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AN EVALUATION OF THE STANDARDIZED PRECIPITATION INDEX, THE CHINA-Z INDEX AND THE STATISTICAL Z-SCORE

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ABSTRACT

The Standardized Precipitation Index (SPI) was developed to detect drought and wet periods at different time scales, an important characteristic that is not accomplished with typical drought indices. More and more users employ the SPI to monitor droughts. Although calculation of the SPI is easier than other drought indices, such as the Palmer Drought Index, it is still relatively complex. In China, an index called the China-Z Index (CZI) has been used since 1995 by the National Climate Centre of China to monitor moisture conditions across the country. The calculation of this index is easier than the SPI. A third index, the statistical Z-Score, can also be used to monitor droughts. This paper evaluates the SPI, CZI and Z-Score on 1-, 3-, 6-, 9- and 12-month time scales using monthly precipitation totals for four locations in China from January 1951 to December 1998 representing humid and arid climates, and cases of drought and flood. Advantages and disadvantages for the application of each index are compared. Study results indicate that the CZI and Z-Score can provide results similar to the SPI for all time scales, and that the calculations of the CZI and Z-Score are relatively easy compared with the SPI, possibly offering better tools to monitor moisture conditions. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: China; China-Z Index; drought; drought index; drought monitoring; precipitation; Standardized Precipitation Index; statistical Z-Score

1. INTRODUCTION

Droughts affect a large number of people worldwide and cause tremendous economic losses, environmental damage and social hardships. Yet, drought is the least understood of all weather phenomena (Obasi, 1994). They are difficult to define, detect and monitor (Wilhite, 2000). Scientists have developed various indices to monitor droughts (Palmer, 1965; Gibbs, 1987; McKee *et al*., 1993; Meyer *et al*., 1993). A drought index is useful if it provides a clear, simple and quantitative assessment of the major drought characteristics: intensity, duration and spatial extent (Hayes *et al*., 2000).

McKee *et al*. (1993) developed the Standardized Precipitation Index (SPI) to monitor the status of drought in Colorado. The National Drought Mitigation Center and the Western Regional Climate Center have also been using this index to monitor drought conditions in the United States (NDMC, 2000; WRCC, 2000). An advantage of the SPI is that it can monitor dry and wet periods over a wide spectrum of time scales from 1 to 72 months (Edwards and McKee, 1997; WRCC, 2000). Based on an analysis of the drought in the Southern Plains and the southwestern United States in the spring of 1996, Hayes *et al*. (1999) argued that the SPI is a more reliable index of developing drought conditions than the Palmer Drought Severity Index (PDSI) (Palmer, 1965). This conclusion is based on the responsiveness of the SPI to emerging precipitation deficits at shorter time scales (e.g. 3 months). Thus, the SPI recognizes moisture deficits more rapidly than the PDSI, which has a response time scale of approximately 8–12 months

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(Alley, 1984; McKee *et al*., 1995). The SPI is simpler than the PDSI in calculation and is more spatially consistent. It can be used, therefore, in risk and decision analyses, fitting a wide range of time scales of interest to the user (Guttman, 1998).

The China-Z Index (CZI) is a drought index (Ju *et al*., 1997) that was introduced to the National Meteorological Centre of China (NMCC) in the early 1990s. Unfortunately, the origin of the CZI cannot be easily documented. This index is called the 'China-Z Index' in this paper in order to avoid confusion with the Z-Index that is a part of the PDSI. Since the National Climate Centre of China (NCC) was established in 1995 as a partner agency to the NMCC with the China Meteorological Administration (CMA, 2000), it has been using the CZI at a 1-month time scale as the principal index to monitor drought and flood conditions in China.

The statistical Z-Score, or Standard Score, can be used as another drought index. The Z-Score is actually a part of the CZI. Sometimes, the Z-Score is confused with the SPI by the user (Hayes, 2000).

In this study, we compared and evaluated the SPI, CZI and Z-Score for multiple time scales in two climate regions: arid and humid; and in two extreme cases: a severe drought and a disastrous flood. Four locations in China were selected: Urumqi, Fuzhou, Beijing and Wuhan (Figure 1). Urumqi in northwestern China has an arid climate with an annual mean precipitation of 243 mm. Fuzhou in southern China has a humid climate with an annual mean precipitation of 1351 mm. The drought case study was in north-central China in 1972, causing a 3–5 m decline in the mean groundwater level in the Beijing area (Li *et al*., 2000). The flood case was in the summer of 1998, affecting Wuhan and lower Yangtze River Valley. The flood was the worst in the last 44 years, affecting 240 million people and damaging 25 million hectares of farmland. Total damages were estimated to exceed US$ 20 billion (CNN, 1998).

2. BACKGROUND OF THE INDICES

2.1. The SPI

In brief, computing the SPI begins with building a frequency distribution from precipitation data at a location for a specified time period. A gamma probability density function is fitted to the precipitation data and the cumulative distribution of precipitation is determined. An equiprobability transformation is then made from the cumulative distribution to the standard normal distribution with a mean of zero and variance of one (Figure 2). This transformed probability is the SPI value, which varies between $+2.0$ and -2.0, with extremes outside this range occurring 5% of the time (Edwards and McKee, 1997). Calculation of the SPI requires that there is no missing data in the time series. The data record length is required to be at least 30 years. Guttman (1999) tested different probability models from which the SPI values are computed and found that the Pearson Type III distribution best fits precipitation data.

One of the strengths of the SPI is that users can choose the time scale most appropriate for their particular application to compute the SPI. The SPI can be computed for any time period from 1, 2, 3, ..., 48, ..., to 72 months (Edwards and McKee, 1997). For example, agricultural users may be interested in shorter time periods, such as the SPI for 3 or 6 months, while hydrologists or water managers might be more interested in SPI values for 12 or 24 months.

2.2. The CZI

The CZI is related to the Wilson–Hilferty cube-root transformation (Kendall and Stuart, 1977).

