APPENDIX A.1 Drought Prediction in the Great Plains: Is It Feasible?

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"Droughts are not mere chance occurrences; they are part of a physical process which can be measured and studied and predicted with increasing precision as our observations of the sun and upper air and oceans continue to accumulate."

The quotation is from Tannehill's classic book on drought, published in 1947. Three decades have passed since Tannehill expressed this view. Millions of items of terrestrial and extra-terrestrial weather data have been collected. The computer now allows us to analyze these data with great rapidity. Have the advances which Tannehill suggested actually materialized? My purpose here is to evaluate our current ability to predict drought, as well as to assess the feasibility of achieving an improved capability in this field within the next decade.

Large portions of the western U.S. recently experienced an extended period of moderate to severe drought. This was a shocking reminder that we remain susceptible to prolonged drought. The recent drought also pointed out weaknesses in the government's ability to deal with the impacts of drought in a coordinated and effective fashion. Breakthroughs in our ability to reliably predict drought occurrence, duration and extent might well improve our ability to cope with this one of Mother Nature's vicissitudes.

DEFINITION OF DROUGHT

There are a great many definitions of drought. Unlike other weather-related natural hazards such as tornadoes, floods and hurricanes, the impacts of drought accumulate slowly over a long period of time. It is difficult to determine when a dry spell becomes a drought, or when a moderate drought becomes severe, regardless of its coverage or duration. H. P. Gillette (1950) referred to drought as a "creeping" phenomenon.
One may also argue, as did Warrick (1975), that "drought is not strictly a physical phenomenon, but rather an interplay between the natural system responsible for the variations in available precipitation, and the particular human-use systems potentially susceptible to those variations." Hence, any useful definition of drought must consider the human activities on which it impacts.

As drought occurrence is best related to particular systems of resource use, a discussion of drought predictability in the Great Plains must examine agricultural drought primarily. The ultimate effect of drought on the Great Plains farmer is the loss of income from his crop or livestock. The resultant impact upon society may extend far beyond the boundaries of drought, perhaps with implications at the national and international level.

Drought can be distinguished from aridity in terms of permanency. Drought represents a temporary condition usually associated with an appreciable negative departure of precipitation from normal. Normal activities are temporarily interrupted. By contrast, aridity is a permanent characteristic of climate. Activities in arid climates are geared to a permanent shortage of moisture.

For our purposes, it may be sufficient to define drought in rather general terms. The Glossary of Meteorology (Huschke, ed., 1959) defines drought as:

"a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area. Drought severity depends upon the degree of moisture deficiency, the duration and, to a lesser extent, the size of the affected area. In general, the term should be reserved for periods of moisture deficiency that are relatively extensive in both space and time."

This is the definition to which we will adhere in this paper.
GREAT PLAINS DROUGHT: AN HISTORICAL PERSPECTIVE

Recurring periods of drought are characteristic of Great Plains climate. Weakly's (1943) examination of a 400-year treering record for western Nebraska confirmed the repeated occurrence of drought. In this record Weakly identified 13 drought periods of five or more years duration. The average duration of drought was 12.8 years and the average recurrence interval was 20.6 years. The drought of greatest duration lasted 26 years (1539-1564 A.D.). Weakly noted, however, that the cycles of precipitation suggested by the tree-ring data were not regular enough to allow the prediction of future droughts. It should be stressed that Weakly's drought periods included only those that persisted for a period of five years or more. In a later article, Weakly (1962) elaborated further on the frequency of drought based on an analysis of 748 years of tree-ring data in central Nebraska. He found that 269 years (36% of the years represented) were sufficiently dry to have adversely affected vegetative growth.

The susceptibility of the Great Plains region to drought has continued in the post-settlement period. Major droughts occurred in the region in the 1860s, the late 1880s to mid-1890s, the 1930s, the mid-1950s and the mid-1970s. Documentation of the 1860s drought in terms of its extent, severity and duration is sparse due to the scarcity of weather stations during that period. Minor droughts have occurred in some portion of the Plains during almost every year of record.

