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THE CLIMATE OF ARIZONA:

PROSPECTS FOR THE FUTURE

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FOREWORD

Because of the current interest in climatic change and its potential impact on the lives of people living in Arizona, three climatologists, with national and international reputations in their fields, have prepared this summary of current knowledge about the future climate of Arizona. Although each comes from a different academic field, all have one thing in common. Their academic preparation and their research efforts have been in the field of climatology.

This report, written by individuals who are citizens of Arizona and who share the concerns of other citizens of this state about their future, should be read and used by those who plan for our future.

As the authors point out in their conclusions, our view of the future is murky and clouded with uncertainty. The forces that drive Planet Earth's weather machine are complex and not completely understood.

In general, professional climatologists support programs to develop new methodologies to predict future climates but warn individuals against placing too much confidence in forecasts currently being made. Given the present state of knowledge about climate, it is impossible to predict with certainty what changes will take place in the natural systems that produce our weather. Forecasts for periods beyond several days have shown a low probability of success. And, predictions of seasonal and longer-term conditions of climate have proved to be only marginally better than chance.

Robert W. Durrenberger
State Climatologist for Arizona
April 27, 1978

THE AUTHORS

ANTHONY J. BRAZEL is a climatologist with the Department of Geography and Laboratory of Climatology of Arizona State University in Tempe, Arizona. He earned his Ph.D at the University of Michigan in 1972, where he specialized in climatology, meteorology, and physical geography. Dr. Brazel has published over 25 articles in scientific journals, most of them concerning meteorology, climatology, and the earth's energy balance. He is co-author of a statistics book in Geography. His current research involves climatic change.

HAROLD C. FRITTS, a plant ecologist, is Professor of Dendrochronology at the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona. He earned a Ph.D in botany in 1956 at Ohio State University where he specialized in forest ecology and tree growth. He has published over 70 articles in scientific journals, most of which concern the use of tree rings as records of past climate. He was a John Simon Guggenheim Fellow and is the author of Tree Rings and Climate, the first comprehensive text on the subject, published by Academic Press. His current research, sponsored by Grant No. ATM77-19216, from the Climate Dynamics Section of the National Science Foundation, involves the calibration of ring-width variations from trees throughout western North America with different climatic measurements and their use in reconstructing past variations in climate.

SHERWOOD B. IDSO is a Research Physicist with the Science and Education Administration of the U.S. Department of Agriculture, stationed at the U.S. Water Conservation Laboratory in Phoenix. He earned his Ph.D at the University of Minnesota in 1967, where he specialized in physics, meteorology, mechanical engineering, and soil science. Dr. Idso has published over 150 research papers in a wide spectrum of scientific journals, many of them dealing with climatic change and processes of desertification. He is a 1977 recipient of an Arthur S. Flemming Award, honoring 5 outstanding scientists under the age of 40 in the Federal Service.

INTRODUCTION

The climate of any region sets the tempo of indigenous life styles and largely dictates the scale and type of economic activity that can be sustained. In Arizona, we are subject to perhaps more climatic restraints than are many other areas, due to the high air temperatures in summer and the rather low yearly rainfall.

But, weather is variable; and its sum total--climate--is not unchanging either. Thus, in planning the future direction economic activity should take, prospects for changes in climate should be considered. In this paper we attempt to marshal the best evidence available to outline the possibilities for Arizona's future climate. We hope that the information will prove useful to those who must make the difficult decisions that will shape the character of our state in the years to come.

ELEMENTS OF CLIMATIC CHANGE

Many different factors play significant roles in causing and structuring climatic change. Among those that have received considerable attention by meteorologists are changes in the energy output of the sun (Opik, 1958a, b), irregular solar activity accompanying sunspot disturbances (Willett, 1961, 1964), cyclic variations in the solar constant (Simpson, 1934, 1957, 1959), changing concentrations of interstellar dust (Hoyle and Lyttleton, 1939; Dennison and Mansfield, 1976), variations in the earth's orbital geometry (Milankovitch, 1941), changes in tidal force intensity (Petterson, 1914; Karlstrom, 1961), mountain building (Flint, 1957), variations in sea level (Ewing and Donn, 1956), continental drift (Runcorn, 1962; Vening Meinesz, 1962), changes in the earth's magnetic field (Wollin, et al., 1971a, b), surging of the

Antarctic ice sheet (Wilson, 1964), dust-induced variations in atmospheric transmittance for solar radiation (Sellers, 1969; Budyko, 1968, 1969) --particularly as enhanced by volcanism (Wexler, 1960; Mitchell, 1961) --deep circulation of the ocean (Newell, 1974), variations in atmospheric carbon dioxide concentrations (Plass, 1956a, b, 1957), and the effects of man (Matthews, et al., 1971). In addition, there is even reason to believe that a multiplicity of different climatic states may be possible for the same set of external boundary conditions or internal system time constants (Lorenz, 1970; Faegre, 1972; Sellers, 1973).

