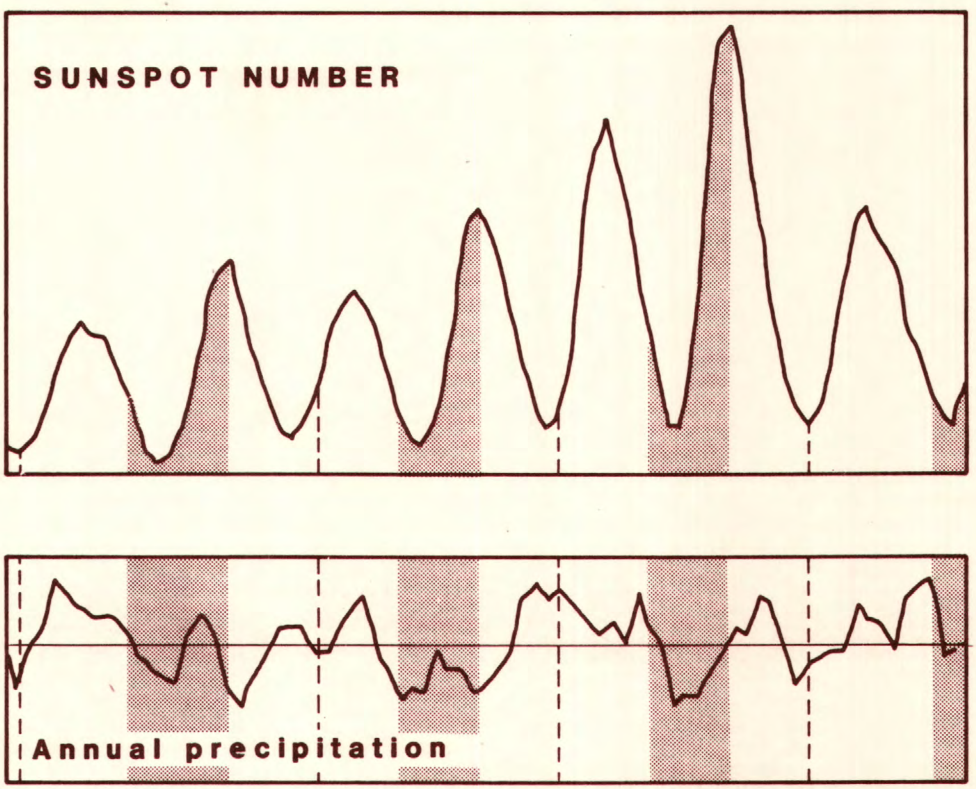
PRELIMINARY ANALYSIS OF REGIONAL-PRECIPITATION PERIODICITY

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-74



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A preliminary analysis of precipitation periodicity was made for eight regions scattered across the central United States. Each region contained 5 to 10 stations with long-term precipitation records that were averaged to obtain yearly regional-precipitation values. Graphic analysis shows 11-year and 22-year cycles that are nearly in phase with the solar cycles.

An example of the effect of cyclic precipitation is presented for the Powder River basin in Wyoming and Montana. A cycle of 22 years exhibits fluctuations of approximately 22 to 27 percent for precipitation and 38 to 50 percent for runoff. A more detailed study that investigates solar-forced precipitation cycles and their relationship to hydrologic processes is needed.

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UNITED STATES DEPARTMENT OF THE INTERIOR

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GLOSSARY OF SPECIALIZED TERMS

Coronal hole - a large area on the surface of the sun where the temperature and density of the sun's gases are reduced.

Cyclone - a large area of winds blowing counterclockwise around an area of lower atmospheric pressure, which possesses clouds and precipitation.

Frontal surface - a region of discontinuity between air masses of different temperature and humidity.

Geomagnetic storm - a violent fluctuation of the earth's magnetic field caused by abrupt changes in solar wind.

Geopotential height - the geometric height of a pressure surface adjusted by the force of gravity to give specific energy.

Magnetic index Ap - a linear scale of daily geomagnetic activity.

Magnetic index Kp - an average measure of 3-hour geomagnetic activity over the earth.

Magnetosphere - the area around the earth that is dominated by the magnetic field of the earth and is distorted by the solar wind.

Maunder minimum - the period from 1645 to 1715 when solar activity was at a very low level.

Orographic lifting - the lifting of air by winds blowing against a large barrier, such as a mountain range.

Solar constant - the radiation intensity received by 1 square centimeter perpendicular to the sun at the upper boundary of the atmosphere; averages 1.94 calories per square centimeter per minute.

Sunspot polarity - sunspots usually occur in pairs, with magnetic-field lines emerging from one spot and entering the other.

Wave trough - a trough in the wave pattern of the upper-air flow associated with clouds and precipitation.

CONVERSION FACTORS

The inch-pound and metric units of measurement given in this report may be converted to the International System (SI) of Units by using the following conversion factors:

Inch-pound unit	Multiply by	SI unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.305	meter (m)
square inch (in^2)	6.45	square centimeter (cm^2)
square mile (mi^2)	2.59	square kilometer (km^2)
knot (kn)	1.85	kilometer per hour (km/h)
cubic feet per second (ft^3/s)	0.283	cubic meter per second (m^3/s)

Metric unit	Multiply by	SI unit
millibar (mbar)	0.100	kilopascal (kPa)
calorie (cal_{IT})	4.187	joule (J)

ABSTRACT

Precipitation variability plays a major role in nearly every aspect of the hydrologic cycle. Precipitation is not a random event, but it occurs after a sequence of prerequisites has been fulfilled. Recent investigations have shown that activity of the sun can affect atmospheric vorticity, an important factor in precipitation formation. Solar activity is known to be periodic; therefore, through a complex series of physical processes, precipitation variance is solar forced to a certain degree.

A preliminary analysis of precipitation periodicity was made for eight regions scattered across the central United States. Each region contained 5 to 10 stations with long-term precipitation records that were averaged to obtain yearly regional-precipitation values. Graphic analysis shows 11-year and 22-year cycles that are nearly in phase with the solar cycles.

An example of the effect of cyclic precipitation is presented for the Powder River basin in Wyoming and Montana. A cycle of 22 years exhibits fluctuations of approximately 22 to 27 percent for precipitation and 38 to 50 percent for runoff. A more detailed study that investigates solar-forced precipitation cycles and their relationship to hydrologic processes is needed.

INTRODUCTION

Precipitation variability plays a major role in nearly every hydrologic investigation. All aspects of the hydrologic cycle are related to temporal and spatial fluctuations in precipitation. Precipitation, in fact, has an exaggerated effect on some hydrologic processes. For example, a 10-percent increase in precipitation may produce an increase in streamflow of 30 percent or more. Hydrologic analyses commonly are based on data from a fairly short period of record, sometimes less than 10 years. If precipitation does have periodic variation, precipitation data for the past 10 years may provide an extremely biased estimate of hydrologic activity for the next 10 years.

The purpose of this report is: (1) to examine the possibility of periodic fluctuations or persistent trends in precipitation that would affect the results of hydrologic studies based on short-term data, and (2) to suggest ways in which a more comprehensive study of regional-precipitation periodicity might greatly increase the reliability of hydrologic estimates.

Most methods of prediction in hydrology assume the year-to-year variations of precipitation are random. This assumption commonly is used in the frequency analysis of peak or base streamflows. If precipitation is found to be affected by cyclic phenomena, the methods used in interpreting hydrologic data could be improved by including these effects in the analysis. The methods used in short-term hydrologic studies would benefit from a knowledge of periodic fluctuation in precipitation.

PRECIPITATION PROCESSES

Formation of Precipitation

Precipitation varies in form, intensity, and distribution from one area to another, but the basic processes of formation are generally the same. Precipitation formation follows a sequence of events that may begin days or weeks before the occurrence.

