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September 3, 2008

Via Hand-Delivery

Chairman Tre Hargett
c/o Ms. Sharla Dillon
Tennessee Regulatory Authority
460 James Robertson Parkway
Nashville, Tennessee 37243

filed electronically 9/3/08

Re: *Petition Of Tennessee American Water Company To Change And Increase Certain Rates And Charges So As To Permit It To Earn A Fair And Adequate Rate Of Return On Its Property Used And Useful In Furnishing Water Service To Its Customers*
Docket No. 08-00039

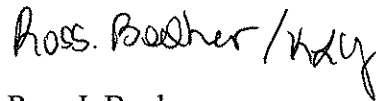
Dear Chairman Hargett:

Enclosed please find an original and seven (7) copies of filing of Tennessee American Water Company's Comment in Opposition to Notice of Administrative Notice.

Please return three copies of this document, which I would appreciate you stamping as "filed," and returning to me by way of our courier.

Should you have any questions concerning the enclosed, please do not hesitate to contact me.

Sincerely,



Ross I. Booher

Enclosure

Chairman Tre Hargett
September 3, 2008
Page 2

cc: Hon. Mary Freeman (*w/o enclosure*)
Hon. Sara Kyle (*w/o enclosure*)
Hon. Eddie Roberson (*w/o enclosure*)
Richard Collier, Esq. (*w/o enclosure*)
Ms. Shilina Chatterjee (*w/o enclosure*)
Ms. Kelly Grams (*w/o enclosure*)

6999368.1

**BEFORE THE TENNESSEE REGULATORY AUTHORITY
NASHVILLE, TENNESSEE**

IN RE:

PETITION OF TENNESSEE AMERICAN)	
WATER COMPANY TO CHANGE AND)	
INCREASE CERTAIN RATES AND CHARGES)	
SO AS TO PERMIT IT TO EARN A FAIR AND)	
ADEQUATE RATE OF RETURN ON ITS)	Docket No. 08-00039
PROPERTY USED AND USEFUL IN)	
FURNISHING WATER SERVICE TO ITS)	
CUSTOMERS)	

**TENNESSEE AMERICAN WATER COMPANY'S
COMMENT IN RESPONSE TO NOTICE OF ADMINISTRATIVE NOTICE**

Tennessee-American Water Company ("TAWC" or the "Company") submits this comment in response to the Notice of Administrative Notice filed in this docket on August 29, 2008 ("Notice"), along with the documents referenced herein, pursuant to Tenn. Code Ann. § 4-5-313(b) and § 65-2-109(3).

The Tennessee Regulatory Authority ("TRA") plans to take administrative notice of the following publications and documents: (1) NARUC, Management Audit Manuals, Vol. I Fundamentals of Management Audits (filed as Hearing Exhibit 58) ("1988 NARUC Manual"); (2) William M. Alley, *The Palmer Drought Severity Index: Limitations and Assumptions*, 23 JOURNAL OF CLIMATE AND APPLIED METEOROLOGY 1100 (1984); and (3) Committee on USGS Water Resources Research, Water Science and Technology Board, Division on Earth and Life Studies, National Research Council, *Estimating Water Use in the United States* (2002) (the latter two collectively, "PDSI articles").

The Company maintains its objections voiced at the Hearing to the introduction of the 1988 NARUC Manual. TAWC objects on the grounds that the document is out-dated, it was not referenced anywhere in the sponsoring witness' pre-filed testimony, and it was not produced in

response to discovery requests as required.¹ To take notice of the 1988 NARUC Manual at this time would reward the Intervenor for failing to comply with discovery obligations with respect to a discovery request that has been outstanding since May 12, 2008.

Under Tennessee law, official notice is only appropriate where the material: 1) could be judicially noticed in the courts of this state; 2) is a record of other proceedings before the agency; 3) is a technical or scientific matter within the agency's specialized knowledge; or 4) is a code or standard that has been adopted by an agency of the United States, of this state or of another state, or by a nationally recognized organization or association.² The 1988 NARUC manual indisputably does not qualify under categories 1 through 3. With respect to the fourth category, the 1988 NARUC Manual does not constitute a code or standard since, on the face of the document, it is a mere guideline:

There are a number of published materials addressing management and operations audits. Accordingly, the manual should not be construed as presenting the only approach or the definitive guideline to implementing a management audit.³

Therefore, it does not qualify for administrative notice.⁴

Alternatively, if notice is taken, then notice should also be taken of a more recent NARUC publication, the Rate Case and Audit Manual, prepared by the NARUC Subcommittee on Accounting and Finance in 2003, which provides:

We (NARUC) do not mean it (Management Audit or Regulatory Audit) in the purist sense of the word, where one might assume a verification of booked numbers to source documents and a strict sampling of accounts. Instead, we use it to mean a regulatory review, a field investigation, or a means of determining the appropriateness of a financial presentation for regulatory purposes. **Clearly, the**

¹ Michael Majoros, Vol. XX, Tr. 1987:6-20, 2000:24-2001:1; Michael Majoros Vol. XXI, Tr. 2088:12-15; TAWC's First Discovery Requests to City of Chattanooga, Discovery Request No. 4 (May 12, 2008).

² Tenn. Code Ann. § 4-5-313(6)(A) (2008).

³ NARUC "Management Audit Manual Volume I of Fundamentals of Management Audits," Hearing Ex. 58 at p. 2; Michael Majoros, Vol. XXI, Tr. 2085:24-2086:4.

⁴ Nor does the 1988 NARUC Manual qualify under Tenn. Code Ann. § 65-2-109(4) (2008) as the type of information that is general, technical, or scientific facts which could be noticed.

reader should distinguish a regulatory audit from financial audits performed by independent certified public accountants.⁵

When two conflicting publications from the same source are presented, one of which is more recent by 15 years, if either of the two is to be credited above the other, it should certainly be the more recent one. This is especially true where the older publication explicitly acknowledges the principle that management audits “evolve.”⁶

TAWC also objects to the PDSI articles on the grounds that these materials were not produced as part of the Intervenor’s ongoing obligation to supplement discovery responses and were not so much as mentioned in the pre-filed testimony of the Intervenor’s witnesses. If the TRA deems it appropriate to take administrative notice of the PDSI articles, then the Company respectfully submits the following articles for administrative notice, which directly rebut any criticisms of the PDSI contained in the articles listed in the Notice:⁷

1. Heddinghaus, T.R. and P. Sabol, “A Review of the Palmer Drought Severity Index and Where Do We Go From Here?,” 7th Conf. on Applied Climatology, pp. 242–46, September 10–13, 1991, Salt Lake City, Utah; American Meteorological Society, Boston, *available at* <http://vlb.ncdc.noaa.gov/oa/climate/research/drought/heddinghaus-sabol-pmdi-article.pdf> (last visited Sept. 3, 2008) (“Heddinghaus article”); and
2. Wells, Nathan, et. al, “A Self-Calibrating Palmer Drought Severity Index”, JOURNAL OF CLIMATE, Vol. 17 at 2335 (2004) (“Wells article”).

In response to criticisms of the PDSI, the Heddinghaus article explains how the PDSI index was modified in 1989 to better identify the beginning and ending of a wet or dry spell.

⁵ NARUC Rate Case and Audit Manual, p. 4 (2003) *available at* http://www.globalregulatorynetwork.org/PDFs/ratecase_manual.pdf (last visited Sept. 3, 2008) (emphasis added).

⁶ Hearing Ex. 58, at 2 (NARUC “Management Audit Manual Volume I of Fundamentals of Management Audits”); Michael Majoros, Vol. XXI, Tr. 2085:24-2086:4.

⁷ See Affidavit of Edward Spitznagel, Attachments A and B, (attached hereto).

The Wells article praises the inventor of the PDSI: “While the procedure presented here for calculating the PDSI is different from Palmer’s original procedure, it does not stray from his objective. By simply automating the processes that Palmer used to derive the empirical constants used in his procedure, it does what Palmer might have done, had he been given access to today’s computing resources. In a sense, the new procedure for calculating the PDSI is simply a modern implementation of Palmer’s ideas.”⁸

The Company also submits the Affidavit of Dr. Spitznagel, pursuant to Tenn. Code Ann. § 4-5-313(6)(B) and § 65-2-109(4) to rebut any significance that might be gleaned from the articles specified in the Notice. According to Dr. Spitznagel, the values posted on the NOAA website that he uses in his model have all been calculated based on the 1989 modifications of the PDSI discussed above. Dr. Spitznagel also states that any current lack of regional comparability in the PDSI is not a problem in his weather normalization, as only the data in the climate division containing Chattanooga is used.

For the foregoing reasons, the Company opposes the taking of administrative notice of the publications and documents referenced in the Notice. In the alternative, if notice is taken of these materials, then the Company respectfully requests that the TRA consider the comments, documents, and Affidavit submitted herein.

⁸ See Affidavit of Edward Spitznagel, Attachment B at 2335-36.

Respectfully submitted,

A handwritten signature in black ink, appearing to read "R. Dale Grimes", written over a horizontal line.

R. Dale Grimes (#6223)

Ross I. Booher (#019304)

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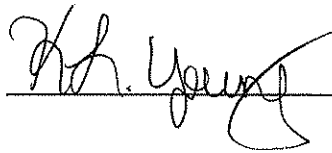
Attorneys for Petitioner

Tennessee American Water Company

CERTIFICATE OF SERVICE

I hereby certify that a true and correct copy of the foregoing has been served via the method(s) indicated, on this the 3rd day of September, 2008, upon the following:

<input checked="" type="checkbox"/> Hand-Delivery	Timothy C. Phillips, Esq.
<input type="checkbox"/> U.S. Mail	Consumer Advocate and Protection Division
<input type="checkbox"/> Facsimile	Office of Attorney General
<input type="checkbox"/> Overnight	2nd Floor
<input checked="" type="checkbox"/> Email	425 5th Avenue North
	Nashville, TN 37243-0491
<input type="checkbox"/> Hand-Delivery	David C. Higney, Esq.
<input type="checkbox"/> U.S. Mail	Counsel for Chattanooga Manufacturers Association
<input type="checkbox"/> Facsimile	Grant, Konvalinka & Harrison, P.C.
<input checked="" type="checkbox"/> Overnight	633 Chestnut Street, 9th Floor
<input checked="" type="checkbox"/> Email	Chattanooga, TN 37450
<input checked="" type="checkbox"/> Hand-Delivery	Henry M. Walker, Esq.
<input type="checkbox"/> U.S. Mail	Counsel for Chattanooga Manufacturers Association
<input type="checkbox"/> Facsimile	Boult, Cummings, Connors & Berry, PLC
<input type="checkbox"/> Overnight	Suite 700
<input checked="" type="checkbox"/> Email	1600 Division Street
	Nashville, TN 37203
<input type="checkbox"/> Hand-Delivery	Michael A. McMahan, Esq.
<input type="checkbox"/> U.S. Mail	Special Counsel
<input type="checkbox"/> Facsimile	City of Chattanooga (Hamilton County)
<input checked="" type="checkbox"/> Overnight	Office of the City Attorney
<input checked="" type="checkbox"/> Email	Suite 400
	801 Broad Street
	Chattanooga, TN 37402
<input type="checkbox"/> Hand-Delivery	Frederick L. Hitchcock, Esq.
<input type="checkbox"/> U.S. Mail	Harold L. North, Jr., Esq.
<input type="checkbox"/> Facsimile	Counsel for City of Chattanooga
<input checked="" type="checkbox"/> Overnight	Chambliss, Bahner & Stophel, P.C.
<input checked="" type="checkbox"/> Email	1000 Tallan Building
	Two Union Square
	Chattanooga, TN 37402



TENNESSEE REGULATORY AUTHORITY
AFFIDAVIT OF DR. EDWARD L. SPITZNAGEL, JR.

STATE OF MISSOURI

COUNTY OF SAINT LOUIS

Having been first duly sworn, Dr. Edward L. Spitznagel, Jr. states under oath as follows:

1. I have appeared as a witness on behalf of Tennessee-American Water Company before the Tennessee Regulatory Authority, Docket No. 08-00039.

2. I have personal knowledge of the facts contained in this affidavit and the exhibits attached hereto.

3. Pursuant to the Notice of Administrative Notice filed in this docket on August 29, 2008 ("Notice"), I submit the following articles and request that administrative notice be taken thereof: Heddinghaus, T.R. and P. Sabol, "A Review of the Palmer Drought Severity Index and Where Do We Go From Here?" In Proc. 7th Conf. on Applied Climatology, pp. 242-246, September 10- 13, 1991, Salt Lake City; American Meteorological Society, Boston, available at <http://vlb.ncdc.noaa.gov/oa/climate/research/drought/heddinghaus-sabol-pmdi-article.pdf> (attached hereto) and Wells, Nathan, et. al, "A Self-Calibrating Palmer Drought Severity Index", JOURNAL OF CLIMATE, Vol. 17 at 2335 (2004) (attached hereto).

4. The Heddinghaus and Wells articles are submitted for consideration in rebuttal of the articles attached to the Notice entitled "The Palmer Drought Severity Index: Limitations and Assumptions" by William M. Alley and "Estimating Water Use in the United States" from the National Research Council.

5. The Heddinghaus article states that in 1989, NCDC modified the method of computing the operational PDSI to account for some of the weaknesses observed over the years.

6. Therefore, some or all of Alley's 1984 critique has been addressed.

7. The values posted on the NOAA website that I use in my model have all been calculated based on the 1989 modifications (even for years prior to 1989).

8. The Wells article proposes a "self-calibrating" PDSI, for better comparisons of one region of the US to another.

9. Any current lack of regional comparability in the PDSI is not a problem in my weather normalization, as only the data in the climate division containing Chattanooga is used.

