The Sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their Calibration Coefficients Including Potential Evapotranspiration*

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ABSTRACT

The Palmer Drought Severity Index (PDSI) is routinely made available by NOAA for operational use, and it has also been calculated across the United States on a historical basis back to 1895 (Karl *et al.*, 1983). Traditionally, the coefficients used in the calculation of the PDSI have been based on an anomalously hot and dry period across much of the United States (1931–60). By changing the base period used to calibrate the coefficients, the magnitude and the sign of the PDSI change significantly in many areas of the United States. Often the changes are larger than those that occur when the potential evapotranspiration is forced to a constant equal to the long-term monthly mean potential evapotranspiration. This sensitivity to base period calibration has important implications in the interpretation of operational or hindcast values of the PDSI for forest fire danger and other applications. The less frequently used Palmer moisture anomaly index (Z-index) is much less sensitive to changes in the calibration periods, and also has some desirable characteristics which may make it preferable to the PDSI for some agricultural and forest fire applications, i.e., it is more responsive to short-term moisture anomalies.

1. Introduction

The Palmer Drought Severity Index (PDSI) has been used as a tool to monitor environmental conditions conducive to forest fire danger (Haines *et al.*, 1976; Haines *et al.*, 1978), and it has found application in countless other studies and real-time environmental monitoring. Since the index is based on a fairly complex bookkeeping water-budget system, only a few studies (Alley, 1984; Karl, 1983) have addressed the sensitivity of the index to its various assumptions and parameterizations. Interested readers are referred to both of these articles for general assessments of many of the weaknesses and strengths of the index. Neither of these articles however, tests the sensitivity of the PDSI to its calibration period. The calibration period is defined as the period of record used to establish whether conditions are unfavorably dry or wet. The effect of the calibration period is discussed in this article based on data from climate division averages (344 in the contiguous United States) of monthly mean temperature and total precipitation (1895–1983) as described by Karl *et al.* (1983).

The National Climatic Data Center has on file in TD9640 (Historical Climate Data) the PDSI and the Z-index for the 344 climatic divisions back to 1895. The calibration period used is 1931–83 (Karl and Knight, 1985a,b). The seldom used Z-index (the monthly moisture anomaly index) is also derived from the Palmer model, and it is quite likely to contain better estimates of forest fire danger and agriculture moisture shortages than the PDSI. The Z-index is much more responsive to short-term moisture deficiencies than the PDSI. One example of its potential to capture short-term moisture deficiencies is provided by Sakamoto (1978) who uses it with considerable success in a wheat yield model. The Z-index has not been tested in assessing forest fire potential, but it may be a useful tool.

2. The Palmer drought model

Palmer originally designed his drought computations for monthly average data using the principles of a balance between moisture supply and demand. Man-made changes (i.e., increased irrigation, new reservoirs, added industrial water use, etc.) in local moisture supply and demand are totally ignored in the index. The PDSI is a meteorological drought index. In this regard the first month the weather begins to change from dry (or wet) to near normal or wet (or dry), the drought or wet spell ends despite the fact that soil moisture and/or the lakes, rivers, and reservoirs may still be considerably below or above their normal levels. When the PDSI is used in an operational mode (calculated in real time), such as is done every month during the warm season by the National Weather Service, the PDSI is no longer a meteorological drought index. The PDSI then refers to what may be more appropriately termed the Palmer

Hydrological Drought Index (PHDI). This distinction will be elaborated upon in subsequent paragraphs. In order to appreciate the origins of this index, it will be necessary to first concentrate on the development of the PDSI. Before the calculations of the monthly values of the PDSI begin, several parameters are derived from the input temperature and precipitation data by calculating quantities that are climatically appropriate for existing conditions (CAFEC; these quantities will be denoted by a circumflex caret). Other parameters which are directly input into the Palmer model are the available water capacity (AWC) of the soil, and heat index terms used in the Thornthwaite potential evapotranspiration equation. The CAFEC quantities are defined by

$$\widehat{ET} = \alpha PE, \tag{1}$$

$$\hat{R} = \beta PR, \tag{2}$$

$$\widehat{RO} = \gamma PRO, \tag{3}$$

$$\hat{L} = \delta PL, \tag{4}$$

$$\hat{P} = \widehat{ET} + \hat{R} + \widehat{RO} - \hat{L}, \tag{5}$$

where ET is the evapotranspiration, PE the potential evapotranspiration, R the soil water recharge, PR the potential recharge, RO the runoff, PRO the potential runoff, L the water loss from the soil, PL the potential water loss from the soil, and P the precipitation. Equation (5) is analogous to the hydrological water balance equation, whereby precipitation (P) is equal to the evapotranspiration (ET) plus runoff (RO) plus or minus any change in soil and/or ground water storage ($R - L$). The parameters α, β, γ, and δ for each of the 12 months at each location are defined by

$$\alpha = (\overline{ET})(\overline{PE})^{-1}, \tag{6}$$

$$\beta = (\bar{R})(\overline{PR})^{-1}, \tag{7}$$

$$\gamma = (\overline{RO})(\overline{PRO})^{-1}, \tag{8}$$

$$\delta = (\bar{L})(\overline{PL})^{-1}, \tag{9}$$

where the overbar quantity within parenthesis denotes the monthly average over the period of record. For the actual calculation of a monthly measure of moisture abnormality, P is compared to $\hat{P}$ such that

$$d = P - \hat{P}, \tag{10}$$

and d is regarded as a moisture departure from normal. Since the final objective measure of moisture conditions is intended to be a standardized index, comparable for a variety of locations for any given month, d is weighted by another parameter K such that

$$Z = dK. \tag{11}$$

The value of Z is regarded as the "moisture anomaly index." Each Z expresses on a monthly basis and from a moisture standpoint the departure of the weather of a *particular month* from the average moisture climate

of that month. The values of Z reflect short-term moisture deficiencies or excesses. These values can indicate favorable moisture conditions over a particularly wet or dry month in the midst of a serious long-term drought or wet period.