Several of the potential mechanisms of climatic change are thought to be responsible for cooling the earth, and others are thought to warm the planet. Some of them are thought to be capable of cooling and warming at different times. Still others are somewhat controversial, sometimes being cited as reasons for warming and cooling at the same time. The complexity of climatic change can not be overemphasized. Therefore, studies that propose to predict future trends of temperature and precipitation based upon only two or three factors must be closely examined with regard to the quality of the prediction and the reliability of the data sources.

A CASE IN POINT

To illustrate, let us consider a recent report that predicts an imminent cooling trend for Arizona, along with significantly increased precipitation--perhaps double that of the present norm (Browning, 1977). It considers only the factors of volcanic dust, solar activity, and the shifting position of the earth's magnetic field--all of which are claimed to lead to cooling and enhanced rainfall in our state.

What is the most scientifically reliable information to date on the effects of these factors? In December 1977, Clifford Mass of the Department of Atmospheric Sciences of the University of Washington at Seattle and Stephen H. Schneider of the National Center for Atmospheric Research at Boulder, Colorado published a paper in the Journal of the Atmospheric Sciences entitled "Statistical Evidence on the Influence of Sunspots and Volcanic Dust on Long-Term Temperature Records," wherin they evaluated the first two of Browning's three factors. With respect to volcanic dust, they did find a definite, albeit weak, correlation with periodic cooling trends. They stated, however, that "clearly, this mechanism is only one of many factors needed to explain the variance in the long-term temperature records." But for sunspots, they concluded that such cycles "cannot be demonstrated to be a significant forcing mechanism for the earth's lower atmosphere," further noting the "proposed mechanisms for Browning's third factor--variations in the earth's magnetic field--must also be considered highly speculative, for he has only used it to predict greater rainfall in conjunction with variations in sunspot activity. Thus, there appears to be little scientific justification for using these three factors to make so drastic a prediction as a possible doubling of precipitation rates for the southern portion of Arizona over the next few decades.

But what if we consider factors additional to those Browning included in his analysis? And what if we obtain a broader base of expert opinion? Recently, a study was conducted by the Research Directorate of the National Defense University in Washington, D.C., wherein 24 international authorities on climatic change were asked to give their best estimates of probable climatic trends to the year 2000, considering all pertinent factors. To quote from the results of the survey, "the derived climate scenarios manifest a broad range of perceptions about possible temperature trends to the end of this century, but suggest as most likely a climate resembling the average for the past 30 years. Collectively, the respondents tended to anticipate a slight global warming rather than a cooling." In addition, they also opted for a "tendency to associate more precipitation and decreased variability of precipitation with global warming, and less precipitation and increased variability with global cooling." Thus, Browning's prediction for Arizona of cooling with more rainfall appears to be just the opposite of predictions for the world as a whole, as envisioned by those scientists.

To be fair, however, we must point out that the climatic trend of a specific region such as Arizona need not be the same as that of the earth as a whole. In fact, some very convincing paleoclimatic information suggests that Arizona climate is the reverse. Also, the change in a specific region can be significantly greater or less than that for average world conditions. Finally, it must also be realized that the combination of these two conditions, cool and wet, is not the normal condition for Arizona, and that very compelling evidence must exist if planners are to accept such an extreme prediction. The data presented by Browning do not represent the best scientific information. Instead, they appear to have been selected to support his extreme point of view.

THE WEIGHT OF THE EVIDENCE

One of the fundamental aspects of climatic change is that the processes involved are greatly moderated by the large mass of the earth and oceans, so that resultant changes are slow. Thus, the best estimate of future climate is that it will be like that of the recent past, or only slightly different. Weather, on the other hand, can be much more variable. What, then, can our past climate tell us about future climate?

There are many kinds of evidence that can inform us of the past climate of the Southwestern United States and Arizona. First is the actual observation of weather parameters by the National Weather Service and its predecessors. For example, the official record for Phoenix, Arizona spans just about 100 years--from 1877 to the present.

The second evidence is proxies of past climate such as tree rings, pollen in the ground, ice cores from large ice sheets, and many other geologic data. Scientists have been able to infer and even reconstruct past climatic conditions by using a variety of these artifacts of the past--some even living today (e.g., old trees).

The annual growth rings in western trees can probably tell us most accurately how Arizona climate has differed in the past on a year-to-year basis. In the semiarid West, unusually dry, warm conditions often produce narrow rings in trees on dry sites and wide rings in trees on cool, high altitude sites. However, the degree and kind of effect can vary considerably for different species, sites, and seasons. Consequently, generalized deductions for a large area such as a state based on the size of one ring, one tree, or even averages from samples of trees from a few locations, as Browning has done, have very limited reliability.