10. The Wells article praises Palmer by saying: "While the procedure presented here for calculating the PDSI is different from Palmer's original procedure, it does not stray from his objective. By simply automating the processes that Palmer used to derive the empirical constants used in his procedure, it does what Palmer might have done, had he been given access to today's computing resources. In a sense, the new procedure for calculating the PDSI is simply a modern implementation of Palmer's ideas." *See Wells at 2335-36.*

11. The PDSI that I use is the most recent version available from the federal government (NOAA).

12. In my extensive study for Kentucky American Water Company in 1997 (mandated by the Kentucky PSC), I compared all four versions of the drought indices made available by NOAA and found the PDSI to be the best predictor of water consumption.

13. TAWC was one of the sixteen companies whose data was used in that study.

14. To date, NOAA has not provided any additional drought measures.

FURTHER AFFIANT SAITH NOT.

Edward L. Spitznagel, Jr.
DR. EDWARD L. SPITZNAGEL, JR.

Sworn to and subscribed before me
This 3rd day of September 2008.

Lisa Caress
Notary Public

My commission expires 4/11/2010

6998510.1

LISA CARESS
NOTARY PUBLIC - NOTARY SEAL
STATE OF MISSOURI, JEFFERSON COUNTY
MY COMMISSION EXPIRES 04/11/2010

A Review of the Palmer Drought Severity Index and Where Do We Go from Here?

Thomas R. Heddinghaus and Paul Sabol
Climate Analysis Center, NWS/NOAA
Washington, DC 20250

1. INTRODUCTION

Droughts are prolonged and abnormal periods (months to years) of moisture deficiency over a given region. The severity depends upon the degree of the moisture deficiency, duration, and size of the affected area. Various indicators have been derived to encapsulate drought severity on a regional basis (Landsberg, 1975; Heddinghaus et al., 1987). Perhaps the best known is the Palmer Drought Severity Index (PDSI) developed by W.C. Palmer (1965) as a climatological tool in assessing long-term meteorological drought. Despite criticism of the PDSI as a measure of drought severity and its employment to assess impact (Changnon, 1980; Wilhite, 1983; Alley 1984), the PDSI is widely utilized by a variety of users: the press and news media to depict areas and severity of drought during periods of crisis; private consultants to describe crop conditions and assess futures in the commodity market; hydrologists to survey levels of streamflow, lakes, reservoirs, and groundwater; field meteorologists, economists, and policy decision makers to estimate soil moisture and rangeland conditions and their effect on the general economy; researchers to study the spatial and temporal characteristics of dry and wet episodes; and foresters to indicate conditions for fire ignition and potential severity.

Monthly values of the PDSI are computed, distributed, and archived by the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (NCDC) in Asheville, NC (Karl and Knight, 1985), while weekly values are calculated by NOAA's Climate Analysis Center (CAC) in Washington, DC. These weekly values are published in the Weekly Weather and Crop Bulletin (Heddinghaus and LeComte, 1989) and Weekly Climate Bulletin (Bergman and Sabol, 1986) and made available on CAC's Climate Dial-Up Service (CDUS), (Finger et al., 1985).

It is the intent of this paper to discuss the PDSI, problems and solutions in its use in an operational mode, and its limitations and shortcomings. A survey is also made of the users of the PDSI who access the data from CDUS to determine how the PDSI is used and receive any suggestions for changes or improvements. Results of the survey and future plans and recommendations are discussed.

2. THE PALMER DROUGHT SEVERITY INDEX

The PDSI is based on the principles of a balance between moisture supply and demand and was empirically derived from historical cases of extreme drought. An index value of -4.0 was assigned for these extremely dry cases and a +4.0 was conversely assigned to represent extremely wet conditions. From these values 11 categories of wet and dry are defined (Table 1). The index is given by the equation:

$$X_i = .897 X_{i-1} + Z_i/3$$

where X_i = current PDSI

X_{i-1} = previous month's PDSI

Z_i = Z index (current moisture anomaly).

The X_{i-1} term accounts for the effect of the duration of the drought or wet spell while the value of Z is given by:

$$Z = k (P - \hat{P})$$

where k = climatic weighing factor

and P = monthly precipitation

\hat{P} = the Climatically Appropriate For Existing Conditions (CAFEC) precipitation

where $\hat{P} = \hat{ET} + \hat{R} + \hat{RO} - \hat{L}$

and \hat{ET} = CAFEC evapotranspiration

\hat{R} = CAFEC recharge of soil moisture

\hat{RO} = CAFEC runoff

\hat{L} = CAFEC loss of soil moisture.

The climatic weighing factor (k) allows the index to have a comparable significance from location to location. P and \hat{L} represent moisture supply, and \hat{ET} , \hat{R} , and \hat{RO} represent moisture demand. The CAFEC terms are computed from current values and constants derived from historical data. Input parameters include precipitation totals and temperature averages for each climatic division. The temperatures are used to compute potential evapotranspiration (Thornthwaite, 1948), from which \hat{ET} is calculated. The runoff, soil recharge and loss are computed by keeping a hydrologic accounting of moisture in a two soil layer model with the surface holding one inch and the underlying layer having an available capacity depending on the type of soil of the location being measured.

Table 1

PDSI classes for wet and dry periods

PDSI	Class
4.00 and above	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.00	Slightly wet
.50 to .99	Incipient wet spell
.49 to -.49	Near normal
-.50 to -.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 and below	Extreme drought

3. OPERATIONAL PROBLEMS AND SOLUTIONS IN USING THE PDSI

The PDSI, as formulated by Palmer, is not continuous but is measured from the beginning of a wet or dry spell which is determined by calculating a 100% "probability" that the opposite spell is over. For example, the first substantial rain, for an area experiencing a prolonged drought, could signify the beginning of a wet spell or might only be a brief respite in the midst of the drought. This is not necessarily determined until months (or even years) later when enough subsequent precipitation has been accumulated to end the drought according to Palmer's definition (i.e. the probability reaches 100%). During this time of "uncertainty" both an X1 term (for an incipient wet spell) and an X3 term (for an established drought) are computed. If the probability that the drought is over becomes 100%, then the positive X1 value is assigned to the PDSI. If, on the other hand, the probability returns to zero, the negative X3 term is assigned and the drought continues.

Problems thus arise in using the PDSI as an operational index since it may not be known until a later date which spell the PDSI is really in. A previous system used at CAC kept the X3 term when the probability was equal to or less than 50% and used the X1 term when the probability was greater than 50%. The rationale for selecting the X1 was that the odds are in favor of the drought being over and the given climate division was likely in a wet spell.

This method was particularly unsatisfactory for areas recovering from extreme drought, as in North Dakota's climate division 9 (Fig. 1), because the index jumps from negative and positive values (or vice versa) when the probability goes over (under) 50%. Notice weeks 46-49 in Figure 2.

A preliminary PDSI modification takes the sum of the wet and dry terms after they have been weighted by their probabilities. The results of this modified preliminary PDSI are shown in Figures 1 and 2. This method eliminates the flipping between positive and negative values when the

probability crossed 50%. During transition periods the preliminary index would not be the same as the final PDSI but would be the same during established weather spells (i.e., when the probability is 0% or 100%). The modified index is continuous and likely to be more normally distributed (unlike the PDSI). After concurrence with experts at NCDC, this new method of computing the operational PDSI was implemented in June 1989.

NORTH DAKOTA - DIVISION 9
GROWING SEASON BEGINS MARCH 5, 1988
ENDS FEBRUARY 25, 1989

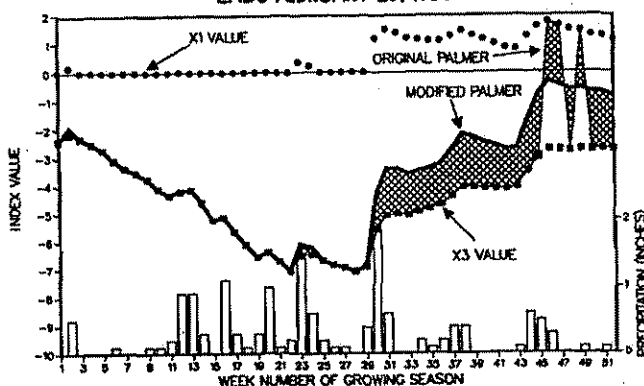


Figure 1. X1 values for the incipient wet spell (circles), X3 values for the established drought (boxes), the previous Palmer Drought Severity Index (light line), and the modified index (heavy line) for climatic division 9 in North Dakota from March 5, 1988 to February 25, 1989. Index values of -4 or less indicate extreme drought conditions. Hatched areas indicate differences in the two indices. Weekly precipitation total are given in bars at the bottom with amount in inches to the right.

NORTH DAKOTA - DIVISION 9
GROWING SEASON BEGINS MARCH 5, 1988
ENDS FEBRUARY 25, 1989

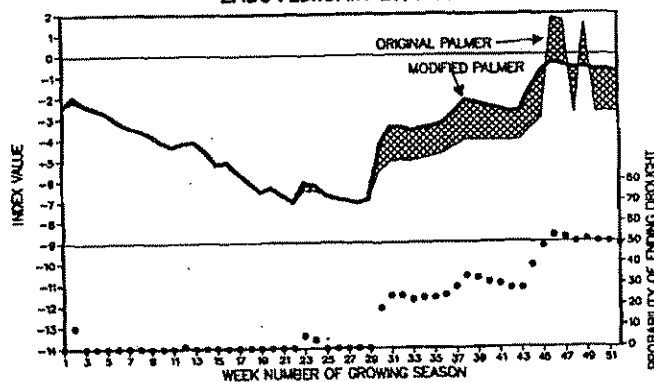


Figure 2. Similar to Figure 1 except the X1 and X3 values are omitted and the probabilities of ending the drought (circles) are plotted at the bottom instead of precipitation.

4. LIMITATIONS AND SHORTCOMINGS OF THE PDSI

A critique of the PDSI was published by Alley (1984) in which he gave a detailed description of the computational procedures to illustrate deficiencies in the method. The primary deficiencies listed were:

1. The index uses arbitrary rules in quantifying both the intensity of drought and their beginning and ending times. The 13 driest intervals of the accumulated Z index in the original study areas in central Iowa and western Kansas were defined as extreme (-4.0) to indicate intensity (Fig. 3). Drought ends when the accumulated moisture received is enough for the index to reach -0.5 (the upper limit of the arbitrarily defined incipient drought).
2. The weighing function (k) used to standardize the values of the PDSI for different locations and months is based on limited comparisons and is weakly justified on physical or statistical grounds. Initially for the two study areas, k (a ratio of moisture supply and demand) was defined as:

$$k = (\bar{P} + R) / (\bar{P} + \bar{L}),$$

where the bar indicates the long-term mean. After this was found unsatisfactory, k was empirically adjusted to a much more complex form using nine climatic divisions (one each in Kansas, Iowa, Pennsylvania, Ohio, North Dakota, and Tennessee and three in Texas).

3. Under certain conditions (i.e., when a small amount of additional precipitation may be enough for the "probability" to reach a 100%), the PDSI values are very sensitive in ending an "established drought" and have a large effect on the PDSI values for several months. A detailed discussion of the sensitivity of the PDSI is given by Karl (1986).
4. The distribution of the PDSI is bimodal (Fig. 4). Thus, conventional time series models are limited in their ability to capture stochastic properties of the index.

Alley also noted that no lag is incorporated to account for the delay between generation of excess water and its appearance as runoff. He concluded that there is a great need for additional research into drought indices and that until a "better" index is developed, the PDSI will likely continue to be widely used.

5. SURVEY OF USERS

A wide variety of users obtain near real-time meteorological products on CAC's

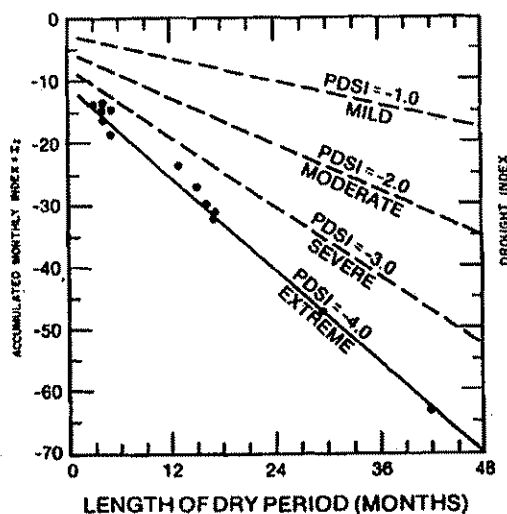


Figure 3. Accumulated values of the moisture anomaly Z index during the driest periods of various lengths in central Iowa and western Kansas (after Palmer, 1965).

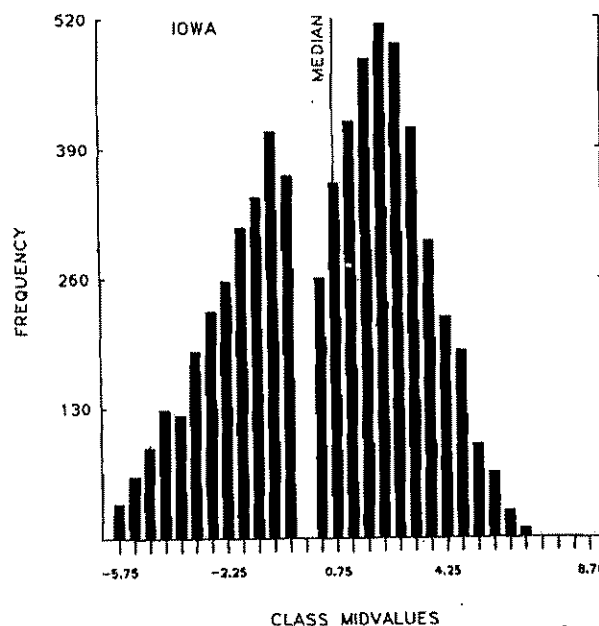


Figure 4. Histogram of the monthly PDSI values for the 9 climatic divisions in Iowa since 1931.

