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ORIGINAL PAPER

Climate extreme and its linkage to regional drought over Idaho, USA

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Abstract To investigate consequences of climate extreme and variability on agriculture and regional water resource, twenty-seven climatic indices of temperature and precipitation over Idaho, USA, were computed. Precipitation, mean temperature and maximum temperature, self-calibrated Palmer Drought Index and Standardized Precipitation Index for 1-, 3-, 6- and 12-month time scales were used to identify spatial and temporal distribution of climatic extreme and variability as well as drought frequency and magnitude. Seven oceanic indices were also used to detect teleconnections between climatic indices and regional droughts. The analyses were conducted for 56 meteorological stations, during 1962–2008, characterized by a long-term and high-quality data set. The result indicates that decreasing trends and increasing trends are identified for precipitation and temperature, respectively. Consequently, it appears that frost and ice days dwindle as growing season (May–August) length, tropical nights and summer days increase. Given current climate conditions, the results also imply that these trends will continue in the future possibly driven by uncertain climate variability. We anticipate that these indices explained by teleconnections will improve drought-forecasting capability in this region.

Keywords Climate change · Climatic indices · Drought · Climate extreme

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1 Introduction

Climate extremes have been defined by World Meteorological Organization (WMO) as infrequent meteorological and climatological phenomena that surpass a defined threshold (Das et al. 2003). Such extremes have profound impacts on human societies (Zhang, et al. 2005) and lead to hundreds of injuries and fatalities, and billions of dollars of economic losses. For instance, a flood in Central and Eastern Europe in August 2002 was responsible for 21.1 billion Euro in economic losses and over 100 fatalities (Munich 2002). Likewise, recent droughts in United States claimed significant economic impacts. It was estimated by the National Drought Mitigation Center at the University of Nebraska that more than 1.3 billion dollars in crop losses occurred due to the 2007 drought in the southeastern United States (Manuel 2008). Understanding the mechanisms associated with extreme events at the regional scale could provide useful insights for resource planners, system managers and policy makers to help mitigate these losses. Recent studies have shown changes in the frequency and intensity of weather extremes over the past century (Alexander et al. 2006; Dos Santos et al. 2010; Frei and Schar 2001; Frich et al. 2002; Kiktev et al. 2003; Moberg et al. 2005; Sen Roy and Balling 2004; Wong et al. 2010). In fact, the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) jointly sponsored by the CCI/CLIVAR project of the World Climate Research Programme (WCRP) is now coordinating a series of regional workshops, where local scientists are supported to conduct the quality control and scientific analysis of daily temperature and precipitation data (Aguilar et al. 2005; Easterling et al. 2003; Haylock et al. 2006; Manton et al. 2001; New et al. 2006; Peterson et al. 2002; Peterson 2005; Vincent et al. 2005; Zhang et al. 2005). Dedicated to this effort, Meehl and his colleagues reported increases in precipitation intensity which do not have uniform spatial distribution (Meehl et al. 2005). Since 1950, minimum and maximum temperature have also increased considerably over the Northern Hemisphere (Christidis et al. 2005), which imply that changes in the intensity of the extreme events, such as drought, are becoming more severe.

There is no universally accepted definition of drought, as drought indicators vary across climate regions, industries and spatial and temporal scales (Keyantash and Dracup 2002). Drought can be defined in different ways for different foci, for example, meteorological, agricultural and hydrological drought, all of which assess the relative dryness or wetness of geographic areas. Meteorological droughts are usually defined as the current precipitation's departure from the average precipitation recorded over a specific period of time, agricultural drought is defined as a deficiency in soil moisture that cannot meet a particular crop's requirement at a specific time and hydrological drought is defined as a shortage of surface and subsurface water supplies, respectively (IDWR 2001). Drought studies have been calculated primarily by applying the Palmer drought severity index (PDSI; Palmer 1965), which is based on a soil–water balance equation, or the standardized precipitation index (SPI; McKee et al. 1993) that is based on a precipitation probabilistic approach. Although onset, duration, magnitude and termination of drought depend on precipitation (Heim 2002), temperature can also contribute to the condition of drought. As the PDSI incorporates temperature in determining moisture demand (i.e., evapotranspiration), it is hypothesized to provide an autoregressive measure of combining precipitation, evapotranspiration and soil moisture conditions.

Given the considerable economic and agricultural damages that can occur due to climatic extremes, trends detection in precipitation and temperature along with drought indicators can provide useful insights for water decision makers to mitigate potential drought by taking beneficial measurements in advance. As such, this paper assesses the potential change in extreme drought conditions throughout the state of Idaho by analyzing temporal trends in meteorological data sets during 1962–2008. Additionally, teleconnections between oceanic indices and regional drought have been identified as potential predictors for climate extremes over Idaho. This paper is organized as follows: a methodology for data analysis and a brief description of the study area are first provided in the next section. Then, the results and a brief discussion are followed by the conclusions from this research.

2 Methodology

2.1 Study area, data and quality control

This study was conducted for 56 meteorological stations in Idaho, for the period 1962–2008, characterized by a long-term and high-quality data set. As shown in Table 1, all the stations have less than 10 % missing value in climatic parameters, including precipitation, minimum and maximum temperature. Figure 1 shows the spatial distribution of stations and the Digital Elevation Model (DEM) with 1 arc-second resolution (available at http://seamless.usgs.gov accessed July 2011). The altitude of the meteorological stations varies from 437.7 (Lewiston Nez Perce Co Airport at Station 10) to 1917 meters (Island Park at Station 51) (Fig. 1).

Daily precipitation, maximum and minimum temperature obtained from National Climatic Data Center (NCDC) were used to calculate monthly PDSI and SPI. To detect errors, missing values and outliers, quality control analyses were performed mainly using RClimDex (available at http://cccma.seos.uvic.ca/ETCCDMI/software.shtml; Zhang and Yang 2004). To conduct data quality control, this software computes indices using the following standard procedure (Zhang and Yang 2004; Alexander et al. 2006): (1) negative precipitation values are changed to missing values (NA); (2) maximum temperature equal to or less than minimum temperature is removed from the data set; and (3) outlier data are determined as those data having values outside the predefined range of mean $\pm (n \times \mathrm{SD})$, where n is defined by users (in this study, 3.5 was used for n) (Alexander et al. 2006).

The Available Water Capacity (AWC), an important parameter in computing PDSI, was obtained from Soil Information for Environmental Modeling and Ecosystem Management website (http://www.soilinfo.psu.edu accessed June, 2011), and 100 cm of soil depth for AWC was used. The oceanic indices, including Atlantic Multidecadal Oscillation (AMO), East Pacific/North Pacific oscillation (EP-NP), Northern Oscillation Index (NOI), North Pacific pattern (NP), Oceanic Nino Index (ONI), Pacific Decadal Oscillation (PDO) and Pacific North American Index (PNA) were obtain from the National Oceanic Atmospheric Administration website at http://www.esrl.noaa.gov (Accessed February 5, 2012).

2.2 Analysis

After data quality and control processes, 16 temperature and 11 precipitation indices listed in Tables 2 and 3, respectively, were computed using the RClimDex, which has been widely used in many previous applications (Alexander et al. 2006; Dos Santos et al. 2010; Haylock et al. 2006; Marofi et al. 2010; Zhang et al. 2005). In addition, the growing season (May–August) precipitation, mean temperature and mean of monthly maximum temperature were calculated to assess possible impacts of climate variability and change on agriculture, as higher temperatures contribute to increased crop evapotranspiration.

Table 1 The selected weather stations in the state of Idaho

Station no.	Station name	Coop. ID	Latitude	Longitude	Elevation (meter)	% of Missing in PRCP	% of Missing in Tmin	% of Missing in Tmax
1	Porthill	107264	49.00	−116.50	541.0	1.05	1.40	1.42
2	Priest River Exp Station	107386	48.35	−116.83	725.4	0.16	0.02	0.02
3	Sandpoint Exp Station	108137	48.3	−116.55	640.1	1.46	1.55	1.56
4	Cabinet Gorge	101363	48.08	−116.05	688.8	0.90	0.09	0.13
5	Bayview Model Basin	100667	47.98	−116.57	632.5	3.51	2.28	2.57
6	Kellogg	104831	47.53	−116.13	707.1	4.30	3.58	3.48
7	Saint Maries 1W	108062	47.32	−116.60	670.6	4.12	2.16	2.18
8	Moscow U Of I	106152	46.73	−116.95	810.8	0.11	0.06	0.02
9	Elk River 1 S	102892	46.77	−116.18	889.4	4.88	4.55	4.86
10	Lewiston Nez Perce Co Airport	105241	46.37	−117.02	437.7	2.74	2.23	2.28
11	Nezperce	106424	46.23	−116.25	987.6	3.45	3.38	3.37
12	Fenn Rs	103143	46.10	−115.53	475.5	2.82	3.72	4.21
13	Grangeville	103771	45.93	−116.12	1,005.8	1.37	1.37	1.37
14	Elk City 1ne	102875	45.83	−115.47	1,236.9	2.24	2.82	3.20
15	Riggins	107706	45.42	−116.32	548.6	5.79	5.61	5.74
16	Mc Call	105708	44.88	−116.10	1,531.6	0.71	0.65	0.74
17	Cambridge	101408	44.57	−116.68	807.7	0.42	0.3	0.36
18	Cascade 1 NW	101514	44.52	−116.05	1,492.3	0.67	0.62	0.65
19	Payette	106891	44.08	−116.93	655.3	2.91	2.78	2.97
20	Garden Valley	103448	44.10	−115.97	944.9	5.72	7.05	7.18
21	Idaho City	104442	43.83	−115.83	1,208.5	0.93	1.10	1.16
22	Emmett 2 E	102942	43.85	−116.47	728.5	0.17	0.94	0.85
23	Parma Exp Station	106844	43.80	−116.95	698.0	1.93	1.86	1.85
24	Deer Flat Dam	102444	43.58	−116.75	765.0	2.40	3.66	4.08

