Evaluation of the Palmer Drought Index on the Canadian Prairies

O. O. AKINREMI AND S. M. MCGINN
Research Station, Agriculture and Agri-Food Canada, Lethbridge, Alberta, Canada

A. G. BARR
National Hydrology Research Centre, Atmospheric Environment Service, Saskatoon, Saskatchewan, Canada

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ABSTRACT

Drought on the Canadian prairies is the single most limiting factor to crop yield. Several indices have been developed that indicate the onset, severity, and persistence of drought. This study was conducted to assess the validity of the Palmer Drought index for characterizing drought on the Canadian prairies. When the empirical relationship used by Palmer for calculating the weighting factor K was applied to historical weather data, the relationship appeared inappropriate. There was only a weak relationship between K and the moisture balance variables from which it is usually calculated. The regional correction factor was calculated to be 14.2, which is lower than the generally accepted value of 17.67. A soil water model, the Versatile Soil Moisture Budget (VMB), was coupled with the Palmer model to improve the modeling of soil water. The drought index obtained with the VMB explained 49% of the variation in wheat yield, while the original Palmer index explained 33%. In addition, a new drought index, which does not rely on the weighting factor K explained 57% of the variation in wheat yield, which is almost twice the variation explained by the original Palmer index.

1. Introduction

The recurrent nature of drought and its impact on agriculture necessitates the analysis of its temporal and spatial extent to provide a better understanding of the characteristics of drought on the Canadian prairies. The concept of drought is, however, an elusive one. While its impact is clearly visible, neither its definition nor its measurement is simple. The problem of definition arises, in part, because drought means various things to various people. Drought has been classified into different types, such as meteorologic, hydrologic, economic, or agricultural drought (Yevjevich et al. 1983). Palmer (1965) defined drought as a prolonged and abnormal moisture deficiency. A drought period is an interval of time, generally of the order of months or years, when the moisture supply of a region consistently falls short of the climatically expected or climatically appropriate moisture supply (Palmer 1965). The temporal and spatial dimensions of drought, both of which affect its severity, create problems in generating a drought index. Not only must an anomaly be normalized with respect to location, it must also be normalized in time if it is to produce a meaningful estimate of drought.

Many indices have been devised for different types of drought, including the Rainfall Anomaly index (Van Rooy 1965), the Palmer Drought index (PDI) (Palmer 1965), the Bhalme–Mooley index (Bhalme and Mooley 1980), and the Standardized Anomaly index (Katz and Glantz 1986). Of these indices, the PDI has gained the widest acceptance.

Although the PDI was developed as a measure of meteorologic drought, it takes into account elements of the hydrologic cycle that permit its use as a hydrologic index (Karl et al. 1987). Its appeal to meteorologists is partly due to its use of climatically appropriate variables, which facilitate spatial and temporal comparisons of drought events. The index is currently used by weather centers in the United States and Canada to assess the severity of droughts and wet spells (Jones 1984, 1987; Louie 1986; Street et al. 1986). In spite of its wide acceptance, the methodology used to standardize the PDI for different locations and months is based on limited locations and is only weakly justified on physical and statistical grounds (Alley 1984). Karl (1986) pointed out that changing the base period used to calibrate the coefficients changes the magnitude and sign of the PDI in many areas of the United States. The Palmer Moisture Anomaly index (Z index), on the other hand, was less sensitive to shifts in the calibration period and may be preferable to the PDI for agricultural

Corresponding author address: Dr. S. M. McGinn, Land Resources Sciences Section, Research Centre, Agriculture and Agrifood Canada, P.O. Box 3000, Lethbridge, Alberta TIJ 4B1 Canada.

and forest fire applications, as it was more responsive to short-term moisture anomalies (Karl 1986).

Palmer (1965) found that the annual sum of the monthly moisture anomaly for the nine regions examined ranged from 12.46 to 20.97 with a mean of 17.67. This value was then used as a regional correction factor to permit the comparison of droughts in different regions (Palmer 1965). This figure is generally accepted and is used on the Canadian prairies when the PDI calculations are made (Jones 1984, 1987; Louie 1986; Street et al. 1986). Studies evaluating the basic equations in the PDI model by testing and validating the relationships for other climatic regions are needed. The original derivation of the PDI involved considerable manual computation, which limited its testing. Today, however, computers make it relatively simple to test the model for various climatic regions. Many relationships in the PDI are empirical, and it is essential that they be tested if the index is to be applied beyond the regions for which the relationships were originally developed.

The objective of this study was to assess the validity of the PDI for characterizing drought on the Canadian prairies. In particular, the relationship between the climatic weighting factor K, used for normalizing moisture departures, and the average moisture supply and demand parameters was evaluated. The regional correction factor for Alberta, Saskatchewan, and Manitoba was compared to that obtained by Palmer (1965). Several of the limitations of the PDI technique, identified by previous researchers, were addressed in this study using two approaches. The first approach used a water budget, the Versatile Soil Moisture Budget (VMB), to provide a more detailed description of soil moisture balance. The second approach involved the development of a new index, which does not rely on K, the climatic weighting factor.