CLASSIFICATION OF DROUGHT PREDICTABILITY STUDIES

Considerable attention has been directed in recent years towards forecasting future climates. Drought is one facet of climate we would wish to see forecast. Long-range drought forecasts can be divided into three categories; short, medium and long (Yevjevich, 1978). Short and medium range forecasts refer to those made for periods of one week and two months in advance, respectively. Long-range forecasts would, therefore, apply to periods greater than two months, i.e., seasons, years or decades. Capability to predict drought would be most beneficial if made a month or more in advance so that management decisions might be
adjusted in response to expected moisture deficiency. Therefore, our discussion will focus on medium and long-range forecasts.

There are four approaches to forecasting future climate. The purely statistical approach assumes that a climate variable (usually rainfall in the case of drought) is statistically predictable through a knowledge of its past history. A major criticism of this approach is that the climatic record for any variable is usually too short to allow reliable prediction even if a well-defined periodicity has been identified. Even so, it must be realized that the statistics of the past may not be adequate in the prediction of future events. Climate may change, not only through natural forces, but also through the impact of man.

Under the rubric of the statistical approach I include attempts to correlate the behavior of a climatic variable with other environmental variables which are statistically predictable. The prediction of rainfall cycles from the 11-year, 22-year, 33-year or 80-90-year sunspot cycles are well known examples. Numerous other cycles have been "discovered" by scores of researchers but, by and large, studies of this type have been unsuccessful as a forecast tool. J. M. Mitchell, Jr. (1964) said on this matter:

"From the historical viewpoint, if all cycle hunters had checked their results by these means (harmonic analysis), very few of their publications would ever have been written. Hasty and uncritical acceptance of the reality of evidence of cycles in climate has evidently been the source of more wasted effort in meteorology than any other kind of scientific misjudgement. Beyond a doubt, meteorology has not been alone in this experience either."

Studies of persistence to predict climate also may be included under the statistical approach. In the Great Plains, studies of this type have produced only marginally useful results. Friedman (1957), for example, investigated the persistence of seasonal rainfall in 57 years of data for south Texas and found that only a limited degree of statistically demonstrable persistence has occurred. Namias (1963) has reported that warm, dry springs
in the Great Plains tend to be followed by warm, dry summers. Lawson, Douglas and Englehart (1978) found that warm, dry periods are usually favored by positive 700 mb height departures in the Plains.

A second approach to drought prediction is the statistical-physical-dynamical method discussed by Gibbs (1968). The reasoning underlying this approach is based on general physical and dynamical principles. For example, rainfall is predicted on the basis of anomalies in sea surface temperature or in atmospheric circulation-pressure distribution. The difficulty has been in identifying sufficiently strong causal relationships between the above-mentioned parameters and patterns of rainfall.

The analogue method represents a third approach and involves the identification of a meteorological situation from the past which is comparable to the current situation. This procedure requires a lengthy historical file of meteorological information from which to extract "analogues." The assumption is made that the situation will evolve in a manner similar to the way in which it evolved in the past. This technique has been used by the American and British Weather Services for some time in the production of 30-day forecasts. A deterrent to the worldwide adoption of this technique has been the time required to analyze past climatic situations. Computers are making the use of this approach more practical, although computer-selected analogues must be evaluated by trained analysts prior to the issuance of a forecast.

A fourth approach is the physical-dynamical-numerical method which was made possible by the introduction of the high speed computer in the post-World War II period, although the idea predates it considerably. This technique is based on the idea that the simulation of future climates should be possible through the solution of the basic equations of motion and thermodynamics of the atmosphere. Reliable simulation can be achieved only after meteorologists have developed a sound quantitative theory of climate. Unfortunately, no one theory is widely accepted as yet.

To date, most attempts to forecast drought have used the first two methods described above.
The latter two approaches will require a great deal of research before significant progress can be realized.