However, Arizona is fortunate to have many high mountains that support forests. There are many usable species, and old trees can be found throughout the mountainous West. The oldest trees are the Bristle-cone pine (Pinus longaeva), which provides more than a 4,000 year record.

Throughout the years, scientists at the Laboratory of Tree-Ring Research have sampled and assembled thousands of different tree-ring records from the West and developed chronologies of climate by averaging the ring widths from 10 to 20 trees on a given site. They have also devised computer methods which calibrate tree-ring records from all over the West with the existing observational record of climatic variables such as temperature and precipitation. The ring sizes may be considered to be analogous to the height of the mercury column in a thermometer and the computer calibration analogous to the marking of the temperature scale on the glass of the thermometer. Just as we read the temperature directly from the calibration marks by using the height of the mercury column, the dendroclimatologist uses the tree-ring measurements in the computer and the mathematical calibrations to reconstruct the past climatic conditions that gave rise to variations in ring width (Fritts, 1976).

Such reconstructions of past climatic conditions are now being made for approximately 100 reporting weather stations throughout the United States, using the records from approximately 1,000 arid-site conifer trees collected from 65 different sites in the West. We can look back in time for at least 300 years by examining reconstructions of total winter precipitation for Flagstaff, Phoenix, Tucson, and Yuma, which are based on the entire set of 1,000 western trees. The reconstructions used here may not be the most accurate ones that will be available, but the values shown in Figure 1 are highly correlated (0.81) with observational records of the twentieth century used in the calibrations. The observational record is plotted above the reconstruction on the right of the figure to show the agreement. The data are plotted in inches, as departures from the 1901-1970 mean and are filtered to obtain approximate 10-year moving averages (Fritts, 1976).

The most noteworthy features in Figure 1 are the numerous successively dry years and the few successively wet years before the twentieth century. Past winter droughts during these earlier centuries were often more severe than the most severe conditions thus far in this century. The average reconstructed winter precipitation for the four Arizona stations mentioned above during 1602-1899 was 2.82 inches, which is 6.6 percent below the average winter precipitation for these stations from 1901 to 1970. Only during the second and last decade of the 1600's was winter moisture as plentiful as in the first two decades of the 1900's, but these intervals in the seventeenth century were terminated by extended droughts exceeding the severity of anything in the observational record for the current century. Further analysis of the winter precipitation shows that winters with less than one inch of rain were 10 percent more frequent during the past three centuries than during the current one. The maximum 10-year value of the filtered reconstructions was 4.26 inches, which is below the maximum value of 4.31 inches in the observational record during the twentieth century.

Contrary to Browning's interpretation of two selected tree-ring chronologies, the objective calibration of the best 65 tree-ring chronologies clearly demonstrates that the winter moisture during the past three centuries has been less than the winter precipitation during the 1901-1970 interval. Similar calibrations of reconstructions from the same tree-ring data for temperatures indicate that the winters in Arizona during the past 300 years have been, on the average, slightly warmer than those of the twentieth century.

Turning now to the observational record of annual averages (Figure 2), we see that the wet years of the early 1900's experienced nowhere near a doubling of the mean rainfall rate, as Browning predicted might occur. Only in 1905, 1911, and 1941 did annual rainfall match or exceed such a figure. Also, the pattern over time at Phoenix is quite variable about the long-term average of about 7 inches per year. Thus, since very few wet, cool periods of significance have occurred back to 1600, we can say with a high degree of confidence that very few, if any, sustained wet, cool periods are likely to occur in the near future. Indeed, the entire record shows that there have been NO sustained periods approaching a doubling of normal annual rainfall for southern Arizona over the past four centuries.

To further clarify the situation, note Figure 3 (taken from Dr. William D. Sellers of the University of Arizona in an article published in 1960). This figure is a time series of winter, summer, and annual precipitation based on 18 selected stations in southern Arizona and western New Mexico for 1898 to 1959. The annual precipitation doubled the norm only once--in 1905. Summer precipitation was fairly consistent, whereas winter precipitation showed that in such an unusual year a high total can be experienced. Based on what has happened from 1877 to the present, we can readily say that 1978 appears to be another unusual year. However, there is no reason whatsoever to believe it to be a trend-setter for a sustained rainfall increase until the year 2000, as Browning has recently suggested.

Table 1 shows decadal average rainfall, which indicates the variation from the norm over longer time intervals (10 years). From the observational records, no decade varied more from the norm (7.33 inches) than 17%; the average variation was only 6.5%. To imagine a doubling of normal precipitation for 10 consecutive years (a 100% variation from the norm) is almost equivalent to imagining zero rainfall for 10 consecutive years!

