Solar-Climatic Relationships in the Light of Standardized Climatic Data

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ABSTRACT

The standardization of climatic data furnishes quite another picture of climatic fluctuations from that obtained with non-standardized data. Standardization of the data shifts the emphasis in the significance of the patterns of change sharply from the winter to the summer season, and from the higher to the lower latitudes.

Analysis of the 80–90 year solar-climatic cycle with the use of standardized hemispheric data indicates that this cycle is most significant in lower middle to subtropical latitudes (the data did not extend into the tropics) during the summer and autumn seasons, and apparently reflects primarily a fluctuation of the effective solar constant.

A similar analysis of the double sunspot solar-climatic cycle indicates that this cycle is quite pronounced in middle and higher latitudes, particularly during the winter season. It is suggested that this cycle probably reflects a change of the transmissive properties of the atmosphere, i.e., the greenhouse effect, in such a manner as to sharpen or suppress the relative heat and cold sources of the continental-maritime monsoonal cells of the general circulation. Atmospheric ozone is a possible physical factor in this pattern of climatic change.

Climatic data from west-central North America not only reflect to a considerable extent both of these solar-climatic cycles, but also the tendency for the predominant significance of the fluctuations to appear during the summer season and in the lower latitudes. Similarities in the fluctuation of total atmospheric ozone and the primary empirical orthogonal function (continentality function) of winter temperature in the continental United States relative to the double sunspot solar-climatic cycle are noted.

1. Standardization of the climatic data

A. Importance of Standardization

All of the pressure and temperature data used in the investigations referred to in the following discussion were subjected initially to standardization in the form of departures/standard deviation ratios. Extensive analysis of climatic data during the past twenty years has convinced the author of the necessity of taking this rather laborious step if seriously misleading statistical results and inferences are to be avoided.

Uniform standardization of climatic data places all departures in true perspective of relative significance. In most cases it changes completely the numerically outstanding features of both the geographical and the seasonal distribution of departures of the weather elements.

Almost without exception in general climatic data the sense of this change is to increase relatively the amplitude, i.e., the significance, of long-term departures and fluctuations in lower compared with higher latitudes, in the summer compared with the winter season, and in general in areas of continental rather than in areas of maritime climate. This low latitude, summer season and continental emphasis in climatic departures is strongly suggestive of a direct solar influence as being a primary cause of the climatic fluctuation.

On the other hand, in some cases solar grouping of climatic data does produce departure patterns that are relatively more significant in the higher latitudes and during the winter season. This may be indicative of some terrestrial or indirect solar disturbance of the mechanics of the general circulation.

The terms “significant” or “highly significant” are used generally in this paper with reference to the probability of occurrence of a given statistical result by “chance,” i.e., without the operation of some real physical “influence” or “control.” In a rough qualitative manner the first term is intended to apply to relationships in the 5% to 1% range of probability of “chance” occurrence, the second to those in the range beyond 1%. However, these terms may be used without a strict quantitative evaluation in some instances.

B. Standardization Procedure

The distribution of monthly and seasonal departures of the two weather elements whose climatic fluctuations
are under discussion in this paper, temperature and pressure, is essentially normal in character. Accordingly the usual procedure of standardization is applied to our extended data series of these two elements. In this procedure each time series of the departures of each element at each data point (grid-point or station) for each calendar month or season is expressed in the form of departure/standard deviation ratios. This standardization makes all departures statistically comparable in magnitude, and permits a probability evaluation of their statistical significance.

Precipitation departures, except perhaps for very long periods, cannot be standardized in this manner, because of the gross deviation of the distribution of departures from the normal pattern. Accordingly the best that readily can be done towards the standardization of precipitation departures is expression in terms of percentages of normal. This procedure makes all departures numerically comparable as to magnitude, but not as to statistical probability of occurrence.

C. Data Series

The following discussion of solar climatic relationships is based on one primary continuous series of northern hemispheric sea-level pressures and upper-level contour heights. The preparation of this northern hemispheric grid-point data series only recently has been completed (Willett and Frohsaka, 1963). It consists of two sets of basic charts, namely:

1. Northern hemispheric monthly and seasonal mean charts of standardized departures from normal of sea-level pressure at a $10^\circ$ grid of 226 points on the northern hemisphere (10N–90N) from 1899–1939, and of 190 points (20N–90N) from 1940–1962. The standardization of the monthly and seasonal departures at each grid-point is carried out entirely from this 63-year series, or from somewhat fewer years for grid-points for which data were missing during World War II. At 10N the standardization is based only on the 1899–1939 period.

2. Northern hemispheric monthly and seasonal mean charts of standardized departures from normal of 500-mb or 700-mb contour heights for the same period, for a 190-point grid commencing at 25N, and thence on the $10^\circ$ parallels to 90N as at sea level.

For the period 1899–1939 Solot's monthly mean 500-mb charts were used, the standardization of the grid-point data being carried out over this period. For the period 1940–1962 the northern hemispheric 700-mb monthly mean contour heights prepared by the Extended Forecast Section of the U. S. Weather Bureau were used. The standardization of the 700-mb contour height departures was carried out over the 1940–1962 period, from which some World War II years were missing at many grid points.

These two sets, one of standardized 500-mb and one of standardized 700-mb monthly and seasonal mean contour height departures were combined for the synoptic and statistical analysis of climatic fluctuations. With regard to the homogeneity of the 63-year grid-point series of contour height departures obtained in this manner, questions may be raised as to the legitimacy of combining 500-mb and 700-mb data, and as to the reliability of Solot's early series. It is believed that after standardization the behavior of the 700-mb and that of the 500-mb contour height is essentially comparable, even quite strictly so, in their reflection of thickness changes. With regard to Solot's data extensive synoptic and statistical analysis of these data has failed to detect any inconsistencies relative to more recent data, and the departures of thickness which they define are found to be remarkably consistent with station observations of temperature departures. It is primarily to define thickness (temperature) departures that the contour height departures are used.

