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

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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 evaportranspiration (Thronthwaite, 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.

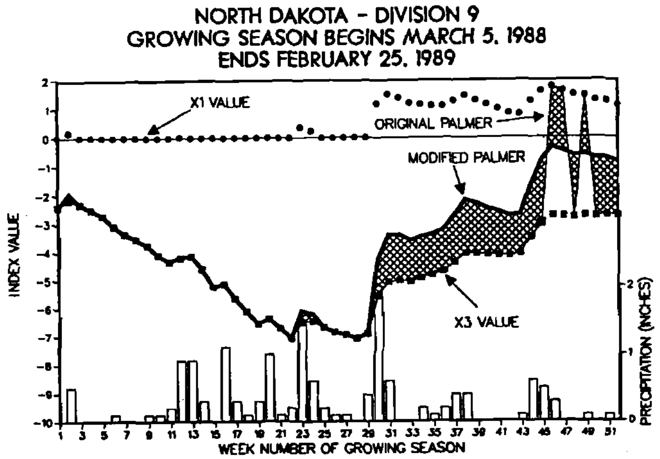

Figure 1. X1 values for the incipient wet spell (circles), X3 values for the established drought (boxes), the previous Palmer Drought Severity Index (light line), and the modified index (heavy line) for climatic division 9 in North Dakota from March 5, 1988 to February 25, 1989. Index values of -4 or 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.

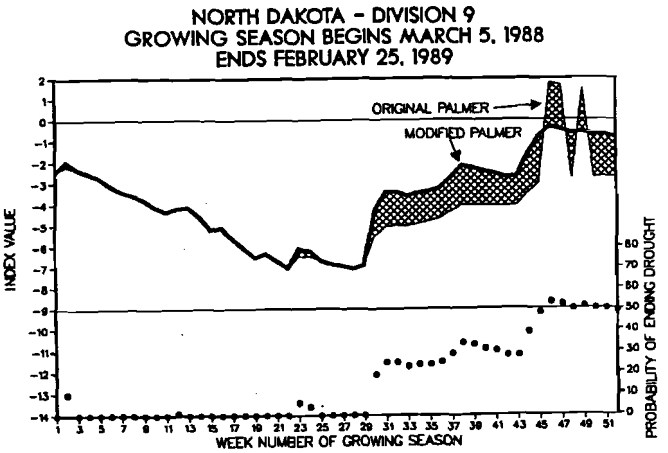

Figure 2. Similar to Figure 1 except the X1 and X3 values are omitted and the probabilities of ending the drought (circles) are plotted at the bottom instead of precipitation.

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 -.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:

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

   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.

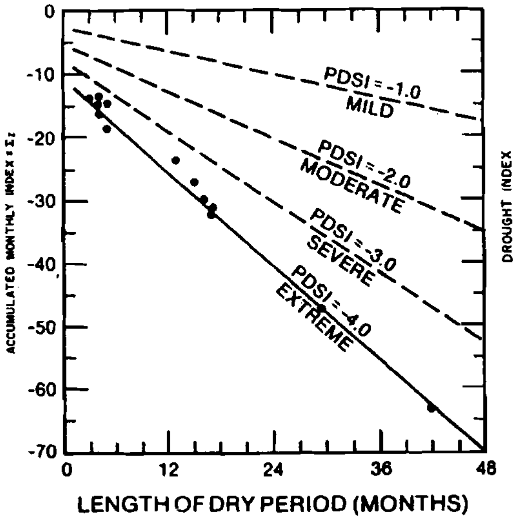

Figure 3. Accumulated values of the moisture anomaly Z index during the driest periods of various lengths in central Iowa and western Kansas (after Palmer, 1965).

