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Analysis of an Iowa Aridity Index in Relationship to Climate and Crop Yield[1]

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An aridity index and its components, temperature and precipitation, for the period from 1900 through April 1993 were defined and characterized. This index describes the anomalous behavior of both temperature and precipitation over time. Our intent was to examine climate variability in Iowa. Moving mean and standard deviations over various lengths of time were calculated from three time series. We found that these indices fluctuate considerably from year to year and from month to month. The lowest aridity index values occurred in the recent summer of 1992, and the highest occurred during the very drought-prone 1930s. The 12-month moving mean and standard deviations for the aridity index were high during the 1930s and the 1980s. However, the period from the late 1950s to the mid-1970s exhibited low mean values and low variation when compared with other times of the series. This was a benign weather period for agriculture in the midwest, and production levels were high. By increasing the length of the moving mean and standard deviations, upward and downward trends were shown. Recent variation of the aridity index was as high as it was earlier this century. The probability of having a number of consecutive months with positive, stressful aridity-index values in Iowa was quite small. Power spectrum analyses of the aridity index and its components (temperature and precipitation) suggested there was, at the 95% level, a significant 11-year periodicity. Significant shorter cycles with lengths varying between 3 and 8 years were also found. These may be associated with El Niño events. After adjusting yields to a time trend, correlations between corn and soybean yields and July and August aridity indices, respectively, were negative and significant.
INDEX DESCRIPTORS: climate change, climate variability, drought.

Most climatic anomalies result from variations in atmospheric circulation. Twenty years ago these anomalies were highlighted by droughts in the Soviet Union (1972-1973), England (1976), Sahel (1976), and the United States of America (1977-1979) (Da Cunha et al., 1983). These occurrences have continued throughout the world in the decade of the 1980s. In many areas of the world, the occurrence of drought is a fact of nature. The effects of climate and weather anomalies upon human lives have become more and more significant in recent years because of the increase in the planet's population, the increase in our society's infrasrructure requirements, and the increase in pressure on agriculture to produce adequate food and fiber supplies. Consequently, crop production has decreased in those regions where climatic anomalies and disasters have become more frequent (Da Cunha et al., 1983). Accordingly, many scientists have been aware of the importance of aridity and its application in the classification of lands prone to rainfall deficiencies. Aridity and drought have been and will continue to be popular topics of discussion among scientists, agriculturalists, and policy makers.

Several approaches have been used to define, analyze, compare and classify drought and aridity characteristics. The studies of scientists such as De Martonne (1926), Gorczynski (1939) and Palmer (1965) are a few examples. Most scientists have estimated drought by using a meteorological characteristic rather than a biological response. However, many discrepancies and difficulties have been noted because of the complexity of the phenomena. The intent of this study was, therefore, not to deal with the difficulties of definition, but to provide a simple approach to the calculation of an aridity index and to examine its mean and variability over time. The first discussions about this aridity index were with visiting Russian scientists (Carlson, personal communication).

METHODS

Monthly precipitation and maximum temperature grand-mean data sets were calculated over the 1900-1993 time period by using 27 selected Iowa weather stations, which provided adequate spatial coverage over the state. By using the basic equation described by Barring and Hulme (1991), monthly values for each year for both grand-mean data sets were standardized by using Eqs. 1-2. A monthly aridity index was calculated by using Eq. 3. Data were obtained from the National Oceanic and Atmospheric Administration (1993) for the period 1900 through April 1993. Although inhomogeneities are present in the air temperature data because of various changes that may have occurred at any of these 27 weather stations, no attempt was made to adjust these data, because available station histories were incomplete, or adjustment methodology was not available. It is assumed that a 27 weather-station average will minimize the effect of most inhomogeneities existing at an individual weather station.