3. A series of derived charts is obtained by subtracting the standardized sea-level pressure departures from the standardized contour height departures to give thickness or mean virtual temperature ($T_v$) departures which correlate very highly with, but tend to run slightly larger in amplitude than, directly standardized departures. Such pseudo-standardized departures of $T_v$ have been plotted and analyzed for all of the seasonal and longer-period mean charts of sea-level pressure and upper-level contour height departures, but not for the monthly charts. They contribute importantly to parts of the following discussion of climatic fluctuations.

2. Response of sea-level pressure to extremes of solar activity

A. Statistical Analysis

A natural starting point to look for solar-climatic relationships is to contrast departure patterns of northern hemispheric circulation for periods of opposite extremes of solar activity. Since any such relationships may be expected to differ with the season of the year and the nature of the solar activity, the climatic data are examined by seasons of maximum and minimum values of selected indices of solar activity.

This particular comparison is restricted to sea-level pressure only, which past experience has shown usually to be the most directly responsive to variable solar activity. Accordingly for each of the four calendar seasons separately the six seasons of maximum and the six seasons of minimum mean value of each of four primary indices of solar activity were selected from the 1899–1962 period. The indices for which these selections were made are the following:

1. Relative sunspot number, SSN
2. Ratio of the total area of sunspot umbrae to the area of whole spots, $A_{um}/A_{ws}$ (Greenwich).
3. The international geomagnetic character figure, $C_i$, and
4. The range of the monthly mean diurnal inequalities of the magnetic declination at Greenwich, averaged for the five geomagnetically most quiet days of each month, $\Delta D$.

Two other solar indices, the double cycle sunspot number ($DSS$) and the mean latitudinal distance of spottedness from the solar equator ($N+S$, Greenwich) were treated for only the winter and the summer seasons, since not much of significance was expected of them. This expectation was verified, hence they will be given no further consideration although the corresponding four mean pressure departure difference profiles are entered as dotted curves in Fig. 1.

Each of these 20 (4 seasons×4 indices+2 seasons×2 indices) six-season groups of standardized departures of sea-level pressure was averaged for the six seasons of maximum value of each solar index, and likewise for the 20 six-season groups for the six seasons of the minimum value of each solar index. Then each of the 20 six-season mean departure patterns of sea-level pressure for minimum index values was subtracted from the corresponding six-season mean departure pattern for maximum index values, to bring out the contrast in the distribution of sea-level pressure between seasons of opposite extremes of each of the solar indices.

As nearly always turns out to be the case with monthly or seasonal mean departure patterns that are averaged by any extreme state or limited phase of solar

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**Fig. 1.** Mean seasonal pressure difference profiles for maximum minus minimum solar index extremes. (Units are standard deviations of seasonal mean pressures or contour heights, 1899–1962.)
activity, the most significant features of these mean seasonal pressure difference patterns for maximum minus minimum extremes of selected solar indices are predominantly zonal in character. Accordingly the latitudinal hemispheric profiles of the 20 mean seasonal pressure difference profiles were computed, and are plotted in Fig. 1. In this figure the ordinates are degrees of latitude (N) as indicated, and the abscissae are mean latitudinal standardized departures, averaged for 36 ten degree meridian grid-points at latitudes 10°–50°N, 18 grid-points at 60°N and 70°N, nine at 80°N, and the pole point.

B. Discussion of Results

Inspection of the mean seasonal pressure difference profiles in Fig. 1 reveals a number of features that deserve comment, notably as follows:

1. The four seasonal difference profiles for each of the four principal solar indices show considerably, perhaps surprisingly much, more similarity than would be expected by chance, i.e., the particular solar influence indicated by opposite extremes of the respective solar indices is surprisingly consistent from season to season, particularly in view of the fact that by no means the same calendar years are included in the four maximum and the four minimum six-season groups for each index.

2. The four SSN seasonal difference profiles are consistent in showing at maximum spottedness compared with minimum a significant relative displacement of atmosphere from lower to higher latitudes. The latitudinal belt most affected by this displacement shifts poleward in a manner that might be expected with the poleward movement of the sun from the winter to the summer season, and moves equatorward again by autumn.

3. The four umbra to spot ratio difference profiles are unique in showing for all four seasons a marked deficit of mass of atmosphere on the northern hemisphere during years of maximum as opposed to years of minimum value of the ratio. This deficit is a maximum in the higher latitudes and disappears at about 10°N. No explanation is offered for this consistent difference. A large umbra/spot ratio is believed to indicate a more vertical orientation of the magnetic lines of force originating in the spot fields.

4. The four seasonal difference profiles for C, are highly consistent in showing a relative poleward shift of atmosphere from lower to higher latitudes in geomagnetically disturbed as opposed to geomagnetically quiet seasons. It may be noted that all four profiles show a maximum relative increase of pressure at 70°N, which is exactly the latitude at which the Duells (1948) and Craig (1951) find the maximum increase of pressure reached on the fourth day following a key day of geomagnetic disturbance. On the other hand, in the short-term reactions the maximum loss of pressure on the 4th day is observed at about 40°N, rather than at still lower latitudes as in these seasonal mean state difference profiles.

5. The four seasonal difference profiles for ΔD are highly consistent in showing an extreme increase of zonal westerlies in high latitudes, particularly from 70–80°N, during seasons of maximum as opposed to seasons of minimum day to day variation of magnetic declination at Greenwich Observatory on geomagnetically “quiet” days. It is interesting to note that ΔD correlates very highly on an annual basis with sunspot number (+0.94) but it has a seasonal fluctuation such that its April–August values average nearly three times as high as the minimum monthly value reached in December, a variation which is not shared in at all by sunspot number. In view of the fact that the north magnetic pole lies directly in the 70°–80° belt of greatly increased westerlies, and also of a comment made to the author by H. Vestine, that he would view fluctuations of ΔD as most probably representing variations of the height or strength of the ionospheric ring current, these profiles are strongly indicative of some tie-in between ionospheric flux and tropospheric zonal circulation, both in relation to sunspot number. There is, however, no hint as to the sense of any cause and effect relationship.

