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Analyzing spatial patterns of meteorological drought using standardized precipitation index

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ABSTRACT: Drought is a slow-onset, creeping natural hazard and a recurrent phenomenon in the arid and semi-arid regions of Gujarat (India). In Asia, the standardized precipitation index (SPI) has gained wider acceptance in the detection and the estimation of the intensity, magnitude and spatial extent of droughts. The main advantage of the SPI, in comparison with other indices, is that the SPI enables both determination of drought conditions at different time scales and monitoring of different drought types. This index captures the accumulated deficit (SPI < 0) or surplus (SPI > 0) of precipitation over a specified period, and provides a normalized measure (i.e. spatially invariant Z score) of relative precipitation anomalies at multiple time scales. In the present study, monthly time series of rainfall data (1981–2003) from 160 stations were used to derive SPI, particularly at 3-month time scales. This 3-month SPI was interpolated to depict spatial patterns of meteorological drought and its severity during typical drought and wet years. Correlation analysis was also done to evaluate usefulness of SPI to quantify effects of drought on food grain productivity. Further, time series of SPI were exploited to assess the drought risk in Gujarat. Copyright © 2007 Royal Meteorological Society

KEY WORDS standardized precipitation index; meteorological drought; drought risk; crop anomaly

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1. Introduction

The climate of a region is determined by long-term average, frequency and extremes of several weather variables, notably precipitation and temperature. In a large semi-arid country such as India, precipitation is precious and varies both in space and time. Thus, any departure in precipitation patterns seldom leads to widespread natural disasters such as drought and floods affecting natural habitats, ecosystems and, importantly, agricultural and economic sectors. Drought, in particular, is considered by many to be the most complex but least understood of all natural hazards, affecting more people than any other hazard (Hagman, 1984). Generally, large-scale spatio-temporal variability in timing and duration of drought impact hinders a universal definition of drought. However, Wilhite and Glantz (1985) have categorized drought into meteorological (lack of precipitation); hydrological (drying of surface water storage); agricultural (lack of root zone soil moisture) and socio-economic (lack of water supply for socio-economic purpose).

In the last century, many drought indices were formulated by integrating weather variables such as rainfall, evapotranspiration and temperature into a single number. The most commonly used drought indices include the Palmer drought severity index (PDSI) and the moisture anomaly index (Z-index) (Palmer, 1965), the standardized precipitation index (SPI) (McKee *et al.*, 1993, 1995), aridity index (Gore and Sinha Ray, 2002) and Percent Normal, Deciles (Gibbs and Maher, 1967). Drought indices, in general, enable the detection of the onset of drought events and enable their severity to be measured, thereby allowing an examination of the spatial and temporal characteristics of drought, and comparisons between different regions to be made (Alley, 1984). The majority of drought indices have a fixed time-scale. For example, the PDSI has a time-scale of about 9 months (Guttman, 1998), which does not allow identification of droughts at shorter time scales, as in the case of agricultural drought. However, SPI is designed in such a way that it can detect drought over different periods at multiple time scales. This index is calculated by fitting a gamma distribution to observed values of precipitation totals at different time steps (e.g. 1, 2, 3, …, 48 months), and then transforming back to the normal distribution with mean zero and a variance of one. The SPI is equal to the Z-score applied to normally distributed precipitation totals at different time scales. For example, the 1-month SPI of September represents standard deviation in precipitation of September only; 3-month SPI of September represents the standard deviation in precipitation totals of September and the previous 2 months. Positive values in SPI indicate greater than mean precipitation, and negative values indicate less

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than mean precipitation. The SPI is produced by standardizing the probability of observed precipitation for any duration. Durations of weeks or months can be used to apply this index to agricultural interests, and longer durations of years can be used to apply this index to water supply and water management interests (Guttman, 1999). The applicability of SPI varies with the time scale because the 1-month SPI reflects short-term conditions and its application can be related closely to soil moisture; the 3-month SPI provides a seasonal estimation of precipitation; 6- and 9-month SPI indicates medium term trends in precipitation patterns (Ji and Peters, 2003). Although it is quite a recent index, the SPI has been used in Turkey (Komuscu, 1999), Argentina (Seiler *et al*., 2002), Canada (Anctil *et al*., 2002), Spain (Lana *et al*., 2001), Korea (Min *et al*., 2003), Hungary (Domonkos, 2003), China (Wu *et al*., 2005), Europe (Lloyd-Hughes and Saunders, 2002) and India (Chaudhari and Dadhwal, 2004) for real-time monitoring or retrospective analysis of droughts.

