NOTES AND CORRESPONDENCE

A Comparison of Weekly Monitoring Methods of the Palmer Drought Index

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(Manuscript received 25 September 2006, in final form 15 March 2007)

ABSTRACT

A method for weekly monitoring of the Palmer Drought Index (PDI) by using four parallel month-long calculation chains in rotation ("ROLLING" method) was tested for the Kansas Northwest Climate Division and the South Carolina Southern Climate Division and compared to two other methods, a modified version of the Climate Prediction Center's weekly Palmer Drought Index monitoring method with a modified set of coefficients ("WEEKLY" method) and the National Climatic Data Center's (NCDC's) projected monthly Palmer Drought Index method using long-term historical daily normal temperature and precipitation ("NORMALS" method). The results for the Kansas Northwest Climate Division and the South Carolina Southern Climate Division generally agreed. The weekly method produced drought severity values that differ most from standard monthly PDI values despite using a modified set of coefficients. The method recently adopted by NCDC successfully estimated Palmer Modified Drought Index (PMDI) values late in the month, but often presented a misleading trend early in the month. The method used in this paper produced PMDI and Z Index values that approximate those found using the standard monthly PMDI code. It also preserves approximately the same length of memory found in that code, provides a tool for progressive drought monitoring allowing users to assess current drought conditions, produces a weekly historical archive of the Palmer Drought Severity Index (PDSI) and Palmer Hydrological Drought Index (PHDI), and enables users to identify the onset of drought early and more clearly.

1. Introduction

Drought is a natural hazard defined as a lack of precipitation for a prolonged period of time and failure to meet water demands. It differs from other natural hazards, however, in that its onset, end, and severity are hard to measure because drought develops gradually, and the spatial extent of the impact is usually large (Wilhite and Buchanan-Smith 2005). One attempt to measure drought, the Palmer Drought Index (PDI; Palmer 1965), has been used for several decades in the United States and other countries. It is based on a simple water balance model, and it was designed to detect the beginning and ending of drought and to provide a drought severity index (Table 1). Despite its limitations (Alley 1984; Karl and Knight 1985) and despite the development of other measures, such as the standardized precipitation index (SPI; McKee et al. 1993), that overcome these weaknesses (Guttman 1998, 1999), the PDI is still considered an effective measure of a drought. In addition to considering precipitation deficit, it integrates the influence of temperature, evapotranspiration, soil moisture, and runoff on the water balance (Heim 2002; Alley 1984).

As originally designed by Palmer (1965), the PDI is typically calculated monthly. However, weekly analysis is often required since it provides more detail, identifies the onset of drought more clearly, and allows progressive monitoring of drought conditions (Palmer 1965). Recognizing these needs, Palmer suggested two weekly monitoring methods in appendix C of his original paper: one calculates weekly PDI for 52 weeks using weekly constants and equations derived from monthly constants and equations, and the other conducts three additional sets of "monthly" analyses in addition to the regular monthly analysis. A detailed explanation follows in the next section. Palmer tested the first method

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DOI: 10.1175/2007JCLI1693.1

TABLE 1. Palmer Drought Index severity category (Palmer 1965).

PDI value	Category
≥4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to −0.49	Near normal
−0.50 to −0.99	Incipient drought
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
≤−4.00	Extreme drought

and compared the weekly analysis with monthly analysis, concluding that for climatological purposes the differences were slight (in agreement over 90%). This method was adopted by the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS)/Climate Prediction Center (CPC).

However, in contrast to Palmer's findings with weekly analysis, the operationally produced weekly PDI from the CPC sometimes shows contrary results from the monthly PDI from the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS)/National Climatic Data Center (NCDC; Heim 2005). Thus, Heim (2005) presented a method for estimating monthly PDI on a weekly basis using long-term historical normal daily precipitation and temperature data for the remaining days of the month. Since the purpose of Heim's method is to estimate the PDI value at the end of the month, the obtained value is not intended for the end of each week. However, monitoring such current conditions has great value for many institutions. Moreover, it is often important to identify clearly the initiation of drought.

In this study, instead of using new sets of constants for weekly analysis (see http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/) or estimating monthly PDI values using long-term historical normals (Heim 2005), an alternative weekly monitoring method using the concept of the Palmer second weekly method was suggested and compared to two other methods. The alternative method was applied to two climate divisions: the Kansas Northwest Climate Division, located within the areas where Palmer originally constructed the PDI, and the South Carolina Southern Climate Division, within the regions where this alternative method is going to be carried on operationally (Fig. 1). A regional-scale drought monitoring system was developed for North and South Carolina in response to an extreme 4-yr drought during 1998–2002 in the Carolinas, and the weekly PDI values are going to be calculated using the alternative method (Carbone et al. 2007).

2. Weekly monitoring of the Palmer Drought Index

a. The recursive characteristic of the PDI

The PDI includes three drought indices: the Palmer Drought Severity Index (PDSI), the Palmer Hydrological Drought Index (PHDI), and the Palmer Z Index. As a moisture anomaly index, the Z Index is calculated from the difference between the actual precipitation in a month and precipitation that is "climatologically appropriate for existing conditions" (CAFEC), weighted by the climate characteristic K. The CAFEC precipitation is derived from the CAFEC quantities, that is, the normal values for each month obtained for a long-term calibration period. CAFEC coefficients include those for evapotranspiration (α), recharge (β), runoff (γ), and loss (δ).

Palmer (1965) determined drought severity classes using empirical relationships between the accumulated Z Index values and the length of dry periods from the 13 driest periods in central Iowa and western Kansas. The final form of his monthly drought severity equation is

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

where X_i and Z_i are the PDSI and Z Index values for the ith month, respectively, for a typical monthly PDI. Since the first term of the equation introduces an autoregressive process, the PDI has a certain length of memory. The length of memory varies with location even though it was designed to be spatially comparable; it is approximately 1 yr (Guttman 1998; Heim 2005).