The temperature standardization is given by:

$$T'_{ij} = \frac{T_{ij} - \overline{T}_i}{S_{ti}} \tag{1}$$

where

T'_{ij} is the standardized monthly maximum temperature for month i and year j,

T_{ij} is the monthly maximum temperature for month i and year j,

$\overline{T}_i$ is the monthly mean maximum temperature for month i over all years,

S_{ti} is the standard deviation of the maximum temperature over all years for month i, and the precipitation standardization is given in a similar fashion by

$$P'_{ij} = \frac{P_{ij} - \overline{P}_i}{S_{pi}} \tag{2}$$

where terms are analogous to the air temperature terms in Eq. 1.

The index of aridity for each month (i) and year (j) is given by:

$$AI_{ij} = T'_{ij} - P'_{ij} \tag{3}$$

Because of the configuration of this equation, positive values of this index are generally associated with warm and dty weather conditions. The opposite would be true for negative values. Both air temperature and precipitation are equally weighted.

The indices were examined for trends in interannual variability and also for recurrent features. Various n-month moving mean and standard deviations were computed to eliminate short-term variations.

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Baker et al. (1993) also utilized this methodology for detection of low variation periods in annual temperature time series. In addition, the procedures described by Tukey (1950), Landsberg et al. (1959), Mitchell (1971), and Haung and Li (1984) were used to identify and statistically test for significant periodicities. Spectral densities were computed and tested for each index.

Stressful conditions associated with successive months of dry and warm conditions would likely be detrimental to agricultural production, especially if they occurred during the warm season. Therefore, the probability distribution for runs of consecutive months with positive aridity-index values was determined.

Lastly, multiple regression and multivariate analyses were used to identify significant relationships between corn and soybean district yields and the monthly aridity indices. The west-central district of Iowa was selected for this study because of frequent stressful weather. The data used in this yield-weather analysis covered the period 1954-1991 and were provided by the Iowa Departments of Commerce and Agriculture.

RESULTS

1. Relationship to yield

The trend of corn yields is shown in Fig. 1 for west-central Iowa. The straight line through these data represents a "least fit" linear regression model given by $\hat{y} = a + bx$. Yield = $\hat{y}$ and is given in kgs/hectare, a = 3588.7, b = 126.86, and time (x) is represented as years (1954 = 1), with r = 0.84. The increase in yield over time reflected by the linear regression line in Fig. 1 results from multiple factors. Better hybrids and management practices are important, but it is difficult to assign proper weight to either factor. Also, the occurrence of diseases or insect influence may be present to some extent. A more refined data set than what was available to these authors would be needed to ascertain these factors. The time period from 1957 until 1973 is notable because yields increased linearly with time and only one year was significantly below expectation. Both high and low yields have been evident since 1973. This has also been reported for Minnesota corn yields (Baker et al., 1993).

Corn yield residuals about the regression line in Fig. 1 were computed and correlated with the following monthly weather variables: July and August heat stress (Carlson, 1990), July 1 and August 1 soil moisture levels (Shaw, 1983), and the aridity indices for July and August. Comparable yield residuals were compiled for district soybean yields. These results are given in Table 1. The highest correlations with both crops were with the aridity indices. Also, the month of significance seems related to crop phenology and sensitivity to moisture deficits. Corn and soybeans were correlated to July and August aridity indices, respectively. As expected, the correlations were negative, indicating that yield reductions are associated with positive aridity-index values, i.e., warm and dry weather conditions. The results given in Table 1 lend credence to the study of long-term trends for this rather crude and simple index of aridity.

