PATTERNS OF CLIMATIC CHANGE REVEALED THROUGH DENDROCLIMATOLOGY

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Harold C. Fritts and G. Robert Lofgren

Laboratory of Tree-Ring Research
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Contract #DACW 72-78-Q-0046
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*Both authors have been involved in assembling these data and in drawing inferences from the results. However, the first author takes full responsibility for meeting the terms of this contract and for the conclusions and remarks included herein. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation or the US Army Coastal Engineering Research Center.
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PROLOGUE

The objectives of this report are, first, to summarize the findings to date of the dendroclimatic work performed by our research team at the University of Arizona with respect to the broad patterns of climatic variations over North America since 1600 AD. A secondary objective, as stated in the contract, is to select set(s) of those past climatic patterns which most closely resemble or provide a perspective for conditions of climatic variability expressed as possessing a substantial degree of mobility of occurrence by the National Defense University (1978) study of climatic changes.

The contract outlines the problem as follows:

Patterns of climate change on a geographically specific basis may be reconstructed from past events and should be used to place a perspective on potential regional variability of longer term future climate change. Specifically, relatively recent cooler climate patterns (1600-1900) would ably reflect conditions of a general drop in latitudinal temperature of 1-2° C in the United States. Similarly, the well documented climatic optimum of 6,000 years before present (BP) is roughly equivalent to an overall increase in temperature of 1-2° C.

Thus, only two significant climate-change scenarios which could conceivably affect perceptible responses of hydrologic, morphometric and ecosystem variables should be considered. These scenarios are:

1. An increase in mean temperature of 1-2° C with a corresponding change in precipitation of ± 10 percent.

2. A decrease in temperature of 1-2° C with corresponding change in precipitation of ± 10 percent.
The following work is to be performed:

Review, summarize and integrate concepts, literature, and work accomplished with respect to dendrochronological techniques developed by the H.C. Fritts group for reconstruction of past climatic variations for North America. Emphasis should be placed on a broad picture of mathematical model construction and evaluation; climatic typing; and summary of the most significant results.

Based on selection of final set of models which represent the best fit of past climatic variations, select those climate periods and/or patterns which most closely represent or provide an instructive perspective of patterns of anticipated future climate changes.

Provide graphical representation of selected climate periods and/or patterns in the form of plates, graphs, or page-size, reproducible computer printouts which clearly supports the narrative.

Discuss potential trends or any evidence in past climate variability which supports or negates a correlation between temperature and precipitation. Discuss any evident or apparent anomalies in any climatic variable or pattern either on a regional-geographical basis; physiographic basis or river basin scale if possible.

The results described in this particular report are the most comprehensive that we could assemble within the time limit of the contract and given the present state of our reconstruction work. As far as possible our results are discussed from the point of view requested in the contract. More definite results will be available within two years with the termination of the present project and publication of the final results.

—H.C.F.

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ABSTRACT

Well-dated proxy information on paleoclimatic variations found in tree rings and historical evidence can provide much needed information on seasonal climatic variations for periods of from one year to several centuries. Synoptic-scale climatic variations resulting from anomalies in the migration of cyclones and anticyclones over the earth's surface can be mapped. Multivariate transfer functions, calibrated with twentieth century climate, scale and convert the past spatial variations in the tree-ring record into estimates of past spatial variations in climate. Information from 65 western North American tree-ring chronologies is used to reconstruct seasonal anomalies of temperature, precipitation, or sea level pressure. Verification of the reconstructions is made using independent meteorological observations, historical data, and proxy data from the nineteenth century.

The reconstructed winter temperature and precipitation during the seventeenth through nineteenth centuries are found to differ from the twentieth century data, with large synoptic-scale variations more evident than any simple hemispheric uniform climatic trend. Cold winters in eastern and central North America are frequently reconstructed, while circulation patterns similar to those occurring in 1976-1977 and 1977-1978 are reconstructed to have been especially frequent in the seventeenth century. The standard deviations of the reconstructions are generally greater in the seventeenth through the nineteenth centuries, but vary in amount for different variables, regions, and seasons. While the annual temperatures averaged over the United States are reconstructed to have been cooler in the past, these values resulted primarily from cold winters in the eastern two-thirds of the country. Part of the reconstructed synoptic-scale fluctuations in winter temperature is in phase with the so-called worldwide changes, but a substantial part of the variation is out of phase with, or unrelated to, these changes. The annual precipitation in the past was lower over large areas of the West, especially in California where it was 15% less. The eastern states were wetter, but when all regions are averaged, there is no annual nation-wide precipitation anomaly.

To the extent that the mapped anomalies do not show a uniform warming trend throughout the country as a whole, they do not substantiate either of the National Defense University scenarios of worldwide cooling or warming. While the mean winter temperature was lower in the past than in the present, the average variation over the entire country is small in comparison to the synoptic-scale variation from one decade to the next. The so-called trend appears to be in large part the result of averaging, a risky method to use in developing strategies for long-term planning needs for particular watersheds and crops. In addition to differences in climate from one region to the next, crops respond differently to the climate in each of the four seasons. Realistic planning might better focus on seasonal climate and the larger variance of information in the smaller regions, which lasts for time periods of several years to several decades. As the climatic conditions to be expected for each of the individual regions are understood, future consequences of their variation can be better anticipated, a composite picture for the country assembled, and a meaningful and reliable nationwide strategy developed.
Chapter I
INTRODUCTION

Proxy records can reveal climatic variations at all time scales and all frequencies. However, most of the early paleoclimatic work dealt primarily with low-frequency variations that persisted for thousands of years. Many studies involved geological stratigraphic series in which sampling intervals were simply too large or the dating too inaccurate to reveal high-frequency changes. Studies of higher-frequency climatic variations with periods of less than 1000 years were left to the meteorologist, climatologist, and occasionally to the historian.

In North America the data available for high-frequency studies are of relatively short duration, limited in geographic coverage, and sometimes discontinuous for significant portions of the record. Only since about 1900 has the spatial and temporal coverage been sufficient to allow for synoptic-scale studies of these climatic variations. During the first 40 years of this century the record was too short for statistical conclusions. Scientific interest during the next 30 years was centered on the war effort, atomic energy, or space exploration. Also, the long period of relatively favorable climate in the 1960's did not stir in the public mind the need for climatic research.

The advent of large-scale and severe droughts having seemingly cyclic behavior and the unexpected severe winters of the 1970's have stimulated scientific interest in and public support for research in climatic variability. There is a growing awareness that statistics from our relatively short climatic record of the past may not provide reliable estimates of future climatic conditions. More people in influential positions are heeding Bryson and Hare's warning that the period from 1931 to 1960, which has been widely used as the climatic normal, may have had the most abnormal climate of the past 500 years, and perhaps the last 1000 years (Bryson and Hare, 1974).

Studies of various proxies of past climate reveal the spectrum of variability at all frequencies with the lower frequencies smaller than $10^{-3}$ clearly dominating (Kutzbach and Bryson, 1974; Mitchell, 1976). Kutzbach and Bryson suggest the possibility that the greater importance of the low-frequency variability in the existing data may reflect the absence of high-frequency proxy information as well as the absence of climatic variability at these time scales, especially variations with periods of 200 to 1000 years. They are concerned about this scarcity of climatic information at the higher frequencies, as these fluctuations can have a major, if not the most significant, impact upon human activity in our modern society. They offer the hope that, "Tree-ring, ice core and historical records, and pollen records from varved sediments should play an important role in defining details of the climatic spectrum in the intermediate range of order 100 to 1000 years."

Since Kutzbach and Bryson made their study, there has been a significant improvement in paleoclimatic information in the high-frequency ranges. More detailed information has been collected at close stratigraphic sampling intervals of geological sequences, and there are more refined methods of dating.
The developments regarding tree rings, ice cores, historical information and pollen records are especially significant, for these data often can be compared on a one-to-one basis with the meteorological record. However, these high-resolution data are highly variable and appear to conflict more among themselves in terms of worldwide synchronicity than do other paleoclimatic data. Bray (1971) went so far as to seriously doubt the high-frequency tree-ring data from arid North America simply because they seemed to conflict with the larger, worldwide patterns. But meteorological data do not exhibit such worldwide and large-scale synchronicity, and evidence is accumulating which raises serious questions about the presence of precise synchronicity even in the long-term proxy records of climate, at least those for the more recent time periods. For example, Wigley (1977) carefully examined geographical patterns of climatic changes from available historical accounts and proxy data. He reports: "Non-synchronicity and large-scale inhomogeneity of climatic change on the 100-year time scale were found to be the rule rather than the exception, and because of these factors there is no certainty that any periods of hemispheric cooling and/or warming have occurred during the past 3000 years. There have however, been periods when the hemisphere has been considerably cooler than the present: there is no inconsistency here because the cooling has been time-transgressive on the 100-year time scale."

We believe that today, sufficient collections of paleoclimatic proxy data are available, and precise methods of extracting the climatic signal are adequately advanced to allow a detailed analysis of high-frequency synoptic-scale climatic variability. This variability stems from the migratory cyclones and anticyclones, with diameters of from 500 to 1250 km, occurring in the lower troposphere.

In this paper we will review some of the important climatic data sets for the last millennium, describe some of the developments which have led to our optimism about the promise of paleoclimatic research, illustrate the nature of our most recent climatic reconstructions using western North American tree-ring chronologies, and discuss the relationship of our reconstructions to popular concepts of general climatic trends.
Chapter II

IMPORTANT PROXIES OF HIGH-FREQUENCY CLIMATIC VARIATIONS

A number of proxy data sets provide relatively precise information of the intermediate and high-frequency climatic variations. Modern man has recorded direct and indirect references to climatic phenomena in his literature, and prehistoric man has left a rich archaeological record. (Ladurie, 1971; Lamb, 1972 and 1977). More historians and meteorologists are becoming interested in the subject. The first International Conference on Climate and History is to be held in England on July 8-14, 1979. However, the historical and archaeological data are commonly dissimilar, fragmented, and are not uniformly available from all regions.

Data from natural sources, such as pollen assemblages in lake sediments, can provide more continuous records of past climatic changes which are reflected by changes in plant communities. Transfer functions applied to such data (Webb and Bryson, 1972) can convert the pollen data to climatic estimates. However, the dating was insufficient to show the higher-frequency variations until Swain (1973 and 1978) showed that pollen and macrofossils from annually-layered sediments could be used to establish a more detailed climatic record. The annual layers are counted for time control, but the layers are so thin that 10 or more are needed for a single pollen sample. In addition, the time required for the pollen-producing plant community to respond to climatic change is estimated to be 30 or more years. Therefore, these series probably contain little information about climatic variations lasting for less than 30 years duration (Swain, 1978).

Fluctuations in the oxygen isotope content of large ice sheets reveal more or less annual climatic variations. However, they have been used more often in the study of longer-term climatic variations (Dansgaard et al., 1971). While these data appear to provide a more or less continuous record extending backwards in time for thousands of years, compaction, diffusion, distortion, and occasional melting of the accumulating snow can obscure the annual layering, especially in the deeper portions of the record, and can lead to significant uncertainty in dating. Bands of fish scales, mollusk shells, and coral skeletons may be related to environmental variations, but few reliable records exist, and they are still too short to provide the needed paleoclimatic information.

Tree rings, varying in size, structure, and chemical and isotopic composition, can often be related to environmental conditions. If these environmental conditions are correlated with macroclimatic fluctuations, similar synchronous growth features can be observed in large numbers of trees throughout a region. Such growth features are used to determine the exact year in which each ring was formed, a procedure referred to as crossdating. The dating involves comparison of ring growth patterns from different sides of a tree, different trees, and different sites, locating where patterns in ring width are not synchronous, and correcting them until no more inconsistencies can be found. Crossdating not only establishes the exact time control of the ring record.
sequence, but it also assures that the rings contain some kind of climatic information, because no factor other than climate can produce such similar, large-scale patterns in ring features (Fritts, 1976).