To sum up the evidence offered by Fig. 1, there are indicated significant relationships between the zonal distribution of seasonal mean pressure on the northern hemisphere and oppositely extreme states of solar activity as indicated by a number of indices, generally in the sense anticipated from previous experience with solar-weather relationships.

3. The 80–90 year solar-climatic cycle

The existence of an 80–90 year cycle of solar activity apparently paralleled by a significant hemispheric climatic cycle has been recognized for some time (Schöne, 1961; Willett, 1961). Space permits only the briefest discussion at this point of the essential features of this solar-climatic cycle as it has been described previously (see Willett, 1961). The solar cycle is defined primarily by a sharp break from peak sunspot activity during the final quarter of the cycle to minimum activity during the first quarter of the following cycle. This sharp transition phase followed the very high 11-year sunspot maxima of 1787, 1870 and presumably 1957 to the very low and delayed 11-year maxima of 1804, 1883–84 and 1970 (7). The second and third quarters of the long solar cycle are marked by irregularly increasing sunspot activity, the first and last of these three cycles having been similar in that this increase was slow and progressive, whereas in the second cycle it was less regular.

The corresponding pattern of climatic change manifests its sharpest break like that of sunspot activity, from a low index cellular blocking stress pattern during
the fourth quarter of peak sunspot activity, to a low-latitude zonal pattern of essentially cool maritime conditions in middle and lower latitudes during the first quarter of minimum sunspot activity. During the second and third quarters of irregularly increasing sunspot activity, the zonal climatic pattern tends to shift poleward with a warming trend in most latitudes, the pattern becoming markedly high-latitude zonal in character during the third quarter. The corresponding weakening of the zonal westerlies in lower middle latitudes that results from their poleward shift and strengthening in higher latitudes causes an intensification of the normal climatic continental-maritime contrasts (monsoonal cells) during the third quarter of the cycle equatorward of 50°N.

It is interesting to note the phase departure patterns of the 80–90 year solar-climatic cycle during the last three quarter-phases of the current cycle in the 1899–1962 series of standardized hemispheric seasonal departure charts. For this purpose the three 20-year periods, 1900–1919, 1920–1939 and 1940–1959 are taken to represent the three successive quarters of the cycle. The standardized seasonal departure charts for sea-level pressure and for the difference between the upper level contour heights and sea-level pressure (departures of thickness or of $\bar{T}_s$) are averaged for each calendar season for each 20-year period.

Once again it is the primarily zonal features of these mean standardized seasonal departure patterns that are strikingly significant. Accordingly Fig. 2 contains the 20-year mean profiles of the standardized seasonal departures of sea-level pressure and of thickness ($\bar{T}_s$) by the four calendar seasons for the second, third and fourth 20-year quarters of the 80–90 year cycle. Since these mean seasonal departure profiles contain some highly interesting and significant features which confirm and amplify earlier impressions as to the nature of this solar-climatic cycle, it is informative to consider these profiles rather closely. We may note in particular the following general and specific features of the profiles in Fig. 2:

1. The general character or shape of both sets of profiles for the four seasons of each 20-year period is strikingly similar. Such a high degree of consistence between the four calendar seasons of each phase period definitely was not anticipated, but it certainly adds to the statistical significance of the cyclical influence.

2. The amplitude of some of the profile point departures, particularly at low latitudes, is surprisingly large, in view of the fact that each such profile point
departure represents the 20-year seasonal average of 36 individually standardized grid-point values, i.e., of 720 individual standardized seasonal departures. The large amplitude of the departure profiles indicates a strikingly significant degree of zonal consistence of the cyclical influence.

3. There is a surprising degree of negative correlation between the sea-level pressure departures and the thickness (temperature) departures. The negative correlation ranges from $-0.94$ for the three sets of winter profiles to $-0.72$ for the three sets of summer profiles. This high negative correlation might be ascribed to some consistent compensating error in the upper level contour height analysis except for the fact that the temperature distributions as indicated by these profiles completely support expectations based on previous studies of long-term station temperature records (Willett, 1950; Mitchell, 1961).

4. The second quarter phase, 1900–1919, shows strikingly the expected low latitude zonal characteristics of the hemispheric circulation patterns. Not in particular the consistently above normal strength of the zonal westerlies from $20^\circ$ to $40^\circ$ in winter and spring and from $30^\circ$ to $50^\circ$ in summer and fall. Equally striking is the consistent coldness in lower middle and subtropical latitudes, particularly the seasonal progression with the sun of the zone of maximum anomalous coldness in lower latitudes, from 25N in winter (unfortunately the temperature data terminate at this latitude) to 35N in summer and back again. Also notable is the fact that for this 20-year period sea-level pressure averaged normal or above at all latitudes for all seasons, excepting only at 10N during the summer season, while the temperature of the lower half of the troposphere was equally uniformly below normal for the period.

5. The third quarter phase, 1920–1939, contains strong evidence of the expected shift towards high latitude zonal characteristics of the hemispheric circulation patterns. Note for all four seasons the fall of pressure in high latitudes from the preceding phase from substantially above to substantially below normal values, while in lower middle and subtropical latitudes the pressure also falls, but remains near or slightly above normal. Particularly during the winter and summer seasons we note zonal westerlies in the higher latitudes strongly above normal as indicated previously by Willett (1961). The trend from low latitude to high latitude zonal circulation patterns is strongly confirmed by the temperature profiles for all four seasons, with changes generally from below normal to above normal temperatures in middle and higher latitudes, and from markedly below to near normal in lower latitudes. Note the strong warming during the winter season in the high latitude belt of increased zonal westerlies, and during the remaining seasons at about 50N in the continental monsoonal thermal belt.