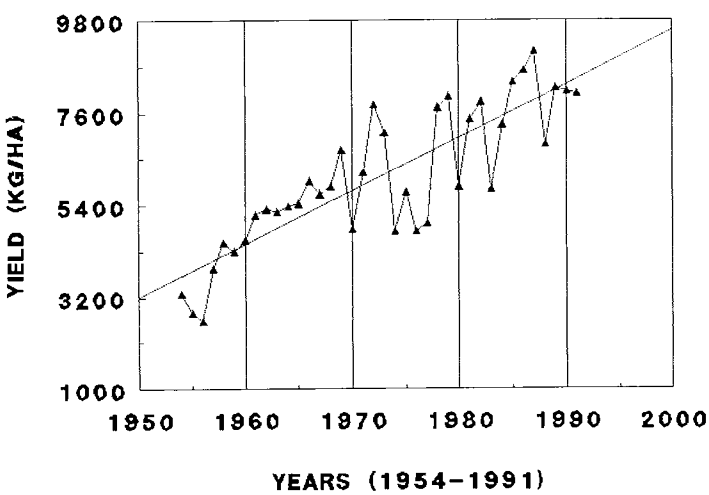

Fig. 1 Time trend of corn yields from the west central district of Iowa.

Table 1. Simple correlations between time-adjusted yield residuals and selected summer weather variables.

	July			August		
	Aridity Index	Heat Stress	Soil Moisture	Aridity Index	Heat Stress	Soil Moisture
corn residual	−0.67[a]	−0.60	0.37	−0.36	−0.46	0.58
soybean residual	−0.39	−0.21	0.23	−0.64	−0.49	0.37

[a] Values exceeding −0.41 or 0.41 are significant at the 1% level.

2. Trends of variation

Figure 2 shows the consecutive monthly pattern for the aridity index. Considerable variation is present as expected for a continental location. The frequent passage of air masses coupled to changing patterns of upper atmospheric winds creates periods of anomalous temperature and precipitation. The lowest extreme values occurred during the recent summer of 1992, and the highest occurred during the dry, hot summers of 1934 and 1936.

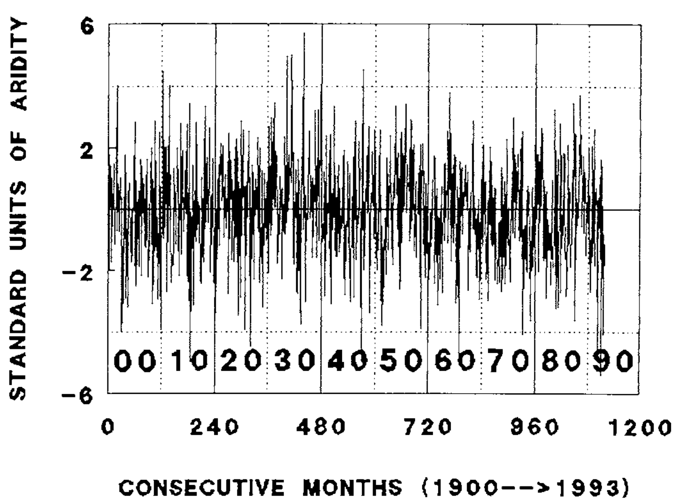

Fig. 2. Month-by-month aridity index with decades indicated in bold.

It is extremely difficult to discern patterns of weather from Fig. 2. Therefore, 12-month moving means were computed. The 12-month moving mean aridity index is shown in Fig. 3. The averaging removed much of the short-term variation but consecutive 12-month periods are still characterized by wide-ranging standardized values, with some recurrent patterns visually evident. Positive anomalies tended to increase from 1900 until 1940 (Fig. 3) and then decline through the seventies. The late 1950s through middle 1970s period is rather low and unchanging from year to year in Fig. 3. Most negative values are present, except for the peak around 1963. The impli-

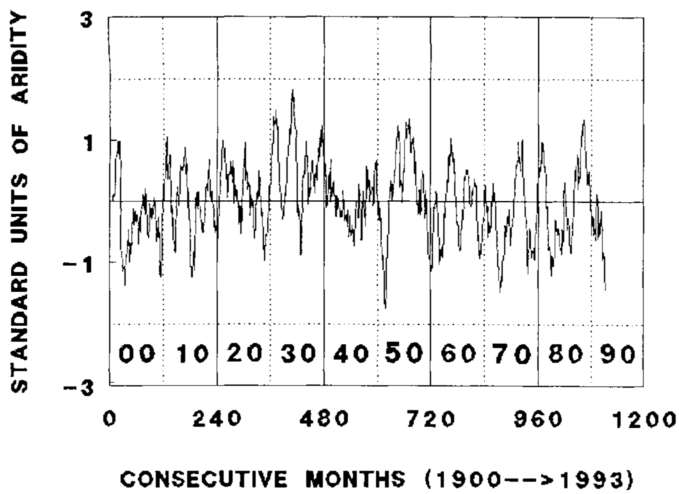

Fig. 3. Twelve-month moving means of the aridity index.

