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ABSTRACT

Droughts are difficult to detect and monitor. Drought indices, most commonly the Palmer Drought Severity Index (PDSI), have been used with limited success as operational drought monitoring tools and triggers for policy responses. Recently, a new index, the Standardized Precipitation Index (SPI), was developed to improve drought detection and monitoring capabilities. The SPI has several characteristics that are an improvement over previous indices, including its simplicity and temporal flexibility, that allow its application for water resources on all timescales. In this article, the 1996 drought in the southern plains and southwestern United States is examined using the SPI. A series of maps are used to illustrate how the SPI would have assisted in being able to detect the onset of the drought and monitor its progression. A case study investigating the drought in greater detail for Texas is also given. The SPI demonstrated that it is a tool that should be used operationally as part of a state, regional, or national drought watch system in the United States. During the 1996 drought, the SPI detected the onset of the drought at least 1 month in advance of the PDSI. This timeliness will be invaluable for improving mitigation and response actions of state and federal government to drought-affected regions in the future.

1. Introduction

In 1996, a severe drought affected the southern Great Plains and the southwestern United States. Some regions along the Rio Grande River in southern Texas had experienced several consecutive years of lower-than-expected rainfall, which increased the severity of the 1996 drought in these areas. Meanwhile, many parts of Texas and Oklahoma had not experienced “severe” or “extreme” drought conditions according to the Palmer Drought Severity Index (PDSI) during the past decade and were caught unprepared as the drought reached its full intensity during the spring months. Plentiful rains during May in Kansas, and during June in New Mexico, relieved the drought conditions there, and rains during July and August brought relief to Oklahoma and Texas, so that the drought was considered over in most areas of these four states by the beginning of fall. Parts of Arizona experienced drought into early 1997.

In general, the 1996 drought was a severe 9-month event that had significant impacts. Agricultural losses in Texas in 1996 have been estimated at $2.1 billion, while overall the drought cost the state more than $5 billion (WGA 1996). One of the most important developments was a movement toward better drought preparedness across the western United States (WGA 1996). This paper will follow the development and progression of the 1996 drought using a relatively new drought index developed at Colorado State University, the Standardized Precipitation Index (SPI; McKee et al. 1993; McKee et al. 1995). A series of maps will be provided to demonstrate the versatility of the SPI in monitoring the dynamics of the drought both nationally and regionally.

The most widely used drought index in the United States was developed by W. C. Palmer in 1965. Palmer recognized the need for a better monitoring tool that could identify drought in terms of its intensity, duration, and spatial extent. Palmer’s index became known

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as the Palmer Drought Severity Index or PDSI. Although there are several variations of the index, each variation has characteristics similar to the PDSI (Palmer 1965; Karl and Knight 1985; Heddinghaus and Sabol 1991). Palmer based the PDSI on anomalies in the supply and demand concept of the water balance equation. Inputs into the weekly or monthly calculations include precipitation, temperature, and the local antecedent soil moisture conditions. The data are standardized to account for regional differences so that PDSI values can be compared from one location to another. Therefore, PDSI values, in theory, indicate the same severity of drought in both western Ohio and western Texas, for example, even though the actual rainfall deficiencies would be completely different at the two locations.

Weekly maps of a modified PDSI (Heddinghaus and Sabol 1991) are produced by the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) and are frequently used in assessments of agricultural conditions around the United States.[1] The PDSI is also used as a factor in policy decisions by the U.S. Department of Agriculture (USDA) regarding states' requests for drought relief and by states themselves as "triggers" for response as part of their state drought plans.

However, the PDSI has limitations that diminish its application and bring into question the practice of basing policy decisions solely on the PDSI. These limitations have been well documented (Alley 1984; Karl and Knight 1985; Smith et al. 1993; Willeke et al. 1994; Kogan 1995; McKee et al. 1995; Guttman 1998). The most significant limitations of the PDSI related to monitoring drought include 1) an inherent timescale that makes the PDSI better suited for monitoring agriculturally related impacts rather than longer-term hydrological impacts; 2) the characteristic that all precipitation is treated as rain so that snowfall, snow cover, and frozen ground are not accounted for, making real-time winter PDSI values of questionable reliability; 3) the characteristic that the natural lag between precipitation and runoff is not considered and that no runoff occurs until the water capacities of the surface and subsurface soil layers are full, leading to an underestimation of runoff; and 4) the "extreme" and "severe" classifications of PDSI values vary widely depending on the location in the country. If a drought index is going to be spatially comparable and useful for policy decisions, extreme and severe classifications must occur consistently and with low frequency (Guttman et al. 1992). An additional concern is that the PDSI does not do well in the mountainous west, especially since a majority of that region's precipitation falls during the winter as snowfall. It also can respond slowly to developing drought conditions and, once a region is in drought, the PDSI can retain values reflecting drought well after a climatological recovery from drought has occurred (T. B. McKee 1996, personal communication). All of these limitations reveal the importance of caution when using the PDSI for drought monitoring and policy decisions, and why the new Standardized Precipitation Index, or SPI, was developed as an attempt to address some of the problems inherent in using the PDSI.