The value of K (the weighting factor) is determined from the climate record before the actual model calculations begin. The derivation of K by Palmer (1965) was by no means a simple task. After considerable experimenting, Palmer finally established empirical relationships for K which appear to give satisfactory results

where

$$K_i = \left(\frac{17.67}{\sum_{i=1}^{12} \bar{D}_i K_i'} \right) K_i', \tag{12}$$

$$K_i' = 1.5 \log\left(\frac{\overline{PE} + \bar{R} + \overline{RO}}{\bar{P} + \bar{L}}\right) + 2.8\bar{D}_i^{-1} + 0.5. \tag{13}$$

In Eqs. (12) and (13), $\bar{D}$ is the monthly mean of the absolute values of d over all years of record, and the subscript i denotes the specific month of consideration. The value of K_i' in Equation (13) is dependent on the average water supply ($P + L$) and demand (PE + R + RO). Simply by trial and error Palmer found that K also should vary inversely with D [Eq. (13)]. The technical details regarding these derivations are provided by Palmer (1965).

Having established the value of K, the values of Z in Eq. (11) are used to determine the monthly PDSI such that

$$PDSI_i = PDSI_{i-1} + \frac{1}{3}Z_i - 0.103PDSI_{i-1}, \tag{14}$$

where the initial months in a spell of dry or wet weather are simply,

$$PDSI_i = \frac{1}{3}Z_i. \tag{15}$$

The third term on the right-hand side of the equality in Eq. (14) is included so that when Z = 0 (an "average

TABLE 1. Classes for wet and dry periods.

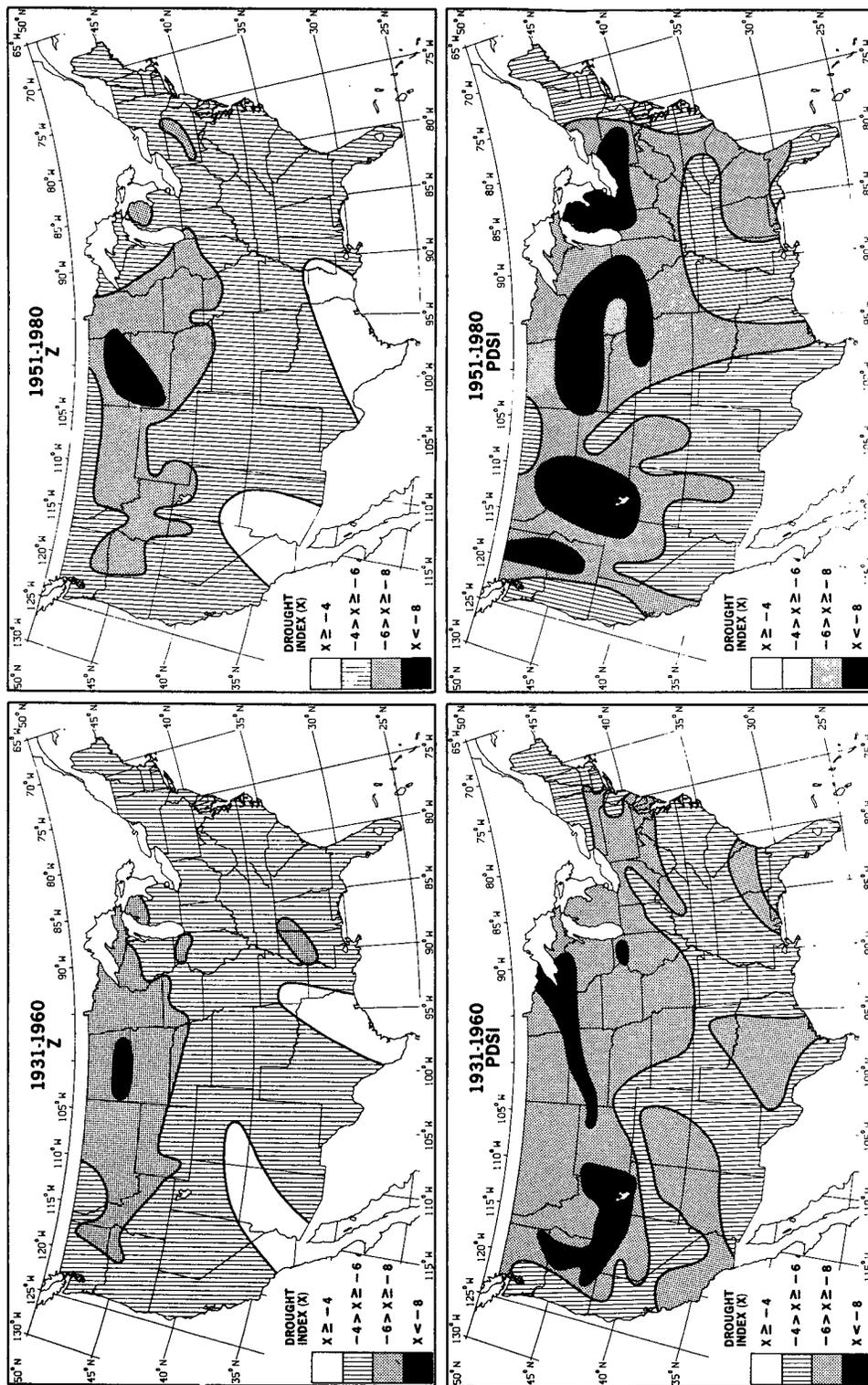| Approximate cumulative frequency (%)	PDSI or PHDI	Category	Z
≥96	≥4.00	Extreme wetness	≥3.50
90–95	3.00–3.99	Severe wetness	2.50–3.49
73–89	1.50–2.99	Mild to moderate wetness	1.00–2.49
28–72	−1.49–1.49	Near normal	−1.24–0.99
11–27	−1.50–−2.99	Mild to moderate drought	−1.25–−1.99
5–10	−3.00–−3.99	Severe drought	−2.00–−2.74
≤4	≤−4.00	Extreme drought	≤−2.75