The science of tree-ring dating, dendrochronology, has traditionally used ring-width measurements, but wood density and earlywood or latewood thickness are equally useful (Schweingruber et al., in press). Studies of stable and unstable isotopes of carbon, hydrogen, and oxygen in wood are also promising possibilities, but the methodologies of the new applications are not yet fully developed.
Chapter III
DENDROCLIMATOLOGY

The analysis of the accurately dated tree-ring features, whether they are ring width, latewood density, earlywood density, etc., usually begins with a procedure called "standardization," which compensates for tree age and site factors. Standardization transforms the data by removing trends due to aging of the trees, but essentially retains all of the high-frequency growth variations due to climatic variability. Not all trends are removed and at least some climatic variations lasting as long as 300 to 400 years are still present, although the magnitudes may be underestimated. The transformed data are called tree-ring "indices" and are averaged year by year for all trees in a sample to bring out the large-scale common climatic signal in the ring widths.

More than a thousand ring-width chronologies are available from western North American conifers. During the early days of this research, spatial anomalies in growth were plotted on maps to show past climatic variations (Fritts, 1965). Now, however, multivariate statistical methods are used to relate variations in growth to corresponding variations in climate to derive a transfer function which converts the records of growth into estimates of past climatic variations (Fritts et al., 1971). While local climatic fluctuations may be reconstructed from tree-ring chronologies in nearby sites (Fritts, 1976), we are concerned with the more complex problem of calibrating large-scale anomalies in growth and using them to obtain information on large-scale variations in past climate.

A. Biological Materials Selected for this Study

We now direct attention to some recent studies illustrating the promise offered by high-frequency paleoclimatic work. The basic tree-ring materials used consist of 65 replicated chronologies obtained from Pseudotsuga menziesii, P. macrocarpa, Pinus ponderosa, P. edulis, P. flexilis, P. Longaeva, P. jeffreyi, and Abies concolor throughout western North America (Fig. 1) (Fritts and Shatz, 1975). All chronologies are from replicated cores obtained from 10 to 30 trees of a particular species in a discrete site.

The diagram in Figure 2 represents the biological model assumed in this analysis (Fritts, 1976). The letter t in the figure designates the year of the climate starting with the autumn of the prior year and ending with the summer concurrent with the growing season. Climatic conditions, represented by water, heat, wind, carbon dioxide, sunshine, and other constituents of the environment, limit one or more plant processes which indirectly or directly govern cell growth and ring width.

Many effects of climate on growth are not instantaneous. Some lag one or more years behind the climatic occurrence, affecting growth by a decreasing amount in subsequent seasons (t+1 up to some constant lag k in Figure 2) after which there is no measurable effect of the climate of year t. In addition, climate can influence many internal conditions of
Figure 1. Site locations of the 65 replicated tree-ring chronologies from western North America.
Figure 2. Model of the effect of climate on growth in a given year, t. The effect of climate is greatest in year t and less in years t+1 up to year t+k, after which there is no substantial effect of year t climate. The growth of year t is also related to growth in the prior year, t-1, through physiological autocorrelated phenomena.
the tree, and can alter the efficiency of its biological processes in subsequent seasons so that, in addition to climatic lagged effects, wide rings tend to follow wide rings and narrow rings follow narrow ones. In other words, there is positive autocorrelation beyond that caused by lags in the response to climate. Thus, the growth of the tree in the prior year (t-1) is also an important modeling component. Both the lagging and autocorrelation relationships must be taken into account to obtain the best estimates of climatic fluctuations.

It has been shown by Fritts (1976) that trees of different species or on different sites often respond differently to the same climatic conditions. Factors such as temperature, precipitation, sunshine, and wind can be directly related (positively correlated) to ring width in one season at one tree site, but inversely related (negatively correlated) in other seasons and at other tree sites. Thus, in addition to regional similarities which allow crossdating, there is some diversity of response which is accentuated by variations in species, topography, and geography, which can modify the particular climatic factors that limit growth. Unfavorable effects on growth of one factor in winter sometimes can be offset by favorable effects of the same or other factors in spring or summer. The same extreme condition in one season may limit growth, while in another season, may favor it.

B. Climatic Data Grids

Five grids of climatic data were chosen for calibration as follows:

1. Sea-level pressure from 1899-1970 at 10° longitude and latitude grid squares from latitude 80°W to 100°E and from 20°N to 70°N, except every 20° of longitude at 60° and 70° latitude north.

2. Temperature from 1901-1970 for 77 stations in the United States and southwestern Canada or for 46 stations in the western United States and southwestern Canada.

3. Precipitation from 1901-1970 for 96 stations in the United States and southwestern Canada or for 52 stations in the western and southwestern United States.

The seasons were defined as: winter, December-February; spring, March-June; summer, July-August; and autumn, September-November. The years which were common to both the tree-ring indices and climatic data were used for calibration.

C. Calibration

Since there is a possibility for some variation in the growth response from chronology to chronology, the simplistic deductive methods used in earlier years involving inferences drawn from plots or maps of tree-ring chronologies over space (Fritts, 1965) are now viewed as only first approximations of past climatic variations. Far more information can be extracted using linear multivariate calibration methods. Transfer functions with large numbers of coefficients not only accommodate the complexity and
diversity of the growth response, but they can also extract seasonal information from differences in the growth response of the various tree samples (Fritts et al., 1971; Fritts, 1976; and Blasing, 1978).

Approximately 1500 such models have been assembled and calibrated at the present time and we have completed the preliminary stages of verification on independent data. Some of these results suggest additional models which we are preparing and testing. When we are satisfied that the reconstructions are as reliable as possible we will apply them to a variety of climatic problems dealing with both seasonal and time-averaged climatic variation.

The Appendix provides an in-depth discussion of calibration, verification, and some applications to problems of climatic variation using those models about which we are most confident. For maximum information the reader should examine the Appendix before proceeding with the main text.

In the following chapters we present maps and data from only a portion of our most reliable results and draw some tentative inferences regarding the nature of climatic variations as they relate to the scenarios mentioned in the preface of this report.
Chapter IV

PAST PATTERNS OF CLIMATIC VARIATION

A. Past Differences in the Seasonal and Average Annual Climate

One way to consider the problem of climatic variation and change is to examine
the statistics of climate for past centuries and compare them to those for
today's climate. We selected our best reconstructions from the seventeenth
through the nineteenth centuries and compared temperatures and precipitation
for each of the four seasons with twentieth century climate. The reconstruc-
tions were averaged among the individual climatic stations for each of 11
regions (Fig. A-6, Appendix), comparing the means and standard deviations for
1602-1900 with those of 1901-1962. Since the reconstructions are regression
estimates, their variances are always smaller than those of the actual data in
proportion to the percent calibrated variance. Therefore, we rescaled each
reconstructed series for its entire length by multiplying it by the standard
deviation of the actual data for 1901-1962 and dividing it by the standard
deviation of the reconstructions for the same time period. The means for tem-
perature for the calibration interval 1901-1962 are subtracted from the
reconstructed means for the time period 1602-1900. The means for precipitation
and the standard deviations for both variables are expressed in percentages as
differences from the means and standard deviations of the 1901-1962 period.

These data, along with the percentage of calibrated variance, are tabulated in
their appropriate region in Figures 3 and 4. The temperature difference for the
region is entered as the top value in degrees Celsius; the middle value is the
percent difference between the standard deviations; and the lower value is
the percent variance calibrated for each region. As pointed out in the Appendix,
since these percentages of calibrated variance are for average regional recon-
structions, they are generally higher than the average calibrated variance
of the reconstructions for the individual climatic stations. The averaged values
of all 11 regions are entered on the right-hand side of each Figure.

The patterns of the mean temperature and precipitation difference for past
winters, shown in Figure 3, are similar to those described for individual
station reconstructions in the Appendix. The magnitude of the differences is
greater, reflecting the rescaling of the reconstructed and climatic data.
These larger adjusted values are more appropriate for making comparisons with
present-day climate. The means of all 11 regions indicate a general lowering
of the average winter temperature for the United States by 1.1°C, while the
nationwide average winter precipitation was the same in the past as in the present.

The standard deviations for both winter temperature and precipitation (middle
item of the columns in Figure 3) are reconstructed to have been approximately
20% to 21% higher in the past than in the present century. The changes in
standard deviation for temperature are markedly greater in the far West than
in the East, while changes in the standard deviations of winter precipitation
Figure 3. Statistics for the 11 regionally-averaged reconstructions of winter and spring temperature and precipitation for 1602-1900 as compared to the 1901-1962 data. All reconstructed values are adjusted so that the standard deviation for 1901-1962 is equal to the standard deviation of the actual data for the same time period. The top figure is the departure of the 1602-1900 mean from the 1901-1962 average expressed in degrees Celsius for temperature and in percentage for precipitation. The middle figure is the percent difference in standard deviation for 1602-1900 from the 1901-1962 standard deviation. The lower figure is the percent calibrated variance for the mean regional reconstruction. The averages of all 11 regions are tabulated on the right hand side of the figure. Models are our best as of August 1, 1978. They are: winter temperature, BI+IM+FM(P); winter precipitation, BI+BM+MF+FFF; spring temperature, BM+FM(P)+FFF; and spring precipitation, BM+M(B)I+MM(P)+FM(P)+FFF. (See Appendix.)
are greater along both the Pacific and Atlantic coasts than they were over the Rocky Mountains. The averaged temperature and precipitation reconstructions for winter presented in Figure 3 along with the time series plots in Figures A-7 and A-8 in the Appendix provide additional perspective to past differences in winter temperature and precipitation from twentieth century values.

It is clear from the winter data that there is no overall trend apparent in all regions, nor do the changes in temperature correspond to the changes in precipitation. The past three centuries' winters were, on the average, dryer for the Southwest, northern portions of the Rocky Mountains, and south of the Great Lakes. For the remaining portion of the 48 states, winters, on the average, were wetter. Temperatures during winter were below the 1901-1962 normal for most of the North, East, and central portions of the continent. Only in the Great Basin were average winter temperatures for 1602-1900 substantially higher than the 1901-1962 averages.

Spring temperatures during 1602-1900 (Fig. 3) varied in the opposite direction from winter temperatures, although the differences were smaller. Past springs were, on the average, warmer in the East and colder along the Pacific Coast and in the Northwest. This pattern is opposite that of winter temperatures. The standard deviations of the reconstructions in the past are higher than those for the twentieth century throughout the North and Southeast. They are about the same as the twentieth century in the Southwest and 2% to 8% lower in the central plains and southward. This result is again at variance to that for winter climate. However, for the spring temperature reconstructions, only 41% of the variance is calibrated for the Atlantic Coast region, so the certainty of these estimates is less than for other regions.

Spring precipitation is better calibrated than spring temperature along the Atlantic Coast, but more poorly calibrated in the Columbia River Basin. The reconstructed precipitation in spring is less than that of the twentieth century for the three southwestern states in which winter precipitation had also been lower. It is higher, however, throughout the five regions in the East. The average for all 11 regions is 2% lower. The standard deviations for spring precipitation are reconstructed to have been higher than those for the twentieth century throughout the Southwest, extending into the Southern Plains. The standard deviation of the Southern Prairie is 1% less than that of the twentieth century.