Assuming that precipitation data obey the Pearson Type III distribution, the CZI is calculated as

$$Z_{ij} = \frac{6}{C_{si}}\left(\frac{C_{si}}{2}\varphi_{ij} + 1\right)^{1/3} - \frac{6}{C_{si}} + \frac{C_{si}}{6}, \tag{1}$$

where Z_{ij} is the CZI, i is the time scale of interest, which can be equal to 1, 2, 3, ..., 72 months, and j is the current month. In the CZI used by the NCC, the parameter i is not used because only Z values for

Figure 1. Map of China with the four locations

a 1-month time scale are computed. In this study, we expand the CZI to include these multiple time scales. In Equation (1),

$$C_{si} = \frac{\sum_{j=1}^{n} (x_{ij} - \bar{x}_i)^3}{n^* \sigma_i^3}, \tag{2}$$

where C_{si} = coefficient of skewness and n = the total number of months in the record,

$$\varphi_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i}, \tag{3}$$

where φ_{ij} = standardized variate, also called the Z-Score, and x_{ij} = precipitation of j month for period i,

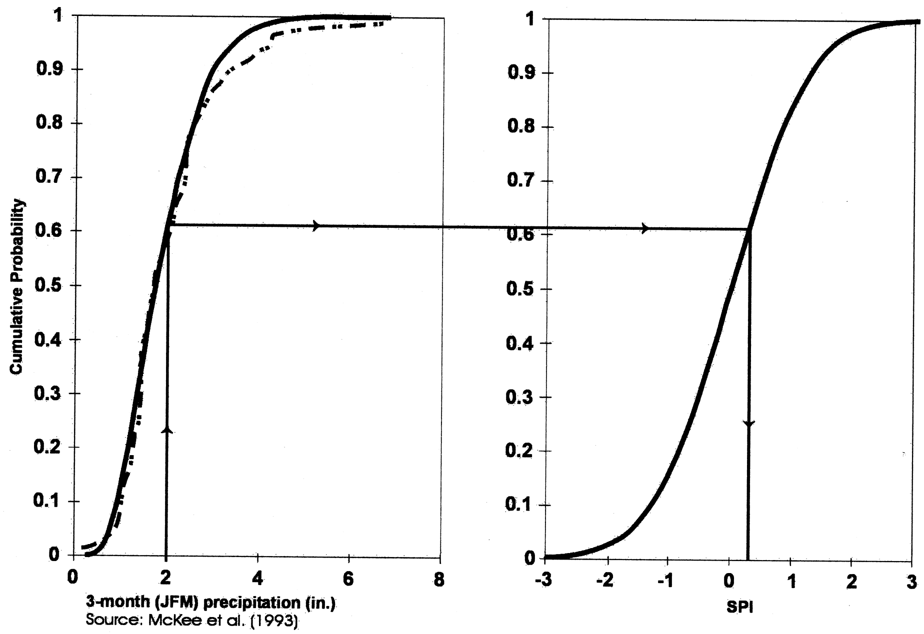

Figure 2. SPI equiprobability transformation. In this example, a 3-month precipitation total for January–March of 2.0 in. has a cumulative probability of 0.59. This is transformed with the Gamma distribution and converted to the normal distribution (0.61). This corresponds to a 3-month SPI of approximately +0.25

$$\sigma_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i)^2}, \tag{4}$$

and

$$\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n} x_{ij}. \tag{5}$$

The CZI allows for missing data in the precipitation time series by excluding the missing values in its calculations.

2.3. Z-Score

Equation (3) in the CZI calculation procedure is used to calculate the Z-Score (Triola, 1995a). The Z-Score does not require adjusting the data by fitting the data to the Gamma or Pearson Type III distributions. Because of this, it is speculated that Z-Score might not represent the shorter time scales as well as the SPI (Edwards and McKee, 1997).

3. DATA AND METHODS

The data used in this study are monthly precipitation totals from January 1951 to December 1998 at four stations: Urumqi, Fuzhou, Beijing and Wuhan (Figure 1). The data were obtained from the NMCC. There are no missing data in the time series.

The SPI, CZI and Z-Score were calculated and compared for five time scales: 1, 3, 6, 9 and 12 months similar to the series of drought watch maps issued monthly by the National Drought Mitigation Center for the United States (NDMC, 2000). Positive values of the SPI, CZI or Z-Score indicate a wet event, negative values a dry event.

Linear regressions between the SPI, CZI and Z-Score from 1951 to 1998 were obtained for Urumqi and Fuzhou to compare the three indices for the five time scales in arid and humid climate regions. The SPI, CZI and Z-Score were also calculated for the five time scales for Beijing from 1971 to 1973 and for Wuhan from 1997 to 1998. To quantify the comparison results, the Pearson correlation coefficients (r) for the SPI versus the CZI, and the SPI versus the Z-Score were computed for the four locations. To inspect the relationships between the three indices in different moisture conditions, r values were computed in three groups: all events, wet events and dry events, respectively. No matter what the sign of either the CZI or the Z-Score, it is classified as a wet event only if the value of the SPI is positive. In the same manner, it is a dry event only if the SPI is negative.

4. RESULTS

Linear regressions between the values of the SPI and CZI from 1951 to 1998 (Figure 3(a)–(d)) indicate that the SPI and CZI generally have a good relationship for the time scales of 3 and 12 months for Urumqi and Fuzhou. At other time scales we found similar strong relationships. The exception is the 3-month time scale at very dry conditions: the CZI can express very dry conditions that do not show in the SPI. For example, in Figure 3(a) for Urumqi, the point farthest off the regression line has an SPI value of -1.69, but CZI value -4.60. The same discrepancy was observed in Figure 3(c) for Fuzhou. The 12-month comparison for Fuzhou (Figure 3(d)) also shows that the CZI tends to have larger negative values in drier conditions. For example, CZI values fall between -4.0 and -6.0 when corresponding SPI values are between -2.0 and -3.0.