2. What is the SPI?

Researchers at Colorado State University (McKee et al. 1993; McKee et al. 1995) designed the SPI in 1993 to be a relatively simple, year-round index applicable to the water supply conditions important to Colorado and as a supplement to information provided by the PDSI and a second drought index, the Surface Water Supply Index (Shafer and Dezman 1982). The SPI is based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of timescales. This versatility allows the SPI to monitor short-term water supplies, such as soil moisture, important for agricultural production, and longer-term water resources such as groundwater supplies, streamflow, and lake and reservoir levels. The ability to examine different timescales also allows droughts to be readily identified and monitored for the duration of the drought. Colorado has now used the SPI information as part of the Water Availability Task Force since 1994—including 1996, when drought affected portions of the state.

Calculation of the SPI for a specific time period at any location requires a long-term monthly precipitation database with 30 yr or more of data. The probability distribution function is determined from the long-term record by fitting a function to the data. The cumulative distribution is then transformed using equal probability to a normal distribution with a mean of zero and standard deviation of one so the values of the SPI are really in standard deviations (Edwards and

[1]These maps are available in near–real time on the World Wide Web: http://nic.fb4.noaa.gov/products/analysis_monitoring/regional_monitoring/usa.html.

McKee 1997). A particular precipitation total for a specified time period is then identified with a particular SPI value consistent with probability. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. The magnitude of departure from zero represents a probability of occurrence so that decisions can be made based on this SPI value. Because SPI values fit a typical normal distribution, one can expect these values to be within one standard deviation approximately 68% of the time, within two standard deviations 95% of the time, and within three standard deviations 99% of the time. A related interpretation would be that an SPI value of less than –1.0 occurs 16 times in 100 yr, an SPI of less than –2.0 occurs two to three times in 100 yr, and an SPI of less than –3.0 occurs once in approximately 200 yr.

McKee et al. (1993) and McKee et al. (1995) originally used an incomplete gamma distribution to calculate the SPI. Efforts are now in progress to standardize the SPI computing procedure so that common temporal and spatial comparisons can be made by SPI users (Guttman 1998).

3. Advantages and limitations of the SPI

What gives the SPI an advantage over the PDSI? The first advantage is its simplicity. The SPI is based only on precipitation. The PDSI calculations are complex, and 68 terms are actually defined as part of the calculation procedure (Soulé 1992). In spite of the complexity of the PDSI, T. B. McKee (1996, personal communication) believes that the main driving force behind the PDSI is precipitation. Second, the SPI is versatile: it can be calculated on any timescale, which gives the SPI the capability to monitor conditions important for both agricultural and hydrological applications. This versatility is also critical for monitoring the temporal dynamics of a drought, including its development and decline, which have always been difficult to track with other indices. The third advantage of the SPI is that, because of its normal distribution, the frequencies of the extreme and severe drought classifications for any location and any timescale are consistent. McKee et al. (1993) suggest an SPI classification scale (Table 1). An extreme drought according to this scale (SPI –2.0) occurs approximately two to three times in 100 yr, an acceptable frequency for water management planning. Finally, because it is based only on precipitation and not on soil moisture conditions as is the PDSI, the SPI is just as effective during winter months and is also not adversely affected by topography.

Although developed for use in Colorado, the SPI can be applied to any location with a dataset of 30 yr or longer. Montana, Wyoming, New Mexico, South Carolina, and Nebraska have investigated or are using the SPI as part of their statewide efforts to monitor drought. Meanwhile, researchers in Mexico, Costa Rica, Argentina, Brazil, Chile, Turkey, Hungary, South Africa, and Kenya have either considered or are using the SPI for projects in their respective countries.

At the National Drought Mitigation Center (NDMC), we have been creating national maps of the SPI at the climatic division level for the continental United States since February 1996. The precipitation dataset comes from the CPC and the SPI values are calculated by the Western Regional Climate Center (WRCC) in Reno, Nevada. These are the same data used to create the near-real-time PDSI values used in weekly maps created by the CPC. The data are archived at the National Climatic Data Center (NCDC), and the archive extends from 1895 to the present, making it possible to examine both historical SPI and PDSI values for all climatic divisions. The NDMC has been making the near-real-time SPI maps available over the World Wide Web, with links to NCDC, CPC, and the regional climate centers.[2] In

[2]The SPI maps are located at http://enso.unl.edu/ndmc/watch/watch.htm#section1a.