6. The fourth quarter phase profiles present strong evidence of the trend of northern hemispheric circulation patterns towards the cellular blocking (climatic stress) type. Note the strong shift of atmospheric mass from lower to higher latitudes, with above normal pressure centered at 70N (polar continent anticyclones) in winter and at 50N (maritime monsoonal highs slightly outweighing continental monsoonal lows during other seasons), while pressures are strongly subnormal during all four seasons in the subtropical high pressure belt. Equally striking is the fall of temperatures to near or slightly below normal levels in polar and higher middle latitudes and continued rise to considerably above normal levels in subtropical latitudes, all in complete conformity with the results obtained from long-term station records (Mitchell, 1961). Most notable again, as in the case of the low-latitude anomalous coldness during the 1900–1919 period, is the seasonal progression poleward with the sun of the maximum of anomalous warmth from below 25N in winter to about 35N in summer and equatorward return through fall to winter.

It may be concluded that the hemispheric mean seasonal phase profiles of standardized departures of sea-level pressure and thickness ($T_v$) of the lower troposphere completely confirm the picture of the 80–90 year solar-climatic cycle obtained from superficial earlier studies. Undoubtedly the most striking and statistically significant feature of these 20-year seasonal profiles of standardized departures is the behavior of the temperature anomaly in low latitudes. Not only does it probably represent the primary thermodynamic drive of these changing hemispheric circulation patterns of the 80–90 year climatic cycle, but it appears to be directly responsive to the sun and to follow directly the 80–90 year cycle of sunspot activity. Apparently it reflects directly a variation of the effective and most probably of the intrinsic solar constant.

4. The double sunspot (20–24) solar-climatic cycle

A. Character of the solar-climatic cycle

The existence of a double sunspot solar-climatic cycle was first proved by Hanzlík (1931), and subsequently verified extensively by Willett (1952, 1959, 1961) and others. The physical reality of the double sunspot solar cycle is reflected in the reversal between alternate sunspot maxima of the polarity of sunspot group magnetic fields, in differences of solar corpuscular emissions and geomagnetic disturbance, and in other indices of solar activity (see Fig. 6).

Climatically the double sunspot cycle is manifested primarily by an opposite trend of change of the pattern of the general circulation in passing from sunspot minimum to alternate maxima. In passing from minimum to major maximum (highest sunspot number) there is a strong trend towards increasing prevalence of the climatic stress circulation patterns, meaning a predominance of polar continental anticyclones in high
latitudes in winter, and warm dry summers in the interior of continents. In passing from sunspot minimum to the alternate minor maximum the trend is towards increasing prevalence of the low latitude zonal pattern of the general circulation, meaning a more southerly course of the prevailing storm tracks in middle latitudes, and in particular generally wetter conditions and cooler wetter summers over the continents in lower middle latitudes.

Following the minor sunspot maximum in the double sunspot cycle there is a pronounced trend towards a shift of the zonal circulation pattern from lower to higher latitudes. This change implies a poleward shift of the prevailing storm tracks and precipitation, with a return to warmer and drier conditions, particularly in continental interiors, in lower and middle latitudes.

B. Manifestations of the Double Sunspot Climatic Cycle in the 64-Year Hemispheric Data Series

1. Seasonal mean phase anomalies and standard deviations. The 64-year hemispheric series of standardized monthly and seasonal departures of sea-level pressure and of upper level contour heights were grouped by 3-year phases of the double sunspot cycle (Willett and Prohaska, 1963). Since the period covers three complete double sunspot cycles, nine years are included in each of the eight phase groups, although a number of phase overlap years obviously must be included in each of two phase groups.

Phase means and phase standard deviations of the standardized seasonal departures were computed for each of the eight nine-year phase groups for all the four calendar seasons. Interestingly enough, and rather unexpectedly, it turns out that only the standard deviations, and not the means of the seasonal phase departures significantly reflect the double sunspot cycle.

Hemispheric charts of the nine-year mean phase departures both of sea level pressure and of upper level contour heights were plotted and analyzed for all four calendar seasons for each of the eight phases of the double sunspot cycle. Extensive statistical analysis (Willett and Prohaska, 1963) of these thirty two sets of seasonal mean phase departures failed to establish them as being significantly different from nine-year seasonal mean departures of three randomly selected 3-year sequences. This result is not particularly surprising in view of the earlier work of Hanzlik and Willett, which indicated the primary manifestation of this cycle to be an opposite trend of change of pattern between separated phases of the cycle and primarily for the winter season.

However, simple inspection of patterns of the standard deviation of the seasonal departures within the different 9-year phase groups indicates a pronounced difference in the year-to-year variability of the seasonal weather patterns in different phases of the double sunspot cycle. To test this statistically, 12 grid-points were selected, three from each of the four hemispheric quadrants, for analysis in this respect. The points taken to be representative of each quadrant are the following:

Quadrant 1, Asia, 30N/60E, 40N/110E and 70N/100E.
Quadrant 2, Pacific, 20 (or 25)N/150E, 50N/180E, and 20 (or 25)N/140W.
Quadrant 3, North America, 70N/100W, 50N/100W, and 30N/100W.
Quadrant 4, North Atlantic, 30N/60W, 30N/30W and 60N/20W.

The standard deviations of the standardized seasonal phase group departures of sea-level pressure and of upper level contour heights for each of the 32 seasonal phase groupings were summed separately for the three selected grid-points in each quadrant, and totalled for the four quadrants. These 128 sums of standard deviations, and the corresponding 32 four-quadrant totals, of sea-level pressure are listed in the upper half of Table 1. The corresponding sums and totals of the standard deviations of the seasonal phase group departures of the upper level contour heights are listed in the upper half of Table 2. The column headings of Tables 1 and 2 indicate the successive eight phases of the double sunspot cycle from the major maximum (M) through the minor minimum (m) to the eighth phase of most rapid increase of spots approaching M of the next cycle. The decimal point in front of the final digit is omitted from all quadrant sums and totals in these Tables.

The last half of Tables 1 and 2 contain identically the same grid-point sums and totals of standard deviations of seasonal group departures of sea-level pressure and of upper level contour heights as in the upper half of the tables, except that the nine departures of each of the 32 seasonal groups (in this case 16 winter and 16 summer) are those of two randomly selected groups of nine years each instead of the double sunspot cycle phase grouping of nine years each.

