring precipitation and Middle Boulder Creek flow are of good quality (Table 3.1; see also Woodhouse 2001), and they reproduce the instrumental records with some accuracy (Figure 3.6). Overall, dry periods in the precipitation record coincide with periods of below-average flow, indicating some coherence between the two variables, as



3.5 The top line is average annual flow for Middle Boulder Creek, as gauged at Nederland, Colorado, from 1908 to 1979. The bottom line is total spring precipitation, averaged for ten stations in the South Platte River basin, 1908–1979.

Table 3.1—Statistics for precipitation and streamflow reconstructions. Correlation (r) and explained variance (R^2) values are used to evaluate the relationships between observed and reconstructed values.

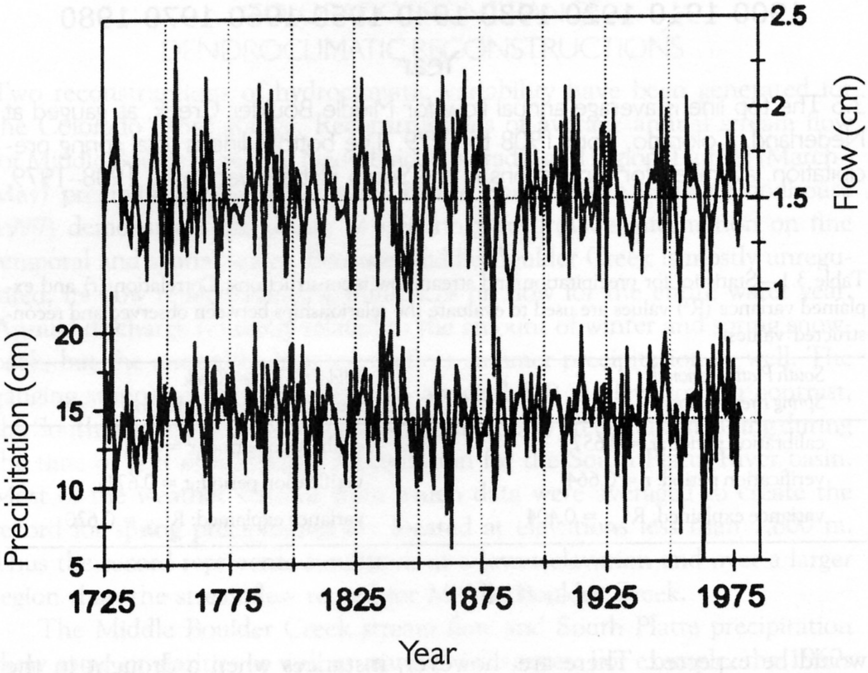
South Platte Regional Spring Precipitation	*Middle Boulder Creek Average Annual Stream Flow*
calibration period: r = 0.657	calibration period: r = 0.812
verification period: r = 0.664	verification period: r = 0.671
variance explained: R^2_{adj} = 0.404	variance explained: R^2_{adj} = 0.620

would be expected. There are, however, instances when a drought in the precipitation record is not reflected in the flow record and vice versa. Table 3.2 shows the five single years of lowest precipitation or lowest flow, three-year averages, and five-year averages (1725–1979). The ranking shows that the two records share two of the extremes (1954 and 1843), but years of extreme conditions are different for the two variables over three- or five-year averaging intervals. Years of lowest spring precipitation in the South Platte basin are primarily clustered in the early 1860s and early to mid-1960s, whereas periods of lowest flow in Middle Boulder Creek occur in the mid-1840s and 1880s. These results suggest that droughts primarily affecting

Table 3.2—Ranking of driest years or clusters of years as shown by low precipitation or low stream flow.

Spring Precipitation, South Platte			*Stream Flow, Middle Boulder Creek*		
Single Year	*3-Year Average**	*5-Year Average**	*Single Year*	*3-Year Average**	*5-Year Average**
1963	1862	1861	1880	1886	1846
1863	1963	1862	1842	1887	1887
1954	1730	1964	1887	1880	1886
1801	1955	1731	1770	1846	1844
1842	1964	1965	1954	1879	1888

*Years shown for averages are the middle year of 3-year or 5-year time spans.