Condensation of water vapor must take place before precipitation is possible. This is accomplished by cooling the air containing water vapor until it is saturated. In the atmosphere, cooling occurs when a parcel of air is elevated by some mechanical process and the pressure of that parcel decreases. Once saturation is reached in the parcel, condensation of the water vapor into water droplets takes place on certain hygroscopic particles called condensation nuclei. Growth of these droplets is governed by temperature, radii of the droplets, and solution effect, as well as the joining of droplets in the accretion process. Growth of snowflakes from supercooled water droplets also affects the process of precipitation formation.

The most important factor in precipitation formation is the physical process of lifting the air to the point of condensation. This can be accomplished by orographic lifting, lifting by frontal activity, localized temperature differences and convergence, and by dynamic lifting. Of these, dynamic lifting is the most significant of the lifting processes. Dynamic lifting and its opposite, dynamic sinking, are generated by large-scale motions of the atmosphere. If present, dynamic sinking will reduce or completely eliminate the effects of the other lifting mechanisms.

Dynamic lifting is associated with surface cyclones and upper-atmospheric low-pressure areas. The development of surface cyclones was best described by Bjerknes (1937), who first drew attention to the role of the upper-atmospheric flow patterns. He visualized two cyclogenic processes. The first of these originates from the dynamic instability associated with a frontal surface, and the second from the unstable growth of an upper-level wave trough. The dynamic instability associated with a frontal surface is the primary source of energy for a developing cyclone. The warm air rises, and the cool air sinks beneath the warm. This overturning represents a great quantity of energy in the form of air motion. This energy is constantly being replenished by unequal heating and cooling of the atmosphere. Due to the rotation of the earth, the moving air begins to spin and form a vortex. However, without a process to eliminate air from the center of the vortex, the development of a low-pressure center is inhibited.

The second cyclonic process envisioned by Bjerknes is that of the unstable growth of the upper-level wave trough. In the northern hemisphere there is a broad belt of winds blowing from the west called the "westerlies." These winds flow nearly parallel to the contours of equal geopotential height, which are in turn dictated by the large-scale thermal fields. These geopotential-height contours form sinusoidal waves, which at times are standing waves and at other times, traveling waves. Due to the earth's rotation, the wind blowing along two parallel contours slows when the air moves south, and speeds up as it passes the bottom of the wave and the air begins to travel north. This process causes a piling up of air to the west of a wave trough, or convergence, and a stretching out, or divergence, to the east (fig. 1A). As the air diverges at the upper levels, air is pulled up from below and convergence occurs at the surface (fig. 1B). This process removes air from the surface by lifting it to upper levels where it is then transported away, thus maintaining a low-pressure area at the surface.

The vorticity patterns of both the upper wave and surface low can affect the area of precipitation because vorticity is an indication of stability. Vorticity can be defined as circulation of air about a central point. The faster this air moves and the smaller its radius of curvature, the greater the absolute value of its vorticity. If the air is curving to the left (cyclonic curvature), the vorticity generated will have a positive value, and, if it is curving to the right (anticyclonic curvature), it will have a negative value. Through vector analysis it can be shown that some horizontal vorticity is converted to a vertical component and that vertical velocities of the air are a result. Cyclonic vorticity produces upward motion of the air, while anticyclonic vorticity produces downward motion.

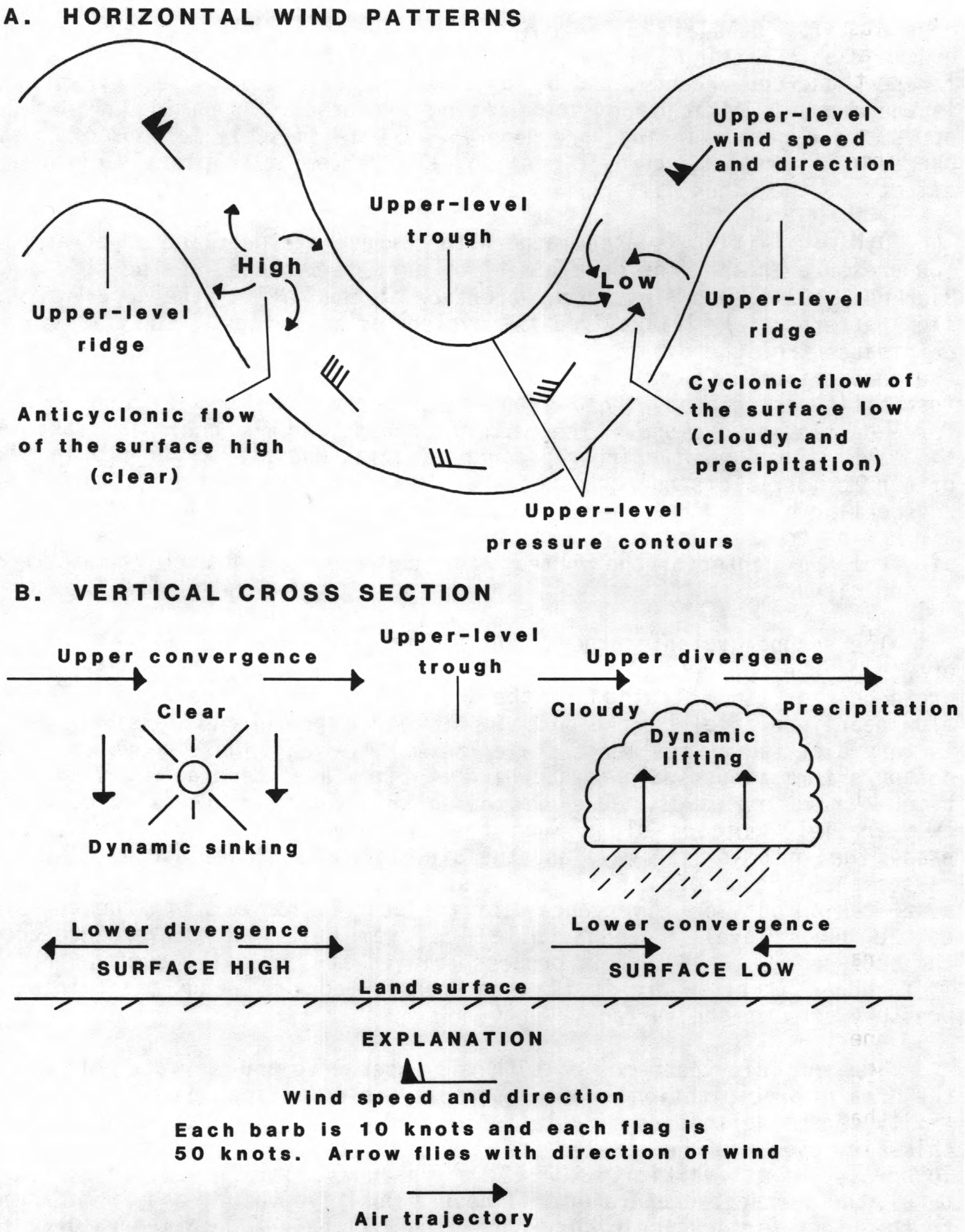
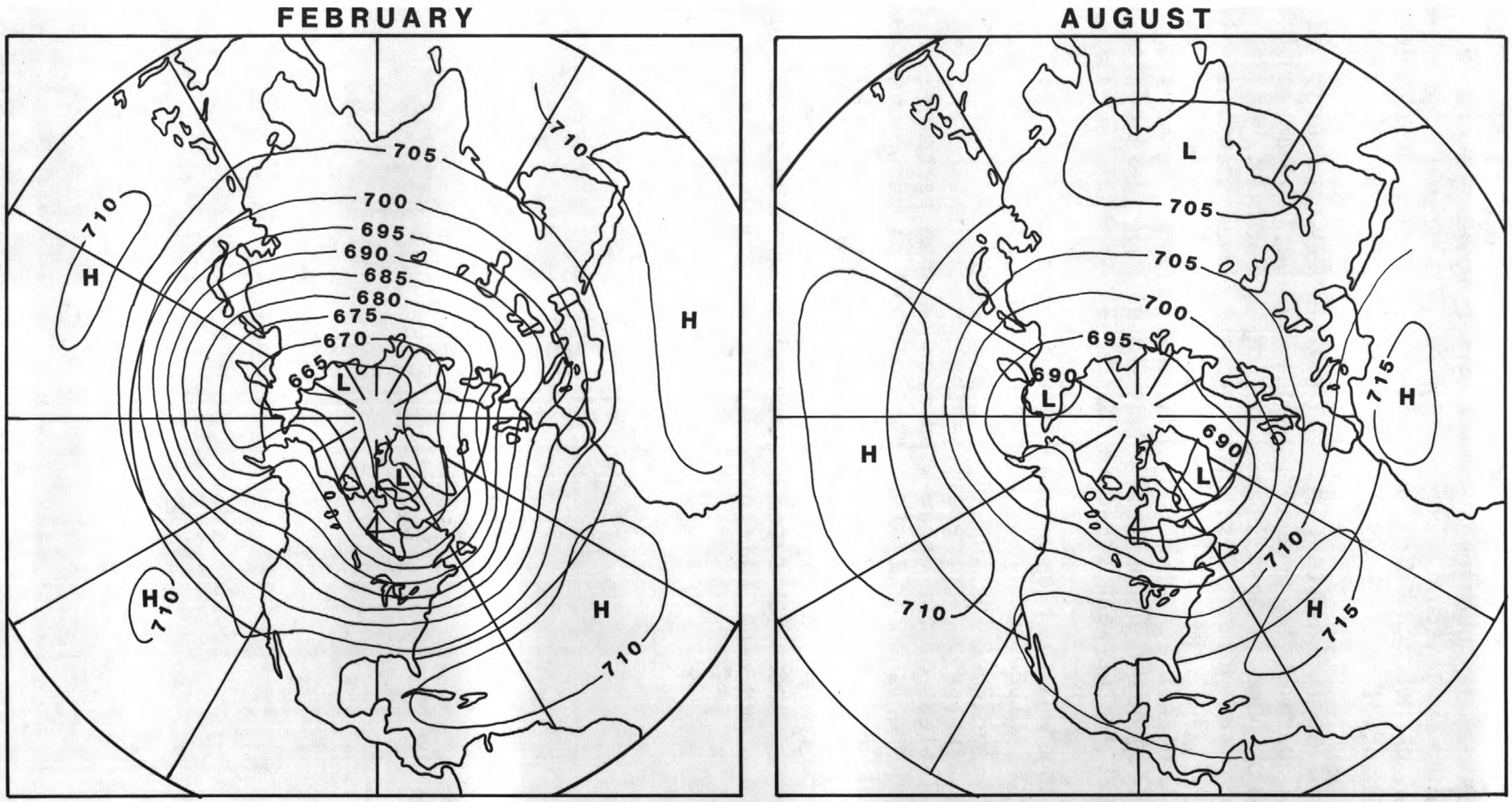