Given the enormous potential of the SPI to detect and characterize drought episodes worldwide, the present study was focussed on investigating the usefulness of the SPI in characterizing the spatio-temporal variability of seasonal drought events in Gujarat, India.

2. Study area

The study was carried out in Gujarat State, located in western India, situated between 20°06′–24°42′ N and 68°10′–74°28′ E (Figure 1). It comprises 19 districts with a total geographical area of 0.196 million square kilometres. Gujarat State has three major physiographic regions, the central highlands, the western hills and the western coast. The western coast covers the major portion of the State and comprises the Gujarat plains, and the Kathiawar and Kuchchh Peninsulas. The climate in Gujarat shows a wide variability ranging from arid, through semi-arid, to sub-humid tropical monsoon type. Gujarat has a highly erratic rainfall pattern which makes it subject to widespread droughts. In general, districts located in the north, southwest (Kathiawar Peninsula) and northwest (Kuchchh Peninsula) parts of the State suffer from drought with re-occurrence intervals of 3–4 years (Gore and Sinha Ray, 2002) The northwestern part of the state is dry and receives <500 mm of rain every year. In the more temperate central part of the State, the annual rainfall is more than 700 mm (GAU, 1997).

3. Materials and methods

3.1. Precipitation and crop statistics

Precipitation data were derived from monthly rainfall measurements for a period of 23 years (1981–2003). These monthly rainfall data were used to compute the SPI for each station. The rainfall data were collected and compiled from various sources such as the Gujarat Ecological commission (http://www.gec.gov.in), Bhaskaracharya Institute of Satellite and Geoinformation (BISAG), Gandhinagar, and the Agro-Meteorological

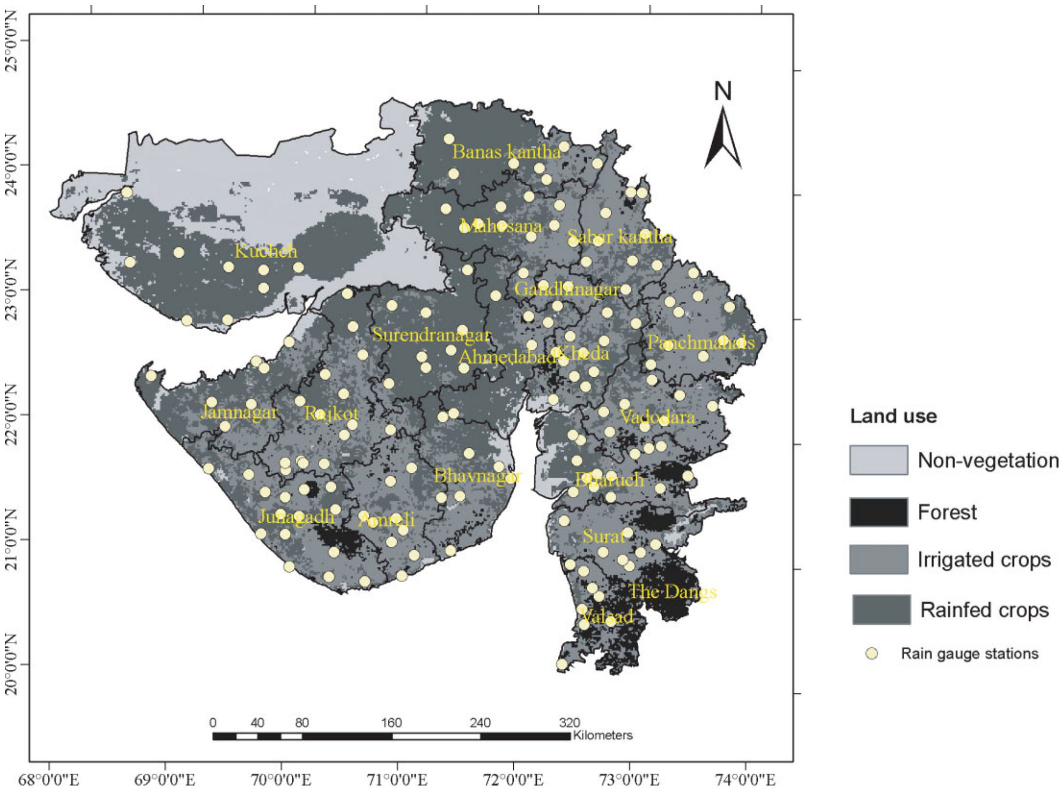

Figure 1. Study area showing land use and location of rain gauge stations (white dots). This figure is available in colour online at www.interscience.wiley.com/ma