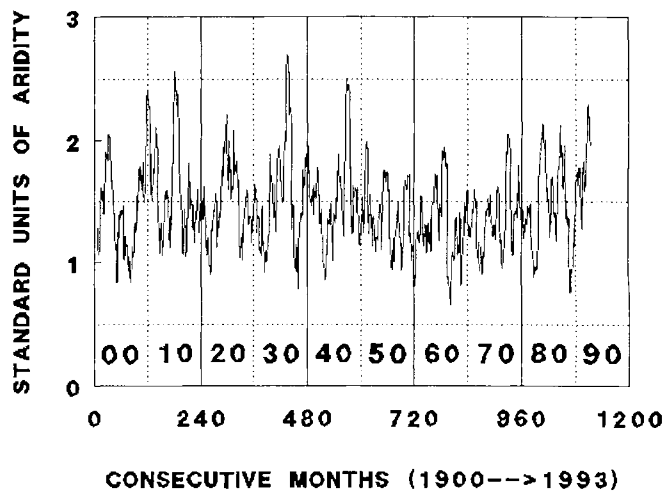

Fig. 5. Twelve-month moving standard deviations of the aridity index.

cations of this will be addressed later. The 1940s were also quite low in value. Although considerable variations were present in Fig. 3, the 1930s, 1950s, and 1980s are renowned for drought, and reveal large positive indices (i.e., warm and dry). Other time periods reveal comparable negative indices (cool and wet weather conditions). The pattern for the precipitation index is not shown, but exhibited a visually more random pattern than either Figs. 2 or 3.

Month to month variations were identified by calculating various n-month moving standard deviations. The reader may gain a better feeling for our intent in this methodology by starting at any month in Fig. 4 and by moving forward a certain number of months (12 will be illustrated shortly). Note the variation in these numbers, then advance 1 month forward and repeat this mental accounting process. We are trying to identify time periods where month to month variation is large or small. In Fig. 4, 1900 and 1904 are rather unchanging, but the other years show marked variation from month to month. It is felt that during periods of high variation, the management of agricultural production is more difficult than when variation is low, especially when the variation is coincident with the crop growing season. Fig. 5 shows the pattern for the consecutive 12-month moving standard deviations of the aridity index. Considerable changes over time in the 12-month variation are evident. Over the entire period from 1900 until June 1992, the middle 1930s contained the 12-month periods that were most variable.

These figures (3 and 5) include the benign period extending from the late 1950s until the mid-1970s. This period was described by Thompson (1969), Carlson (1990), and Baker et al. (1993) as being very favorable for agricultural production in the midwest. With the exception of the peak during the mid-1960s, weather conditions were generally cool and moist, and production of corn and soybeans was high relative to contemporary levels of technology (Fig. 1). There is a tendency for the values in Fig. 5 to increase from 1900 through the 1930s, to decrease until the mid-1970s, then to increase through the present. The reason for this is unknown, but may be important relative to global warming implications. Fig. 6 highlights the 1940s and the 1950s. The change in weather conditions from June 1947 to July and August 1947 produced a remarkable index change from –5 to 4. This is the largest month to month change for the entire time