The probability of ONE year having double the normal rainfall can be calculated from the histogram shown in Figure 4. Only 3 years out of 100 (probability 0.03) had double the normal rainfall at Phoenix--and these years were not consecutive. The probability of 10 years in a row of double normal rainfall is almost infinitely small (0.03 times 0.03 times 0.03 ... ten times). Thus, to predict a sustained doubling of the annual precipitation rate for southern Arizona would be to go against all scientific odds and against the almost four century's record.

SUMMARY

The climate of semiarid and arid locations such as Phoenix and large areas of Arizona is variable over short- and long-term time intervals. At the moment, there is no clear-cut consensus within the scientific community as to the direction our climate will take. It is, therefore, most judicious not to assume some extreme trend about to take place, but to plan on climate fluctuating within the limits of variability evidenced over the recent past. This is not to say that Arizona's climate will remain static. Any variation in the near future, however, is likely to be similar to that of the last four centuries which, on the average, has been somewhat drier and warmer, not cooler and wetter, than the observational record. Thus, we do not find any reasonable scientific justification supporting a doubling of rainfall nor a monotonic cooling trend to the year 2000. We must not be misled by attractive brochures and selected evidence into thinking that one instance of high annual rainfall in Arizona, such as the winter of 1977-1978, is the inevitable forerunner of the next 30 years. This has not been true in the past, and it is unlikely to be true in the future.

TABLE 1

PHOENIX DECADAL RAINFALL

Period	Average Precipitation (inches)	Percent Variation from Normal
1877-86	7.15	- 2.5
1887-96	7.19	- 1.9
1897-06	7.86	+ 7.2
1907-16	8.09	+10.4
1917-26	7.78	+ 6.1
1927-36	7.36	+ 0.4
1937-46	7.94	+ 8.3
1947-56	6.10	-16.7
1957-66	6.75	- 7.9
1967-76	7.07	- 3.5
Long-term Average	7.33	± 6.5

Figure 1.

The observational winter precipitation (actual) for four Arizona stations and reconstructed (recon) winter precipitation derived from 65 replicated tree-ring chronologies throughout western North America. Data are smoothed into approximate 10-year running means and plotted in inches as departures from the 1901-1970 mean of 3.02 inches.

RECON AND ACTUAL WINTER PRECIP FOR FLAGSTAFF, PHOENIX, TUCSON, AND YUMA, AZ.