Table 1 continued

Station no.	Station name	Coop. ID	Latitude	Longitude	Elevation (meter)	% of Missing in PRCP	% of Missing in Tmin	% of Missing in Tmax
25	Boise Air Terminal	101022	43.57	−116.23	857.7	2.37	2.18	2.27
26	Arrowrock Dam	100448	43.60	−115.92	986.0	5.22	5.58	6.01
27	Swan Valley 2 E	108937	43.25	−116.38	1,633.7	1.86	2.67	1.73
28	Reynolds	107648	43.20	−116.75	1,197.9	1.17	1.14	1.15
29	Grand View 4 NW	103760	43.02	−116.18	731.5	2.83	2.80	3.18
30	Ketchum Rs	104845	43.68	−114.37	1,795.3	1.58	3.05	3.23
31	Picabo	107040	43.32	−114.07	1,472.2	1.06	0.99	0.96
32	Richfield	107673	43.05	−114.15	1,305.2	2.44	2.60	2.50
33	Shoshone 1 WNW	108380	42.93	−114.42	1,204.0	1.56	3.12	3.42
34	Jerome	104670	42.73	−114.52	1,140.0	0.60	0.44	0.46
35	Hazelton	104140	42.60	−114.13	1,237.5	0.82	1.34	1.43
36	Paul 1ene	106877	42.63	−113.77	1,264.9	1.58	1.47	1.49
37	Burley Municipal Airport	101303	42.55	−113.77	1,262.5	2.36	2.36	2.37
38	Minidoka Dam	105980	42.68	−113.50	1,269.2	2.64	2.67	2.65
39	Oakley	106542	42.23	−113.90	1,389.6	0.34	0.21	0.26
40	Chilly Barton Flat	101671	43.98	−113.83	1,908.0	2.88	3.83	3.40
41	Mackay Lost River Rs	105462	43.92	−113.63	1,797.4	4.45	5.40	5.92
42	Arco	100375	43.63	−113.3	1,623.1	9.23	8.44	8.74
43	Howe	104384	43.78	−113.00	1,469.1	5.64	6.31	7.26
44	American Falls 6 NE	100227	42.85	−112.88	1,345.7	1.60	1.79	1.81
45	Pocatello Rgnl Airport	107211	42.92	−112.57	1,364.9	2.36	2.19	2.33
46	Ft Hall 1 NNE	103297	43.05	−112.42	1,360.9	2.14	2.87	3.05
47	Idaho Falls 16 SE	104456	43.35	−111.78	1,776.4	2.21	2.37	2.22
48	Idaho Falls—Kifi	104455	43.52	−112.02	1,445.4	8.81	4.80	4.58

Table 1 continued

Station no.	Station name	Coop. ID	Latitude	Longitude	Elevation (meter)	% of Missing in PRCP	% of Missing in Tmin	% of Missing in Tmax
49	Hamer 4 NW	103964	43.97	−112.27	1,460.0	1.68	3.57	4.06
50	Dubois Exp Station	102707	44.25	−112.20	1,661.2	0.10	0.06	0.07
51	Island Park	104598	44.42	−111.37	1,917.2	8.00	6.96	7.35
52	St Anthony 1 WNW	108022	43.97	−111.72	1,508.8	3.65	2.62	2.65
53	Ashton 1n	100470	44.05	−111.27	1,588.6	3.25	2.35	2.61
54	Driggs	102676	43.73	−111.12	1,865.4	6.23	5.43	6.08
55	Swan Falls P H	108928	43.45	−111.30	708.7	1.55	1.70	1.65
56	Lifton Pumping Station	105275	42.12	−111.32	1,806.2	0.41	0.39	0.38

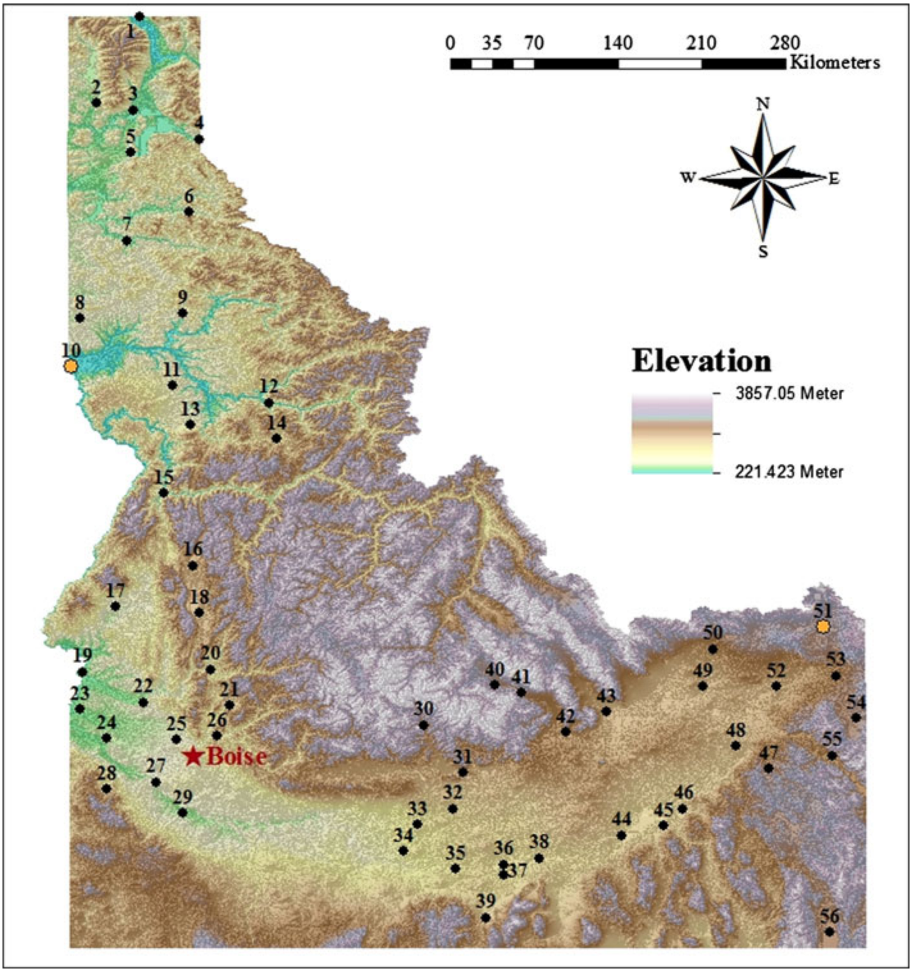

Fig. 1 Spatial distribution of weather stations in the study area. Note that stations in *orange color* are the highest (station's number 10) and the lowest (station's number 51) stations

The PDSI is a critical index to monitor drought so that monthly precipitation and temperature data were used to compute the monthly PDSI following Palmer (1965). Since the PDSI has shown poor performance in the western United States (e.g., Guttman 1992), the self-calibrated Palmer Drought Severity Index (sc-PDSI) was introduced to further emphasize site-specific drought condition based on historic climate data at each location following Wells et al. (2004). To evaluate meteorological drought, monthly precipitation was used to calculate SPI (McKee et al. 1993).

In general, drought duration is defined as the number of consecutive months with a negative drought index value (started from a month with negative value in drought index and continued to meet a month with non-negative value in drought index) (McKee et al. 1993). For this study, three time-dependent drought conditions, including (1) short- (2–6 months), (2) mid- (6–12 months) and (3) long-term drought (longer than 12 months),

Table 2 Temperature indices (Karl et al. 1999; Peterson 2005)

Index	Descriptive name	Definition	Units
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN > 10th percentile during 1962–2008	Days
DTR	Diurnal temperature range	Monthly mean temperature difference between TX and TN	°C
FD	Frost days	Annual count of frost days when daily minimum temperature TN < 0 °C	Days
GSL	Growing season length	Annual count between first span of at least 6 days with TG > 5 °C after winter and first span after summer of 6 days with TG < 5 °C	Days
G-Tavg	Growing season mean temperature	Mean temperature of May through August	
G-Tmax	Growing season average of monthly Tmax	Average of monthly maximum temperature from May through August	
ID	Ice days	Annual count of icing days when TX < 2 °C	Days
SU	Summer days	Annual count of summer days when daily maximum temperature (TX) > 27 °C	Days
TR	Tropical nights	Annual count when TN > 5 °C	Days
TXx	Max Tmax	Monthly maximum value of daily maximum temperature. Tx_{kj} can be defined as the daily maximum temperatures in month k, period j	°C
TNx	Max Tmin	Monthly highest TN	°C
TXn	Min Tmax	Monthly lowest TX	°C
TNn	Min Tmin	Monthly minimum value of daily minimum temperature. Tx_{kj} can be defined as the daily minimum temperatures in month k, period j	°C
TN10p	Cold nights	Percentage of days when monthly value of daily minimum temperature (TN) < 10th percentile during 1962–2008	%
TX10p	Cold days	Percentage of days when monthly value of daily maximum temperature (TX) < 10th percentile during 1962–2008	%
TN90p	Warm nights	Percentage of days when monthly value of daily minimum temperature (TN) > 90th percentile during 1962–2008	%
TX90p	Warm days	Percentage of days when monthly value of daily maximum temperature (TX) > 90th percentile during 1962–2008	%
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile during 1962–2008	Days

Additional information is also available at http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml)

TG stands for daily mean temperature

are classified to investigate the impacts of frequency and magnitude of drought in the past, especially focusing on growing season (May–August) over the state. To detect statistically significant trends, a p value of 0.1 was applied using the student's t test at a 10 % level of statistical significance. Note that negative and positive index values indicate dry and wet condition, respectively.