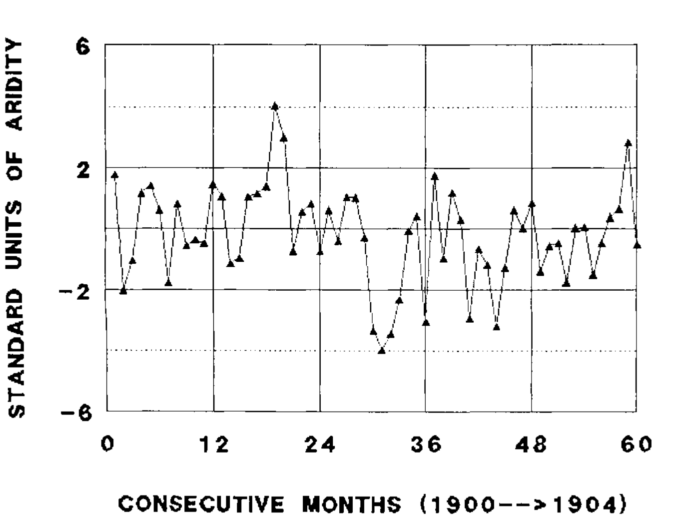

Fig. 4. Month-to-month variation in the aridity index for 1900 until 1904.

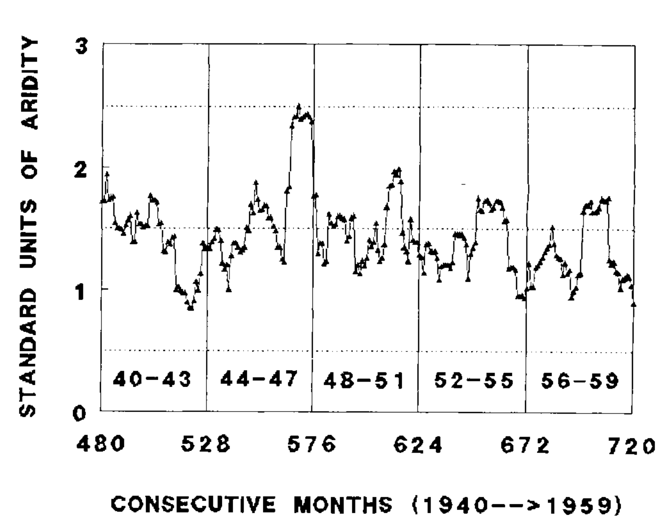

Fig. 6. Twelve-month moving standard deviations of the aridity index for 1940 through 1959.

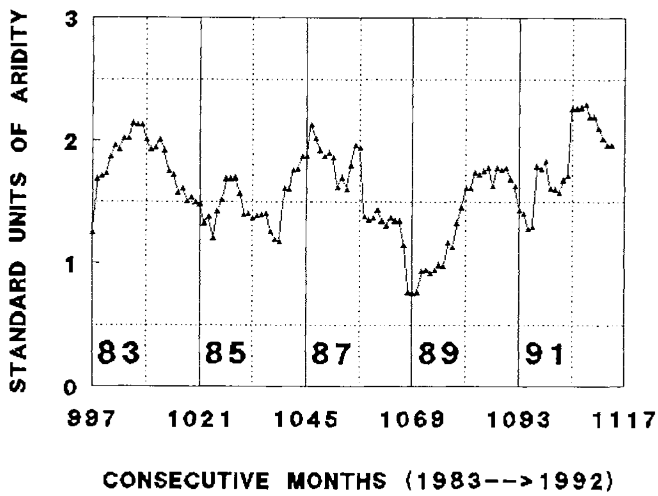

Fig. 7. Like Fig. 6, except for 1983 through 1992.

series. Our Iowa experience tells us that the recent decade has expressed wide extremes of weather. This is confirmed by Fig. 7.

The index of aridity was further smoothed by calculating moving standard deviations over 24, 48 and 120 months. As expected, increasing the length of the moving time period greatly masks the inherent month to month variation by reducing the amplitude. Still, time periods exhibit large or small month to month variation. The increase in variation of 1960s and 1970s, is more like what was experienced by Iowans earlier in this century. Similar results have been obtained by using the same methodology applied to seasonal, rather than monthly data (Fig. 8). The reason for the gradual increase of this variation during the 1970s and the 1980s is unknown, but variation at these levels has occurred before in Iowa during this century.