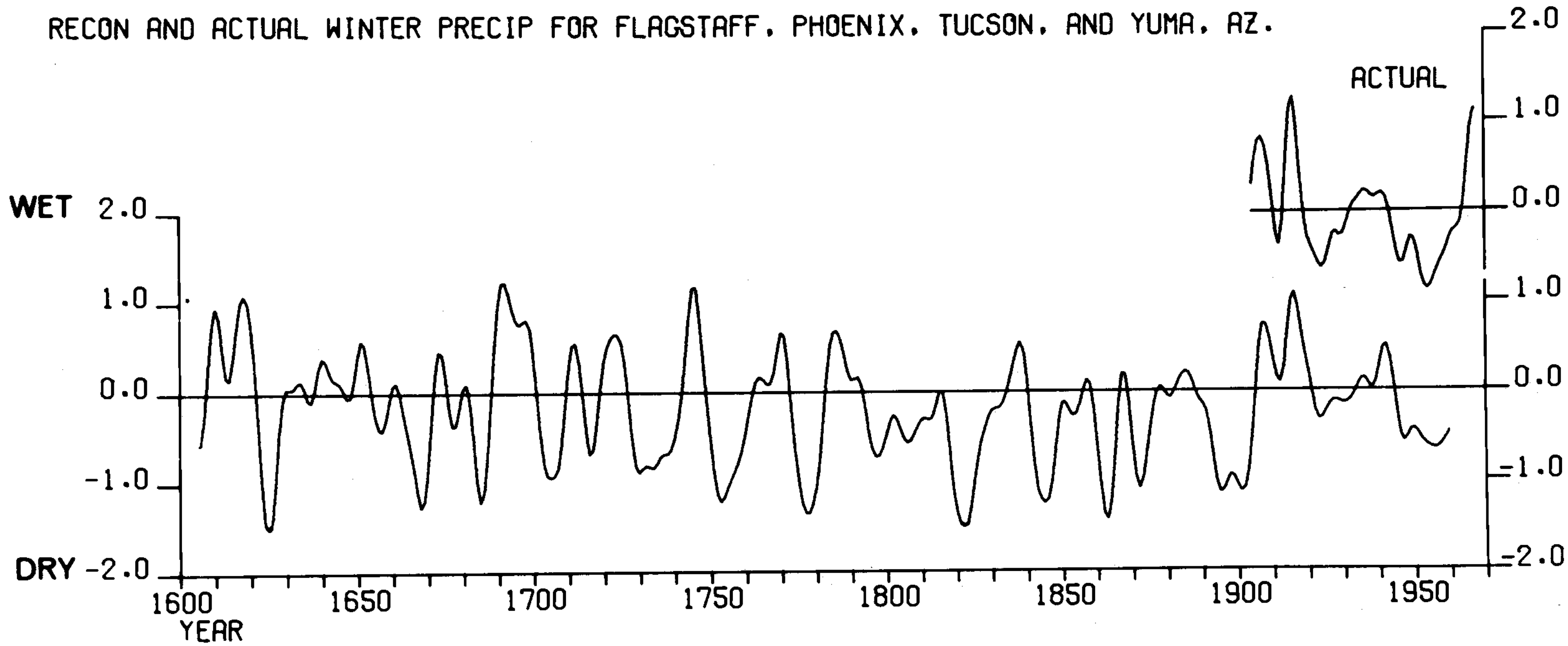


Figure 2.

Annual precipitation for Phoenix, Arizona 1877-1977. Three years in the record had twice the normal total--1905, 1911, and 1941. Note in each succeeding year rain totals dropped to normal or below normal. The mean is shown here. The median rainfall for Phoenix is less than 7 inches.

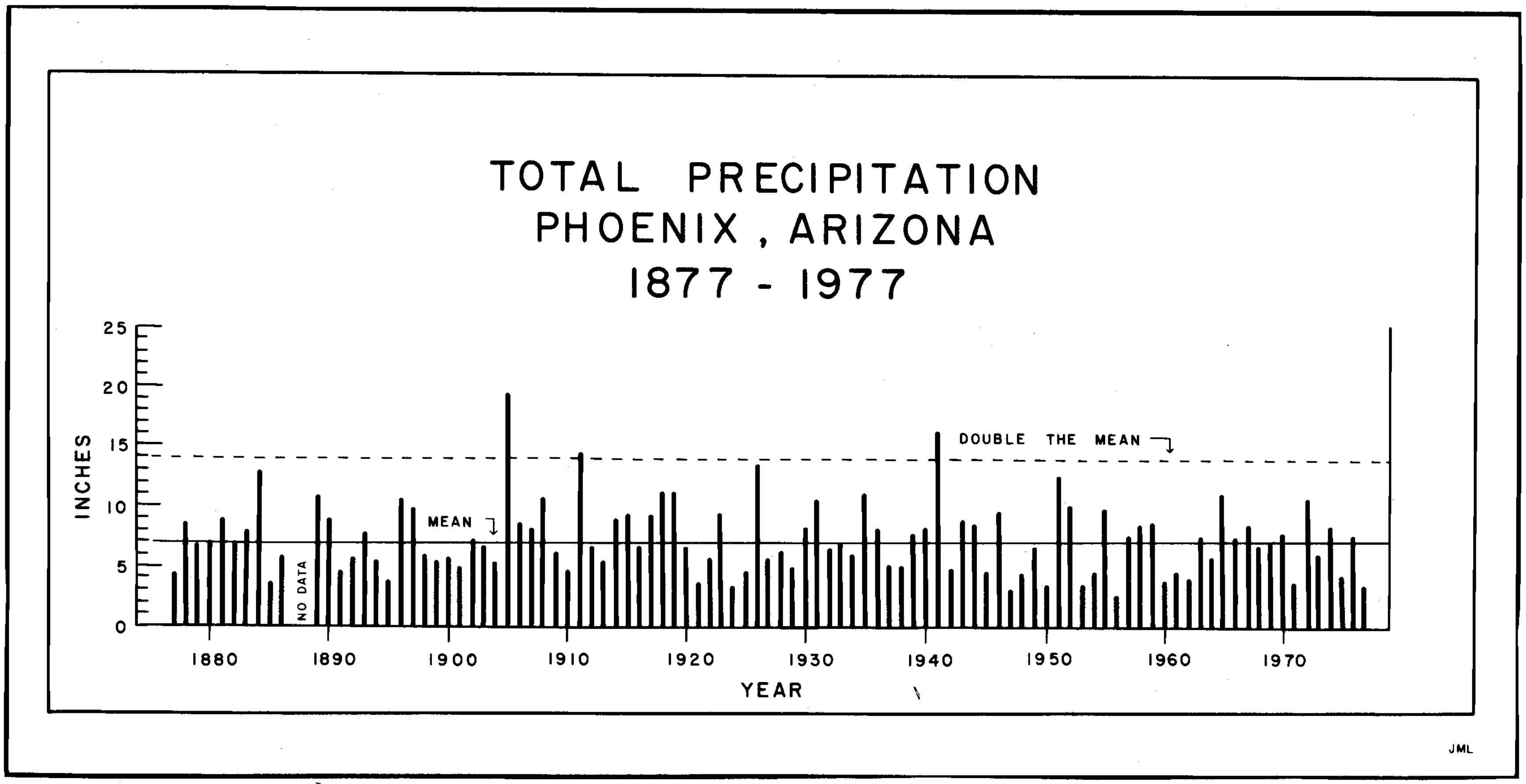

TOTAL PRECIPITATION
PHOENIX, ARIZONA
1877 - 1977
INCHES
25
20
15
10
5
0
NO DATA
MEAN
DOUBLE THE MEAN
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
YEAR
JML

Figure 3.