TABLE 1. Classification scale for SPI values.

SPI values	Category
2.00 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
–0.99 to 0.99	Near normal
–1.00 to –1.49	Moderately dry
–1.50 to –1.99	Severely dry
–2.00 and less	Extremely dry

February 1997, the WRCC also made near-real-time SPI maps, and associated products, available on the World Wide Web in the form of a matrix that allows the user the opportunity to choose the SPI map for any time period.[3]

The SPI has several limitations and unique characteristics of its own that must be considered when it is used. For example, the SPI is only as good as the data used in calculating it. Up through July 1996, the preliminary data used by NCDC, which were the same data used to calculate the PDSI, were gathered from approximately 600 stations each month across the nation. After 2–3 months, when all data had been collected and quality controlled, the final database contained approximately 6000 stations (R. Heim 1998, personal communication). Since July 1996, however, all monthly station data come from the CPC's dataset, which contains approximately 6000–8000 stations in any given month (T. R. Heddinghaus 1998, personal communication). Coverage is still somewhat limited in the western United States where terrain differences increase the spatial variability of climatic variables. Colorado, Montana, Nebraska, and South Carolina have improved the data coverage by using station networks within their states to calculate the SPI on a site-by-site basis.

The timeliness of the preliminary data is also a factor. National SPI maps for the previous month are usually not available until the second or third weeks of the month. Efforts are under way to improve this timeliness.

Another SPI feature to remember is that because of characteristics associated with the normal distribution, severe and extreme droughts measured by the SPI occur with the same frequency for all locations across the country over a long time period. Thus, the SPI by itself cannot identify regions that may be more "drought prone" than others.

Before the SPI is applied in a specific situation, a knowledge of the climatology for that region is necessary. At the shorter timescales (1, 2, or 3 months), the SPI is very similar to the percent of normal representation of precipitation, which can be misleading in regions with normally low seasonal precipitation totals (i.e., seasonal rainfall regime). For example, in California during the summer or the Great Plains in winter, low precipitation totals are normal. As a result, large positive or negative SPI values may be caused by a relatively small anomaly in the precipitation amount. Understanding the climatology of these regions improves the interpretations of the SPI values. For this reason, the NDMC has included an interpretation of regional climatology in its presentation of monthly SPI maps on its World Wide Web site.

4. The 1996 drought and the SPI

The 1996 drought really began in October 1995. Before then, conditions in the southern plains and Southwest were relatively moist. The 9-month SPI map (Fig. 1a) through the end of September, comparing the January through September precipitation totals in 1995 with the same period throughout the dataset (1895–1996), showed SPI values greater than +1.0 from northern Missouri into northern Texas. Most of the western United States, including all of California, Oregon, Nevada, Utah, and Colorado, also had SPI values greater than +1.0. Meanwhile, climatic divisions in the Northeast had SPI values in the moderate (≤ -1.0) to extreme (≤ -2.0) dryness categories. In fact, 1995 was considered a drought year in the Northeast. The period from October 1994 through September 1995 was the driest for the Northeast region in 100 yr of data (Brown 1995). The Northeast drought peaked in intensity and spatial extent during August and ended abruptly during a very wet October (Fig. 1b). The 1-month SPI map for October shows wet conditions extending from Florida to New England and across the upper Midwest. Dry conditions for the month stretched from the central and southern plains to California. Although dry 1-month SPIs do not mean there is drought, in this case the dry values during October were reflecting the beginning of drought in the southern plains.

From late 1995 into January 1996, very little precipitation fell in the southern plains and Southwest. February 1996 was a very dry month from southern Minnesota and South Dakota to the Texas–Mexico border (Fig. 1c). The 5-month SPI map (Fig. 1d), for precipitation from October 1995 through February 1996, indicated that most climatic divisions from southern Nebraska to California had SPI values of less than –1.0. The SPI was less than –2.0 (extreme dryness category) in eight of nine climatic divisions in Kansas.

By the end of February, the SPI clearly indicated that drought was occurring in the southern plains and Southwest, especially in Kansas, Oklahoma, New Mexico, and northern Texas (Fig. 1d). Other indica-

[3]The WRCC's SPI matrix is located at http://www.wrcc.sage.dri.edu/spi/.