Average summer temperatures (Fig. 4) reconstructed for the six western regions are near or below the twentieth century figures, while they are higher in the Prairie, Great Lakes, and Atlantic Coast, a pattern at variance with the winter reconstructions. As for winter temperature, the greatest differences in standard deviations occur where the average temperature departures are highest. Values of 35% to 42% are attained in the Great Lakes and the Atlantic Coast, and for all 11 regions the average standard deviation is higher by 11%.
Figure 4. Same as Figure 3, but for summer and autumn. Models are: summer temperature, BI+IF+MF+IM(F)+FFF; summer precipitation, BI+IM(F)+FFF; autumn temperature, I+MF+IM(F)+FM(F); and autumn precipitation, BI+M(B)+IF+MM(F)+FFF. (See Appendix.)
Precipitation in summer was substantially higher throughout the far West by as much as 41% in California. However, the average California precipitation for the twentieth century amounts to only 2 mm, so the percentage increase is inconsequential. The summer precipitation in the other western regions for the twentieth century ranges from 39 mm to 72 mm, so their percentages, even though smaller, represent a much larger amount. The average calibrated variance for summer precipitation for all 11 regions is lower than those for summer temperature and for both temperature and precipitation in the winter and spring seasons. This poorer calibration in summer precipitation is probably due to the greater spatial variability from convective storms at that time of year.

Autumn temperatures in the past are reconstructed to have been from 0.1°C to 0.4°C higher than the twentieth century for the West and South. Temperatures are reconstructed to have been 0.2°C to 0.4°C lower for the north central states and the Northeast. All standard deviations for autumn temperatures in the past are substantially greater than those for the twentieth century, averaging 37%. However, the reconstructions for autumn temperatures are the poorest for all variables and seasons with the reconstructed variance for the 11 regions averaging only 46%. Thus, the estimated values for autumn temperature are least certain.

Autumn precipitation exhibits substantially higher percentages of calibrated variance than does temperature. The values are below 50% only for California, while they are below that amount in eight of the regions for autumn temperature. The reconstructed averages for 1602-1900 are below those for 1901-1962 in six regions. The Great Basin and the Southern Plains are lower by 19% and 16%, while precipitation in the Southwest Deserts and along the Atlantic Coast is reconstructed to have been 16% and 14% higher. The standard deviations for autumn precipitation in the three earlier centuries are below the twentieth century values for four regions, which is a greater number than we obtained for any other variable and season. The greatest difference occurred in the Northern Plains where the standard deviation is 13% below the twentieth century, while in the Great Lakes region, the Southeast, and along the Atlantic Coast, the standard deviations are 29% to 33% higher than the twentieth century.

The mean annual temperatures (Fig. 5) are dominated by the changes in winter. They are reconstructed to have been less in 1602-1900 than in 1901-1962 for eight of the 11 regions. This difference amounts to an average decrease of 0.18°C for all regions. (These calculations are carried to one more digit because the range of variation is less.) The largest negative difference is -0.67°C in the Northern Prairie. However, in the Great Basin annual temperatures are higher by 0.17°C. The standard deviations average 19% higher in the past centuries over all regions, with a maximum value of 30% in the Great Lakes. The average calibrated variance is 59%, ranging from 51% for the Northern Plains and the Atlantic Coast to 71% for the Southwest Deserts.
Figure 5. Same as Figures 3 and 4, but for mean annual temperature and total annual precipitation. The seasonal means and standard deviations are weighted by numbers of months and averaged or totaled for all seasons. Departures and percentages are recalculated.
The reconstructed annual precipitation, when averaged over all regions, does not differ by a significant amount from the mean of the twentieth century. However, precipitation in California was 15% below that of the twentieth century, and along the Atlantic Coast, it was 8% higher. The differences throughout the agriculturally important prairie regions are lower by 2% to 3%, while over the Great Lakes, it is 2% higher. The difference in standard deviations of past precipitation, averaged over all regions, is 16% greater. It is greater than zero for all but the Northern Plains. It is greater by 30% in California and by 23% to 24% in the three eastern regions. The average calibrated variance for precipitation is 59%, ranging from 53% for the Southern Prairie to 73% for the Southwest Deserts.

The statistics for climatic reconstructions for the prior three centuries, when compared to the current one, differ markedly between variables, regions, and seasons. The greatest differences occurred with winter temperature, which is reconstructed to have been lower, causing a reduction in the annual averages. The temperature differences averaged for all four seasons are approximately ¼ of the winter difference and are in the same direction as the so-called average Northern Hemisphere changes for eight out of 11 regions. In the Great Basin, the Southwest Deserts, and the Southern Plains, the annual temperature trends in the past are in the opposite direction. California exhibits the most marked change in past annual precipitation, amounting to 15% less than the twentieth century figures. In the eastern United States the annual precipitation was substantially higher, with standard deviations 16% larger than those for the twentieth century.

It is important to note here that winter temperatures in the past were lower than the twentieth century, but summer temperatures were higher for four regions in the eastern half of the country, increasing the seasonal spread of temperature. Temperatures were lower for both seasons in the California Valleys, the Columbia Basin, and the Northern Plains, and higher in the Great Basin. In addition, the growing season temperatures from March through August are reconstructed to have been higher throughout the agriculturally productive plains states; but there is also an increase in the standard deviations, indicating more climatic variability. Because the spring temperatures in the northern regions were warmer and autumn temperatures were cooler, it is not clear whether or not there was actually a difference in the mean length of the frost-free season. However, one could infer from the greater standard deviations that the range of variation in the frost-free season from year to year was greater. Coupled with warmer temperatures and lower summer moisture, the increased hazards to past agriculture could well have been significant. This would suggest that in the future, a variety of hazards to agricultural production, such as late spring or early autumn frosts, flooding, or drought, could increase again in the plains states.
B. Higher-frequency Variations for the Winter and Spring Seasons

1) Half-Century Variations

In order to study details of the variations that have occurred within the last three centuries, we have averaged the seasonal reconstructions of winter temperatures, winter precipitation, and spring temperatures over approximately 50-year intervals. Figure 6 includes the anomaly maps of temperature and precipitation reconstructions (uncorrected for differences between the actual and reconstructed means and standard deviations) for the seventeenth century plotted as departures or as percentages of the 1901-1970 averages. Reconstructed pressures are used to assist in the interpretation but are not shown in this paper.

a. 1602-1650

Many winters in the first half of the seventeenth century (Fig. 6) are reconstructed to have resembled the winter of 1976-1977 and to some extent the winter of 1977-1978 (see Appendix). Winters were colder in the East and warmer in the West than in the twentieth century with drought common throughout the Southwest Deserts and in the Mississippi Basin. The only area which was markedly wet was the extreme Northwest. Surface pressures (not shown) are reconstructed to have been well below the modern means in the North Pacific, with higher pressures along the North American west coast. This ridge of high pressure apparently deflected many of the North Pacific storms northward to the Canadian-United States border and cyclonic flow drew cold Arctic air southward and brought severely cold conditions east of the Rocky Mountains, especially to the Great Lakes and Midwest.

Springs, on the average, were cooler in the Pacific Northwest and in the extreme Southwest, and warmer in the East. Surface pressures in spring were, on the average, higher than normal over the North Pacific off the West Coast, inducing a southward flow of cold air into the West; but low pressures prevailed over the mid-continent, inducing a northward flow of warm air throughout the central plains and the East. The magnitude of the temperature differences was less for spring than winter, in part because the spring season included four rather than three months.

b. 1651-1700

Winter temperature anomalies resembled the prior period except that the West was not as warm and the coldest anomalies were in the Dakotas rather than in the Midwest. Winter moisture was nearer the twentieth century values except for a localized area of wet conditions centered in Kansas. Winter pressure anomalies are reconstructed to have been nearer to values of the twentieth century
Figure 6. Reconstructed mean anomalies in winter temperatures and precipitation and spring temperatures for 1602-1650 and 1651-1700. Data are plotted as temperature departures in °C or as percentages of the mean precipitation. The period of the mean is 1901-1970. All data are regression estimates with no adjustments made for the difference in actual and reconstructed means and standard deviations for 1901-1962. (See Figs. 3-5.)
over the North Pacific, but higher pressures are reconstructed over the western North American Arctic with a ridge extending southeast in the lee of the Rocky Mountains. Storms must have been deflected somewhat northward of the normal twentieth century path over the western portion of the continent, but to a lesser extent than earlier in the century, so that more Arctic air was drawn behind them near the Rocky Mountains, reducing the winter temperatures there but raising temperature to the east (Fig. 6). Spring temperatures were slightly above the twentieth century figures in the Northwest, cooler in California, and generally mild elsewhere throughout the United States. Surface pressures in spring were similar to those earlier in the century, but the anomalies were not as marked.

c. 1701-1750

The anomalies in winter temperatures are reconstructed to have been negative but not as low over the plains as in the previous century (Fig. 7), while they were not as warm in the far West. The Southern Plains were wet. Surface pressures in winter remained substantially higher over the western North American Arctic than in the twentieth century for the first few decades, but in the last decades they resembled the seventeenth century pattern. The Aleutian Low was reconstructed to have been near the twentieth century averages and pressures were slightly lower for much of the central and western North Pacific. These anomalies suggest less blocking of North Pacific storms than occurred earlier with more storms regenerating in the central Rocky Mountains and travelling in an easterly to northeasterly direction to bring near-average moisture to the eastern part of the country.

Pressure anomalies for spring were variable throughout the period, but, on the average, resemble those in the seventeenth century with higher-than-normal pressures over the eastern North Pacific. The mean temperature anomalies in spring (Fig. 7) were also similar in pattern but less extreme than those of the prior century.

d. 1751-1800

Winter temperature anomalies (Fig. 7) were below the modern means almost everywhere, but the extremes were not as low as earlier in the north central states. A moisture deficit is reconstructed in the southwest for winter, but elsewhere moisture was adequate. Surface pressures in winter became higher in the American Arctic. Spring temperatures are reconstructed to have been substantially lower in the northwestern half of the United States and in Canada with higher temperatures throughout the southeastern portions of the country. Surface pressures over the North Pacific were higher than before.
Figure 7. Same as Figure 6 except for 1701-1750 and 1751-1800.
e. 1801-1850

Winter temperatures in the far West were near, but below, the 1901-1970 averages (Fig. 8) and departures were lower in central United States. However, the east coast was warming after the severe conditions of the seventeenth and eighteenth centuries. Moisture was lower than in the twentieth century for large areas of the West, but in the central plains and southern Texas, precipitation was higher. Near normal winter moisture fell in the East.

A strong North Pacific Low is reconstructed in winter for the first two decades. This was followed by higher pressures in the last two decades. These two patterns cancel one another, so that the contrast in average pressure anomalies is small with lower-than-normal surface pressures, on the average, in the western North Pacific. Averaged pressures are lower than normal over Hudson Bay. Winter pressures average slightly above the twentieth century norms over large portions of western North America and the eastern North Pacific Coast. The pressure gradient in winter from west to east over Canada appears to have increased the southward flow of cold Arctic air into the central portions of the United States.

Spring temperatures throughout most of the United States were warmer than the twentieth century figures (Fig. 8). Average spring pressures are lower than for the prior century in both the Siberian and American Arctic. Higher-than-normal pressure persisted over the United States, suggesting an earlier establishment of the summer storm track in the Arctic and higher spring temperatures over the United States.

f. 1851-1900

Winters were warmer than the twentieth century in the western interior, but colder elsewhere (Fig. 8). Low temperatures were, however, less extreme over the Dakotas, but cooler conditions than those for the prior half century are reconstructed along the Atlantic coast. The patterns of moisture are similar to those earlier in the century, except they indicate somewhat dryer conditions along the Gulf and Atlantic Coasts.