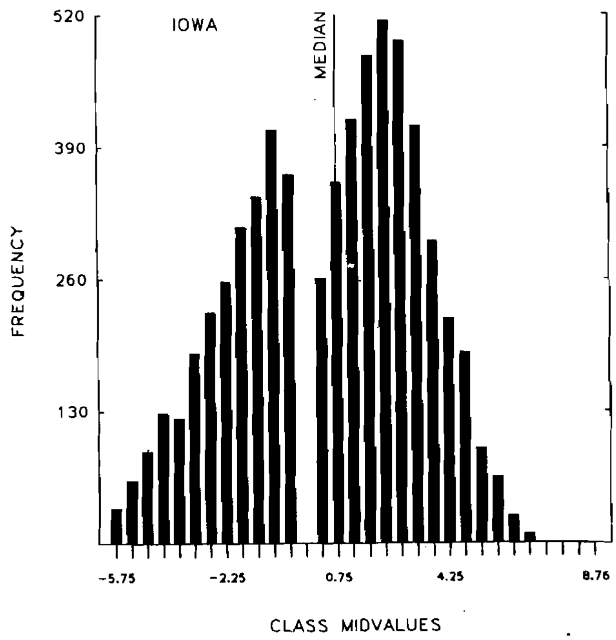

Figure 4. Histogram of the monthly PDSI values for the 9 climatic divisions in Iowa since 1931.

5. SURVEY OF USERS

A wide variety of users obtain near real-time meteorological products on CAC's 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 (F)	PRCP (IN)	SOIL MOISTURE UPPR LAYR (IN)	SOIL MOISTURE LOWR LAYR (IN)	PCT FLD CPC END WEEK	POT EVAP (IN)	RUN OFF (IN)	CROP MOIST INDEX	CHNG FROM PREV WEEK	MONTH MOIST ANOML (Z) INDEX	PRELIM-P FINAL -F PALMER DROUTH INDEX		PRCIP NEED TO END DROUTH (IN)
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	0.62	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	P	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	-1.18	0.38	P	
AZ	7	68	0.0	0.00	2.57	37	0.83	0.00	0.19	0.03	-0.01	2.82	P	
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	-1.14	-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	P	3.14
CA	4	56	0.0	0.00	3.53	50	0.55	0.00	-0.79	-0.15	-2.51	-5.30	P	8.68
CA	5	58	0.5	0.00	4.73	68	0.55	0.00	-0.19	0.16	-1.40	-4.14	P	7.55
CA	6	60	0.0	0.00	3.75	54	0.60	0.00	-0.64	-0.10	-2.28	-4.88	P	7.66
CA	7	69	0.0	0.00	0.00	0	0.87	0.00	-2.75	-0.12	-3.22	-5.96	P	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.

3. What parameters listed on the table you access do you find the most useful and what parameters the least?

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

Many who redisseminated 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 a stations and are therefore suspect. Current efforts are being made to replace the field

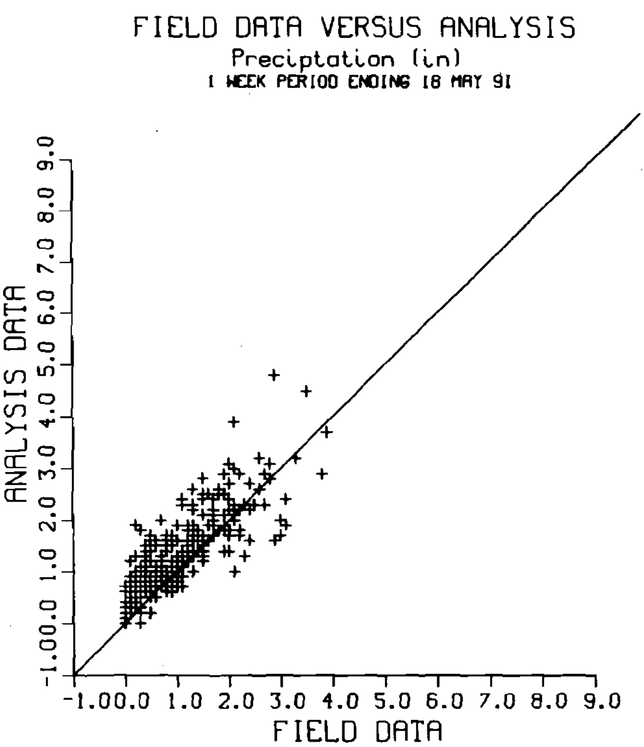

Figure 6. A comparison between weekly field data (sent through Weather Service Forecast Offices from each state) and analysis data (derived from data from RFC's) for the week ending May 18, 1991.

data with data derived from an analysis of a dense data set received form 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.

