Some Causes of United States Drought[1]

JEROME NAMIAS

University of California, San Diego, Scripps Institution of Oceanography, La Jolla, CA 92093

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ABSTRACT

Some physical causes of United States drought are outlined. Among the associated factors is subsidence, either in the upper level anticyclones or to the south of strong jets, or sometimes under prevailing northerly components of upper level flow. These conditions are engendered by abnormal forms of the atmosphere's general circulation. Causative factors vary in kind and degree according to area, so that droughts over the Far West differ from those of the Great Plains or the East. Examples of each of these are shown as well as treatment of a rapidly developing drought. It should be obvious from this report that a successful numerical (dynamical) solution of the drought problem should be high on meteorologists' agendas.

1. Introduction

This report deals with some probable physical causes of drought. As with many meteorological and climatological phenomena, there is never only one, but multiple causes. In order to understand the phenomenon, it must be treated as a manifestation of the atmosphere's general circulation and its variable forms. While drought may usually be easily ascribed to regional pressure and wind systems, physical understanding must include larger-scale atmospheric teleconnections and, probably, interactions between the atmosphere and abnormalities at its lower boundary, such as variations in sea surface temperatures, snow and ice cover and, particularly in the warm seasons, the character of the soil, including moisture content. These three types of surface variations are, in turn, often generated by special antecedent as well as contemporary atmospheric conditions. In fact, one must deal with an interactive system of feedbacks in which the participating media have different time constants. For example, snow and ice, sea surface temperature and soil moisture anomalies last much longer (typically an order of magnitude longer) than atmospheric wind patterns, and therefore surface-based anomalies often provide a "memory" to the atmosphere. Hence, during a given season, the atmosphere may be forced back to a particular drought-producing circulation pattern.

Once an anomalous atmospheric wind pattern is generated in one area, fluctuations in other remote areas are related in a manner now reasonably understood theoretically from long-wave and blocking synoptics. These teleconnections in atmospheric phenomena help explain why droughts are sometimes observed simultaneously in different regions of the world.

The immediate drought-producing mechanism almost always involves persistent and persistently recurrent subsidence of air (approximately a few hundred meters per day) which results in compressional warming and lowered relative humidity. Thus in warm-season droughts over the Great Plains of the United States or the continental interiors elsewhere in temperature latitudes, heat waves usually accompany drought, and cloud development is retarded. After a sufficient period of desiccation, drought is reflected in soil moisture deficits which, through radiative and thermodynamic processes, may lead to further sinking motion of the air columns aloft. The dryness can also lead to high dust counts, thereby providing myriads of nuclei for water droplets so tiny that rain formation may be inhibited because of the increased difficulty of droplet coalescence.

In cold-season droughts such as those observed in the western United States, the sinking motion of air is usually associated with anticyclonic vorticity and high pressure areas. These anticyclonic systems are usually associated with cyclonic atmospheric wind patterns upstream over the North Pacific and accompanying sea surface temperature anomalies. These western droughts are also aided by topographical features of the Great Basin which help contain the excess mass of air by providing barriers to its low level escape. In addition, western high pressure areas may be periodically reinforced by downstream strong cyclonic systems developing over central and eastern North America—a phenomenon where ageostrophic

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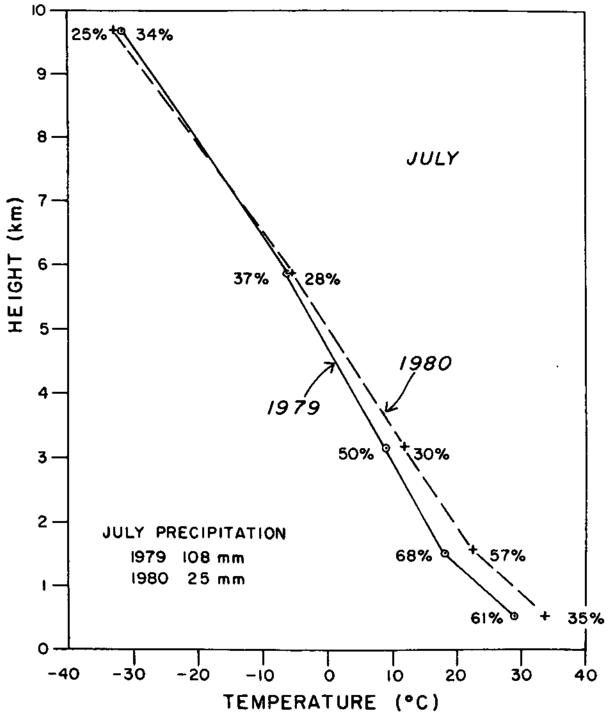

FIG. 1. Upper air temperatures in the core (Little Rock, AR) of the summer drought in the Great Plains during July 1980, as compared to July 1979. Numbers beside temperature plots give relative humidities. Rainfall amounts are given at lower left.

northwest winds may pile up air to the right of the current.

Throughout the history of drought research it has tacitly been assumed that premonitory signs appear in long period trends over months. However, this assumption runs counter to observations of formation of some severe droughts, like that over the Great Plains of the United States in summer of 1980, which saw a severe heat wave and drought develop in approximately a week. In this case, wind and weather patterns which had developed over several antecedent spring months were apparently unstable for summer, and the drought pattern was likely triggered by changes in seasonal forcing both in the immediate drought-prone area as well as in adjacent areas. In this manner, drought may be a phenomenon determined by the "receptivity" of the general circulation and the characteristics of the underlying surface.

