DROUGHT PREDICTION

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Abstract. Drought prediction has been an age-old problem, but in more recent times the magnitude of the Sahelian drought has brought into focus the need to improve the techniques for predicting such droughts with some measure of accuracy. From the present state of knowledge, drought prediction is difficult, if not impossible. Two major approaches appear to be prominent in the search for appropriate techniques. These include the use of teleconnections and the development of numerical models.

Essentially, time-lagged teleconnections rely on the assumption that changes induced in any one area of the world may produce changes elsewhere on a world-wide scale, though time-lagged. The 1972–73 El Niño off the west coast of South America is a good case in point. The development of numerical models which allow the incorporation of not only climatic factors but also man's impact on the natural environment, offers some ray of hope that the general circulation models (GCMs) may help to improve the techniques of drought prediction.

1. Introduction

The ultimate objective of drought prediction is to be able to forestall and, if possible, avert any hardship that may be attendant on the eventual occurrence of such droughts. However, accurate predictions of such drought occurrences is at present impossible. There is evidence that ancient people managed to predict the occurrence of drought with some measure of accuracy, but the basis of such prediction is not clear and such prediction may be regarded as subjective.

This can be contrasted with the objective and systematic experimentation of modern scientific approach to crop-weather analysis, and with the increase in data collection and application of quantitative techniques to model crop-weather relationships. Such techniques include the use of multiple regression to relate yield to the amount of rainfall and temperature, and the use of the Monte Carlo simulation technique to answer questions concerning drought frequencies during given time periods (Eddy and Cooper, 1978). The purpose of this paper is to review at some depth the achievements and problems of the various techniques of drought prediction. In the succeeding sections therefore we shall consider:

- Climate/rainfall variability as a major factor in the occurrence of drought,
- Drought prediction, is it possible?, and
- Summaries and conclusions.

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2. Climate and rainfall variability

According to Hare (1979), climate is the generalization of atmospheric behavior over a period longer that a few weeks. Most authorities would indeed say, longer than a few years. In reality, climate consists of an endless succession of individual weather states.

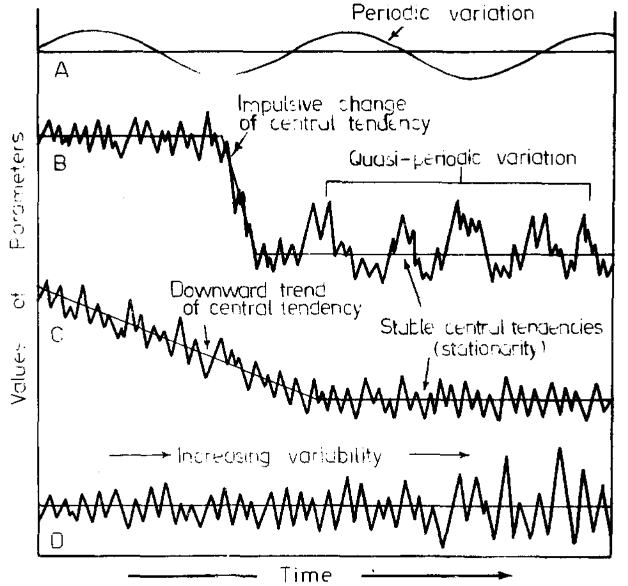

Figure 1. Various types of variability.

We seek, however, to get a mental grasp of this succession by defining climate with the following sorts of measures (Fig. 1):

- Estimates of the average values or central tendencies of the more important elements such as temperature and precipitation,
- Estimates of the characteristics kinds of variability about these averages; and these include:
  - *periodic effects*, defined in terms of frequency (or period) and amplitude, such as those connected with day and night, or winter and summer,
  - *quasi-periodic effects*, which tend to recur at approximately the same frequency or period, *e.g.*, monsoonal rainy seasons or the sunspot cycles, and
  - *non-periodic effects*, such as those that display themselves between successive days in the week, or between years in the decade.

Periodic phenomena reproduce themselves regularly, and have a predetermined period and phase (though not always amplitude); quasi-periodic phenomena are less regular and generally present characteristic response or relaxation times for processes that are not really periodic.