FIG. 1. Lowest PDSI and Z-index for two different calibration periods, but identical sample sizes (1931–83).
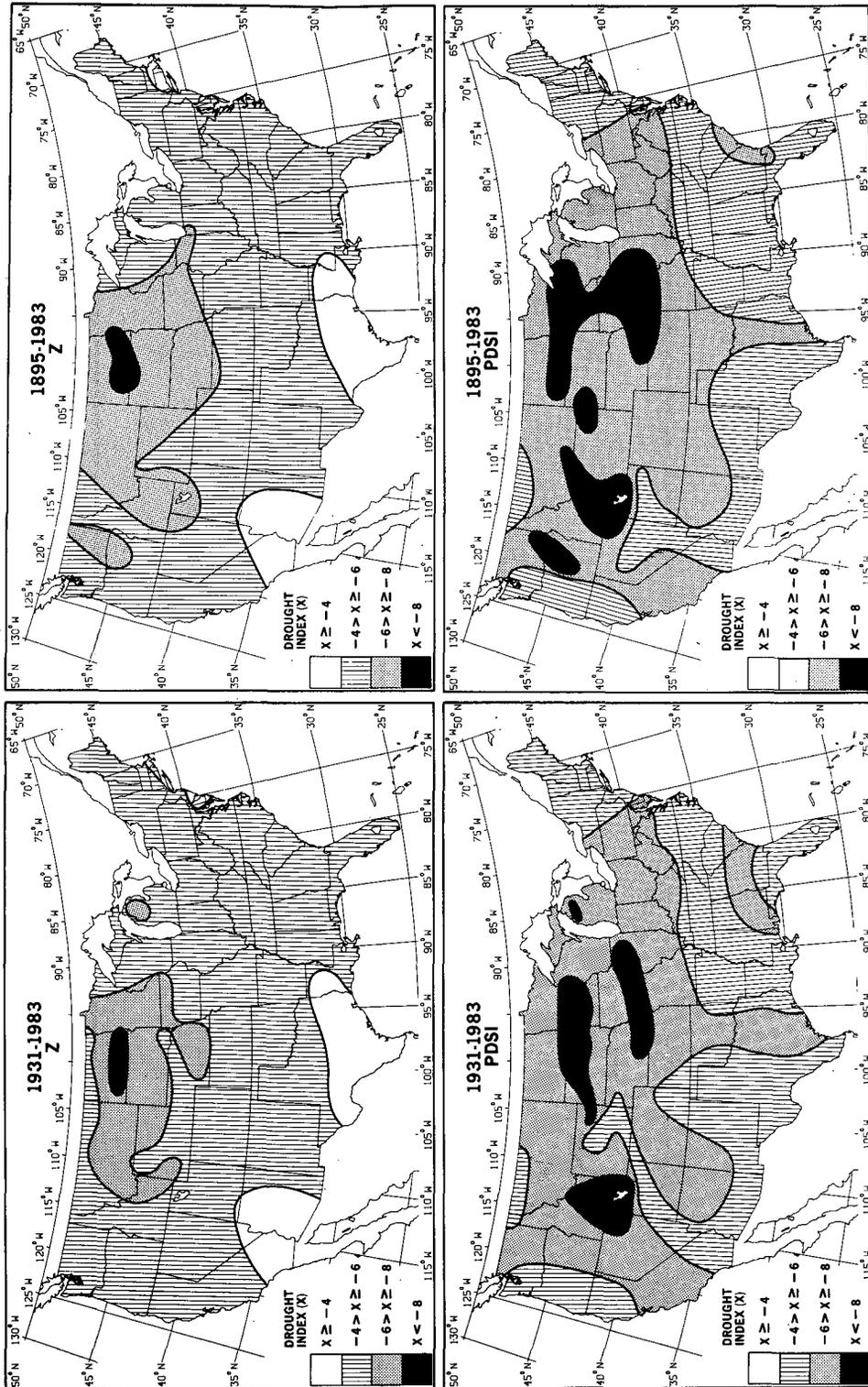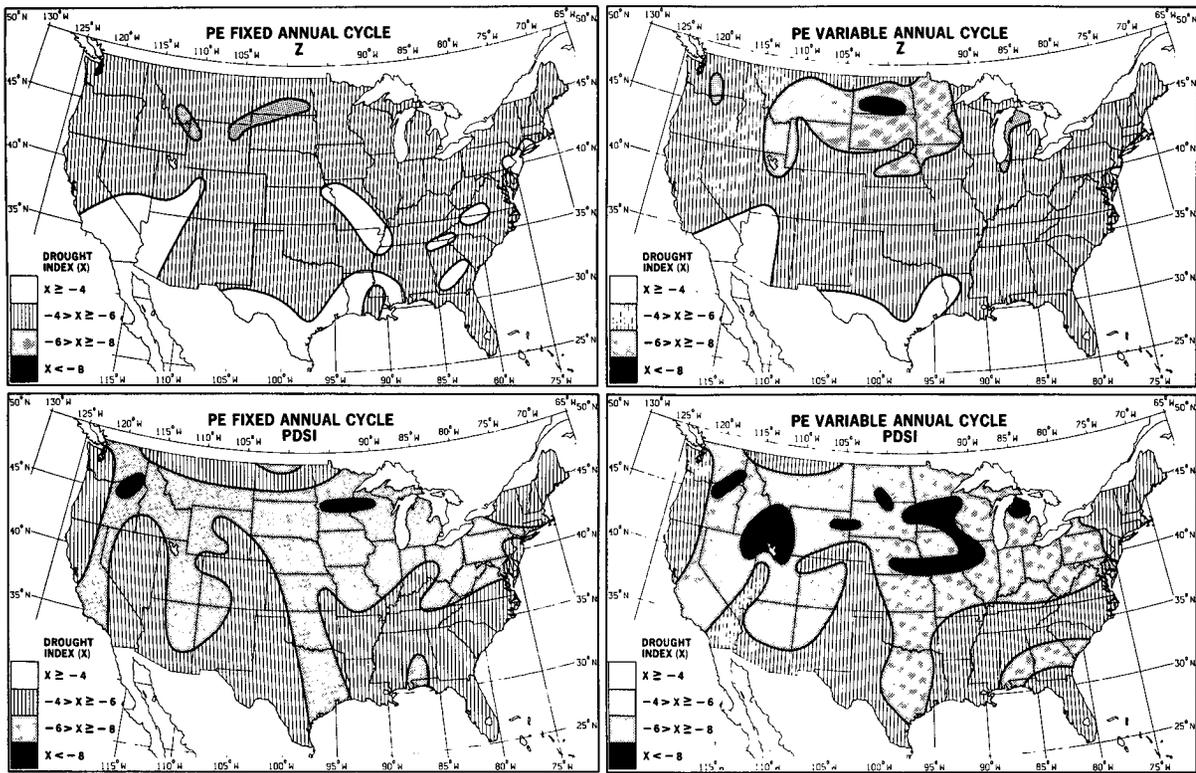
FIG. 2. As in Fig. 1.