Palmer (1965) introduced the concept of the "percentage probability" and three intermediate indices (X1: an incipient wet spell, X2: an incipient drought, and X3: the existing spell) and used them to determine the PDSI and PHDI values by means of a backstepping process. For example, X1 is chosen for the PDSI if an existing drought is over according to the probability, X2 is chosen if an existing wet spell is over, and X3 is chosen if the probability does not reach 100%. PHDI always equals X3. Because of the backstepping procedure, the moisture anomaly of a given month can affect the PDI values of several months. For real-time operational calculations, Heddinghaus and Sabol (1991) developed a Palmer Modified Drought Index (PMDI), which can be obtained from the sum of the wet and dry terms weighted by the probability values. The PMDI

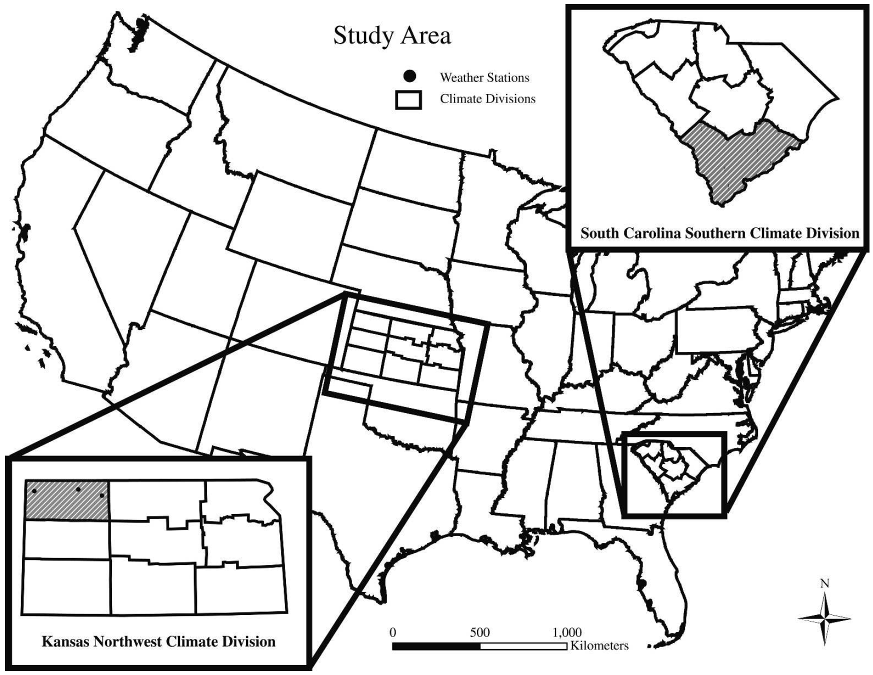

FIG. 1. Study areas include the Kansas Northwest Climate Division, located within the areas where Palmer originally constructed the PDI, and the South Carolina Southern Climate Division, within the regions where the alternative method is going to be carried on operationally. Data from three weather stations in the Kansas Northwest Climate Division and five weather stations in the South Carolina Southern Climate Division were used and equally averaged to create climate division data.

has the same value as the PDSI during established dry or wet spells but can be different during transition periods. Detailed procedures for calculating the Palmer Drought Index are in the original report of Palmer (1965) and are briefly summarized in Alley (1984), Karl and Knight (1985), and Heim (2002).

b. "WEEKLY" method

The CPC provides weekly PDI values by climate division. For weekly analysis, the coefficient of the first term in Eq. (1) was modified to 0.975 and other coefficients derived using Eq. (1) were also modified accordingly (Table 2; T. R. Heddinghaus 2006, personal communication). The weekly CAFEC coefficients and the climate characteristic K were derived from the monthly values using amplitudes and phases of six harmonics for each coefficient, and the coefficients of recharge (β) and runoff (γ) were divided by 4.35 considering the difference between weekly and monthly time scale (see http://www.cpc.noaa.gov/products/analysis_monitoring/cdus/palmer.fort). The weekly PDI calculations are reinitiated each year on the first Wednesday of March using the February monthly analysis outputs from the NCDC and are continued until the first Wednesday of March the following year (see http://www.cpc.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/wpdanote.shtml). Since the weekly calculated Z Index based on a simple water budget has about a quarter of the monthly Z Index, the CPC program calculates the 4-week Z Index separately. CPC also produces soil moisture in upper and lower layers, Crop Moisture Index (CMI),

TABLE 2. Equations originally used by Palmer (1965) and modified by CPC.

Variable	Palmer (1965) monthly analysis equation	CPC weekly analysis equation
PDSI	$X_i = 0.897X_{i-1} + Z_i/3$	$X_i = 0.975X_{i-1} + Z_i/3$
Z value that will end a drought	$Z_e = -2.691X_{i-1} - 1.50$	$Z_e = -2.925X_{i-1} - 1.50$
Z value that will end a wet spell	$Z_e = -2.691X_{i-1} + 1.50$	$Z_e = -2.925X_{i-1} + 1.50$
Effective wetness	$U_w = Z + 0.15$	$U_w = Z + 0.04$
Effective dryness	$U_d = Z - 0.15$	$U_d = Z - 0.04$

