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A Spectral Solar/Climatic Model

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The problem of solar/climatic relationships has been the subject of speculation and research by a few scientists for many years. Understanding the behavior of natural fluctuations in the climate is especially important currently, because of the possibility of man-induced climate changes ("Study of Critical Environmental Problems," 1970; "Study of Man's Impact on Climate," 1971). This paper consists of a summary of pertinent research on solar activity variations and climate variations, together with the presentation of an empirical solar/climatic model that attempts to clarify the nature of the relationships.

The study of solar/climatic relationships has been difficult to develop because of an inadequate understanding of the detailed mechanisms responsible for the interaction. The possible variation of stratospheric ozone with solar activity has been discussed by Willett (1965) and Angell and Korshover (1973). The empirical evidence for statistically significant effects of solar flares on Earth's weather has recently been summarized by Roberts and Olson (1973). A brief summary of solar/climatic effects has been given by Bray (1971), and more complete discussions have been given by Rubashev (1964) and Lamb (1972). Recent developments in the field of solar/climatic relationships have been discussed by Willett (1965), Suess (1968), Damon (1973), Mitchell (1973), and Stuiver (1973).

SOLAR ACTIVITY BEHAVIOR

Summaries of the state of the art in solar activity analysis and forecasting have been given by Vitinskii (1962, 1969). Recent attempts to improve our understanding of solar activity variations have been based upon planetary tidal forces on the Sun (Bigg, 1967; Wood and Wood, 1965) or the effect of planetary dynamics on the motion of the Sun (Jose, 1965; Sleeper, 1972). Figure 1 presents the sunspot number time series from 1700 to 1970. The mean 11.1-yr sunspot cycle is well known, and the 22-yr Hale magnetic cycle is specified by the positive and negative designation. The magnetic polarity of the sunspots has been observed since 1908. The cycle polarities assigned prior to that date are inferred from the planetary dynamic effects studied by Jose (1965). The sunspot time series has certain important characteristics that will be summarized.

Secular Cycles

The sunspot cycle magnitude appears to increase slowly and fall rapidly with an 80- to 100-yr period. Jose has identified a basic 180-yr period associated with the resonance structure of the planets, and 80- and 100-yr subperiods related to planetary dynamics and the resulting orbit of the Sun about the center of gravity of the solar system. The center of gravity moves from the Sun's center as much as two solar radii (Jose, 1965). Secular solar cycles started about 1700, 1800, 1880; and a new one is expected by 1980.

Intrasecular Cycles

The secular cycles can be further analyzed into shorter epochs of 30 to 40 yr duration, depending on mean cycle magnitude or other characteristic criteria. The most recent intrasecular epoch of potential importance is the interval from about

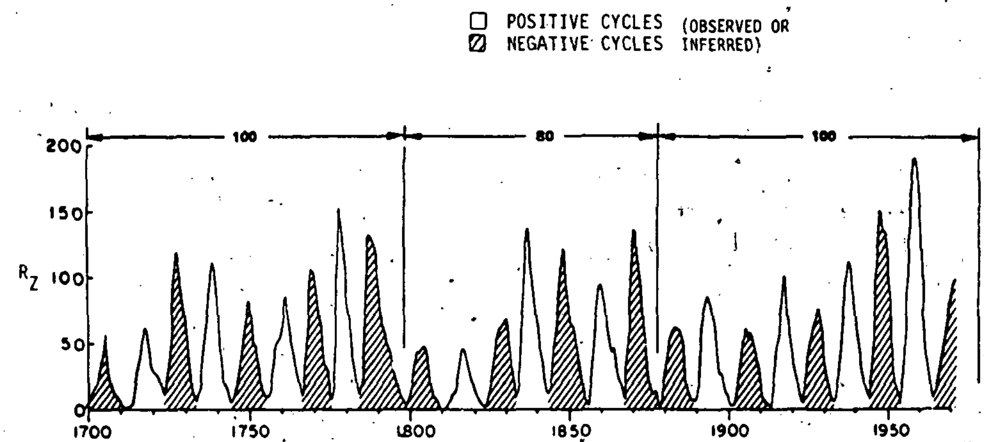

FIGURE 1.—Observed sunspot variations from 1700 to 1970. (R_Z = mean sunspot number.)