Before the question of climatic change arose, climatologists adopted the practice of forming the above estimates for thirty year reference periods *e.g.*, 1931–1960. It was found that small differences occur between successive reference periods because of the extremely variable character of *climatic noise* which is actually part of the variation of climate attributable to short-term weather changes. For instance, the chance location of the start and end of averaging periods with respect to short-term events may produce small statistical differences between successive periods. Their chance occurrence does not indicate a real climatic change. Climatic variability occurs within a typical averaging period but is usually larger than those associated with climatic noises. For example, a severe summer drought, without precedent perhaps for two or three centuries, may be part of a real variation towards a drier climate. With this background we shall take a closer look, in the succeeding paragraphs, at the achievements, problems and prospects of drought prediction at the present time.

3. Is drought prediction possible?

According to Hare (1977), there are three directions in which progress might be made in the prediction of future climate:

- the prediction of climate phenomena,
- the use of numerical general circulation models, and
- the identification of time-lagged teleconnections.

We shall consider each of these avenues with respect to the potential return that might result from major directed research effort.

3.1 Periodicities of climatic phenomena

The prediction of periodicities of climatic phenomena can assume a purely statistical approach in which a variable such as rainfall—in the case of drought—is statistically auto-predictable through a knowledge of its past history (Wilhite, 1978). A major criticism of this approach is that the climate record for any variable is usually too short to allow reliable prediction even if a well-defined periodicity has been identified. Furthermore it must be realized that the statistics of the past may not be adequate in the prediction of future events (Schneider, 1978). Not only are natural forces at work in changing climate, but also the impact of man must be recognized as a potential factor.

Attempts to correlate the occurrence of a climatic variable with other environmental variables which are statistically auto-predictable fall within the rubric of the statistical approach (Wilhite, 1978). The prediction of rainfall cycles from 20–22 years or 80–90 years sunspot cycles are well-known examples. Such examples have suggested that there is a correlation between the Hale Solar Cycle and recurring periods of drought. The mid-1970's, for instance, were expected to coincide with a minimum sunspot activity and a major effect on the climate of the Great Plains of USA. In reality drought did return to the Great Plains in 1974.

Critics of the students of periodicities and the forecasts which they provide contend that there is no physical theory which explains the suggested connection between the double sunspot cycle (20–22 years) and the drought in the Great Plains (Schneider, 1978). It is generally agreed that all cyclic phenomena must have a "forcing function". Some believe that sunspots are symptomatic rather than causative. They note that the changes in "storminess" appear to be related to the solar magnetosphere sweeping over the Earth. Although these changes are on a scale of only a few days, they feel that similar forces may be at work at a time-scale of double the sunspot cycle.

Mitchell (1964) summarizes the lack of success of the use of cycles as a forecast tool in the following words:

> "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 misjudgment. Beyond a doubt meteorology has not been alone in this experience either."

Other writers, like Friedman (1950) and Schneider (1978), have also criticized the sunspot-drought linkage. On the other hand, Mitchell (1964), who was once a critique of such a linkage, appears to have shifted ground (Mitchell, 1978) when he remarked that there is an implied relationship linking widespread drought in the western United States to solar magnetic activity. The inference from the on-going debate therefore shows that there is no unanimity amongst researchers on this issue of sunspot-drought linkage.

3.2 Time-lagged teleconnections

The atmosphere does much of its work on large geographical scales so that climatic anomalies tend to be extensive in space. If one station in Central North America or Asia has a cold winter, a very large area around it is likely to be similarly affected (Hare, 1979). The Sahelian drought spanned the whole continent of Africa in longitude. Hence climatic distributions typically show considerable consistency over wide areas. The chief exceptions arise from, for example, thunderstorm-type rainfall which is usually patchy.

On even larger scales it is common to find the variation of one element in one area correlated with its variation in another area sometimes quite remote (Pittock, 1983); or correlations may exist between different elements over such distance (Pittock, 1973). These teleconnections as they are called, are of great interest because they must be caused by some process that might otherwise escape attention. Moreover, some of the observed teleconnections have time-lags, meaning that a change of some element in one area typically precedes a correlated change in another (Namias, 1976; Pittock, 1983).