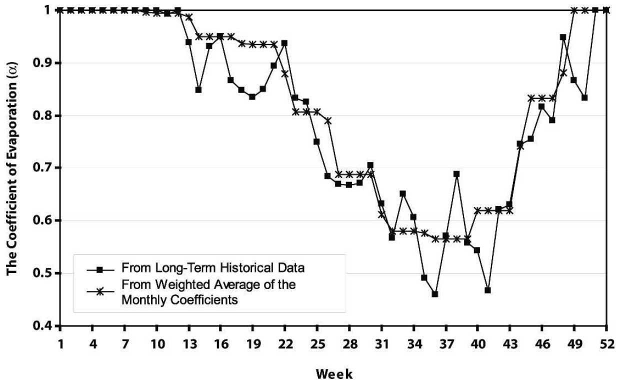

FIG. 2. The coefficient of evaporation (α) values for 52 weeks obtained from the long-term historical data from 1961 to 1990 were compared to the values obtained from the weighted average of the monthly coefficients in the Kansas Northwest Climate Division. The weighted-average values cannot fully represent the weekly variation of the coefficient.

and the amount of precipitation needed to end drought. For this study, the weekly CAFEC coefficients and the climate characteristic K were calculated using long-term historical data from 1961 to 1990 since the interpolated coefficients cannot fully represent the weekly climatological characteristics. As an example, the coefficient of evapotranspiration (α) values for 52 weeks obtained from the long-term historical data from 1961 to 1990 were compared to the values obtained from the weighted average of the monthly coefficients in Fig. 2. The weekly analysis method (WEEKLY method) is simple to use, but it may produce a different drought severity value than that produced using the standard PMDI monthly code.

c. "NORMALS" method

Heim (2005) explored several methods to estimate the monthly PDI before the month's end. In one, he filled each of the remaining days of the month with the location's long-term historical normal daily precipitation and temperature data (NORMALS method). This method produced PMDI values that approximate those at the month's end. It is a very useful tool for estimating the end-of-month PDI from any day during a month, but it does not produce an index value for conditions on a particular day before the end of the month. Heim addresses this shortcoming with another technique that uses a moving 31-day window of observed data preceding the current date. In this method, he retains the original monthly CAFEC coefficients and the climate characteristic K for the current and previous month rather than recalculating them for the specific 31-day window. Also, the PDI value of the previous month, which overlaps about 3 weeks with the new 31-day window, was used as the previous PDI value in Eq. (1) instead of using a nonoverlapping period. The criterion for selecting the best method is the ability to estimate the PDI at the end of the month, and the NORMALS method was selected in his study.

d. "ROLLING" method

Given the sensitivity of Palmer's Drought Index to the CAFEC coefficients and the climate characteristic K, a variation could advance Heim's moving-window approach. This paper considers such a variation wherein four separate sets of monthly analyses produce weekly values of the PMDI (ROLLING method). Palmer (1965) mentions this method in appendix C of his original paper, but no examples of its implementation appear in the literature. The method centers on generating CAFEC coefficients and the climate characteristic K using long-term historical data for the given period or a weighted average of the standard monthly values and, thus, differs from Heim's (2005) approach. The procedure is described and the resulting outputs are evaluated in the following sections.

3. Data

The daily U.S. Historical Climatology Network (USHCN) dataset was used. It includes daily maximum/minimum temperature, precipitation amount, snowfall amount, and snow depth from 1062 weather stations in the United States, which are the subset of the 1221 weather stations of the monthly USHCN dataset (Williams et al. 2004). Daily maximum–minimum temperature and total precipitation data from 1961 to 2000 for three weather stations in the Kansas Northwest Climate Division and five weather stations in the South Carolina Southern Climate Division were downloaded from the FTP server of NCDC (Table 3; Fig. 1). Missing records in the daily USHCN dataset were filled with the 1961–90 daily historical normal values instead of the value obtained by spatial interpolation from neighboring stations. Daily mean temperature values were averaged from the daily minimum–maximum temperature. The period of 1961–90 was used as a calibration period for missing data, CAFEC coefficients, and the climate characteristic K; the period of 1991–2000 was used for analysis. Daily mean temperature and precipitation data for individual weather stations were equally averaged to produce the daily climate division data.

4. Procedure

The daily climate division data were temporally averaged using three distinct methods. The WEEKLY

TABLE 3. Weather stations located in the study area. Daily mean temperature and precipitation data for individual stations were equally averaged to produce the climate division data.

Climate division	Station ID	Station name	Lat (°)	Lon (°)	Elev (ft MSL)
Kansas Northwest	145856	Norton 9SSE	39.70	−99.83	2360
	145906	Oberlin 1E	39.83	−100.52	2540
	147093	Saint Francis	39.77	−101.80	3362
South Carolina Southern	380559	Beaufort 7SW	32.38	−80.77	20
	380764	Blackville 3W	33.37	−81.32	324
	381549	Charleston City	32.78	−79.93	10
	388426	Summerville	32.98	−80.18	35
	389469	Yemassee	32.68	−80.85	25

method followed the method used by the CPC. Daily data were aggregated for each 7-day period starting each 1 January to create a total of 52 weeks per year (the last week has 8 or 9 days). The NORMALS method followed that of Heim (2005), wherein daily data were aggregated for each month. At the ending date of each monitoring week, the remaining days of the month were filled with the daily historical normals. For the ROLLING method introduced here, four separate and parallel calculation chains were constructed, each with 28 days (the last week has 29 or 30 days) corresponding to the same 4 weeks of the WEEKLY method, and staggered by 1 week (Fig. 3). Four chains calculate the PDI values by rotation; one of the chains, with its time unit ending the current week, is used for monitoring the PDI of the current week. Using this method, a monthly index value can be calculated each week. As in the WEEKLY method, a year has 52 weeks and the four chains have 13 time units each. CAFEC coefficients and the climate characteristic K for each of the 13 time units can be obtained using long-term historical data instead of using a weighted average from two subsequent standard monthly values. In fact, Palmer (1965) explicitly recommends this approach as opposed to deriving the coefficients from the monthly constants and equations.

The PDI program used in this study is based on the code from the NCDC with slight modification by the CPC for calculating the weekly solar declination angle. The use of weighted-average CAFEC coefficients and the climate characteristic K for the ROLLING method was also tested. The weekly monitoring values were produced at the end of each week starting 1 January of each year and the monthly monitoring results were also provided for comparison.