1920 to 1961. According to Svalgaard (1973), the geomagnetic data available from 1926 to 1973 indicate a possible cyclic fluctuation of solar wind sector structure with a period of about 40 yr. The solar wind structure is related to the Sun's corpuscular emissions, with a corresponding influence on Earth's magnetic field fluctuations (Wilcox, 1968).

Decadal Cycles

The decadal cycles consist of 11-yr cycles of opposite magnetic polarity, positive and negative. The mechanism for the magnetic field reversal of successive cycles has been described by Babcock (1961) in terms of an empirical dynamo model, with the interaction of toroidal and poloidal magnetic fields generated by the Sun's surface differential rotation. Jose's analysis suggests that the simple 22-yr cycle breaks down every 80 to 100 yr. According to his model, the next 11-yr cycle will be of negative polarity, the same as cycle 20. The Sun's dipole magnetic field may change sign about 3 yr after the maximum sunspot activity (Wilcox and Scherrer, 1972), although there is considerable evidence for reversal near sunspot maximum.

Subcycles

There is some substantial evidence indicating that the nominal mean 11-yr solar cycle is a superposition of two or three subcycles closely related to the corpuscular emission from the Sun. These subcycles of 4 to 7 yr duration are further discussed by Sleeper (1972). Differences in subcycle structure may account for differences in the shape of positive and negative magnetic cycles. A new dynamo theory, derived from first principles, leads to a subcycle structure with periods of less than 11 yr in duration (Nakagawa, 1971).

CLIMATE VARIABLE BEHAVIOR

Climate variables of temperature, precipitation, pressure, wind direction, trough or ridge position have been used to study climate fluctuations over periods of several hundred years. Instrumental measurements have been available for only about 200 yr. Other sources of climate variation such as tree-ring growth, carbon-14 variation, and glacier ice-core oxygen isotope ratios have been used to extend the range of measurement to thousands of years. Evidence for climatic cycles will be briefly summarized.

Secular Cycles

Evidence of secular cycles has been found in climate-related variables. Johnsen et al. (1970) studied variations in the O^{16}/O^{18} ratio as a function of depth in a Greenland ice core. From their age calibration, they determined characteristic periods of 78 and 181 yr. They also found periods of 400 and 2400 yr. A period of 180 yr has been discussed by Lamb (1972) and Damon (1973).

Intrasecular Cycles

There have been numerous discussions in the literature of climate cycles or epochs with periods of about 40 yr. Dzerdeevski (1966) discussed a fluctuation that began about 1922. Troup (1962) pointed out that there was a reasonable correlation between equatorial temperatures and the 11-yr sunspot cycle until about 1922, and then the correlation failed or reversed. Namias (1969) pointed out that there appeared to be a substantial change in general circulation in 1961 associated with significant changes in the North Pacific Ocean temperature. Davis (1972) has shown that the last date of spring in England changed significantly about 1920, and changed back near 1960. Sleeper (1973) discussed these and other atmospheric and solar changes in 1961 that may indicate the termination of an intrasecular epoch in both the Sun's and Earth's atmospheres.

Decadal Cycles

Searches have been made for a simple 11-yr period in climatic variables. The data in which such variation was evident were equatorial surface temperatures and African lake levels (Mitchell, 1961). However, this simple correlation breaks down about 1920 (Mitchell, 1961) and has caused considerable confusion. This breakdown appears to be closely related to the intrasecular epoch initiated in the general circulation about 1920 and terminated in 1961. This particular epoch appears to have been a short duration climatic optimum with a sudden onset and a sudden termination. It is possible that the general circulation has returned to the state where the climate is again sensitive to the 11-yr solar cycle at the equator. This may account for the rainy African equatorial conditions in the 1960's and the relatively dry conditions in the early 1970's.