Table 3 Precipitation indices (Karl et al. 1999; Peterson 2005)

Index	Descriptive name	Definition	Units
CDD	Consecutive dry days	Maximum number of consecutive dry days	Days
CWD	Consecutive wet days	Count the largest number of consecutive days where $RR_{ij} \geq 1$ mm, where RR_{ij} is the daily precipitation amount on day i in period j	Days
G-PRCP	Growing season precipitation	Sum of May through August precipitation	
PRCPTOT	Wet day precipitation	Annual total precipitation from wet days	mm
R10mm	Heavy precipitation days	Annual count of days when RR $\geq$ 10	Days
R20mm	Very heavy precipitation days	Annual count of days when RR $\geq$ 20	Days
R50mm	Number of days have precipitation above 50 mm	Annual count of days when PRCP $\geq$ 50 mm	Days
R95p	Very wet days	Count the largest number of consecutive wet days when the amount of rainfall falling above the 95th percentiles during 1962–2008	mm
R99p	Extremely wet days	Count the largest number of consecutive wet days when the amount of rainfall falling above the 99th percentiles during 1962–2008	mm
RX1day	Max 1-day precipitation amount	The maximum 1-day precipitation each month	mm
RX5day	Max 5-day precipitation amount	The maximum 5-day precipitation each month	mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/day

3 Results

3.1 Temperature indices

3.1.1 Hot indices

Temperature indices listed in Table 2 were utilized to investigate climate extremes over the state. Most of the stations exhibited warming in temperature extremes as shown in Figs. 2 and 3. Increasing trends in maximum of maximum temperature (TXx) at the 48 stations have been found, and 25 of the stations have significant trends. Maximum of minimum temperature (TNx) shows considerably smaller numbers of increasing and significant trends than that of TXx.

Warm days (TX90p) and warm nights (TN90p) indicate similar results. In TX90p, for example, positive trends were observed at 46 stations, and 21 stations out of them indicate statistically significant trends, and TN90p also shows similar number of increasing and significant trends. Summer days (SU) show a higher number of positive trends than tropical nights (TR), while TR indicates higher significant trends (see Fig. 2). Meanwhile, decreasing trends in growing season length (GSL) shown in Fig. 3 have been seen at 10 stations, but none of them is statistically significant. Significant increasing trends in GSL

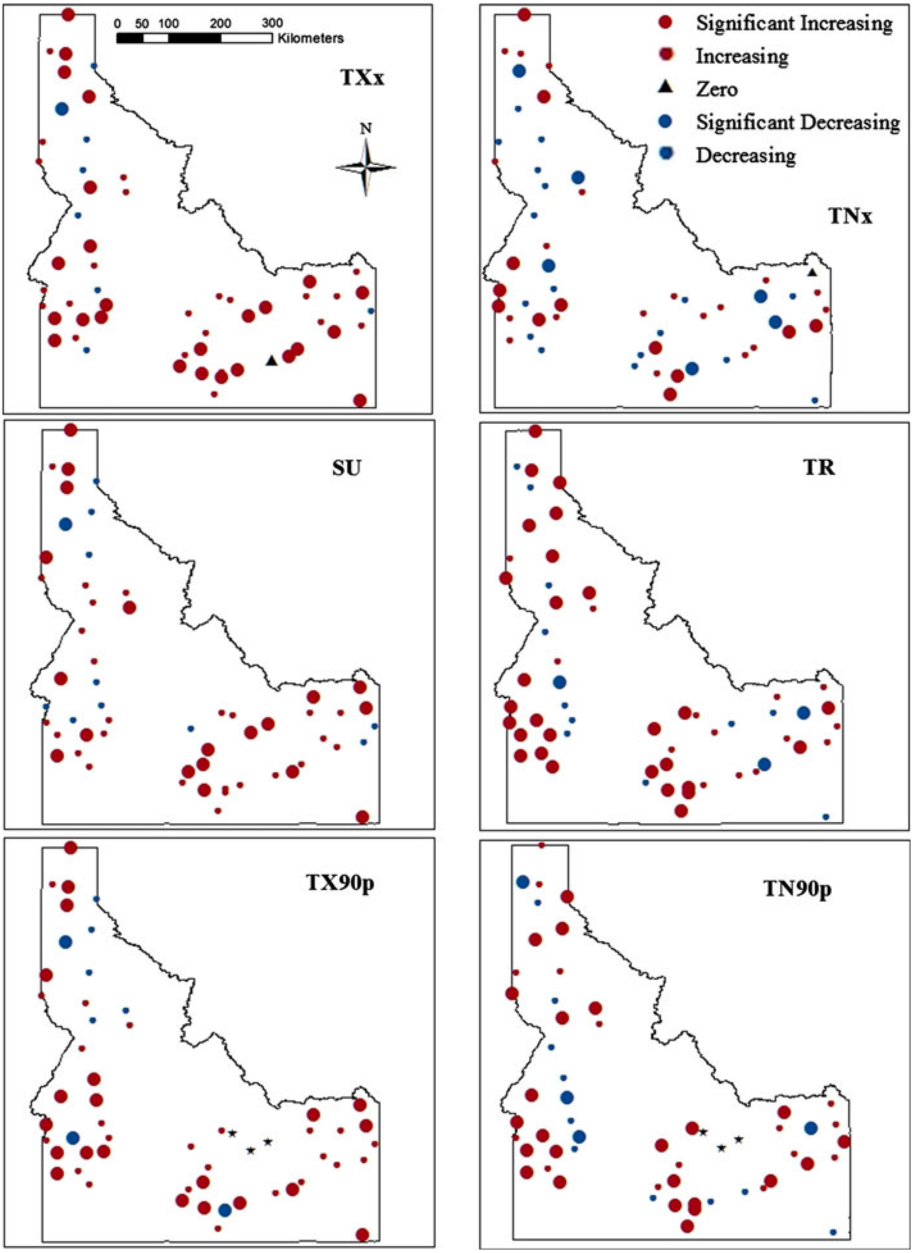

Fig. 2 Spatial and temporal distributions of hot extremes, including TXx, TNx, SU, TR, TX90p and TN90p during 1962–2008. A *star symbol* represents that an index is not calculated for a station

are also identified at 12 stations (see Fig. 3). Interestingly, both decreasing and increasing trends in warm spell duration indicator (WSDI) are identified almost equally and significantly. Average temperature (G-Tavg) and maximum temperature (G-Tmax) during

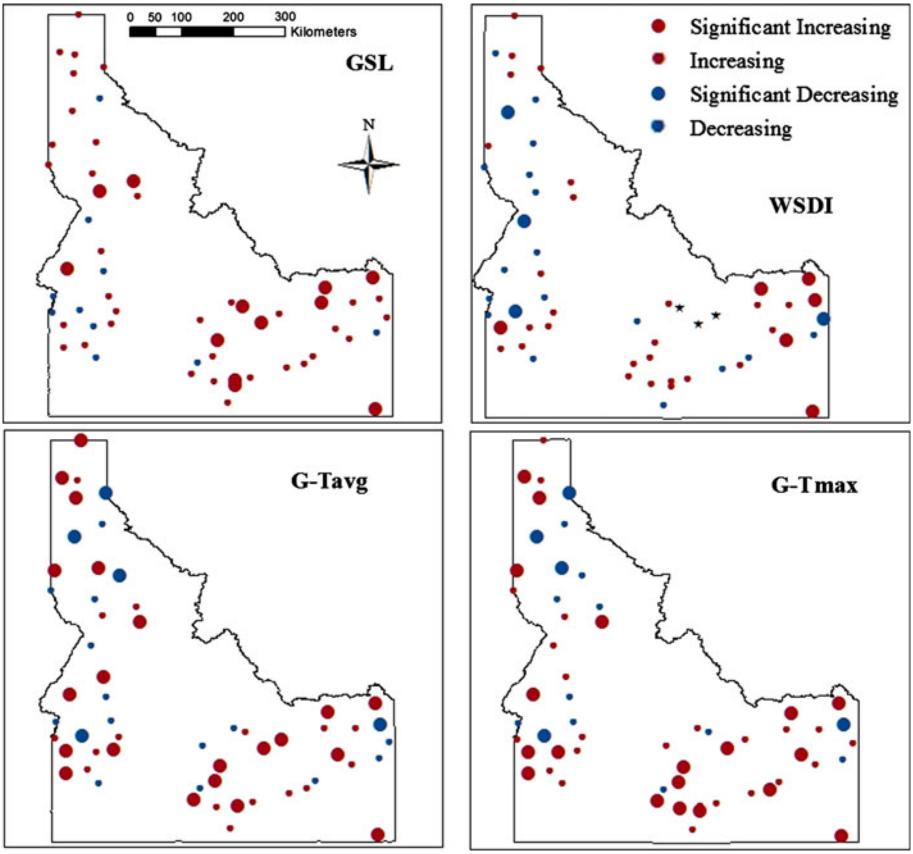

Fig. 3 Spatial and temporal distributions of hot extremes, including WSDI, G-Tavg and G-Tmax during 1962–2008. A *star symbol* represents that an index is not calculated for a station

growing seasons indicate similar results, which are 21 and 19 significant trends identified, respectively.