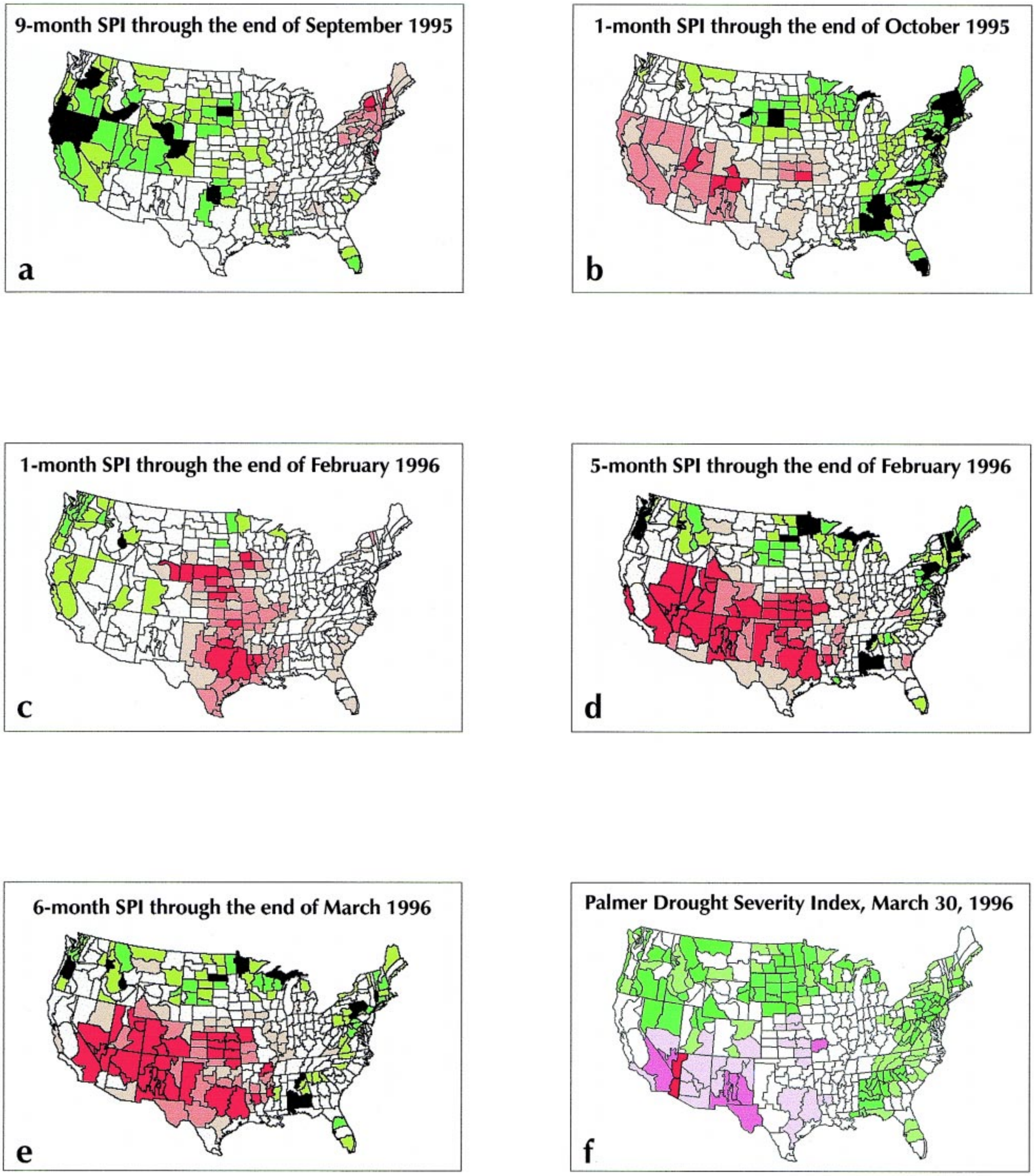

FIG. 1. Index values for the climatic divisions of the 48 contiguous states. The legend for the SPI maps: (a–e) tan, −1.00 to −1.49; light red, −1.50 to −1.99; dark red, −2.00 and less; light green, +1.00 to +1.49; dark green, +1.50 to +1.99; black, +2.00 and above. The legend for the PDSI map: (f) pink, −2.0 to −2.9; dark pink, −3.0 to −3.9; red, −4.0 or less; light green, +2.0 to +2.9; dark green; +3.0 to +3.9; black, +4.0 and above.

tions were also beginning to confirm the existence and severity of this drought. On 12 March 1996, the Joint Agricultural Weather Facility published a chart in the *Weekly Weather and Crop Bulletin* (NOAA/USDA 1996a) showing that precipitation for the October 1995–February 1996 period for the major region of hard red winter wheat production, from southern Nebraska to northwest Texas, was the second lowest in 101 yr (Fig. 2). Wheat farmers, particularly in Kansas, Oklahoma, and Texas, already knew their wheat crops were in trouble, and this was verified in USDA reports (Associated Press 1996; Edwards 1996). In Texas and Oklahoma, wildfires caused by hot, windy conditions burned across dry rangeland. These fires received considerable national media attention and prompted Texas Governor George W. Bush to request that the entire state be declared a disaster area on 22 February (*Los Angeles Times* 1996).