CDUS, a system that has been operating since January 1983 on a twenty-four hour day, seven day per week, basis. Many of these users access files related to the PDSI (Fig. 5). Letters were mailed to those customers who received these files on a regular basis. Customers were asked in the letter to respond to some or all of the following questions:

1. For what purpose do you use the PDSI?
2. How accurately does the PDSI meet your needs?

WEEKLY PALMER DROUGHT AND CROP MOISTURE DATA
FOR THE CLIMATE DIVISIONS IN THE WESTERN REGION
CLIMATE ANALYSIS CENTER-NMC-NWS-NOAA
WEEK 11 OF THE 1991 GROWING SEASON
ENDING MAY 18, 1991

ST	CD	TMP	PRCP	SOIL		PCT	POT	RUN	CROP	CHNG	MONTH	PRELIM-P	PRECIP
		(F)	(IN)	MOISTURE		FLD	EVAP	OFF	MOIST	FROM	ANOML	PALMER	TO END
				UPPR	LOWR	CPC	(IN)	(IN)	INDEX	PREV	(Z)	DROUTH	DROUTH
				LAYR	LAYR	END					INDEX		(IN)
				(IN)	(IN)	WEEK							
AZ	1	65	0.0	0.00	0.35	5	0.76	0.00	-1.64	-0.26	-2.05	-4.07 F	5.30
AZ	2	56	0.0	0.00	3.48	50	0.82	0.00	-0.62	-0.11	-2.30	-1.27 F	1.05
AZ	3	63	0.0	0.00	3.06	44	0.74	0.00	-0.53	-0.12	-1.48	-0.89 F	0.69
AZ	4	65	0.0	0.00	4.04	58	0.74	0.00	-0.25	-0.11	-1.33	-0.63 F	0.40
AZ	5	76	0.0	0.00	0.00	0	1.15	0.00	-1.42	0.01	-1.66	-1.42 F	0.55
AZ	6	73	0.0	0.00	0.95	14	1.00	0.00	-0.87	-0.02	-1.28	0.38 F	
AE	7	68	0.0	0.00	2.57	37	0.83	0.00	0.19	0.03	-0.01	2.82 F	
CA	1	54	0.4	0.00	5.44	78	0.54	0.00	-0.10	0.01	-1.60	-3.26 F	7.18
CA	2	56	0.5	0.00	5.44	78	0.58	0.00	-0.08	0.04	-1.24	-2.97 F	7.26
CA	3	42	1.0	1.00	6.00	100	0.30	0.66	-0.72	0.66	1.76	-1.75 F	3.14
CA	4	56	0.0	0.00	3.53	50	0.55	0.00	-0.79	-0.15	-2.51	-5.30 F	8.68
CA	5	58	0.5	0.00	4.73	68	0.55	0.00	-0.13	0.16	-1.40	-4.14 F	7.55
CA	6	60	0.0	0.00	1.75	54	0.60	0.00	-0.64	-0.10	-2.28	-4.88 F	7.66
CA	7	69	0.0	0.00	0.00	0	0.87	0.00	-2.75	-0.12	-3.22	-5.96 F	7.60

Figure 5. Listing of the weekly PDSI and related parameters for climatic divisions in Arizona and California that are available on CAC's CDUS.

- What parameters listed on the table you access do you find the most useful and what parameters the least?
- What additions of changes would you like to see developed in a general drought index?

Responses were returned by 38 of the 54 who were surveyed. The primary response to the first question is listed in Table 2.

Table 2

Principal use of the PDSI

	Reissue	Monitor	Crop	Monitor
		Hydrologic	Forecast	Potential
		Trends		Fire
				Severity
No.	17	9	7	5

Many who redissemated the data, also said they used the PDSI as an aid in observing hydrologic conditions which seemed to be its primary use.

The almost universal answer to given to the second question was that the PDSI was used as a general indicator and was often used in conjunction with three or four other indicators to monitor drought. Sample responses to the question included statements such as: "used for general trend"; "reasonably accurate"; "gives the general picture"; "used qualitatively rather than quantitatively"; and "accuracy is seldom an issue, we track the consistency".

The overwhelming answer to what parameter was the most useful was, not surprisingly, the PDSI itself. About a third of the respondents said they used only the PDSI, a third used all of the parameters, and the remaining used a combination of some of the parameters such as the Z index or the temperature and precipitation data used as input for the calculations.

There was very little response to the last question about what changes they would like developed in a general drought index. This is a difficult question because most uses are directed to specific interests. Several respondents did request a surface water supply index which incorporated storage and snowpack.

6. RECOMMENDATIONS

Near-real-time indices are important because they condense a much larger amount of information into usually one number and thereby greatly aid the decision-making process. An excellent discussion of climate indices and their need was made by Redmond (1990) in which desirable properties of climate indices are enumerated.

One important property (unrelated to the merits or shortcomings of a climate index) is that they be derived from high-quality data from a sufficient number of stations. A recommendation to improve any operational index is to improve the input of the index. The PDSI currently derived at CAC uses temperature and precipitation averages sent in from field offices from each state (these values are eventually substituted with cooperative data from NCDC and calculations rerun). The quality of the field data varies from division to division. Some climatic divisions, particularly in mountain areas, use a sparse number of stations and are therefore suspect. Current efforts are being made to replace the field

FIELD DATA VERSUS ANALYSIS

Precipitation (in)
1 WEEK PERIOD ENDING 18 MAY 91

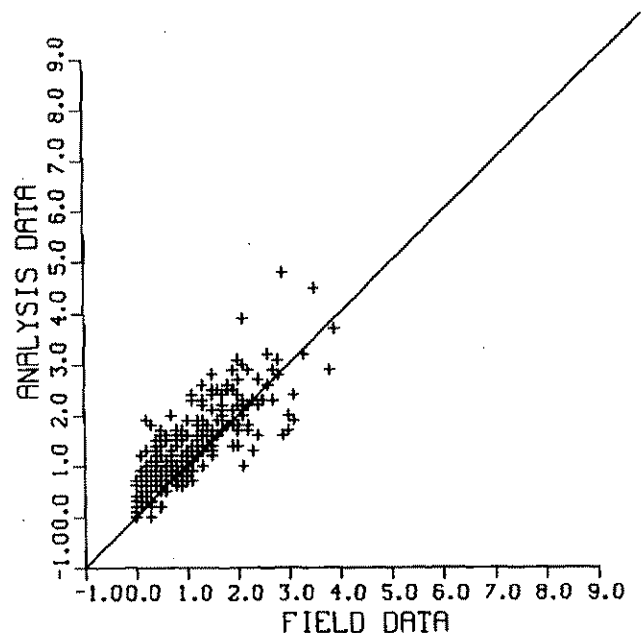


Figure 6. A comparison between weekly field data (sent through Weather Service Forecast Offices from each state) and analysis data (derived from data from RFC's) for the week ending May 18, 1991.

data with data derived from an analysis of a dense data set received from River Forecast Centers (RFC's). A comparison of field and analysis data is shown in Figure 6 in which a wet bias (compared to the field data) is observed in the analysis data. Comparisons with the NCDC data and the two preliminary data sets will be made to determine which preliminary set is the better.

An alternative to the PDSI is the Surface Water Supply Index (SWSI) currently in operational use in the West as a measure of hydrologic drought for river forecast basins (Shafer and Dezman, 1982). The SWSI uses streamflow and reservoir storage data but a homogenous time series of this data is often difficult to obtain. Other alternative indicators are the Cumulative Moisture Anomaly Index (CMAI), (an experimental index developed at CAC, Bergman et. al., 1988) and the Precipitation Anomaly Classification (PAC), (a modification of the method developed by the Australian Bureau of Meteorology, Janowiak et. al., 1986). Both the CMAI and PAC are applicable on a global basis as opposed to the PDSI which was calibrated for the United States as was noted earlier. The PAC, however, is not an index but merely classifies droughts over regions or stations into several categories, while the CMAI use a number of empirical constants which are not yet well calibrated. Both methods also suffer from threshold and sensitivity problems as does the PDSI.

A possible recommendation would be to replace the PDSI with another climate index. However, there are still no indices that have been demonstrated to be a "better" index. Another drawback in replacing the PDSI, is that it has been used for 25 years and has become widely accepted. In order to replace the PDSI, an alternative index should clearly be demonstrated to be superior with the realization (as noted by Redmond) that no matter how well an index is formulated, every meteorological and climatological situation has facets that will not be well portrayed by that index.

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SEVENTH CONFERENCE ON APPLIED CLIMATOLOGY

September 10-13, 1991

Salt Lake City, Utah

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Front Cover: The impact of urbanization on our temperature record is perhaps best reflected in the thermometric record at Phoenix, Arizona. The top diagram shows the difference in temperature between the average temperature of two nearby rural stations with the Official Records for Phoenix. The bottom diagram reflects the broadband radiances from the visible and near-infrared wavelengths derived from the Defense Mapping Satellite Project (DMSP). Applied climatologists are using space-based information such as this to help identify urban effects in temperature time series.

Back Cover: The relationship between the urban-rural temperature differences for 37 cities in the United States as a function of the Normalized Difference Vegetation Index (NDVI) derived from the NOAA Advanced High-Resolution Radiometer aboard NOAA satellites. Urban and rural areas are identified by DMSP brightness data as depicted on the front cover.

The diagrams on the front and back covers represent a common thread for many of the topics discussed at the Seventh Conference on Applied Climatology, specifically, the new challenges in Applied Climatology associated with Global Change and the new tools to surmount the challenges.

Figures are courtesy of NOAA/NESDIS and are discussed in more detail within this preprint volume (Gallo et al.).

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A Self-Calibrating Palmer Drought Severity Index

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ABSTRACT

The Palmer Drought Severity Index (PDSI) has been used for more than 30 years to quantify the long-term drought conditions for a given location and time. However, a common critique of the PDSI is that the behavior of the index at various locations is inconsistent, making spatial comparisons of PDSI values difficult, if not meaningless.

A self-calibrating Palmer Drought Severity Index (SC-PDSI) is presented and evaluated. The SC-PDSI automatically calibrates the behavior of the index at any location by replacing empirical constants in the index computation with dynamically calculated values. An evaluation of the SC-PDSI at 761 sites within Nebraska, Kansas, Colorado, Wyoming, Montana, North Dakota, and South Dakota, as well as at all 344 climate divisions shows that it is more spatially comparable than the PDSI, and reports extreme wet and dry conditions with frequencies that would be expected for rare conditions.

1. Introduction

The Palmer Drought Severity Index (PDSI) (Palmer 1965) was one of the first procedures to demonstrate success at quantifying the severity of droughts across different climates. Palmer's objective was to "develop a general methodology for evaluating (the drought) in terms of an index that permits time and space comparisons of drought severity" (Palmer 1965). Instead of being based purely on precipitation, the PDSI is based upon a primitive water balance model. As detailed in section 2, the basis of the index is the difference between the amount of precipitation required to retain a normal water-balance level and the amount of actual precipitation. The other parts of the PDSI calculation account for climatic differences between locations and seasons of the year. These computations attempt to scale the index values so that they fit Palmer's 11 categories, shown in Table 1, and to allow for comparisons across time and space.

In the years since its development, the PDSI has become a standard for measuring meteorological drought, particularly in the United States. There have been many criticisms of the PDSI over the years, but perhaps one of the most common complaints is that PDSI values are not comparable between diverse climatological regions.

The performance of the PDSI in the western United States has been particularly poor. This work addresses the spatial comparability problem identified by Karl (1983, 1986), Alley (1984), Heddinghaus and Sabol (1991), and Guttman et al. (1992).

Palmer calculated empirical constants for the climatic characteristic and the duration factors used in the computation of the PDSI, which directly affect the spatial comparability of the index, by averaging the values from only a few locations representing a small number of climates. These averaged values of the climatic characteristic and the duration factors have since become a fixed part of the calculations of the PDSI, regardless of the climate in which it is used. Advances in computing technology make it possible to improve the performance of the PDSI by dynamically replacing the averaged constants with values based on the characteristics of the local climate. This is achieved by correctly weighting the climatic characteristic, which affects the range of PDSI values, and the automatic calculation of the duration factors, which adjusts the sensitivity of the index. These two modifications cause the index to behave in a consistent, predictable manner as well as to more realistically represent the climates of diverse locations.

While the procedure presented here for calculating the PDSI is different from Palmer's original procedure, it does not stray from his objective. By simply automating the processes that Palmer used to derive the empirical constants used in his procedure, it does what

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TABLE 1. Classification of the PDSI values.

PDSI value	PDSI category
Above 4.00	Extreme wet spell
3.00–3.99	Severe wet spell
2.00–2.99	Moderate wet spell
1.00–1.99	Mild wet spell
0.50–0.99	Incipient wet spell
0.49 to –0.49	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
Below –4.00	Extreme drought

Palmer might have done, had he been given access to today's computing resources. In a sense, the new procedure for calculating the PDSI is simply a modern implementation of Palmer's ideas. By following Palmer's example, a self-calibrating PDSI (SC-PDSI) has been created that will behave as he intended and, more importantly, as decision makers and researchers expect it to.

2. A brief review of Palmer's procedure

The procedure Palmer developed will be referred to many times throughout this study, so for the sake of convenience, an abbreviated explanation of his procedure has been included. The following explanation is based directly on Palmer's paper (Palmer 1965), which describes in detail how to calculate the PDSI using a 1-month time step.

Each month of every year, four values related to the soil moisture are computed along with their complementary potential values. These eight values are evapotranspiration (ET), recharge (R), runoff (RO), loss (L), potential evapotranspiration (PE), potential recharge (PR), potential runoff (PRO), and potential loss (PL). The potential evapotranspiration is estimated using Thornthwaite's method (Thornthwaite 1948). The calculation of these values depends heavily on the available water holding capacity (AWC) of the soil. The PDSI itself depends on a two-stage "bucket" model of the soil. The top layer of soil is assumed to hold one inch of moisture. The amount of moisture that can be held by the rest of the underlying soil is a location-dependent value, which must be provided as an input parameter to the program.