REFERENCES

Alley, W., 1984: The Palmer Drought Severity Index: limitations and assumptions. J. Climate Appl. Meteor., 23,1100-1109.

Bergman, K.H. and P. Sabol, 1986: Weekly assessment of global climatic anomalies using near-real time data. Preprints, The Human Consequences of 1985's Climate, August 4-7, 1986, Asheville, NC, pp. 262-267. (Published by American Meteorological Society, Boston, MA).

Bergman, K.H., P. Sabol, and D. Miskus, 1988: Experimental indices for monitoring global drought conditions. Proceedings of the Thirteenth Annual Climate Diagnostics Workshop, October 31-November 4, 1988, Cambridge, MA, pp. 190-197. (Published by National Technical Information Service, U.S. Dept. Commerce, Springfield, VA).

Changnon, S.A., 1980: Removing the confusion over droughts and floods: the interface between scientist and policy makers. Water Int., 5, 10-18.

Finger, F.G., J.D. Laver, K.H. Bergman, and V.L. Patterson, 1985: The Climate Analysis Center's user information service. Bull. Amer. Meteor. Soc., 413-420.

Heddinghaus, T.R., J.E. Janowiak, and R. P. Motha, 1987: Survey of various techniques used for drought assessment. Preprints, the Fifth Conference on Applied Climatology, March 9-13, 1987, Baltimore, MD, pp. 49-54. (published by American Meteorological Society, Boston, MA).

Heddinghaus, T.R. and D.M. Le Comte, 1989: A century of agriculture and weather data: the Weekly Weather and Crop Bulletin. Preprints, Sixth Conference on Applied Climatology, March 7-10, Charleston, SC, pp. 137-144. (Published by American Meteorological Society, Boston, MA).

Janowiak, J.E., C.F. Ropelewski, and M.S. Halpert, 1986: a method for monitoring regional precipitation deficiency and excess on a global scale. J. Climate. Appl. Meteor., 25, 565-574.

Karl, T.R. and R.W. Knight, 1985: Atlas of Monthly Palmer Drought Severity Indices for the Contiguous United States. Historical Climatology Series 3-10 (1895-1930) and 3-11 (1931-1983), National Climatic Data Center, Asheville, NC.

Karl, T.R., 1986: The sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. J. Climate Appl. Meteor., 25, 77-86.

Landsberg, H.E., 1975: Drought, a recurrent element of climate. Special Environmental Report No. 5, WMO, No.403, Geneva, Switzerland, pp. 41-90.

Palmer, W.C., 1965: Meteorological drought. Weather Bureau Research Paper No. 45, U.S. Dept. of Commerce, Washington, DC, 58 pp.

Redmond, K., 1990: Climate monitoring and indices. Proceedings of the Seminar and Workshop: Drought Management and Planning, May 30-June 1, 1990, Denver, CO, pp. 29-33. (published by International Drought Information Center, Lincoln, NE).

Shafer, B.A. and L.E. Dezman, 1982: Development of a Surface Water Supply Index (SWSI) to access the severity of drought conditions in snowpack runoff areas. Proceedings of the 50th Annual Western Snow Conference, pp. 164-175.

Wilhite, D.A., 1983: Government response to drought in the United States: with particular reference to the Great Plains. J. Climate Appl. Meteor., 22, 40-50.

SEVENTH CONFERENCE ON APPLIED CLIMATOLOGY

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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 broadbased 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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