FIG. 3. Lowest PDSI and Z-index when the annual cycle of PE is artificially held constant from year-to-year vs a variable annual cycle of PE.

month") the PDSI for the current spell of wet or dry weather tends to approach zero. The "1/3" factor in the second term is a result of empirical relationships derived from negative values of Z (the moisture anomaly index) which have accumulated during various time intervals in western Kansas and central Iowa.

Palmer (1965) could have stopped at this point and used Eq. (14), which would then perhaps be more appropriately termed a hydrological drought index. The term hydrological drought index is used as it pertains to a systematic accounting of the terms associated with moisture inflow (P), outflow (PE + RO), and a change in storage ($R - L$). This was not his original intent, however; he went on to develop a meteorological drought index. This meant he had to consider when the spell of anomalously dry or wet weather was over, and not wait to end a drought or wet spell when the average moisture demand was satisfied. In order to accomplish this he developed the term P_e which expresses the moisture received as a percentage of the moisture required to definitely terminate a drought (wet spell); i.e., meet the average moisture demand PE + R + RO. This term P_e can be viewed as the percentage probability that a drought (wet spell) has ended and is defined as

TABLE 2. The effect of various calibration periods and methods of calculating PE on the various drought indices. E represents the standard error of estimate between the two data sets and s is the standard deviation of the data set listed first (top row of each column).

	Calibration period or calibration technique of PE		
Quantity	1931–60 vs 1951–80	1931–83 vs 1895–1983	Variable annual cycle (PE) vs fixed annual cycle (PE)
	PSDI		
s	2.44	2.34	2.34
E	1.09	0.65	0.75
E/s	0.45	0.28	0.32
	Z		
s	1.98	1.90	1.90
E	0.54	0.25	0.36
E/s	0.27	0.13	0.19
	PHDI		
s	2.55	2.46	2.46
E	1.02	0.59	0.66
E/s	0.40	0.24	0.27

$$P_e = \frac{\sum\limits_{j=0}^{j=j^*} U_{i-j}}{Z_e + \sum\limits_{j=1}^{j=j^*} U_{i-j}} \times 100\%, \qquad (16)$$