5. Results

To compare the methods for a real-time operational setting without backstepping procedures, PMDI and Z Index values were examined for the period from 1991 to 2000 for the Kansas Northwest Climate Division and the South Carolina Southern Climate Division. This decade exhibited a wide range of moisture conditions especially in the Kansas Northwest Climate Division (Fig. 4). A long wet period continued from mid-1992 to 1996 interspersed with short normal periods. A severe drought occurred during 2000. Mild to moderate drought conditions were observed in mid-1993 and mid-1994 in the South Carolina Southern Climate Division followed by very wet periods and mild drought periods. Although other parts of South Carolina experienced very severe drought during the period, 1998–2002, the Southern Climate Division had only mild drought conditions (Figs. 1 and 4; Table 1).

Since the purpose of the weekly monitoring is to detect the start of drought early and to keep up with the current drought conditions, the year 2000 in the Kansas Northwest Climate Division (Figs. 5a,b) and the year 1993 in the South Carolina Southern Climate Division (Figs. 5c,d) were more closely examined. A near-normal condition progressed to an almost extreme drought in late summer and early autumn during 2000 in the Kansas Northwest Climate Division and a very wet spell developed into a severe drought during 1993 in the South Carolina Southern Climate Division (Fig. 4).

The first thing that can be noticed from Figs. 5a and

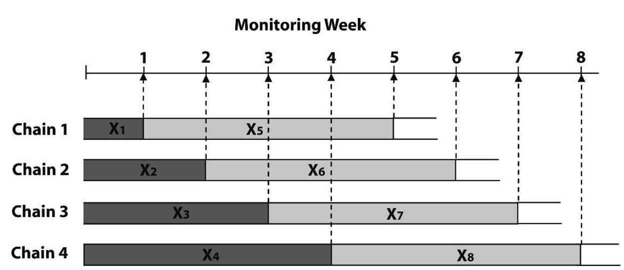

FIG. 3. Conceptual diagram for the ROLLING method: four separate and parallel calculation chains were constructed, each with 28 days (the last week has 29 or 30 days) and staggered by 1 week.

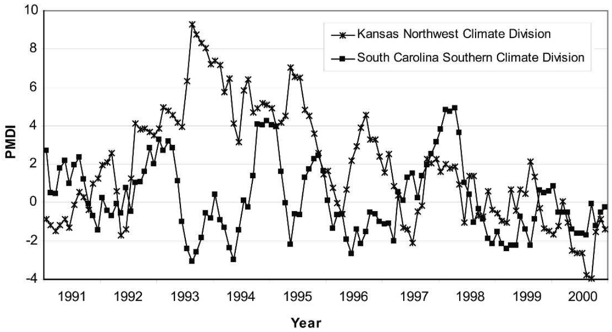

FIG. 4. Monthly PMDI from 1991 to 2000 in the Kansas Northwest Climate Division and the South Carolina Southern Climate Division. In the Kansas Northwest Climate Division, a long wet period continued from mid-1992 to 1996 interspersed with short normal periods. A severe drought occurred during 2000. On the contrary, mild to moderate drought conditions were observed in mid-1993 and mid-1994 in the South Carolina Southern Climate Division followed by very wet periods and mild drought periods.

5c is that the Z Index values produced by the WEEKLY method are much closer to the near-normal condition (around zero) whenever it is dry or wet. The moisture anomaly Z Index is calculated as the sum of evapotranspiration, recharge, and runoff, minus the sum of precipitation and water loss for the given time period (then it is standardized by multiplying by the climate characteristic K for spatial standardization). The time period of the WEEKLY method is 7 days except the last week and the time period of standard months are from 28 to 31 days, so the Z Index values by the WEEKLY method are supposed to be about a quarter of the standard monthly values. The PMDI values by the WEEKLY method, on the other hand, are supposed to have a similar range of values with the standard monthly PMDI values since the coefficients of the several equations were modified to do so (Table 2). However, the WEEKLY method also produced more near-normal PMDI values than standard monthly values (Figs. 5b,d), indicating that the modification of coefficients was not sufficient.

When the NORMALS method and the ROLLING method are compared, it should be noted that the purposes of the two methods are different: the ROLLING method is designed to detect the drought condition of the current week (for the latest 4 weeks), while the NORMALS method is designed to estimate the drought conditions anticipated at the end of the current month. However, the ultimate goal for both methods is to monitor current drought conditions without waiting until the month ends. The Z Index values produced by the NORMALS method early in each month typically differed greatly from those produced by the ROLLING method, demonstrating the effect of filling data with daily normal values (Figs. 5a,c). During the course of a month, the Z Index value produced by the NORMALS method approached current conditions and approximated the standard monthly value near the end of the month (Figs. 5a,c). The differences between the NORMALS and ROLLING methods appeared most clearly during very wet or very dry periods (Figs. 5a,c). In the Kansas Northwest Climate Division, the misleading fluctuations of the NORMALS method were observed during the dry periods of early June and early September in 2000 (Fig. 5a). During the wet period of early November in 2000, the NORMALS method stayed near-normal conditions while the ROLLING method responded to the heavy precipitation accordingly (Fig. 5a). The effect of filling daily normal data by the NORMALS method was clearly expressed in the Z Index values (Figs. 5a,c) and suppressed in the PMDI values (Figs. 5b,d) because of its recursive nature. For this reason, the NCDC only presents weekly PMDI and PHDI values. However, it is still observed in the PMDI values when the effect of filling daily normal data was especially large, obscuring the trend in the PMDI values (Figs. 5b,d).