The preceding discussion applies chiefly to droughts which occur over periods from a month to a season. Droughts which last over several years, as during the Dust Bowl decade of the 1930's or in the Sahel in the 1970's are more difficult to understand. Apparently, anomalous boundary conditions may persist or be recurrently established during spells of years. Speculations concerning how this comes about include the slow changing thermal anomalies (sometimes lasting years) in the upper ocean, along with the tendency

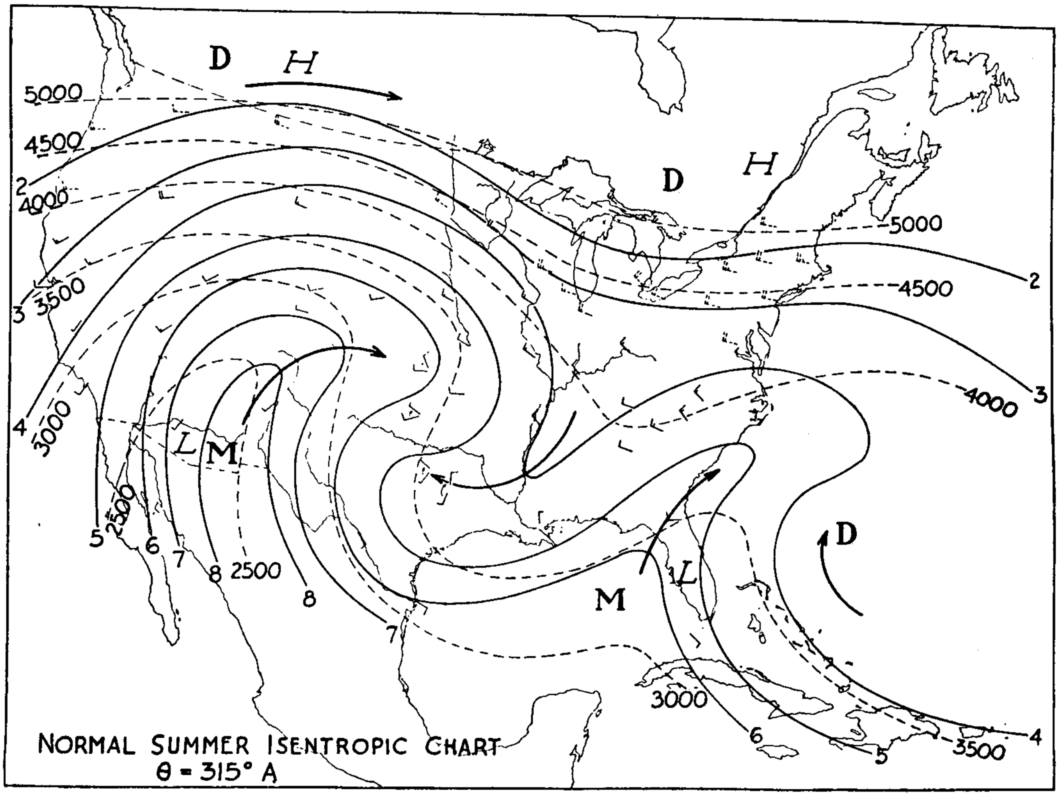

FIG. 2. Isentropic chart representing summers of 1934–38, based on monthly mean data. Taken from Petterssen (1940).

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of anomalous cold or warm water pools to re-emerge in fall and winter as wind stirring dredges up cold or warm subsurface water often covered in summer by a shallow lens of warm water, or the tenacity of abnormal soil moisture and vegetation conditions.

There is a tantalizing suggestion that droughts over the western two-thirds of the United States may be associated with the double sunspot cycle resulting in a tendency for drought recurrence in 20–25 year periods. However, no satisfactory physical explanation of the mechanism leading to such a correlation has been suggested, and the solar-caused drought hypothesis pertains to a very large area and is not site-specific.

This report shows a few selected cases of long and short period United States drought whose analyses were partly responsible for the ideas suggested above. Thus, it draws upon a body of details formed largely from empirical studies and circumstantial evidence to which the reader will be referred. Along more quantitative lines, a major step forward has recently begun with modeling efforts to explain the cause of the subsidence aloft and thus the precipitation deficits, and this effort will also be cited.

2. Immediate manifestations of drought

At the start it should be emphasized that drought has different manifestations at different times and places. From an agricultural standpoint, perhaps the most researched and most important droughts occur in the heartlands of continents, like those in the Great Plains of the United States during summer. These are almost always associated with high surface temperature and low relative humidity extending into the mid-troposphere. A typical atmospheric sounding for such a drought is shown in Fig. 1, which characterized the extensive drought of the summer of 1980 over the Central and Southern Plains. In the core of the heat wave for the summer season, temperatures averaged as much as 4.5°C above normal and precipitation was less than 25% of normal. Note in Fig. 1 the contrast with the more normal July of 1979—a wetter and cooler month. The reasons for the relatively high temperatures in 1980 were probably associated with subsidence in an upper level anticyclone indicated by the low relative humidities, with the concomitant lack of cloud and high insolation. This drought has been described in numerous papers (Dickson, 1980; Livezey, 1980; Wagner, 1980; Erickson, 1981; Karl and Quayle, 1981; Namias, 1982). Similar lapse rates and abnormalities of temperatures and humidity characterized summer droughts in Russia, western Europe and England. (Katz, 1973; Ratcliffe, 1977; Namias, 1978a).