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Department, Anand Agriculture University, Anand. The number of rainfall stations between 1981 and 1989 was 164, from 1990 to 1997 the number of these stations had increased to 174 and reached 218 in 2000–2003. Therefore, to maintain consistency in data, rainfall data over 164 rain stations spanning from 1981 to 2003 were used in the present study. The geographical coordinates of these stations were used to create a map of rain gauge stations using ERDAS Imagine software (Figure 1).

The historical crop statistics for cereals (rice, pearl millet, sorghum and other coarse millets) and pulses (chickpea, mung, pigeonpea and blackgram) grown during *kharif* (June–October) was obtained from the Department of Agriculture, Government of Gujarat. These statistics were used to compute the food grain productivity of the *kharif* season for 1981–2000.

3.2. SPI algorithm and interpretation

Conceptually, SPI is equivalent to the Z-score used in statistics and is formulated as,

$$SPIij \approx \frac{Xij - \mu\ ij}{\sigma\ ij} \tag{1}$$

where, *SPIij* is the SPI of i^{th} month at j^{th} time-scale, Xij is precipitation total for i^{th} month at j^{th} time-scale, μij and σij are long-term mean and standard deviation associated with i^{th} month at j^{th} time-scale. Since precipitation has a skewed distribution, the precipitation data are first transformed to a more normal or Gaussian distribution, and then calculated in a manner as demonstrated in Equation (1). The SPI is an index normally calculated on the basis of selected periods of time (typically 1, 2, 3, 6, 9, 12, 24 and 48 months of total precipitation) and indicates how the precipitation for a specific period compares with the complete record (possibly 25 or 50 or 100 years) at a given station. SPI at different time scales, e.g. 1- or 3-month SPI of a particular month represents deviation in precipitation totals for the same month and current plus previous two months, respectively. Positive values indicate greater than mean precipitation and negative values indicate less than mean precipitation. If the 1-month SPI for September 1987 is −2.00, then the precipitation is much less than normal compared to all other records of precipitation totals of September; and when the 1-month SPI for September is +1.00, then the precipitation for the same month is substantially above normal. When interpreting SPI, one should consider that dryness and wetness are relative to the historical average rather than the absolute total of precipitation of particular location. For example, a given magnitude of precipitation at a dry station such as Rajkot in Gujarat, supposedly produce negative SPI, whilst an extremely dry station (e.g. Bhuj) with the same magnitude of precipitation may show positive SPI values.

3.3. Data processing

The 3-month SPI was calculated for 164 rainfall stations using monthly rainfall data of the kharif crop-growing season (June–October) for the period of 1981–2003. The threshold for indicating severity of meteorological drought based on SPI has been adopted from the US Drought Mitigation Centre http://www.une.edu/~rowelett/units/scales/drought.html). The threshold representing 'No drought' category has been added to the existing drought severity classification table (Table I) for the reclassification of the SPI maps.

In earlier studies, SPI values were interpolated using ordinary krigging taking a grid size of 8 km. The krigging method reportedly provides optimal areal estimates both for drought and flood (Bonifacio and Grimes, 1998), but in the present work, interpolation by ordinary krigging did not give good results since no particular semi-variogram model parameters could be established due to the lower number of rain gauge stations. Therefore, the most commonly used method, inverse distance weighted (IDW), was chosen to interpolate the SPI values. IDW interpolation explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart. It means a rainfall or its derived quantity at any desired location is interpolated from the given data using weights that are based on the distance from each rainfall gauge and the desired location (Burrough and McDonnell, 1998). This approach produces a smooth surface of rainfall or its derivable along with the undesirable troughs and peaks. The interpolation of SPI datasets was performed by the IDW function in-built within ArcGIS v. 9.0 software.