Since the uniqueness of the ROLLING method centers on its treatment of CAFEC coefficients and the climate characteristic K, differences that result from using weighted averages of the standard monthly coefficients versus deriving new coefficients for each period from the historical record were also explored (Figs. 5a–d). The Z Index values produced by the two CAFEC coefficient calculation schemes in the ROLLING method were similar during much of the decade, especially when they indicate near-normal conditions, and slightly different during wet or dry conditions (Figs. 5a,c). There were greater differences in PMDI values (Figs. 5b,d) because of the inherent memory of the PMDI. The CAFEC coefficients and the climate characteristic K used for three different methods are shown in Figs. 6a–e. The use of the standard monthly coefficients of the current month of the NORMALS method may be proper for estimating the drought conditions anticipated at the end of the current month, but it is not appropriate for obtaining the actual drought condition of the current week (for the latest 4 weeks). The long-term historical weekly coefficients of the WEEKLY method are not suitable since they have a different range of values due to the short time period (Figs. 6a–e). While the weighted-average coefficients from two subsequent standard monthly values of the ROLLING method may approximate the coefficients of each period, they cannot show the weekly variations successfully due to excessive smoothing (Figs. 2 and 6a–e). The CAFEC coefficients and the climate characteristic K of

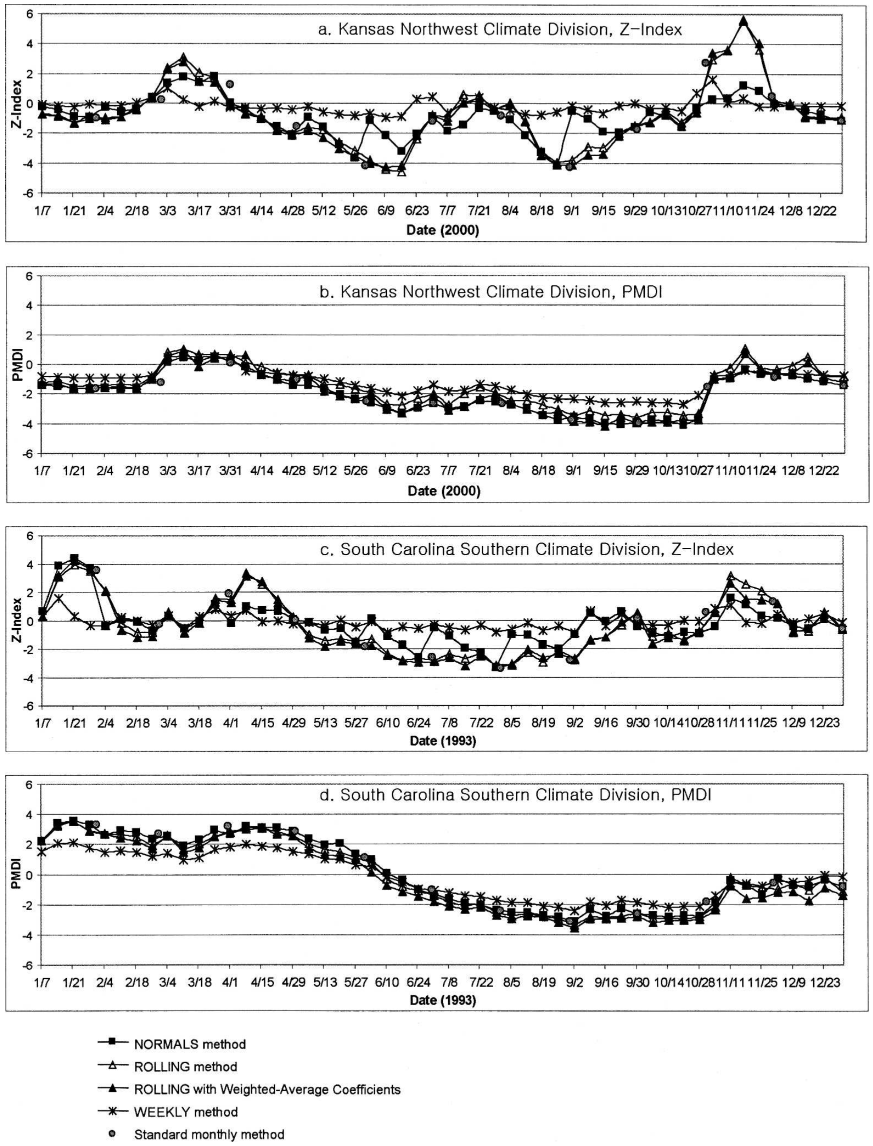

FIG. 5. Time series graphs for (a) Z Index values during 2000 in the Kansas Northwest Climate Division, (b) PMDI values during 2000 in the Kansas Northwest Climate Division, (c) Z Index values during 1993 in the South Carolina Southern Climate Division, and (d) PMDI values during 1993 in the South Carolina Southern Climate Division using various methods. The standard monthly values were also shown as reference. The WEEKLY method produced more near-normal Z Index and PMDI values than standard monthly values. The effect of filling daily normal data by the NORMALS method was clearly expressed in the Z Index values but suppressed in the PMDI values because of its recursive nature.

the ROLLING method based on the long-term historical data for each period are most appropriate since they provide a range of values similar to the standard monthly coefficients and represent the actual conditions of the current week (Figs. 6a–e).