The large-scale wind systems associated with Great Plains droughts usually consist of a deep warm an-

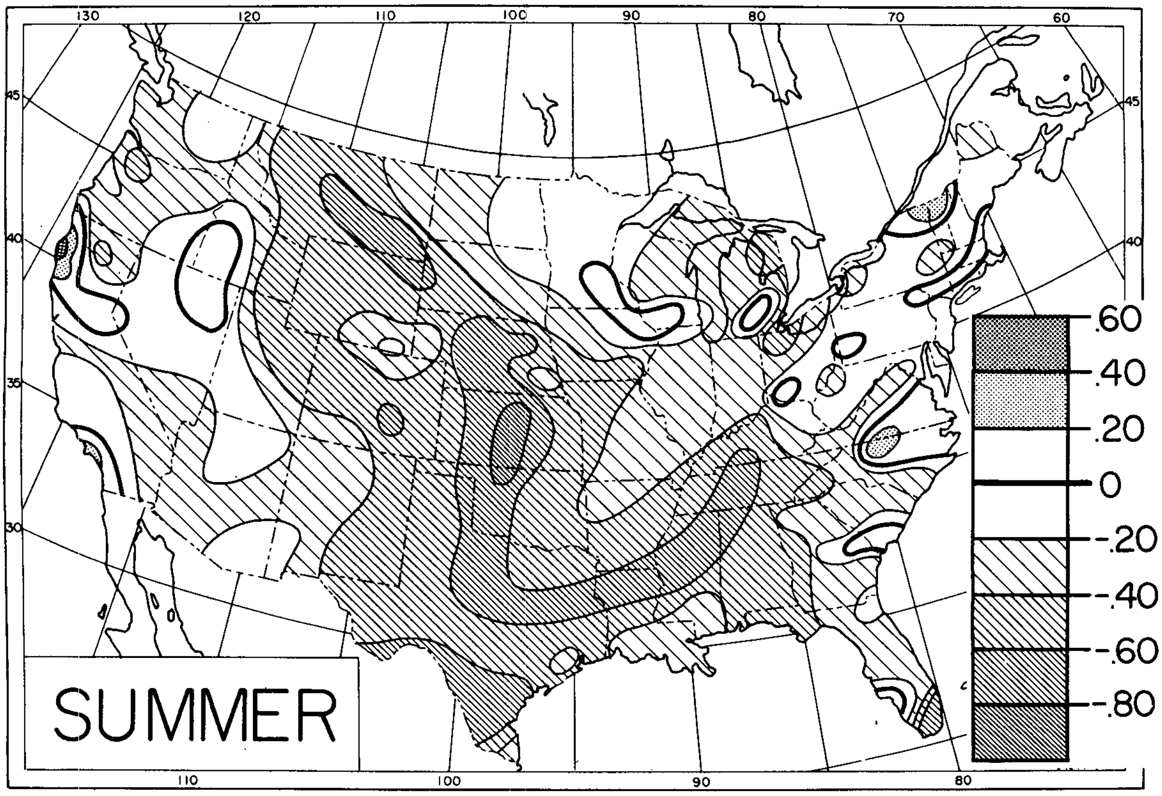

FIG. 3. Contemporaneous seasonal correlations between temperatures and precipitation in Summer (based on data for 1947–1972). (Isopleths drawn for each 0–20, beginning with ±0.20. Note high negative correlations over Great Plains.

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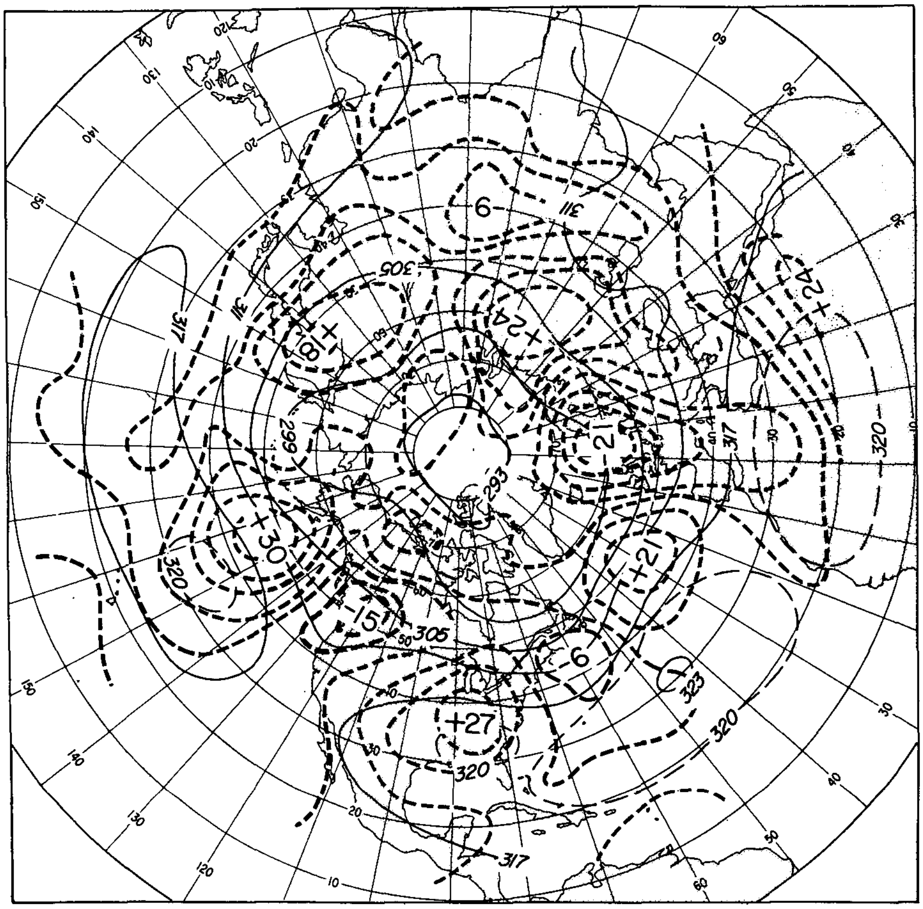