Evidence for a nominal 22-yr cycle has been found in climate variables in the midlatitudes. Bollinger (1945) found evidence for a 22-yr period in the rainfall in Kansas and Oklahoma. This is related to the 20-yr drought cycle in the great plains. Willett (1965) found a 22-yr cycle in continentality and related it to ozone variations in the atmosphere. Sleptsov-Shevlevich (1972) found a 22-yr period in high-latitude, sea level pressure variations. Spar and Mayer (1973) found a 20.8-yr period in the New York City January temperatures since 1870. They did not recognize that this period corresponds with the mean 20.8-yr solar magnetic cycle forcing function since 1870. A. I. Ol' (1969) has presented other evidence for a 22-yr period in midlatitude climate variables.

Subcycles

In the study of the 22-yr cycles, Bollinger (1945) and Sleptsov-Shevlevich (1972) found evidence for subcycles of a few years' duration, with substantial fluctuation in precipitation and atmospheric pressure. Thus a 1- or 2-yr very rainy epoch could appear in the middle of a drought period of several years duration, or vice versa.

A SPECTRAL SOLAR/CLIMATIC MODEL

Meteorologists have studied climatic changes on the basis of observations of a series of irregular, quasi-random fluctuations superimposed on a general trend for a given climate variable. These irregular but important changes were of unknown origin. A number of models for climate change have been suggested based on the effect of volcanic dust, manmade CO_2, ocean temperature, and solar activity. While there are undoubtedly effects due to volcanic dust, manmade dust, CO_2, and ocean temperature, the fundamental effects will be assumed to be due to changes in solar activity.

Typical decadal and secular fluctuations are presented in figure 2 for several climatic variables over the last 100 yr. The fluctuation of the mean world temperature (after Mitchell, 1971) indicates a secular cycle of about 100 yr, from 1870 to 1965. The data show a rapid drop in temperature in the 1870's, a relatively low value until 1920, and then a sudden rise until 1940, with a subsequent fall. The sudden rise about 1920 appears to signal a very warm intrasecular epoch, and may be related to a corresponding intrasecular epoch on the Sun. Willett (1965) showed that the cumulative summer temperature change for representative cities in the southwestern United