Percent frequency distributions of Z Index and PMDI values obtained by various methods for the period 1991–2000 for PDI drought categories are presented as tables (Tables 4–7) and line charts (instead of histograms only for enhancing visibility; Figs. 7a–d). The percent frequency distributions based on the 111 yr of monthly data for the period from 1895–2005 (long term) were also added for comparison (see http://www1.ncdc.noaa.gov/pub/data/cirs/). Even the long-term distributions of PDI for drought categories are not perfectly Gaussian (Figs. 7a–d). This is partly because

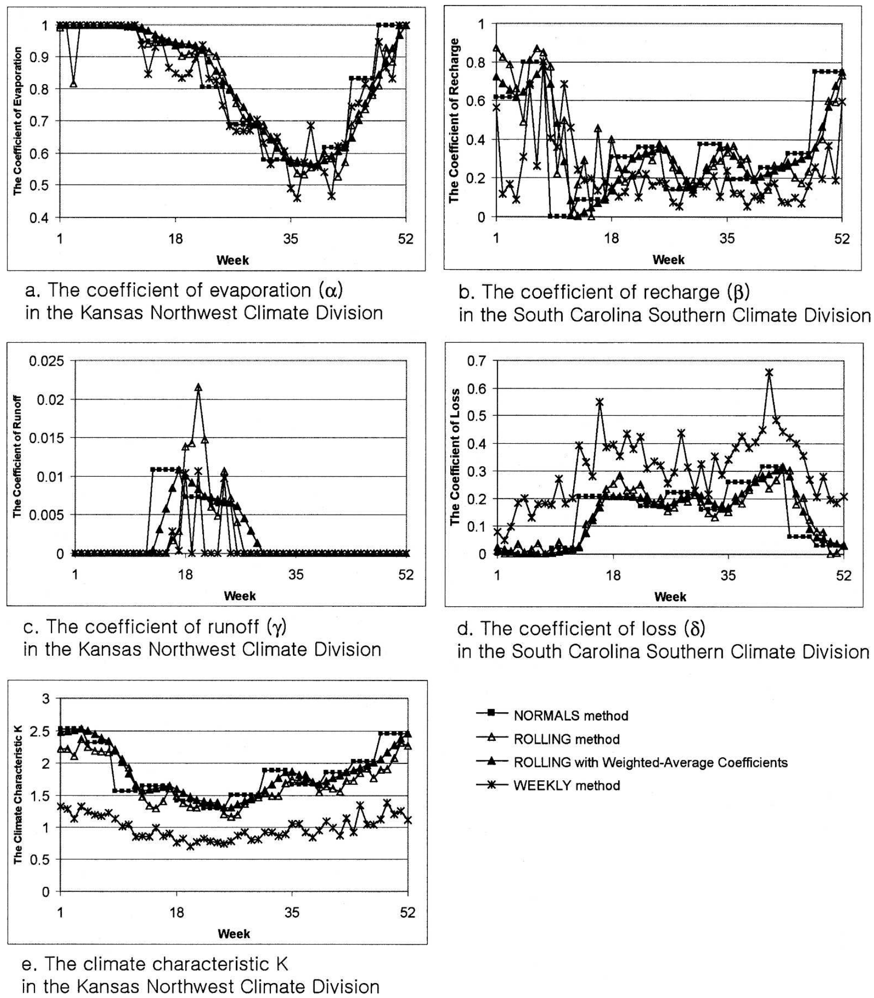

FIG. 6. The CAFEC coefficients and the climate characteristic K by various methods: (a) the coefficient of evaporation (α) in the Kansas Northwest Climate Division, (b) the coefficient of recharge (β) in the South Carolina Southern Climate Division, (c) the coefficient of runoff (γ) in the Kansas Northwest Climate Division, (d) the coefficient of loss (δ) in the South Carolina Southern Climate Division, and (e) the climate characteristic K in the Kansas Northwest Climate Division.

TABLE 4. Percent frequencies (%) for PDI drought categories: Z Index in the Kansas Northwest Climate Division (WA devotes the weighted average).

Category	NORMALS	ROLLING	ROLLING WA	WEEKLY	MONTHLY (1991–2000)	MONTHLY (1895–2005)
Extreme drought	0.19	0.38	0.96	0.00	1.67	1.28
Severe drought	0.77	1.15	1.92	0.00	0.83	1.65
Moderate drought	2.12	4.81	4.62	0.00	5.00	5.26
Mild drought	9.23	12.50	15.38	0.00	12.50	17.12
Incipient drought	11.35	15.58	13.46	6.73	18.33	13.44
Near normal	33.46	22.88	21.35	76.15	14.17	22.67
Incipient wet spell	12.50	11.15	9.42	10.00	10.83	10.29
Slightly wet	15.58	11.35	11.92	5.77	16.67	12.84
Moderately wet	7.12	8.65	8.08	1.15	8.33	7.36
Very wet	3.46	3.85	4.42	0.19	4.17	3.83
Extremely wet	4.23	7.69	8.46	0.00	7.50	4.28

TABLE 5. Percent frequencies (%) for PDI drought categories: PMDI in the Kansas Northwest Climate Division.

Category	NORMALS	ROLLING	ROLLING WA	WEEKLY	MONTHLY (1991–2000)	MONTHLY (1895–2005)
Extreme drought	0.58	0.00	0.19	0.00	0.00	7.28
Severe drought	1.92	1.92	2.69	0.00	1.67	2.63
Moderate drought	2.88	1.54	3.85	2.50	3.33	3.83
Mild drought	11.73	14.23	13.85	5.00	14.17	10.66
Incipient drought	8.27	9.04	8.27	16.35	6.67	8.11
Near normal	11.15	10.38	10.38	18.27	10.00	14.11
Incipient wet spell	6.35	6.35	4.81	11.73	8.33	7.36
Slightly wet	12.50	15.38	13.46	15.00	10.00	15.62
Moderately wet	8.46	9.62	9.42	15.96	10.00	10.59
Very wet	10.19	9.62	10.38	9.42	10.00	10.51
Extremely wet	25.96	21.92	22.69	5.77	25.83	9.31