FIG. 4. 700 mb contours (light lines) and departures from normal (heavy dashed lines) for average of summers, 1952–54. Contours and anomalies labeled in tens of meters and meters, respectively. 700 mb solid contours have intervals of 60 m, broken contours have intervals of 30 m, and anomaly isopleths have intervals of 5 m.

ticyclone which is periodically fed by dry subsiding tongues of air emanating from westerlies along the northern United States border. The nature of the flow in and around these anticyclones is perhaps best illustrated with the help of isentropic charts. Such a mean chart for the five summers 1934–38 for the 315 K (42°C) isentropic surface is reproduced in Fig. 2. At the time this chart was prepared (Petterssen, 1940, Chapter VIII), it was thought that the mean of these five summers represented a normal summer picture.

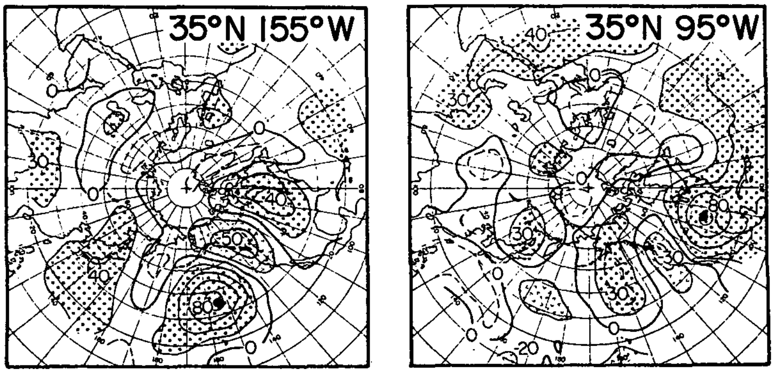

FIG. 5. Summer teleconnections (cross correlations) of 700 mb height from two key points associated with Great Plains drought. From Namias (1981).

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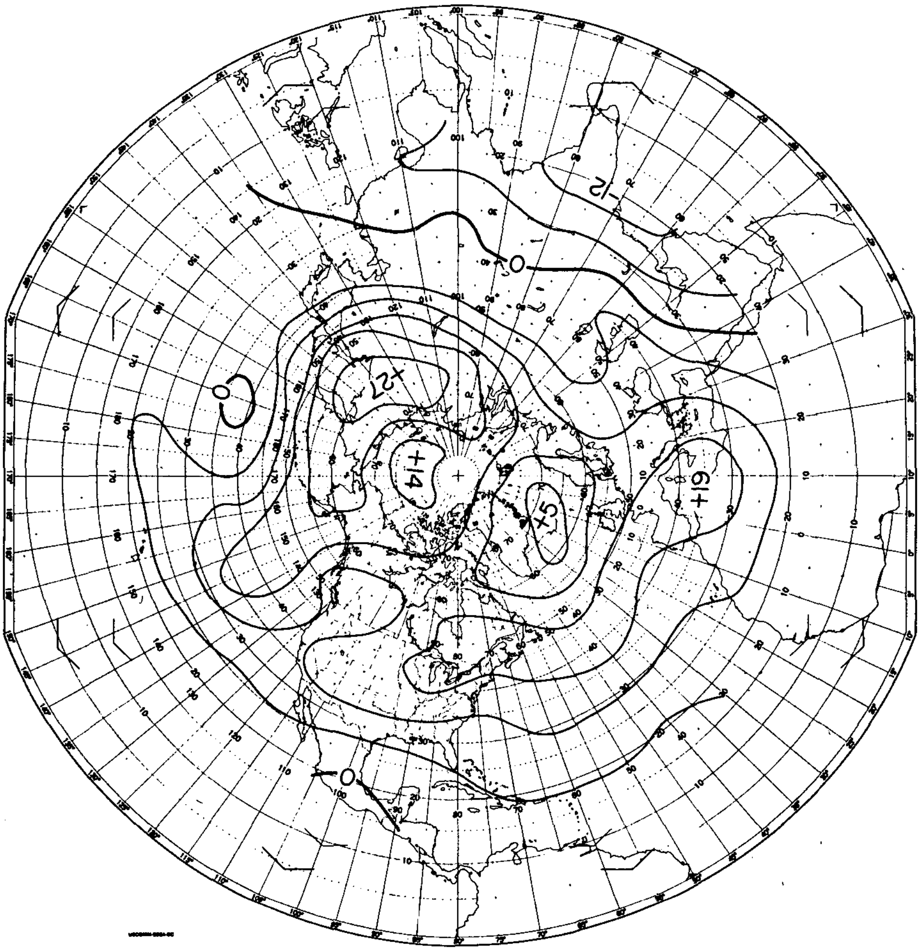

FIG. 6. Changes in normal 700 mb height from May to June. Centers labeled in m and isopleths drawn for each 15 m. Based on 1947–72 period.

As is now well known, those years were dominated by the Dust Bowl drought, and thus the implied anticyclonic spiral of dry air was quite exaggerated. Consequently, this figure provides a fairly typical picture of sustained Great Plains droughts. Later in this paper, some suggestions are given to try to explain how these anticyclonic cells arise and are sustained.