Winter pressures averaged higher than the twentieth century norms over North America and the eastern North Pacific, although considerable variability occurred. The highest average pressures occurred over Alaska and the Canadian northwest.

Spring temperatures along the west coast were somewhat lower than the twentieth century means. Warmer temperatures prevailed to the east, although they were less extreme than earlier in the nineteenth century.

Spring pressure was less anomalous than earlier in the century. An area of somewhat higher pressure off the North Pacific Coast suggests southward advection of cold air there.
Figure 8. Same as Figure 6 except for 1801-1850 and 1851-1900.
2) Selected Decadal Variations

More variability appears in the reconstructions as we form averages of shorter and shorter time periods. Small anomalies in the 50-year averages described in the previous section are often the result of large and opposing anomalies occurring at different times within the half-century. We have selected six interesting decades (but not necessarily the most extreme ones, as we were not yet at that stage in our project work). We have added spring precipitation and the corresponding tree-growth anomalies, but unlike the climatic data, we have normalized tree-growth information by subtracting the mean and dividing by the standard deviation for 1601-1963. The tree-growth maps are expressed as anomalies from the 363-year period, while the climatic estimates are expressed as departures from the 70-year period, 1901-1970. The tree-growth departures are handled in this way because the means for the twentieth century are very large due to the prolonged mild and moist growing conditions, and if subtracted from the earlier data, these large patterns dominate the smaller anomalies in the earlier three centuries, obscuring the interesting variations that occurred then.

a. 1602-1610

Tree growth was above average for large areas of the far West except in Wyoming, Mexico, southern Arizona, and eastern New Mexico (Fig. 9). Growth was above the normalized value of 0.4 (4 on the map) in southern British Columbia, in a band extending from central Oregon southeast into Utah and the Four Corners area, bending back into southern Nevada, northwestern Arizona, and southern California.

Slightly lower-than-normal pressures are reconstructed for winter over the Great Basin so that this area of high growth was apparently subjected to a larger number of storms than normal, resulting in favorable growing conditions in the West. Areas of growth anomalies may thus be inferred to be associated with anomalies in storm tracks and precipitation amounts. Temperature anomalies are related to specific tree-ring chronologies scattered over the grid for which temperature was most limiting to growth.

Winter temperature anomalies in 1602-1610 were below normal east of the Rocky Mountains, with above-normal temperatures in the Great Basin. Drought was present in the Mississippi and Ohio River valleys, but conditions were more moist than for the 49-year period 1602-1650 (Fig. 6) for large portions of the West.
Figure 9. Mean anomalies in tree-ring widths and reconstructed temperatures and precipitation for winter and spring, 1602-1610. Tree-ring data are normalized values multiplied by 10, calculated with the 1601-1963 means and standard deviations. The climatic data are departures expressed as degrees Celsius or percentages of the 1901-1970 mean precipitation. All reconstructions are regression estimates with no adjustments made for differences in actual and reconstructed means and standard deviations for 1901-1962. (See Figs. 3-5.)
Winter pressures were lower than normal for a broad area over the North Pacific, stretching from the Asian mainland to southwestern Canada and northwestern United States. Higher-than-normal pressures over most of the North American mainland deflected the North Pacific storms to the North over the Canadian Rocky Mountains, bringing warmth to the Great Basin desert. The storms moving southeast out of the northern Rocky Mountains brought cold Arctic air into the central plains and eastern United States. The moist area reconstructed in Colorado and Kansas suggests that storms may have regenerated more often in the central Colorado Rocky Mountains than they did in the 1602-1650 average shown in Figure 6.

Temperatures were mild, and moisture was above average in spring for all but the Southwest, where it was cool and dry. Surface pressures were higher than normal over the larger parts of the eastern North Pacific and North America. A low pressure zone along 30°E to 160°E suggests some northward displacement of the Subtropical High. The higher-than-normal pressures in the eastern North Pacific and higher-than-normal temperatures and precipitation for large areas of the United States suggest a somewhat early movement of the Subtropical High to the north, with more southwestern drought and an early retreat of the Arctic front to the north. Trailing cold fronts behind Canadian storms brought unstable conditions, and high precipitation throughout much of the United States.

b. 1701-1710

Tree growth was above average in the northwestern United States and in Mexico and New Mexico (Fig. 10). Growth was below average along the eastern Canadian slopes of the Rocky Mountains, in the central Rockies, and southwestward to California.

Winter temperatures were below the 1901-1970 values everywhere except in Florida. The lowest anomalies were in western Canada, Montana, and the Dakotas, southward to Texas. Temperatures were less anomalous than in 1602-1610 in the eastern United States.

Winter drought was severe in southern California with above-normal moisture in western Canada, the central United States, and eastward through the Gulf and Atlantic Coast states.

Pressures in winter and spring were moderately low from central Asia eastward over the North Pacific south of 40°N. Higher pressures prevailed in Alaska and southward over the eastern North Pacific and North American continent.

Spring temperatures were lower than the 1901-1970 norms for the northwestern half of the United States, but higher in the southeast. Drought is reconstructed from California to western Texas. Spring pressures were lower in the northern Arctic than they were in 1602-1610, suggesting an earlier beginning of the summer circulation than in the earlier decade.
The changes in the 1701-1710 tree growth and climatic reconstructions from the 1602-1610 values suggest a weakening of the southern North Pacific storm track with somewhat more blocking off the California coast causing a reduction in winter and spring moisture throughout the Southwest.

c. 1831-1840

Tree-growth patterns were similar, but not identical, to the early 1600's, with high values for large areas of the Southwest (Fig. 11). This suggests an increasing importance of the southerly storm track through southern California and the Southwest. Such an increase is in agreement with winter pressure, which is reconstructed to have been below normal along the north Pacific Coast. Winter temperature anomalies were similar to 1701-1710, but the reconstructed southwestern drought was replaced by a moist anomaly which extended northeastward to the Great Lakes. Moisture was also above average over much of the East. Spring temperatures were above the 1901-1970 figures in the Northwest, the Great Basin, the southern Rockies, and eastward to the Atlantic Coast. Spring was moist, especially in the Southwest.

There was probably little blocking in the West during this decade, with more abnormally frequent storms crossing the west coast, the Southwest, and travelling eastward across the United States, bringing moisture to large areas of the midcontinent.

d. 1861-1870

High tree growth during this decade dominated southern California and the Great Basin (Fig. 12), with lower values in the northern Rockies, in New Mexico, and further south. Winter temperatures were below the twentieth century normal throughout most of the United States. Winter drought is reconstructed in the extreme Southwest and in the Mississippi River Basin and Great Lakes. Moisture is reconstructed to have been higher in the central Rocky Mountains and adjacent plains states. Winter pressures were generally lower than the twentieth century values throughout the North Pacific.

Spring temperatures were mild throughout large areas of the West. Moisture was deficient throughout large parts of the United States, especially in a band stretching from Mexico to Minnesota. This suggests an earlier beginning of summer with less vigorous storm activity in spring in the West.
Figure 11. Same as Figure 9 except for 1831-1840.
Figure 12. Same as Figure 9 except for 1861-1870.
Lower-than-normal pressures are reconstructed throughout the Arctic region and North Pacific, suggesting that less cold Arctic air moved into the north central states than in the three earlier decades. Storms may well have been travelling north of their normal track. We hypothesize that the Subtropical North Pacific High may have moved northward and eastward at an earlier date in spring than in the seventeenth and eighteenth centuries, deflecting the moisture-bearing storms to a more northerly track.

e. 1931-1940

During this decade, a time well-known for the Dust Bowl and persistent drought, tree growth was extremely low throughout the northwestern states, but high in the Southwest (Fig. 13). Some storm activity is suggested along the southern California coast bringing cooler winter temperatures and moisture to the Great Basin, central Rocky Mountains, and Southwest Deserts.

Winters were mild throughout the plains states and in the East. Winter moisture was below the 1901-1970 average in central portions of the continent, but spring was not as anomalously dry as it is reconstructed to have been in 1861-1870.

Low-pressure systems were displaced north of their normal track for both winter and spring seasons, indicating that cyclonic activity was greater at high latitudes. The North Pacific Subtropical High extended farther north than the average for 1901-1970.

It should be noted here that the climatic anomalies do not appear as pronounced as the tree-growth anomalies because the climatic data are expressed as departures from the mean of the anomalously warm twentieth century rather than the mean of 360 years which was used to normalize the tree growth.

f. 1951-1960

This decade follows the peak of the so-called worldwide warming which began after the cold interval of the Little Ice Age. The areas of extreme tree growth of this decade (Fig. 14) were in the opposite direction to those for 1931-1940, and they were different from the patterns of the other five decades described in this manuscript. Growth was high in the Pacific Northwest and the two western Canadian provinces. Growth was lower than average in the remaining areas, especially in the Great Basin, the southwestern states, and Mexico.

Winters were milder than the 1901-1970 average throughout the entire United States. Precipitation was higher in California, the Great Basin, and in the Canadian west, but below the 1901-1970 averages throughout the United States Rocky Mountains, the Southwest, and to some extent, the Southeast. The areas with warmest anomalies in
Figure 13. Same as Figure 9 except for 1931-1940.
Figure 14. Same as Figure 9 except for 1951-1960.
winter had the coldest anomalies in spring. Spring precipitation was low in the Southwest and somewhat below normal in the central Rocky Mountains, Northern Plains, and Ohio River valley. The East was generally warm and moist. As in 1931–1940, these data are part of the warm normal period, 1901–1970, so the anomalies do not appear to be as marked as those reconstructed for earlier centuries.
Chapter V

THE SIGNIFICANCE OF TREE-RING RECONSTRUCTIONS
TO REGIONAL PLANNING FOR FUTURE CLIMATE

The primary objective of this contract has been to summarize our empirical and objective findings to date with respect to the broad patterns of past climatic variation over North America. In Chapter IV and in the Appendix we present the available data as of August, 1978, which in our judgment provides the best perspective for anticipating future climatic variation and change. In the following pages we summarize our results and consider the secondary objective regarding the use of such data in climate planning. We also deal with the relationship of our data to the NDU scenarios of hemisphere-wide warming or cooling.

This paper, unlike the NDU study, has not been a matter of expert opinion, but rather a presentation of objectively derived empirical climatic estimates. The conditions we reconstruct are those which are calculated to have occurred in the past, given the particular association of twentieth century climate with twentieth century tree growth and the past three-century records of annual growth variations throughout the North American West.

To examine a more generalized form of the data, the 11 regions described in the Appendix were combined into 4 larger regions proposed by Eugene Stakhiv, the contract monitor, as meaningful for the purposes of the project. Each of the maps on decade and half-century averages were scanned, the values were averaged visually, and the data entered on a table. Specific climatic conditions ranging from cold to warm and from drought to wet are defined (Table I) and the word for each condition is entered in Tables I and II in place of the numerical estimate. When conditions differed from the twentieth century normals by less than 0.5°C for temperature and 5% for precipitation, they are considered as normal, which is tabulated as N in the tables. Temperature conditions are listed on the first line of the tables and precipitation on the second.

Since the regional conditions are averages of from one to four of the smaller regions, there is less variation apparent in the table for the decades than is seen on the maps. Averaging and summarizing of the data from several regions into one of five categories obscures much synoptically important information related to standing waves in the atmosphere and the resulting cyclones and anticyclones at the surface. Additional averaging of the data into half-century seasonal values, into 300-year seasonal averages, and into the annual totals generalizes and destroys most of the remaining information content.