Such effects are actually predicted by general circulation models developed for the atmosphere. Figure 2 shows, for example, a model prediction of the effect on precipitation of a large increase of surface albedo over the Sahara and the dry western regions of North America (See also Laval, 1986, this issue). The model predicts considerable decreases of precipitation over and near the regions of albedo changes. In addition, it predicts changes over other quite remote areas—teleconnections in fact. Some of these are increases in precipitation. The general principle involved is quite vital—that changes induced in any one area of the world are likely to produce other changes elsewhere, on a world-wide basis.

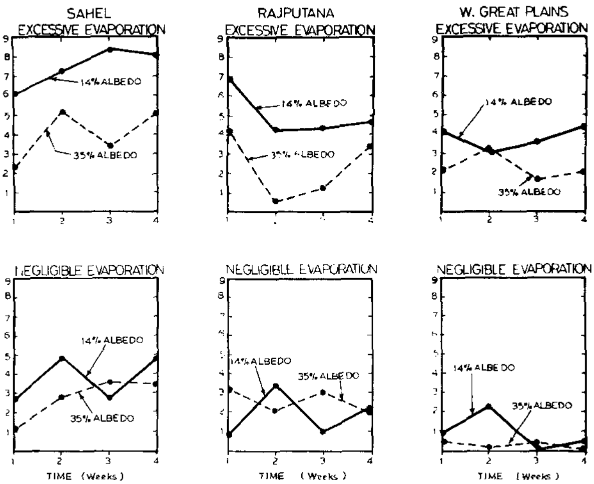

Figure 2. Weekly average rainfall rates from GCM experiments. Each column shows two experiments, with different hydrological assumptions. (After Charney *et al.*, 1977).

Many examples of such teleconnections have been demonstrated. The most remarkable is the Southern Oscillation of the Pacific and Indian Ocean first demonstrated over 50 years ago by Sir Gilbert Walker. It has been defined as

> "...a fluctuation in the intensity of the inter-tropical general atmospheric and hydrospheric circulation over Indo-Pacific region; the fluctuation being demonstrated by an exchange of air between the South-West Pacific subtropical high and Indonesian Equatorial low.
>
> It can be measured by means of the simple pressure difference between Eastern Island in the South East Pacific and Darwin in tropical Australia. Pressure at these two places is negatively correlated, the difference between them varying from small values to as much as 20 mb. More elaborate indices exist but confirm the reality of the effect. The Oscillation varies in periods from 3 to 7 years. In effect it is an immense standing East-West oscillating system involving large shifts of masses of air and water." (Wyrtki *et al.*, 1976).

The Oscillation has been shown to influence precipitation over India, tropical Australia and Indonesia and to be correlated also with rainfall variations in the remarkable equatorial dry belt of the west Pacific, which extends from Ecuador to Nauru in 170°W (Flohn, 1972). The most dramatic of these effects is the El Niño, the remarkable marine anomaly that recurs every few years off the west coast of Equatorial South America. Normally cold upwelling water occupies these areas which are prolific in marine life and the scene of rich fisheries, notably anchovy. But about a year after each peak of the Southern Oscillation (with strong trade winds over equatorial central Pacific) there is a tendency for warm water to invade the area—El Niño as it is called—with dramatic reductions in fish yield. The 1972–73 El Niño, in particular, preceded the collapse of the anchovy fishery, with drastic effects on world agricultural markets because of its relation to fish meal (Cushing, 1979).

Other teleconnections are known from the tropical Atlantic, for example, between sea temperature in the Guinea sector off Africa and the rainfall in the dry belt of north east Brazil. Hastenrath and Heller (1977) reported a link between departures of large-scale circulation over Equatorial Atlantic and the occurrence of droughts and floods several months later in the Ceara province of Brazil. They have also discovered a strong negative link between the north east Brazil rainfall and sea-surface temperatures along the Ecuador/Peru coast.

Few of these connections have significant predictive capabilities because they are overridden by other effects and do not explain much of the total variability. Their main importance is the challenge they throw to the theorist. For they say something about the characteristic time and space scales of atmospheric behavior in many cases well ahead of our capacity to explain them (Hare, 1979). Effective models of the general circulation must be capable of predicting the existence of such teleconnections (Pittock, 1983).