It was pointed out that summer drought over the Great Plains is usually associated with high temperatures. The negative correlation between temperature and precipitation is well illustrated in Fig. 3, where correlations exceeding −0.60 and even −0.80 have been observed in records extending over the 26 summers from 1947 to 1972. Note from Fig. 3 that such high correlations are confined to the Plains. This fact in itself suggests that the causes of drought may differ depending upon area (a topic treated later on in the discussion of West and East Coast droughts).

3. Teleconnections

There are usually teleconnections between regional drought-producing circulations and other large scale features. The associated upper level anticyclone observed over the Plains is usually accompanied by and probably partly responsive to other anticyclones, one in the East Central Pacific and the other in the East Central Atlantic. An example of such a series of anticyclones with intervening troughs is shown in Fig. 4, which represents a mean of the three summers 1952–54 when drought prevailed over the Southern Plains. Note from Fig. 4 that each of these anticyclones is anomalously strong as shown by the broken lines. This type of teleconnection is easily recognized as a reflection of standing Rossby waves. The teleconnection is also shown by empirically-derived charts (Namias, 1981) such as those shown in Fig. 5, where cross-correlations of 700 mb height (based on a record of ~30 years of summer months) are shown between the black heavy circle and other areas. Note that if the upper level high in the Central Pacific is strong (left hand chart), there is a good probability of low heights along the West Coast and high heights over the Plains. A compatible pattern arises if heights are high over the Plains (right hand chart in Fig. 5),

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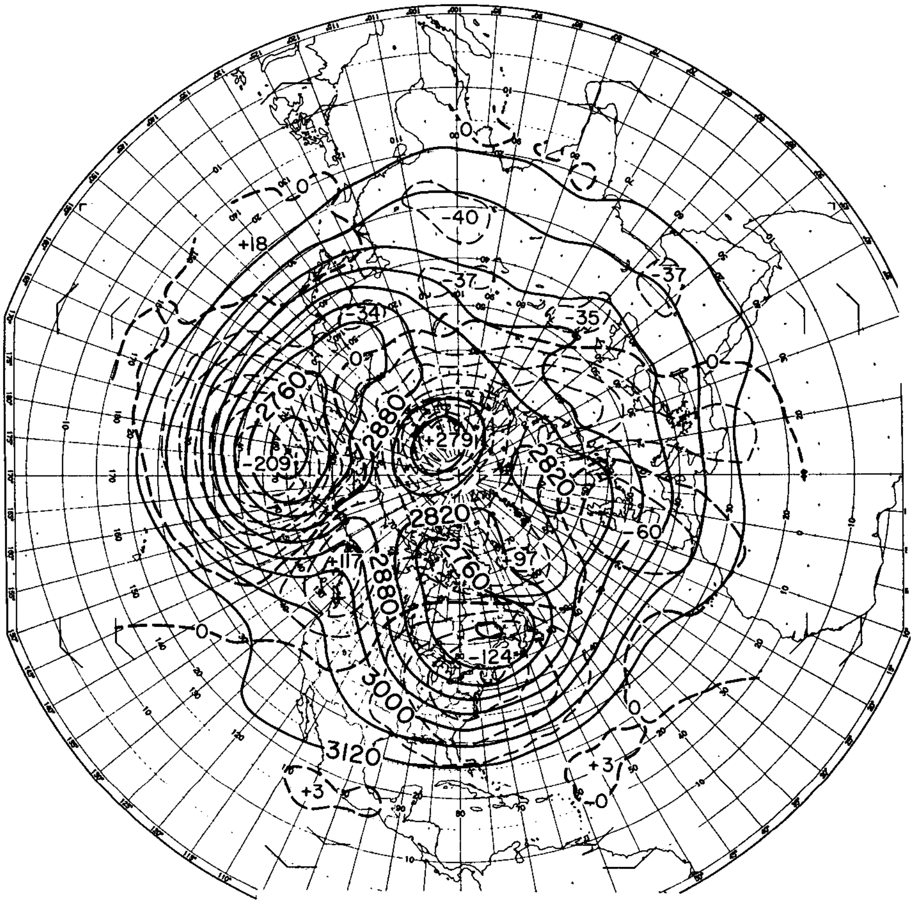

FIG. 7. 700 mb height contours and isopleths of departure from normal, January 1977.

which also favors high heights in the East Central Pacific and low heights along the West Coast. An analogous teleconnection is seen between the Atlantic High and the Great Plains. Thus it is probable that the susceptibility of the Great Plains to summer drought depends not only on local processes but also on conditions over the adjacent oceans. As for the mechanisms, Illari (1981) has shown that the anticyclonic vorticity in drought anticyclones is supplied by transient eddies, where sinking motion of air transfers the vorticity to lower levels where it can be dissipated.

Normal seasonal forcing favors the incidence of summertime Great Plains drought, as suggested by the changes in 700 mb heights observed between spring and summer and between May and June (Fig. 6) where the largest increases in heights frequently occur in the seat of the Pacific High and over the Plains, while lesser rises (favoring troughs) occur off either coast. Hence, the development of Great Plains drought is reinforced by the normal seasonal forcing indicated in Fig. 6. Some explanation for these changes has been found in numerical simulations (Smagorinsky, 1953; Manabe *et al.*, 1979).