At this point one might ask just how much averaging is wise if the objective of the study is to aid in planning for future climatic variations which affect crops, watersheds, or particular regions within the North American continent. A three-factor analysis of variance program was used to estimate the information loss due to averaging. The variance components were measured for
TABLE I

Climatic Conditions for Winter and Spring Inferred from the Numerical Data on the Maps in Figures 3 through 14. Conditions are Expressed as Anomalies from the Twentieth Century Means.a

The 11 Regions of the United States and Southwestern Canada b are Visually Averaged within the Following Broad Areas:

West--Regions 1, 2, 3, and 4  Grasslands--Regions 5, 6, 7, and 8
Midwest--Region 9  East & South--Regions 10 and 11

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<th>Decades</th>
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<tr>
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</tr>
<tr>
<td>1931-1940</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>1951-1960</td>
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</tr>
<tr>
<td></td>
<td>Moist</td>
<td>Dry</td>
</tr>
</tbody>
</table>

Half-Centuries

| 1602-1650     | Warm   | Cool   | Cold   | Cold  | Cool   | N      | Warm    | N     |
|               | N      | Dry    | Dry    | N     | N      | --     | --      | --    |
| 1651-1700     | N      | Cold   | Cold   | Cool  | N      | N      | N       | N     |
|               | N      | N      | N      | N     | --     | --     | --      | --    |
| 1701-1750     | N      | Cold   | Cold   | Cool  | N      | N      | N       | N     |
|               | N      | Moist  | N      | N     | --     | --     | --      | --    |
| 1751-1800     | N      | Cool   | Cold   | Cool  | N      | N      | N       | N     |
|               | Drought| N      | N      | N     | --     | --     | --      | --    |
| 1801-1850     | N      | Cold   | Cold   | Cool  | N      | Warm   | Warm    | Warm  |
|               | N      | N      | N      | N     | --     | --     | --      | --    |
| 1851-1900     | N      | Cool   | Cold   | Cool  | N      | Warm   | N       | N     |
|               | Dry    | N      | N      | N     | --     | --     | --      | --    |

Temperature Conditions (°C): Cold < -1.0 < Cool < -0.5 < N < 0.5 < Warm ≤ 1.0
Moisture Conditions (%): Drought < 85 < Dry < 95 < N < 105 < Moist < 115 < Wet
N indicates that conditions are Normal (near those of the twentieth century).

bSee Figure A-6 in the Appendix.

cNo data.
TABLE II

Mean Climatic Conditions for the Seventeenth through the Nineteenth Centuries over the Same Four Regions as in Table I. Inferred from Data included in Figures 3-5. Conditions are Expressed as Anomalies from the Twentieth Century Means. Climatic Categories are the Same as in Table I.

<table>
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</tr>
<tr>
<td>Spring</td>
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<td></td>
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</tr>
<tr>
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<td></td>
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</table>
the yearly patterns of winter temperature, the 50-year patterns and the means of the 50-year maps. The synoptic-scale yearly variations (not shown on the decade maps) and the decadal variations together contribute 33% of the total variance. The means of the yearly and decadal maps contribute an additional 29%. These two components are summed to obtain 62% of the total variance, a figure which points to the importance of the synoptic-scale variations that are contained in the tree-ring-derived estimates of paleoclimate, including averages from one decade to the next. The spatial patterns of the 50-year mean maps contribute an additional 20% of the variance, leaving only 18% of the variance attributed to the 50-year means averaged over the entire map, the only variance in our data comparable to the scenarios of the NDU project.

We therefore conclude that while averaging over large regions may be useful for examining the overall trends in climate, this is not necessarily the information that is most needed for anticipating future constraints in planning for watersheds or crops, for the synoptic-scale variations from the detailed maps are four to five times more important (82% as compared with 18%).

To the extent that our data show past winter climates in the central and eastern portions of the United States to be considerably cooler than the twentieth century climate, they resemble the cooling scenario of the NDU report. However, we are hesitant to identify any one period as more like the NDU scenario than the rest. One of the obstacles to a valid choice is that such a selection depends upon what character of the reconstruction is assumed to be most like the particular scenario. If it is the most extreme departure, then the decade for 1831-1840 winters (Fig. 11) would be the best candidate for the cooling scenario. If the character is the largest area below the twentieth century norms, then 1701-1710 and 1801-1840 are the best examples. Using Table I, the decade 1602-1610 might be considered appropriate, as then the greatest number of regions were designated as having a cold climate. In addition to this problem, the NDU study dealt with annual averages. Since spring and summer temperatures on the average are reconstructed to have been warmer in the East, and autumn temperatures to have been warmer in the South (Figs. 3 and 4), it is likely that the average annual temperature during the selected "cold" period could have been substantially reduced (Fig. 5).

The decade of warmest temperatures in winter throughout the United States occurred in 1951-1960, a period of the normal interval. There are now summer and autumn reconstructions that may be examples of substantially warmer periods, but these data were not available in time to be considered in this report.

There is no average precipitation anomaly for the whole United States, but variations among the different regions included in the maps are apparent.

Another reason for our hesitation in choosing a time period that resembles each scenario is the frequent occurrence of see-saw variation between winters that are cool in the West and warm in the East, and those that are warm in the West and cool in the East. The nodes of this see-saw variation usually lie along the Rocky Mountain crest or are displaced to the northwest, sometimes bending back in a southerly direction along the North Pacific Coast. Such a
pattern is predominant as one of the first few eigenvectors of winter temperature and is seen in the extreme winter of 1966-1967 and 1967-1968 to be a result of large-scale blocking and a standing wave in the atmosphere (see Appendix). Thus, this important pattern and other similar features that make up a larger part of the variance must be considered carefully, not excluded, if we are to develop meaningful and reliable plans for future climatic variation.

The patterns in winter precipitation appear to be smaller scale and relatively uncorrelated with patterns of temperature. One exception is an association of both warm or cold extremes on the maps with low precipitation as storm activity is less and an association of steep temperature gradients with high precipitation as storms are enhanced. Evidence from the spatial eigenvectors of both precipitation and temperature and from the correlation between time series of temperature and precipitation from one region to the next, suggests that several interesting and meaningful temperature-precipitation relationships may exist. We have not researched the subject adequately to respond to that question in this contract but our reconstructions are ideally suited for such an analysis. In time we will be examining these and other climatological questions after completion of the remaining reconstruction and verification analysis.
Tree-ring data and historical accounts are unique proxies of past climate. When dated to the exact year of occurrence, the sequences of wide and narrow rings can be statistically calibrated with seasonal or yearly variations in climate. A calibration transfer function is obtained which, when multiplied by past proxy data, provides an estimate or reconstruction of the associated past climate. The discontinuous but well-dated historical information becomes more meaningful in the context of the tree-ring reconstructions, and, along with early meteorological records, can be used to independently test which types of tree-ring calibrations are the best. In this manner relatively short meteorological records can be lengthened and their statistics adjusted to include past modes of variation that in recent times may not have been evident. Such reconstructions of past climate imply that the mechanisms of past circulation are the same as those in the present; anomalies occur when the magnitudes and frequency of modes in circulation change from one time period to the next. Both tree ring and historical data are available from large numbers of situations and habitats. Thus they may be used together in a dense spatial array of precisely dated information on synoptic-scale climatic variations stretching from polar regions to the subtropics.

In this study 65 tree-ring arid-site chronologies provide continuous growth records for AD 1601 through 1963 in the North American West. Tree-ring collection for climatic study is beginning around the world, but could be encouraged by national and international support, along with more opportunity for information exchange, collaboration, and coordination of collecting efforts.

The general methods and multivariate models for tree-ring and climate calibration have been successfully developed, and reconstructions that have been verified with independent data indicate reliable results. The predictors for estimating surface pressure, temperature, and precipitation are ring-width data for the same year as the climatic occurrence, for one and two years following the climate occurrence, and for one year preceding the climatic occurrence. Estimates are obtained for each climatic variable, for each year and season, and for different spatial grids. The highest calibrated variance is found between filtered tree-ring widths and climate which have been regionally averaged and filtered to preserve the decadal or longer-term variations in climate. Filtering is applied after reconstructing climate for each year, season, and climatic station grid point. Principal components are used in the calibrations to simplify large data sets and to concentrate the large-scale information into orthogonal variables, while permitting expression of the synoptic-scale features of climate.

One aspect of our future work will be to assess the degree of reliability of our reconstructions prior to the twentieth century and to identify, if possible, each source of error and its importance in the different climatic estimates.
Error sources thus far identified include: 1) the statistical uncertainty in the transfer function itself, 2) the decreasing number of trees in the earlier portions of the tree-ring chronology record, 3) the lack of response of the trees to the particular microclimatic conditions that were measured by meteorological instruments, and 4) the unknown quality of certain meteorological observations, especially those in the nineteenth century which are used in the verification work. However, some uncertainty is unavoidable in all statistical estimates, so the important point to stress at this time is that climatic information in our reconstructions prior to the twentieth century resembles (is statistically related to) the available meteorological evidence. This resemblance substantiates our claim that the reconstructions now provide a statistically reliable, continuous, and quantitative record of three climatic factors as they varied through space for time periods before meteorological records were kept.

The reconstructed patterns resemble twentieth century anomalies in the movement of cyclones, anticyclones, storm tracks, standing waves in the atmospheric circulation, and other conditions that cause widespread drought, excessively wet seasons, and other variable conditions of climate. The reconstructions are expressed as departures from the twentieth century means and vary in both sign and magnitude from north to south and from east to west. The temperature patterns in winter are of a larger scale than those for precipitation and in the individual regions averaged as much as 3.1°C lower than the twentieth century climate. See-saw patterns over the United States are prominent in winter with a warm West and cold East common in the seventeenth through nineteenth centuries and a cool West and warm East common in the twentieth century record. Spring and summer are reconstructed to have been warmer in the East and cooler in the West for the seventeenth through nineteenth centuries than for the twentieth century measurements. Past autumns are reconstructed to have been somewhat warmer in the South and cooler in the North, but the error terms for autumn temperature indicate that these are the least reliable estimates. The annual temperature departures reconstructed for the past are lower than the twentieth century values everywhere but the Southwest, primarily as a result of the extremely cold winter climate.

Precipitation patterns varied from season to season and from one region to the next. California is reconstructed to have been dryer in the past three centuries than in the twentieth century by 15%, but in the Southwest and in the plains states, the annual reconstructed deficit in precipitation was less, with the relative percent contribution of moisture in the different seasons varying from one region to the next. The eastern United States, in the seventeenth through nineteenth centuries, is reconstructed to have been 2% to 8% wetter than the twentieth century normal amounts.

The climate in general has been more variable in the past three centuries than in the present one. The average standard deviation for temperature and precipitation was higher by 21% and 20% for winter, 11% and 12% for spring, 11% and 19% for summer, and 37% and 10% for autumn. The average increase in variability for each of the individual regions for all four seasons ranged...
from 10% to 30% for temperature and from zero to 30% for precipitation. In the East there was a greater spread between the average winter and average summer temperatures for 1602-1900 than for 1901-1962. In the West the spread was less.

The greatest amount of information in these climatic reconstructions is found in the synoptic-scale variations, with wavelengths of 1000 to 2500 km. The yearly anomalies in winter temperatures have the greatest variance; when the data are averaged, either through space or time, a large portion of the variance is cancelled out. Fifty-year-average maps eliminate 62% of this variance and retain only 38% of variance. When the 50-year grid values are averaged into a single 50-year mean, 20% more of the variance is lost. While the 50-year mean departures for winter temperature average 1.1°C cooler than the twentieth century norms, they are of limited value for regional planning, as they express only 18% of the climatic variance. The variance due to regional climatic variations is 82% or 4.6 times as important. Since the spatially-averaged means have so little variance and since none of our reconstructions show the same climatic anomaly throughout the map, we did not believe it was appropriate to select a particular decade or half-century that most resembles the worldwide cooling or worldwide warming scenario of the NDU report.