3.1.2 Cold indices

Similar to hot indices, cold indices shown in Fig. 4 also show trends that are consistent with warming. The decreasing trend in the minimum of minimum temperature (TNn) is identified at only one station, Station 20, and it was not statistically significant. Furthermore, decreasing trends in the minimum of maximum temperature (TXn) have been detected without significance at just three stations, while most of the stations indicate increasing trends. Consequently, frost days (FD) have been declined in considerable number of the stations with significance along with decreasing trends in ice days (ID). But, decreasing trends in ice days (ID) at most of the stations did not show statistical significance (see Fig. 4). The highest number of significant decreasing trends in cold nights (TN10p) was observed at many stations, while the relatively small number of significant

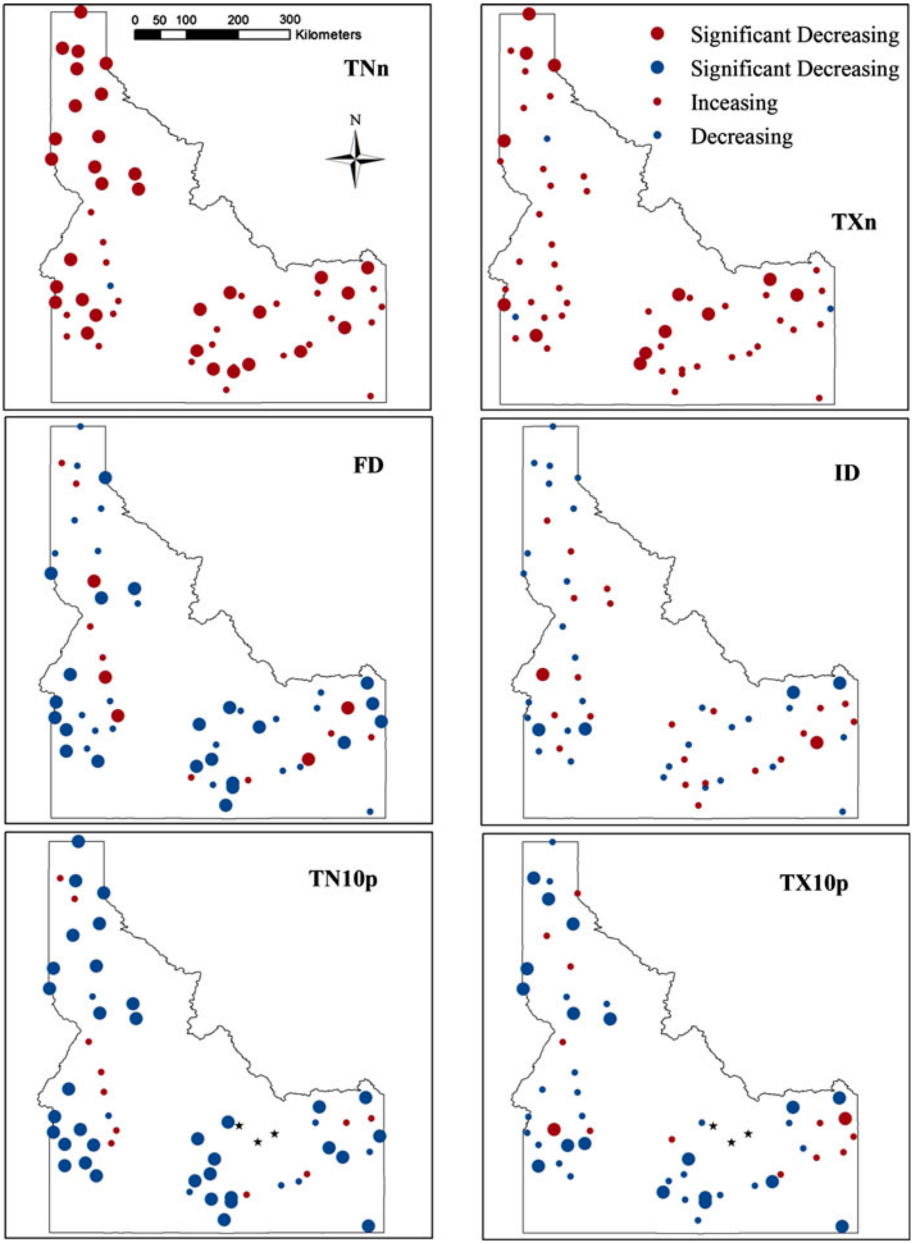

Fig. 4 Spatial and temporal distributions of cold extremes, including TNn, TXn, FD, ID, TN10p and TX10p during 1962–2008. A *star symbol* represents that an index is not calculated for a station

decreasing trends in cold days (TX10p) was detected along with positive trends at few stations. Note that relatively no significant trends in cold spell duration indicator (CSDI) are identified except 5 stations as shown in Fig. 5.

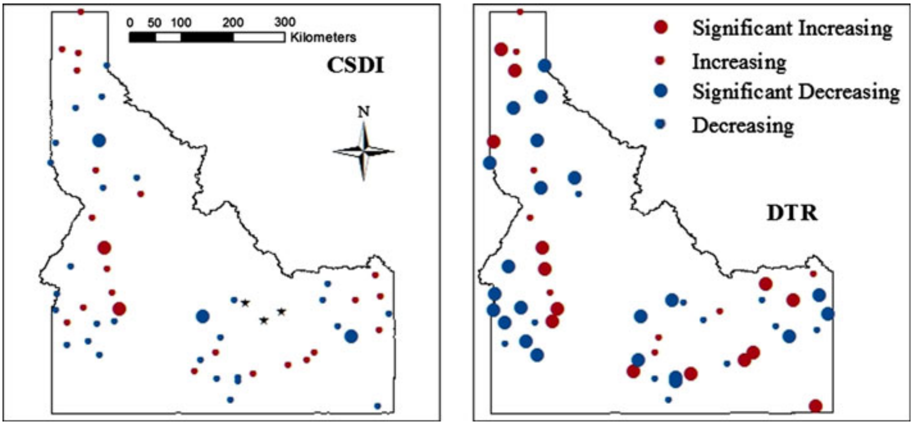

Fig. 5 Spatial and temporal distributions of cold extremes, including CSDI and DTR during 1962–2008. A *star symbol* represents that an index is not calculated for a station

3.1.3 Diurnal temperature range

The large number of decreasing trends in diurnal temperature range (DTR) indicates that daily minimum temperature increases with higher magnitude than daily maximum temperatures at most of the stations. Note that the number of statistically significant decreasing trends in DTR is almost double on increasing trends with significance as shown in Fig. 5.

3.2 Precipitation indices

Unlike temperature indices, precipitation indices show a relatively small number of significant trends. Generally, decreasing trends in the amount, frequency and intensity of precipitation in southern Idaho has been observed, while increasing trends have been detected in northern Idaho, as shown in both Figs. 6 and 7.

The largest number of significant trends among precipitation indices is related to the daily intensity index (SDII) with 16 negative and 10 positive trends (see Fig. 7). Wet day precipitation (PRCPTOT) shows statistically significant decreasing trends at many stations. Growing season precipitation (G-PRCP) has also decreased at most of the stations, especially those located in the Eastern Snake Plain aquifer region (ESPA) (not shown in the figure) situated in southern Idaho.

3.3 sc-PDSI and SPI

The sc-PDSI and SPI-12 month indicate similar patterns at most of the stations. Thus, the annual average of sc-PDSI and SPI-12 month shows the same trends (both increasing and decreasing trends) for most of the stations. For example, negative significant trends in annual average of sc-PDSI and SPI-12 month have been seen at 19 and 15 stations, respectively (see Fig. 8). As we expected, a general distribution of precipitation trends in annual average of SPI-1, 3, 6 and 12 month agrees well within the study area, while the SPI-12 month is also well matched with annual sc-PDSI.

It appears that the monthly sc-PDSI shows a larger number of negative significant trends than the monthly SPI-12 month. In terms of the seasonal variation related to drought