Compared with the relationship between the SPI and CZI, the SPI has a closer correlation with the Z-Score. However, the scatter diagrams of the SPI versus the Z-Score in Figure 4 show that the Z-Score generally appears more positive (or wetter) than the SPI in both extremely wet and dry conditions. For example, when the SPI is -3.03, the corresponding Z-Score is -1.71 and when the SPI is $+2.84$ the corresponding Z-Score is $+3.79$ (Figure 4(a)).

The SPI, CZI and Z-Score were calculated for 1-, 3-, 6-, 9- and 12-month time scales for Beijing during a drought that lasted from 1971 to 1973 to evaluate the indices in representing this drought (Figure 5(a)–(e)). All three indices at 9 and 12 months show that mid 1972 to early 1973 was a dry period. The CZI indicates a more severe drought than either the SPI or Z-Score. The maximum negative value of the 12-month CZI is -2.1 for August 1972, while the SPI and Z-Score for the same month are -1.6 and -1.3, respectively. Throughout the drought from the summer of 1972 to the summer of 1973, the Z-Score is the least sensitive and the CZI the most sensitive to the meteorological conditions at the 12-month time scale. The indices at 1- and 3-month scales actually show that the 1972–1973 drought was a series of severe dry events with short wet and normal periods sandwiched in between. This result is not surprising, and it supports the statement that: 'the frequency, duration and intensity of drought at any particular point are dependent upon time scale (McKee *et al.*, 1993).

The three indices were also calculated for Wuhan in 1997 and 1998 to investigate the relationship between the indices during a flood event that occurred in that region (Figure 6(a)–(e)). These three indices are very similar at the five time scales. The 1- and 3-month indices show that a series of several short-term wet periods occurred during 1998 in Wuhan with some intermittent periods with normal rainfall. The indices clearly indicate that the second half of 1998 was very wet for the 6-, 9- and 12-month time scales. In April 1998, the peak value of the Z-Score for the 6-month period was $+2.6$ when the corresponding SPI and CZI values were $+1.9$ and $+2.1$, respectively, indicating that the Z-Score reveals a wetter event than the other two indices suggested.

The values of Pearson correlation coefficients (r) between the SPI and CZI, and the SPI and Z-Score, for both Urumqi and Fuzhou are shown in Table I. The ranges of the correlation coefficients generally increased with time scale and ranged from 0.813 to 0.987 for the 1-month time scale, from 0.832 to 0.991 for 3 months, 0.886 to 0.994 for 6 months, 0.877 to 0.997 for 9 months, and from 0.919 to 0.999 for 12 months. These results show that the SPI is highly correlated with both the CZI and Z-Score at all five time scales. In addition, in wet events these indices have a higher correlation than in dry events.