March 1996 was again dry across most of the United States. The 6-month SPI map for the October 1995 through March 1996 period (Fig. 1e) shows that the SPI values generally declined during March in the drought regions of the southern plains and Southwest. The PDSI map for 30 March (Fig. 1f), meanwhile, is only beginning to show that drought might be a problem in parts of this region. However, it completely fails to reveal the drought's severity in the winter wheat belt from Kansas to Texas. The PDSI continued to show a deterioration of conditions throughout April and into May and June for most of the region. The true severity of the drought was not reflected by the PDSI until mid-May. However, the month or more delay between the SPI and the PDSI identification of the drought is especially noteworthy.

Conditions remained dry during April 1996 in the drought-affected regions. However, in May 1996, rains returned to Kansas, although it remained dry elsewhere. Plentiful rains then fell in parts of New Mexico during June 1996. Finally, generous rains fell across most of the drought-affected regions during July, August, and September. Figure 3 shows how the drought decreases in intensity and spatial extent with the June 9-month, July 10-month, August 11-month, and September 12-month SPI maps. The next section will look at how well the SPI detected and monitored the 1996 drought for Texas. Similar case studies could also be made illustrating the versatility of the SPI for any of the states impacted by the drought, demonstrating how different timescales reveal important information unique to each case.

5. Texas and the 1996 drought

Although October, November, and December were dry across northern Texas in 1995, the drought did not really hit the entire state with full force until January 1996 (Fig. 4a). Both January and February were extremely dry statewide (Figs. 1c, 4b), which was also true in Oklahoma. It was during February and early March that wildfires broke out because of dry, warm, and windy conditions, causing major problems in both states. Some of the worst fires occurred just west of the Dallas–Fort Worth metropolitan area, with one fire destroying homes and injuring 49 people (O'Hanlon 1996). Ranchers in Texas began to experience difficulties during February. One of the problems ranchers experienced throughout the drought, especially in Texas, was that beef prices were very low while grain, and therefore feed, prices were extremely high (Fairbank 1996). This problem meant that ranchers either got very little return for selling their cattle or had to pay the high grain prices to feed the cattle they would have preferred to sell.

Conditions across Texas deteriorated through June for most of the state. This is reflected in the March 6-month SPI map (Fig. 1e) and the June 9-month SPI map (Fig. 3a). The June 6-month SPI map (Fig. 4c) highlights the fact that very little precipitation fell between the beginning of January and the end of June across most of the state. Seven of the state's 10 climatic divisions were in the extreme dryness category. In the far western part of the state, precipitation is typically low throughout the year.

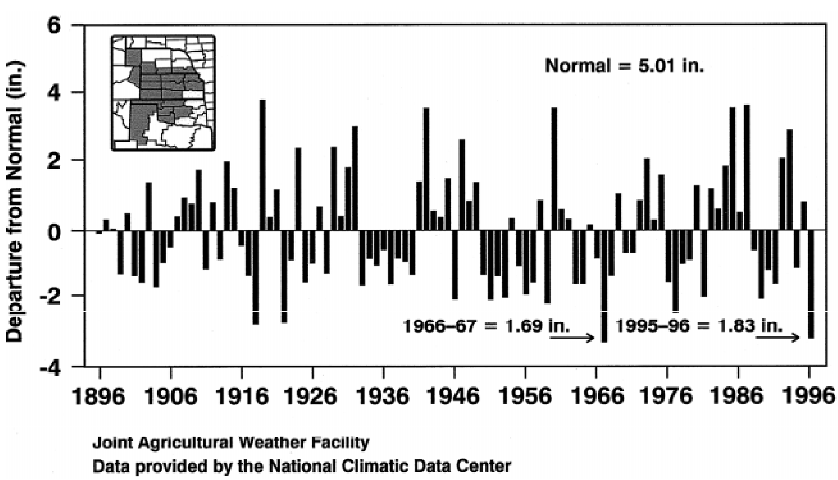

FIG. 2. Precipitation for the October 1995–February 1996 period for the major hard red winter wheat production region from Nebraska to Texas.