2. Computation of the PDI

Several publications describe aspects of PDI, including the computational procedures (Alley 1984, 1985; Karl 1983; Karl 1986; Karl et al. 1987; Palmer 1965). The first step in calculating the PDI is the determination of monthly departure of moisture from normal,

$$d_i = P_i - \hat{P}_i, \quad (1)$$

where d_i is the moisture departure for month i, P_i is the actual precipitation for month i, and $\hat{P}_i$ is the precipitation that Palmer denoted as "climatically appropriate for existing condition" (CAFEC-P). The CAFEC-P is obtained from other CAFEC parameters as

$$\hat{P} = \widehat{\mathrm{ET}} + \hat{R} + \widehat{\mathrm{RO}} - \hat{L}, \quad (2)$$

where $\widehat{\mathrm{ET}}$ is the "expected" or climatically appropriate evapotranspiration (CAFEC-ET), $\hat{R}$ is the expected soil water recharge (CAFEC-R), $\widehat{\mathrm{RO}}$ is the expected runoff (CAFEC-RO), and $\hat{L}$ is the expected water loss from the soil (CAFEC-L). Equation (2) is a simple water balance in the soil–plant system that deducts the expected supply ($\hat{L}$) from the expected demand factors to obtain the water demand that must be met by precipitation. The CAFEC quantities in (2) are obtained as follows:

$$\widehat{\mathrm{ET}} = \alpha \mathrm{PE}, \quad (3)$$

$$\hat{R} = \beta \mathrm{PR}, \quad (4)$$

$$\widehat{\mathrm{RO}} = \tau \mathrm{PRO}, \quad (5)$$

and

$$\hat{L} = \delta \mathrm{PL}, \quad (6)$$

where PE is the potential evapotranspiration, PR is the potential recharge, PRO is the potential runoff, and PL is the potential loss from the soil. The constants α, β, τ, and δ are derived for each month of the year as the ratios of historical averages of ET/PE, R/PR, RO/PRO, and L/PL, respectively. The PDI is calibrated by applying a simple water balance to historical data of a 30-yr normal. The constants α, β, τ, and δ are obtained during this calibration period.

The moisture anomaly index Z_i is obtained as the product of d and the weighting factor K for month i:

$$Z_i = d_i K_i. \quad (7)$$

The PDI, denoted X_i for month i, is a combination of Z_i and the PDI of the previous month:

$$X_i = Z_i/3 + 0.897 X_{i-1}. \quad (8)$$

The weighting factor K is determined initially as K' using an empirical relationship obtained by Palmer (1965):

$$K' = 1.5 \log\left(\frac{\dfrac{\mathrm{PE} + R + \mathrm{RO}}{P + L} + 2.8}{D}\right) + 0.5. \quad (9)$$

The term D in (9) is the mean of the absolute values of d for each month of the year obtained during the calibration period. Finally, the K' for each month is adjusted using a regional correction factor to account for variation between locations:

$$K_i = \left(\frac{17.67}{\Sigma D_i K_i'}\right) K'. \quad (10)$$

Palmer (1965) found that the annual sum of monthly $D_i K_i'$ ($\Sigma D_i K_i'$) for the nine regions examined ranged from 12.46 to 20.97 with a mean of 17.67. This value was then used as a regional correction factor so that all $\Sigma D_i K_i'$ equal 17.67, facilitating comparisons of droughts in different regions (Palmer 1965).

In examining the above derivation of the PDI, Alley (1984, 1985) and Karl (1986) identified some limita-

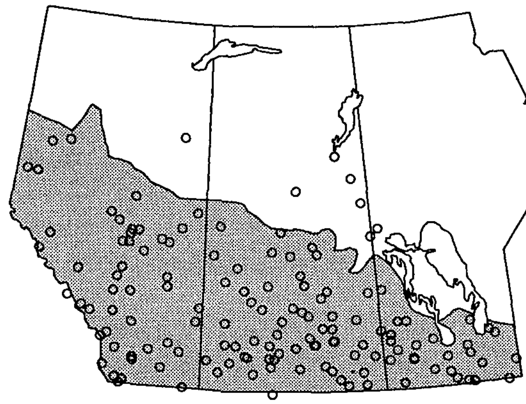

FIG. 1. The location of climatological stations on the Canadian prairies.

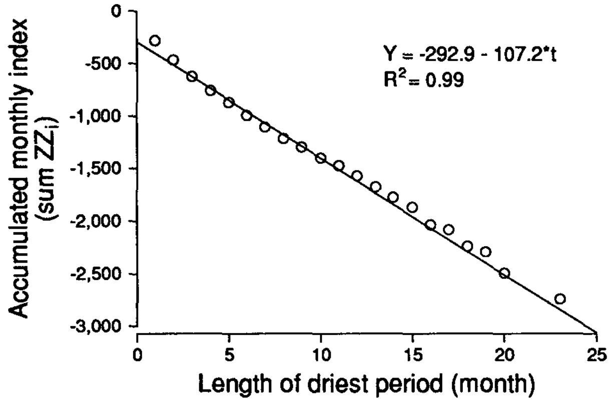

FIG. 2. The accumulated moisture anomaly index (Σ ZZ) during the driest periods of various lengths.

tions and shortcomings of the PDI, which include: (i) the use of a simplistic water balance; (ii) the absence of a physically based equation for PE; (iii) the use of threshold method to estimate runoff; (iv) the lack of consideration of snow accumulation, snow melt, and the influence of frozen soil; and (v) the use of a monthly timescale for the water balance, which may not account for short-term water deficits. Many of these limitations are particularly relevant to the cold prairie region.

3. Methods

a. Test of the relationships for the weighting factor for the prairies

In order to characterize drought on the Canadian prairies using the PDI, we tested the validity of (9) by repeating its derivation using data from 142 stations on the Canadian prairies. For example, we calculated K for the driest 12-month period at each station by dividing Palmer's expected value of $\Sigma\ Z(-25.60)$ by $\Sigma\ d$ during those months.