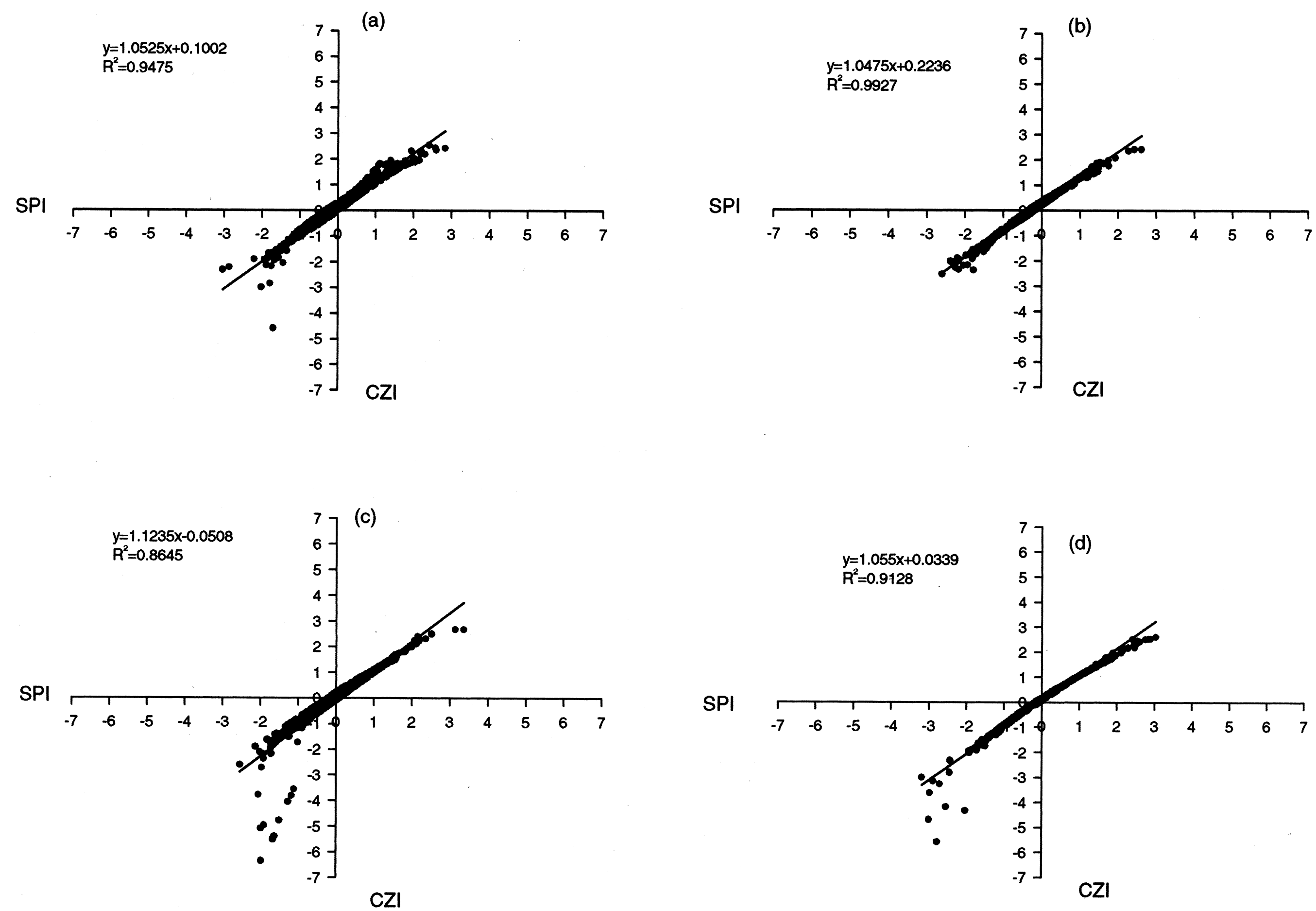

Figure 3. Scatter diagrams of the SPI and CZI for Urumqi and Fuzhou from 1951 to 1998. The abscissa denotes the SPI values and ordinate denotes the CZI values. Positive values indicate wetter than normal, negative values drier than normal: (a) 3-month SPI vs CZI for Urumqi; (b) 12-month SPI vs CZI for Urumqi; (c) 3-month SPI vs CZI for Fuzhou; (d) 12-month SPI vs CZI for Fuzhou

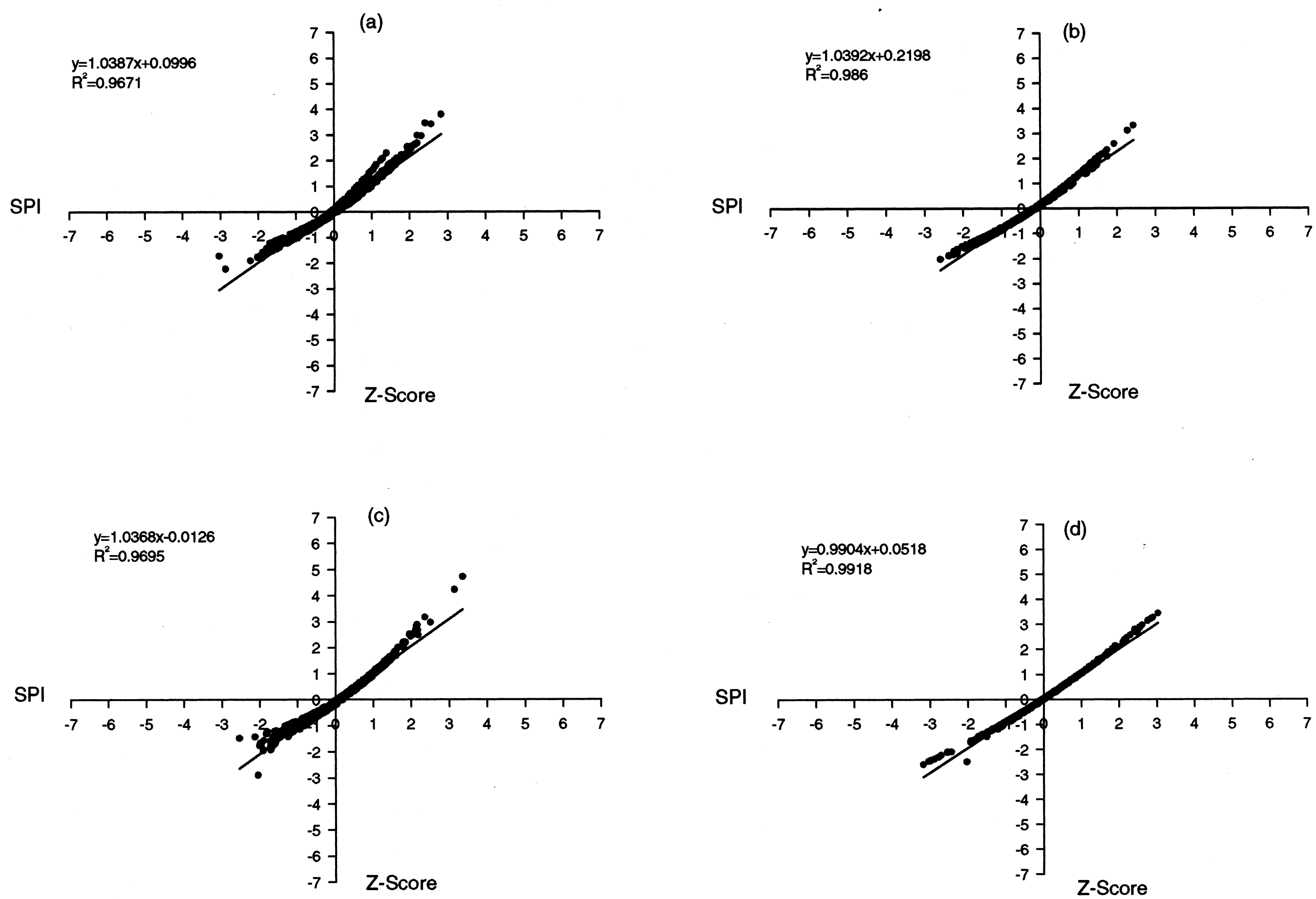

Figure 4. Scatter diagrams of the SPI and Z-Score for Urumqi and Fuzhou from 1951 to 1998. The abscissa denotes the SPI values and ordinate denotes the Z-Score values. Positive values indicate wetter than normal, negative values drier than normal: (a) 3-month SPI vs Z-Score for Urumqi; (b) 12-month SPI vs Z-Score for Urumqi; (c) 3-month SPI vs Z-Score for Fuzhou; (d) 12-month SPI vs Z-Score for Fuzhou