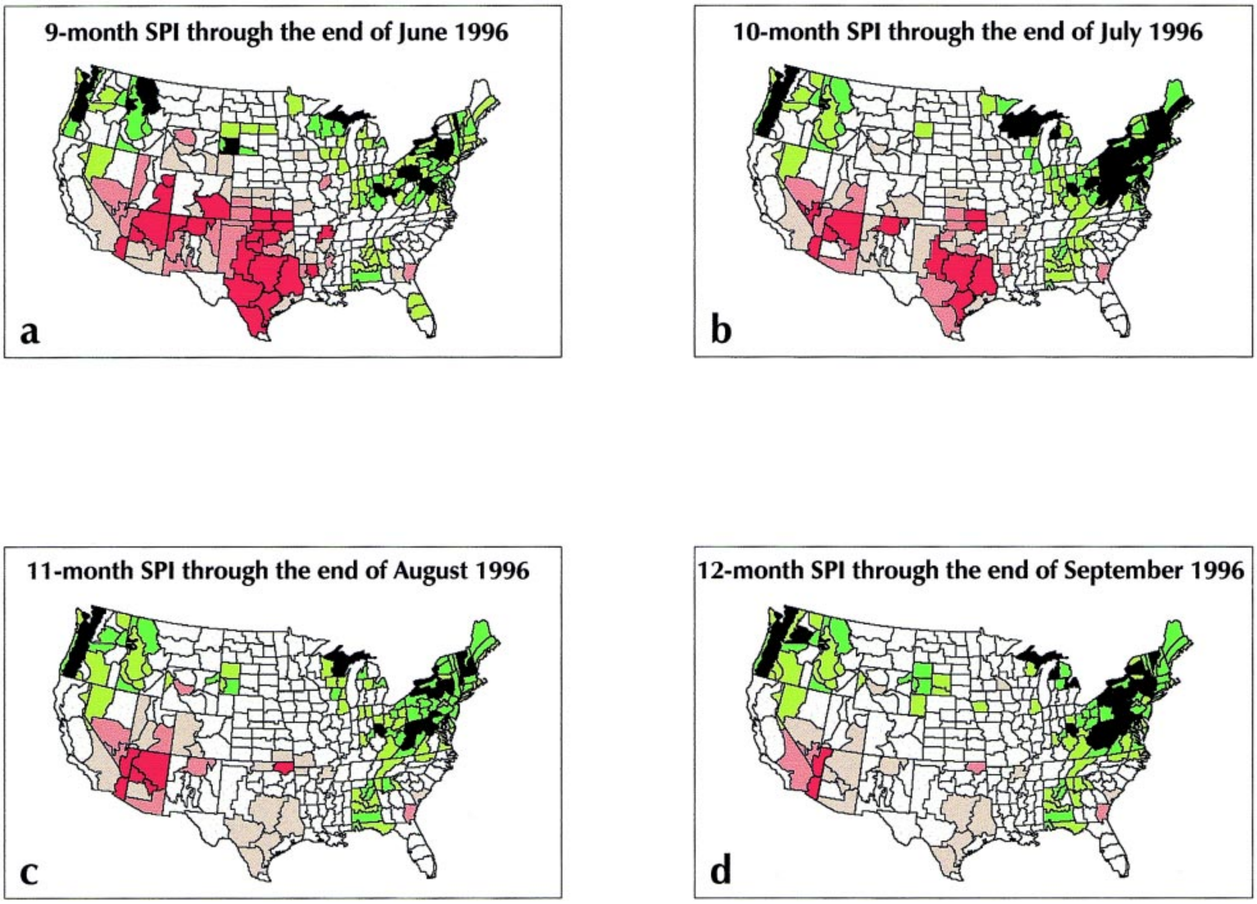

FIG. 3. SPI values as in Fig. 1. Legend: tan, −1.00 to −1.49; light red, −1.50 to −1.99; dark red, −2.00 and less; light green, +1.00 to +1.49; dark green, +1.50 to +1.99; black, +2.00 and above.

However, above-normal precipitation events did occur during April and June in the Trans-Pecos Climatic Division, which includes the city of El Paso, putting this division into the near-normal category. Meanwhile, beneficial rains also fell in June in the Panhandle, including Amarillo, diminishing the severity of the 6-month SPI values in this region.