Figure 1.--Effect of upper-level wave patterns on dry and wet weather, with (A) horizontal wind patterns and (B) a vertical cross section showing areas of dynamic lifting and sinking.

The intensity and distribution of these upper-level wave patterns tend to make minor day to day changes as small short waves are created and move through the long-wave pattern. The long-wave pattern can travel eastward, remain stationary, or retrograde. The long-wave pattern for the entire hemisphere can change between a range of three and seven complete wave lengths.

Time of year also is important for upper-level wave patterns, as shown by the comparison of barometric pressure fields during February and August in figure 2. The atmosphere is most active during the winter, having increased pressure gradients and winds. Resulting cyclone development is stronger in the winter than in the summer. The map for August shows weak pressure gradients that tend to discourage strong cyclone development. Thunderstorm activity in the summer is dependent upon small upper-level wave development, which is difficult to detect in the weak pressure field.

All these changes in the flow of upper-level wind affect the surface weather and, therefore, the distribution of precipitation. Flow of moisture from the oceans to different parts of the continents is governed by upper-wind patterns, as well as by land barriers. The result is that precipitation amounts are more sensitive to variations of the upper-wind flow in some parts of the continent than in others. There is no doubt that the patterns of upper-atmospheric wind dictate precipitation distribution. This fact shows the importance of the mechanism that dictates the upper-wind patterns, and of any perturbation that creates the short waves and causes the change in the number of long waves for the hemisphere. Recent studies have shown a definite connection between solar activity and upper-wind patterns.



Modified from U.S. Weather Bureau
"Normal Weather Maps," 1946

Figure 2.--Normal barometric-pressure distribution, in millibars, at the 10,000-foot level for February and August.

It has been known for a long time that solar activity tends to be cyclic, with periods of about 11 and 22 years. This is best shown by the number of sunspots detected on the sun since the early 1600's (fig. 3). These spots vary systematically in location and polarity during each 11- or 22-year cycle. Other solar phenomena, such as flares, prominences, and coronal holes also are known to have fairly systematic, 11-year variations.

Since the beginning of the space age, measurements of solar activity by satellites outside the earth's atmosphere have revealed features from which new theories and concepts have emerged. Combined with data from new and improved instruments and methods at earth-based observatories, these concepts have brought about a new comprehension of the sun's activity.

Along with this new comprehension of the sun's activity has come a better understanding of the responses of the earth's geomagnetic field to solar effects. Geomagnetic indexes have shown correlations with solar activity. Magnetic storms in the earth's magnetosphere are directly related to changes in the polarity of the IMF (interplanetary magnetic field). These changes in the IMF are affected by magnetic features on the sun, such as sunspots, solar flares, prominences, or coronal holes.

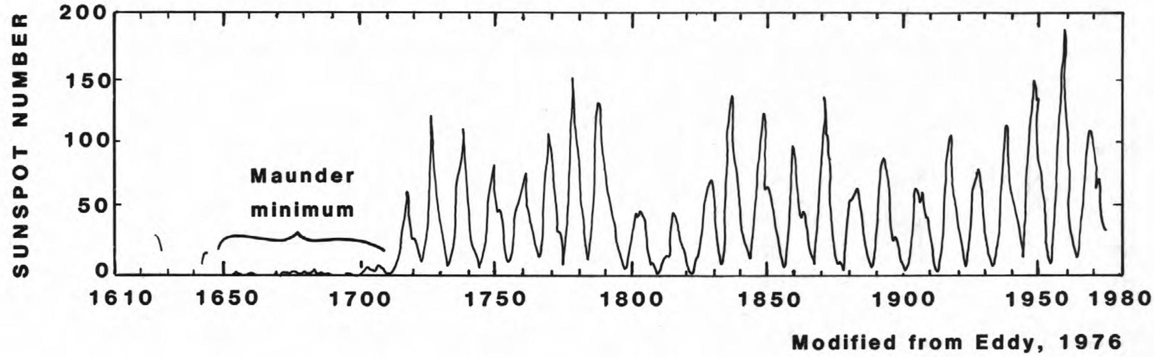


Figure 3.--Annual mean sunspot number, 1611-1974. Data not available for 1614-24, 1628-41, and 1646-49.