where

$$Z_e = -2.691(PDSI_{i-1}) - 1.5 \qquad (17)$$

in a drought, and

$$Z_e = -2.691(PDSI_{i-1}) + 1.5 \qquad (18)$$

in a wet spell. The term Z_e is the value of Z in a single month required to bring the PDSI to -0.5 (0.5 in a wet spell) as derived from Eq. (14). In Eq. (16) j indicates the number of months of lag, j^* is the first month of the current wet or dry spell, and U is equal to Z + 0.15 in a drought and $Z - 0.15$ in a wet spell. In a drought or wet spell when P_e equals 100%, the drought or wet spell is definitely over, but the drought or wet spell is not ended during the month when P_e reaches 100%. The drought or wet spell is considered to have ended the first month when P_e became greater than 0% and then continued to remain above 0% until it
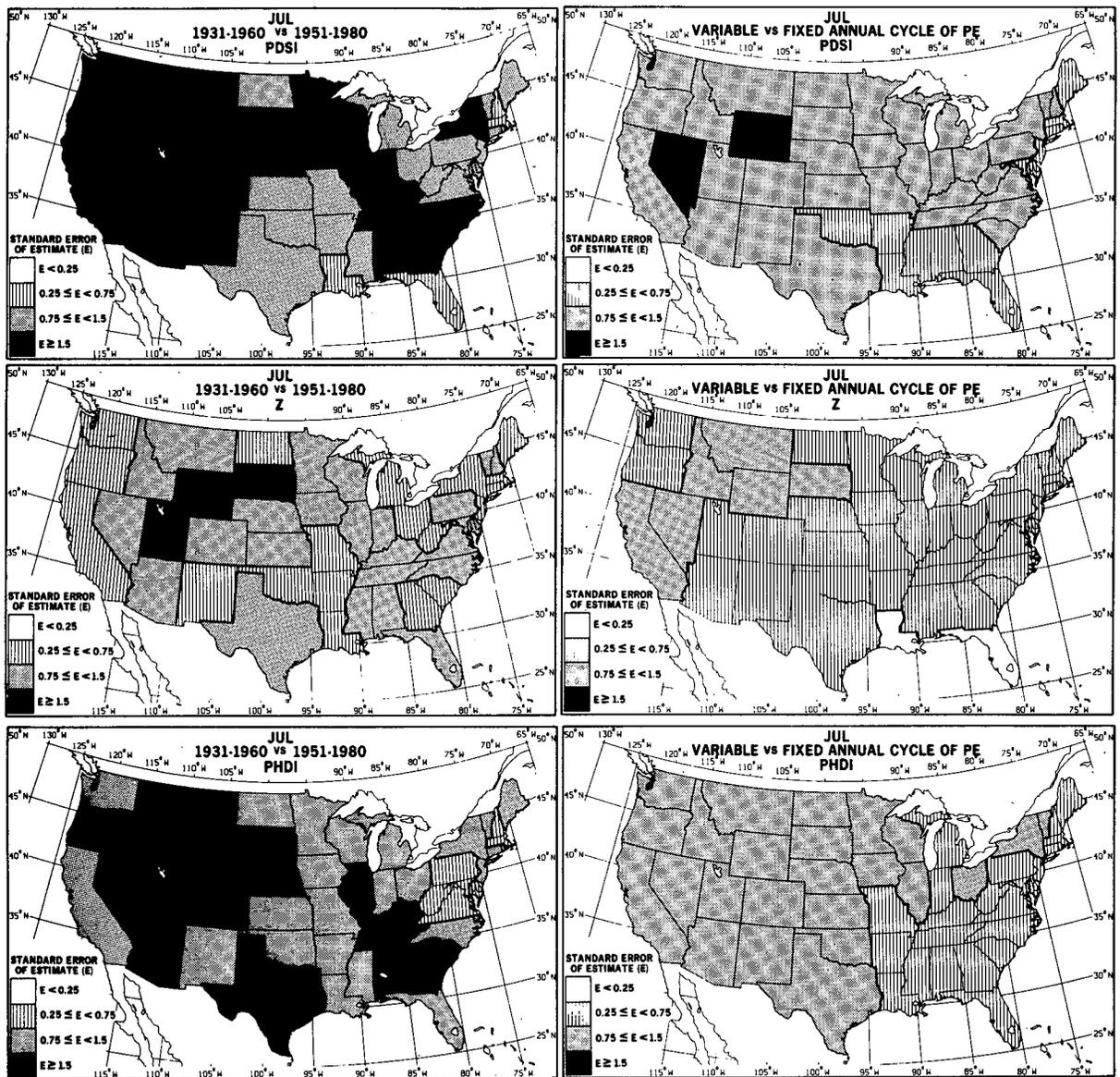

FIG. 4. Statewide averages of the standard errors of estimate between the PDSI, PHDI, and the Z-index for two different calibration periods, and when the annual cycle of PE is artificially held constant from year-to-year vs a variable annual cycle of PE.

attained the value of 100%. For example, if P_e is equal to 0, 5, 25, 75, and 100% during a five-consecutive month sequence, then the drought is considered to have ended during the second month in the sequence, i.e., when P_e equals 5%. It is apparent that this backstepping procedure of ending droughts or wet spells cannot be satisfactorily used for real time calculations of PDSIs (operational PDSIs) since one cannot know in advance whether a few months of wet or dry weather are the beginnings of a new spell of wet or dry weather or merely a temporary interruption of the current drought or wet spell. The so-called Palmer Hydrological Drought Index does not change sign until P_e equals 100%, and it only differs from the actual value of the PDSI when a series of months are encountered when $0 < P_e < 100\%$.

Qualitatively, the main difference between the PDSI and the PHDI is in their treatment of the beginning and ending times of droughts or wet periods. During the maximum severity of a drought or wet spell these indices are identical. The PDSI is a meteorological drought index and it attempts to classify spells of weather. This means that once the weather begins to return to a new regime, regardless of soil moisture conditions, streamflow, or lake levels, etc., the index will rapidly respond and return to near normal values. The PHDIs should more closely reflect water availability (i.e., soil moisture, streamflow, and lake levels) when a drought or wet spell is ending than the traditional PDSI using the backstepping process. Once the weather begins to establish a new regime, the index will only slowly respond because it is more closely tied to the water storage. The Z-index on the other hand will be quite sensitive to unusually wet (or dry) months even in an extended period of dry (or wet) weather. Table 1 contains a qualitative description of the various classes of the PDSI, PHDI, and Z. The classes are based on the cumulative percent frequency distribution of the PDSI and the Z-index across all months and climate divisions. It should be emphasized that these qualitative descriptions are rather arbitrary. It is important to realize that the Z-index is standardized across all 12 months. This means that it is quite possible and common for some months which typically have low precipitation, and/or low moisture reserves, and/or high potential evapotranspiration, and/or low run-off (i.e. northern locations in winter, arid areas during the dry season) to never have Z-indices less than minus two. Contrarily, areas and times of the year which typically have favorable moisture conditions, high reserves, ample precipitation, low potential evapotranspiration, and high runoff, can have very low Z indices (< minus five) during a dry month. Additionally, the Z-index has no theoretical upper limit (i.e., precipitation has no upper bound), but it does have a theoretical lower limit (i.e., precipitation is zero with little or no moisture reserve). In practice the PDSI and the PHDI attain nearly the