The test of (9) was accomplished by plotting the values of K [obtained independently of (9)] against the values of the parameters of (9) obtained during the calibration period. This plot shows the nature as well as the strength of the relationships of (9) for the Canadian prairies.

b. Derivation of the regional correction factor for the Canadian prairies

The climate of the Canadian prairies is at the low-temperature extreme of the geographic area originally studied by Palmer. The Canadian prairies experience 3–5 months per year with mean monthly temperatures below 0°C. Of the nine regions considered by Palmer (1965), only northwestern North Dakota, with the lowest $\Sigma\ D_i K_i$ of 12.4, has a climate similar to that of the Canadian prairies.

Our study used data from individual weather stations as opposed to areal averages. It has been suggested that areal averages are better than point-source data because of their reduced variability (Palmer 1965). However, the number of weather stations used in this study (Fig. 1) was large enough to compensate for point-source variability.

Daily maximum and minimum temperatures and precipitation at 142 ordinary and principal climatological stations across the Canadian prairies between 1960 and 1989 were obtained from Environment Canada and used to calculate the $\Sigma\ D_i K_i$ for each location. The available water holding capacity for each location was obtained from De Jong and Shields (1988).

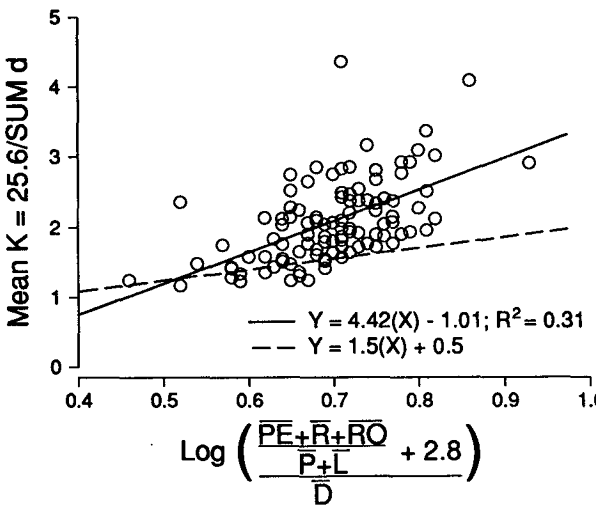

FIG. 3. The relationship of the mean annual weighting factor to the average moisture demand (PE + R + RO), average moisture supply (P + L), and average absolute moisture departure (D) on the Canadian prairies.

TABLE 1. Latitude, longitude, elevation, and $\Sigma D_i K_i$ obtained at 30 representative weather stations across the prairies.

Station	Latitude	Longitude	Elevation	$\Sigma D_i K_i$	Station	Latitude	Longitude	Elevation	$\Sigma D_i K_i$
1	52.3	111.5	746.8	13.8	16	51.3	109.9	658.4	11.9
2	53.3	113.6	713.2	13.3	17	50.3	106.2	707.1	13.8
3	53.7	113.5	685.8	13.8	18	50.0	108.5	905.3	14.4
4	53.7	113.2	618.7	13.5	19	50.0	109.5	762.0	14.2
5	53.5	112.0	634.0	12.3	20	50.2	106.6	707.1	14.0
6	51.8	113.2	853.4	13.3	21	50.3	107.7	823.0	12.9
7	50.0	113.7	1018.0	15.0	22	49.0	106.4	874.8	13.4
8	50.1	112.1	777.2	13.3	23	53.3	106.5	478.5	13.7
9	52.5	116.1	1319.8	15.5	24	51.5	107.1	539.5	12.3
10	54.8	113.5	624.8	14.3	25	52.1	101.9	509.0	14.5
11	50.9	104.3	554.7	13.1	26	50.7	100.8	588.3	15.3
12	50.5	103.7	603.5	14.1	27	49.4	98.3	338.3	16.5
13	51.3	103.8	670.6	14.3	28	49.5	96.8	253.0	14.9
14	49.7	105.4	685.8	13.1	29	50.1	97.3	249.9	15.6
15	51.7	105.5	539.5	13.5	30	50.9	97.1	222.5	15.1

c. Estimating the PDI using the Versatile Soil Moisture Budget

A form of the Versatile Soil Moisture Budget (VMB-3.2), developed by Baier and Robertson (1966) and modified by Dyer and Mack (1984), was used to increase the accuracy of the water balance estimates over those used by Palmer.

Sections of the VMB model that were modified for this study were the following. (i) The Soil Conservation Service (SCS) curve number technique (U.S. Department of Agriculture Soil Conservation Service 1972) was used to replace a simple runoff calculation algorithm. (ii) The equation of Baier and Robertson (1965) for calculating PE was replaced with the Priestly–Taylor equation (Priestly and Taylor 1972). In this approach a value of 1.28 was used for the Priestly–Taylor α, while net radiation was obtained from observed solar radiation using a regression equation given by Linacre (1993) for a grass surface. (iii) The drainage algorithm was replaced with the simple cascade algorithm of Ritchie and Otter (1985). (iv) Finally, the section of the model that determines whether precipitation was in the form of snow or rainfall was bypassed since we had actual measurements of snowfall and rainfall. The modified model was validated using soil moisture data at two locations, for over winter (November–May) moisture recharge and under summer fallow and wheat crops.