Considering the evidence in Table 1 we may note in particular the following:

(a) Most evident in the 12-grid-point (4-quadrant) totals of the seasonal phase group sums of standard deviations is a consistent tendency for these sums to average higher during the major maximum half of the cycle (phases 8–3, inclusive) and lower during the minor maximum half (phases 4–7, inclusive). Only in the spring season is this average insignificantly different.

(b) There is an equally consistent tendency for the maximum of these sums, or the maximum variance of the seasonal patterns, to be reached at the major sunspot maximum phase, M, and for the minimum variance to be reached at the minor sunspot maximum.
### Table 1. Sums of selected grid-point standard deviations, sea-level.
(Decimal points omitted before the last digit.)

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<th>6 m</th>
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<td>24</td>
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<td>27</td>
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*M*. Even the spring season adheres closely to this 8-phase cycle.

(c) There is some indication that the seasonal random group sums average slightly, but insignificantly, higher in groups 8–3 than in groups 4–7, inclusive.

(d) The phase group totals for all four seasons, the third double line from the bottom of Table I, reflects a highly significant and consistent double sunspot cycle of variance of seasonal phase departures, both in the averages of the two halves of the cycle, and in the
extreme contrast between the \( M \) and \( M \) phases. A \( t \)-test of the significance of the grouping of the 128 seasonal quadrant sums of standard deviations between the 64 sums in phases 8–3 and the 64 sums in phases 4–7 places the statistical significance of the separation of the two groups at the 0.03% level.

(e) The random group totals for all four seasons in the second double line from the bottom of Table 1 reflect in the averages a slight but insignificant random grouping of variance. There is no cyclical pattern to this change of variance, since both extremes fall in phases 8–3, and the \( t \)-test places the significance of the separation of the grouping of the 64 quadrant seasonal sums in phases 8–3 from those in phases 4–7 at only the 25% level of significance.

Considering the evidence in Table 2, we may note in particular the following:

(a) The totals of the seasonal phase group sums of standard deviations average even more consistently higher in phases 8–3 compared with phases 4–7 than is the case in Table 1, in that the difference is significant also for the spring season.

(b) At upper levels the 8-phase cycle of the sums is a little less consistent in the seasons individually than at sea level, particularly in the phase at which the minimum is reached.

(c) At upper levels not only is there no suggestion whatsoever of a cycle of the random group sums, but there is not even the slightest tendency to any grouping of higher or lower sums in any consecutive four groups of the eight total.

(d) The phase group totals for all four seasons, the second from the bottom double line in Table 2, reflect a double sunspot cycle of the phase totals equal in significance to that in Table 1, differing only in that the minimum value is reached one phase sooner. The difference of the phase total averages in Table 2 is notably more significant than in Table 1. In Table 2 the grouping of the 64 seasonal quadrant sums in phases 8–3 is different from the grouping of the 64 sums in phases 4–7 at the 0.0012% level of significance by the \( t \)-test.

In Table 2 there is no distinctive grouping whatsoever, either cyclical or by consecutive groups, of the random group totals of sums. On the other hand, there are differences of the random group totals that are almost as large as the differences of the phase group totals, but they occur scattered at random, and oddly enough, they do not correlate at all (\( +0.08 \)) with the random group totals of sea-level pressure in Table 1, although they are for identically the same random groups of years. The phase group totals at the bottom of Table 2 correlate at an amazingly high \( +0.92 \) with the corresponding phase group totals at the bottom of Table 1.

It appears beyond much question from Tables 1 and 2 that the amplitude of the year-to-year variability of hemispheric seasonal mean circulation patterns under- goes a significant cycle of change with the double sunspot cycle, such that the variability is greater during the major maximum half of the cycle and less during the minor half. The maximum variability tends to be reached in the years at or just preceding the major sunspot maxima, and the minimum variability in the years at or just preceding the minor sunspot maximum. It is interesting to note in this connection that a current study of day-to-day reactions of the general circulation to sudden solar disturbance fails to establish any significant relationship of the patterns themselves to the key day or post key days of the disturbance, yet there does appear to be a significant suppression of the variability of the circulation patterns on days succeeding compared with days preceding the key day.

The question may be raised as to how it happens that the year-to-year variability of hemispheric seasonal mean circulation patterns is significantly related to the phase of the double sunspot cycle, and yet the mean patterns themselves are not significantly shaped by the phase of the cycle. Probably the greater year-to-year variability of the seasonal mean circulation patterns at the major sunspot maximum reflects the predominance of cellular blocking patterns at that time, but cellular blocking patterns are notoriously shifting in their meridional orientation, hence fail to impose any distinctive strong features on mean patterns over a period of years. On the other hand, the predominance of zonal patterns during the minor half of the double sunspot cycle is reflected in a relatively small amplitude of seasonal mean departures of grid-point pressures, or of the year-to-year variability of the seasonal mean pressure patterns, which due to latitudinal shifts also fail to impose any distinctive strong features on mean patterns over a period of years.

One more feature of interest of Table 1 deserves comment. The figures on the bottom double line of this table contain the count of the relative frequency of arbitrarily defined intensities of cyclogenesis and anticyclogenesis, i.e., 24-hour change of central pressure of closed lows and highs, on the daily maps of the original Weather Bureau 40-year historical map series (Willett, 1961). This count tallied about 4600 individual cases of anticyclogenesis, and 8400 of cyclogenesis. It is to be noted that the frequency of cyclogenesis and anticyclogenesis also is significantly related to the double sunspot cycle, but in the opposite sense from the year-to-year variability of the seasonal mean pressure patterns. Cyclogenesis and anticyclogenesis of specific intensities occur significantly more frequently during the minor half of the double sunspot cycle with its predominantly zonal circulation patterns, significantly less frequently during the major half with its relative predominance of cellular blocking patterns. This opposition of these two circulation parameters is exactly in the sense that is to be expected.