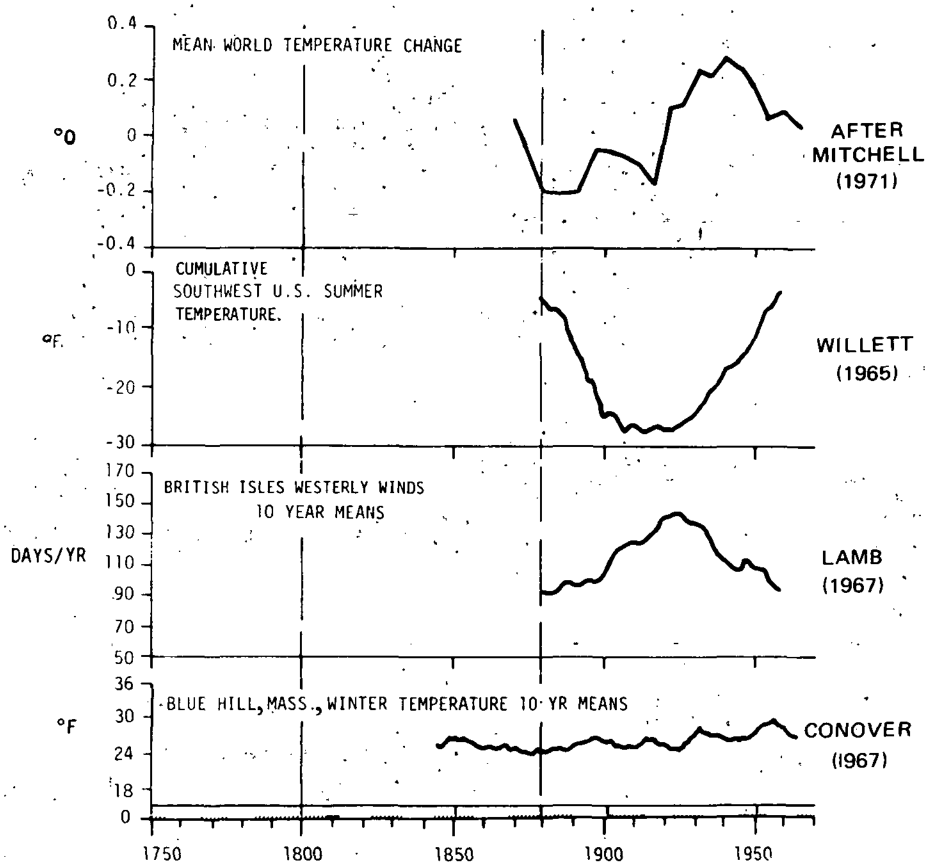

FIGURE 2.—Observed climate variations.

States decreased rapidly from 1880 to about 1900, stayed nearly constant until 1920, and increased steadily until 1960. Lamb (1967) demonstrated a secular change in frequency of westerly winds over the British Isles, with a noticeable change from increasing to decreasing frequencies about 1920. Conover's (1967) 10-yr mean winter temperatures for Blue Hill indicate a small decrease from 1850 to 1880 and a noticeable increase from 1880 to 1960, together with a substantial indication of a 20-yr periodicity. This nominal 20-yr periodicity in northeastern U.S. winter temperatures since 1880 has also been studied by Spar and Mayer (1973). The abrupt decadal fluctuations are not apparent in most of these parameters because 10-yr means have been used to display the data.

The sudden decadal changes are more clearly demonstrated in figure 3. Namias (1969, 1970) showed an abrupt change in San Diego sea level in 1957 and a change in the mean Atlanta winter temperature in 1947, 1957, and 1970.

New York City mean temperatures for January and February also indicated an abrupt increase after 1947 and a decrease about 1957. The changes subsequent to his date are not as abrupt as for Atlanta. This may be due in part to the local moderating effects of the ocean near New York City. The crosshatched regions are epochs when the solar wind was changing its structure from that characteristic of one sign of a solar dipole field to the opposite sign (Wilcox and Scherrer, 1972); the annual modulation of the solar wind structure was uncertain, or changing phase. With the exception of the anomaly in 1961, this change in solar wind structure seems to be a characteristic of the 22-yr solar magnetic cycle. These epochs of uncertain solar wind phase may