same magnitudes, both positive and negative, across all 12 months of the year.

3. Results

The period of record used to calculate the CAFEC quantities has traditionally been 1931–60. The National Climatic Data Center until recently (Karl *et al.,* 1983) used this base period exclusively in their operational and archived PDSIs. To date the National Weather Service still uses this base period exclusively in their operational PDSIs. Figures 1 and 2 depict the
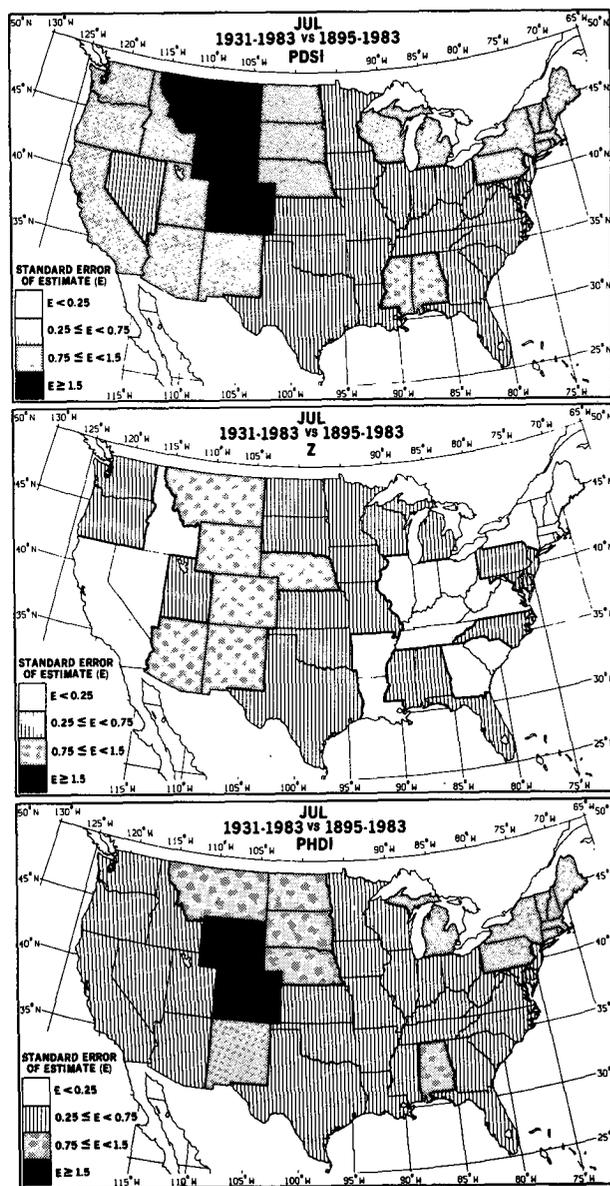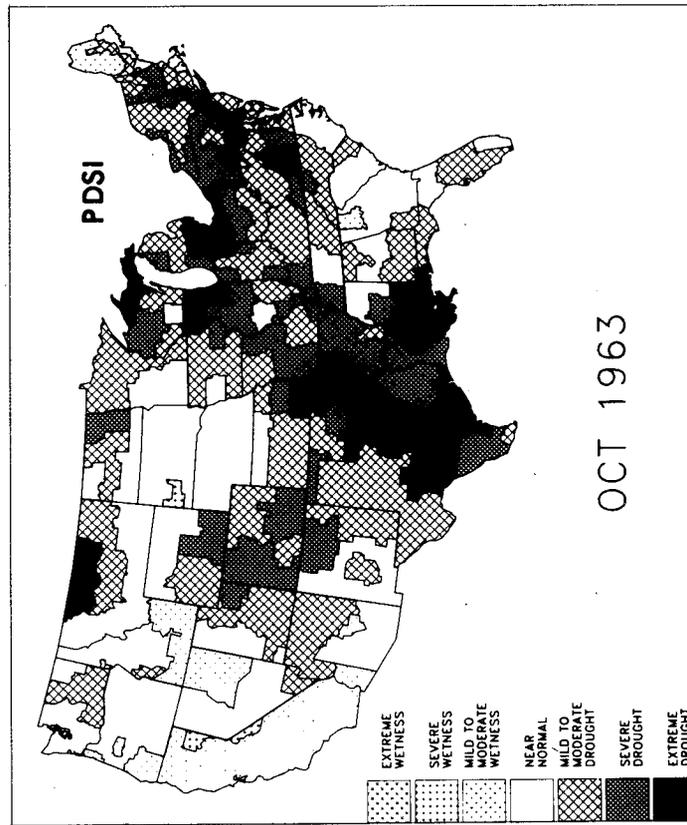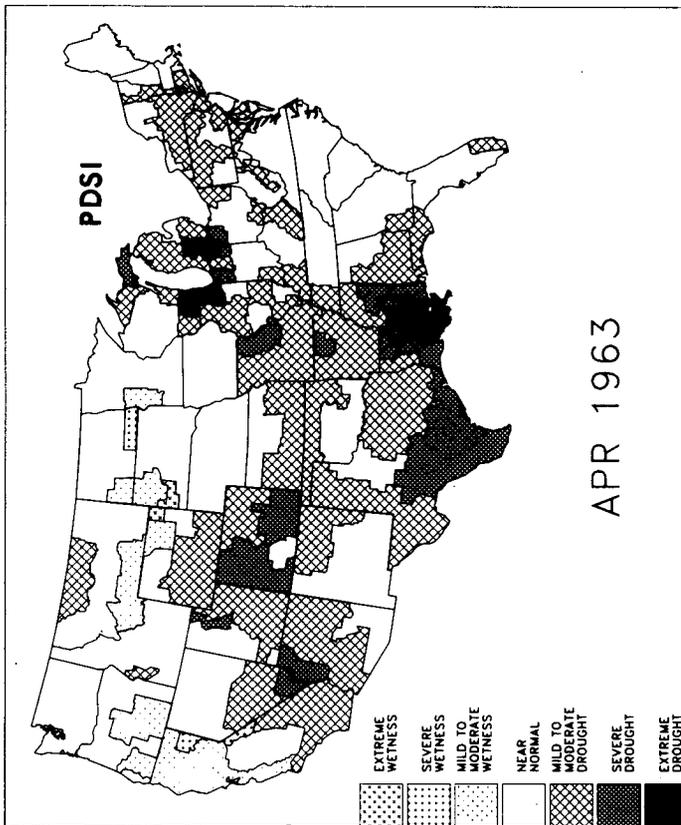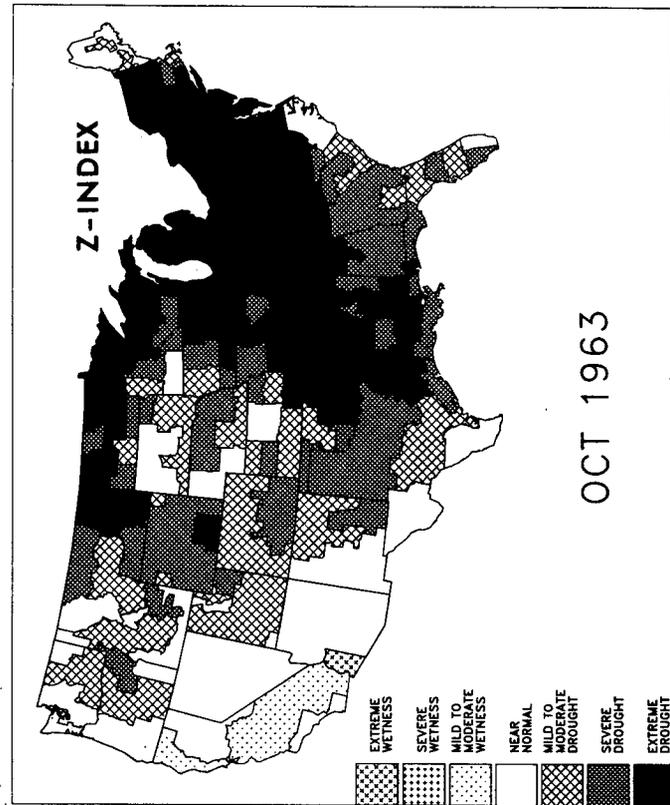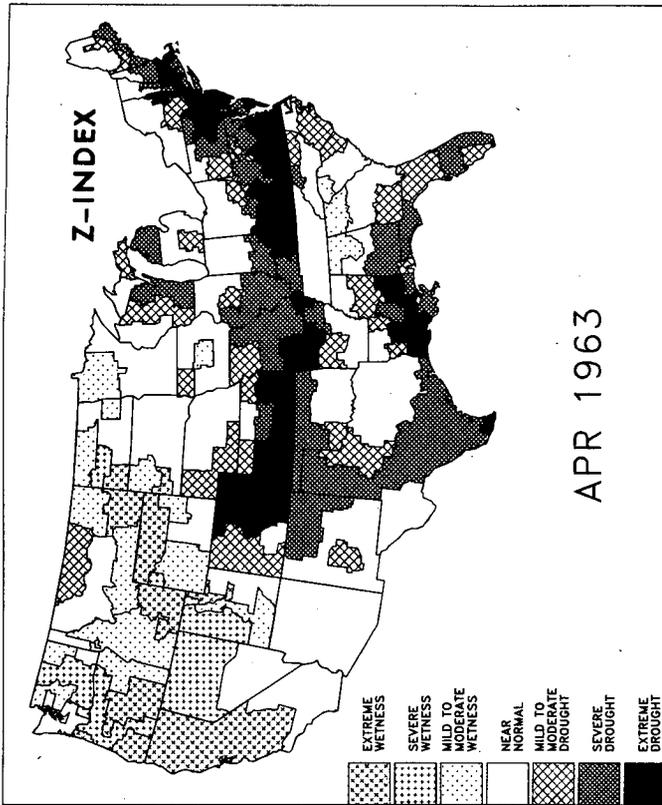

FIG. 5. Statewide averages of the standard errors of estimate between the PDSI, PHDI, and the Z-index for two different calibration periods.