Southern Arizona precipitation for 1898-1959 for winter, summer, and annually. The figure is after W.D. Sellers, 1960. Note only one year--1905--had a doubling of annual rainfall.

SOUTHERN ARIZONA PRECIPITATION
1898 - 1959

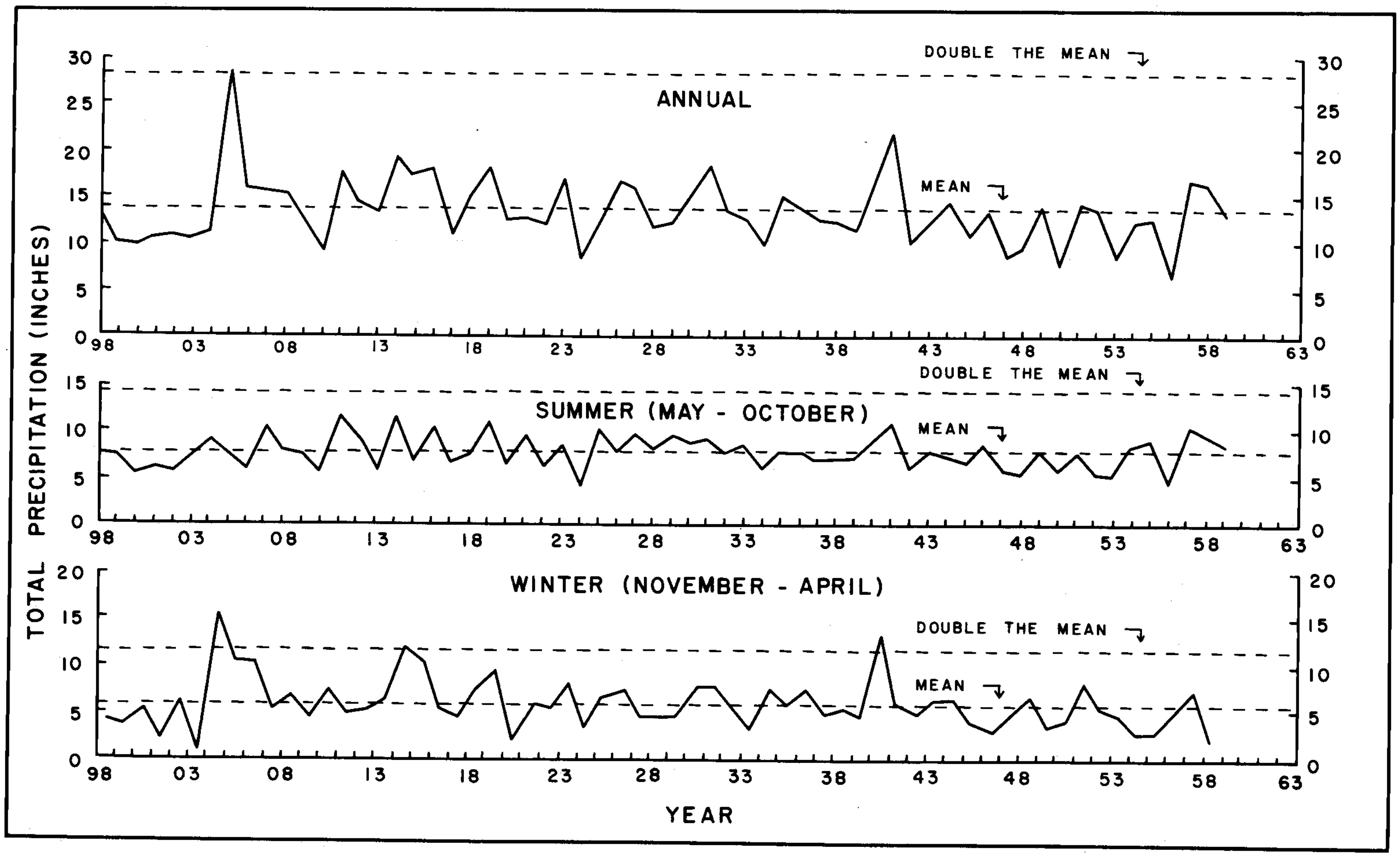
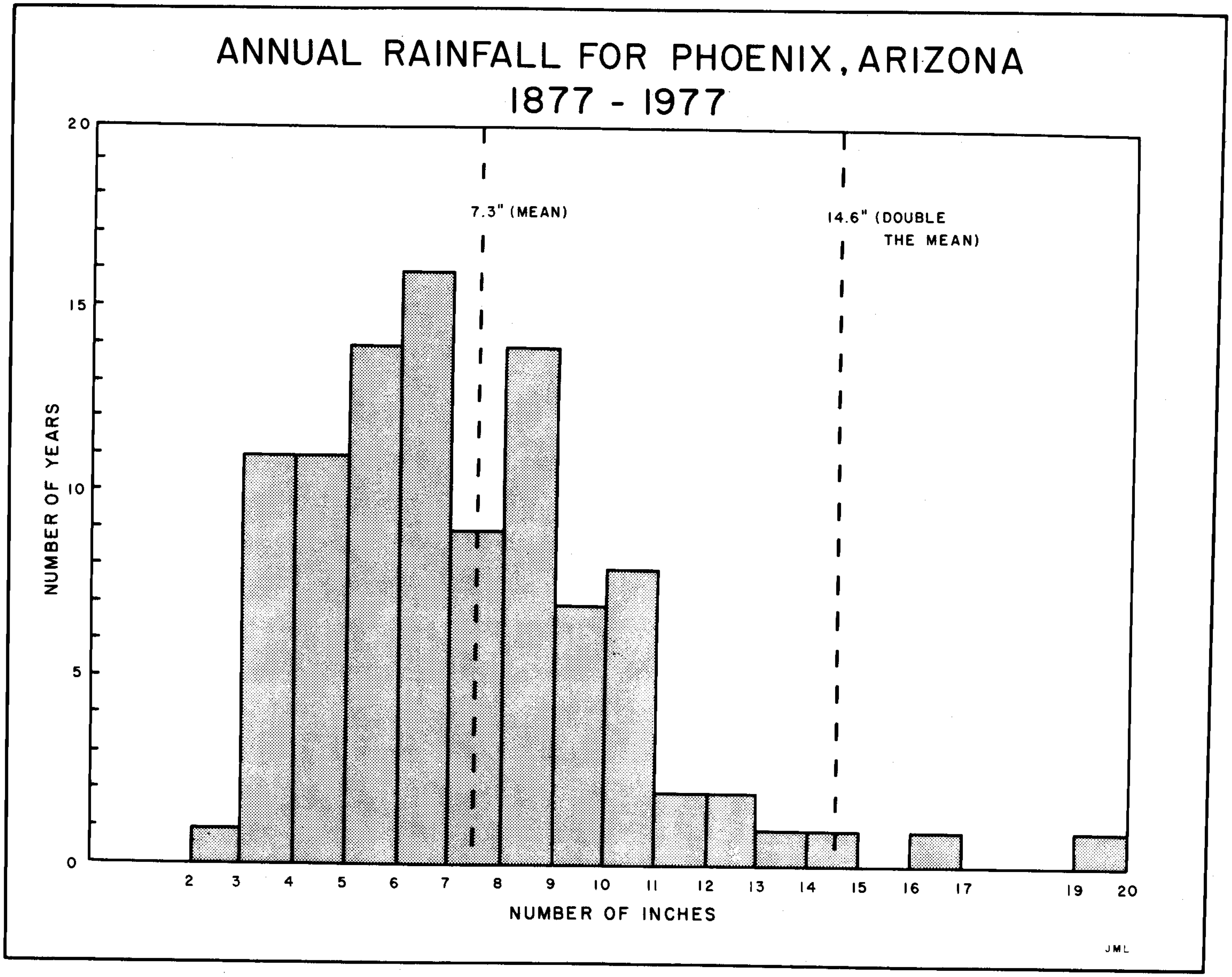