One even more detailed feature of opposition may be noted. Phase 6, \( M-m \), is markedly out of line with the
rest of the cycle of cyclogenetic and anticyclogenetic frequencies at the bottom of Table 1, in the sense that it is an outstandingly low value in the cyclical sequence. In the same manner, but to a less extreme degree, this same phase is out of line in the opposite sense (too high) in the cyclical sequence of phase totals at the bottom of both Table 1 and Table 2. It is particularly interesting to note that exactly at this $M-m$ phase of the minor half of the double sunspot cycle the irregular geomagnetic disturbance, which is strongly associated with cellular blocking patterns of the general circulation (Fig. 1), reaches a minor peak of activity second only to that attained at $MM$. (See Fig. 6). Hence, it appears again that sudden solar disturbance tends to be associated with a suppression of day-to-day variability of the pressure patterns, i.e., a suppression of cyclogenetic and anticyclogenetic activity, but with a predominance of slowly changing blocking patterns that are reflected in large departures and large year-to-year variability of seasonal mean pressures.

2. Difference of trend of the general circulation patterns at the major and at the minor maxima of the double sunspot cycle. Since the clearest manifestation of the double sunspot cycle found by Hanzlik and Willett is that of the contrasting trend of change of the mean state of the winter season pattern of the general circulation of the northern hemisphere in passing from sunspot minimum to the major as opposed to the minor sunspot maximum, it is only natural to check this particular difference of phase change in the 64-year data series. This check was made for the summer season as well as for the winter to determine to what extent the phenomenon may be detectable at the opposite season.

In order to check these two seasonal difference of phase changes, the standardized hemispheric departure charts of sea-level pressure and of upper level contour heights are averaged separately for the nine winter seasons and for the nine summer seasons of the 64-year period that lie, respectively, in the major maximum phase $MM$, in the preceding minimum phase m, in the minor maximum phase $M$ and in the preceding minimum phase mm of the double sunspot cycle. The changes of the hemispheric grid-point seasonal mean departures from phase $m$ to phase $MM$ are given by the differences of the means ($MM-m$), and correspondingly from phase mm to phase $M$ by the difference of the means ($M-mm$). The differences of the phase changes of the seasonal departures of the mean hemispheric circulation patterns going into a major maximum in contrast to those going into a minor maximum are given by the differences of the two sets of change patterns, i.e., by $[(MM-m) - (M-mm)]$. Corresponding pseudostandardized differences of the phase changes of thickness $T_o$ are obtained by subtracting the phase change differences of sea-level pressure from those of the upper level contour heights. The three sets of phase-change difference charts (of standardized departures of sea-level pressure, of upper-level contour heights and of thickness) obtained in this manner were plotted and analyzed for the winter and summer seasons, and the hemispheric profiles were computed and drawn. Since once again the outstanding features of these six seasonal charts are primarily zonal in character, the six profiles are presented in Fig. 3.

On these profiles the abscissae are differences of individual mean gridpoint standardized departures averaged for all grid-points on each latitude circle. Positive values show that the change is towards a relatively higher mean latitudinal value of the element going into the major sunspot maximum, negative values towards a relatively higher value going into the minor sunspot maximum. The significance levels which are assigned to each of the six profiles in Fig. 2 represent F-tests of the significance of the between-group to within-group variance of the total 226 or 190 mean grid-point departures represented by each profile. The groups are the grid-point values on each $10^\circ$ latitude circle, the within-group variance is taken about the mean of each group, the between-group variance is that of the group means about the total mean. The significance level of each F-ratio is computed on the basis of $n-r$ and $r-1$ degrees of freedom, where $n$ is the total number of grid-points and $r$ is the number of latitudinal means on the profile.

With regard to the six difference of change profiles presented in Fig. 2 we may remark the following:

(a) It is highly indicative of the physical significance of the double sunspot solar-climatic cycle that the most distinctively contrasting trends of the general circulation and thermal patterns are found during the two periods of rapid increase of sunspot number to the alternate maxima. This phasing suggests strongly that it is not primarily any difference of sunspot number or trend, but some physical difference of the sunspots themselves (perhaps reversal of magnetic polarities) that is responsible for the apparently opposite climatic significance of the major and minor halves of the double sunspot cycle.

(b) It is noteworthy that the climatic significance of the double sunspot cycle is more clearly reflected by the winter season profiles than by the summer, and in middle rather than in subtropical latitudes. The implication of these facts is that the solar disturbing influence in the double sunspot cycle is not one of the direct heating effectiveness of the solar constant, such as was clearly implicated in the 80--90 year solar climatic cycle, but rather one that is indirect and most effective in the winter season in disturbing the dynamic stability of the strong winter season circulation patterns.

(c) The difference profile of the sea-level pressure departures in winter shows a strong relative tendency at the major maximum for mass of atmosphere to be displaced poleward from the lower-latitude high pres-
Fig. 3. Mean seasonal hemispheric difference profiles, change from sunspot minimum to major maximum minus change from sunspot minimum to minor maximum, i.e., \(-\frac{MM-mm}{M-mm}\). (Abscissae are latitudinal averages of 20-year grid-point means of standardized seasonal departures.)

Sure belt into polar latitudes, with corresponding pronounced weakening of the zonal westerlies and subtropical easterlies, and strengthening of the polar easterlies. This difference is completely typical of a strong relative trend of the general circulation towards a cellular blocking pattern going into the major maximum. In summer the trend is similar but much weaker, and the whole pattern is shifted 10⁰ poleward, corresponding to the poleward shift of the low latitude high pressure belt, represented at this season by the expanded Atlantic and Pacific anticyclones centered between 40N and 50N.

(d) The contour height difference of change profiles for both seasons are significantly weaker than those of sea-level pressure, but they are similar in form, with the same poleward displacement of the pattern. Both of them, relative to the difference of phase change profiles at sea level, are displaced towards the negative in high latitudes and towards the positive in low.