The model requires the depth of the soil layers in the root zone, the water-holding characteristics of each soil layer, and the initial moisture content. As well, the seeding date and dates corresponding to five different crop stages are required. This information was available for the full study period only for the Swift Current and the Lethbridge weather stations.

A continuous wheat rotation from 1960 to 1989 was used to run the model. To minimize the complexity of the model, the seeding date as well as the dates for other crop growth stages were assumed constant from year to year. The dates used for our simulation were: seeding, 15 May; emergence, 30 May; jointing, 25 June; heading, 15 July; soft dough, 15 August; and ripening, 30 August.

In the VMB, soil moisture is calculated for each layer on a daily basis. The daily water balance was summarized to monthly water balance to permit comparison to the Palmer technique. When the VMB was used in place of Palmer's original soil water balance, it was used both in model calibration (determining the constants α, β, τ, and δ based on historic data) and in model application.

d. A new drought index

We began the derivation of a new index by using the Palmer monthly moisture departure d in (1). The main challenge was to find an improved means of normalizing d to obtain a new anomaly index, ZZ. This was accomplished by normalizing d using the technique of Bhalme and Mooley (1980). This technique uses the standard deviation (SD) of the monthly rainfall as a weighting factor. The new anomaly index ZZ is given by

$$\mathrm{ZZ}_i = (P - \hat{P})/\mathrm{SD}. \tag{11}$$

The justification for using the SD of the monthly precipitation to normalize d is that both P and $\hat{P}$ (from which d is obtained) are measures of precipitation. While P is the actual monthly precipitation, $\hat{P}$ is an indirect measure of the long-term mean precipitation or its expected value. According to Bhalme and Mooley (1980), the index obtained through this process of normalization can be compared, within reasonable limits, in space and time.

Bhalme and Mooley (1980) obtained ZZ only for the 4 monsoon months, but we calculated ZZ for each month of the year, as did Palmer in (7). The new anomaly index ZZ differs from the Palmer Z by avoiding the

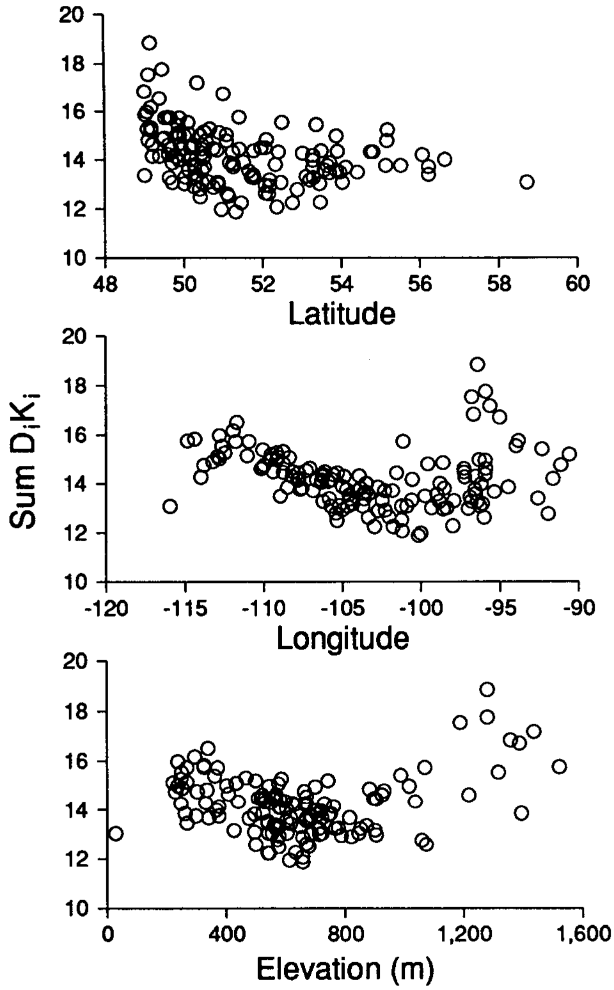

FIG. 4. The spatial distribution of ΣD_iK_i across the Canadian prairies. The relationship with (a) the weather station latitude, (b) the weather station longitude, and (c) weather station elevation.

use of K and the empirical equation from which it is derived. The data plotted in Fig. 2 were obtained as a mean of the cumulative anomaly for various intervals of months across the 142 stations. Not all of the points in Fig. 2 are means of 142 individual data points—the longer the drought periods, the fewer the number of stations with that number of dry months.

The parameters of the new drought index XX were obtained from the regression equation following the approach of Bhalme and Mooley (1980), derived from the original work of Palmer (1965). The new index is given by

$$XX_i = \frac{\Sigma ZZ_i}{(26.8t + 73.2)}, \qquad (12)$$

where t is the time in months. The regression coefficients in Fig. 2 were divided by -4 to obtain the denominator in (12), implying that the regression line in Fig. 2 represents an XX index of -4, the index for extreme drought.

From (12) the final expression for a new drought severity index can be derived by repeating the procedures used by Bhalme and Mooley (1980) or Palmer (1965). Otherwise, it can be derived by noting that (12) and (8) can be represented as $XX_i = \Sigma ZZ_i/(At + B)$ and $XX_i = ZZ_i/C + DXX_{i-1}$, respectively. The regression constants, A and B, have the values of 26.8 and 73.2, respectively. The constant C determines the contribution of the current anomaly to the current drought index, while D is the "persistence" factor, accounting for the contribution of previous month's drought. The value of C is given by $C = A + B$, while D is equal to $(1 - A/(A + B))$. Our new drought index, the equivalent of (8), is given by

$$XX_i = ZZ_i/100 + 0.732XX_{i-1}. \qquad (13)$$

The new index has a persistence factor of 0.732, while the original Palmer index (8) has a persistence factor of 0.897.