The four potential values are weighted according to the climate of the area using α , β , γ , and δ to give the climatically appropriate for existing conditions (CAFEC) potential values. The weighting factors α , β , γ , and δ are called the water-balance coefficients and are found in the following manner:

$$\alpha_i = \frac{\overline{ET}_i}{\overline{PE}_i} \quad \beta_i = \frac{\overline{R}_i}{\overline{PR}_i}$$

$$\gamma_i = \frac{\overline{RO}_i}{\overline{PRO}_i} \quad \delta_i = \frac{\overline{L}_i}{\overline{PL}_i},$$

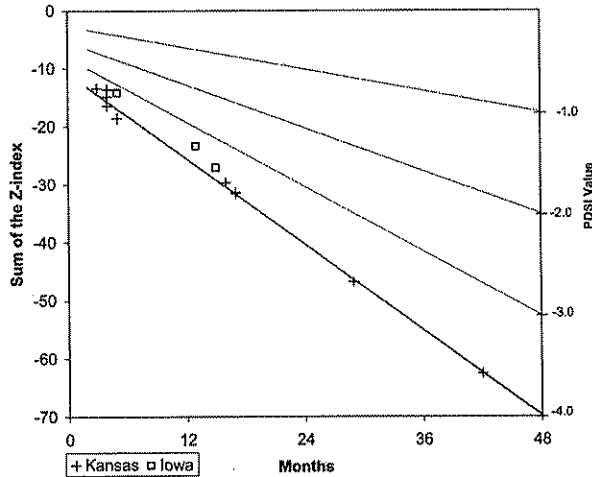


FIG. 1. Accumulated Z index over the driest intervals of varying lengths from Palmer's Table 7 (Palmer 1965, p. 20). The overlying lines represent the PDSI values according to the accumulated Z index. Redrawn from Palmer's (1965, p. 20) Fig. 1.

where i ranges over the months of the year. The bar over a term indicates an average value. For example, the average loss is computed for January by

$$\overline{L}_1 = \frac{\sum_{\text{all years}} L_1}{\text{number of years of data}}.$$

The CAFEC potential values are combined to form the CAFEC precipitation, \hat{P} , which represents the amount of precipitation needed to maintain a normal soil moisture level for a single month:

$$\hat{P} = \alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL.$$

The difference between the actual precipitation that fell in a specific month and the computed CAFEC precipitation is the moisture departure, denoted d :

$$d = P - \hat{P} = P - (\alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL).$$

The moisture departure, d , is the excess or shortage of precipitation compared to the CAFEC precipitation. Of course, the same d will mean different things at different times, as well as at different locations. This prevents straightforward comparisons from being made between different values of d . To correct for this, the moisture departure is weighted using K , which is called the climatic characteristic. Here K is actually a refinement of K' , which is Palmer's general approximation for the climate characteristic of a location. Palmer derived Eqs. (1) and (2) for K' and for K , respectively, where \overline{D}_i is the average moisture departure for the appropriate month:

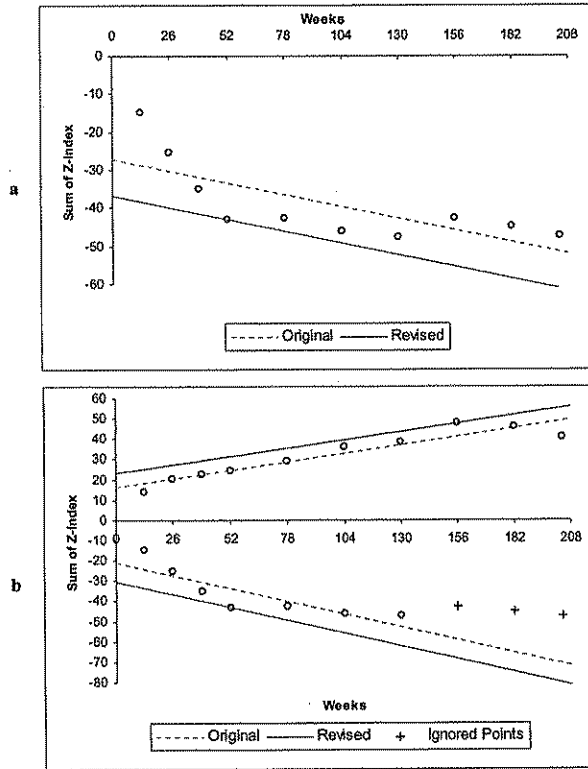


FIG. 2. (a) An example of poor linear correlation. Neither the original nor the revised line appears to fit the data. This particular figure shows only the dry periods. (b) The final lines used in calculating both the wet and dry duration factors. By ignoring the last three data points in the bottom portion, the regression lines fit the data better. Data from the Nebraska station Sidney 6 NNW (1948–2001).

$$K'_i = 1.5 \log_{10} \left(\frac{\overline{PE_i} + \overline{R_i} + \overline{RO_i}}{\overline{P_i} + \overline{L_i}} + 2.8 \right) + 0.5 \quad (1)$$

$$K_i = \frac{17.67}{\sum_{j=1}^{12} \overline{D_j} K'_j} K'_i \quad (2)$$

The value of 17.67 in (2) is an empirical constant that Palmer derived using data from nine different locations in seven states (Palmer 1965). The purpose of the climatic characteristic, K , is to adjust the value of d according to the characteristics of the climate in such a way as to allow for accurate comparisons of PDSI values over time and space.

The result of multiplying the moisture departure, d , by K is called the moisture anomaly index, or the Z index, and is denoted by Z , shown as

$$Z = dK \quad (3)$$

The Z index can be used to show how wet or dry it was during a single month without regard to recent precipitation trends. The Z index is used to calculate the PDSI value for a given month using the general formula:

$$X_i = 0.897X_{i-1} + \left(\frac{1}{3}\right)Z_i \quad (4)$$

For example, to calculate the current value of X_i , 0.897 times the previous PDSI value X_{i-1} is added to one-third of the current moisture anomaly Z_i . Palmer called the values 0.897 and 1/3 the duration factors. They were empirically derived by Palmer from two locations (western Kansas and central Iowa) and affect the sensitivity of the index to precipitation events.

Three PDSI values are actually computed each month: X_1 , X_2 , and X_3 . The values of X_1 and X_2 are the severity of a wet or dry spell, respectively, that might become established. A spell becomes established when it reaches the threshold of ± 0.5 . This threshold follows from the fact that index values between -0.5 and 0.5 are regarded as “normal” values; X_3 is the severity of a wet or dry spell that is currently established. If there is no established spell, the PDSI value is set to either X_1 or X_2 , according to which spell is most likely to become established. This is determined by which index is closer to the threshold of an established spell, which is simply the index with a larger absolute value. If there is a current spell established, that is, when X_3 is not zero, the PDSI value for that month is X_3 . However, when the index is calculated at a later date, it may be discovered that the current spell actually ended earlier. In this case, the PDSI values will be replaced by values of either X_1 or X_2 . This replacement of previously calculated PDSI values will be referred to as backtracking. Exactly how backtracking works, and what factors set it off are beyond the scope of this study. However, the existence of backtracking means that a small change in how the indices are computed may cause backtracking, which has a substantial effect on the final values of the index.

3. A method for calibrating the PDSI

The SC-PDSI replaces the empirically derived climatic characteristic (K) and duration factors (0.897 and 1/3) with values automatically calculated based upon the historical climatic data of a location. This section explains how these values are computed as part of the SC-PDSI.

a. Climatic characteristic

The moisture departure, d , does not accurately reflect how and to what extent the lack (or excess) of moisture affects a region. To correct for this, the PDSI is based on the moisture anomaly, Z (or Z index), which is the product of the moisture departure and the climate characteristic, K , as shown in (3). The role of the climate characteristic is to correct for the natural aberrations that appear in the moisture departure due to the climate of the region and how it changes with the seasons.

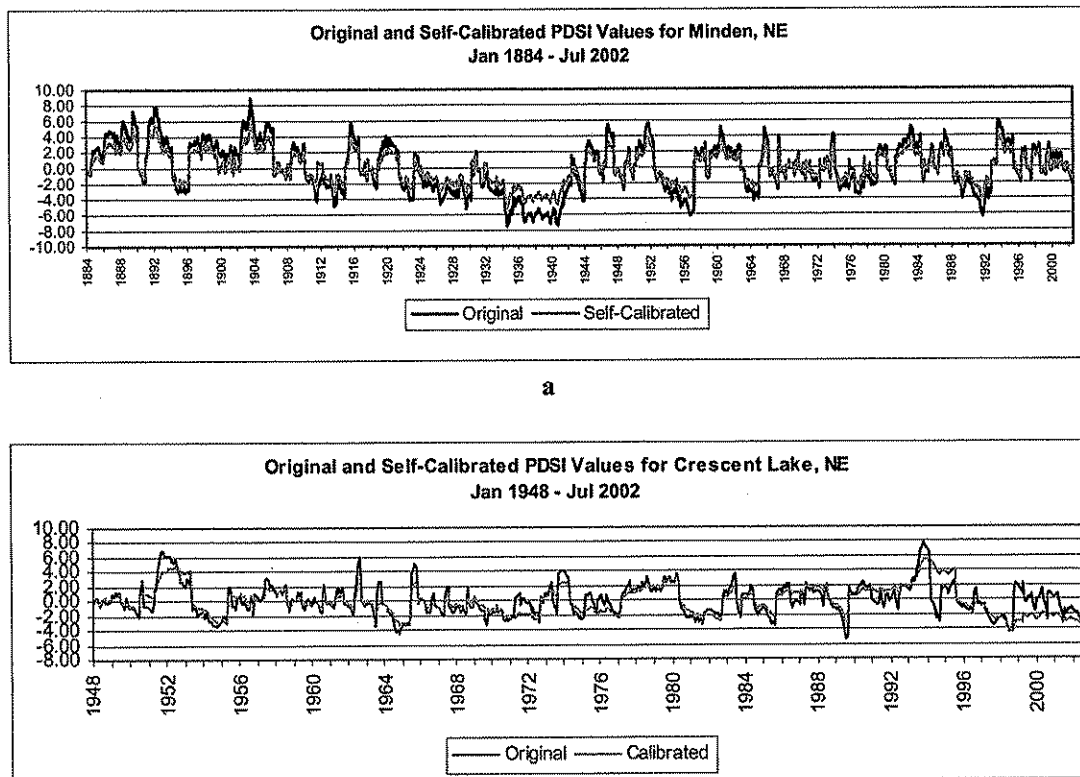


FIG. 3. Time series plots of the original PDSI and the SC-PDSI at (a) Minden, NE, from Jan 1884 to Jul 2002; and (b) Crescent Lake, NE, from Jan 1948 to Jul 2002.

There are two clear parts to (2), the first being the ratio \tilde{K} and the second being K' of (1), where

$$\tilde{K} = \frac{17.67}{\sum_{j=1}^{12} |\bar{d}_j| K'_j} \quad (5)$$

The climate characteristic must vary over both time and space to account for the changes in the climate. Here K' approximates the average precipitation and conditions of the soil of each month, so it will vary from one month to the next. However, \tilde{K} only varies over space. The criticisms of the PDSI have revolved around its inconsistencies from one location to the next, rather than over time at a single location. Altering the ratio shown in (5) addresses the spatial inconsistencies of the PDSI without changing the way it handles seasonal changes in the climate.

The denominator of (5) is the product of the average absolute value of the moisture departure d and K' , summed over the 12 months of the year. The product of d and K' is a first-order approximation of the moisture anomaly Z for a given month. Thus, the denominator of (5) can be viewed as an approximation of the annual sum of the average absolute value of Z over a 12-month period. Let

$$\tilde{Z} = \sum_{j=1}^{12} |\bar{d}_j| K'_j \quad (6)$$

The numerator of (5), 17.67, is the average value of \tilde{Z} shown in (6) using data from nine different climate divisions: three from Texas and one each from Kansas, Iowa, North Dakota, Ohio, Pennsylvania, and Tennessee. Thus, the ratio \tilde{K} can be rewritten as the ratio of the expected value of \tilde{Z} to the observed value of \tilde{Z} . If \tilde{Z} is considered as the average annual sum of the moisture anomaly, then the PDSI itself can be used in its place since the PDSI is based on the accumulated moisture anomaly. This results in the following ratio:

$$\tilde{K} = \frac{\text{expected average PDSI}}{\text{observed average PDSI}} \quad (7)$$

Equation (7) for \tilde{K} has a major problem because one would expect the average PDSI value to be zero. Instead of using the central tendency of the PDSI distribution, as (7) does, its tails can be used. Palmer defined the range of nonextreme PDSI values to run from -4.00 to 4.00 . In practice, however, this range varies. If the PDSI really were a standardized measure of drought severity, then the frequency of values outside that range would be about the same. If this frequency of extreme events is defined