Instead, important synoptic-scale features are emphasized, such as the see-saw pattern in winter temperatures between the East and the far West. The features of precipitation, though of smaller scale than those for temperature, are also important. Correlation between winter precipitation and temperature exists. Only one correlation pattern is identified at present, as the details of other correlation patterns and the various climatic relationships have yet to be analyzed.

We do not view our work as an accomplished fact, but rather as the beginning and developmental stage of a promising method for the study of past and future climates. Much longer and larger numbers of tree-ring chronologies must be collected, dated, processed, and analyzed with observations on climate. Other types of proxy data must be gathered and compared to the tree-ring reconstructions of climate. Also, the many meteorological relationships must be carefully studied and worked out. We are confident that, if this is done carefully, the precisely-dated synoptic-scale reconstructions of climatic variations derived from tree rings and other proxies will lead to a more fundamental understanding of important physical causes behind past as well as present variations in climate. Such an understanding is basic to predicting possible variations in future climate.
APPENDIX: METHODOLOGY, DETAILED RESULTS, AND APPLICATIONS TO PROBLEMS OF CLIMATIC VARIATION AND CHANGE

A. Statistics of Calibration

The transfer functions are large multiple regression equations which convert many tree-ring chronologies into reconstructions of climate. Many predictor variables are needed because the trees respond to the climate of prior years and because trees in different sites and of different species respond differently to the same variables of climate. Figure A-1 represents a four-variable transfer function model in which the regression coefficients, $b_t$, are derived by least-square methods to scale and convert growth indices at different lags into expressions of year $t$'s climate.

The procedure of establishing values for the coefficients is calibration. It involves least-squares techniques which fit the varying growth increments, or their principal components, to the corresponding varying meteorological data, or their principal components. Coefficients are derived for each site and lage depending upon the particular calibration and are applied to the standardized index when few sites are used, or when large numbers of chronologies are used, to their principal components. The principal components are used to simplify the calculation procedures and to separate the large-scale features from the small-scale noise.

The principal components for chronologies matched with the year concurrent to growth are designated as I; those of the prior year's growth as B; those for the following year as F; those for two years following as FF (Fig. A-1).

There are a number of statistics which can measure the success (or lack of success) of a calibration, but the percentage of climatic variance reduced, i.e., the amount in common between climatic data and the tree-ring estimates, is the best single statistic. It is equivalent to the square of the correlation coefficient, $r$, expressed as a percentage with a zero value representing no agreement and 100% representing perfect agreement. A value of 30% ($r=0.55$) signifies a worthwhile, but low, calibration while 60% to 70% ($r=0.77$ and 0.84) is considered excellent.

One method of dealing with autocorrelation, the effect of prior growth, is to remove the first-order autocorrelation from each index, $x_t$, of a chronology as follows:

$$Y_t = x_t - \rho(x_{t-1} - \bar{m})$$

where the subscripts designate values for year $t$ and year $t-1$, $\rho$ is the first-order autocorrelation, and $\bar{m}$ is the mean of the chronology indices. The letter M in Figure A-1 denotes matrices of all such data sets ($Y_t$) from which first-order autocorrelation has been deleted and the principal components extracted.
Figure A-1. A multivariate statistical transfer function model of the biological relationships described in Figure 2 of the main text. The growth indices $x_t^*$ are multiplied by coefficients $b_t^*$ and the sums of the products used as estimates of year $t$ climate. Letters below the cross sections represent matrices used in this study, where $I$ represents the principal components of all ring-width chronologies for year $t$, and $F$, $FF$, and $B$ represent the principal components for years $t+1$, $t+2$, and $t-1$. The letter $M$ designates the tree-ring data for the same years, but with first-order autocorrelation removed. (See text.)
Canonical regression described by Blasing (1978) and outlined by Fritts (1976) was used to obtain the transfer function coefficients. The procedure now has been modified from the original descriptions to use a stepwise process which enters each canonical variable (taking the highest canonical correlation first), tests whether the variance due to regression at that particular step is greater than that expected by chance, and accepts or rejects the canonical variable depending on the outcome of the test. If a variable is rejected and a new variable is entered at the next or later step, the stepwise procedure rechecks the calibrated variances of all previously rejected variables and enters any that become significant. This forward and backward checking procedure continues until the least well correlated canonical variate (the last one) has been entered (or rejected). The first-order autocorrelation \( r \) of the residuals is calculated at each step, and the degrees of freedom available for the significance test \( df \) are adjusted to \( df' \):

\[
df' = df \frac{r_1 - 1}{r_1 + 1}
\]

The canonical regression coefficients from all significant steps are applied to the respective tree-ring principal components from 1601-1963 to obtain estimates of the climatic principal components. These are then transformed into "real world" climatic variables by multiplying by the appropriate eigenvectors of climate. The errors of estimate and the percent variance reduced at each climatic grid point are calculated. The average percent variance for all stations, along with other statistics, is calculated and the percentages mapped over the climatic data grid (Fig. A-2).

B. Model Building

Since there was a minimum of 61 years available for calibration, we used no more than 30 tree-growth predictors and 20 climate predictands. The stepwise selection process excludes one-half to two-thirds or more of the canonical variates, so that error terms remain small enough for reasonable significance.

The first models we calibrated included the first 15 principal components of tree growth as predictors for a given year such as year \( t-1 \), \( t \), \( t+1 \), or \( t+2 \), corresponding to matrices \( B \), \( I \), \( F \) or \( FF \) (Fig. A-1). We then found improvement when we combined 15 principal components for two years giving 30 predictors, such as \( 15B \) and \( 15I \), \( 15I \) and \( 15F \), or \( 15F \) and \( 15FF \) designated as \( BI \), \( IF \), and \( FFF \) respectively. Two combinations of the 15 principal components for data with autocorrelation removed were also used, \( M(B)M \) or \( MM(F) \), but mixed combinations such as \( M(B)I \), \( IM \), \( IM(F) \), and \( FM(F) \) reduced still more climatic variance. The word "couplet" is used to describe the model calibrated from the combination of two such sets of principal components. The number of climate principal components we used ranged from seven to 20.
Figure A-2. Percent variance reduced in calibrations, (i.e., percent agreement between reconstructed and observational records) over the spatial grid of three different variables for winter. Models used were: pressure, BI+BM+MM(F)+FM(F)+FFF; temperature, BI+IM+MF+FM(F); and precipitation, BI+BM+IF+MM(F)+FF. (See text for fuller explanation.)
At first we chose only those with eigenvalues greater than the noise level. After much trial and error, we learned that better results were obtained by using no fewer than 15 principal components for pressure and temperature and up to 20 principal components for precipitation. Small numbers of principal components constrained the number of possible canonical correlations and appeared to produce inconsistencies in the stepwise selection procedure. As the coefficients of the transfer functions differed among the different climatic variables, season, and station grids, we were required to make hundreds of separate calibrations to handle the three climatic variables, four seasons, and five climatic grids that were chosen.

C. Calibration Results

The best calibration percentages reduced for any season and grid that we obtained using couplet models are 53.9% for summer temperature, 49.4% for winter precipitation, and 40.9% for winter pressure. However, we learned that the percentages of calibration variance could be substantially improved by averaging the results from several of the couplets. This apparently occurs because the couplet models containing principal components of growth for only two years involve only a portion of the total response relationship modeled in Figure 2 of the main text and Figure A-1 of this Appendix. More of the lagging and autocorrelated relationships were utilized when all seven tree-ring sets, B, I, F, FF, M(B), M, and M(F) were used in various proportions. The mean reconstructions were always compared to the actual data to obtain calibration statistics including the percentage of the predictand variance reduced.

Combinations of models giving the best overall statistics were consistent with the expected model shown in Figure 2 in the main text and Figure A-1 in this Appendix, in that year \( t \) was involved most frequently, followed by years \( t+1, t-1, \) and \( t+2 \). Usually, information from all four matrices, B, I, F and FF, as well as the M sets, had to be included to obtain the best statistics. Combinations that made the least biological or physical sense usually resulted in substantially low variance reduced and other poor statistics.

As of June 15, 1978, the best averaged results reduced 61.7% of the variance for spring temperature over the entire United States and southwestern Canada. This was 13.2% higher variance than the best couplet model for this variable, grid, and season. The best averaged results for precipitation reduced 60.1% of the variance and were obtained for winter for the western United States and Canadian grid. This was 10.7% higher variance than the best couplet model for the variable, grid, and season. The best averaged result for pressure was 55.7% for spring, an increase of 12.8% over the best couplet.

If the results are examined by season without regard to variable and grid, the reconstructions for spring gave the best results, partly because spring spanned a large part of the growing season, and partly because it was the longest season (four months). Winter gave the second best results, followed by summer, with autumn being the poorest. Winter preceded summer in
importance, probably because it had three months and summer had only two, and partly because the winter circulation normally brings a large portion of the moisture available for tree growth. In addition, spring initiates many growth phenomena affecting the next year's growth and summer comes at a time when growth is ceasing, so the principal component sets for F, FF, and M(F) are very prominent in the best models for spring and summer climate. In spite of the fact that plant processes may be more active in autumn than in winter, the autumn climate reconstruction is not as good as those of the other three seasons. We attribute this to less moisture derived from autumn precipitation and to the delay of up to six months before the autumn climate can influence any growth process. There is simply more chance for subsequent limiting factors in winter and spring to modify and reduce the effects of autumn climate.

The percentage of variance reduced for three winter climatic variables for the period 1899-1961 is mapped in Figure A-2. The percentages of variance calibrated for pressure mapped at the top of the figure are for the average of models BI, BM, MM(F), and FFF with 53.3% of the total variance reduced. The highest percentage, 79.2%, was for the Canadian Arctic, with a maximum of 72.2% in the western North Pacific and 64.6% in the eastern North Pacific. The lowest percentage reduced was 20.0% in northern Siberia and 21.2% for the southeast coast of China.

The percentages of variance calibrated for temperature at each climatic station are shown in the lower left portion of Figure A-2. They are the averaged reconstructions of models BI, IM, (MF) and FM(F) which reduced a total of 54.7% of the actual variance. The area of best calibration was in the East with 75.1% reduced for Lynchburg, Virginia. A secondary maximum occurs over the Southwest with 69.6% for Yuma. The lowest percentage is along the Washington coast with 36.3% at Aberdeen, Washington. The percentages of calibrated variance for precipitation are for the averaged reconstructions of models BI, BM, IF, MM(F), and FFF and reduced a total of 50.1% of the variance. The pattern is variable with several maxima occurring in the West, the highest being 71.3% in Boise, Idaho, and the lowest being 18.1% at Bismarck, North Dakota. Fifty percent or higher percentages were obtained for most of the West and for an area in midcontinent from Dodge City, Kansas, to Washington, D.C. Percentages are 50% or higher for Marquette, Michigan, and for Baton Rouge, Louisiana. The variability over these grids is consistent with the variability in the synoptic weather systems which relate variations in climate at each station to the tree growth throughout the western North American continent.