Location of the sunspots in relation to the sun's latitude also is important. The sunspots appear closer to the sun's poles in the beginning of each sunspot cycle and become closer to the sun's equator as the cycle progresses. The earth's orbital plane varies from 7°N to 7°S of the sun's equator. Because the sunspots point radially to the earth during the latter part of the cycle, their effect would be at a maximum. Also, the polarity of the sunspot groups changes from one 11-year cycle to the next, which results in an approximate 22-year cycle. It is from this new understanding of magnetic fluctuations that a renewed interest in sun-weather relationships has developed.

Sun-Weather Relationships

Many studies have been conducted that have looked for connections between the variability of the sun and the earth's weather. Most of the studies have analyzed weather data for cycles corresponding to 11- or 22-year sunspot cycles with various degrees of success. Some investigators have used point precipitation data (Shaw, 1965), and others have used the entire latitude bands (Gerety, Wallace, and Zerefos, 1977) in their sun-weather correlative work and have found no connections. Conversely, when regional weather data are used, the results improve. For example, much attention has been given to the postulated 22-year drought cycle that occurs from the Great Plains westward.

A recent study by Mitchell, Stockton, and Meko (1979), using tree-ring data from 1600-1979 in 40 regions west of the Mississippi River, established a statistical association between the number of regions experiencing degrees of drought on the DAI (Drought Area Index) and the 22-year sunspot cycle (fig. 4). The DAI is a reconstruction of the PDSI (Palmer Drought Severity Index) from tree-ring data.

The data from Mitchell, Stockton, and Meko (1979) also are presented in figure 5 showing the relationship between large numbers of drought areas and the 22-year sunspot minimum. It is also noteworthy that the amplitude of the 22-year drought cycle decreased to a very low value (Mitchell, Stockton, and Meko, 1979) during the Maunder minimum of solar activity during 1645-1715 (fig. 3). Mitchell describes the solar control as a "...modulation of terrestrial drought-inducing mechanisms, such that it alternately encourages and discourages the development of major continental droughts which are set up by evolutionary climatic processes unrelated to solar activity." This same process may affect wet periods, but lack of moisture for growth in tree-ring analyses is easier to detect than an overabundance. Connections between drought periods in different parts of the Nation have been investigated by Marshall (1972), who found a relationship between the Great Plains and the Northeast--while one area had drought the other had adequate rainfall, and vice versa.

In the past it was thought that variations in the solar constant between periods of high- and low-sunspot number were the mechanism for modulation of weather patterns. When the 22-year sunspot cycle was found, it was then suspected that the mechanism for triggering weather changes was some form of magnetic activity.

During the last decade, advances have been made toward the possibility of establishing a physical link between variations in the solar magnetic field, the magnetosphere of the earth, and the weather. Woodbridge (1971) found a positive correlation between geomagnetic storms and trough development at the 300-millibar level of the atmosphere during the 1956-57 solar activity maxima. Roberts and Olson (1973) confirmed Woodbridge's study.

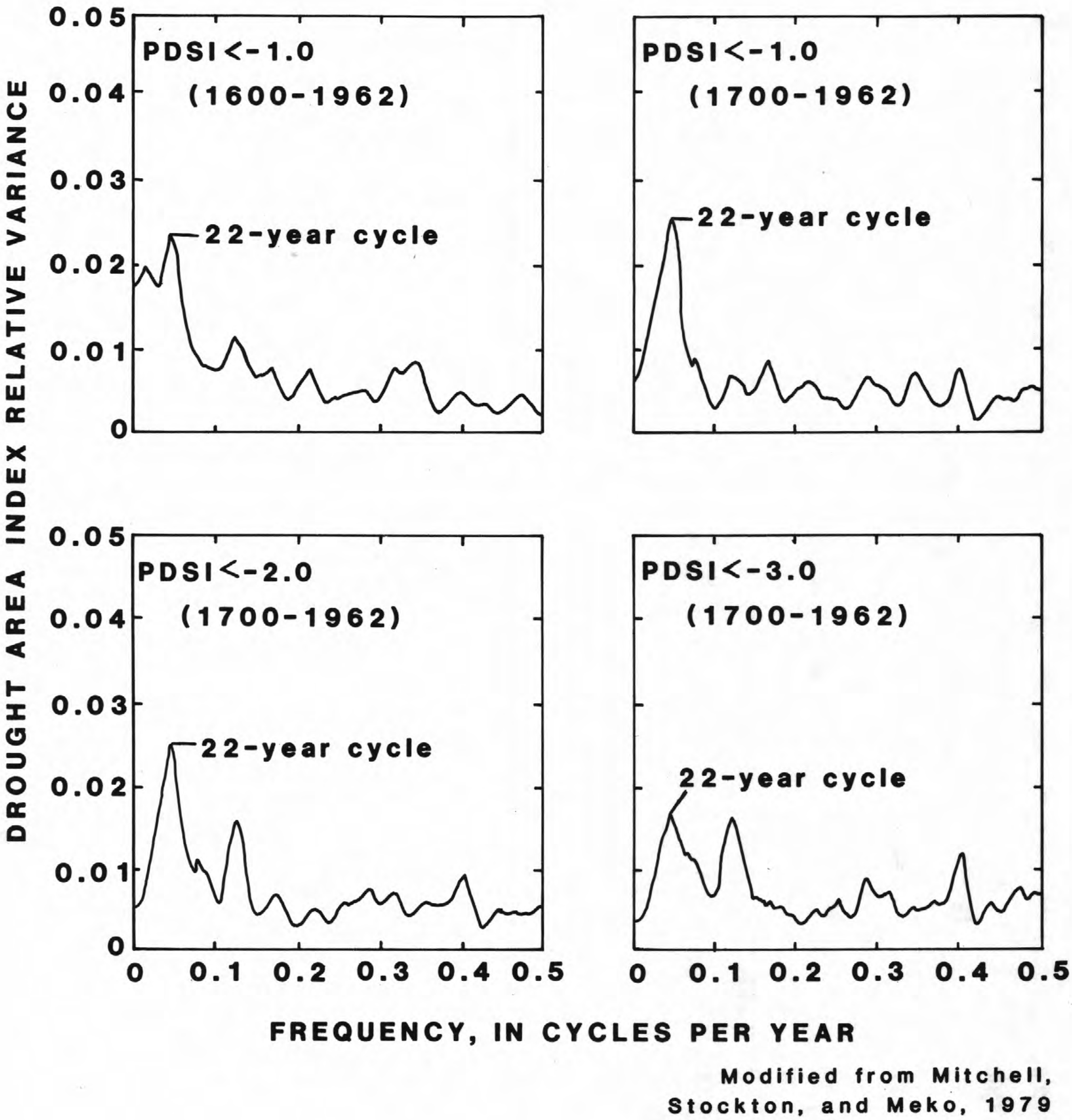
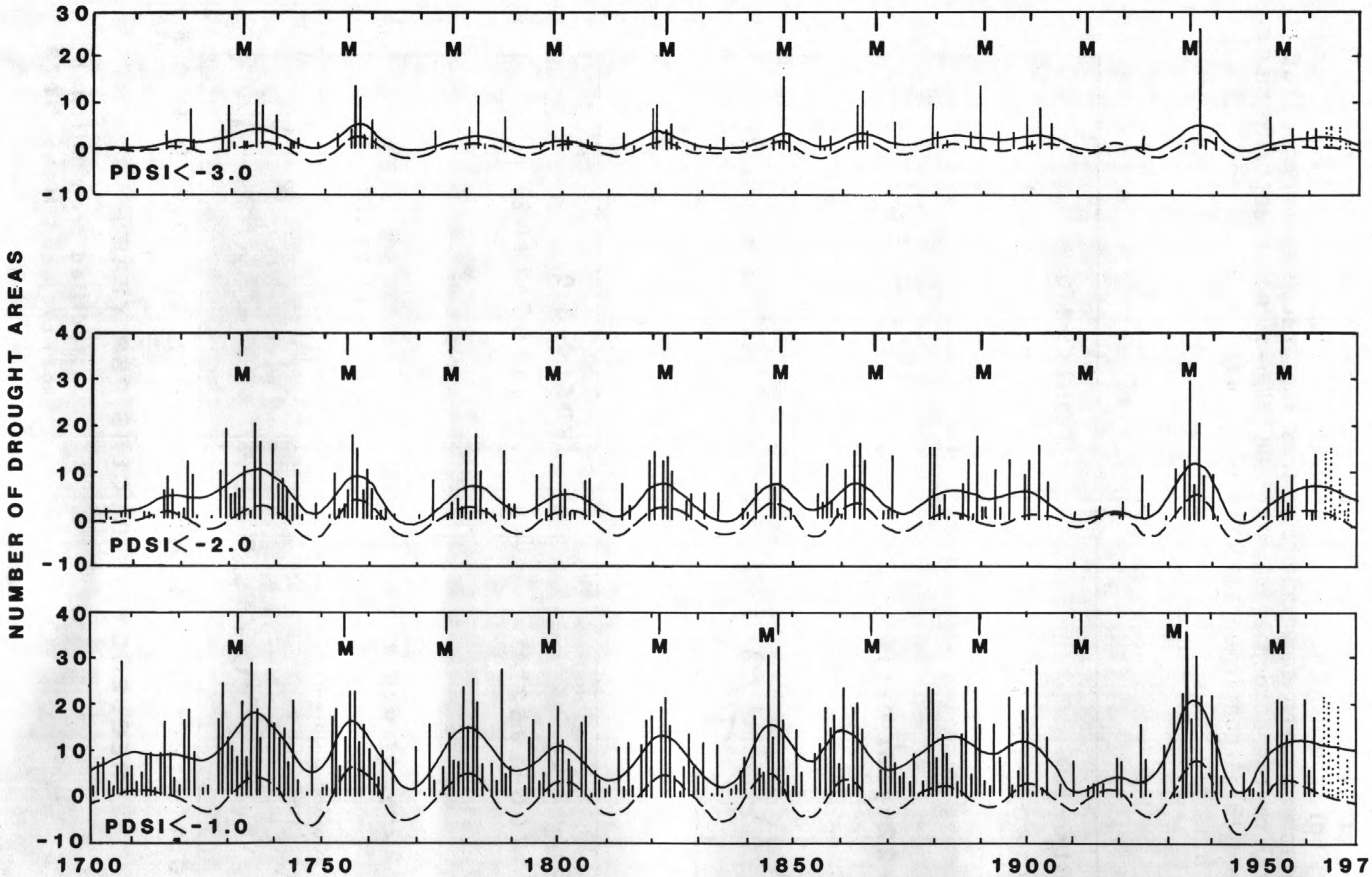