(e) The changes of temperature (thickness) in the winter season, and less strongly in the summer, are towards relatively lower temperatures in the high latitudes and relatively higher temperatures in the low latitudes going into the major sunspot maximum in contrast to the minor. These difference of temperature change profiles reflect for the major sunspot maximum a relative minimum in winter at 60-70N (peak of anomalous continental cooling) which is displaced poleward to the Arctic Ocean in summer, and a relative maximum of temperature in winter in the subtropical high pressure belt, a maximum which in summer is displaced to 50N (peak of anomalous continental heating during this season).
The clear implication of these seasonal differences of change profiles is that the general circulation at the major sunspot maximum, in contrast to the minor, is significantly disturbed by something that aggravates the monsoonal (continental-maritime) thermal contrasts, thereby favoring cellular blocking as opposed to zonal patterns of the general circulation. In this connection it may be noted that high levels of solar corpuscular radiation, as indicated by the international geomagnetic character figure $C_p$, are observed to have this affect at all seasons (see Fig. 1 above). Furthermore, $C_q$ (and presumably also the incidence in the upper atmosphere of solar corpuscular radiation) reaches its highest level at the major sunspot maximum, but is significantly below its average level at the minor maximum. It does, however, reach a delayed minor peak in the following $M-m$ phase of the double sunspot cycle, as noted above. It is possible that atmospheric ozone, its total amount and/or latitudinal distribution, is a primary physical link between the solar activity of the double sunspot cycle and the thermal effectiveness of the continental seasonal sources and sinks (monsoonal circulations) in middle and higher latitudes (see Fig. 6).

5. Reflection of solar-climatic cycles in the temperature regime of West-Central North America

West-central North America represents a geographical area of homogeneously continental climate and wide latitudinal extent for which a reasonably homogeneous coverage of climatic data since the early eighties is available. Such an area reflects most clearly thermal responses to variable solar activity.

Figs. 4 and 5 present cumulative trend curves of standardized departures of seasonal mean temperature at selected stations in this area, taken from a previous study of climatic fluctuations (Willett, 1959). Each curve represents the cumulative trend of standardized seasonal departures of temperature as computed

![Cumulative totals of winter season standardized departures of temperatures averaged for selected stations.](image-url)
individually at each of three or four stations and averaged together by three latitudinal zones, as follows:

1. Upper curve, northern Canadian wheat belt, Edmonton, Alberta, to Winnipeg, Manitoba.
2. Middle curve, west central United States, Denver Colorado, to Omaha, Nebraska, and
3. Lower curve, southern, close to Mexican border, Phoenix, Arizona, to Abilene, Texas.

The record of the seasonal mean temperature at each station is averaged for the entire period, and the individual station departures from this average are standardized and averaged by the three or four stations in each latitudinal group. Since these are cumulative trend curves of average normalized departures, it is the slope of the curve which expresses the magnitude of the seasonal departure for any year or period of years. The successive major ($MM$) and minor ($mm$) maxima of the double sunspot cycle are indicated on the time scale (abscissae).

It is particularly instructive to compare the winter season curves for the three groups of stations in Fig. 4 with the summer season curves in Fig. 5. Note particularly the following:

1. In general, the winter season curves are weak in character and irregular in comparison with the summer season. This seasonal difference is characteristic of most standardized seasonal temperature data.

2. In general, and in particular during the summer season, it is the arid southwest which shows the strongest and most consistent long-term trends of temperature. This latitudinal difference is characteristic of most standardized seasonal temperature data.

3. The last three 20-year phases of the 80–90 year solar-climatic cycle are reflected in all of these curves in general agreement with the indications of the hemispheric data discussed in Section 3 above. Unfortunately, the first and generally coolest phase of the cycle, previous to 1900, is not covered by the data in Section 3. Note that in both the northern and middle sections during both seasons the fourth quarter of the
cycle (since 1940) witnesses a return to cooler (nearly normal) temperatures, whereas in the southern section the warmth continues unabated.

(4) The extremity and consistency of the 80–90 year cycle in summer in the arid southwest is truly amazing. For the first and coolest phase (1880–1899) not a single summer season was warmer than the long-term mean, and the accumulation of temperature deficit amounted to twenty six standard deviations. From 1923 to 1957, on the other hand, only one summer season averaged cooler than the long-term mean. It might be assumed in that area that coolness is associated primarily with cloudiness and precipitation, but this proves not to be the case. The minor maximum half of the very cool phase (1880's) was very wet, but the equally cool major maximum half (1890's) was of an extreme dryness exceeded only during the 1950's, when it was very warm.

(5) The double sunspot cycle influence on the temperature is evident in these trend curves primarily during the latter, or solar-wise active, half of the 80–90 year cycle. Particularly during the summer season we note warm periods during the MM half of the double cycle during the teens and the thirties on the northern section (record ends before the fifties), particularly during the thirties (dust-bowl decade) and less strongly during the fifties, in the middle section, and particularly during the drought of the fifties and less strongly during the thirties in the southern section. It is interesting to note that the decades of both the thirties and the fifties were quite wet in the northern section (poleward shift of storm tracks) whereas the greatest drought on record in that section occurred in the eighties when it was very wet in the southern section (equatorward shift of prevailing storm tracks).

In general we may conclude this discussion by saying that in the western plains of North America the climatic fluctuations of temperature for the past 80 years quite clearly reflect the two solar climatic cycles consistently with the hemispheric changes. The 80–90 year cycle is clearly evident in all latitudes and seasons, but much more strongly in the southern section and during the summer season. The double sunspot solar climatic cycle shows up primarily during the middle and latter half of the long cycle, when solar activity is at an increasingly high level, and is marked particularly by warm periods during the MM half of the cycle. Even the latitudinal shifting of the belts of surplus and deficit

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**Fig. 6.** Mean winter season departures of selected solar and atmospheric indices by phases of the double sunspot cycle. (Ordinates are units of \( t = (x - \bar{x})/S(n) \))
of precipitation follow consistently the long cycle, as
does the tendency for the periods of severe drought,
particularly during the past 40 years of high solar
activity, to occur during the MM half of the double
sunspot cycle.