3.3 Numerical general circulation models

Numerical general circulation models constitute the third approach to drought prediction. The development of such models, greatly fostered under the auspices of the Global Atmospheric Research Programme (GARP), began in the 1960s. Such models must incorporate the essential dynamical and physical processes that are known to bear on the problem, and must be capable of predicting the consequences of specific changes of external forcing, including the inadvertent or deliberate action of man.

In the recent past there has been a major increase in modeling exercises. They are the only way in which to test quantifiable hypotheses as to the causes of climatic variation. In particular, it is by this route that one can hope to identify the relative importance of such influences as a varying Sun, altered land use or anomalies of sea temperature. Since the climax of the Sahelian drought, particular attention has been drawn to the problem of dry climates.

Models can be constructed on many different scales. Local hydrological soil processes for example, can be studied by means of simple models capable of solution on a desk calculator. At the other end of the scale, the general circulation of the atmosphere and ocean can be simulated by means of general circulation models (GCMs) requiring enormous amount of data and the largest present-generation computers. Between these two extremes a wide variety of useful exercises is possible. For success, all require

- the incorporation of governing physical and chemical laws into a manageable framework,
- the establishment of suitable simplifications and computational algorithms, and
- the determination of boundary conditions (Hare, 1983).

GCMs portray the three-dimensional circulation of a hemisphere or of the globe. There are related models that confine themselves to a more restricted region. Over long periods they produce a set of global statistics of temperature, pressure, wind and precipitation that resemble those of the present-day climate. The external inputs to such a model can then be varied deliberately to see how the models responds. With caution or even skepticism, it is possible to infer how the real atmosphere will react to a real perturbation of the same kind. In view of the importance of the air-sea interaction, such models ought to incorporate the oceans, but the very different response times of the two media, and the differences of computational procedure required, make this a difficult thing to do properly. It is also crucial that they deal effectively with the coupling between the extent of polar snow and ice surfaces, and world temperatures.

The Sahelian drought prompted much speculation that land use changes were the cause of the growing dessication. Questions were raised as to whether human misuse was responsible for desertification and as to whether such desertification then fed back on the climate by reducing rainfall still further. Is the hypothesis that desert feeds on desert valid?

Most recent attempts to answer such questions have been related to the scientific feedback processes that may augment or retard a naturally induced climatic variation along the desert margin. Most of these have been concerned with the effect of changed albedo (*i.e.*, reflectivity of the ground with respect to solar radiation) and other consequences of the degradation of vegetation cover.

The albedo feedback hypothesis was introduced by Otterman (1974, 1975) who reasoned that the destruction of vegetation and exposure of soil would increase albedo and hence lower the surface temperatures. This would lower the sensible heat and latent heat fluxes to the atmosphere and suppress the convective shower formation. Jackson and Idso (1975) countered Otterman's hypothesis (from studies of data on Sonoran Desert of Mexico); they concluded that the denuding of soil may have thermal and climatic effects just the opposite of those that Otterman postulated.

Regardless of the validity of Otterman's hypothesis others quickly seized on albedo feedback as a mechanism of desertification. Charney (1975a, 1975b) noted that the central and northern Sahara, eastern Saudi Arabia, and southern Iraq actually have a *negative* radiation balance *at the top of the atmosphere* on hot summer days in spite of the intense input of solar radiation through the cloudless atmosphere (Figs. 3, 4). This deficit arises because