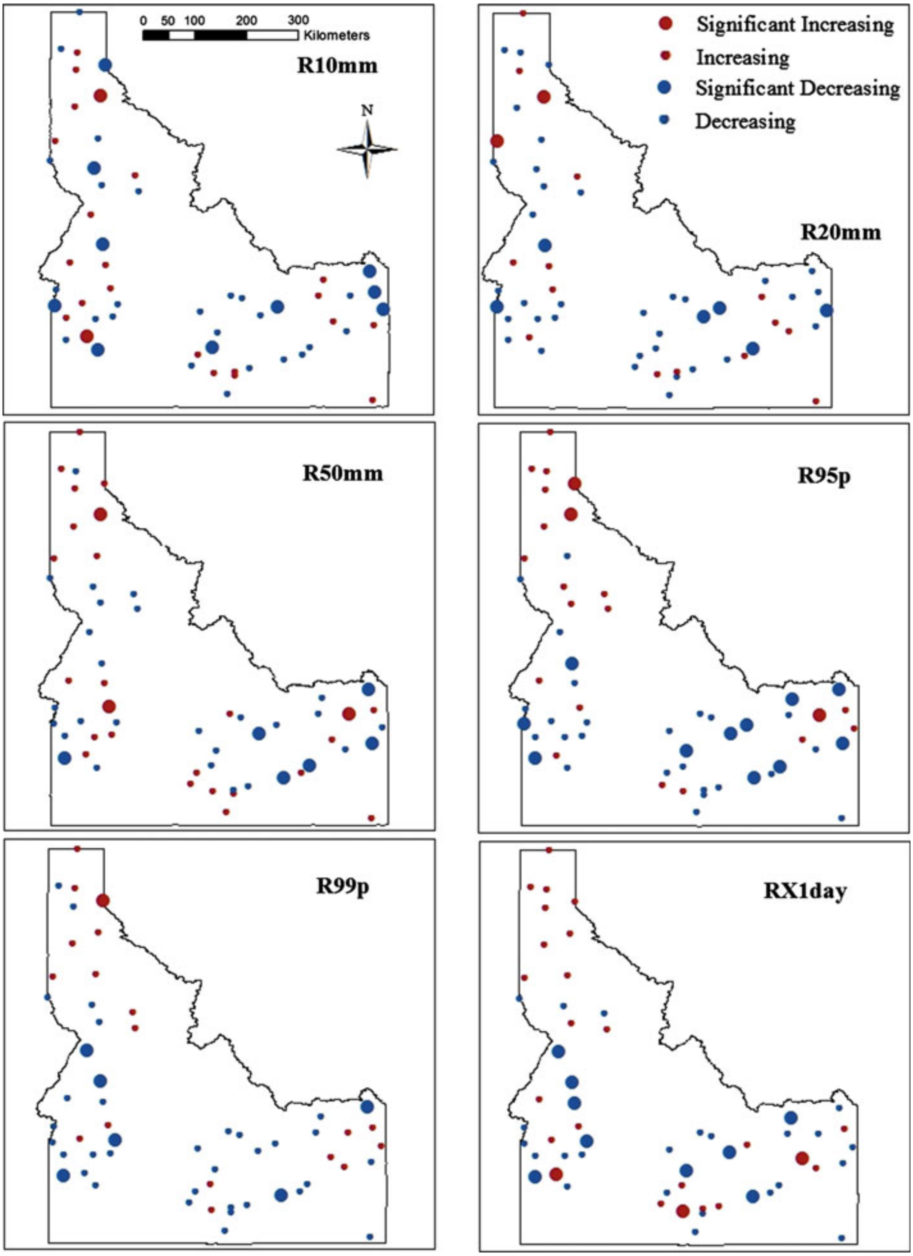

Fig. 6 Spatial and temporal distributions of precipitation extremes, including R10mm, R20mm, R50mm, R95p, R99p and RX1day during 1962–2008

evolvement, the highest number of negative significant trends in monthly sc-PDSI was observed in September. This may result from the time lag embedded in the AWC during PDSI computation that contributes to drought conditions for the growing season, as warm-dry summer conditions could maximize soil moisture deficits. The frequency of sc-PDSI,

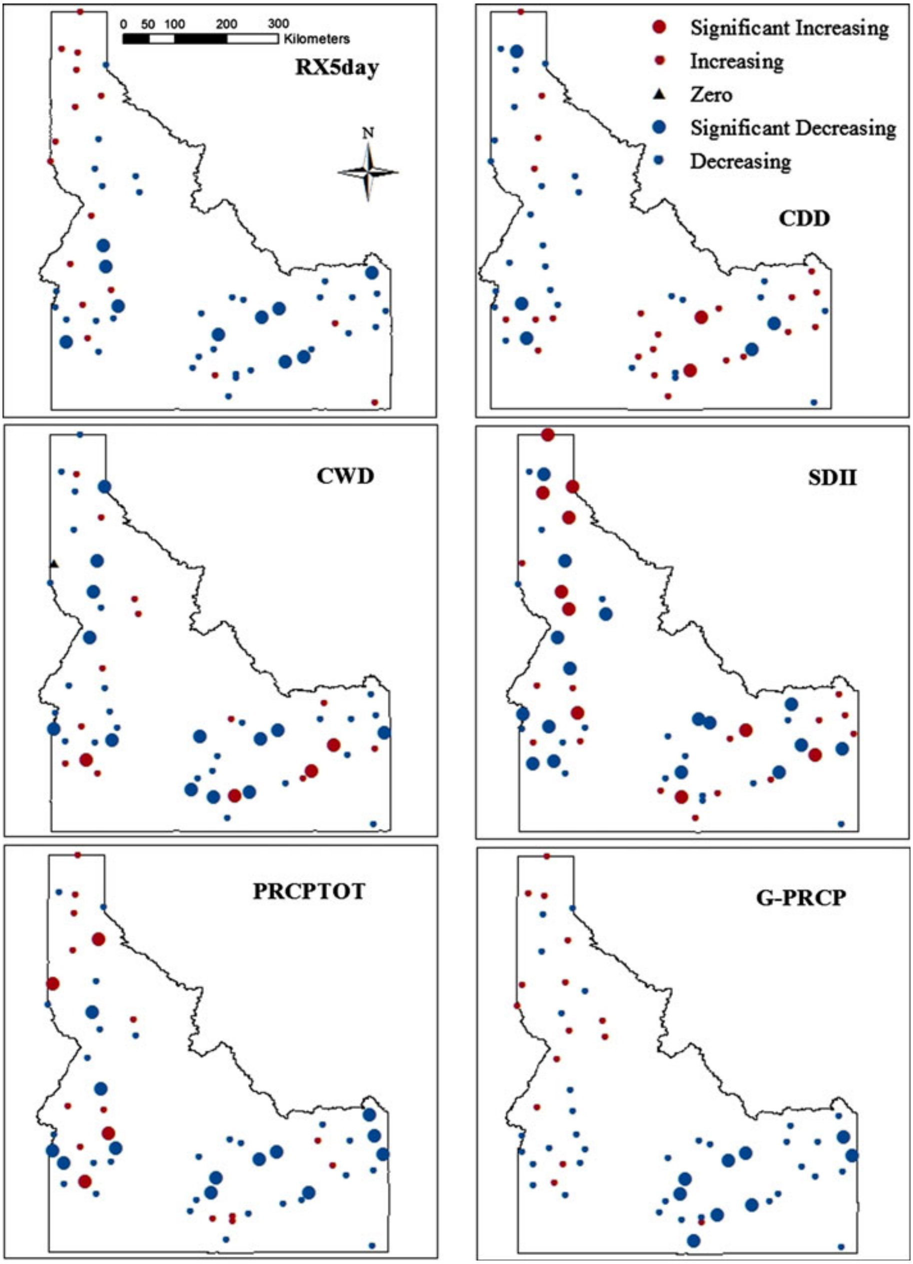

Fig. 7 Spatial and temporal distributions of precipitation extremes, including RX5day, CDD, CWD, SDII, PRCPTOT and G-PRCP during 1962–2008

SPI-1, SPI-3, SPI-6 and SPI-12 month with three time-dependent drought conditions, including short-, mid- and long-term drought, was also analyzed and listed in Tables 4, 5 and 6 of "Appendix".

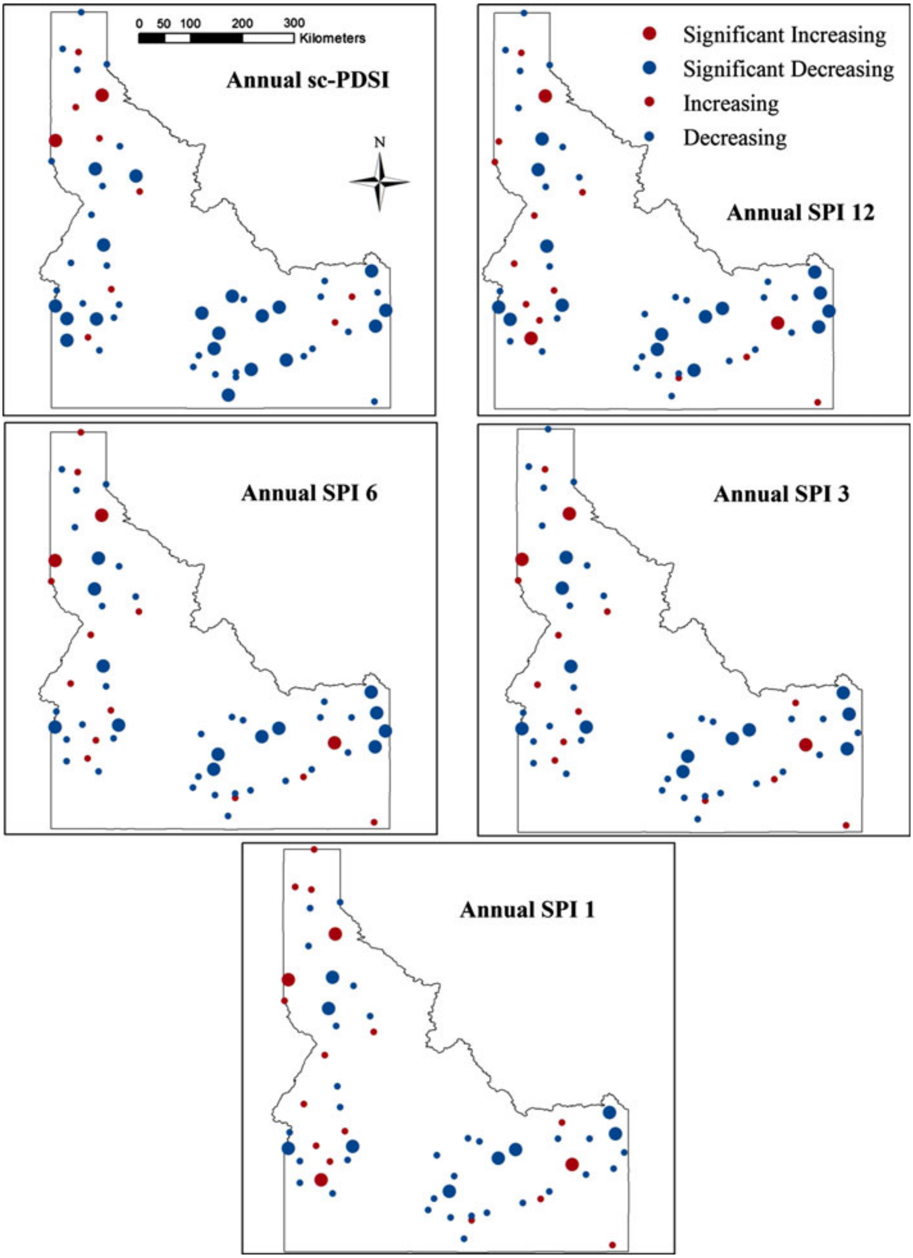

Fig. 8 Spatial and temporal distributions of annual sc-PDSI and annual SPI 12-, 6-, 3-, 1- month time scale during 1962–2008