Figure 4.

Histogram of rainfall for Phoenix, Arizona 1877-1977. Diagram shows number of years certain amounts of rainfall occurred. For example, 16 years had annual totals between 6 and 7 inches. The Browning "doubling" of 14.6 inches is a rarity indeed. This frequency distribution is "skewed" toward the higher values--the usual type of distribrution found for desert areas.



ANNUAL RAINFALL FOR PHOENIX, ARIZONA
1877 - 1977
NUMBER OF YEARS
0
5
10
15
20
7.3" (MEAN)
14.6" (DOUBLE THE MEAN)
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
19
20
NUMBER OF INCHES
JML

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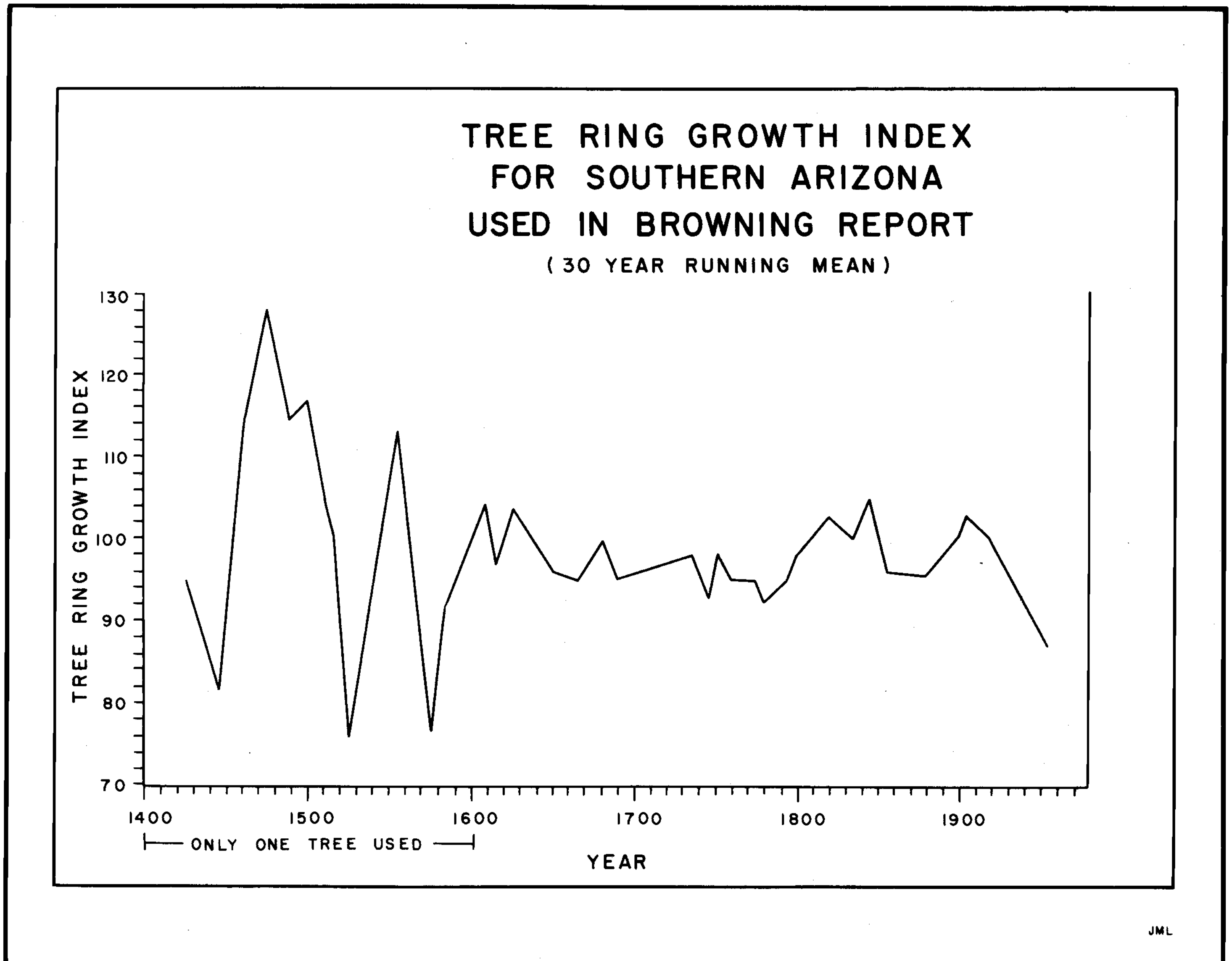
APPENDIX I

The figure shown on the next page is a 30-year running mean of the tree-ring growth index from 1402-1950. It represents essentially the same tree-ring data for the one of the two plots used by Browning in Figure 5 of his paper entitled "The Climate and Arizona's Future." Note the extreme variation between the period 1430 and 1600. From 1600 to 1900 the variation is much less.

The data used were 25 years old and were selected from a much larger set of data available for Arizona. The particular data set is unreliable for the years 1414-1602 because it represents a sample from the younger portion of only one tree. The large fluctuations at that time are more likely to reflect the varying and rapid growth of a single young tree in the Santa Rita Mountains than the effects of climate. The record after 1602 fluctuates less, probably due to the larger sample of trees. Extrapolation by Browning to state-wide climate from such a limited sample of trees (too few trees at only two locations) when more data are easily available in published form (Drew, 1976; Fritts and Shatz, 1975; Stockton and Fritts, 1971) can lead to illogical and misleading conclusions.


TREE RING GROWTH INDEX
FOR SOUTHERN ARIZONA
USED IN BROWNING REPORT
(30 YEAR RUNNING MEAN)
TREE RING GROWTH INDEX
130
120
110
100
90
80
70
1400
1500
1600
1700
1800
1900
ONLY ONE TREE USED
YEAR
JML