6. Reflection of the double sunspot cycle in selected
solar and climatic indices

In view of the above implication (see end of Sec. 4)
of the involvement of geomagnetic disturbance (solar
corpuscular radiation) and possibly of atmospheric
ozone in changes of the hemispheric patterns of circula-
tion and of temperature which apparently pertain to
the double sunspot cycle, it is interesting to take brief
note of the double sunspot cycle phase variations of a
few selected indices.

Fig. 6, which suffers somewhat from over-crowding,
presents the double sunspot cycle phase variation of
the winter season values of five such indices as averaged
for the successive 3-year phases of the cycle for the
period 1899 to 1960, or for as much of that period as
there are available winter-season values of each index.

These five indices, and the total number of winter
season values entering into the phase means of each
index, are the following:

(1) The Zurich relative sunspot number, RSS, 72
years.
(2) The international geomagnetic character figure,
Cₙ, 72 years.
(3) The mean latitudinal distance N+S, from the
solar equator of the total area of sunspots (Greenwich
Observatory), 66 years.
(4) The number one function, OT₁, of Gilman’s
(1957) orthogonal functions of temperature in the
continental United States, 55 years. This function
accounts for 38.3% of the total variance of winter mean
temperature in the continental United States, and is
not at all predictable from the preceding state of the
hemispheric circulation. Its geographical pattern is one
of a centrally located (over Iowa) area of maximum
anomaly, sloping away in all directions, towards zero
values on the west coast and well off the east coast.
OT₁ is taken as positive when the temperature departure
field is positive. It is believed to represent par excel-
ence the effectiveness of the continental seasonal ther-
mal (monsoonal) influence, and is referred to as the
“contineliness function.”
(5) Mean winter-season values of total atmospheric
ozone, 0₃, 32 years. The values are taken from Willett
(1962), as averaged for all station records available
to that study.

The abscissae in Fig. 6 represent the time sequence
of the successive phases of the double sunspot cycle,
with repetition of two phases at the right to make
clearer the continuity of the phase sequence of index
values. The ordinate values plotted in Fig. 6 for the
winter mean phase group values of each index are the
t values given by:

\[ t = \frac{x - \bar{x}}{s(N)^{1/2}} \]

where

X = total mean of all N values (72, 72, 66, 55 and 32,
respectively) of each index,
\( \bar{x} \) = the individual phase group mean of each index
for all the winter means in the record of the index,
varrying between nine for the indices of complete
record to as little as three for some phases for
ozone,
S = standard deviation of all N individual winter
season mean values of each index.

This t-value was selected to represent the phase
means of this varied group of indices in order to give
the plotted values some degree of comparability. It
measures the significance that would attach to a single
season mean x equal to the given \( \bar{x} \) among the N
seasonal values of each index, on a scale that is almost
identical for all five indices.

The percentage figure that stands to the right of the
terminal point of each index phase curve is a measure of
the statistical significance of the double sunspot cycle
in the data sample from which the curve is derived.
It is the significance of the F-ratio of between group to
within group variance in each index data series, where
the between group variance is that of the eight phase
mean values (\( \bar{x} \)’s) about the total mean (X), and
the within group variance is that of the individual seasonal
means (\( x_i \)’s) about their respective phase group mean
(\( \bar{x}_i \)). We may note that only for the continentality
function \( OT₁ \) does the double sunspot cycle fail to test
as highly significant.

Of the individual phase mean departures of \( OT₁ \)
those at phases mm-M, M-m and m are significant
respectively at the 12%, 10% and 4% levels, which is
strongly indicative of reality of the cycle even of this
index.

Concerning the individual curves in Fig. 6 we may
remark the following facts of interest:

(1) The cyclical variations of RSS and of N+S are
statistically the most significant, but the difference
between the major maximum and the minor maximum
is much stronger in the sunspot number than in the
mean latitude of the area of spottedness.
(2) High positive correlation exists between the
phase variation of \( OT₁ \) and 0₃, the linear correlation
of the eight pairs of phase values being +0.83. The cor-

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Since there are just 3 complete double sunspot cycles, or 24
complete 3-year phase periods, included between 1899 and 1960,
the maximum number of winter-season values for those indices for
which the record is complete is 72. This requires that values for
some overlapping years between phases are used twice, once in
each of two consecutive phase-period means.
relation is in the sense that might be expected, more ozone, warmer continent in winter.

(3) $O_3$ and $N+S$ correlate highly negatively as previously noted (Willett, 1962), the coefficient for the eight phase pairs being $-0.81$. $N+S$ correlates highly positively with sunspots one phase later $(+0.83)$, while ozone correlates significantly negatively with sunspots one phase later $(-0.64)$.

(4) $C_4$, usually assumed to represent primarily the effects of solar corpuscular radiation, correlates highly positively with $OT_1$ and $O_3$ at one phase lag, i.e., with the two atmospheric indices taken one phase later than $C_4$. The correlation coefficients of the eight phase pairs are, respectively, $+0.55$ with the "continuity function" and $+0.79$ with ozone.

(5) Most notably, the phase relationship of the three indices $C_4$, $OT_1$ and $O_3$ with respect to $RSS$ and $N+S$ differs in the same respect between the major and the minor sunspot maxima, in that all three indices lag the sunspot indices one phase later at the minor than at the major maximum, and fall less to the following minimum than to the minimum following the major sunspot maximum. Whereas $C_4$ reaches its highest level at the major maximum $MM$, at the minor maximum $M$ it is well below its mean, and one phase later at $M-m$ it reaches a secondary but quite significant peak. There is strong evidence that this secondary peak at $M-m$ represents the effect of $M$-region corpuscular radiation, whereas that at $MM$ represents strong sunspot magnetic field corpuscular radiation (Willett and Prohaska, 1960).

The above index phase relationships seem, insofar as they may be taken at face value, to support the very tentative suggestions which were offered in Section 4 concerning a possible physical basis of the double sunspot solar-climatic cycle. Admittedly the observational record is too short, in particular that of atmospheric ozone is both short and nonhomogeneous, to justify firm statistical deductions. Further speculation in this direction must await a longer extension of the program of ozone observations started during the IGY.

REFERENCES