inconsistencies that can arise in the magnitude of the most extreme droughts across the United States when different calibration periods are used for the CAFEC quantities and K. In Figs. 1 and 2 and throughout this paper all assessments regarding the effects of varying calibration periods are based on a 53-year sample 1931–83, regardless of the calibration period used. Figure 1 indicates that the extreme PDSIs are rather seriously altered by changes in the calibration period. Notice the large expansion of the darkest shaded areas of extreme drought when the wetter period 1951–80 is used to calibrate the data compared to the anomalously hot and dry 1931–60 period. The darkest shaded areas also expand in the 1951–80 calibration period versus the 1931–60 calibration period for the Z-index, but by a considerably smaller amount compared to the PDSI. The similarity of the lowest Z-indices in all areas of the country for the two calibration periods is greater than that of the PDSI. Similar characteristics are found in Fig. 2, but the differences between the magnitude of the Z-index and the PDSI for each of the two calibration periods decreases. This is attributed to the longer calibration periods used which result in more consistent quantities of CAFEC and K. In order to demonstrate the seriousness of this problem the PDSI and the Z-index were calculated using identical calibration periods, but in one data set these indices were calculated by artificially forcing the annual cycle of PE to a constant equal to its long-term mean monthly values and in the other data set the PE was allowed to vary in its normal manner from year-to-year. Figure 3 depicts the results of such an experiment for the lowest values of Z and the PDSI. The differences between the two data sets for Z and the PDSI are substantial, but, more importantly, Fig. 3 indicates that the changes introduced by different 30-year calibration periods can be even greater (Fig. 1) than the effects of gross simplifications of the PE estimates.

Given that substantial differences are noted in the magnitude of the *most extreme* droughts using different 30-year calibration periods, the effect of different calibration periods across *all* values of the data sets was investigated by calculating the standard errors of estimate (E) between the two data sets as well as the standard deviation (s) of any given data set. Table 2 contains this information. The ratio of E/s is used as a measure of the artificial variability E compared to the natural variability s of the data. The larger the ratio of E/s the more serious is the error associated with calibration periods or *PE* modifications. The values in Table 2 are calculated across all 12 months for each data set. By focusing attention on the rows of E/s it is apparent that the most serious discrepancies are introduced by using 30-year calibration periods and the least serious by using longer calibration periods. The lowest

ratios of E/s are for the Z-index followed by the PHDI and the PDSI respectively. These results demonstrate

1) the Z-index is less sensitive to the calibration period compared to either the PDSI or the PHDI; and
2) the longer calibration periods provide more consistent estimates of the CAFEC quantities and K and thus the PDSI, PHDI and Z-index.

Figure 4 provides information on the spatial patterns of the differences of E during July for the two calibration periods, 1931–60 versus 1951–80, and the two methods of calculating PE using the same calibration periods. Again, the drought indices are shown to have greater changes associated with different calibration periods compared to gross alterations in the PE calculations. The advantage of using a longer calibration period can be noted by comparing the left column of Fig. 4 with Fig. 5. Also apparent are the relatively large standard errors associated with the PDSIs compared to the Z-index.

Some of the characteristic differences of the PDSI and the Z-index can be observed in Fig. 6. In 1963 many parts of the eastern half of the United States had several times more than the expected number of forest fires (Banks and Little, 1964; Brotak and Reifsnyder, 1977; Haines et al., 1978). In April of that year a drought, as depicted by the PDSI, was becoming established over the central United States, and by the autumn it became more severe and widespread. Nonetheless, even by the end of October 1963 the drought was still mostly in the mild to severe categories over much of central and northeast United States. Since the PDSI is slow to respond to moisture shortages this is not surprising, but the record breaking dry weather over much of the east during April and particularly October of 1963 is not adequately reflected in the values of the PDSI. On the other hand, the Z index captures the extremely dry weather that occurred over much of the east. In many areas in the east, October of 1963 had the lowest Z-index of any October during the past century (Karl and Knight, 1985c; Karl and Knight, 1985d). The main reason for these differences in the two drought indices can be attributed to Eqs. (11) and (14). The Z-index exclusively includes the moisture anomaly of the ongoing month whereas the PDSI weights the moisture anomaly of previous months more heavily than the current month.

One example of the improved estimates of forest fire potential using the Z-index as opposed to the PDSI is also provided in Fig. 6. In 1963, Pennsylvania had more than the expected number of forest fires (Haines, 1978). Springtime is the peak fire season in the state, but the autumn has a secondary maximum (Haines, 1978). In Fig. 6 the severity of the forest fire potential is more accurately depicted by the Z-index than the PDSI. In

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FIG. 6. Palmer Drought Severity Indices and Z-Indices for various drought categories as defined in Table 1.

April much of the eastern portion of the state is in an extreme moisture deficiency (Z ⩽ −2.75) with Z-indices the third lowest since 1895. The PDSI indicates only a mild-to-moderate drought in the northern half of the state and near-normal conditions elsewhere. In October the Z-index is critically low, lower than any time in the past century, but the PDSI indicates a range of drought conditions across the state from mild to extreme drought. Both the Z-index and the PDSI in Fig. 6 are based on data calibrated from 1931–83.

4. Conclusion

The Z-index is recommended over the PDSI or the PHDI for use in assessing short-term moisture deficiencies. A long calibration period is recommended when using these drought indices, 50 years or more. The Z-index however, is found to be less sensitive to the calibration period compared to the PDSI or PHDI.

The utility of the Z-index in forest fire assessment is yet to be established, but it has some desirable properties that make it attractive for such applications. One such example is indicated in this paper. Most forest fire meteorologists and agricultural interests should find the Z-index more useful than the PDSI.

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