In deriving the new index, the VMB was not used. Rather, the new index was obtained using the original Palmer water balance method. The parameters for the new index were generated using data from all the weather stations, but we did not have access to the soil moisture data required by the VMB at all the weather stations.

4. Results

a. Test of the relationships for the weighting factor for the prairies

The results of the test of the empirical weighting factor, given in (9), are shown in Fig. 3. Only 107 of the 142 stations available were included because not all

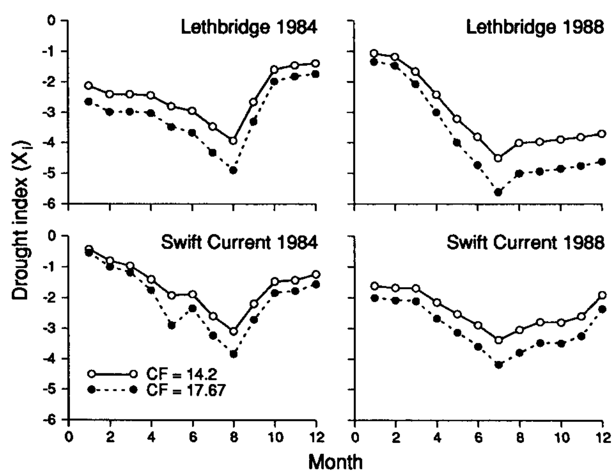

FIG. 5. The effect of the original (17.67) and the adjusted (14.2) regional correction factors (CF) on the drought index at two weather stations during two drought years.

TABLE 2. Mean monthly hydrological parameters obtained using the VMB-PDI and the PDI methods at Swift Current during the 1960–1989 calibration period.

Month	P	PE	ET	PR	R	PL	L	RO
				Parameters from VMB-Palmer technique				
1.0	4.9	1.7	0.6	179.9	2.7	0.5	0.1	1.8
2.0	14.4	6.8	3.0	177.3	5.4	1.7	0.2	6.2
3.0	27.6	30.7	10.9	172.2	5.6	7.1	1.4	12.5
4.0	25.2	73.0	20.3	168.0	6.1	13.1	4.8	3.6
5.0	43.0	109.1	34.0	166.6	12.9	16.6	4.3	0.4
6.0	68.1	126.1	69.3	158.0	11.1	40.2	14.1	1.7
7.0	46.7	141.5	86.8	161.0	0.3	70.3	40.8	0.1
8.0	39.7	114.7	47.2	201.5	4.8	33.7	12.4	0.1
9.0	32.0	64.8	15.6	209.1	17.8	11.3	1.6	0.2
10.0	15.2	33.8	9.0	192.9	7.7	6.6	1.7	0.2
11.0	7.2	9.1	2.3	186.9	2.8	2.2	0.4	2.5
12.0	7.1	2.5	0.7	184.5	3.5	0.6	0.1	2.9
				Parameters from Palmer technique				
1.0	19.9	0.0	0.0	131.7	19.0	0.0	0.0	0.9
2.0	16.4	0.0	0.0	112.6	16.0	0.0	0.0	0.4
3.0	18.9	1.2	1.2	96.6	17.4	1.2	0.1	0.5
4.0	25.2	28.1	26.4	79.4	8.7	23.5	11.7	1.8
5.0	44.8	76.9	62.3	82.3	4.2	44.6	22.7	0.9
6.0	68.1	111.5	87.1	100.8	4.9	54.3	25.0	1.2
7.0	46.7	131.7	81.2	120.9	0.0	51.5	34.5	0.0
8.0	39.7	114.6	54.5	155.5	1.1	25.4	15.9	0.0
9.0	33.9	64.1	34.7	170.3	5.4	9.9	6.2	0.0
10.0	18.0	28.9	18.0	171.1	3.7	6.8	3.7	0.0
11.0	14.4	0.5	0.3	171.1	14.1	0.2	0.0	0.0
12.0	21.2	0.0	0.0	157.0	21.2	0.0	0.0	0.0

stations had 12 consecutive dry months within the 30-yr period. A linear relationship was indicated between K and the logarithm of the moisture balance parameters. In addition to the regression line, we also plotted the line represented by (9) for comparison. The reason for the poor fit ($R^2 = 0.31$) of this relationship is unclear, although Palmer (1965) anticipated greater scatter of the points along the regression line if more stations or areas were added. The weighting factor K evidently has limited applicability to the Canadian prairies, and for this region the relationship should be used with caution.

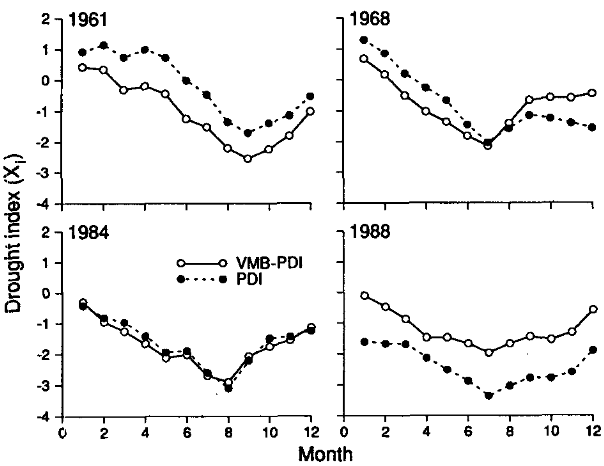

FIG. 6. Comparison of drought indices obtained using the original Palmer water balance (PDI) and the versatile moisture budget (VMB–PDI) at Swift Current station during four drought years.

b. The regional correction factor for the Canadian prairies

The latitude, longitude, elevation, and $\Sigma\, D_i K_i$ obtained for 30 representative stations are listed in Table 1. The mean value of $\Sigma\, D_i K_i$, taken across the 142 weather stations, was 14.2 with a standard deviation of 1.2, which is lower than the value of 17.67 obtained by Palmer (1965).