4. Western United States drought

Drought (abnormally low rainfall) along the West Coast occurs in winter rather than summer because there the rainfall season is confined to the cold season. But here also the isobaric signature of drought suggests anticyclonic vorticity associated with high pressure ridges, or at times, high pressure cells. These ridges serve as blocks to cyclonic activity from the Pacific, and often displace storm tracks north of the United States/Canadian border. Here again the anticyclonic ridge may often be responsive to an upstream deep trough over the eastern United States. An extreme example of this kind was observed during the winter of 1977 (Fig. 7), which saw one of the most extensive Far Western droughts in recent history. Such cases have causes well outside the immediate area of drought. An extensive synoptic study of this drought (Namias, 1978b) suggests multiple causes, including 1) the normal forcing of the general circulation which was in phase with abnormal forcing, thus favoring the development of the West Coast ridge, 2) the presence of El Niño which apparently assisted the development of a strong Aleutian Low,

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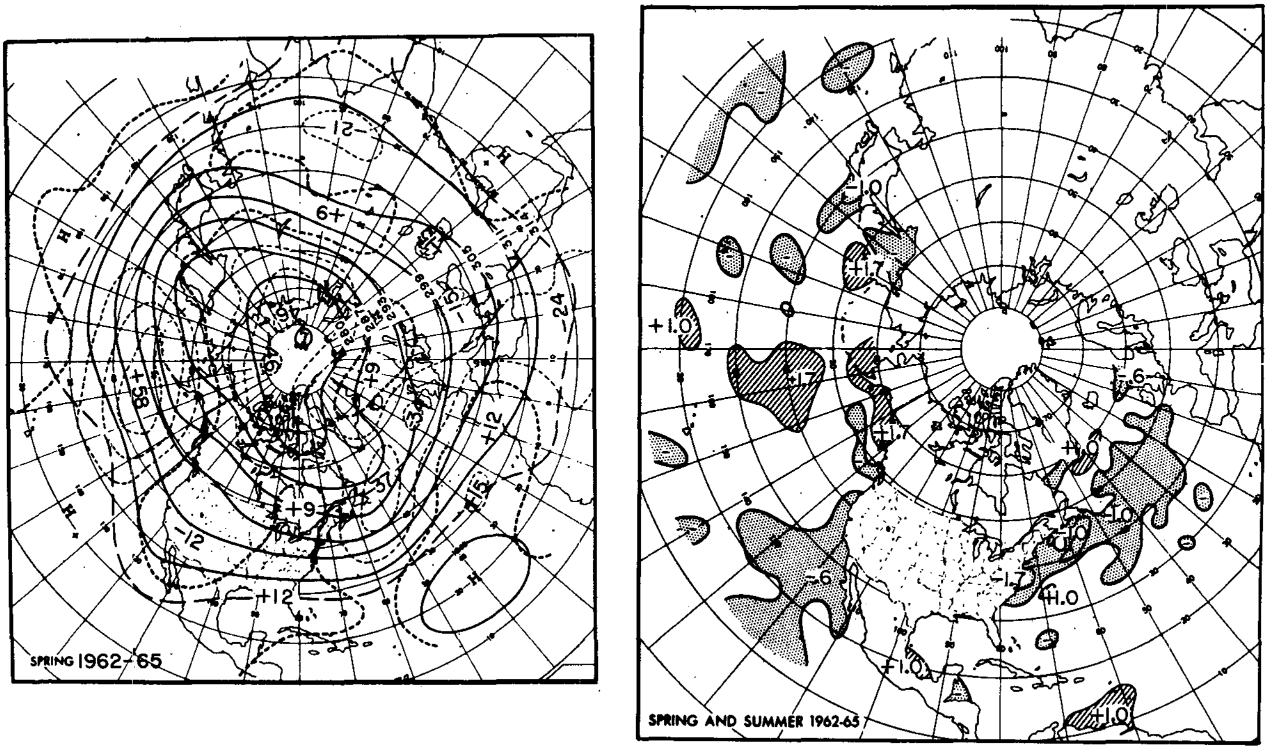

FIG. 8. Left: 700 mb contours and isopleths of departure from normal (dashed line) in m for mean of springs, 1962–1965. Right: sea surface temperature departure for mean of springs and summers 1962–1965. Stippling indicates below normal and shading above normal, by more than 1.1°C, respectively.

3) teleconnections between the deep Aleutian Low and the United States western ridge and eastern trough, 4) the presence of snow over the East and Midwest which assisted the further development of the East Coast trough which may have helped strengthen the western ridge, and 5) the development of a North Pacific sea surface temperature pattern (warm in the extreme east and cold in the center) which may have influenced the overlying air flow and storm tracks to amplify and stabilize the drought pattern.

An attempt to model the abnormal general circulation of the 1977 Winter with a sophisticated iterative numerical model was carried out by the Princeton GFDL group with strikingly good results for a January prediction from initial data of 1 January 1977 (Caverly *et al.*, 1982). Although experiments on two other January cases by the GFDL group were not successful, this approach represents a fresh attack on long-range forecasting in general and drought in particular.

5. Northeast United States drought and influence of SST

Droughts along the eastern seaboard of the United States are frequently of a different nature than those elsewhere, although they do exhibit the characteristic subsidence. One type of Northeast drought occurs when the jet stream and upper level westerlies are displaced north of their normal position and sinking motion prevails south of the jet. This type of drought occurred in 1952 and was described in detail by Klein (1952). Another type of Northeast drought occurred during the springs and summers of 1962–65. This severe and long lasting drought was associated with recurrent trough activity and cyclonic surface activity just off the Atlantic Seaboard, as indicated in the chart on the left of Fig. 8. The predominance of northerly wind components over New England and the Middle Atlantic states resulted in dry conditions there during these four years. In effect, the cyclones moved out to sea, depriving the land areas of moisture and inducing the sinking motions characteristic of subsidence. However, the prevailing advection of dry air from the north resulted in *cooler* than normal temperatures during this drought. A detailed study of the various conditions establishing and maintaining the drought is given in Namias (1966), showing that synergistic factors came into play. In that article it was shown that colder than normal sea surface temperatures off the Atlantic Seaboard produced an enhanced gradient east of the continental shelf, (see the right panel of Fig. 8). It was proposed that this gradient forced the