D. Verification with Independent Data

If one is to be completely objective, no statistical calibration should be accepted as valid without independent verification. Where possible, the reconstructions for each season and variable should be checked against actual climatic information for the grid points used in calibration, but for years before or after the interval used for calibration. Consistency with independent meteorological observations or proxy data is the proof that the reconstructions are valid, and inconsistencies can be used to identify mistakes, inappropriate modeling, errors in dating, and other possible uncertainties in the reconstructions.
In this study temperature and precipitation records are available for many of the calibration stations for years prior to 1901. Couplets and averaged models with the highest percent variance reduced in calibration are verified against all available observational records from the nineteenth century. The reconstructions and actual climatic data are compared, using a number of statistical tests. The agreement during the independent data period measured by the verification tests is less than that for the calibration period, but in many cases the verification tests indicate significant agreement, not only for western stations included in the area near the tree sites, but for eastern stations at great distances from the tree sites. For example, the winter temperature model over all stations passed 25% of the verification tests, where only 5% would be expected by chance. Of six possible tests, 26% of the stations, many of which are located in the eastern United States, passed with at least three different statistical tests.

The results of the verification analysis suggest that we may be able to substantially improve our calibrations by utilizing combinations of couplet models which verify, but do not reduce, large amounts of variance. Therefore, the work included in this report may well be superseded by significantly better reconstructions determined through further research. The present results must thus be considered tentative. However, the models presented provide a sample of the climatic variations that are emerging.

Since reliable independent sea level pressure data are unavailable for our grid in the nineteenth century, verification of the reconstructed pressure anomaly patterns can be achieved only by using temperature and precipitation records over North America for the same time period. Consistency of the pressure pattern with other proxy reconstructions is also helpful, as well as evidence from historical and geological sources. In addition, we are using tree-ring data for verification from sites outside the area of the tree-ring grid used for calibration but within the area of the climatic reconstruction grid (Blasing and Fritts, 1975).

Figures A-3 and A-4 illustrate some quantitative comparisons of typical reconstructions and observational data for two winters prior to calibration. Available temperature data for the winter of 1872-1873 (Fig. A-3, bottom) indicate a cold Midwest and East with temperatures as low as 4.7°C below normal at Madison, Wisconsin, and 3.4°C below normal at St. Louis. The few records available in the West indicate above-normal temperatures at San Francisco (0.2°C), Sacramento (1.4°C), and Boise (2.5°C) and below-normal temperatures at San Diego (-0.7°C), Denver (-1.3°C), and Cheyenne (-2.1°C). Data for precipitation indicate dryer than normal conditions in the Northeast, Great Lakes, Plains, Southwest, and central California. Precipitation is above normal over the northern Great Basin, the lower Mississippi and Ohio River Basins, and eastward to the Atlantic.
Figure A-3. Reconstructions of pressure, temperature, and precipitation along with available meteorological observations of temperature and precipitation for winter 1872-1873 as compared to the mean period 1901-1970. The models are the same as those in Figure A-2.
The reconstructed pressure anomalies show a deepened Aleutian Low and higher than normal pressure over the west coast of the United States which could block storms moving into the West. This pattern is consistent with warmer temperatures and lower than normal to near normal precipitation in California, the Southwest, and adjoining areas. Arctic air would enter the United States east of the Rocky Mountains. This pattern is consistent with the lower than normal temperatures reported and reconstructed for the Midwest and east coast (Stockman, 1904).

The reconstructed precipitation anomalies are less consistent as they show generally dry to average conditions in the far West, North, Appalachian Plateau, and upper Mississippi drainage. They disagree with the observational record primarily in the Great Basin and the lower Mississippi drainage. Too few observational records are available to make more detailed comparisons.

The observational data for 1889-1890 (Fig. A-4) indicate a winter of contrasting temperature and moisture patterns across the 48 states. The entire West Coast and northern Rockies were colder than normal with temperatures near 7°C below normal in northern Montana. Temperatures were 2°C or higher than normal for eastern portions of the continent. Precipitation was markedly high, especially for the Great Basin and central Rocky Mountains. It was also high for areas over the Great Lakes and Ohio Valley, but was below normal for the high plains, Gulf states, and south Atlantic Coast.

Pressure for winter 1889-1890 is reconstructed to have been higher than normal over the North Pacific, indicating a greatly weakened Aleutian Low. More normal pressures are reconstructed for much of the United States, with lowest values centered over the West Coast. Pressures are reconstructed to have been 4 mb above normal for Alaska and the Canadian Arctic. Such a pattern would be associated with fewer storms than normal in the area of the Aleutian Low and Canada with more warm, moist air than normal flowing into the southern Rocky Mountains, the high plains, and eastern states. Under these conditions, the Northwest and Pacific Coast would be frequented by storms with cool, cloudy weather and high precipitation. However, the reconstructed temperature for this winter is less consistent with the pressure pattern and actual data than in the 1872-1873 winter. The reconstructed cold in the far Northwest did not extend as far southward into the Pacific coastal states as indicated by the observational data. However, the reconstruction correctly shows warmth through the remainder of the United States but underestimates the magnitude of the warming. Precipitation reconstructions are in relatively good agreement with the observational data with above normal moisture reconstructed throughout much of the West, the Great Lakes, and Ohio River Basin. Lower than normal precipitation is reconstructed for the southern plains to the southern Atlantic Coast and is consistent with the actual data.

Thus, we can note form figures A-3 and A-4 that there is relatively good agreement for winter 1872-1873 between the observational record and the pressure and temperature reconstructions, but the reconstructed precipitation pattern is
Figure A-4. Same as Figure A-3, except for 1889-1890.
In large part a disappointment. In 1890 the pressure and precipitation reconstructions are in agreement with the observations, but the reconstructed temperature patterns are less consistent. A thorough examination of the reconstructions for the different years in the late nineteenth century indicates that approximately two out of three maps agree with the observational record. The other one-third represent the uncalibrated portion of the variance which is indifferent or contradictory to known conditions. However, when the results are averaged for several stations or are smoothing into several-year averages, there is a marked increase in agreement between the reconstructions and the observational record (see Figures A-7, A-8, Table A-1 and accompanying discussion).

E. Applications to the Study of Variations in Winter Climate

Paleoclimatologists should apply their data to climatic problems as well as making their reconstructions, for they are the ones most qualified to judge the limitations and strengths of their own data sets. Therefore, we have developed a variety of computer programs to retrieve desired data from any designated model, analyze the data, and plot or tabulate the results. The data can also be handled in a variety of ways to portray various climatic conditions, or they can be smoothed to bring out longer term variations.

1) Comparison of Long-Term Means with Twentieth Century Data

Figure A-5 is the result of a test for differences between individual station data from the prior three centuries and the present one. The reconstructed winter temperature and precipitation were averaged for 1602-1900 and plotted as departures from the 1901-1970 normals. The temperature in the past is reconstructed to have been lower throughout much of the country, especially in the north central plains and Midwest. Warmer temperatures are also reconstructed in the Southwest. Conditions are reconstructed to have been more moist than in the twentieth century for large parts of the nation, but dryer in the Great Lakes, Mississippi Valley, the northern Rockies and adjoining plains, as well as throughout the Southwest.

The twentieth century, therefore, has been warmer than the past in the East but colder in the West, and wetter than normal in the Midwest and far West, where the map (Fig. A-5) indicates the past was dryer. The winter temperature trends in the eastern and central United States follow the so-called global warming trend, but in the Southwest they are in opposition. Other proxies of winter temperatures from the Southwest would be expected to show the same out-of-phase behavior, while for the East and central states such proxies would be in phase with the worldwide pattern. Additional examples of differences from the twentieth century are included in the main text.
Figure A-5. Mean reconstructed temperature and precipitation for the interval 1602-1900 plotted as departures from the mean observational record for the period 1901-1970. The models used are the same as those in Figure A-2.
2) Comparison of Regional Variations

What kind of results might be obtained if all reconstructions were averaged within a given region? To answer this question, we chose 11 regions shown in Figure A-6 and plotted the average of the yearly reconstructions similar to the reconstructions of winter precipitation for Regions 1 and 2 as shown in Figures A-7 and A-8. (The corresponding observational data for the twentieth century are averaged for the region and plotted as dots in the figure.) Smoothed representations of the averaged reconstructions were also obtained by multiplying a 13-weight, low-pass digital filter and plotting the resultant data (Fritts, 1976). Such filtering is comparable and preferable to calculating a 10-year moving average (Mitchell et al., 1966). Smoothed versions of the reconstructions and the observational record are also included in the figures. There are some periods of drought which coincide between the two western regions, but the long-term downward trend in moisture from 1602 through the 1800's is apparent only for the Columbia Basin (Fig. A-7).

Intervals of change observed in pollen sampled from varved sediments in Gillette Lake, Washington, (Albert M. Swain, 1978, personal communication) are shown at the bottom of Figure A-7. *Pinus ponderosa* (PP) and *P. contorta* (LP), which grow on open and dry habitats, are shown above those for *P. monticola* (WP), which grows on wetter habitats. The long-term changes in these two pollen types are consistent with the trends in our reconstructions with dryer habitat pollen increasing during dryer intervals and wetter habitat pollen increasing during wetter intervals. The precipitation for the two intervals when the percentage of *P. monticola* pollen did not change were reconstructed as near the average.

Several statistical comparisons were made between the reconstructions and the observational records in these two regions. Table A-1 summarizes these comparisons. Row 1 shows the number of stations in each region, and row 2 shows the average percent calibrated variance calculated by averaging the nine percentages for the nine stations. Row 3 is the variance of the data expressed in millimeters after the nine reconstructions were averaged into a single time series (Figs. A-7 and A-8). Row 4 is the variance of the averaged data after they were filtered (Figs. A-7 and A-8). Row 5 is the percentage of calibrated variance represented by the low-frequency or smoothed data set. There is more variance and the low-frequency variations are a higher percentage for California, 40% as compared to the 31% for the Columbia Basin. This suggests that there is considerably more low-frequency variation in the climate of California. Such a result might be expected because of the close proximity of California to the North Pacific and its susceptibility to persistent blocking resulting from sea surface anomalies which change slowly over time.
Figure A-6. The 96 precipitation stations used for calibration and reconstruction. The data are averaged and analyzed for each of 11 regions: 1) Columbia Basin, 2) California Valleys, 3) Intermountain Basins, 4) Southwest Deserts, 5) Northern Plains, 6) Southern Plains, 7) Northern Prairie, 8) Southern Prairie, 9) Great Lakes and Midwest, 10) Southeast, and 11) East.
Figure A-7. Average yearly reconstructions of winter precipitation for the nine meteorological stations in Region 1, the Columbia Basin, expressed as departures from the 1901-1970 observational record. A is unfiltered, and B has been treated with a 13-weight, low-pass digital filter passing 50% at a period of eight years. The observational record from 1901-1970 is plotted as dots on the right. Vertical marks at the bottom of the plots designate those values which exceed two standard errors and which may be considered statistically significant. Year designations are for January of each winter season. Intervals of change in the percentage of pollen assemblages of Pinus ponderosa (PP), P. contorta (LP), and P. monticola (WP) observed in the varved sediments from Gilette Lake, Washington, are indicated below the filtered time series. See Table A-I for additional statistics.
Figure A-8. Same as Figure A-7, except for Region 2, California Valleys.
TABLE A-I

Statistics for Reconstructions of Winter Precipitation for Regions 1 (Columbia River Basin) and 2 (California Valleys) Using Model BI+BM+IF+MM(F)+FFF

<table>
<thead>
<tr>
<th>Region No.</th>
<th>Statistic</th>
<th>Region Name:</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of stations in region</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Average variance reduced in calibration</td>
<td>50.9</td>
<td>62.3</td>
<td></td>
</tr>
</tbody>
</table>

**Regionally averaged reconstructions**

| 3 | Unfiltered variance 1602-1961 | 1204 | 2754 |
| 4 | Filtered variance 1602-1961 | 371 | 1090 |
| 5 | Percent variance passed by filter | 30.8 | 40.0 |

**Correlation Coefficients: Averaged reconstructions and observational data sets**

| 6 | Unfiltered | 0.793 | 0.837 |
| 7 | Filtered | 0.872 | 0.955 |

**Percent variance reduced**

| 8 | Unfiltered (square of row 6 x 100) | 62.9 | 70.0 |
| 9 | Filtered (square of row 7 x 100) | 76.1 | 91.3 |

**Percent improvement due to:**

| 10 | Regional averaging (row 8-2) | 12.0 | 7.7 |
| 11 | Filtering (row 9-8) | 13.2 | 21.3 |
| 12 | Total improvement (rows 10+11) | 25.2 | 29.0 |

*a Low-pass digital filter with 50% passing for periods of eight years.*
Rows 6 and 7 include the correlations between the averaged reconstructions and observed data for the calibration period for both unfiltered and filtered time series, while rows 8 and 9 are the percent variance reduced found by squaring rows 6 and 7. The variances shown in rows 2, 8, and 9 may be compared to show the effects of averaging by region and smoothing. Rows 10, 11, and 12 are the differences in percentages. The regional averages reduced 62.9% and 70.0% of the averaged observational record, values which are 12.0% and 7.7% higher than those in row two. After filtering, the reduced variances are 76.1% and 91.3%, which are even higher by 13.2% and 21.3%.