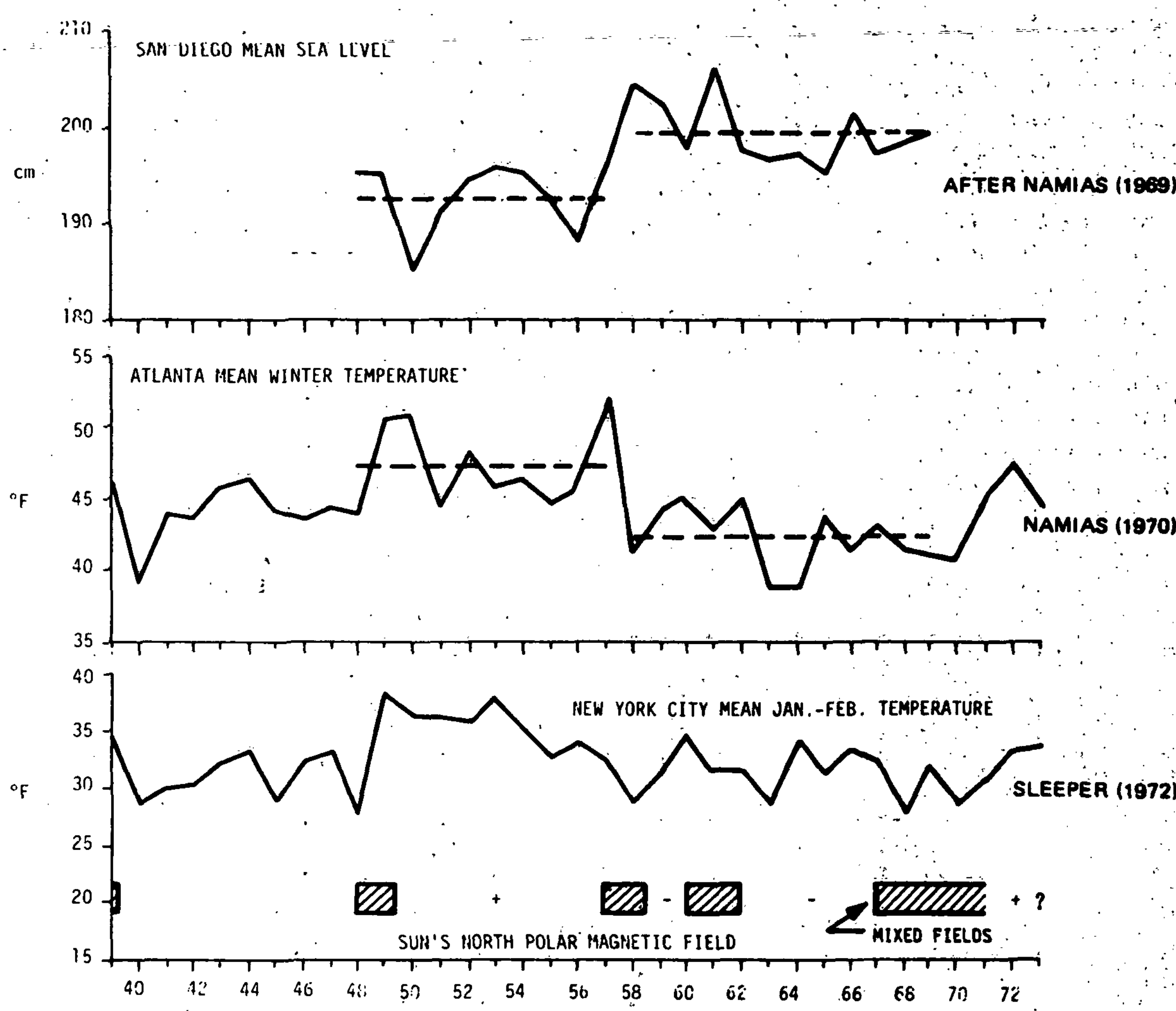

FIGURE 3.—Decadal changes in geophysical variables.

be related to local climate shifts and may serve as indicators or precursors of such climatic shifts. Recently these climate mode switches have occurred near the 11-yr solar cycle maximum.

Qualitative evidence for an intrasecular warm epoch from about 1922 to 1961 is summarized in figure 4. Flohn (1969) has demonstrated that the Lake Victoria level had an 11-yr fluctuation from 1900 to 1922, and then changed variance structure until 1961. Davis (1972) demonstrated a sudden change in the mean final date for spring near 1920 and a return to the early conditions by 1965. The abrupt change in world mean temperature about 1920 has already been mentioned (Mitchell, 1971), and Budyko (1969) showed a change in direct solar radiation near 1920 and a change back to lower levels by 1960.

Theoretical approaches to the study of climate stability have been made on the basis of simplified models. Budyko (1972), Faegre (1972), and Sellers (1973) have studied different but related models that suggest that the climate can exist in one of several quasi-stable states from an ice-free world to an ice-covered world. Changes from one quasi-stable state to another can occur relatively abruptly. On the basis of those studies, and the empirical data on solar activity and climate cycles, a working hypothesis for a new solar/climatic model has been developed. This model views the small changes as abrupt shifts from one stable