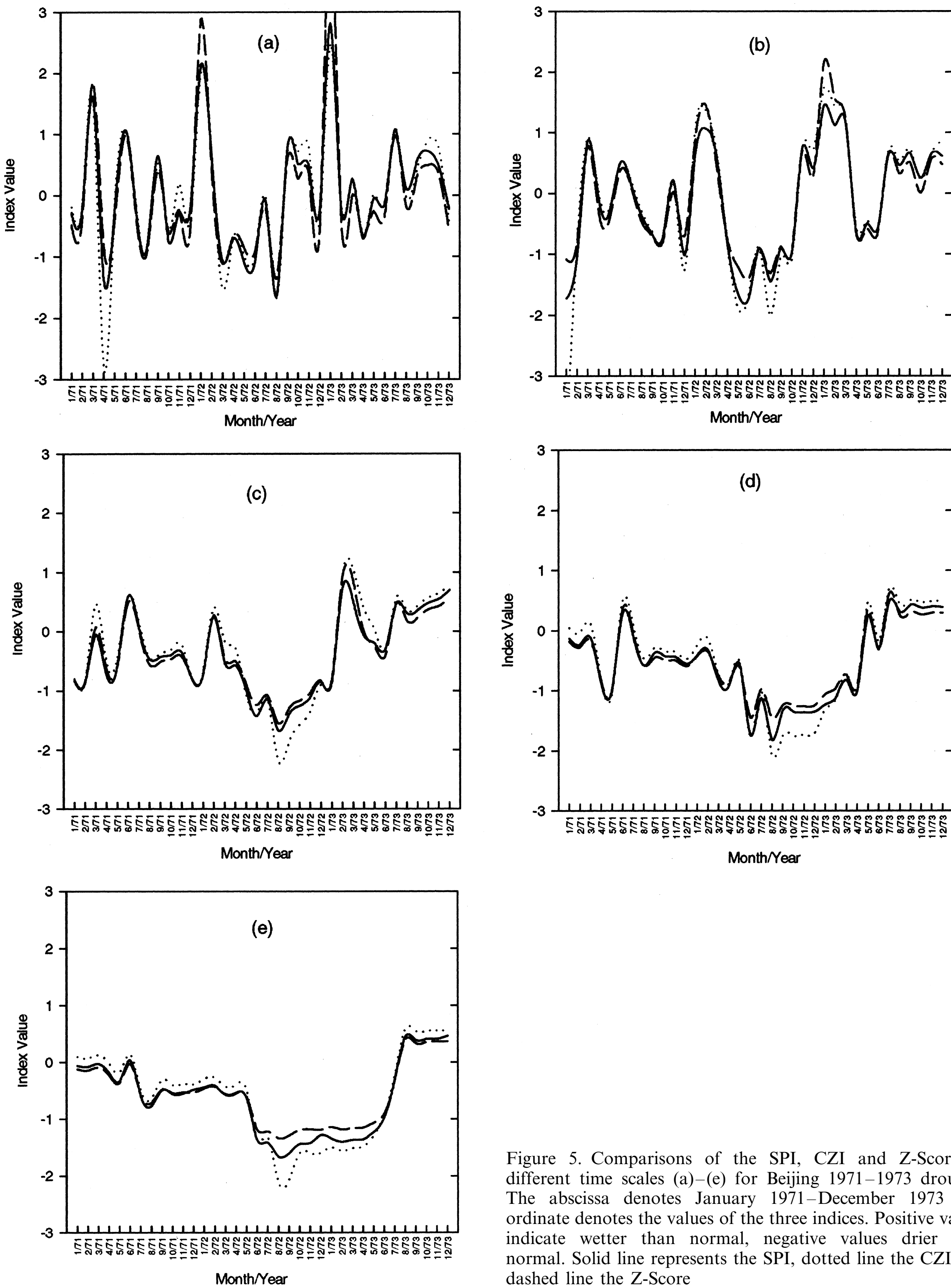

Figure 5. Comparisons of the SPI, CZI and Z-Score at different time scales (a)–(e) for Beijing 1971–1973 drought. The abscissa denotes January 1971–December 1973 and ordinate denotes the values of the three indices. Positive values indicate wetter than normal, negative values drier than normal. Solid line represents the SPI, dotted line the CZI and dashed line the Z-Score