The interpolated maps have thus been reclassified into different drought severity classes (Table I). Interpolated 3-month SPI of September months was reclassified because the 3-month SPI of September comprises the accumulated precipitation total of the rainfall received in July, August and September which is crucial to the major *kharif* crops in Gujarat. Further, the interpolated 3-month SPI of September for each of 20 years (1981–2000) was categorized into a binary mask of 1 (drought) and 0 (no drought) by using thresholds: an SPI value of −0.99 and below was assigned a value of 1, the rest were assigned a value of 0. The resultant maps were added to obtain frequency of drought occurrence over a period of 20 years (1981–2000) and, subsequently, to characterize drought risk to indicate highly drought-prone areas. Two model years for drought (1982 and 1987) as well as wet conditions (1987 and 1988) have been chosen to present

Table I. Drought severity classification (modified). Source: (US National Drought Mitigation Centre).

Category	Description	SPI
D0	No drought	> − 0.5
D1	Abnormally dry	−0.5 to −0.7
D2	Moderate drought	−0.8 to −1.2
D3	Severe drought	−1.3 to −1.5
D4	Extreme drought	−1.6 to −1.9
D5	Exceptional drought	−2 or less

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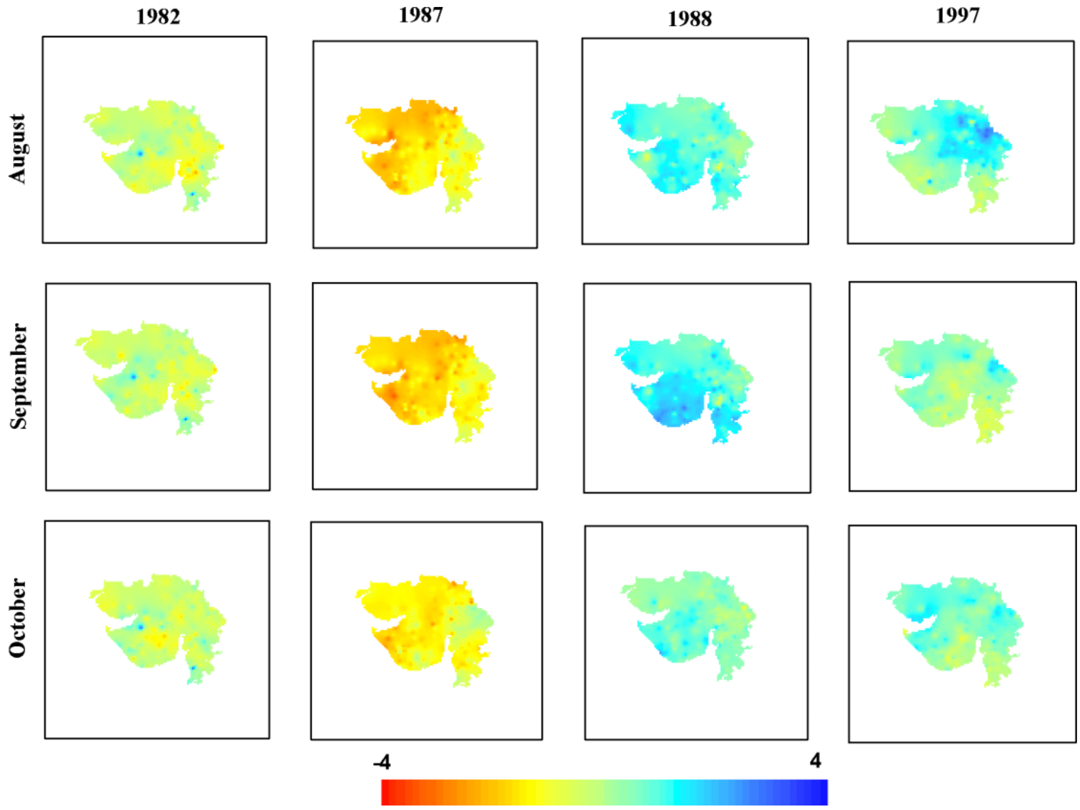

Figure 2. Spatial patterns of 3-month SPI over 3 months during drought (1982 and 1987) and wet (1988 and 1997) years. This figure is available in colour online at www.interscience.wiley.com/ma

the drought severity classes in these two different conditions.