3. Runs of specific index types

Because successive months of dry and warm weather would be detrimental to agricultural production, the probability distribution for consecutive months with positive aridity indices was determined. The probabilities of having three, six, nine or twelve consecutive months were only 20, 8, 4, and 1%, respectively. Fortunately, these probabilities are quite low. The longest runs identified were of lengths 11, 12, and 10 months occurring in 1931, 1934, and 1954, respectively. The longest run of positive monthly maximum temperature indices was 10 months and it ended in August of 1934. A run of 17 consecutive months with negative temperature indices progressed through October of 1993. This established a new run-length record. Below-normal monthly precipitation runs maximized at 14 months, and that run of below normal rainfall ended in June of 1956.

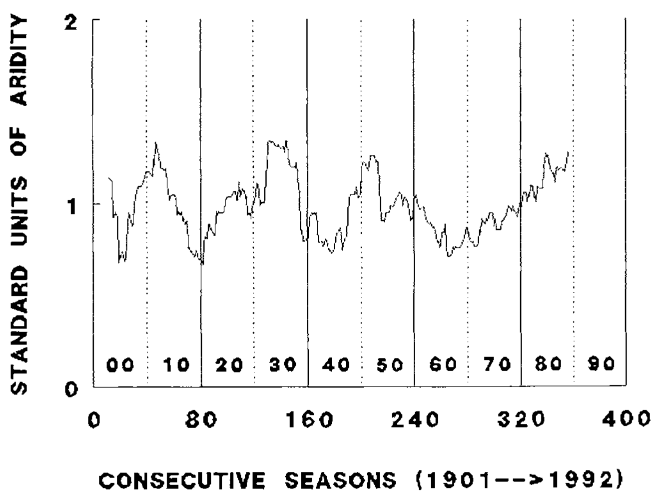

Fig. 8. Twenty four-month moving standard deviations of the seasonal aridity index..

4. Spectral analyses

Spectral analyses were used to test for periodic variation in these time series. The raw, unsmoothed values of aridity, temperature and precipitation were used in the computation of the spectral densities. The power spectrum of the index of aridity revealed three significant peaks near 38.9 (3), 52.1 (4) and 138.5 (11) months (years). The behavior of the peak at 138.5 months is somewhat similar to the well-known sunspot cycle (Waldmeier, 1961) and the shorter cycles maybe related to El Niño events. These events recur approximately every 3 to 8 years (Rasmusson and Wallace, 1983). Other peaks observed at very low or high periods were likely caused by noise or random components (Bloomfield, 1976). The power spectrum for standardized rainfall also showed three peaks, which were near 38.9 (3), 49.7 (4) and 123 (10) months (years). Like the aridity index peaks, the first two are somewhat like the El Niño cycle. The power spectrum of temperature shows a number of significant peaks near 4, 6, 8 and 11 years. The tests for significance at the 95% level were determined by using the method developed by Mitchell et al. (1966).

CONCLUSIONS

Results from the time-series analysis of the index of aridity indicated that extreme indices occurred during the summers of 1936 (high) and 1992 (low). The 12-month moving mean and standard deviations for this index revealed extreme conditions throughout the 1900-1993 time period. A period of low mean values and low variation was evident during the late 1950s until the middle 1970s. This was concurrent with consistent corn and soybean yields. The change in variabilities over time for rainfall was less pronounced than were maximum air-temperatures. Trends of variation observed by employing moving standard deviations revealed an increase in variation in the last 2 decades. The present level is similar to the variation experienced earlier in this century. Results from the spectral analyses revealed 10 to 11-year recurrence for all indices. This may be related to known solar activity. Other significant peaks were observed near 3, 4, 6, and 8 year cycles. These may be associated with the El Niño recurrence.

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