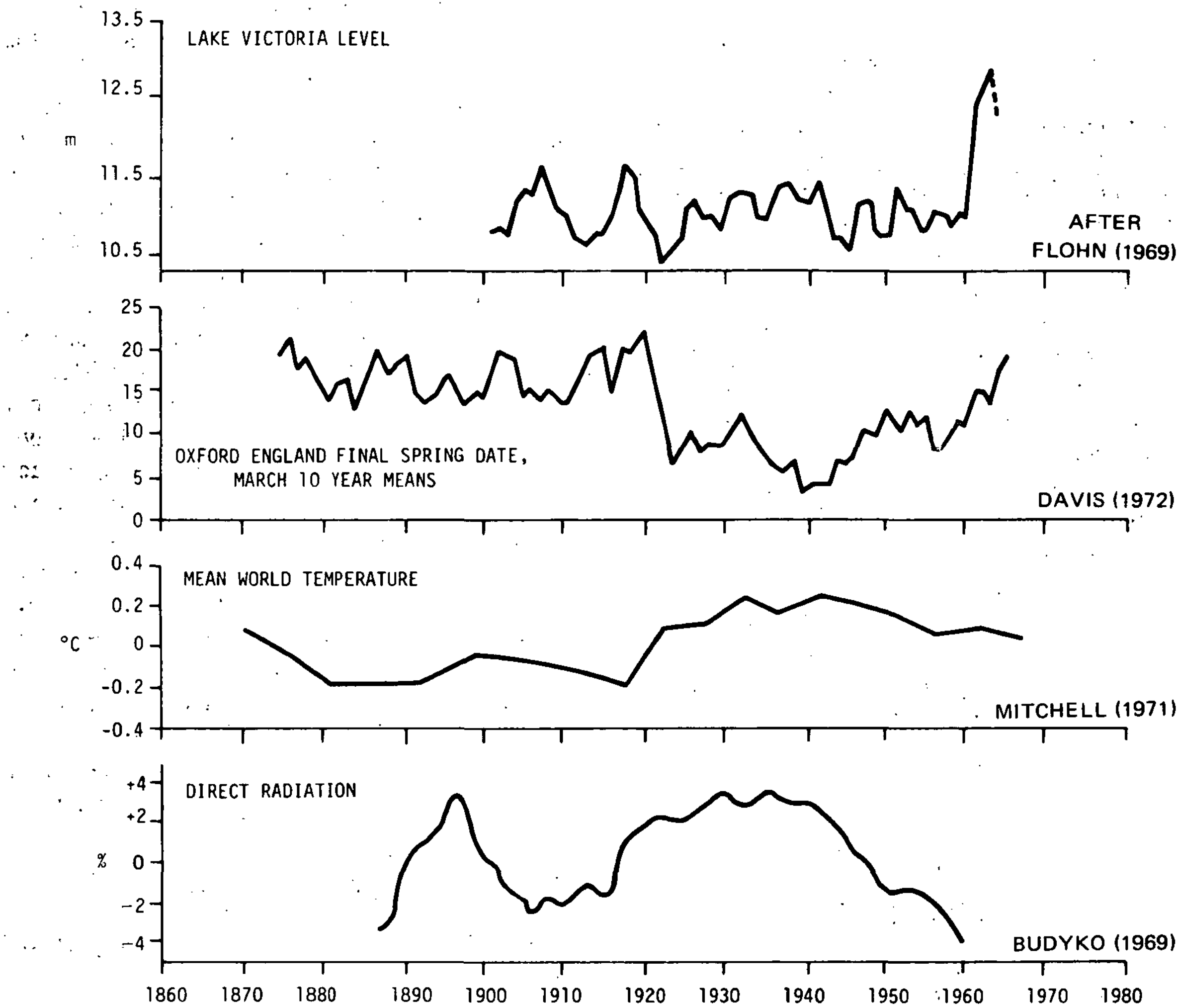

FIGURE 4.—Intrasecular epochs in geophysical variables.

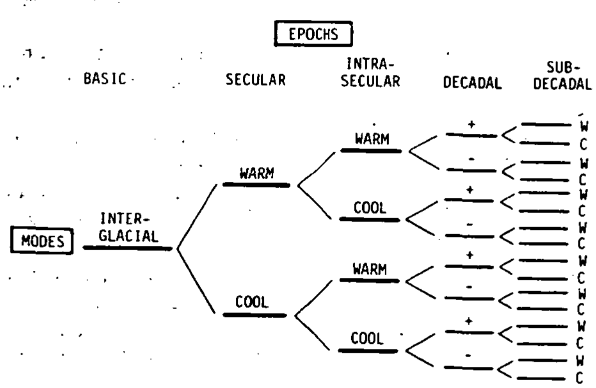

FIGURE 5.—Spectral solar climatic model.

climatic mode to another and assumes that they correspond to a change in solar activity. Some of the changes are small, but they are abrupt changes within a general trend. The basic assumptions are as follows:

(1) Both the Sun and Earth's atmosphere operate in a succession of pairs of stable states or modes. A consecutive related pair of these states, of any duration, constitutes a solar or climatic cycle.