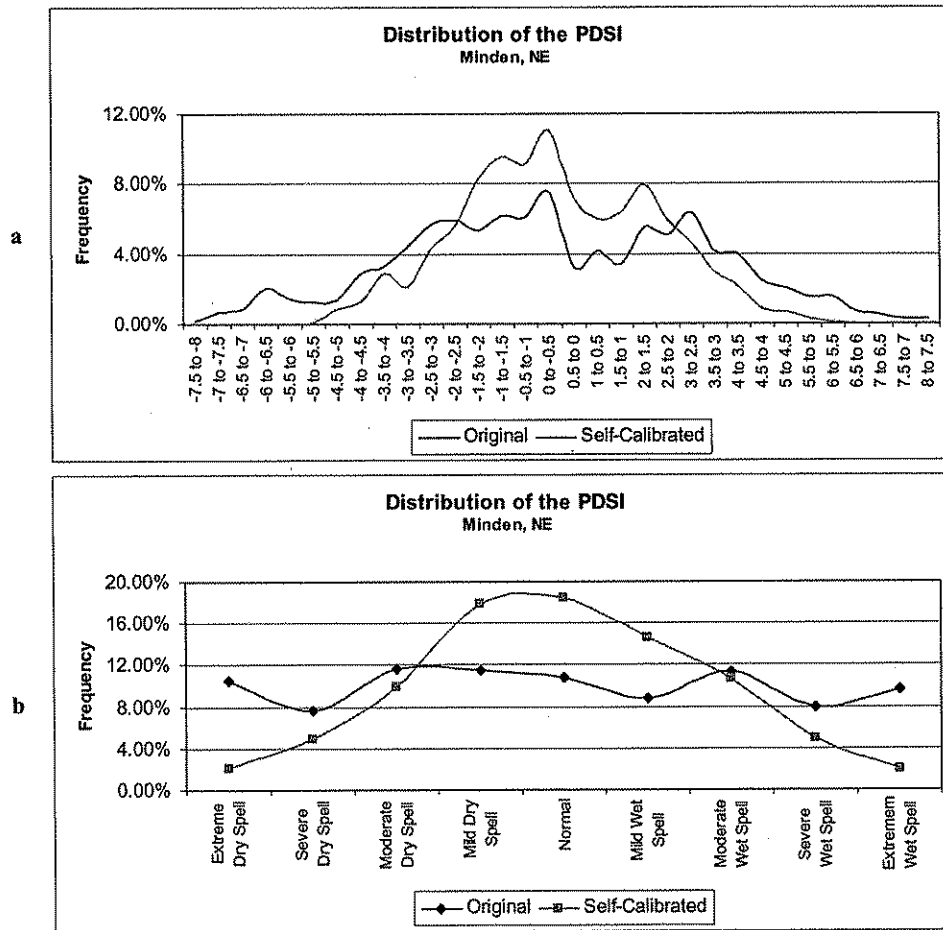


FIG. 4. Plots showing the frequency of original and self-calibrated monthly PDSI values (a) over the entire range of PDSI values and (b) over the major PDSI categories for Minden, NE.

as some value, f_e , then the f_e th percentile should be -4.00 and the $(100 - f_e)$ th percentile should be 4.00 . This gives the following equation for \tilde{K} :

$$\tilde{K} = \frac{\left\{ \begin{array}{l} \text{expected } f_e \text{th percentile of the PDSI} \\ \text{observed } f_e \text{th percentile of the PDSI} \end{array} \right\}}{\left\{ \begin{array}{l} \text{expected } (100 - f_e) \text{th percentile of the PDSI} \\ \text{observed } (100 - f_e) \text{th percentile of the PDSI} \end{array} \right\}} \quad (8)$$

The question remains of what value f_e should be, which depends on how an "extreme" drought is defined. Defining extreme drought as a "one in 50 year event" does not determine what percentage of PDSI values should be below -4.00 because it could last for two months or two years. For this implementation, the value of f_e used was 2%, which gives the following equation for the climate characteristic:

$$K = \begin{cases} K'(-4.00/2\text{nd percentile}), & \text{if } d < 0 \\ K'(4.00/98\text{th percentile}), & \text{if } d \geq 0. \end{cases} \quad (9)$$

To calculate K , as it is defined in (9), the PDSI must first be calculated using $Z = dK'$, where K' is computed using (1). After computing this first-order approximation of Z , the 2d and 98th percentile of PDSI values are used to compute K with (9), and then the PDSI is recomputed.

The climatic characteristic, as it is defined in (9), is computed using the method that Palmer used but based on the definition of the index instead of an average value derived from a set of sites. This removes from the climatic characteristic, and therefore from the index itself, the dependence on the climatic conditions that were experienced at the nine locations used in Palmer's study. Instead, the climatic characteristic is based solely on how the climate of the location, namely the range of its moisture departures, d , is related to the defined range of the PDSI. This is reasonable because the climate characteristic is intended to map the moisture departures to the appropriate values of the Z index such that the PDSI matches its defined behavior.

A side effect of this method is that the climate characteristic, and therefore the value of the index itself, is

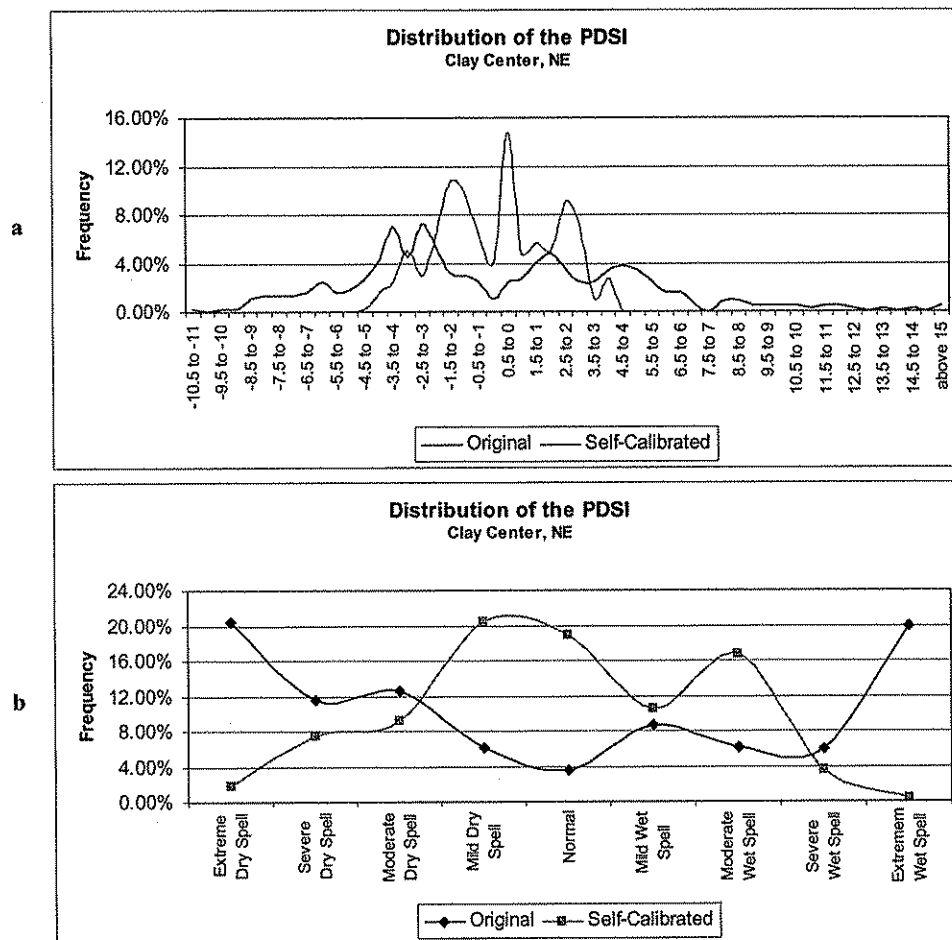


FIG. 5. Plots showing the frequency of original and self-calibrated monthly PDSI values (a) over the entire range of PDSI values and (b) over the major PDSI categories for Clay Center, NE.

now based on the historical record of a location. That means that changing the length of the record over which the PDSI is calculated will change the values of the index. In other words, the index values in 2000 will be different if they are calculated using data from 1975 to 2000 than they would be if calculated using data from 1948 to 2000. Therefore, it is important to note the period of record used in the analysis of the PDSI. The current version of the SC-PDSI supports an option that defines the calibration interval; by default, the entire historical record is used.

b. Duration factors

The PDSI is an accumulating index, that is, an index where each successive value is based on the preceding value. Specifically, any given PDSI value X_i is a weighted sum of the previous PDSI value X_{i-1} , which represents the current climate trend or spell, and the current moisture anomaly Z_i , which represents how wet or dry it has been over the current period. The weights given to each of

these two components are determined by the duration factors, represented by the variables p and q in (10):

$$X_i = pX_{i-1} + qZ_i. \quad (10)$$

In practical terms, the duration factors determine how sensitive the index is to precipitation and the lack thereof. Equation (10) is a generalization of (4) in which $p = 0.897$ and $q = 1/3$. These constants directly affect the sensitivity of the index. For example, if p is larger and q smaller, the index will be less sensitive to sudden changes in the precipitation. Thus, the problem is to compute duration factors that are appropriate for a given location. We begin with a brief explanation of how Palmer computed the duration factors of 0.897 and $1/3$ used in (4). We then explain how the SC-PDSI automatically computes duration factors whenever it is computed for a given site.

1) PALMER'S DURATION FACTORS

Palmer defined his duration factors based on the linear relationship found using empirical methods between the

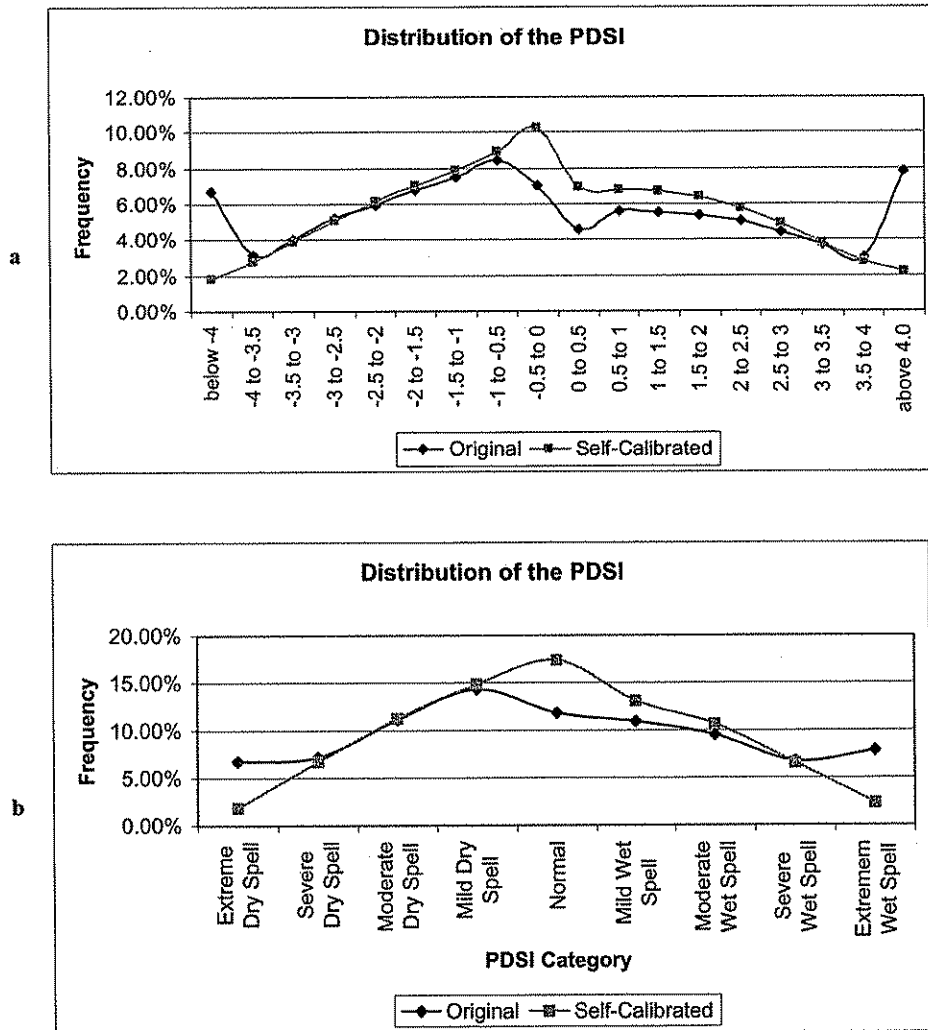


FIG. 6. Plots showing the frequency (a) over the range from -4.0 to $+4.0$ and (b) over the major PDSI categories of original and self-calibrated monthly PDSI values, calculated at 761 stations in CO, KS, MO, NE, ND, SD, and WY.

length and severity of the most extreme droughts that he studied in Kansas and Iowa. To estimate the severity of a drought, he summed the Z index over the periods of severe droughts and plotted the summation (severity) against the duration, as shown in Fig. 1. Palmer then drew the lowermost line in Fig. 1, and derived the linear relationship expressed in (11). He defined this line to represent the PDSI value of -4.0 as extreme drought. As Palmer (1965) noted, he drew this line not as a true best-fit line but rather by eye, trying to encompass the most severe drought conditions. That explains why the data from Iowa does not appear to be represented by the line. The other lines in Fig. 1 can be expressed using Eqs. (12), (13), and (14) and represent the linear relationships that Palmer defined for PDSI values of -3 , -2 , and -1 :

$$\text{PDSI} = -4.0 \Rightarrow \sum_{i=1}^t Z_i = -1.236t - 10.764 \quad (11)$$

$$\text{PDSI} = -3.0 \Rightarrow \sum_{i=1}^t Z_i = -0.927t - 8.073 \quad (12)$$

$$\text{PDSI} = -2.0 \Rightarrow \sum_{i=1}^t Z_i = -0.618t - 5.382 \quad (13)$$

$$\text{PDSI} = -1.0 \Rightarrow \sum_{i=1}^t Z_i = -0.309t - 2.691 \quad (14)$$

$$\sum_{i=1}^t Z_i = (0.309t + 2.691)X_t \quad (15)$$

For a given PDSI value X_t , these linear relationships

TABLE 2. Summary of the PDSI analysis performed for 156 NE weather stations.

	Original monthly (%)	Self- calibrating monthly (%)
Total percentage of sites in which the frequency of extremely dry PDSI values ($\text{PDSI} \leq -4.00$) was between 1% and 3%	12.18	98.08
Total percentage of sites in which the frequency of extremely wet PDSI values ($\text{PDSI} \geq 4.00$) was between 1% and 3%	3.21	94.23
Average percentage of time ≤ -4.00	6.47	1.93
Average percentage of time ≥ 4.00	12.98	2.11
Average percentage of time ≤ -3.00	13.63	7.81
Average percentage of time ≥ 3.00	6.72	8.21

TABLE 3. Summary of the PDSI analysis performed for 761 stations from NE, KS, CO, WY, MO, ND, and SD.