of the change of calculation methods; all available representative stations within each climate division were used for the period from 1931 to the present, while the divisional values were estimated from the statewide values using regression techniques for the period prior to 1931 (Guttman and Quayle 1996). The more important causes of the skewed distributions are the climate characteristic *K* and the duration factors. Because the duration factors [coefficients of the Eq. (1)] and the climate characteristic K were derived empirically based on several locations in two and seven states, respectively, the PDI has skewed distributions and is not proper for spatial and temporal comparison (Wells et al. 2004). The 10-yr standard monthly distributions for the period from 1991 to 2000 are more skewed than the long-term distributions (Figs. 7a–d). The differences between the 10-yr standard monthly distributions and the long-term distributions are partly due to the different calibration periods, 1961–90 and 1895–1990, respectively, and mainly because of the unusual weather conditions in both climate divisions during 1993 (Fig. 4). Both the Midwest and the southeastern U.S. regions experienced moderately wet conditions in 1992. While the heavy precipitation during 1993 in the Midwest aggravated the previous wet conditions and led to the great Midwest flood, the extremely dry conditions during 1993 in the southeastern United States were alleviated by the previous wet conditions (Lott 1994). The effects of the unusual weather conditions during 1993 were shown especially well in PMDI distributions as increased frequencies for the extremely wet category in the Kansas Northwest Climate Division (from 9.31% to 25.83%; Table 5; Fig. 7b) and as decreased frequencies for the extreme drought category in the South Carolina Southern Climate Division (from 0% to 2.18%; Table 7; Fig. 7d).

Wells et al. (2004) developed a method for creating spatially and temporally comparable PDI with reduced extreme conditions by dynamically calculating the duration factors and the climate characteristic *K* based on the long-term historical climate data. Although the long-term standard monthly distributions using the self-calibrating method probably will be much closer to Gaussian, the combination of these techniques is beyond the scope of this study. The source code, available via the National Agricultural Decision Support System (NADSS; Wells et al. 2004), provides the weekly calculation of PDI with various temporal scales of 1, 2,

TABLE 6. Percent frequencies (%) for PDI drought categories: *Z* Index in the South Carolina Southern Climate Division.

Category	NORMALS	ROLLING	ROLLING WA	WEEKLY	MONTHLY (1991–2000)	MONTHLY (1895–2005)
Extreme drought	0.00	0.00	0.00	0.00	0.00	0.08
Severe drought	0.38	0.96	2.12	0.00	2.50	2.10
Moderate drought	2.50	9.62	10.00	0.00	10.00	10.36
Mild drought	13.08	18.85	19.42	0.00	17.50	19.97
Incipient drought	15.77	11.92	12.12	5.96	14.17	12.16
Near normal	39.04	21.15	20.96	78.85	15.83	22.07
Incipient wet spell	12.31	9.04	7.50	10.96	5.00	8.18
Slightly wet	10.38	15.77	15.38	4.04	20.00	12.91
Moderately wet	4.04	7.12	6.92	0.19	9.17	5.86
Very wet	1.73	3.46	3.65	0.00	2.50	3.08
Extremely wet	0.77	2.12	1.92	0.00	3.33	3.23

TABLE 7. Percent frequencies (%) for PDI drought categories: PMDI in the South Carolina Southern Climate Division.

Category	NORMALS	ROLLING	ROLLING WA	WEEKLY	MONTHLY (1991–2000)	MONTHLY (1895–2005)
Extreme drought	0.00	0.00	0.00	0.00	0.00	2.18
Severe drought	0.19	0.19	2.12	0.00	0.83	3.15
Moderate drought	11.15	12.31	18.27	1.54	11.67	11.34
Mild drought	18.46	19.23	19.62	14.42	17.50	18.69
Incipient drought	11.15	10.77	10.00	11.15	14.17	10.29
Near normal	19.62	18.65	14.23	29.62	15.83	15.77
Incipient wet spell	8.08	6.35	5.38	17.50	6.67	9.61
Slightly wet	11.73	14.42	14.62	17.50	14.17	13.66
Moderately wet	10.58	9.42	7.31	8.27	8.33	8.78
Very wet	4.62	5.00	5.58	0.00	5.00	4.05
Extremely wet	4.42	3.65	2.88	0.00	5.83	2.48

4, and 13 weeks. The 4-week PDI is similar to the ROLLING method, but the use of four parallel month-long calculation chains in rotation was not included. A single set of the duration factors and the climate characteristic K should be determined for all four calculation chains to enable the week-to-week comparison when combined with the ROLLING method.

Even calculated using the self-calibrating technique, the 10-yr standard monthly distributions will still be skewed due to the effects of the unusual weather conditions during 1993. Thus, the weekly monitoring method, which shows the distribution closest to the 10-yr monthly monitoring distribution, is preferable, in that the existing monthly monitoring distribution has been familiar to climatologists of the region and there should be consistency between the weekly and the monthly monitoring.

The frequency for the extremely wet category by the WEEKLY method was much smaller (5.77%; Table 5) than other methods (about 22%–26%) in the Kansas Northwest Climate Division. As observed in the time series graphs (Figs. 5a–d), the WEEKLY method usually produced far more near-normal Z Index values (about 40%–58% more), mainly because the WEEKLY method produced Z Index values which were about a quarter of the standard monthly values. It also produced about 7%–15% more near normal and up to about 12% more incipient drought/wet spell PMDI values (Tables 4–7; Figs. 7a–d) in both climate divisions, showing that the WEEKLY method does not retain the same length of memory with standard monthly analysis.

The NORMALS method produced 10.58% more near-normal Z Index values than the ROLLING method in the Kansas Northwest Climate Division, and 17.88% more near normal and about 3%–4% more incipient drought/wet spell Z Index values in the South Carolina Southern Climate Division (Tables 4 and 6; Figs. 7a,c). This suggests that the use of long-term historical normals moderates the number of individual wet and dry months. There were no noticeable differences in the distributions for PMDI due to the influence of its recursive nature (Tables 5 and 7; Figs. 7b,d).

The distribution differences between the two ROLLING methods with different calculation schemes of the CAFEC coefficients and the climate characteristic K were relatively small compared to the differences to other methods in both climate divisions, and the distribution differences for PMDI were slightly larger than those for Z Index (Tables 4–7; Figs. 7a–d).