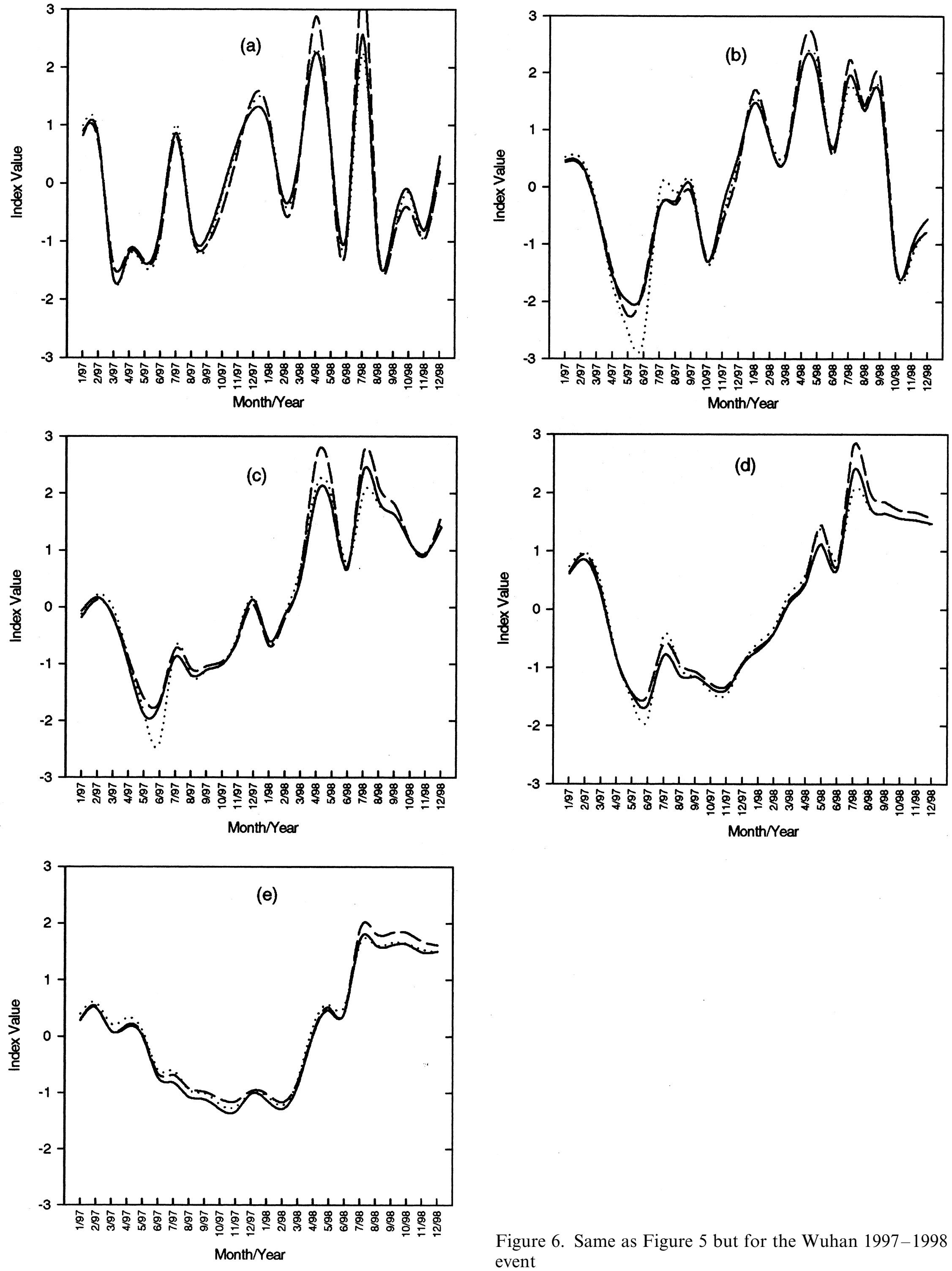

Figure 6. Same as Figure 5 but for the Wuhan 1997–1998 wet event

Table I. Pearson correlation coefficients (r) of the SPI vs CZI and the SPI vs Z-Score

Location	Event	Cases	1-Month	3-Month	6-Month	9-Month	12-Month
Fuzhou	All	SPI vs CZI	0.970	0.93	0.942	0.933	0.955
		SPI vs Z-Score	0.965	0.985	0.99	0.993	0.996
	Wet	SPI vs CZI	0.984	0.991	0.993	0.996	0.995
		SPI vs Z-Score	0.987	0.988	0.994	0.997	0.999
	Dry	SPI vs CZI	0.848	0.832	0.886	0.877	0.919
		SPI vs Z-Score	0.917	0.969	0.983	0.989	0.997
Urumqi	All	SPI vs CZI	0.946	0.973	0.979	0.97	0.996
		SPI vs Z-Score	0.968	0.983	0.989	0.99	0.993
	Wet	SPI vs CZI	0.977	0.975	0.98	0.975	0.986
		SPI vs Z-Score	0.987	0.983	0.991	0.991	0.998
	Dry	SPI vs CZI	0.813	0.923	0.941	0.922	0.979
		SPI vs Z-Score	0.938	0.985	0.994	0.995	0.996

Fuzhou represents a humid climate. Urumqi represents an arid climate.
In the 'Event' column, 'All' indicates normal, dry and wet conditions; 'Wet' indicates events whose SPI values are positive and 'Dry' indicates whose SPI values are negative. The fourth to eighth columns show r values at indicated time scales.

5. DISCUSSION

A closer investigation of the differences between the indices is necessary. For very dry conditions, large differences existed between the SPI and CZI. The CZI had larger negative values indicating very dry conditions compared to the SPI. For example, the 6-month SPI for May 1996 for Beijing was -1.52 when the precipitation was 30% of the mean, while the corresponding CZI reached -4.28. The value of the CZI is positively correlated with the term $((C_{si}/2)\varphi_{ij}+1)$ in Equation (1) when C_{si} is greater than zero, and is negatively correlated with $((C_{si}/2)\varphi_{ij}+1)$ when C_{si} is less than zero. Large negative values of CZI will also result when$((C_{si}/2)\varphi_{ij}+1)$ is negative ($C_{si}>0$), or when $((C_{si}/2)\varphi_{ij}+1)$ is positively large ($C_{si}<0$). This situation occurs when the standardized variate φ_{ij}, takes on a large negative value, which results when the actual precipitation for a specified time period is much smaller than the mean value for the same time period.

The median precipitation was used in place of the mean precipitation in the calculation of the CZI, which is now called the Modified CZI (MCZI), attempting to reduce the differences between the SPI and MCZI. However, it was found that the differences between the SPI and MCZI changed in two ways. By using the median precipitation instead of the mean precipitation, the differences in the values of the SPI and MCZI will decrease if the value of the term$((C_{si}/2)\varphi_{ij}+1)$ increases when C_{si} is greater than zero, or decreases when C_{si} is less than zero. For instance, the 1-month SPI in January 1963 for Fuzhou is -1.97, the CZI is -3.78 and the MCZI is -1.90. In this example, for the SPI, $((C_{si}/2)\varphi_{ij}+1)$ was –0.03 and C_{si} was 1.92, while for the MCZI, the same parameters had values of 0.0018 and 2.31. On the other hand, the differences between the values of the SPI and MCZI will increase if the value of $((C_{si}/2)\varphi_{ij}+1)$ decreases when C_{si} is greater than zero, or increases when C_{si} is less than zero. For instance, the 9-month SPI in August 1962 for Urumqi is -2.43, CZI is -3.39 and MCZI is -5.71. In this example, for the SPI, $((C_{si}/2)\varphi_{ij}+1)$ was 0.0363 and C_{si} was 1.12, while for the MCZI, the same parameters had values of -0.0081 and 1.22. Overall, the differences between the SPI and MCZI will not be reduced significantly compared with the differences between the SPI and CZI when using the median instead of the mean precipitation.