Figure 4.--Range of variance of four selected Drought Area Index series indicating the suspected 22-year cycle. (PDSI = Palmer Drought Severity Index).



Modified from Mitchell,
Stockton, and Meko, 1979

Figure 5.--Chronology of drought areas (number of regions) for selected PDSI (Palmer Drought Severity Index) limits, 1700-1962. Wavy lines denote series using band-pass filters (Bier, 1961); "M" denotes 22-year sunspot-cycle minima.

Wilcox, Scherrer, and Svalgaard (1974) related the hemispheric vorticity-area index to solar magnetic sector-boundary passages, which have been measured from spacecraft since 1964. The vorticity-area index is a measure of the area in the northern hemisphere with a vorticity value of greater than 2.0 x 10^{-4} sec^{-1}, computed for the 300-millibar level. The solar-magnetic-sector structure is extended outward from the sun like pinwheel blades by the solar wind. The polarity of the IMF is predominantly in one direction, but the polarity reverses at the sector boundaries and is in the opposite direction for the next sector. This reversal of polarity is immediately detectable on earth by a rapid increase in geomagnetic activity. Wilcox found that the average vorticity over the northern hemisphere during the winter reached a minimum approximately 1 day after the passing of a sector boundary and then increased during the following 2 or 3 days. The average response of the vorticity-area index to solar-magnetic-sector structure during the winter (November-March), 1964-70, for 54 boundary passages is shown in figure 6. In the first set of data (fig. 6A), the dotted curve represents 24 boundary passages in which the IMF polarity changed from toward (-) the sun to away (+), and the dashed curve represents 30 boundary passages in which the polarity changed from away (+) to toward (-) the sun. In the second set of data (fig. 6B), the dotted curve represents 32 boundary passages from November 1 to January 15, and the dashed curved represents 22 boundary passages from January 16 to March 31. In the third set of data (fig. 6C), the dotted curve represents 26 boundary passages from 1964-66, and the dashed curve 28 boundary passages from 1967-70. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is each interval equal to 5 x 10^5 km^2. The curves indicate that there is trough or low-pressure intensification, or cyclogenisis, 2 or 3 days after passage of the sector boundary.

The Gulf of Alaska is an area of cyclogenisis in the winter months due to temperature differences between the Pacific Ocean and northern North America. Activity generated there directly affects the weather in the western two-thirds of the United States. Enhancement or suppression of storm systems by solar activity would affect precipitation amounts for this area and also for the eastern part of the Nation.

A study by Reiter (1976) found that the atmospheric electric field and air-earth current density changes by more than 10 percent at the time of sector-boundary passage. The vertical electric field decreases significantly in the days before the sector boundary passage and increases sharply at the boundary passage. One interpretation of this result is that thunderstorm activity increases significantly at sector-boundary passage.

Undoubtedly, there is a sun-weather relationship that interacts with the general circulation of the earth's atmosphere. This interaction manifests itself in dry and wet periods for certain regions. The areal extent, duration, and time distribution of these periods need to be studied in order to better interpret the impact on hydrologic investigations, which are so dependent upon precipitation.