6. Conclusions

A method for weekly monitoring of the PDI by using four parallel month-long calculation chains in rotation was tested and compared with the weekly PDI monitoring method and the method for estimating monthly PDI using long-term historical daily normals. The results for the Kansas Northwest Climate Division and the South Carolina Southern Climate Division generally agreed. The WEEKLY method, a modified version of the CPC's method, produced a somewhat different magnitude of drought severity when compared with the typical monthly results. This occurred even though it used a modified set of coefficients. The NORMALS method, introduced by Heim (2005) and used by NCDC, estimated PMDI and Z Index values well late in the month, but it sometimes presented a misleading trend early in the month. It also produced Z Index values that underestimated the magnitude of both wet and dry periods. The ROLLING method successfully produces PMDI and Z Index values that approximate those found using drought severity and preserves approximately the same length of memory found in the standard monthly PDI.

Although the differences in the PMDI percent frequency distributions for PDI drought categories between the NORMALS and ROLLING methods were not large, the ROLLING method overall performed

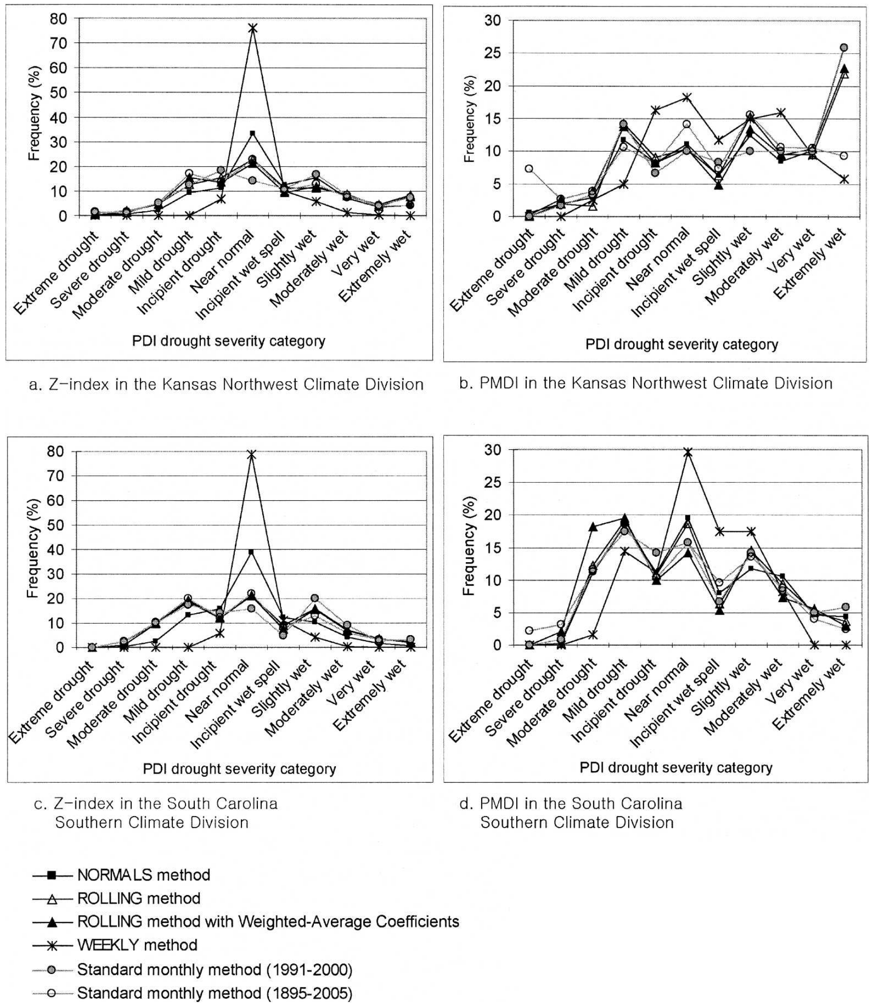

FIG. 7. Percent frequency distributions for PDI drought categories for (a) Z Index values in the Kansas Northwest Climate Division, (b) PMDI values in the Kansas Northwest Climate Division, (c) Z Index values in the South Carolina Southern Climate Division, and (d) PMDI values in the South Carolina Southern Climate Division using various methods. The standard monthly values for the period from 1991 to 2000 and for the period from 1895 to 2005 were also shown as reference.

better in the Z Index frequency distributions and the week-to-week time series movement of drought conditions. More importantly, the ROLLING method provides a progressive monitoring tool. While the NORMALS method estimates the drought conditions anticipated at the end of the current month, the ROLLING method provides the drought condition of the current week just as the standard monthly PDI values provide the drought condition at the end of the current month. While the NORMALS method can provide only the monthly historical archive of PDSI and PHDI, the ROLLING method, because of its backstepping procedure, provides a weekly historical archive of the PDSI and PHDI for further analysis on the historical magnitude and frequency of drought and in impact assessment. The ROLLING method also allows users to detect drought early.

The ROLLING method will be included in the near-real-time operational Web-based drought monitoring application for North and South Carolina and will be used as one of the alternative methods for weekly monitoring of the PDI. This interactive regional-scale drought monitoring application resides at the South Carolina Department of Natural Resources Web site (see http://drought.dnr.sc.gov) and will include weekly calculations of PDI values after May 2007. The weekly drought information will be used by the drought monitoring committee during severe droughts (Carbone et al. 2007). Potential beneficiaries of this method include water resources managers who are going to use weekly PDI values as one of their criteria for determining water usage during dry periods.

Acknowledgments. The authors thank the editorial assistance of Karen Beidel as well as the helpful comments of two anonymous reviewers. This work was supported by a grant from the NOAA Climate Program Office under NOAA Contract NA06OAR4310007.

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