	Original monthly (%)	Self- calibrating monthly (%)
Total percentage of sites in which the frequency of extremely dry PDSI values ($\text{PDSI} \leq -4.00$) was between 1% and 3%	9.33	85.15
Total percentage of sites in which the frequency of extremely wet PDSI values ($\text{PDSI} \geq 4.00$) was between 1% and 3%	4.86	84.01
Average percentage of time ≤ -4.00	6.73	1.85
Average percentage of time ≥ 4.00	7.86	2.32
Average percentage of time ≤ -3.00	13.93	8.54
Average percentage of time ≥ 3.00	14.62	8.87

can be expressed using (15), which reduces to Eqs. (11) through (14) for PDSI values of $X_i = -4, -3, -2$, and -1 , respectively. Equation (15) can also be used to describe the linear relationship assumed for positive PDSI values since Palmer used the same duration factors for deficit and excess moisture conditions—even though he only calibrated his index to extreme drought conditions.

Equation (15) can be further generalized to the basic slope intercept form describing the linear relationship between the summation of the Z index and the current PDSI value, as shown in (16), where m is the slope of the line and b is the y intercept:

$$\sum_{i=1}^t Z_i = (mt + b)X_i. \quad (16)$$

As previously described, Palmer calibrated his index using the most severe droughts of various durations, which were assigned an index value of -4 . Thus, Palmer found the slope and y intercept of the “best fit” line fitting the Z-index plots of these droughts. After finding the slope and y intercept of the most severe droughts, Palmer simply divided these values by -4 (his calibration index) and multiplied them by the other indices that he used to categorize wet and dry spells (i.e., $4, 3, 2, \dots, -3$).

Although Palmer calibrated his index using “ -4 ” droughts, the index could be calibrated to any category of drought or wet spell. The general formula for doing this is shown in (17), where C represents the value of the calibration index (e.g., $-4, -3, \dots, 4$). Observe that with $m = -1.236$, $b = -10.764$, and $C = -4$, Eq. (17) reduces to Eqs. (11) through (14) for respective values of X_i :

$$\sum_{i=1}^t Z_i = (mt + b) \frac{X_i}{C}. \quad (17)$$

Assuming the change between any two values of X_i is constant for a given severity of drought (or wet spell)—just as Palmer did, Eq. (17) can be used to derive

a generalized version of (4) that computes the PDSI value for month t :

$$X_t = \left(1 - \frac{m}{m+b}\right) X_{t-1} + \frac{CZ_t}{m+b}. \quad (18)$$

Comparing (18) to (10) shows that the duration factors, as defined in (10), can be calculated using m , b , and C in the following manner:

$$p = \left(1 - \frac{m}{m+b}\right) \quad (19)$$

$$q = \frac{C}{m+b}. \quad (20)$$

Thus, the index can be calibrated for any dry or wet category, specified as C , as long as m and b can be computed.

Although Palmer calibrated his index with $C = -4$ and used the same duration factors for wet and dry spells, this process can be repeated to find separate duration factors for wet periods by finding the linear relationship between the intensity of extreme wet spells and their respective lengths. This is important because different locations have different sensitivities to precipitation events and some locations have different sensitivities to periods with precipitation and periods without. For example, a location that more effectively retains water in the soil will likely be more sensitive to heavy precipitation than to a lack of precipitation. Thus, two sets of duration factors, one each for dry periods and wet periods, are required for each location at which the PDSI is calculated. By automating the procedure that Palmer used to calculate his duration factors, both sets of duration factors can be calculated dynamically for any location.

2) AUTOMATED CALCULATION OF THE DURATION FACTORS

The SC-PDSI established separate duration factors for wet and dry spells. The index duration factors are com-

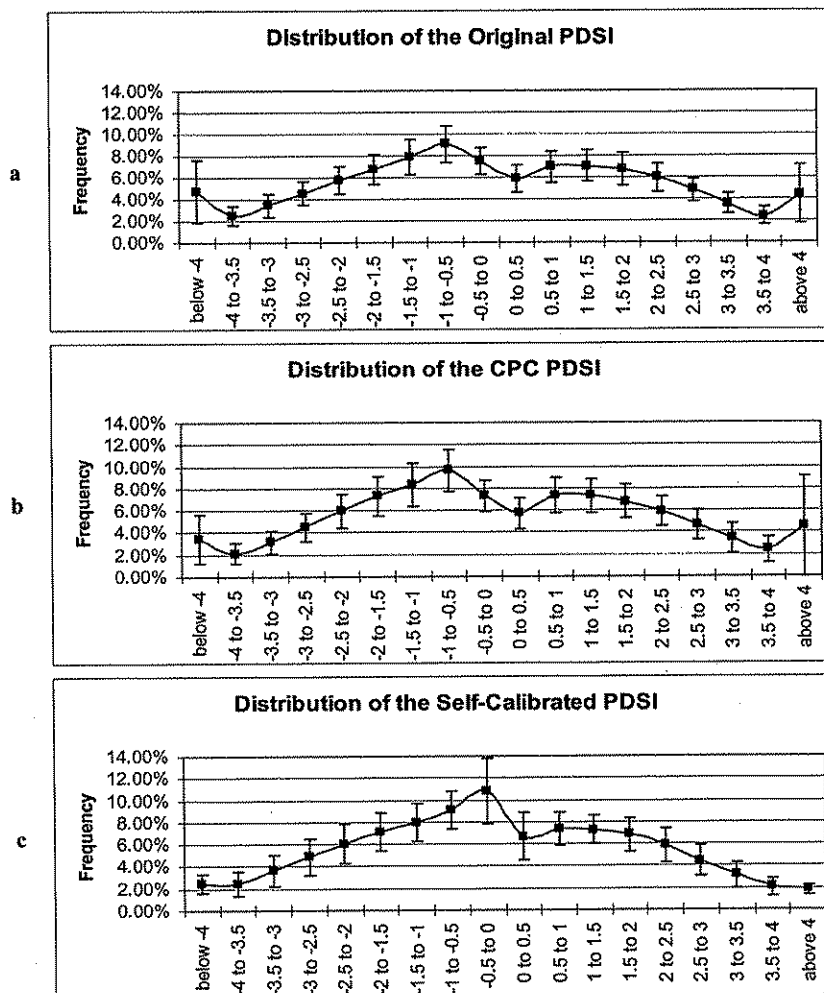


FIG. 7. Distribution plots of the mean frequency of index values from the 344 climate divisions using (a) the original PDSI, (b) the CPC's PDSI, and (c) the SC-PDSI. Error bars represent one standard deviation from the mean.

puted using the least squares method for both extremely wet and extremely dry conditions, which will give two sets of m and b parameters such that

$$\sum_{i=1}^t Z_i = mt + b. \quad (21)$$

Two instances of Eq. (18) are created: X_1 for dry spells and X_2 for wet spells.

Theoretically, the SC-PDSI could be calibrated to any category of drought and/or wet spell. However, calibrating to extreme wet and dry spells is the easiest to defend: 1) Palmer calibrated his index to extreme dry spells, and 2) a frequency of 1%–3% for extreme wet and dry conditions are defined in the literature (e.g., Guttman et al. 1992; Hayes et al. 1999), whereas there is no commonly accepted frequency of events for Palmer's other wet and dry categories.

As one would expect from a simple linear regression, there will be several points below and above a best-fit line of accumulated Z -index values over various lengths of time. That means that the PDSI will reach values below (above) -4.0 (4.0) on occasion. To make a line that is more representative of the most extreme periods of dryness (wetness), a new line needs to be created that is "lower" ("higher") than the true best-fit line, as shown in Fig. 2a for extreme drought conditions at Sidney, Nebraska, station 6 NNW, with climate data from 1948 to 2001.

Only the y intercept was changed; the slope remains the same. Thus, by (18), decreasing the y intercept results in a larger coefficient in front of X_{t-1} and a smaller coefficient in front of Z_t . This means when calculating the PDSI, more weight will be given to the previous PDSI value and less to the current moisture anomaly.

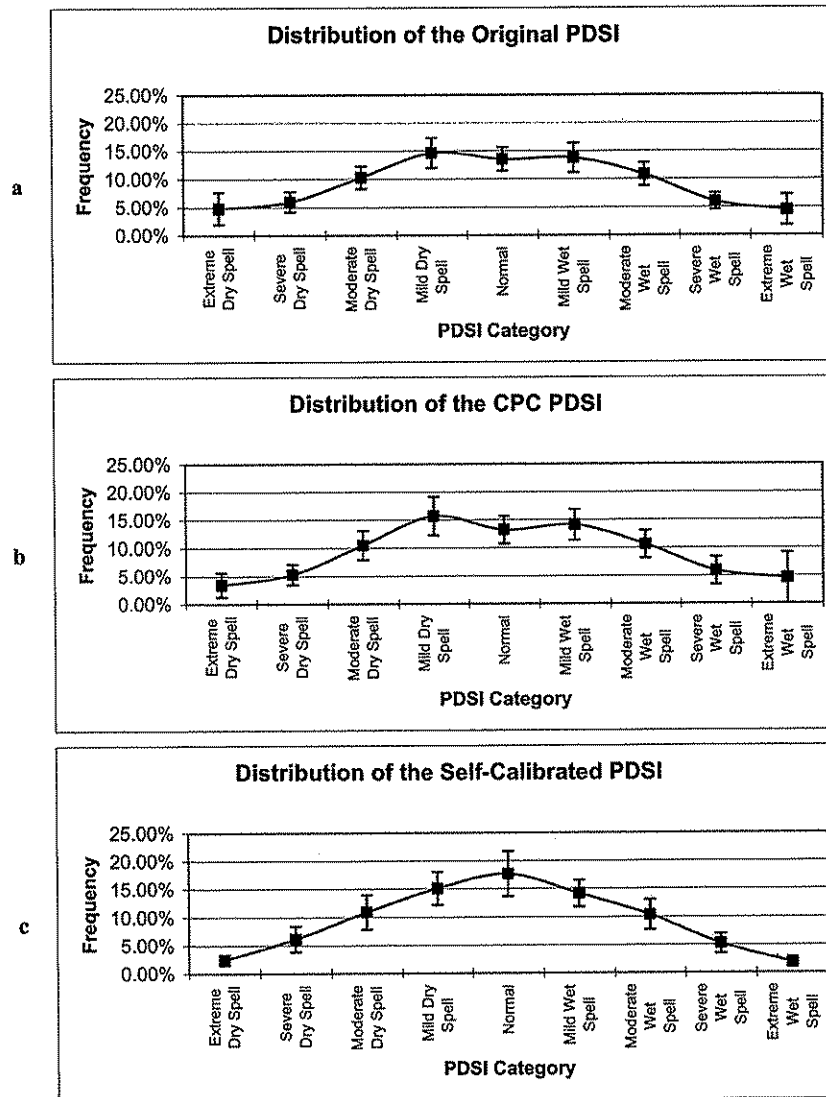


FIG. 8. Distribution plots of the mean frequency of index values in each of the main PDSI categories from the 344 climate divisions using (a) the original PDSI (b) the CPC's PDSI, and (c) the SC-PDSI. Error bars represent one standard deviation from the mean.

The change in the y intercept has the effect of mapping a wider than expected range of the Z index to the desired PDSI range from -4.0 to 4.0 .

There is another problem with using a simple linear regression to identify the slope and y intercept of best-fit lines for extreme wet and dry conditions. Notice that neither line in Fig. 2a demonstrates a good linear correlation between all of the data points. (The correlation of the data points is $-0.744\ 922$ for the initial line.) For this and many other sites, it was discovered that the accumulated Z index values over various lengths of time was better represented by a nonlinear function, for example, a logarithmic function (see Wells 2002, for more details). However, a nonlinear function cannot be used

with Palmer's method of calculating duration factors. Since the goal of this project was to modernize Palmer's work and not create a completely new drought index, it was decided a better approach would be to check the correlation between the data points before performing the linear least squares regression on the dataset. This is essentially what Palmer did when he drew his best-fit line.