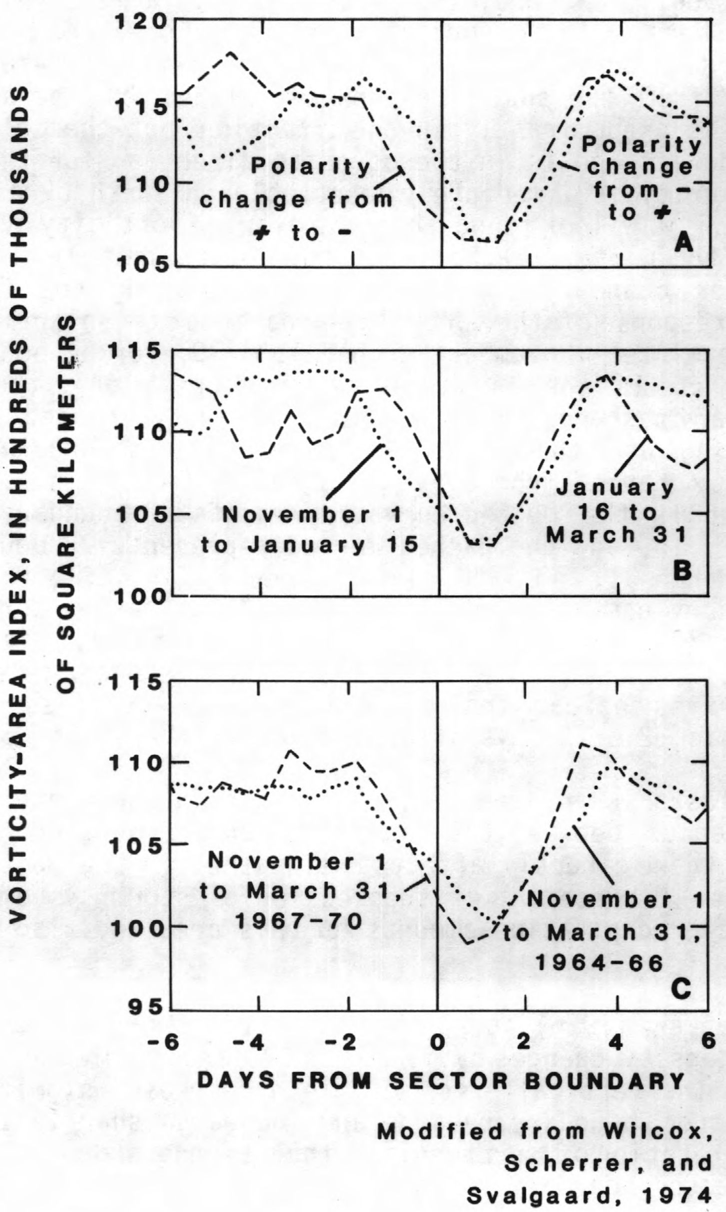


Figure 6.--Average response of vorticity-area index to solar-magnetic-sector structure during the winter, 1964-70, comparing (A) different directions of polarity change, (B) first and last halves of winter, and (C) winters of 1964-66 to winters of 1967-70.

PRELIMINARY ANALYSIS OF REGIONAL PRECIPITATION

A preliminary analysis of regional precipitation was made to determine if there are indications of trends or periodicity. Average annual precipitation for regions of about 300 to 700 square miles in the central one-third of the United States was investigated.

Selection of Regions

Eight regions in nine States were selected on the basis of sensitivity to prevailing storm patterns, current importance for hydrologic studies, and length of record. Regions selected are shown in figure 7. Regions 1, 4, and 5 include areas of existing or future surface mining; region 2 includes an area apparently having changes in rainfall-runoff relationship; and regions 3, 6, 7, and 8 were chosen for comparison of different sources of moisture. Regions 4, 5, and 6 receive moisture from the Pacific Ocean; regions 1, 7, and 8 receive moisture predominantly from the Gulf of Mexico; and regions 2 and 3 receive moisture from a combination of these two sources.

Analysis

Each region contains precipitation stations having individual records of greater than 60 years. Yearly average precipitation for each region was calculated, and 3-year moving averages were computed and plotted. Solar data in the form of annual sunspot number and the annual number of sudden geomagnetic-storm commencements were averaged and plotted in a similar manner (fig. 8). Correlations between regional precipitation and solar data were calculated by a standardized computer program, using the yearly moving-average values.

The 3-year moving-average plots of areal precipitation for each region and of solar data are shown in figure 9. The 22-year major drought cycle is evident, as shown by the shaded areas. The major droughts tend to begin on the downward limb of the even-numbered sunspot cycles and end near the peaks of the odd cycles. The length and severity of the precipitation deficiency during the droughts varies from region to region. For example, the lack of precipitation during the 1930's was the worst for northwest Kansas, South Dakota, Wyoming, and Montana, but the lack of precipitation during the 1950's was the worst for the Texas region. Evidently the persistent upper-level wind field, which dictated the precipition patterns, was somewhat different during the two droughts.

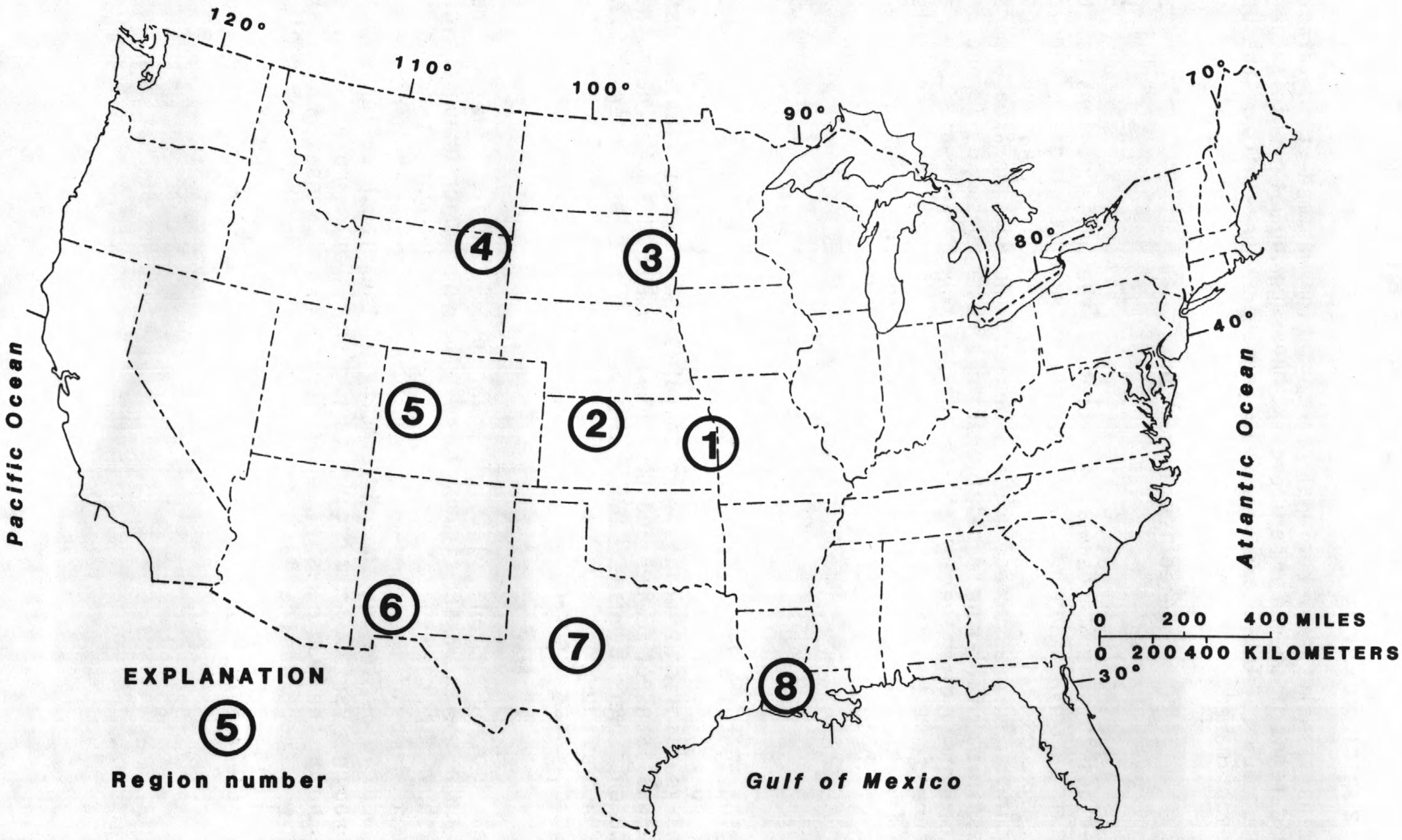


Figure 7.--Regions used in preliminary analysis of precipitation.