By the end of June, impacts from the drought in Texas reached across the state and across many sectors of the state's economy. Winter wheat production was estimated to be down 24% from 1995 production, which was also poor (UPI 1996). Vegetable, fruit, and cotton production in the Rio Grande Valley was also severely affected, with impacts in harvesting, transportation, processing, and marketing lasting into 1997 (Antosh 1996; Fohn 1996). Production in this region normally totals $447 million annually (Lee 1997). Across the state, ranchers and the dairy industry were hit hard, and more than 130 counties applied for emergency federal subsidies (Smith 1996). Reservoir levels fell to record-low levels by May, especially along the Rio Grande River at the International Armistad and International Falcon Reservoirs (NOAA/USDA 1996b). Tourism was also affected by these low levels, as well as by low streamflows in rivers, such as the Guadalupe River, where rafting is an important industry (Arrillaga 1996; Curliss 1996). About 280 public water systems around the state were considered to be at risk of water shortages because of the drought (Jensen 1996). The Edwards Aquifer, which provides water for San Antonio and five surrounding counties, was approaching its record-low level. This impact also had environmental consequences involving endangered species within the aquifer and along the Comal and San Marcos Rivers (Holmes 1996). Finally, the drought was having an impact on forests, and the survival rate for new commercially planted seedlings in the state was expected to be only 60% (Jensen 1996).

In July, it began raining again across portions of northern Texas, with abundant rains falling in most of the drought-stricken regions of the state in August (Fig. 4d). Departures from the normal August precipi-