Since Palmer placed more emphasis on short-term droughts than long-term droughts in computing his duration factors (Palmer 1965), it was decided to repeatedly throw out the point corresponding to the longest interval until a minimum threshold of ± 0.85 for the linear correlation is attained. This threshold was deter-

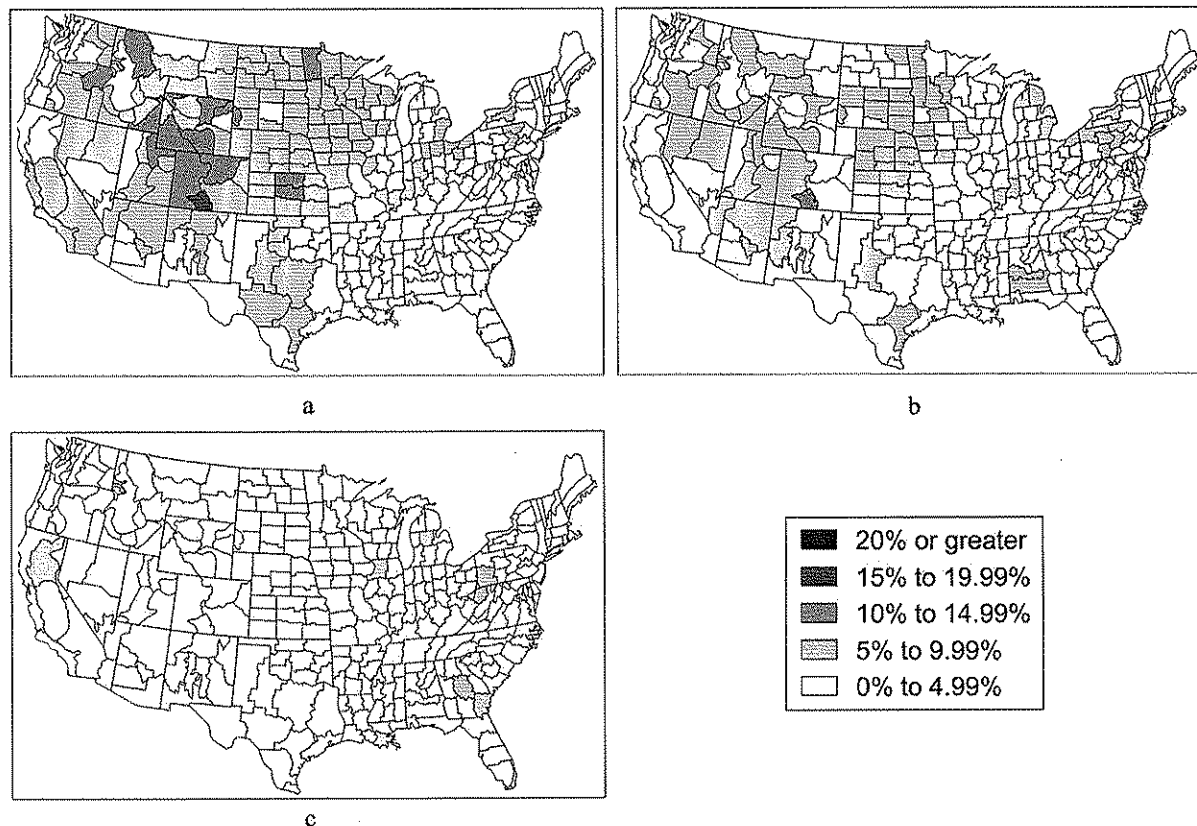


FIG. 9. The frequency at which (a) the original PDSI, (b) the CPC's PDSI, and (c) the SC-PDSI programs reported an extreme drought (i.e., the percent of time the PDSI was at or below -4.0) at each climate division.

mined by trial and error to give the best results in the High Plains region. In the majority of sites with poor overall linear correlations, there was a good correlation among the first four data points. This fact led to the additional requirement of having at least four points from which to calculate the duration factors. In this example, if the last three points are ignored, the resulting correlation is $-0.859\ 83$, which is above the threshold. Performing the regression on the remaining seven points, as described previously, results in the bottom portion in Fig. 2b.

Figure 2b shows the approximations to the appropriate linear relationships for both extreme wet and dry periods. Notice that, even though there was a poor correlation over the dry spells, there is a good correlation between the wet spells, and all ten points are used in the regression. The revised lines shown in Fig. 2b represent the correct linear relationships between the most extreme periods of wetness and dryness and the respective lengths. The slope and y-intercept terms for each line are used in Eqs. (19) and (20) to compute wet and dry duration factors for the site. The SC-PDSI program repeats this process automatically whenever it computes a PDSI value for a specified site.

c. Summary

The process of replacing all empirical constants in Palmer's procedure for calculating the PDSI has resulted in a process that is slightly more complicated than before. It is worthwhile to review the updated procedure step by step.

- 1) Calculate all moisture departures.
- 2) Calculate all moisture anomalies using K' of (1).
- 3) Calculate the duration factors, as described in section 3b(2), using the moisture anomalies computed in step 2.
- 4) Calculate the PDSI using the moisture anomalies and duration factors computed in steps 2 and 3, respectively.
- 5) Find the 98th and 2d percentile values of the PDSI.
- 6) Compute the new moisture anomalies using (9).
- 7) Calculate the SC-PDSI.

This is a more computational intensive process than Palmer's original procedure. However, the power of the current generation of computers means that the PDSI can be calculated in a matter of seconds, even for stations with over a hundred years of data.

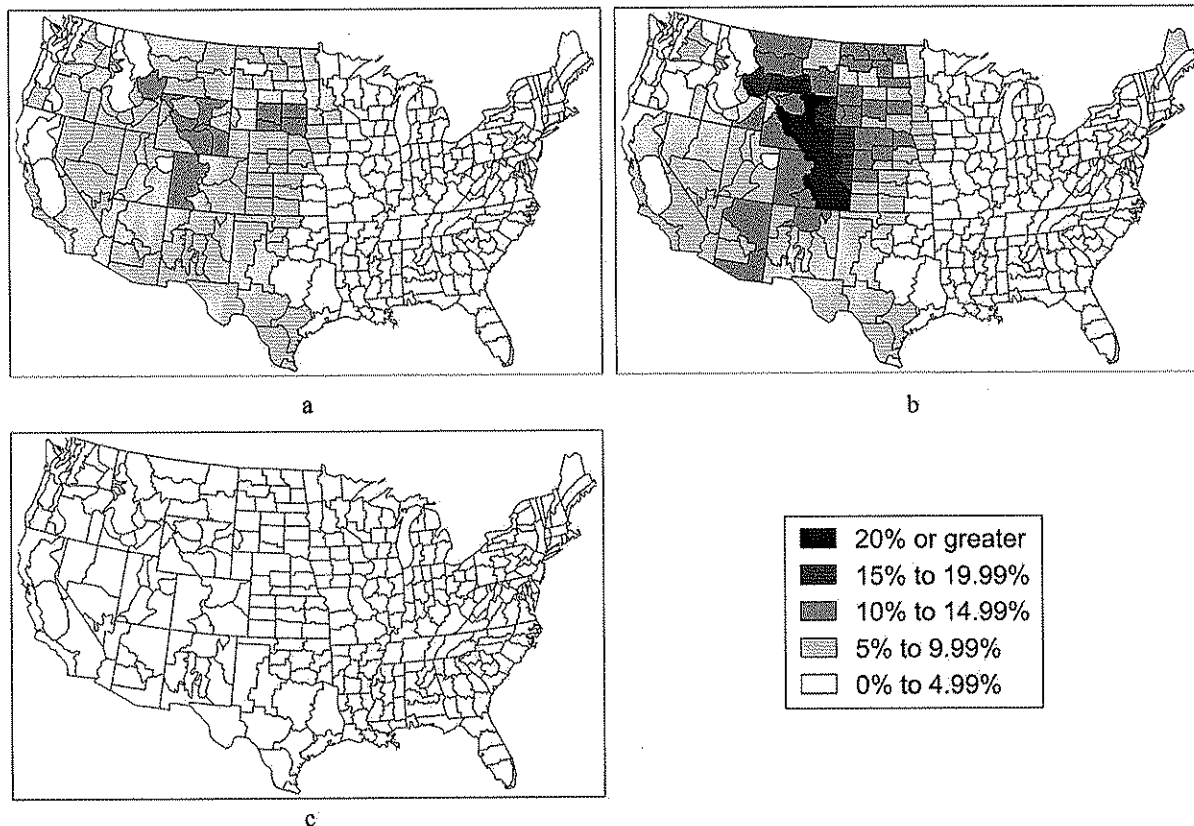


FIG. 10. The frequency at which (a) the original PDSI, (b) the CPC's PDSI, and (c) the SC-PDSI programs reported an extreme wet spell (i.e., the percent of time the PDSI was at or above +4.0) at each climate division.

Using the redefined climatic characteristic and a set of duration factors derived in the described manner to calculate the PDSI has several positive consequences:

- The range of the PDSI values is close to an expected range of -5.0 to 5.0 , where values below -4 and above 4 represent extreme conditions.
- The sensitivity of the index is based upon the local climate.
- Different sensitivity to moisture and lack of moisture.
- The PDSI can be updated at different time intervals (e.g., weekly, biweekly, monthly, etc.).

The consequences of dynamically calculating the climatic characteristic and the duration factors have the overall effect of calibrating the index based on the actual characteristics of a given location. This means the conditions of any climate should be realistically represented by the index within the definition of the PDSI. In other words, the index should show an extreme drought only when the conditions exemplify an extreme drought relative to that area and not relative to some default location. Thus, the SC-PDSI will allow more accurate comparisons between different locations and times. The SC-PDSI will also give more statistically accurate results by showing severe and extreme readings less frequently than the cur-

rent implementations of the PDSI, which often show extreme readings with a frequency much higher than one would expect, as shown in section 5.

4. Methodology and data sources

The goal of this work was to improve the spatial comparability of the PDSI with as little change as possible to Palmer's process. The major changes are the redefined climatic characteristic and the automatic calculation of the duration factors, both of which were based on the procedure Palmer used to derive his climatic characteristic and duration factors. No attempts were made to address other previously documented deficiencies of the PDSI [e.g., the water-balance model, Alley (1984)]. Thus, the evaluation of the SC-PDSI is limited to time series plots, analyses of the frequency of extreme conditions, plots showing the distribution of the index, and spatial comparisons of the frequency that the index is above or below a threshold.

The analysis was conducted in two stages. In the first stage, monthly PDSI values were computed for 761 individual weather stations with at least 25 serially complete years of data in the states of Colorado, Kansas, Nebraska, North Dakota, South Dakota, Wyoming, and

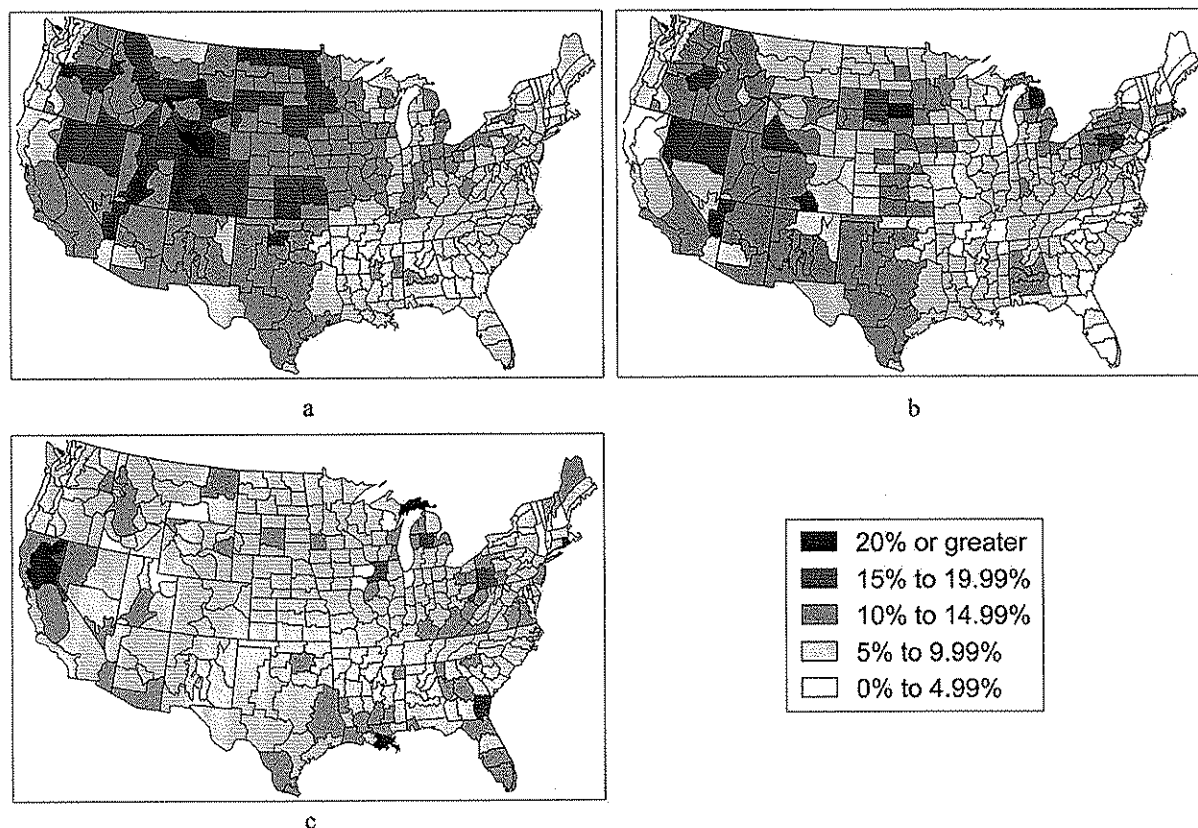


FIG. 11. The frequency at which (a) the original PDSI, (b) the CPC's PDSI, and (c) the SC-PDSI programs reported a severe or extreme drought (i.e., the percent of time the PDSI was at or below -3.0) at each climate division.

Montana. Monthly index values computed using the SC-PDSI program were compared with values computed using a PDSI program developed by Karl et al. (2001) from the National Climatic Data Center (NCDC). Henceforth, the NCDC PDSI program is called the original PDSI program since Guttman et al. (1992) and Guttman (1991, 1998) used it in previous studies.

Temperature and precipitation data for the 761 weather stations analyzed in the first stage were retrieved from the High Plains Regional Climate Center (HPRCC 2002). For qualified stations, the PDSI was calculated using all available years of data ranging from January 1880 to July 2002. The first four years were disregarded in the analysis as Guttman (1991) recommended. To reduce the effects of backtracking, the last two years were also left out of the analysis. The AWC for each site was derived from the State Soil Geographic (STATSGO) database for the conterminous United States, which is produced and maintained by the U.S. Department of Agricultural Natural Resources Conservation Services (NRCS).

A time series plot was created for the 156 qualified stations in Nebraska and for a selected subset of stations in other states. A separate program was used to create a histogram of the PDSI values at each of the stations.

This program also calculated several statistical values such as the percentage of PDSI values that were above and below the values of -4 , -3 , 3 , and 4 . The results of these analyses are summarized in section 5.