3.4. De-trended yield anomaly

The de-trended yield anomaly (DYa) is computed as follows:

$$DYa_i = [\{(Ya_i/Yt_i) - 1\}100] \qquad (2)$$

where, DYa_i is the de-trended food grain yield anomaly for i^{th} year, and Ya_i and Yt_i are actual and time trend based yields ($Yt = a + b^*year$) of i^{th} year, respectively.

4. Results and discussion

4.1. SPI and drought

The interpolated maps of the SPI, for typical drought (1982 and 1987) and wet (1988 and 1997) years have been presented to show the pattern of SPI during these years (Figure 2). The 3-month SPI for the months of August, September and October show the temporal dynamics of below and above normal precipitation distribution in Gujarat. It can be seen that during the drought years of 1982 and 1987, negative SPI values noticed in western, central and southwestern Gujarat, which indicate that there was rainfall deficit in these areas during the southwest monsoon season, i.e. during June–September. In 1987, the spatial patterns of 3-month SPI across crucial months for kharif crops depicts negative SPI, with a majority of areas having an SPI value below −2.0. Thus, the spatio-temporal evolution of the SPI clearly indicates that 1987 was a severe drought year taking into account the magnitude, duration and extent of a negative SPI. The results are also in agreement with those reported earlier (Gore and Sinha Ray, 2002). However, during the normal years of 1988 and 1997 the observed 3-month SPI values across 3 months are mostly positive, and the maximum reached a value of 3, which shows that these years were wet years. The spatial pattern of 3-month SPI of September shows an explicitly more negative and positive SPI than other months during drought and wet years, respectively. This proves that the 3-month SPI of September accurately captured the deficiency or excess of precipitation for detecting seasonal drought in Gujarat.

Furthermore, graphically, the patterns of 3-month SPI of September for 164 rain stations in Gujarat (Figure 3) reveal that in 1987 the SPI dropped as low as −3.5 and most of the stations had 3-month SPI below −1.5. These results further indicate that 1987 was a more severe drought year than 1982 where the SPI dropped to −2 only for two stations. This indicates that 1982 was less severely drought affected than 1987. However, looking at the SPI patterns during the normal years, with the exception of a few stations the SPI values dominantly range between 0 and 2.0, indicating moderately wet conditions. The large negative values of the SPI experienced at a few stations might be caused by large intra-seasonal variation in rainfall patterns and low mean seasonal precipitation. Such problems often arise when applying the

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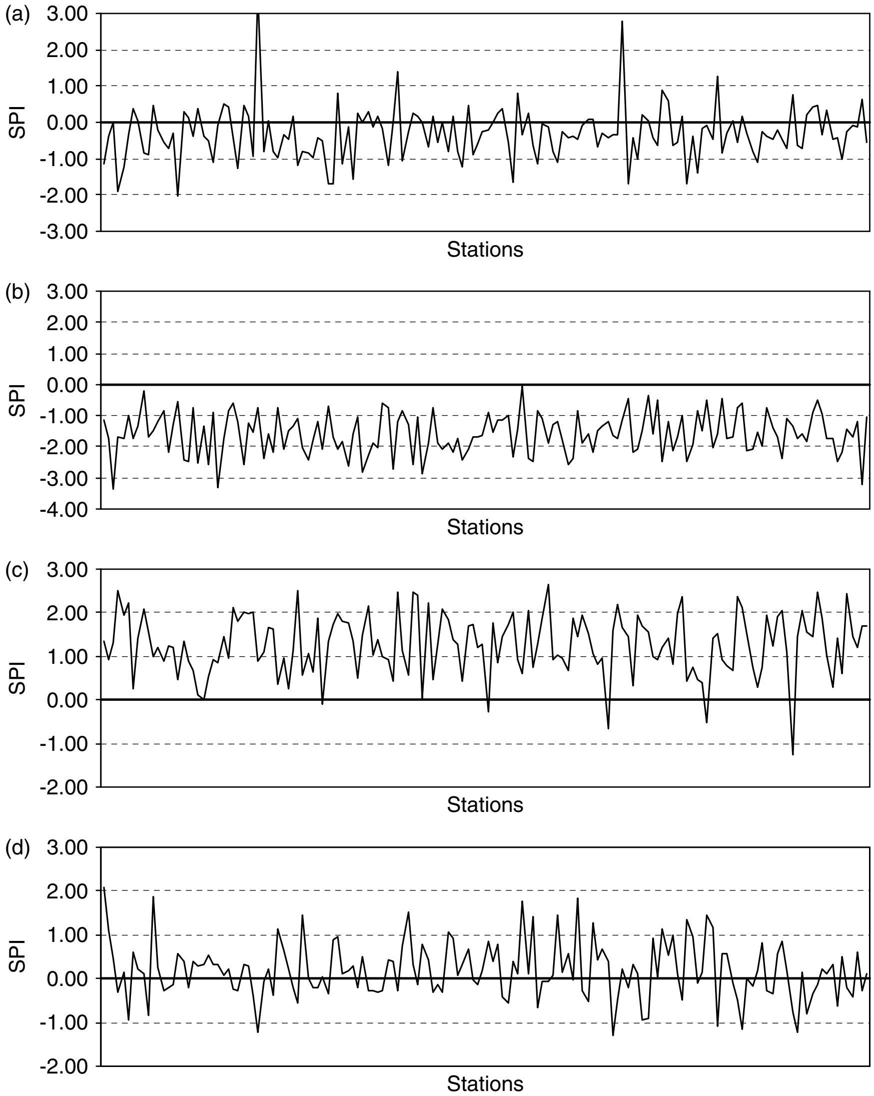