The lower value of the mean of $\Sigma\, D_i K_i$ in the prairies may have been caused by lower winter temperatures, longer winters, and lower winter precipitation compared to the nine regions considered by Palmer (1965). Also, D is the summation of the absolute values of d for each month of the year, $d = P - \hat{P}$, and the major component of $\hat{P}$ is PE, which was near zero in winter. Although K' is inversely related to D in (9), the increase in K' for the winter months did not compensate for the lower D, and the value of $\Sigma\, D_i K_i$ is lower than predicted by Palmer.

Palmer (1965) reasoned that if (9) produced reasonably "correct" values of K, then the annual sum of weighted average departures ($\Sigma D_i K_i$) should be about the same for all locations. The differences between the values of $\Sigma D_i K_i$ obtained in the nine regions were attributed to the departures being given more weight in some places than in others (Palmer 1965). This problem was overcome by using the mean of $\Sigma D_i K_i$ in the nine regions as a regional correction factor. Our results indicate that $\Sigma D_i K_i$ varies from one location to another. However, this variation may not be random but have a spatial pattern (Fig. 4). The spatial pattern may be due to the poor performance of the relationship for K in this region. As a result of the spatial pattern of $\Sigma D_i K_i$, it may not be possible to obtain a single regional correction factor through simple averaging, which assumes random variation.

Drought indices were obtained with the correction factors of 14.2 and 17.67 during the 1984 and 1988 droughts at Swift Current and Lethbridge (Fig. 5). Using a correction factor of 17.67 increased the value of the PDI compared to that obtained with 14.2. The use of the value 17.67 on the prairies may produce "inflated" values of drought index, which may not reflect reality. Henceforth, all drought index calculations were based on the regional correction factor of 14.2.

c. *Estimating the PDI using the Versatile Soil Moisture Budget*

The VMB integrates present and past weather events to simulate daily water content in up to six layers of the soil. The model was selected, in part, because it has been used extensively on the Canadian prairies and it permits the estimation of soil moisture on a regional scale (De Jong and Bootsma 1988). The data requirements are simple, and the VMB model has proved reliable for estimating soil moisture in the root zone of several crops (De Jong and MacDonald 1975; Baier et al. 1979; Dyer and Mack 1984; De Jong 1988).

Table 2 compares mean monthly hydrologic parameters obtained by the PDI to those obtained using the VMB (VMB–PDI) during the 1960–1989 calibration period at Swift Current. The two methods used identical values of mean monthly precipitation except during the winter months, when precipitation values from the VMB were lower because the VMB used a snow blow-off coefficient to account for the wind effect. The snow blow-off coefficient of 0.7 was used, and this assumes that 30% of snowfall is blown off the field. Also, in the VMB approach, snow is accumulated and counted as precipitation after melting, which explains the higher mean March precipitation (Table 2).

The Priestly–Taylor equation used in the VMB calculated PE on a daily basis, which when summed over a month, produced values similar to Thornthwaite's equation, calculated monthly. During the winter months, November to March, the Thornthwaite (1948) method gave PE values close to zero, resulting in low values of ET.

During summer, the ET obtained by the two methods was similar except for May, when the VMB predicted a lower ET than the Palmer technique. The use of actual crop stages in the VMB was probably responsible for the lower ET since the soil was assumed to be bare until crop emergence (30 May) in the VMB, limiting ET to bare soil evaporation in May. On the other hand, the ET calculation by the Palmer technique is limited only by the available soil moisture, as no distinction is made between bare soil evaporation and ET with a crop. The Palmer technique does not consider snow accumulation during winter, which was reflected by the lower snowmelt runoff obtained by this technique. When the VMB was used, snowmelt runoff was calculated in all the winter months, with the highest amount in March, as expected. Whereas the amounts of runoff were small and played a negligible role in the final value of the original PDI, this was not the case when the VMB was used.

The drought indices obtained using the PDI and the VMB–PDI models yielded similar values during 4 drought years (Fig. 6). In drought years, there was no consistent, significant difference between the PDI calculated by the two methods. However, the VMB–PDI was more closely related to wheat-yield departure from normal than was the PDI (Fig. 7). The coefficient of determination between yield departure and the PDI was