3.4 Teleconnections

To detect teleconnections between regional drought and climatic extremes, seven oceanic indices, including (1) AMO, (2) EP-NP, (3) NOI, (4) NP, (5) ONI, (6) PDO and (7) PNA, were analyzed. Except AMO, the other indices show changes in sea-surface temperature (SST) and sea level pressure (SLP) of different locations in the Pacific Ocean. AMO represents SST of Atlantic Ocean from 0 to 70 N latitudes, and its linkage to USA's drought has shown in many previous studies, such as Hidalgo (2004) and Nigam et al. (2011). EP-NP presents changes in intensity of the Pacific jet stream from eastern Asia to the eastern North Pacific. NOI, which is the difference in SLP anomalies at the North Pacific High and near Darwin Australia, represents changes of SST at eastern North Pacific. NP that describes as the area-weighted sea level pressure from 30 to 65 N latitudes and 160 E to 140 W longitude indicates interannual to decadal variations in the atmospheric circulation. In other words, NP shows variations in the intensity of the Aleutian low. ONI is defined as 3-month moving average of SST in the Nino 3.4 region so that it is used to represent ENSO phenomenon while PDO can be represented as a function of SST anomalies in the North Pacific Ocean, above 20 N latitude. PDO shows interdecadal climate oscillation, also known as long-term El Nino and La Nina. Strong fluctuations in the strength and location of the East Asian jet stream are associated with PNA, which is strongly affected by El Nino Southern Oscillation (ENSO). Additional information about these oceanic is available at National Oceanic and Atmospheric Administration (NOAA)'s website at http://www.esrl.noaa.gov. To demonstrate a linkage between oceanic indices and regional drought, sc-PDSI, SPI-1-month and 12-month were selected for further analysis. DTR, TXx, TNn, RX1 day and RX5 day were also utilized to verify teleconnections based on the user-defined selection criteria, especially focusing on water management perspectives. Note that Pearson method (Pearson 1903) was simply used to compute correlation coefficient between oceanic indices and drought/climatic indices with 0.05 level of significance.

In most of the stations, sc-PDSI and SPI-12-month show significant correlation with AMO, NOI, ONI and PDO (Fig. 9). Negative correlation of AMO, EP-NP, NOI and ONI explains that Idaho drought is likely to occur when SST is cooler than normal in the eastern Pacific Ocean. NOI and ONI, in particular, imply that severe droughts occur during strong La Nina events when higher SLP is established at the North Pacific. It appears that considerable number of significant negative correlation between EP-NP and sc-PDSI in southern Idaho resulted in severe drought due to strong mid-latitude jet stream driven by enhanced anticyclone over southern Idaho. The results show the strong influence of variations in SST and SLP of North Pacific (extratropic indices) on the climate of the region.

The results also show that all the selected climatic extremes are connected to NP based on the area-weighted SLP over the region 30°N–65°N, 160°E–140°W. It appears that NP has a positive correlation with the selected temperature indices, while the selected precipitation indices (e.g., RX1day, RX5day) show a negative correlation with NP (except in southeastern Idaho) (Fig. 10). This implies that variation in NP can change direction and intensity of mid-latitude jet stream and leads to establish a ridge or trough of dry spells over Idaho.

This negative correlations also imply that decreasing patterns in intensity and amount of precipitation were observed during La Niña in the sense that higher SLP at North Pacific high coincides with decrease in intensity and amount of precipitation. Note that, however, increasing patterns in temperature (TNn) over the state of Idaho are related to positive phase of PNA during El Niño (Fig. 10a).

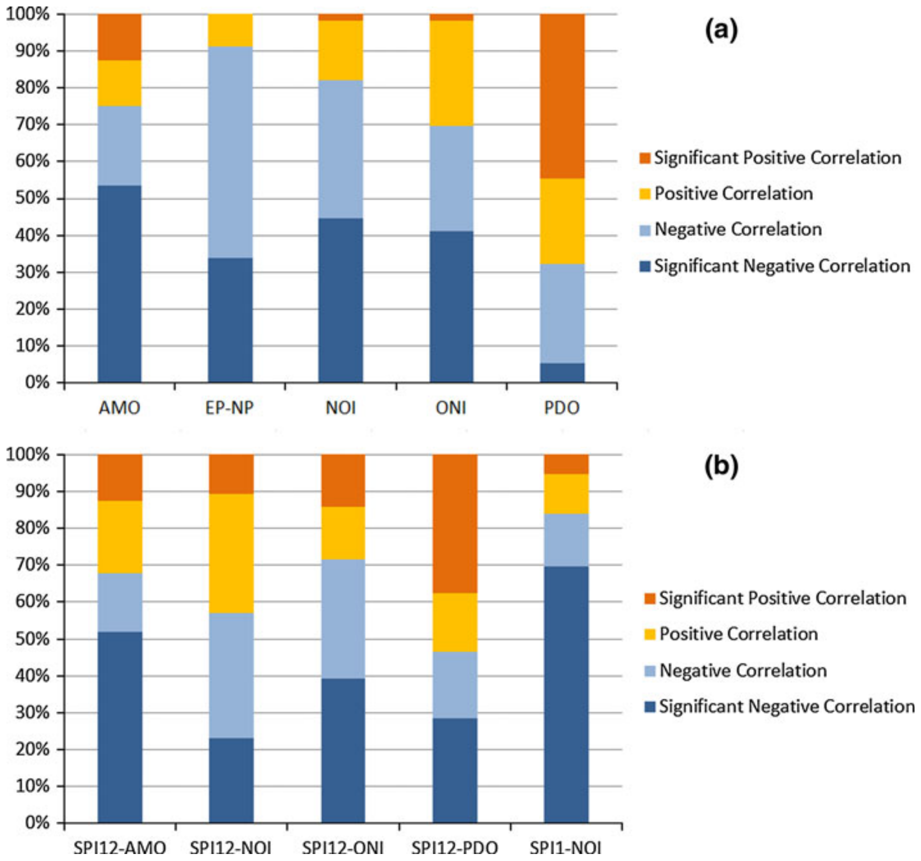

Fig. 9 **a** Percent of stations regarding to correlation of sc-PDSI to oceanic indices including AMO, EP-NP, NOI, ONI and PDO. **b** Correlation of 12-month SPI to oceanic indices including AMO, NOI, ONI and PDO, and correlation of 1-month SPI to NOI

4 Conclusions

Based on temperature indices, the research findings reveal a higher magnitude in minimum temperature increases than that of maximum temperature in most of the stations. Significant decreasing trends in DTR and FD are also identified at many stations. Since considerable dwindling of FD and increase of TNn can affect the type of precipitation and snow coverage, these indices may contribute to identify how climate variability can improve streamflow forecasting.

Precipitation indices show a smaller number of significant trends than that of temperature indices. However, it is noticeable that the amount, intensity and frequency of precipitation have considerably dwindled in southern Idaho, particularly in the Snake River basin, while most of the northern stations have experienced increasing trends in these indices.

Climatic indices also well agree with drought conditions identified by the PDSI and SPI. For example, frequency of the sc-PDSI and SPI associated with short-, mid- and long-term

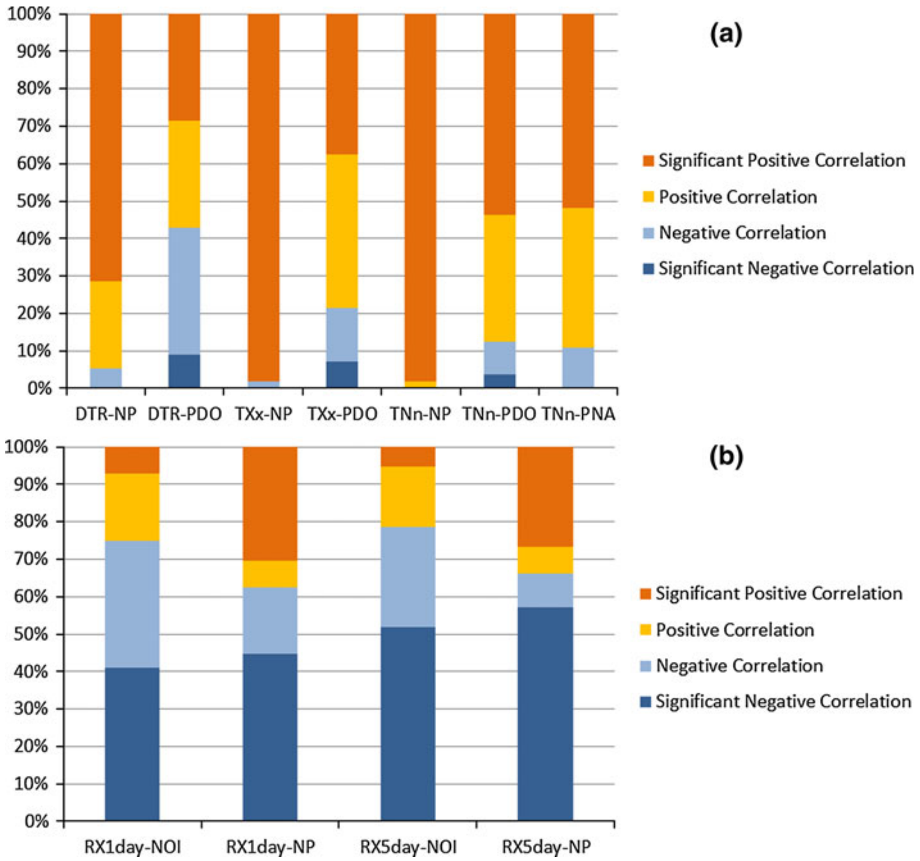

Fig. 10 **a** Correlation of the selected temperature indices including DTR, TXx and TNn to NP, PDO and PNA. **b** Correlation of the selected precipitation indices including RX1day and RX5day to NOI and NP

drought clearly indicate that the state of Idaho has experienced drought frequently since 1962. The result also shows that the sc-PDSI and SPI-12 month have similar patterns, which was noted in several previous studies (Lloyd-Hughes and Saunders 2002; Vincente-Serano et al. 2009). The findings from this research on the sc-PDSI and SPI-12 month are also well verified by drought reports published by Idaho Department of Water Resources (IDWR 2001). This implies that the sc-PDSI and SPI-12 are suitable indices to identify drought in this region, and they can be used as potential predictors for future drought.