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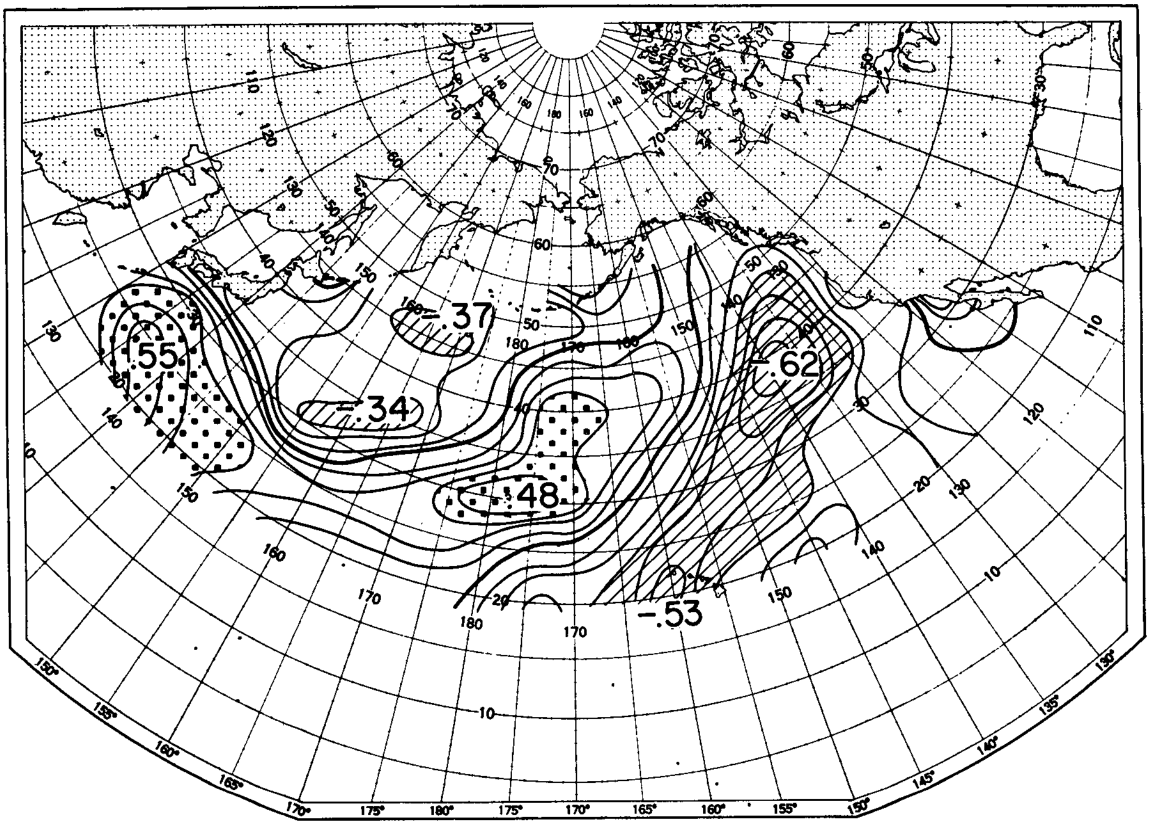

FIG. 9. Correlation of sea surface temperature in the North Pacific with temperatures over the Great Plains (summers of 1947–80). Average temperatures for the following Great Plains States were used: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri and Arkansas. Stippling and shading indicates areas ⩾ 0.3 and ⩽ −0.3, respectively. 0.3 is approximately the 95% confidence limit, assuming normally distributed data. (Courtesy of Dr. Arthur Douglas, Creighton University, Omaha, NE.)

cyclones to pursue a course farther east than usual, resulting in northerly wind anomalies and less precipitation along the Atlantic Seaboard.

6. Other air–sea interactions associated with drought

Large-scale air–sea interactions can be found in many drought cases. A manifestation of Great Plains drought is seen in sea surface temperature patterns of the North Pacific. For example, a correlation of summer temperatures over the Great Plains states with sea surface temperatures over the North Pacific (Fig. 9) shows significant negative correlations in the central East Pacific. Of course, this figure indicates an *association* between sea surface temperature patterns and United States drought, not a cause. However, in view of the wind patterns described earlier, it is clear that the anomalous Pacific anticyclone associated with the Plains drought produces the sea surface temperature anomaly patterns over the eastern Pacific. In turn, the sea surface temperature anomaly patterns may feed back to reinforce the east Pacific anticyclone. Cause and effect remain to be resolved.

7. Rapidly developing drought

Earlier in this report it was mentioned that a drought sometimes develops rapidly as did the great heat wave and dryness of the summer of 1980 over the Central and Southern Plains.

Fig. 10 shows the observed temperature anomaly pattern for the two months of rapid transition, May and June, while the corresponding 700 mb mean circulations are shown in Fig. 11. The great circulation changes to be noted between May and June are 1) the development in June of the Southern Plains anticyclone, replacing the fast westerlies of May, 2) the development of a strong ridge over the east–central Pacific in June, and 3) the June development of strong troughs off both coasts. All these features, it will be remembered, are typical of drought in the Plains. Once the drought pattern was established in June it was quite tenacious.