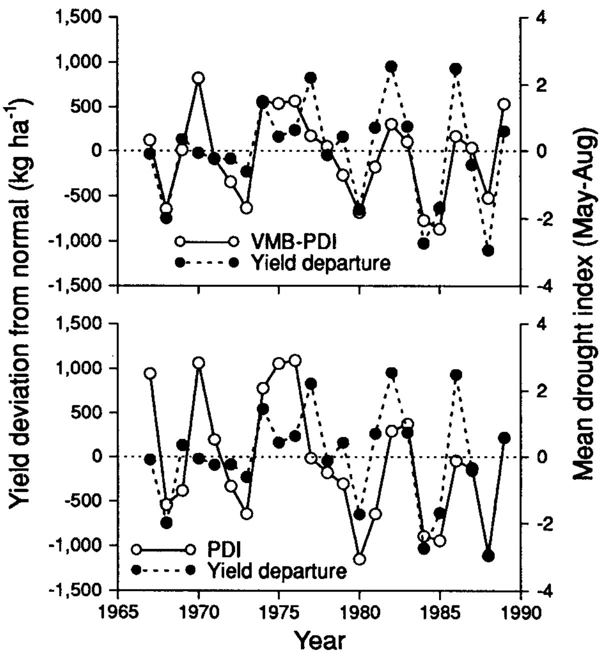

FIG. 7. The mean growing season (May to August) drought indices (VMB–PDI and PDI) as related to wheat-yield departure from normal at the Swift Current research station (23-yr mean yield is 1300 kg ha^{-1}).

0.33, and the corresponding value for the VMB–PDI was 0.49. In a study encompassing southern Saskatchewan, Jones (1984) obtained r of 0.33 between yield departures and the absolute October PDI averaged for 11 weather stations. Absolute correspondence between drought indices and yield was not expected, especially in wet periods (PDI positive), as there are other factors besides moisture that influence yield, such as fertility, insects, diseases, frost, technology, etc. Thus, the use of the VMB produced an index that was more sensitive than unmodified PDI to wheat-yield reductions associated with drought on the Canadian prairies.

d. Evaluation of the new drought index

The results of our evaluation of the relationship for K calls into question the validity of (9) in this region. This served as an impetus for deriving a new drought index that is independent of K. Louie (1986), working on an operational drought severity index program for Canadian Synoptic Stations, noted that the weighting factor did not normalize the index value over time and space in some regions of Canada.

Figure 8 compares the original PDI with a modified PDI (denoted BM–PDI), based on Palmer's original soil water budget but using the Bhalme–Mooley normalization technique instead of (9). The two indices behaved similarly during 2 drought years. However, the new index showed more sensitivity to current moisture conditions, as it recovered faster than the PDI from extreme drought. This was due to the lower persistence factor of the BM–PDI.

Figure 9 shows a comparison of the BM–PDI, generated using the VMB, to wheat-yield departures at Swift Current (Campbell et al. 1992). In general, the BM–PDI coincided with trends in wheat yield. Regression analysis between yield departures and drought indices produced a coefficient of determination (R^2 = 0.57) for BM–PDI that was almost twice the value for the PDI (R^2 = 0.33). All the three indices (PDI, VMB–PDI, and BM–PDI) followed the yield patterns (Figs. 7 and 9), and the discrepancies between yield departures and the original PDI index in years such as 1977, 1981, and 1986 (Fig. 7b) were reduced by VMB–PDI and BM–PDI. The only exception was in 1970, when all the three indices indicated wet conditions (PDI = 3), but an average yield was obtained. In 1970 at Swift Current, the precipitation pattern was such that there was a moisture deficit during most of the growing season until June, when 216 mm of rainfall was received within two weeks. Although the growing season precipitation was higher than normal, which is reflected by the drought indices, the distribution was such that the moisture came too late for the wheat crop to recover from earlier stress, resulting in average yield.

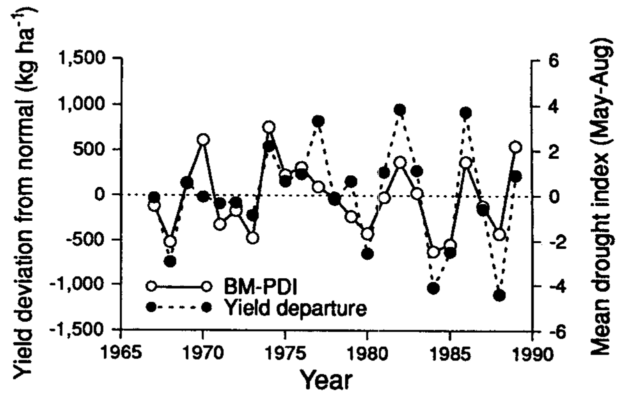

FIG. 9. Comparison of the new drought index (BM–PDI) with yield departures from normal at Swift Current.

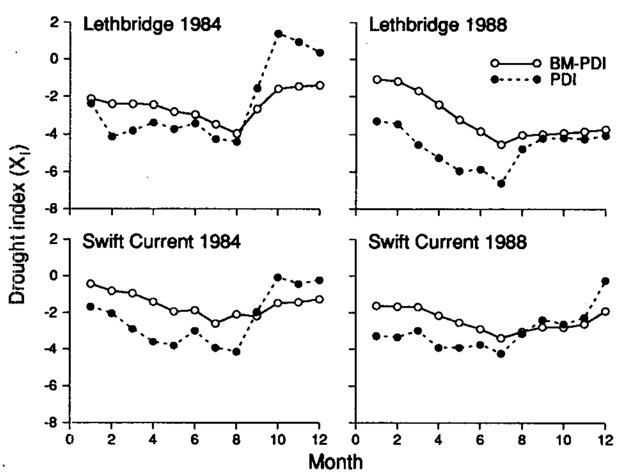

FIG. 8. Comparison of the new index (BM–PDI) with original Palmer Drought index at Lethbridge and Swift Current during drought years 1984 and 1988.

5. Conclusions

The empirical relationship used to generate the PDI weighting factor K may not be applicable to the Canadian prairies, as, for this region, K was only weakly related to the variables from which it was derived.