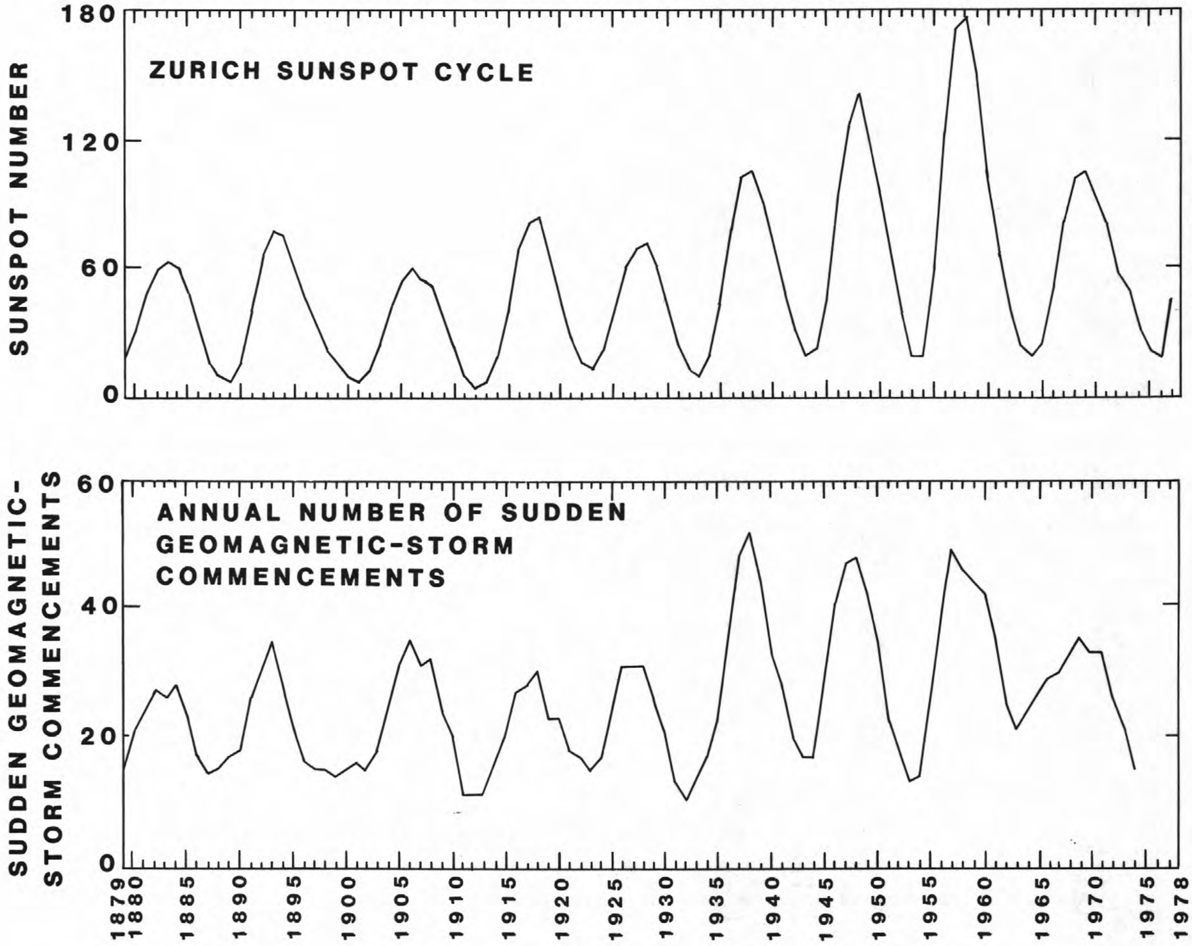


Figure 8.--Relationship of sunspot cycle to annual number of sudden geomagnetic-storm commencements. (Values are 3-year moving averages.)

These two major droughts during the 1930's and 1950's and the very wet 1940's occurred at the same times that the SSC (sudden-storm commencement) cycle had its greatest amplitudes since records began in 1870. The processes that favor dry weather were operating during cycle change 16-17 and 18-19, while the processes that favor abnormally wet conditions were operating during cycle 18. The effects of odd-to-even cycle changes for sunspot and SSC number show up as short-term or slightly dry periods. These occurred during the periods centered on 1901, 1924, 1944, and 1964. Less than average precipitation was received over nearly every region studied. It also was noted that most regions had precipitation amounts greater than average during the periods between the droughts. Two cycles appear to be operating, one an 11-year and the other a 22-year. When they are in phase, major dry or wet periods occur; when the cycles are out of phase, minor dry or wet periods occur. Shorter term periodicities may be present, but they were not evident in this analysis.

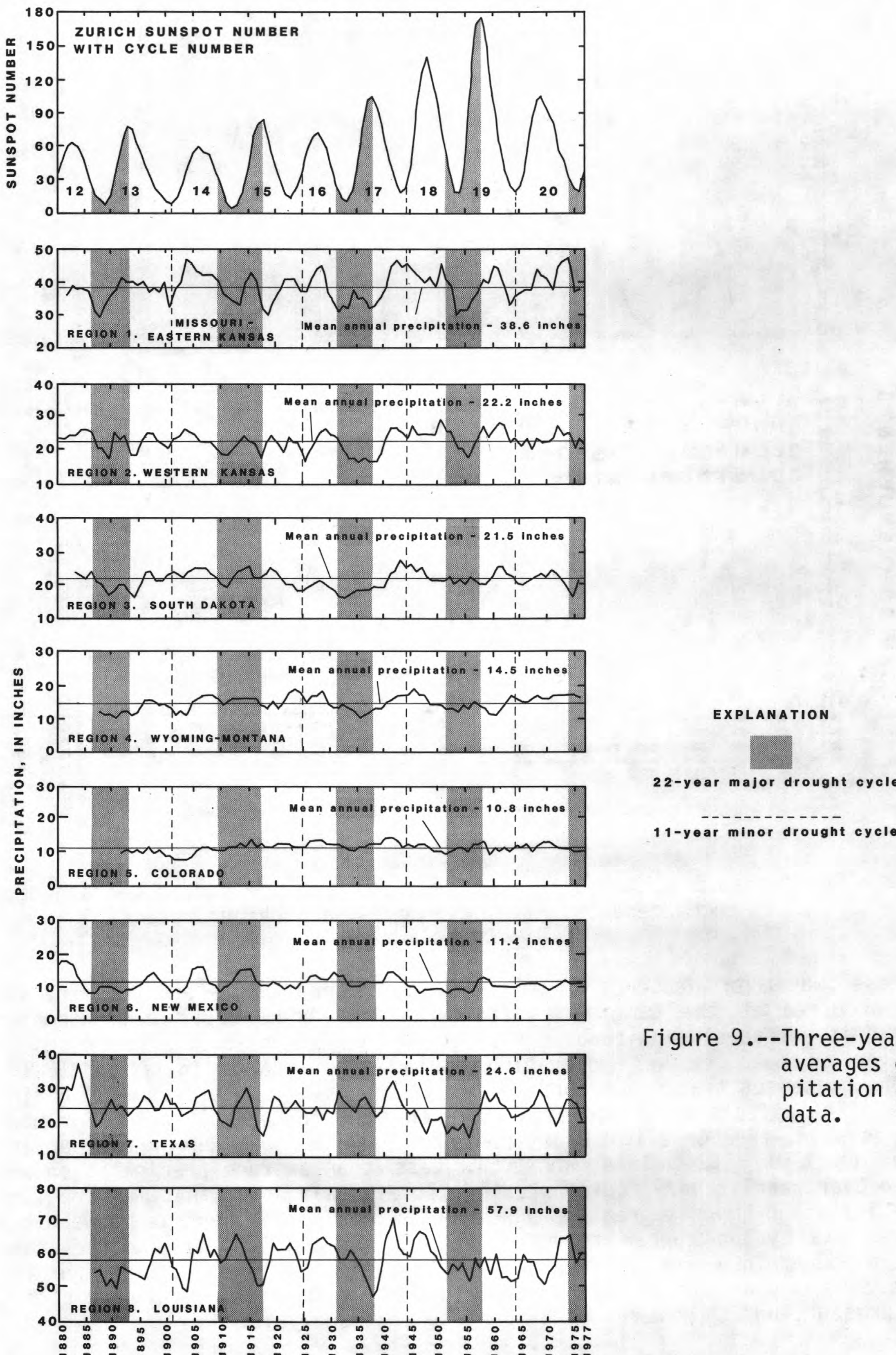


Figure 9.--Three-year moving averages of precipitation and solar data.