Figure 3. Three-month SPI for drought years (a) 1982 (b) 1987 and wet years (c) 1988 and (d) 1997.

SPI at short time scales (1, 2 or 3 months) to a region of low seasonal precipitation (Loukas *et al*., 2003). This is the limitation of the SPI at short-term scales, particularly in regions with low seasonal precipitation. The stations with the large negative SPI values, obtained during wet years, have mean seasonal rainfall less than 500 mm.

4.2. SPI and drought severity

The interpolated map of the 3-month SPI for the month of September was classified into severity classes (Table I) for selected years and presented in Figure 4. The classified maps show that 1982 had a drought up to class 3, indicating severe drought, whereas 1987 had extreme drought in western, parts of central and southwestern Gujarat. It is, therefore, inferred that the 3-month SPI for September is well suited to categorize the severity of seasonal drought in Gujarat, which receives the southwest monsoon rainfall. The usefulness of the SPI to characterize severity of seasonal and long-term drought is mainly attributed to an ability of the SPI to quantify dry spell and wet spell at multiple time scales. Many studies have also demonstrated that a short-term (3-month) SPI provides an indication of the seasonal anomaly in precipitation and thereby considered as an agricultural drought indicator (McKee *et al*., 1993; Hayes *et al*., 1999; Ji and Peters, 2003). Hence a 3-month SPI of September was used in the present work to quantify the severity of drought for selected drought and wet years.

4.3. SPI and food grain productivity

Apart from interpreting meteorological drought from the SPI, the effect of drought on agricultural production was also analysed. The 3-month SPI for September within each district was averaged by the area-weighting method. This area-weighted averaged 3-month SPI of each district was correlated against corresponding de-trended food grain anomaly (Table II) of Kharif season for 1981–2000 period. The results showed a significant positive relation between these 3-month SPIs and a de-trended food grain anomaly. This close association