**IS A FORECAST OF DROUGHT FEASIBLE?**

Our attention will now focus on the feasibility of drought forecasting. Attempts to forecast future climate have been hampered by two critical deficiencies. First, networks for observing land and sea surfaces and upper-air conditions are inadequate. Although portions of mid-latitude Northern Hemisphere land areas possess impressive land surface networks, the same cannot be said for low and high latitude land areas in the Northern Hemisphere, nor for the entire Southern Hemisphere land surface area. Seasurface reports are increasing in volume but the network is sparse at best. Of the 25,000 surface weather reports collected daily, only 3,000 are collected over the sea surface (Namias, 1978). The quantity of upper-air data is also inadequate.

Secondly, the complexity of atmospheric forecasting is appreciated by only very few scientists. Meteorologists must develop a better understanding of the physics of the atmosphere and ocean before weather can be successfully predicted on a long or medium range time scale. Improved understanding of the system is, in fact, an objective of the Global Atmospheric Research Program (GARP). According to Lorenz (1975) GARP's success rests on our ability to model the atmospheric system through larger, more sophisticated computers.

Climate predictions can be differentiated into two kinds. Climate predictions of the first kind refer to the chronological order in which atmospheric states occur. An example would be a forecast of seasonal rainfall for several consecutive seasons. Predictions of the second kind involve a forecast of change to a new long-term climatic state, such as that which might result if the atmospheric concentration of CO\textsubscript{2} is doubled. Today, for the Great Plains, we are probably most interested in an evaluation of the feasibility of drought prediction of the first kind. The forecast of a change to a new long-term climatic state would be of less immediate concern to the inhabi-
tants of the region. Many consider that long-term climatic change would probably occur gradually enough to allow the adaptation of agricultural practices suited to the evolving climatic state (see Wittwer, et al., 1979).

What are our current forecast success rates? Namias (1978) reported success rates at 61 percent and 58 percent for 30-day and seasonal temperature forecasts in the United States, respectively. A prediction skill of 50 percent represents pure chance. Thirty-day and seasonal forecasts of precipitation show an average skill about 5 percent lower. Although current forecasts of both temperature and precipitation are only slightly better than chance, they do indicate some understanding of long-term atmospheric behavior. However, these success rates do not warrant a farmer's confidence when making critical management decisions are to be made.

Which avenues of research offer the greatest promise of achieving the substantial gains in long-range forecast skill necessary to convince farmers to modify customary cultural practices? F. Kenneth Hare (1977) identified three possible avenues by which progress might be made in forecasting future climate: first, the use of periodicities of climatic phenomena; second, the identification of time-lagged tele-connections; and third, the use of numerical-general circulation models. Each of these avenues is explored below in terms of the potential returns which might accrue from a major directed research effort.

PERIODICITIES OF CLIMATIC PHENOMENA

As mentioned above, many researchers have examined climatic data with the hope of discerning some degree or kind of periodicity. The Great Plains have received a large share of attention in these studies because of the suggested correlation between the Hale solar cycle and recurring periods of drought. The mid-1970s were expected to coincide with a period of minimum sunspot activity with major effects on climate. Drought did, in fact, return to the Great Plains, commencing in 1974.
Schneider (1978) has been especially critical of studies of periodicities and the forecasts which they provide. He contends that there is no physical theory which explains the suggested connection between the double sunspot cycle (20-22 years) and Great Plains drought. It is generally agreed that all cyclic phenomena must have a "forcing function." Olson, Roberts and Zerefos (1975) reported on a link between cyclonic activity in the Northern Hemisphere and solar flares. They found that cyclonic activity increased two days following a flare and then sharply decreased when the geomagnetic storm which often accompanies a flare ended. Studies of this type may help to explain the suggested links between sunspot activity and rainfall in the Great Plains.

A study by Holzworth and Mozer (1979) indicates that a series of solar flares which occurred in August, 1972, resulted in a modification of stratospheric electric fields. Their study indicated that variations in the vertical atmospheric electric field were directly caused by solar flare particles. The vertical atmospheric field is often considered to be the result of thunderstorm activity. The mechanism by which this field might serve as a cause of thunderstorm activity is not yet understood. However, the possibility of a link between solar-induced changes in atmospheric electrical properties and the occurrence of weather phenomena is currently under investigation.