In the second stage, SC-PDSI and original PDSI monthly values were compared with monthly PDSI values reported by the National Weather Service Climate Prediction Center (CPC) for each of the 344 climate divisions of the conterminous United States from January 1895 to April 2000, with analysis performed on the 100-yr period from 1889 to 1998. Monthly temperature and precipitation data were obtained from NCDC for each climate division over the interval of study (NCDC 2002a). (Data for the rest of the year 2000 were available from a different NCDC location, but for the purposes of this analysis, these data were not needed.) The latitude of the centroid of each climate division was also obtained from NCDC (NCDC 2002b). The AWC for each climate division was determined using output files of the weekly PDSI program used by the CPC, which shows the soil moisture and percent of capacity (CPC 2002).

Thus, the original and SC-PDSI programs were executed using the same data parameters that, as far as we can determine, were used by the CPC to generate their

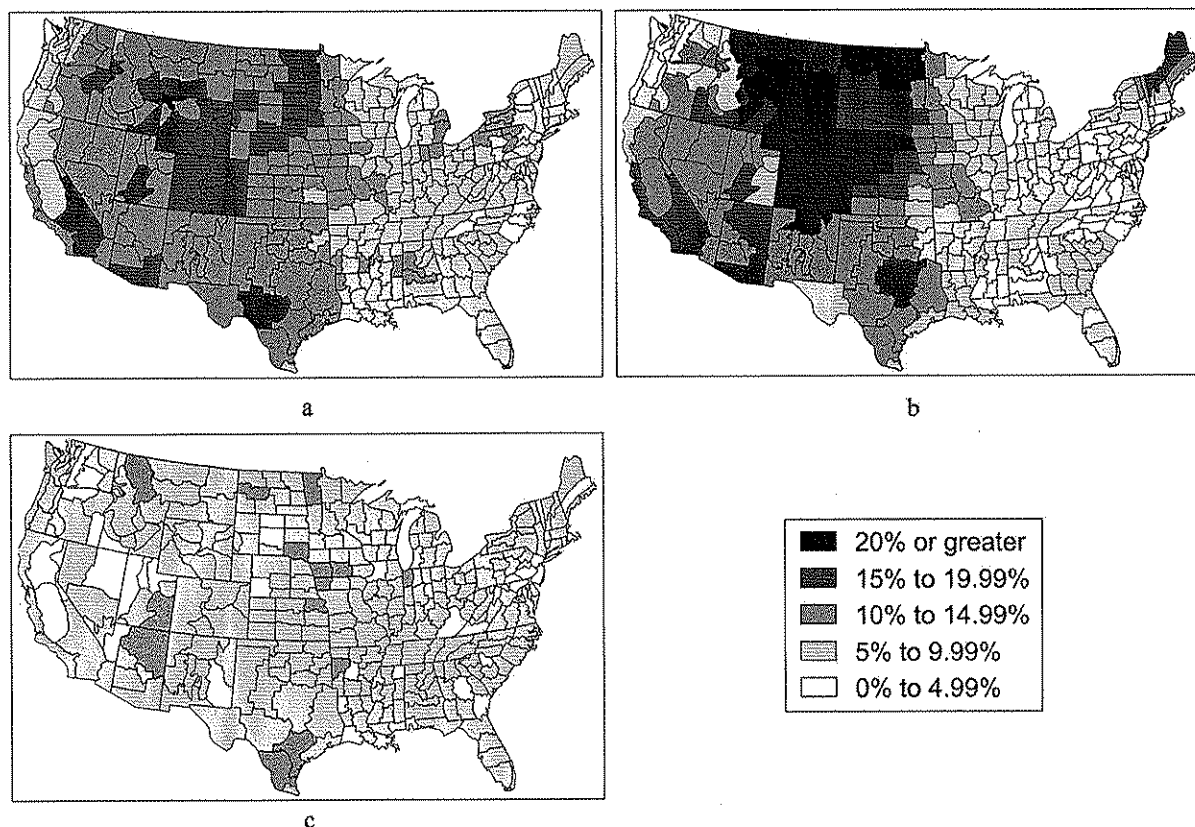


FIG. 12. The frequency at which (a) the original PDSI, (b) the CPC's PDSI, and (c) the SC-PDSI programs reported a severe or extreme wet spell (i.e., the percent of time the PDSI was at or above 3.0) at each climate division.

reported PDSI values. The CPC, however, uses a different method to estimate the potential evapotranspiration and a different method to calculate K' than what is used in the original implementation of the PDSI. This dataset is serially complete and represents a large range of climates, which should give a good indication of how the three indices behave spatially.

Once the indices were obtained, the percent of time the PDSI values were in each category was calculated for each climate division. For each of the PDSI programs, a plot of the mean frequency of PDSI values in each category for the climate divisions was created. One standard deviation from the mean frequency was also computed for each category.

5. Results

The results of the study are organized by analysis method rather than the stages in which the study was conducted. First, time series plots comparing the original and SC-PDSI are presented for individual weather stations. Second, an analysis of the frequency of extreme conditions and plots showing the distribution of the index are presented. Third, spatial comparisons of the frequency climate division PDSI values at or below -4 ,

at or above 4, at or below -3 , and at or above 3 are presented.

a. Time series plots

Time series plots of the SC-PDSI with the original PDSI are useful tools to evaluate the SC-PDSI. The time series plots will, of course, not be identical. However, both should show some of the same trends, especially during extreme droughts and wet periods. There can be no analysis done on periods of moderation because by changing the duration factors the sensitivity of the index to precipitation was changed, which means periods of moderation may be represented very differently, especially considering backtracking.

A visual examination of the plot of the original PDSI and SC-PDSI values at 156 stations in Nebraska was conducted as a preliminary assessment of the SC-PDSI algorithm. Any large discrepancies between the two indices during periods in which either index was showing extreme values could indicate possible errors in the algorithm. Most plots of the SC-PDSI algorithm followed the original monthly version during extreme periods of drought or excessive wetness, as shown in Fig. 3a.

However, one of the 156 locations in Nebraska, Cres-

cent Lake, showed greater deviations than expected. As shown in Fig. 3b, there are substantial differences between the original PDSI and the SC-PDSI around 1995 and again in 1999. This occurred when backtracking was triggered in the original PDSI but not in the SC-PDSI. In both instances, the original PDSI soon reversed course a second time to follow the SC-PDSI. This would suggest that the backtracking may have been induced prematurely, but it is unclear which of the two indices is actually more correct during those periods of discrepancy. It should be noted, however, that the vast majority of sites resulted in time series plots that followed the same general pattern of the original PDSI, but with a PDSI range of approximately -5 to 5 , which is what one should expect from a spatially comparable index.

b. Statistical analysis

Palmer performed some statistical analysis on his index with test locations in western Kansas and central Iowa (Palmer 1965). In western Kansas, he found that drought occurred 37% of the time and wet periods 37% of the time. He explained the relatively low percentage of normal readings by the fact that "normal" weather occurs very infrequently, even at a monthly level, in western Kansas. In Iowa, drought was under way 32% of the months and a wet spell 50%.

Our results are similar to Palmer's in that we found that few of the individual 761 sites examined in the High Plains states had normal weather. Plots representing histograms of original and self-calibrated PDSI values resulted in multimodal distributions for most of the sites. Figures 4 and 5 show the distributions for the Minden and Clay Center sites, respectively, in Nebraska.

The distribution of the PDSI is somewhat difficult to represent graphically. Showing the distribution over equally sized bins will usually split the normal category of PDSI values into separate bins. This results in strange curves around zero since backtracking causes more negative than positive normal values. As Table 1 shows, the ranges of the incipient wet and dry spell categories are half the size of all other categories. This prevents explicitly showing the distribution over the PDSI categories. One way to correct for this is to ignore the incipient wet and dry spells in the graphs. Each distribution is shown using both a standard representation and one over just the major PDSI categories.

The curve through the normal range of -0.5 to $+0.5$ is quite common in the distributions studied. The frequency of original PDSI values from -1.0 to -0.5 tends to be higher than the frequency of values from -0.5 to 0.0 . Similarly, the frequency of values from 0.5 to 1.0 tends to be higher than the frequency of values between 0.0 and 0.5 . This certainly does not fit with the belief that normal values should occur more frequently than nonnormal values.

The plot in Fig. 6 shows the distribution of the orig-

inal and SC-PDSI values as calculated at weather stations across Nebraska, Kansas, Colorado, Wyoming, Montana, North Dakota, and South Dakota. The original PDSI shows a lower frequency of normal values than would be expected, with the mode of the distribution being a mild dry spell. Perhaps the most interesting aspect of the distribution of the original PDSI values is the tails of the distribution. Extreme and severe droughts are reported with nearly the same frequency (approximately 7%) while extreme wet spells are reported with greater frequency than severe wet spells (approximately 8% and 7%, respectively).

The SC-PDSI, on the other hand, has a near-normal distribution. The only irregularity in its distribution is that there is a slightly lower frequency of mild wet spells than mild dry spells. Moreover, the frequency of extreme conditions is approximately 2%.

Table 2 summarizes the statistical analysis for the 156 Nebraska sites, and Table 3 summarizes results for all 761 sites in the seven-state study region. The performance of the SC-PDSI algorithm came closer to the expected behavior of the PDSI than the original PDSI.

The first two rows in Tables 2 and 3 are the best indicators of success in achieving spatial comparability with the SC-PDSI. Ideally, 100% of the stations would report extreme drought ($\text{SC-PDSI} \leq -4$) between 1% and 3% of the time. This was the case 98.08% of the time in Nebraska and 85.15% of the time in the seven-state High Plains region. Moreover, only 8 stations out of 761 reported extreme drought greater than 5% of the time (but less than 10% of the time). In comparison, the original PDSI reported extreme drought greater than 5% of the time in a majority of the sites, with two sites reporting extreme drought more than 25% of the time.

Figures 7 and 8 plot the mean frequency of original PDSI, SC-PDSI, and CPC reported monthly values in each category for all 344 climate divisions over the period of study. Error bars represent one standard deviation from the mean. The results are similar to that shown for the High Plains region.

Figure 8a shows that the original PDSI has an irregular distribution and appears slightly bimodal. The original PDSI has a large variance in the frequency of extreme events. Over 40% of the divisions have a frequency of extreme drought above 5%, and 16 have a frequency above 10%. Similar results can be observed for extreme wet spells.

The plot of the CPC reported PDSI values, shown in Fig. 8b, also has an irregular distribution. This distribution also appears to be slightly bimodal, but has larger standard deviations for mild spells. The standard deviations for the frequency of wet spells, especially extreme wet spells, are much larger than the standard deviations for the frequency of dry spells.

The SC-PDSI, shown in Fig. 8c has a regular distribution, with very low variance of the frequency of extreme events. The variance increases as the categories decrease in severity. Of the 344 divisions, 6 have a

frequency of extreme droughts between 5% and 6% and 3 between 7% and 8%; the rest are below 5%. None of the divisions has a frequency of extreme wet spells above 4.99%.

c. Spatial comparisons

A set of 12 maps was created to make spatial comparisons of the original, CPC-reported, and SC-PDSI values over the 344 climate divisions in the conterminous United States. Figure 9 shows the frequency of the original, CPC-reported, and SC-PDSI values for the climate divisions are at or below -4 . The original PDSI program reported 15 climate divisions in extreme drought at least 15% of the time, most in the western states, and 1 climate division in extreme drought more than 20% of the time. The CPC reported 71 climate divisions in extreme drought at least 5% of the time, with only 1 climate division in extreme drought more than 15% of the time. The SC-PDSI program reported all but nine climate divisions in extreme drought less than 5% of the time, with no climate division in extreme drought more than 8% of the time. The SC-PDSI program came closest to the ideal condition of all climate divisions in extreme drought less than 5% of the time.

Figure 10 shows the frequency that the original, CPC-reported, and SC-PDSI values for the climate divisions are at or above 4. The original PDSI program and the CPC PDSI program performed extremely well on the eastern half of the United States, where both were near the ideal; however, they performed poorly in the western half. It appears that the CPC has calibrated their PDSI program for extreme droughts in such a way that it outperforms the original PDSI program in extremely dry conditions, but reports wet conditions in portions of the west with much higher frequency. The SC-PDSI clearly performed better than the other two versions under wet conditions with no climate divisions reporting extreme wet spells more than 4.99% of the time.

Figure 11 shows the frequency that the original, CPC-reported, and SC-PDSI values for the climate divisions are at or below -3 . Overall, the SC-PDSI resulted in the most uniform reporting frequencies with 80% of the climate divisions reporting extreme or severe drought between 5% and 9.99% of the time.

Figure 12 shows the frequency that the original, CPC-reported, and SC-PDSI values for the climate divisions are at or above 3. Overall, the SC-PDSI resulted in the most uniform reporting frequencies with more than 80% of the climate divisions reporting extreme or severe wet spells between 5% and 9.99% of the time.

In summary, the SC-PDSI is more spatially comparable at the climate division level than either the original PDSI program or the CPC-reported PDSI values. This result matches our spatial comparison of the original PDSI and SC-PDSI at the weather station site level in the study region.

6. Conclusions

The SC-PDSI addresses the recommendation made by Guttman et al. (1992) to modify the way the PDSI is computed to account for the expected variability of precipitation between locations. The SC-PDSI does this by automatically adjusting the climatic characteristic and calculating the duration factors based on the characteristics of the climate at a given location. As a result, the index performs more consistently and allows for more accurate comparisons of the index at different locations, as predicted by Guttman et al. (1992).

In a study of all the climate divisions in the conterminous United States, the SC-PDSI showed considerable improvement over the NCDC and CPC versions. It is important to note that, while the SC-PDSI is more spatially comparable than either the NCDC or CPC versions, it is not as comparable as an index computed using nonlinear methods (e.g., the Standardized Precipitation Index; McKee et al. 1993). Nonetheless, a conscious effort was made in developing the SC-PDSI to follow the linear method proposed by Palmer.

Users can download the source code to the SC-PDSI, compute original and SC-PDSI values for weather stations throughout the United States, or generate original and SC-PDSI coverage maps for all states in the conterminous United States via the National Agricultural Decision Support System (NADSS; online at <http://nadss.unl.edu/>).

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