The SPI and CZI calculated in this study are distributed normally as stated in the assumptions associated with these relationships. The CZI decreased to values of -3 or lower, as the distribution frequency of the CZI increased. In other words, the left tail of the CZI distribution curve shifted away from the normal curve (Figure 7), creating the observed increasing differences between the SPI and CZI in extremely dry conditions.

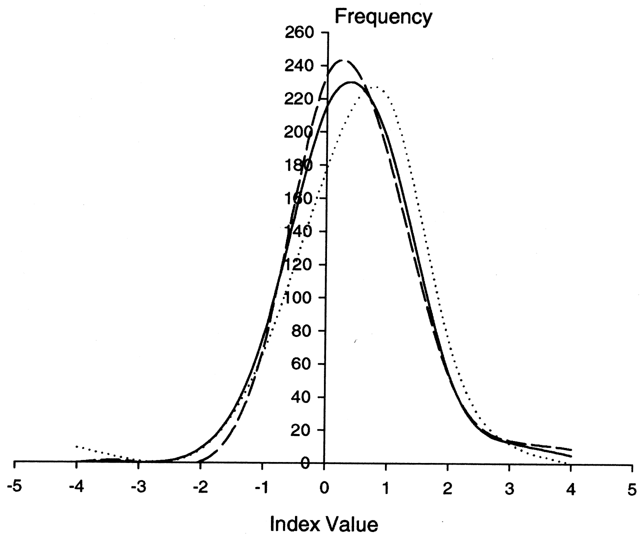

Figure 7. Frequency distribution of the three indices at the 9-month time scale for Beijing from 1951 to 1998. Solid line represents the SPI, dotted line the CZI and dashed line the Z-Score

Considering that the relationships among the values of the SPI, CZI and Z-Score may not be linear, the Spearman's rank correlation coefficient (Triola, 1995b) was computed in addition to the Pearson correlation coefficient (r). Each value of the SPI, CZI and Z-Score are replaced by its corresponding rank among all the values, and then the linear correlation coefficients of these ranks are computed. As can be seen from Figures 8 and 9, the discrepancies in the extreme values found in Figures 3 and 4 are removed by using the rank correlation coefficient. This result gives confidence that all three indices consistently represent dry and wet events.

6. CONCLUSIONS

This study shows that the SPI, CZI and Z-Score are good tools to define, detect and monitor droughts and floods. It was found that the CZI can be developed over a wide range of time scales rather than only on the 1-month time scale to monitor drought and flood. The versatility of the SPI, CZI and Z-Score allows for the monitoring of water resources or precipitation anomalies at different time scales. Further, they are simpler than PDSI and they are derived solely from precipitation data.

The CZI and Z-Score are very similar to the SPI for 1-, 3-, 6-, 9- and 12-month time scales. The major advantages of the CZI and Z-Score against the SPI are that the calculations of these two indices are simpler than the SPI and both indices allow for missing data. This flexibility is particularly important for regions where weather data are often incomplete.

The CZI is more responsive to precipitation deficits than the other two indices in extremely dry conditions. When the actual precipitation is much lower than the mean precipitation for a period, the CZI could reach large negative values compared to the other two indices. The Z-Score, on the other hand, has a wet bias compared to the other two indices in extreme wet and dry conditions, and may not detect serious drought conditions. However, from the view of the rank correlation coefficient, all three indices can provide consistent results in dry and wet events.

Except in extremely dry or wet conditions, the CZI and Z-Score provide the same measure of conditions as the SPI. In certain situations, the CZI and Z-Score can be considered more appropriate tools for monitoring droughts and floods than the SPI because they are easier to calculate.