Schneider (1978) also questions the reality of a link between the cyclic behavior of rainfall in the Plains states and sunspot activity on the grounds that the phenomenon seems to be confined to one region. Why should not this relationship be identifiable in the rainfall records of other regions? Mitchell et al. (1978) suggest, on the other hand, that the relationship may indeed exist in other regions but may not yet have been identified because of inadequate data.

Schneider's third criticism of the sunspot-drought linkage idea is that droughts are not precisely aligned with the double sunspot cycle. This lack of alignment is shown by Friedman (1957) in his study of the droughts of south and southwest Texas. Schneider also notes that drought occurrence, severity and duration have not been
geographically comparable from one drought to another. For example, the 1930s drought primarily impacted the northern and central Great Plains, whereas the southern Plains states were most affected by the 1950s drought.

Mitchell et al. (1978) provide important new information on the relationship between the apparent cyclic pattern of drought occurrence in the western U.S. and solar activity. Their aim was to reconstruct the history of drought in the western two-thirds of the U.S. and to verify early indications of a bona-fide drought "cycle" and assertions of its connection to solar cycles.

Mitchell was cited earlier as being a critic of cycle hunters. However, in the 1978 study intensive analysis of tree-ring data back to either 1600 A.D. or 1700 A.D. indicates to him a statistical association between drought area changes and the Hale sunspot cycle. He expressed the opinion that other areas may illustrate similar solar/climate relationships if an adequately long data base can be developed. This is, of course, always a major limitation in studies of periodicities, but one that can be obviated through the use of "proxy" paleoclimatic techniques such as dendrochronology.

Mitchell indicates that there is an implied and indirect relationship between widespread drought in the western U.S. and solar magnetic activity. Mitchell states that:

"the solar control is best described as a modulation of terrestrial drought-inducing mechanisms such that it alternately encourages or discourages the development of major continental droughts which are set up by evolutionary climatic processes unrelated to solar activity."

**TIME-LAGGED TELECONNECTIONS**

Hare (1977) suggests the development of time-lagged teleconnections for climate prediction. Teleconnection refers to the correlation of parameters at two or more localities. Markham and McLain (1977) have reported a correlation between rainfall in the Ceara province in northeast Brazil and sea surface temperature in the south
Atlantic Ocean. The operating mechanism is apparently the stabilizing effect of cold water on the overlying air with a resultant decrease of wind flow and convection over the Atlantic. A reduction in the thickness of the layer transporting moisture into the Ceara region results.

Namias has expended a great deal of effort on teleconnections as a tool in longrange forecasting. He has recently reported that the development of a strong trough extending from Hudson Bay to the U.S. Rockies and a strong Bermuda High can be predicted from an unusually strong eastern Pacific upper-level anticyclone (Namias, 1978). This pattern leads to dominance of the western U.S. by cold Arctic air and the prevalence of warm air in the East. The result is an increase in storminess and precipitation in the zone between the areas of cold and warm air. If teleconnections of this type can be established consistently, the development of probabilistic models for the Great Plains region will be facilitated.

**NUMERICAL-GENERAL CIRCULATION MODELS**

The third approach identified by Hare is the application of numerical general circulation models (GCM's) for the prediction of climate. Considerable progress has been made in this direction under the auspices of the Global Atmospheric Research Program (GARP), which began in 1967.

One objective of GARP is to achieve an understanding of the factors that determine the statistical properties of the general circulation of the atmosphere which should lead to a better understanding of the physical basis of climate. However, considering the complexity of the atmospheric-ocean system, it is difficult to develop global circulation models which can simulate it satisfactorily. C. E. Leith of the National Center for Atmospheric Research (1975) offers little hope for forecasts of seasonal climate using GCM's. Among the numerous difficulties identified by Leith are our present inability to construct a three-dimensional model that includes a statistical version of an atmospheric general circulation model and a dynamical model of the wind-driven and thermohaline circulation of the ocean. Hubert Lamb, (according to Gribben, 1976) concurs. He states that:
"numerical models .... simply cannot cope with the complexities and detail which would be required .... to provide us with accurate forecasts for seasons, year and decades ahead."