The calculated correction factor for the Canadian prairies (14.2) is lower than that obtained by Palmer (1965) in his original work (17.67). The relationship of $\Sigma\, D_i K_i$ to latitude and longitude, although weak, suggests that a single regional correction factor may not be obtainable through simple averaging.

The use of the VMB produced an index that was numerically similar to the PDI. The index obtained with the VMB, however, was better correlated than PDI with yield departures from normal. The new drought index, BM–PDI, derived from the Palmer monthly moisture departure, was normalized using the standard deviation of precipitation. Compared to the PDI and the VMB–PDI, the BM–PDI was more responsive to current moisture conditions and was better correlated with yield departures from normal.

This study has taken two approaches to improve the PDI. The first approach used the VMB to provide a more detailed description of soil moisture balance. The second approach modified the index through a process of normalization that is less empirical.

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REFERENCES

Alley, W. M., 1984: The Palmer drought severity index: Limitations and assumptions. *J. Climate Appl. Meteor.,* **23,** 1100–1109.

——, 1985: The Palmer drought severity index as a measure of hydrological drought. *Water Resour. Bull.,* **21,** 105–114.

Baier, W., and G. W. Robertson, 1965: Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.,* **45,** 2276–284.

——, and ——, 1966: A new versatile soil moisture budget. *Can. J. Plant Sci.,* **46,** 299–315.

——, J. A. Dyer, and W. R. Sharp, 1979: The versatile soil moisture budget. Tech. Bull. 87, Agrometeorology Section, Research Branch, Agriculture Canada, Ottawa, ON, Canada, 52 pp.

Bhalme, H. N., and D. A. Mooley, 1980: Large scale droughts/floods and monsoon circulation. *Mon. Wea. Rev.,* **108,** 1197–1211.

Campbell, C. A., R. P. Zentner, F. Selles, V. O. Biederbeck, and A. J. Leyshon, 1992: Comparative effects of grain lentil-wheat and monoculture wheat on crop production, *N* economy and *N* fertility in a Brown Chernozem. *Can. J. Plant Sci.,* **72,** 1091–1107.

De Jong, E., and K. B. MacDonald, 1975: The soil moisture regime under native grassland. *Geoderma,* **14,** 207–221.

De Jong, R., 1988: Comparison of two soil–water models under semi-arid growing conditions. *Can. J. Soil Sci.,* **68,** 17–27.

——, and A. Bootsma, 1988: Estimated long term soil moisture variability on the Canadian prairies. *Can. J. Soil Sci.,* **68,** 307–321.

——, and J. A. Shields, 1988: Available water-holding capacity maps of Alberta, Saskatchewan and Manitoba. *Can. J. Soil Sci.,* **68,** 157–163.

Dyer, J. A., and A. R. Mack, 1984: The versatile moisture budget—version three. Tech. Bull. 1984-1E, LRRC, Research Branch, Agriculture Canada, Ottawa, ON, Canada, 24 pp.

Jones, K. H., 1984: An evaluation of the Palmer drought index in southern Saskatchewan. Rep. CSS-R84-01, Atmospheric Environment Service, Regina, Canada, 33 pp.

——, 1987: An evaluation of the crop moisture index for southern Saskatchewan. Rep. CSS-R87-02, Atmospheric Environment Service, Regina, Canada, 17 pp.

Karl, T. R., 1983: Some spatial characteristics of drought duration in United States. *J. Climate Appl. Meteor.,* **22,** 1356–1366.

——, 1986: The sensitivity of the Palmer drought severity index and Palmer's *Z*-index to their calibration coefficients including potential evapotranspiration. *J. Climate Appl. Meteor.,* **25,** 77–86.

——, F. Quinlan, and D. S. Ezell, 1987: Drought termination and amelioration: Its climatological probability. *J. Climate Appl. Meteor.,* **26,** 1198–1209.

Katz, R. W., and M. H. Glantz, 1986: Anatomy of a rainfall index. *Mon. Wea. Rev.,* **114,** 764–771.

Linacre, E. T., 1993: Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agric. For. Meteor.,* **64,** 237–256.

Louie, P. T. Y., 1986: An operational drought severity index program for Canadian synoptic stations. *Proc. Canadian Hydrology Symposium No 16,* Regina, SK, Canada, National Research Council, 101–112.

Palmer, W. C., 1965: Meteorological drought. Research Paper 45. U.S. Department of Commerce, Weather Bureau, Washington, D.C., 58 pp.

Priestly, C. H. B., and R. J. Taylor, 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Wea. Rev.,* **100,** 81–92.

Ritchie, J. T., and S. Otter, 1985: Description and performance of CERES-wheat: A user-oriented wheat yield model. USDA-ARS, 38, 159–170.

Street, R. B., B. F. Findlay, and P. T. Y. Louie, 1986: An applied climatology of drought in the prairies provinces. Rep. 86-4, Can. Clim. Cent., Atmospheric Environment Service, Downsview, ON, Canada, 137 pp.

Thornthwaite, C. W., 1948: An approach toward a rational classification of climate. *Geogr. Rev.,* **38,** 55–94.

U.S. Department of Agriculture, Soil Conservation Service, 1972: *National Engineering Handbook.*

Van Rooy, M. P., 1965: A rainfall anomaly index independent of time and space. *Notos,* **14,** 43–48.

Yevjevich, V., L. da Cunha, and E. Vlachos, Eds., 1983: *Coping with Droughts.* Water Resources, 417 pp.