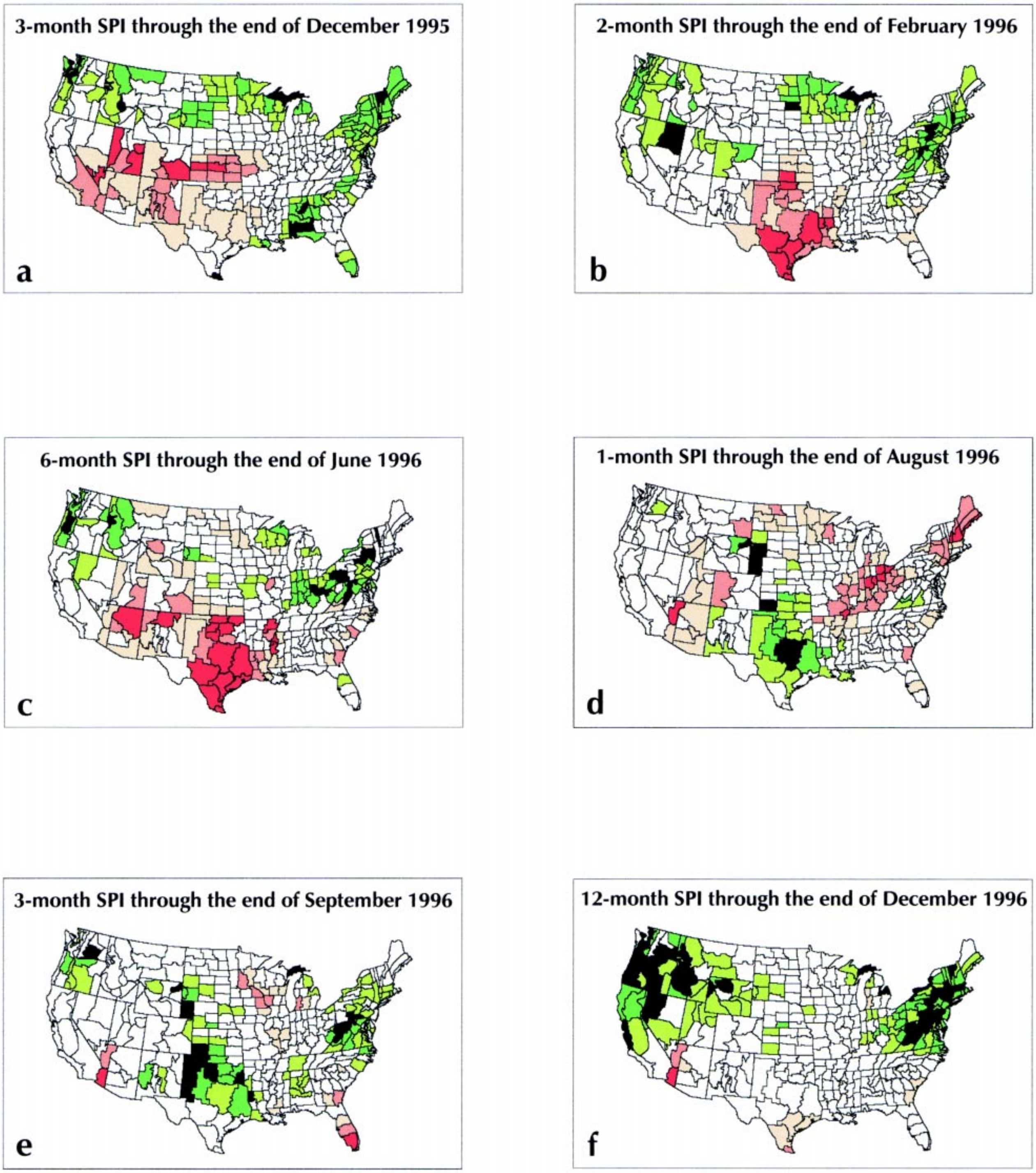

FIG. 4. SPI values as in Fig. 1. Legend: tan, −1.00 to −1.49; light red, −1.50 to −1.99; dark red, −2.00 and less; light green, +1.00 to +1.49; dark green, +1.50 to +1.99; black, +2.00 and above.

tation ranged from 113% in San Antonio to 410% in Austin, with most of the state greater than 200% of normal (NOAA/USDA 1996c).

During September, abundant precipitation continued for the hard-hit Houston, Austin, and Brownsville areas. San Antonio and Del Rio, along the Rio Grande River, were near normal for the month. At the end of September, the 3-month SPI map (Fig. 4e) shows the four climatic divisions across northern Texas either in the moderately, very, or extremely moist categories.

Eight of nine climatic divisions in Oklahoma are also in the same categories. The 12-month SPI map at the end of September 1996 (Fig. 3d) indicates that long-term drought conditions may still have existed across southern and eastern Texas. The 12-month SPI map for December 1996 (Fig. 4f), which captures the drought's January 1996 start across southeastern Texas, demonstrates that long-term drought was still a concern in that part of the state. This is an area that includes the cities of Houston, Austin, San Antonio, Del Rio, and Brownsville. Levels in the Amistad and Falcon International Reservoirs were still far below what they normally are for the end of December (USGS 1997). By the end of January 1997, state officials were still declaring that drought existed in the Rio Grande Valley and that the continuing low reservoir levels could have a major impact on crop production and municipal water supply during the rest of 1997 (Lee 1997).

6. Conclusions

When the SPI was developed in 1993, it filled a void in the capability to monitor the onset and duration of droughts. The PDSI is widely used because it has been the best drought index available, but there has always been dissatisfaction with its limitations and its complexity. In comparison to the PDSI, the SPI is relatively simple and versatile and does not have many of the limitations associated with the PDSI. The most important characteristic of the SPI is its flexibility to observe different timescales. This characteristic makes the SPI a valuable tool for all water resource managers interested in either short- or long-term moisture supplies.

During 1996, the SPI demonstrated that it would have been a beneficial tool for detecting and monitoring the drought in the southern plains and southwestern United States. Although the drought was regionwide, the dynamics of the drought varied by location. This paper has illustrated how the SPI could have been used operationally to follow both the regional and local progression of the drought from its development in late 1995 to its conclusion during the summer and fall of 1996 for most areas. Because the SPI is relatively new, the ability to make the SPI maps available nationally only began in February 1996 at the NDMC. Since then, awareness of the SPI has grown, and near-real-time maps are available on the NDMC and Western Regional Climate Center Web sites and occasionally in the *Climate Variations Bulletin* produced by the National Climatic Data Center, so that the capability now exists to monitor drought conditions across the country using timely SPI values.

The 1996 drought also demonstrated that the SPI identified the onset and severity of the drought at least 1 month in advance of the PDSI. This is very important because most policy decisions involving drought and drought relief up to this point have been based on the PDSI. In 1996, attention focused on the drought in response to certain highly visible events, such as the wildfires in Texas and Oklahoma during February and March and the severe impact on the winter wheat crop. The PDSI values significantly lagged these drought-related impacts. Using the SPI as a drought-monitoring tool will improve the timely identification of emerging drought conditions that can trigger appropriate state and federal actions.

One aspect of the SPI not included in this study is how the SPI might be able to monitor conditions leading up to a major flooding event. For the northwest and northeast part of the United States, 1996 was a very wet year, with damaging floods observed in both regions (Fig. 4f). It is possible that the SPI could also be used as a tool to monitor the development of conditions with excess moisture.

In the future, the SPI will receive much more visibility as water resources managers and policy makers become aware of its existence. Research will continue on the SPI to see if improvements to the index, or its interpretation, can be made. A possible improvement might be to calculate it on a weekly or biweekly basis rather than by the month, as it is currently done. Even with the current optimism about the SPI, it must be remembered that the SPI cannot solve all moisture monitoring concerns. Rather, it is one tool that can be used in coordination with other tools, such as the PDSI or remote sensing data, to detect the development of droughts and monitor their intensity and duration.

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