Actually the change from the May to June patterns largely took place in the last week of May, a fact which complicates the drought forecasting problem. Apparently, by the end of May the atmospheric sys-

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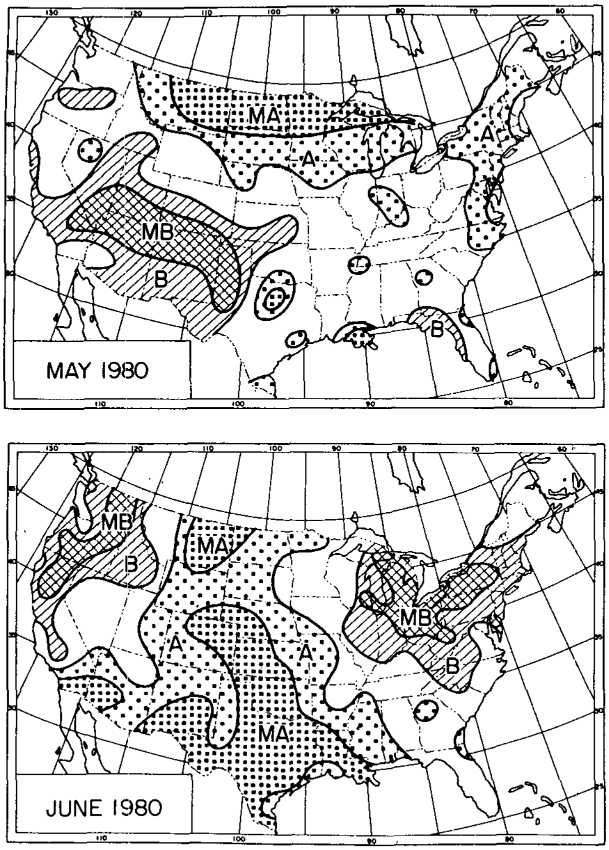

FIG. 10. Observed departures for the coterminous United States during May and June 1980. Departures are given in five classes: Much Above Normal (MA), Above Normal (A), Near Normal (N), Below Normal (B) and Much Below Normal (MB), representing climatological frequencies of occurrence of 10, 20, 40, 20 and 10%, respectively.

tem, together with the underlying land and sea surface conditions, were in a highly receptive state for such a transition. Among the physical factors conducive to this change were 1) forcing by the normal May–June circulation changes (see Fig. 6) operating on a labile pattern, 2) cooler than normal sea surface temperatures in the east Pacific where the strong Pacific ridge developed (possibly producing reduced atmospheric drag coefficients), and 3) drier than normal late spring soil over some of the Southern Plains.

Empirical evidence for the influence of deficient soil moisture on drought has been presented by the author (Namias, 1960) and confirmed by numerical modeling experiments by Mintz and Shukla (1982). In addition, simulation experiments by Charney (1975) indicate that dry soil establishes sinking motions aloft through radiative and dynamic processes.

8. Concluding remarks

From the above material it should be clear that while synoptic and statistical studies have brought to light many phenomena associated with drought often leading to generalization and speculation, an investigation with the help of dynamical methods is required for true understanding.

When a dynamical method has been developed we will better understand:

1) What causes the onset of drought;
2) What makes drought persist;
3) The extent of influence by air–sea–land boundary conditions;
4) The teleconnections involved.

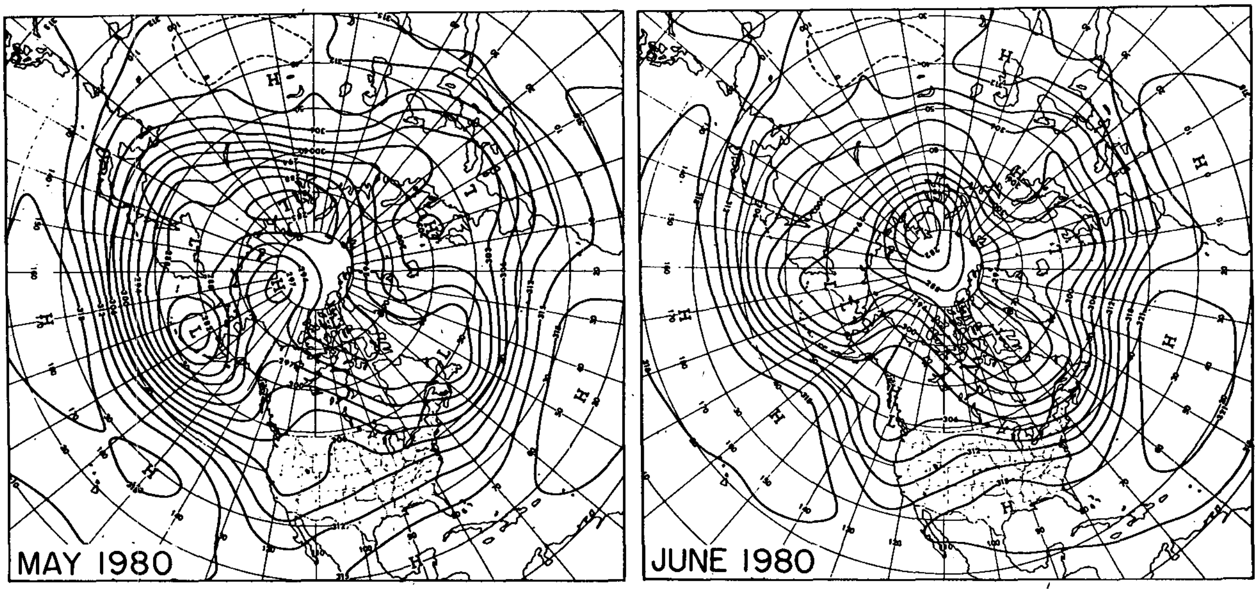

FIG. 11. 700 mb height contours (in 10 m intervals) for May and June, 1980.

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