GSL has expanded as a result of changes in maximum and minimum temperature. Since considerable increase in G-Tavg and G-Tmax affects temperature regime change, elevated evapotranspiration rates are expected during growing season. This implies that irrigation activities during this season compromise water losses driven by the decreased precipitation and increased temperature. The monthly and annual sc-PDSI and SPI in different time scales also show that the state has experienced drought frequently since 1962 along with considerable changes in precipitation, maximum and minimum temperature. As such, one of the important research questions is how these trends are going to evolve in the future due to climate change and variability. If these trends continue, surface and groundwater usage to make up for the elevated evapotranspiration rate will increase significantly. On the other hand, the decreased precipitation will facilitate water shortages driven by the decreased snowpack and other uncertain future climate variability (e.g., rain on snow), particularly during the growing season. Consequently, oceanic indices, such as NP, PNA and NOI, would be a good predictor to define future drought in the sense that these indices have well explained historic droughts over Idaho, especially driven by high temperature and low precipitation.

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Appendix

See Tables 4, 5 and 6.

Table 4 Duration and frequency in sc-PDSI index

Station no.	Maxdu	Begd	Endd	#Sdu	#Mdu	#Ldu
1	132	Nov-83	Nov-94	8	2	5
2	123	Jun-84	Sep-94	14	7	3
3	78	Jan-62	Jul-68	6	5	5
4	61	Jun-84	Jul-89	3	10	7
5	41	Oct-00	Mar-04	18	8	6
6	63	Jan-75	Apr-80	5	4	8
7	51	Sep-65	Dec-69	7	13	10
8	58	Jan-65	Nov-69	19	9	6
9	59	May-72	Apr-77	11	9	7
10	96	Jun-84	Jun-92	6	4	5
11	102	Nov-86	May-95	8	2	6
12	50	Jul-90	Sep-94	7	7	6
13	36	Sep-86	Sep-89	14	8	10
14	31	Feb-65	Sep-67	2	8	10
15	45	May-91	Feb-95	12	8	8
16	52	Oct-00	Feb-05	8	7	8
17	45	Feb-99	Nov-02	19	6	7
18	73	Sep-86	Oct-92	5	5	7
19	75	Sep-86	Dec-92	17	5	6
20	62	Feb-99	Apr-04	12	12	5
21	63	Jun-98	Sep-03	7	4	10
22	67	Oct-86	May-92	4	2	7
23	78	Apr-86	Oct-92	8	2	8

Table 4 continued

Station no.	Maxdu	Begd	Endd	#Sdu	#Mdu	#Ldu
24	50	Jul-87	Sep-91	19	9	6
25	79	Sep-98	Apr-05	4	1	6
26	58	Dec-87	Oct-92	7	12	7
27	73	Sep-86	Oct-92	8	8	4
28	81	Jul-98	Apr-05	8	6	4
29	45	Jan-88	Oct-91	9	7	8
30	44	Oct-00	Jun-04	11	9	8
31	64	Feb-99	Jun-04	9	9	6
32	72	Feb-99	Feb-05	8	6	8
33	67	Jul-99	Feb-05	3	7	9
34	72	Feb-99	Feb-05	10	6	7
35	72	Oct-86	Oct-92	5	7	4
36	67	Oct-86	May-92	7	8	7
37	61	Feb-00	Mar-05	6	7	7
38	65	May-87	Oct-92	4	7	7
39	54	Jul-99	Jan-04	3	8	7
40	66	Jul-87	Jan-93	20	5	9
41	37	Apr-01	May-04	19	8	8
42	63	Jul-87	Oct-92	11	7	8
43	85	Nov-00	Dec-07	9	8	5
44	63	Jun-99	Sep-04	11	5	9
45	51	Aug-99	Nov-03	18	4	8
46	49	Oct-99	Nov-03	18	6	9
47	42	May-00	Nov-03	11	7	6
48	47	Aug-99	Jul-03	15	3	10
49	59	Jun-99	May-04	10	4	7
50	53	Jun-99	Nov-03	8	12	7
51	36	May-89	May-92	13	11	4
52	91	Oct-84	May-92	14	5	7
53	47	Jan-99	Dec-02	12	9	7
54	66	Jul-87	Jan-93	4	6	8
55	65	Aug-87	Jan-93	8	5	7
56	62	Jun-99	Aug-04	11	6	6

Maxdu shows maximum consecutive months with negative sc-PDSI value, and begd and endd indicate onset and end date of maxdu. #sdu, #mdu and #ldu explain number of occurrence (frequency) of short-, mid- and long- term drought with respect to their definitions in the methodology section

Table 5 Duration and frequency in SPI 1- and 3-month time scales

Station no.	Maxdu1	Begd1	Endd1	#Sdu1	#Mdu1	#Ldu1	Maxdu3	Begd3	Endd3	#Sdu3	#Mdu3	#Ldu3
1	11	Aug-76	Jul-77	51	4	0	11	Apr-87	Mar-88	36	13	0
2	8	Aug-76	Apr-77	60	4	0	13	Sep-93	Oct-94	34	9	3
3	8	Aug-76	Apr-77	52	6	0	13	Sep-93	Oct-94	42	9	1
4	11	Oct-93	Sep-94	51	5	0	13	Apr-00	May-01	30	12	4
5	9	Aug-91	May-92	46	7	0	11	Oct-93	Sep-94	39	11	0
6	24	Jan-73	Jan-75	42	4	1	32	Jul-72	Mar-75	26	9	4
7	10	Jul-87	May-88	51	6	0	13	Sep-72	Oct-73	33	12	2
8	7	Mar-66	Oct-66	57	3	0	15	Aug-65	Nov-66	37	10	2
9	9	Jun-91	Mar-92	43	10	0	14	Mar-00	May-01	32	9	4
10	9	Oct-84	Jul-85	54	5	0	15	Feb-63	May-64	29	12	2
11	14	Oct-96	Dec-97	50	6	1	19	Jul-96	Feb-98	33	12	2
12	7	Dec-84	Jul-85	55	4	0	13	Sep-72	Oct-73	36	13	1
13	7	Nov-91	Jun-92	57	7	0	26	Nov-00	Jan-03	31	12	2
14	11	Sep-72	Aug-73	51	7	0	14	Oct-65	Dec-66	28	13	4
15	19	Apr-79	Nov-80	47	6	1	21	Apr-79	Jan-81	31	12	2
16	9	Sep-00	Jun-01	51	7	0	19	Mar-00	Oct-01	30	12	3
17	7	Sep-76	Apr-77	58	3	0	14	Aug-93	Oct-94	32	12	3
18	7	Apr-02	Nov-02	54	7	0	13	Sep-93	Oct-94	30	15	1
19	9	Nov-65	Aug-66	63	4	0	12	Jan-02	Jan-03	33	14	1
20	20	Oct-89	Jun-91	57	4	1	25	Aug-87	Sep-89	33	9	3
21	8	Oct-00	Jun-01	54	6	0	15	Aug-93	Nov-94	32	12	3
22	11	Nov-65	Oct-66	61	5	0	13	Mar-87	Apr-88	39	9	3
23	11	Nov-65	Oct-66	60	5	0	21	Apr-01	Jan-03	40	9	2
24	10	Dec-87	Oct-88	59	5	0	20	Apr-01	Dec-02	34	11	2
25	11	Nov-65	Oct-66	56	5	0	25	Mar-62	Apr-64	30	9	4