The primary difficulties in simulating the general circulation are the major voids in the atmospheric and sea surface data collection network, the incompleteness of knowledge regarding the climatic system and the computational effort involved.

**MAN'S IMPACT ON FUTURE CLIMATE**

A brief overview of the potential impact of inadvertent climatic change appears relevant as a footnote to our discussion of man's ability to forecast drought. Man's activities may impact on climate through increasing injections of CO₂, dust, aerosols, fluorocarbons and heat into the atmosphere. While there are conflicting views regarding the potential impact of these ingredients, CO₂ appears to offer the greatest threat of a major climatic change in the future.

Atmospheric CO₂ affects the radiation balance through the absorption of infrared radiation. Concentrations have increased from approximately 312 parts per million in 1958 to about 330 parts per million in 1978 apparently due to the increased burning of fossil fuels. The current rate of increase is about 1 part per million per year. This change in CO₂ concentration is expected to lead to a gradual warming of the earth's surface. The implications of increasing CO₂ concentration on our ability to forecast future climate/drought are these: first, statistical studies of drought probability which are based on historical data, may become invalid; second, increasing CO₂ may cause a shift to a new long-term climatic state with a consequent disruption of present world climatic zones. In recent years, numerous attempts have been made to estimate the effect of a doubling of CO₂ concentration on world climate. The effects are not likely to be uniform for all parts of the globe. Manabe and Wetherald (1975) have modeled climatic change due to a doubling of CO₂ and predict a 2°C increase in surface temperatures in the low latitudes. Increases of 3°C and 10°C are projected for lati-
tudes of 40° and 90°, respectively.

More recently, Manabe and Wetherald (1979) have made some preliminary assesments of the geographical distribution of climatic responses to increased concentrations of CO₂. Globally, non-uniform response is corroborated. Additionally, the results indicate increased runoff in the high latitude regions, a zonal belt of diminishing soil moisture around 40° latitude and a zone of increased wetness along the east coast of subtropical regions of the model continent.

The zone of diminishing soil moisture at approximately 40° latitude should be of some concern in our discussion of Great Plains drought. Should CO₂ concentrations continue to increase at anticipated rates the impacts on the region could be very severe. However, we should stress that these results of modelling are preliminary and must be considered as an alert. The models used are based on an idealized geography, no seasonal variation of insolation and simplified interaction between cloud and radiative transfer. The implications of the models, however, clearly deserve consideration.

SUMMARY

The feasibility of drought prediction, with special reference to the Great Plains, has been discussed in the preceding pages. Three investigative avenues which may lead to improvements in our ability to forecast future climate have been identified. These are: (1) the use of apparent periodicities of climatic phenomena; (2) the identification of time-lagged teleconnections; and (3) the application of numerical general circulation models.

Recent advances in the study of periodicities appear, in my view, to offer the most immediate prospects for improvement in drought prediction, especially in the Great Plains. The broad spectrum of statistical approaches now in use may also improve probabilistic forecasts based on past observations of the meteorological variables frequently used in the definition of drought. Advances are being made in the field of long-range climate modelling but these are more heavily
dependent on the development of new technologies and a broadening of our present data collection network. If these obstacles can be overcome, climate modeling will clearly offer a promising avenue for improving our long-range forecasting ability.

Regardless of the avenue of research, it seems clear that we are years away from developing spatially and temporally reliable drought predictions for the Great Plains. In the interim we must concentrate on providing farmers and other decision-makers with the best available information on the probability of drought recurrence and the periods of high risk as well as alternative strategies to cope with the hardships that drought creates.
LITERATURE CITED