(2) The change from one mode to another in the climate can frequently be related to a similar change on the Sun. The interval from one mode

change to another is called a solar or climatic epoch.

The general scheme for the model is shown in figure 5. In this scheme, the basic condition is either a glacial or interglacial state or mode. Only the present interglacial mode is shown. The figure shows the relationship of the different modes of various time durations within the interglacial state; i.e., 80- to 100-yr (secular), 40-yr (intrasecular), 11-yr (decadal), and shorter epochs (subdecadal). In general, two closely related modes are designated warm and cool. The decadal or 11-yr modes are designated as positive or negative and may be related to the magnetic cycles on the Sun. These decadal modes appear to be related to shifts in longwave structures in the midlatitudes, with corresponding changes in mean temperature at a given location, such as the East Coast of the United States.

The general features of this working model appear to allow correlation of changes on the Sun and in Earth's atmosphere. A more thorough analysis of this model will have to be made before it is generally accepted as a useful tool. The diagram is only schematic. In practice, some of the numerous subdecadal modes may overlap in average temperature.

DISCUSSION

Some of the concepts that have been described may be applied to the current state of the climate in the United States and the world. The model specifies various discrete modes, with corresponding states for both the Sun's and Earth's atmosphere. Mode switches on Earth appear to depend on mode switches on the Sun.

The results of these studies, and the new solar/climatic model, lead to the following conclusions:

(1) The epoch from 1800 to 1880 was a cool secular mode, and the epoch from 1880 to ~1980 is a warm secular mode. A new cool secular epoch is likely to be initiated by 1980 and will extend to about 2060.

(2) The epoch from about 1920 to 1961 was a warm intrasecular mode (~ 40 yr).

(3) In the absence of more definite information, we will assume that in 1961 the atmosphere reverted to the same secular mode as prior to 1920. However, it should be remembered that this "warm" secular mode included such anomalies as the cold U.S. winter of 1917–1918 and the extreme winter of 1899.

(4) In the Eastern United States, the decadal mode switched from warm to cool in 1957 and from cool to warm in 1970. These switches are associated with changes in the North Pacific Ocean temperature, southern California sea level, and Atlanta winter temperatures.

(5) The current climate anomalies of less than 11 yr in length are such that we may be observing 100- or 180-yr extremes in such variables as northward shift of storm track and very low atmospheric pressure levels, with attendant heavy precipitation, violent thunderstorms, tornado activity, and potential extreme hurricane generation.

(6) The anomalous character of the present solar cycle (20) is such that a breakdown is expected in the simple "20-yr" period in midlatitude climatic variables that has been observed for the last 100 yr. Corresponding anomalies may develop in the Sun's dipole magnetic field structure, the solar wind annual phase structure, and the nominal "20-yr" drought and east coast cold winter behavior. The solar cycle sunspot minimum is not expected until about 1977.

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DISCUSSION

STURROCK: I was very interested to note in your first slide that you state whether the solar cycle is major or minor. How is that determined in the 16th and 17th centuries? I wonder how you infer the sign of the field then.

SLEEPER: Yes, that is a key question. How do we infer magnetic polarity for cycles occurring, say, 100 to 200 yr ago when no magnetic measurements were available? The answer is, of course, we cannot determine them absolutely. The determination was inferred by some studies from Paul Jose in which he showed a change in the center of gravity of the solar system moving outside the surface of the sun by two solar radii and having a characteristic period of 80 and 180 yr and associating these changes with changes in the 22-yr period of the Sun.