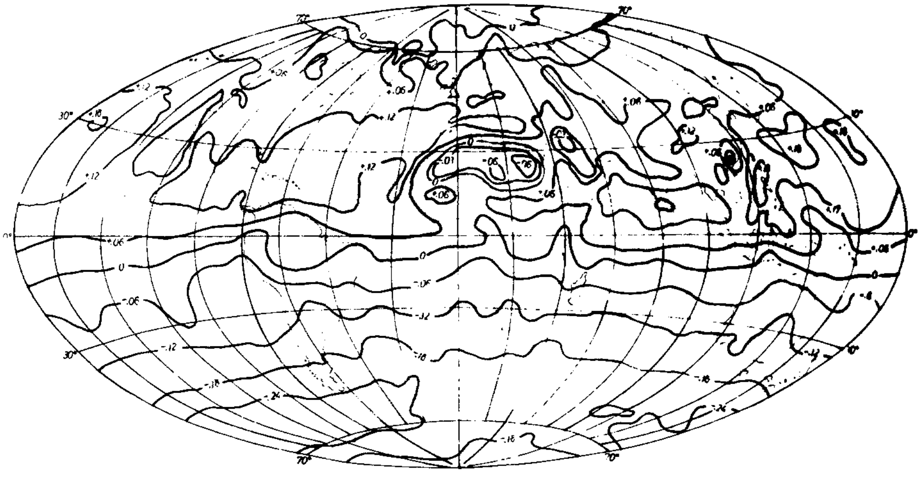

Figure 3. Radiation balance at the top of the atmosphere, July 10–31, 1969, in cal cm^{-2} min^{-1} (1 cal cm^{-2} min^{-1} $\approx$ 697 W m^{-2}), as measured by Nimbus 3.

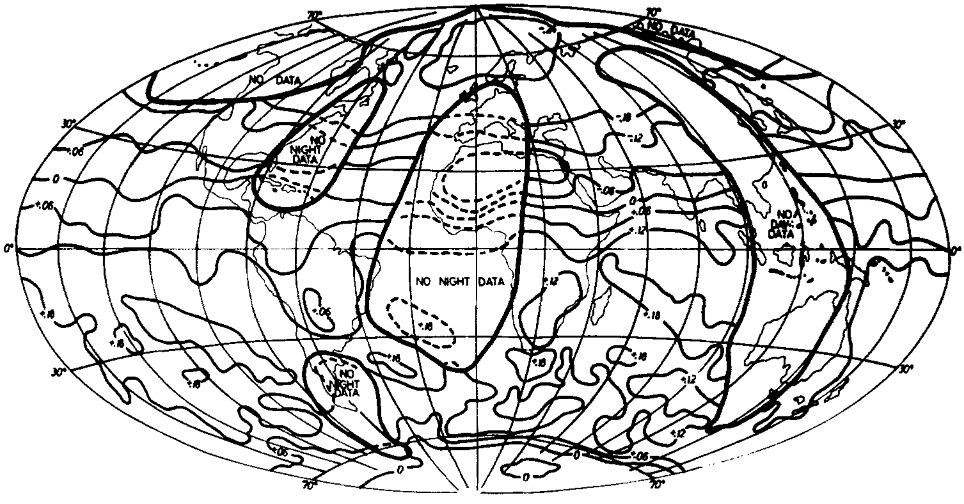

Figure 4. Radiation balance at the top of the atmosphere, January 21–February 3, 1970, in cal cm^{-2} min^{-1}, as measured by Nimbus 3.

- outgoing terrestrial radiation is enhanced by the high surface temperatures, cloudlessness and low humidities, and
- the high surface albedo (of 0.35 over sandy deserts) increases the reflection of solar radiation. Hence the North African and South West Asian deserts are actually sinks for the rest of the hemisphere. Even the Arctic has a positive radiation balance at this season. Only Greenland and Antarctic with perpetual ice compare with the

desert belt as radiative heat sinks in the summer hemisphere.

Charney set up a limited sector radiation-dynamical model of North Africa which suggested that an increase in albedo would enhance meridional overturning such that the rate of subsidence in tropical latitude (with a maximum at about 5 km) could be more than doubled in the summer season. Charney, Stone and Quirk (1975) then used the Goddard Institute for Space Studies (GISS) GCM (which includes clouds, precipitation and evaporation) to simulate the effect of change in albedo from 14 to 35% and found sharp reductions of cloud and rain following the increase.

This model has been criticized by Ripley (1976) on the ground that the model dealt inadequately with the role of evapotranspiration in regulating surface temperature and hence the Bowen Ratio (H/LE). In addition real albedo changes are also smaller than those assumed by Charney.