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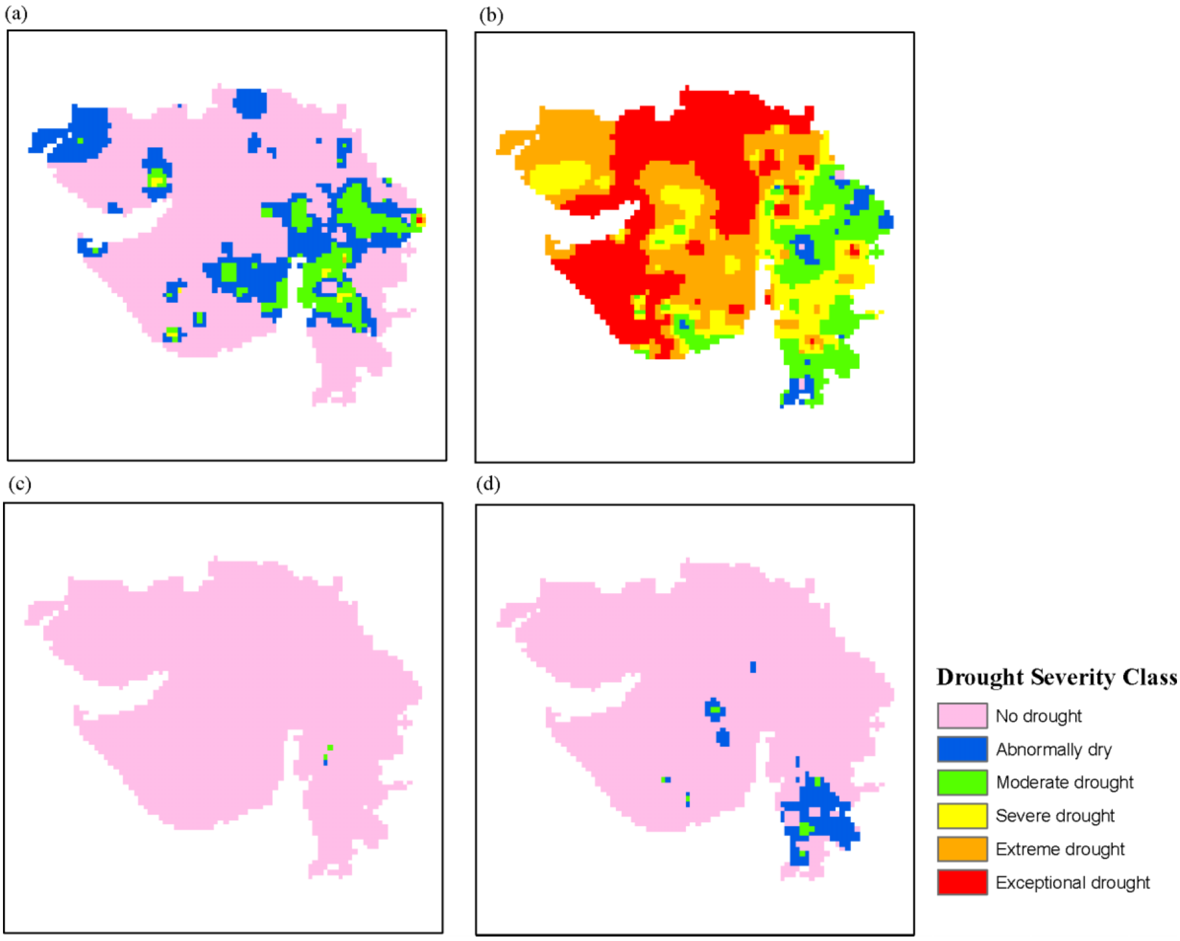

Figure 4. Drought severity for drought years (a) 1982 (b) 1987 and wet years (c) 1988 and (d) 1997. This figure is available in colour online at www.interscience.wiley.com/ma

Table II. Correlation between a 3-month SPI (September) and de-trended food grain anomaly.

Station number	Districts	Correlation coefficient
1	Ahmedabad	0.631**
2	Amreli	0.676**
3	Banaskantha	0.302
4	Bharuch	0.538**
5	Bhavnagar	0.631**
6	Gandhinagar	0.055
7	Jamnagar	0.725**
8	Junagadh	0.640**
9	Kuchchh	0.097
10	Kheda	0.317
11	Mahesana	0.334
12	Panchmahals	0.706**
13	Rajkot	0.655**
14	Sabarkantha	0.599**
15	Surat	0.356
16	Surendranagar	0.540**
17	The Dangs	0.344
18	Vadodara	0.666**
19	Valsad	0.361

** Indicates significant at 99% level.

reveals that the 3-month SPI for September could provide a strong signal about any departure in food grain productivity due to a meteorological seasonal drought. Districts such as Ahmedabad, Amreli, Bharuch, Bhavnagar, Jamnagar, Junagadh, Panchmahal, Rajkot, Sabarkantha and Surendranagar showed positive correlation with 3-month SPI values of September. Strong and significant correlation particularly in drought prone districts shows that the 3-month SPI could also help to assess, in advance, the decline in food grain production due to drought in these districts. These results are commensurate with those reported by Chaudhari and Dadhwal (2004), who have also observed strong agreement between a 3-month SPI and production of major *kharif* crops such as pearl millet in Rajasthan and groundnut in Gujarat.