3.6 Reconstructions of Middle Boulder Creek average annual flow (TOP) and South Platte regional spring precipitation (BOTTOM) for 1725–1979. Reconstructions have also been smoothed with a 5-weight binomial filter.

winter snowpack (the main source of annual flow) in the Middle Boulder Creek watershed may not always affect regional spring precipitation, whereas a deficit in spring rainfall is not always linked to low average annual flow at the Nederland gauge, even though spring is typically the time of greatest snowfall accumulation.

Inconsistencies between sites are likely related to topographic differences. Heavy snow at high elevations in spring may not coincide with high precipitation at lower elevations. Similarly, spring upslope storms may provide moisture to lower elevations but not to higher elevations. The flow record also appears to indicate more periods of persistent dry conditions than the precipitation record, suggesting that factors controlling drought at high elevations primarily in winter and spring are more persistent from year to year than those influencing spring precipitation at low elevations.

The two reconstructions appear to resolve geographic differences and can be used to explore the record of past drought. The longer records provide a broader temporal context for evaluating twentieth-century droughts. These records suggest that the twentieth-century South Platte precipitation record is a fairly good representation of the past 200 years. The dry years in the 1960s are well matched by a period in the 1860s, although the value for 1963 is the lowest in the 254-year record. The twentieth-century flow record is not quite as representative of the reconstructed long-term record. The most severe and persistent low-flow episodes of the twentieth century appear to have been exceeded several times in the nineteenth century (1840s, late 1880s). The extended record is still rather limited, however. Evidence from other proxy data in the central and western United States suggests that a drought in the late sixteenth century lasted up to two decades (Woodhouse and Overpeck 1998). It is not yet clear whether this drought also affected Front Range stream flow and precipitation in the South Platte basin.

Tree-ring data are useful for extending records of climatic and hydrologic variability into the past. These extended records provide information about a more complete range of natural variability than provided by instrumental records, which are mostly limited to the twentieth and twenty-first centuries. Although past climate is not necessarily an analog to the future, records of past variability can be used as a guide to the range of variability that may be expected in the future. Tree-ring reconstructions of past climate could be used by water-resource managers to establish an expected range of natural variability.

REFERENCES

Cook, E. R., and L. A. Kairiukstis. 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences.* Kluwer Academic Publishers, Dordrecht.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland. 1999. Drought reconstructions for the continental United States. *Journal of Climate* 12: 1145–1162.

Fritts, H. C. 1976. *Tree Rings and Climate.* Academic, London.

Grissino-Mayer, H. D. 1996. A 2129-Year Reconstruction of Precipitation for Northwestern New Mexico, U.S.A. In *Tree Rings, Environment, and Humanity.* J. S.

Dean, D. M. Meko, and T. W. Swetnam, eds. Radiocarbon, Tucson, AZ, pp. 191–204.

Grissino-Mayer, H. D., and H. C. Fritts. 1997. The International Tree-Ring Data Bank: An enhanced global database serving the global scientific community. *Holocene* 7: 235–238.

Riebsame, W. E., S. A. Changnon, and T. R. Karl. 1991. *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987–89 Drought.* Westview, Boulder.

Stockton, C. W., and G. C. Jacoby. 1976. Long-Term Surface Water Supply and Streamflow Levels in the Upper Colorado River Basin. Lake Powell Research Project Bulletin No. 18. Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

Woodhouse, C. A. 1999. Artificial neural networks and dendroclimatic reconstructions: An example from the Front Range, Colorado, USA. *Holocene* 9: 521–529.

———. 2001. A tree-ring reconstruction of streamflow for the Colorado Front Range. *Journal of the American Water Resources Association* 37: 561–569.

Woodhouse, C. A., and J. T. Overpeck. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* 79: 2693–2714.