Table 5 continued

Station no.	Maxdu1	Begd1	Endd1	#Sdu1	#Mdu1	#Ldu1	Maxdu3	Begd3	Endd3	#Sdu3	#Mdu3	#Ldu3
26	7	Apr-02	Nov-02	58	6	0	16	Apr-00	Aug-01	32	9	5
27	9	Jan-64	Oct-64	60	4	0	19	Apr-00	Nov-01	32	10	4
28	11	Jan-02	Dec-02	55	9	0	14	Aug-87	Oct-88	31	8	4
29	15	Nov-65	Feb-67	61	3	1	19	Sep-65	Apr-67	33	13	1
30	8	Oct-72	Jun-73	54	6	0	12	Nov-00	Nov-01	34	12	3
31	8	Apr-02	Dec-02	58	5	0	14	Jan-02	Mar-03	34	9	4
32	12	Mar-02	Mar-03	47	7	2	22	Jan-02	Nov-03	27	9	5
33	15	Sep-65	Dec-66	60	5	1	14	Oct-65	Dec-66	35	14	1
34	13	Sep-65	Oct-66	61	3	1	14	Jan-02	Mar-03	36	10	3
35	7	Feb-00	Sep-00	60	4	0	18	Oct-65	Apr-67	30	11	4
36	10	Jul-87	May-88	59	6	0	18	Sep-65	Mar-67	24	16	2
37	11	Feb-62	Jan-63	55	6	0	14	Jan-02	Mar-03	29	11	3
38	8	Oct-86	Jun-87	52	8	0	15	Sep-65	Dec-66	26	10	4
39	6	Nov-91	May-92	56	5	0	18	Jan-88	Jul-89	29	11	3
40	9	Nov-65	Aug-66	53	6	0	14	Jan-74	Mar-75	34	10	5
41	8	Aug-84	Apr-85	49	8	0	13	Apr-69	May-70	30	13	2
42	13	Jul-97	Aug-98	52	6	1	28	Jun-96	Oct-98	26	10	3
43	16	Oct-74	Feb-76	56	5	1	24	Apr-74	Apr-76	21	10	6
44	9	Nov-65	Aug-66	47	7	0	18	Sep-65	Mar-67	27	11	3
45	9	Jan-88	Oct-88	46	7	0	36	Nov-00	Nov-03	26	8	5
46	9	Jan-88	Oct-88	54	7	0	25	Mar-00	Apr-02	31	9	3
47	9	Oct-02	Jul-03	52	6	0	22	Jan-02	Nov-03	34	8	4
48	12	Jul-75	Jul-76	46	8	1	21	Aug-65	May-67	24	14	2
49	11	Nov-00	Oct-01	51	6	0	13	Feb-02	Mar-03	28	14	3

Table 5 continued

Station no.	Maxdu1	Begd1	Endd1	#Sdu1	#Mdu1	#Ldu1	Maxdu3	Begd3	Endd3	#Sdu3	#Mdu3	#Ldu3
50	9	Nov-65	Aug-66	53	5	0	14	Oct-65	Dec-66	28	11	4
51	12	Mar-87	Mar-88	43	8	1	31	Jul-86	Feb-89	20	11	3
52	21	Sep-76	Jun-78	47	6	1	27	Apr-76	Jul-78	31	10	3
53	9	Feb-92	Nov-92	56	7	0	21	Sep-99	Jun-01	32	13	4
54	13	Dec-82	Jan-84	57	3	2	18	Dec-82	Jun-84	26	13	4
55	8	Feb-66	Oct-66	70	4	0	24	Jan-01	Jan-03	37	10	3
56	10	Dec-87	Oct-88	53	7	0	13	Jan-88	Feb-89	24	13	4

Maxdu shows maximum consecutive months with negative SPI value, and begd and endd indicate onset and end date of maxdu. #sdu, #mdu and #ldu explain number of occurrence (frequency) of short-, mid- and long- term drought with respect to their definitions in the methodology section. The numbers in front of the expressions indicate SPI time scale (i.e., #sdu3 shows frequency of short-term drought in SPI 3-month time scale)

Table 6 Duration and frequency in SPI 6- and 12-month time scales

Station no.	Maxdu6	Begd6	Endd6	#Sdu6	#Mdu6	#Ldu6	Maxdu12	Begd12	Endd12	#Sdu12	#Mdu12	#Ldu12
1	18	Oct-78	Apr-80	19	5	8	44	Nov-91	Jul-95	10	5	7
2	31	Dec-84	Jul-87	17	11	6	53	Feb-85	Jul-89	6	5	7
3	15	Jul-00	Oct-01	24	10	5	36	Jan-92	Jan-95	9	5	8
4	31	Dec-86	Jul-89	14	8	7	58	Dec-84	Oct-89	9	6	7
5	27	Sep-00	Dec-02	18	12	2	40	Oct-99	Feb-03	9	6	7
6	33	Sep-72	Jun-75	10	14	5	49	Nov-71	Dec-75	8	7	6
7	28	Dec-86	Apr-89	6	10	6	33	Jan-87	Oct-89	4	6	7
8	41	Apr-65	Sep-68	16	11	4	36	Oct-65	Oct-68	8	5	9
9	16	May-00	Sep-01	18	7	6	49	Nov-01	Dec-05	8	2	6
10	24	Jun-62	Jun-64	14	13	5	57	Jul-84	Apr-89	4	7	7
11	20	Sep-96	May-98	19	9	6	31	Dec-86	Jul-89	7	5	7
12	20	Sep-78	May-80	14	11	6	22	Dec-86	Oct-88	7	5	11
13	46	Apr-99	Feb-03	9	15	4	46	Jan-87	Nov-90	7	4	7
14	21	May-65	Feb-67	9	18	5	29	Nov-00	Apr-03	8	8	8
15	29	Dec-78	May-81	3	13	7	40	Nov-89	Mar-93	2	5	10
16	28	Jul-99	Nov-01	10	8	8	42	Oct-99	Apr-03	6	4	8
17	24	Oct-86	Oct-88	16	10	7	39	Nov-89	Feb-93	15	4	9
18	26	Aug-71	Oct-73	8	13	6	42	Oct-99	Apr-03	7	7	9
19	33	Jul-00	Apr-03	10	13	5	36	Nov-00	Nov-03	9	5	8
20	50	Aug-87	Oct-91	12	13	4	72	Dec-86	Dec-92	5	8	4
21	23	Nov-86	Oct-88	8	6	11	47	Oct-00	Sep-04	3	3	8
22	23	Feb-01	Jan-03	11	11	5	35	Dec-65	Nov-68	3	3	10
23	38	Feb-01	Apr-04	11	16	4	46	Nov-00	Sep-04	5	7	7
24	28	Nov-00	Mar-03	16	7	7	67	Apr-99	Nov-04	6	1	8
25	34	Nov-65	Sep-68	9	13	5	44	Jan-01	Sep-04	5	6	7
26	23	Nov-86	Oct-88	11	14	5	40	Oct-89	Feb-93	6	4	9

Table 6 continued

Station no.	Maxdu6	Begd6	Endd6	#Sdu6	#Mdu6	#Ldu6	Maxdu12	Begd12	Endd12	#Sdu12	#Mdu12	#Ldu12
27	23	Apr-89	Mar-91	8	9	7	39	Apr-88	Jul-91	6	5	7
28	18	May-00	Nov-01	11	7	11	98	Dec-84	Feb-93	2	2	6
29	29	Sep-86	Feb-89	12	9	6	31	Feb-87	Sep-89	8	4	6
30	26	Jan-01	Mar-03	10	14	6	45	Dec-00	Sep-04	10	9	7
31	23	Dec-01	Nov-03	16	12	7	51	Oct-99	Jan-04	9	6	9
32	28	Jul-99	Nov-01	10	9	8	51	Oct-99	Jan-04	9	3	7
33	17	Jun-00	Nov-01	12	14	5	36	Feb-90	Feb-93	9	6	8
34	28	Jun-99	Oct-01	14	9	7	49	Oct-99	Nov-03	14	4	7
35	21	Nov-86	Aug-88	13	9	7	50	Nov-99	Jan-04	11	5	6
36	31	Jul-86	Feb-89	16	12	4	35	Jan-01	Dec-03	10	2	9
37	43	Sep-99	Apr-03	13	11	5	23	Jan-00	Dec-01	16	11	3
38	28	Jul-99	Nov-01	10	9	8	75	Nov-86	Feb-93	4	6	6
39	26	Sep-99	Nov-01	13	9	8	51	Mar-00	Jun-04	7	2	9
40	15	Apr-03	Jul-04	20	16	2	41	Apr-01	Sep-04	7	6	8
41	19	Jul-65	Feb-67	16	9	7	35	Apr-00	Mar-03	8	6	9
42	30	Jun-96	Dec-98	10	12	4	86	Feb-92	Apr-99	8	4	6
43	60	Sep-99	Sep-04	13	5	6	65	Oct-99	Mar-05	3	3	7
44	26	Sep-99	Nov-01	9	10	9	64	Dec-99	Apr-05	7	3	9
45	50	Oct-99	Dec-03	7	9	7	55	Oct-99	May-04	4	5	7
46	54	Sep-99	Mar-04	11	9	5	61	Aug-99	Sep-04	8	6	6
47	29	Jun-99	Nov-01	10	3	10	56	Aug-99	Apr-04	7	3	8
48	47	Jan-73	Dec-76	8	13	5	53	Jan-73	Jun-77	7	5	5
49	25	Oct-99	Nov-01	10	12	7	53	Apr-00	Sep-04	9	3	8
50	17	Jun-00	Nov-01	18	15	4	53	Apr-00	Sep-04	9	7	7
51	59	Jul-86	Jun-91	12	9	4	93	Mar-85	Dec-92	7	0	7
52	27	May-76	Aug-78	15	11	4	44	Sep-76	May-80	6	6	7

Table 6 continued

Station no.	Maxdu6	Begd6	Endd6	#Sdu6	#Mdu6	#Ldu6	Maxdu12	Begd12	Endd12	#Sdu12	#Mdu12	#Ldu12
53	52	Apr-99	Aug-03	16	11	4	59	Mar-99	Feb-04	9	1	7
54	23	Nov-64	Oct-66	11	7	10	44	Oct-89	Jun-93	11	3	9
55	33	Jul-00	Apr-03	24	9	5	60	Jul-98	Jul-03	9	2	9
56	31	Aug-99	Mar-02	12	13	7	60	Sep-99	Sep-04	7	5	6

Maxdu shows maximum consecutive months with negative SPI value, and begd and endd indicate onset and end date of maxdu. #sdu, #mdu and #ldu explain number of occurrence (frequency) of short-, mid- and long- term drought with respect to their definitions in the methodology section. The numbers in front of the expressions indicate SPI time scale (i.e., #sdu12 shows frequency of short-term drought in SPI 12-month time scale)

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