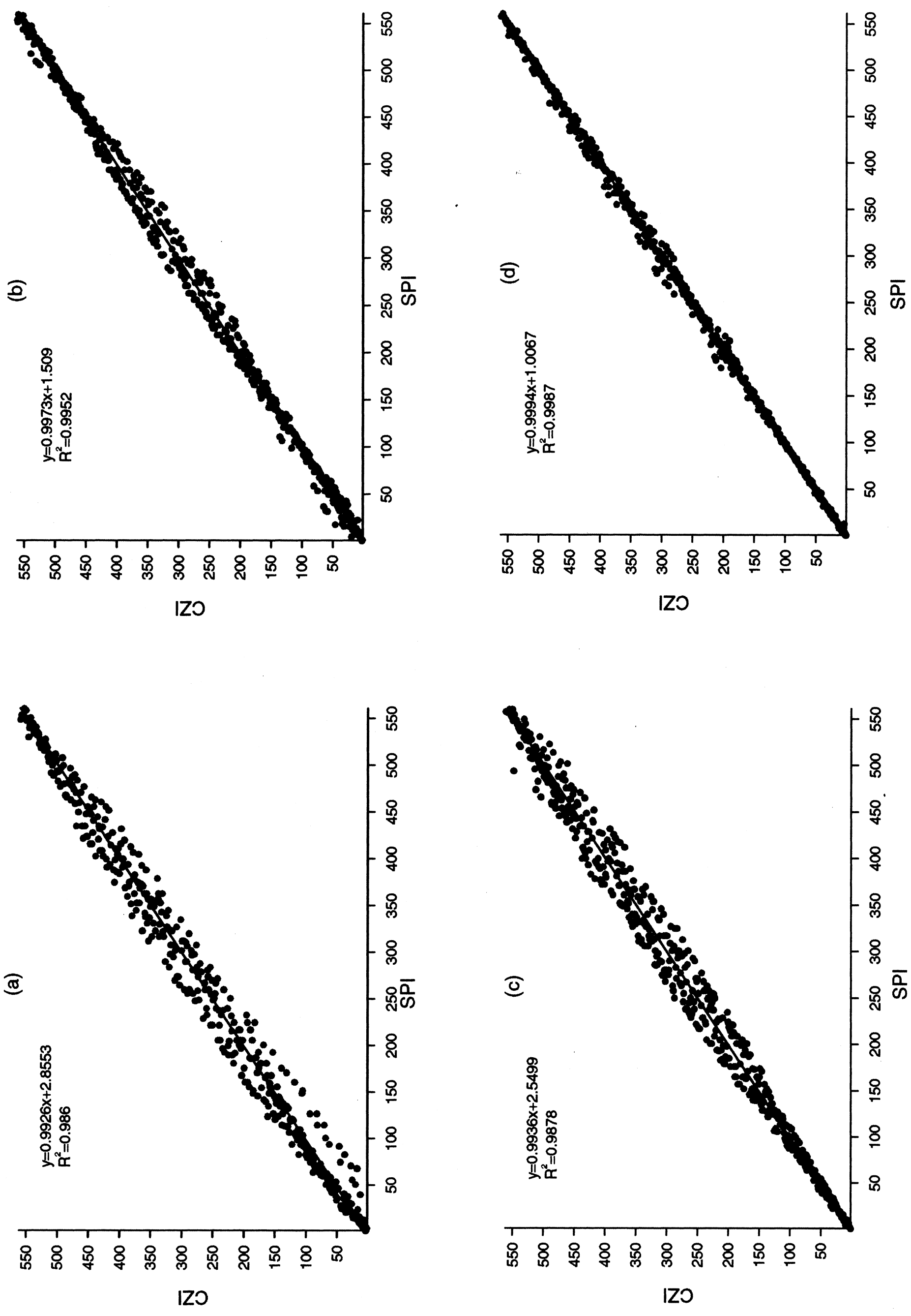

Figure 8. Same as Figure 3 but for the ranks of the SPI and CZI

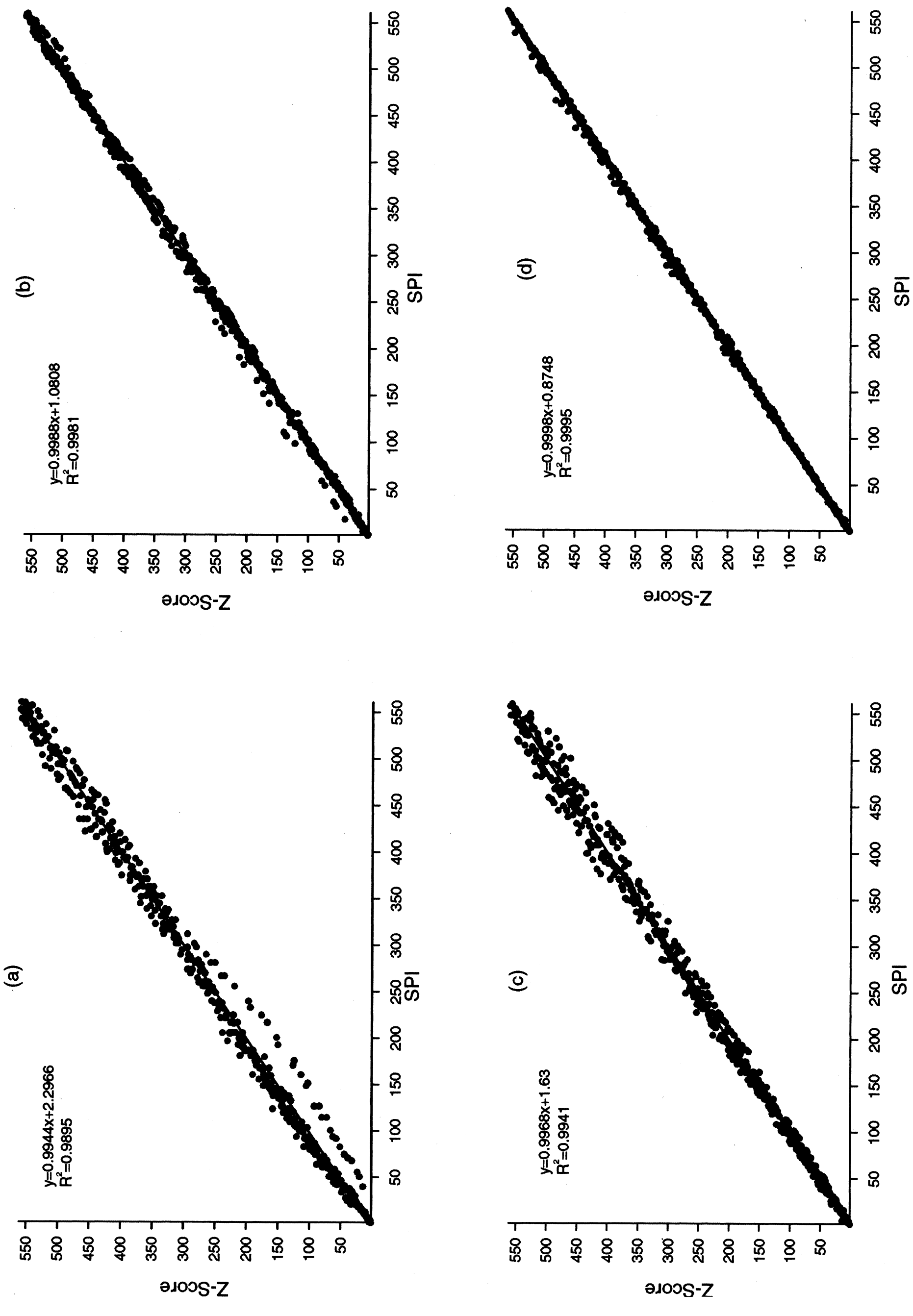

Figure 9. Same as Figure 4 but for the ranks of the SPI and Z-Score

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