Simple correlations between solar data and yearly precipitation data were inconclusive. As stated above, the major droughts begin on the downward limb of the even-numbered sunspot cycles and end near the peak of the odd-numbered cycles; thus, a significant correlation coefficient would not be expected between precipitation and concurrent sunspots. Some factor, which remains unknown, inhibits cyclone development when the sunspot number is high, or encourages development at other times when the sunspot number is low.

Serial correlation coefficients were calculated using the areal precipitation for the Missouri-eastern Kansas region (region 1) as another test for periodicities. The largest correlation coefficient was +0.30, which was for a lag of 20 years.

An example of how discharge is affected by cyclic precipitation fluctuations is shown by the data from the region in northeastern Wyoming and southeastern Montana (region 4). The 90-year average annual precipitation for the region is 14.5 inches. The 44-year average annual discharge for the Powder River near Moorhead, Mont., the major stream in the drainage basin, is 456 cubic feet per second. The following precipitation values were computed from annual areal averages:

Period	Years	Average annual precipitation (in)	Long-term average precipitation (percent)	Average annual discharge (ft^3/s)	Long-term average discharge (percent)
1919-29	11	16.25	+12	---	---
1930-40	11	12.30	-15	392	-14
1941-51	11	16.14	+11	572	+25
1952-62	11	13.12	-10	344	-25
1963-73	11	16.21	+12	514*	+13*

* Average annual discharge estimated from Powder River near Locate, Mont., record.

The increase or decrease in precipitation of approximately 22 to 27 percent from one 11-year period to the next caused a variance in the rate of discharge of about 38 to 50 percent. An extension of the 22-year cycle fluctuation, evident since 1919, indicates that precipitation and discharge will be 13- to 25-percent less than average from 1974 to 1984. A decrease of this magnitude would have a significant impact on the hydrology of this coal-producing area.

NEED FOR COMPREHENSIVE STUDY

Due to recent world energy shortages, the development of domestic energy resources through surface-mining techniques has accelerated greatly. In order to estimate environmental response to accelerated surface mining, hydrologic studies are being conducted as part of more comprehensive investigations.

Hydrologic investigations of surface mining commonly are concerned with describing or predicting changes in the environment from premined to postmined conditions. Because precipitation does have periodic fluctuations other than seasonal, these fluctuations need to be accounted for in the environmental analysis.

An aspect of surface mining that is susceptible to precipitation variability is the reclamation of mined areas. Reclamation includes smoothing the spoil banks, covering with a soil having the quality to support vegetation, and then reseeding with a native species of plants that will hold and protect the material below. The climate in much of the western one-half of the Nation is arid or semiarid. In these areas, reclaimed land needs to be reseeded every year until precipitation in 1 year, or a series of years, is adequate to allow the new plants to take root and survive. If it could be predicted that precipitation probably would be favorable for reseeding in a given set of years, then expenses for reclamation of the land could be reduced by choosing those years for reseeding.

Precipitation variability also has an important relation to the amount of sediment discharged from a watershed, mined or unmined. If increased knowledge of the variability of precipitation were available, improved methods could be devised for solving the problems associated with sediment discharge, reservoir sedimentation, stream-channel morphologies, and many aspects of water quality.

Ground-water investigations nearly always include generalized estimates of recharge. These investigations could be enhanced by including long-term precipitation variability. Long-term planning for irrigation and municipal water supplies would benefit from time-series analysis of precipitation.

The existence of trends or periodic fluctuations need to be examined in a detailed study. Also, in order to predict that the trends or fluctuations will continue in the future, the physical processes involved in the production of precipitation need to be examined, and the triggering devices isolated, if possible.

In order to meet these objectives, both meteorological and solar data need to be acquired and placed into a format compatible with a high-speed computer. Pertinent data have been collected and compiled by other agencies and are available in machine-readable formats. Additional data collection would not be a factor in a detailed investigation.

Solar-activity data in the form of monthly sunspot number, daily geomagnetic indices, sudden geomagnetic-storm commencements, and sector-boundary passages are readily accessible in the format of magnetic tapes. Length of record varies for each type of data, with sector-boundary passages having been collected since 1964, the geomagnetic index Kp since 1932, the geomagnetic index Ap since 1868, sudden geomagnetic-storm commencements since 1868, and standardized sunspot numbers since 1848.

Length of precipitation records varies from region to region, but tends to follow the pattern of settlement of the Nation. There was an ample number of reporting stations in the eastern part of the study area by 1868 when collection of geomagnetic data began. By the mid-1880's most of the remaining States or territories had a network of precipitation stations. In 1948, hourly precipitation data became available. Measurements of supporting meteorological data followed the establishment of precipitation stations. It was not until the 1920's that movements of the upper air were understood and not until the 1930's that upper-wind charts became available.

Annual, seasonal, monthly, and daily series of precipitation could be investigated in order to determine the response time and the degree of response of areal precipitation volume to solar activity. Precipitation intensity also could be studied for a region, and its link to solar activity investigated. Findings may shed new light on apparent changes in rainfall-runoff relationships for areas. Likewise, snowfall variability may be linked to solar activity.

The methods of analysis would need to be chosen for their ability to isolate the fluctuations in precipitation that are related to periodic solar phenomena. The first step would be to examine the interrelations between sunspot activity, location of sunspots on the sun's disk, sector-boundary passages, and disturbances in the earth's magnetic field. Droughts tend to occur at the end of the even-numbered sunspot cycles, when the last cycle's sunspot groups are near the sun's equator and the next cycle's groups are just beginning to appear at the higher latitudes. This point in the cycle would be compared with the other minimum for differences in sector-boundary passage numbers and polarity. Then, the geomagnetic indices Kp and Ap and the sudden geomagnetic-storm-commencement features would be examined for differences between the even and odd sunspot cycles.

Next, these fluctuations in solar and magnetic parameters would be superimposed upon the seasonal fluctuations in regional precipitation and fluctuations in the monthly average atmospheric vorticity for that region. In essence, a precipitation model could be developed empirically. Regions could be compared by using departures or percentages of departure from the long-term precipitation average.

The relationships between solar and terrestrial data would be analysed by standard statistical methods. Relationships could be tested by simple and multivariate correlative analysis. Periodicities in daily, monthly, seasonal, and yearly precipitation amounts could be tested by Spectral or Fourier analysis.

If periodicity does exist in regional precipitation, then precipitation models could be developed and calibrated for each region studied. From these models an estimate of the pattern of precipitation for the next 22-year solar cycle could be made. Also, patterns or trends that precede major droughts or periods of abundant precipitation could be analysed, and their use as predictors investigated.

CONCLUSIONS

There are at least two cycles evident in annual precipitation. These are an approximate 22-year cycle, which manifests itself in the major droughts, and an approximate 11-year cycle, which is evident by dry periods midway between the major droughts. These two cycles are in phase with the solar 11-year and 22-year cycles. Discharge in an area studied in Wyoming and Montana followed a cycle of 22 years.

The results obtained from the preliminary analysis indicate that there is a relationship between solar activity and precipitation, but this relationship is more complex than just a direct response of precipitation to a particular solar activity. This is the reason that most investigations of periodicity of precipitation in the past have been inconclusive.

A detailed study is needed that investigates all of the factors that are involved in the occurrence of precipitation over an area. Changes in upper-wind patterns need to be compared to the magnetic nature of the sun. Seasonal changes in precipitation for an area need to be compared with seasonal changes in magnetic activity. Each factor needs to be isolated, and its effects on the others studied. Only then will the relationships between solar activity and precipitation be known, and the periodicities confirmed.

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