In a later study Charney *et al.* (1977) extended their study to real boundary layer conditions. They used two parameterizations of the surface water balance, one given little, and the other excessive evaporation. Figure 2 gives the results of the experiments with 14% (typical of well watered forest) and 35% albedo (typical sandy desert) in the Sahel, Rajputhana (Rajasthan desert) and the US Western Great Plains, in each case in July. Clearly the high albedo cases were sharply drier than the low cases in the Rajputhana but not in the Great Plains. The process was much more effective with excessive evaporation. This suggested that the albedo process works mainly by suppressing convective rainfall derived from local evapotranspiration.

The mechanism by which albedo is changed may, of course, be the removal of vegetation by drought, by over-stocking, by cultivation or all three; or it may be by dessication of the soil itself, soil albedo being linearly and inversely related to soil water content (Jakson and Idso, 1975). In practice the three mechanisms are likely to occur simultaneously, so that the soil moisture content may itself serve as a positive feedback for drought, wet soil favoring renewed rainfall derived from local evaporation.

Investigation of soil-moisture-related effects has been a main object of the United Kingdom research. Walker and Rowntree (1977) and Rowntree and Boltom (1982) applied a limited area eleven-level baroclinic model to parts to Africa to test the effect of variable soil moisture on rainfall. Their major results have been summarized as follows (Rowntree, 1982):

- the simulation of rainfall over North Africa in general circulation models is highly sensitive to the initial specification of surface and atmospheric humidity,
- the availability of soil moisture to the atmosphere at the start of the North African summer wet season may affect the intensity and northward spread of the summer rains,
- without either the positive feedback effects of humidity or radiation, or the negative feedback effects of cloud, subtropical moisture anomalies can persist for over six months in perpetual July context,

- large-scale changes of albedo have major effects on pressure and rainfall distributions. Generally a decrease in land albedos lowers pressures and increases rainfall over the continents, and
- the dependence of albedo on soil moisture tends to enhance contrasts between wet and dry regions.

It is thus becoming clear that the albedo effect first postulated by Otterman and then espoused by Charney is a key feedback mechanism in controlling sub-tropical and tropical climates. Several of the studies cited, moreover, indicate statistically correlated effects in other regions of the globe (teleconnections). These include relations with marine weather or sea-surface temperature anomalies (*e.g.*, Namias, 1974; Hastenrath, 1976; Lamb, 1978; Trevelyan and Rowntree, 1981). It is quite apparent however, that the albedo-induced mechanisms cannot be treated properly except in the context of surface-moisture conditions, and not merely because albedo is itself related to soil-moisture content.

The prominence attained by the albedo feedback mechanism has led to many studies of the observed albedos, and of the progress (or lack of it) in the containment of desertification. Distinct variation of surface albedo is detectable in areas of severe deterioration, especially during drought phases. The originator of the albedo hypothesis, J. Otterman, has continued to quantify the effect, using satellite and field observation (Otterman, 1981). So far, broad regional increases in albedo on a scale likely to produce or intensify drought have been conclusively demonstrated; the use of satellite technology on a systematic basis is likely to produce valuable evidence. The Global Environment Monitoring System (GEMS) has already moved in this direction (GEMS PAC, 1980), largely in the field of ecological monitoring.

4. Summary and conclusions

Drought prediction has been an age-old problem; but the enormity of the recent Sahelian drought has kindled greater interest in improving the technique for predicting droughts. The main aim being to be able to forestall the adverse effects of severe droughts. Statistical technique (*e.g.*, correlation) has been one of the earliest techniques. The main difficulty with this method is the shortness of available data needed to allow for reliable prediction. The use of periodicities has also been explored; this has been criticized for a lack of physical theory which explains the suggested link between drought and, for example, sunspot cycles. Though teleconnections have been proved to exist (sometimes time-lagged), few such connections have predictive values because they are overridden by other effects. Numerical GCMs appear to offer some hope for prediction of droughts. The use of computers facilitates the simulation of varying climatic conditions by varying the relative importance of various parameters in the model (*e.g.*, the variation of surface albedo or soil moisture). One can conclude that as of now there is no fool-proof technique for drought prediction and so the search continues.

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