4.4. Drought risk assessment based on the SPI

The 3-month SPI map of September for individual years provides information on the severity of seasonal drought only. However, the drought risk pertains to the vulnerability of a region to drought episodes, and is mainly evaluated by analysing the frequency of historical drought events (Wilhite, 2000). Therefore, all 20 years of the 3-month SPI for September were converted to binary images showing 1 and 0 values. The resulting 20

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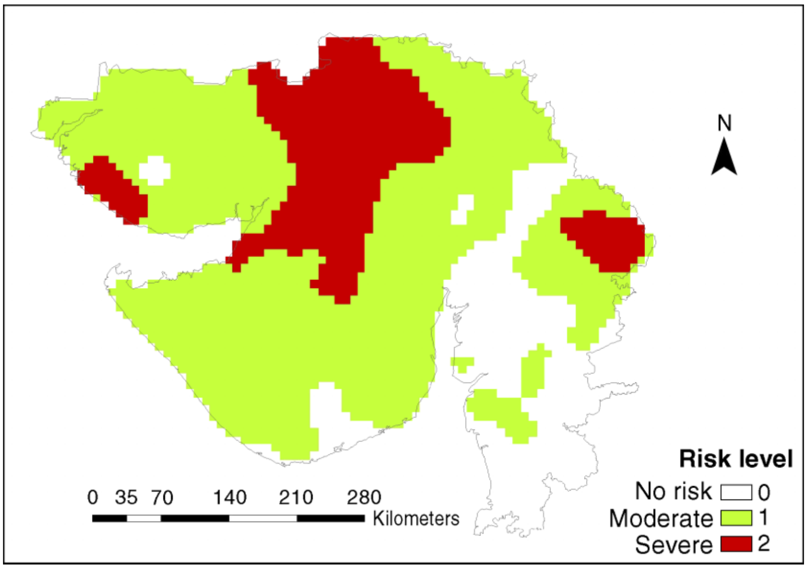

Figure 5. SPI-based meteorological drought risk. This figure is available in colour online at www.interscience.wiley.com/ma

binary masks were added together, yielding pixel values in the range of 0–6. These pixel values represent the frequency of seasonal drought occurrence. Those areas that were above the threshold throughout the 20 years were classified as no risk. Pixels that fall below the threshold for three and more years out of the 20 years were classified as moderate (1–3) and severe risks (4–6) respectively.

The pixel level frequency of drought occurrence resulted in merely three classes, i.e. no risk, moderate and severe (Figure 5), which does not represent the true picture of the seasonal drought occurrence in Gujarat over the period 1981–2000. Previous study of drought occurrence using percentages of normal rainfall for the period 1901–1999 showed that the western region comprising Kuchchh and Saurashtra are the most vulnerable to drought with decadal frequencies of 3–5 drought years (Gore and Sinha Ray, 2002). However, in the present study the same areas are classified as moderate risk (<3 drought years).

The results thus demonstrate that the 3-month SPI may not be a good indicator of drought risk or vulnerability and it is mainly attributed to longer time-scale, i.e. 3-months, and an insufficient number of years with monthly rainfall data used to calculate the SPI in this study. When the SPI time-scale increases, the frequency of dry periods decreases. Droughts have a different frequency according to the time-scale used for analysis. At shorter time scales dry and moist periods change with a high frequency. At the longest time scales the droughts are less frequent but their duration is higher (Vicente-Serrano and L'opez-Moreno, 2005). Hayes *et al*. (1999) have shown that for some regions a good rainfall for one month can create the impression that the drought is over but until the SPIs are not above a certain value at all scales (typically −1) a drought will still affect a region one way or another.

5. Conclusions

The present study explores the usefulness of the SPI to spatio-temporal variability in meteorological drought at seasonal scale in arid to semi-arid parts of India. The SPI at a 3-month time-scale was found effective in capturing seasonal drought patterns over space and time in Gujarat. This is evident from the unique ability of the SPI to categorize year 1987 as the worst drought in the last 20 years. Further, the present study concludes that the 3-month SPI of September is a good indicator of any anomaly associated with food grain production particularly in drought-prone areas. However, the 3-month SPI of September has not yielded a true picture of drought risk in Gujarat due to a longer time-scale and short period of rainfall data used to derive the SPI.

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