It is clear that we are better at reconstructing the large-scale regional variations lasting 10 years or longer. When the data are both regionally averaged and filtered, there is a 25.2% to 29.0% net increase in the explained variance. Similar increases in explained variance occur in other regions and seasons for both temperature and precipitation.


During the winter of 1976-1977 the eastern United States was subjected to extremely low temperatures, while warmth and drought persisted throughout the western states. Figure A-9 includes maps of the climatic anomalies showing an intensified Aleutian Low 13.9 mb deeper than normal, but near its usual position. Anomalous high pressure, centered over Vancouver Island, blocked storms from moving into the western portions of the North American continent. Instead they passed northward through Alaska steering cold Arctic air from northeastern Siberia and Canada into the central and eastern United States. Conditions along the West Coast were mild and dry.

The winter of 1977-1978 was cold east of the Rockies, but precipitation was above normal over much of the United States. The map of pressure anomalies (Fig. A-10) resembled the previous winter, except that the below-normal anomaly associated with the Aleutian Low was less extreme and was centered 10 degrees farther south and east. Also, there was no blocking high over the Pacific Coast, and surface pressures were higher over the Canadian Arctic. More storms moved inland across the Pacific Coast instead of being directed northward into Alaska as in 1976-1977. Record-breaking floods were reported for California. The southwestern deserts received twice the normal precipitation, and throughout most of the country precipitation was above average. Temperature anomalies were similar to the previous winter except that Arctic air from Canada produced record-breaking low temperatures in an area centered farther west. Examination of the twentieth century record shows that pressure anomalies over the North Pacific similar to those for both winters with accompanying low temperatures throughout the East occurred in 1935-1936, 1939-1940, 1960-1961, and 1969-1970. In 1960-1961 a high pressure cell persisted over the coastal states preventing storms from entering the West. In 1935-1936 and 1939-1940 pressures along the coast were below normal, and
Figure A-9. Pressure, temperature, and precipitation anomalies for winter of 1976-1977 plotted as departures from the observational record for 1901-1970.
Figure A-10. Same as Figure A-9, except for winter of 1977-1978.
storms brought precipitation to the western United States. During the winter of 1969-1970, a break in the high-pressure anomaly resulted in above-normal precipitation over northern California and Oregon.

Our pressure reconstructions which extend back to 1602 provide us with a long, hemisphere-wide record of the past atmospheric circulation which can be compared with particular observed patterns. We can identify years of similar anomalous circulation by correlating the observed and reconstructed patterns. The reconstructions for the averaged winter models BM+IM+IF (Model 1) and BI+BM+IM(F)+PM(F)+MFF (Model 2) were correlated for each year with the observed anomalies for the winters of 1976-1977 and 1977-1978. The correlation coefficients for Model 1 are plotted in Figure A-11.

Experience with the meteorological data suggested that when correlation coefficients were 0.5 or higher, the two anomaly patterns depicted very similar anomalous circulation. Therefore, we counted all the cases as similar when the correlation coefficient between them is equal to or greater than 0.5. To correct for over- or under-representation in the reconstructions, the counts for past centuries were multiplied by the ratio of the counts for the observed data to the counts for the reconstructed data for the calibration period. Table A-II shows these counts corrected and converted to frequencies. The results for both models were averaged and expressed as a percentage of the 1901-1978 observations. During the 377 years from 1602-1978, the frequency of winters with a circulation pattern like 1976-1977 was 0.178 or 17.8 years per century. The frequency of winters like 1977-1978 was 0.086 or 8.6 years per century. Winters like 1976-1977 varied the most from one century to the next and were very frequent in certain intervals of time and infrequent in others. We estimate that from 1615-1655 the circulation patterns resembled the winter of 1976-1977 with a frequency of 0.574, which is 57.4 years per century, or 407% of the 1901-1978 figure. However, during the same interval from 1615 through 1655, the winters resembled 1977-1978 only 12.5% of the time. From 1667 through 1720 no winter circulation was reconstructed like 1976-1977, but 8% of the time it was like the 1977-1978 pattern.

The long-term expectation for winters like the last two based upon these 377 years of data is 12% to 26% higher than occurred during the 1901-1978 interval. In addition it is possible that the circulation pattern of 1976-1977 could occur as frequently as one year out of two for intervals as long as 41 years as was reconstructed for 1615-1655. This is a frequency four times that of the twentieth century. Thus, there is a reasonable likelihood that winters like the last two extreme ones could occur considerably more frequently than indicated by the observational record.
Figure A-10. Plots of the correlation coefficients of winter pressure reconstructions with anomalies of winter pressure in 1976-1977 and 1977-1978 shown in Figures A-9 and A-10. The calibration model is BM+IM+IF. Frequencies of occurrence (Table A-II) were derived from the counts of years with values of 0.5 or greater. Year designations are for January of each winter season.
TABLE A-II

Fast and Present Frequencies of Two Winters' Climate Derived from Counts of Correlations Between Actual and Reconstructed Pressure Anomalies with Values of 0.5 or Greater. Two Different Calibration Models are Used and Results Averaged.

<table>
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<td>Model 2</td>
<td>Average</td>
<td>Model 1</td>
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<td>.141</td>
<td>.141</td>
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<tr>
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<td>.138</td>
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<td>.120</td>
<td>.120</td>
<td>85</td>
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<td>.296</td>
<td>.309</td>
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<td></td>
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<td>.538</td>
<td>.574</td>
<td>407</td>
</tr>
<tr>
<td></td>
<td>1602-1978</td>
<td>.183</td>
<td>.172</td>
<td>.178</td>
<td>126</td>
</tr>
</tbody>
</table>

Note: Counts were multiplied by the numbers reconstructed/numbers actual during 1901-1961 to compensate for model reconstruction bias.

Counts of both actual meteorological data and reconstructions are identical in the twentieth century after corrections.
We checked our reconstructions for the period 1615-1655 to see if the mean patterns were consistent with the 1976-1977 patterns. The mean anomalies are shown in Figure A-12. The mean reconstructed pressure anomaly resembled 1976-1977 but is not as extreme, for the 43% winters unlike 1976-1977 dilute the pattern. Blocking occurs but is not as strong, and the mean circulation pattern is more zonal. The average temperature patterns in the Southwest and Northeast are reconstructed to have been similar, but temperatures were lower in the Northwest and higher in the Southeast suggesting that the mean trajectory of Pacific storms was not as far north in the West and not as far south in the East. Therefore, moisture fell in the Northwest and central Rocky Mountains. Drought prevailed in parts of the Southwest and in the eastern half of the country.

Our results suggest that we are able to reconstruct past conditions compatible to other paleoclimatic data because the modes of seasonal circulation and climatic variation in the past are similar to those of the present. They differ only in their severity and frequency. Persistent blocking patterns or unusual modes of circulation persist for longer periods of time producing stronger seasonal anomalies which occur more frequently. Therefore, we are able to study the various meteorological phenomena in the observational records and use the paleoclimatic record to indicate which ones increased in frequency and which ones diminished to bring about climatic changes. However, there are undoubtedly extreme cases where our method would not work such as the full glacial period when boundary conditions were so different that there was no analog in the observational record with which we could calibrate.

4) Precipitation and Temperature Outlook for Winter

The Sahel drought, the severe drought of 1977 throughout the western United States, and the two cold winters of 1976-1977 and 1977-1978 created national concern and debate as to possible future climatic conditions (National Defense University, 1978). Some experts argue that a drought of the severity of 1977 was uncommon and unlikely to occur in the near future, while others argue that similar droughts may have occurred in the past and thus are likely to occur in the future. The majority of scientists believe that warming due to carbon dioxide and other substances is likely to cancel any trend towards global cooling.

Our averaged precipitation and temperature reconstructions for winter presented in Figure A-5 along with the time series plots in Figures A-7 and A-8 provide an interesting perspective to this question. It is clear from these data that there is no overall trend throughout the entire North American continent. The past three centuries' winters were, on the average, dryer for the Southwest, northern portions of the Rocky Mountains,
Figure A-12. Mean reconstructed anomalies of pressure, temperature, and precipitation for the 41-year interval 1615-1655. Data are expressed as departures from the mean 1901-1970 observational record. Models are the same as in Figure A-2.
and south of the Great Lakes. For the remaining portion of the 48 states, winters on the average, were wetter. Temperatures during winter were below the 1901-1970 normal for most of the North, East, and central portions of the continent. Only in the Southwest were winter temperatures for 1602-1900 higher than the 1901-1970 averages.

The winter precipitation anomalies shown in Figures A-7, A-8, and A-12 indicate that much more drought occurred in the past in California than in the Columbia River Basin. The marks near the bottom of the plot in Figures A-7 and A-8 designate those values which were greater or less than two standard errors of the mean and, hence, more significant.

The true extent of recent winter droughts in California is revealed by comparing the 1602-1900 counts of significant positive and negative departures with those of the twentieth century. Significant droughts, exceeding two standard errors, are reconstructed for 11% of the years in the twentieth century, but in the seventeenth, eighteenth, and nineteenth centuries, significant droughts are reconstructed 18%, 30%, and 22% of the time. Significant wet years are reconstructed 11% of the time for the first 61 years of the twentieth century, and in the previous three centuries they are reconstructed at frequencies of 19%, 3%, and 9%. Winter droughts in California appear to have been 12% more frequent for the 1602-1900 period than for the 1901-1962 period. Significant wet spells in the earlier period occurred only 1% less frequently than in the twentieth century, suggesting the likelihood of more precipitation variability. The filtered plots in Figure A-8 also show eight distinct 10-year or longer intervals of significant drought which were more severe than in the twentieth century, and only four comparable extremely wet intervals. The outlook for winter droughts in California on a long-term basis is thus more bleak than the twentieth century data would lead us to believe. This high probability of drought is coupled with prospects for considerably more variability from one year to the next.

Reconstructions for the Columbia River Basin (Fig. A-7) show fewer significant variations, in part due to the lower calibrated variance there. However, extensive winter droughts occurred during the 1830's and 1840's. Less severe droughts occurred during the 1860's and early 1870's. Prior to that time, winters were generally wetter than the current "normal" period. The wettest interval is reconstructed early in the seventeenth century and the next wettest late in the nineteenth century. These were times when winters were dryer in California.
REFERENCES


Swain, Albert M. 1978. Personal communication.

