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ORIGINAL PAPER

Influence of climate variation on seasonal precipitation in the Colorado River Basin

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Abstract This study analyzed the influence of large-scale climate pattern on precipitation in the Colorado River Basin. Large-scale climatic oscillations, like ENSO, PDO, NAO, and the global warming trend are associated with regional hydrologic variation. Ten types of climate indices were gathered and analyzed to investigate their influence on seasonal precipitation variation in the basin based on a linear correlation analysis and an influence index analysis. The influence index was developed in this study to measure the effect of climate variation on the seasonal precipitation in the basin. The statistical evidence achieved in this study confirms that the Colorado River Basin is subjected to the phase of climate variation. The strength of the seasonal response of precipitation to the climate variation varies in different localities in the basin. The methods of analysis used in this study were proposed in the hope that progress in understanding and modeling dynamic climatic systems can result in developing a valuable long-term forecasting model for water resources management.

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1 Introduction

Teleconnections are long distant consequences of climate anomalies affecting hydrologic processes. The studies on teleconnections have been one of the major subjects in hydrology and water resources engineering since significant connections were perceived to exist between climatic variation and regional hydrologic extremes like floods and droughts. Changes and shifts in tropical atmospheric circulation and precipitation are strongly linked to the sea surface temperature (SST), and they also influence seasonal temperature and precipitation throughout the world (Bonan 2002). Variations of SST and sea level pressure (SLP) in the ocean are significantly associated with interannual and interdecadal variations in regional and global precipitation, snow, and streamflow (Hu and Feng 2001). A number of studies have also identified the statistical significance of teleconnections throughout the world. Studies on teleconnections related to hydrology have primarily focused on extreme events, e.g., floods and droughts, examining streamflow and precipitation (Dracup and Kahya 1994; Chiew et al. 1998; Cayan et al. 1999; Hu and Feng 2001).

It has been believed that the patterns of hydrologic variation are teleconnected to the state of the climate over the ocean, especially over the equatorial Pacific (Kahya and Dracup 1994). Several modes of climatic variability in the Pacific like El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) have frequently been used as an indicator for hydrologic forecasting models (Chiew et al. 1998; Liu et al. 1998; Piechota et al. 1998; Hamlet and Lettenmaier 1999; Piechota and Dracup 1999; Gutiérrez and Dracup 2001). The ENSO is the dominant mode of the Pacific Ocean climatic oscillation. It has been noted that the ENSO is significantly teleconnected with hydrologic variations in the USA. It is well-known that wetter winters are more likely during El Niño winters in the southwest USA, and drier winters are more likely in the Pacific northwest USA with El Niño. Generally opposite patterns are seen with La Niña. Ropelewski and Halpert (1986) related precipitation and temperature over the continental USA and parts of southern Canada to the occurrence of ENSO events. The Pacific Northwest was observed to have below average monthly precipitation and above average temperature in the winter following the onset of an ENSO event, while the Southwest showed above average precipitation in the same period. Hu and Feng (2001) revealed that, when the teleconnections was active, the central USA was at a center of a deformation field in wet summer corresponding to the warmer phase of ENSO. It was also a center of a reversed flow field in dry summers corresponding to the cold phase of ENSO. Other major teleconnections are the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO), which exert a strong influence on year-to-year climate variation and evidence of long-term trends in hydrologic variations (Jones et al. 1997; Hamlet and Lettenmaier 1999).

In the Colorado River Basin, various types of climatic information have been identified for decision-making for dam operations and adaptive water resources management (Pulwarty and Melis 2001). The study described facilitated responses during the major ENSO event of 1997–1998, since dam operations and adaptive management decisions are strongly influenced by variations in regional climate. Kahya and Dracup (1994) indicated that streamflow in the region is influenced by ENSO events with respect to the geographical extent, sign, and magnitude of seasonal anomalies. For example, ENSO events are consistent with the major dry and wet spells in Arizona. Lane et al. (1999) showed that the water resources in the Colorado River Basin are highly affected by a climate scenario based on the Goddard Institute for Space Studies.

Although there have been no definite answers on physical processes on how teleconnections affect hydrologic processes on a regional and global scale, hydrologic processes are believed to be teleconnected to climate oscillations to a statistically significantly degree. The information of climate oscillation has representative statistical potentials for improving long-term streamflow and precipitation forecasts, which are useful for water resources management. In order to allocate the water resources available in a basin, the water resources management is usually accomplished according to the basin response system to climate variation. The progress in understanding and simulating climatic dynamics results in developing a valuable long-term forecasting model for water resources management in a basin. The development of a hydrologic forecast model considering teleconnections is based on the analysis of relationship between hydrologic variables as an output and climatic variations as causative inputs. The main objective of this study is to identify the linear dependence of precipitation on the climatic variation and investigate the potential influence of the dependence between them in the Colorado River Basin. The procedure of analyses performed in this study is diagrammed in Fig. 1. The following sections give a full detail of the analyses.

2 Colorado River Basin and data

The Colorado River Basin covers seven states in the southwestern USA and two states in the northern Mexico. In the basin, two largest reservoirs (Lake Mead and Lake Powell) in the USA provide municipal and industrial water for nearly 25 million people, agricultural water for 3 mil-

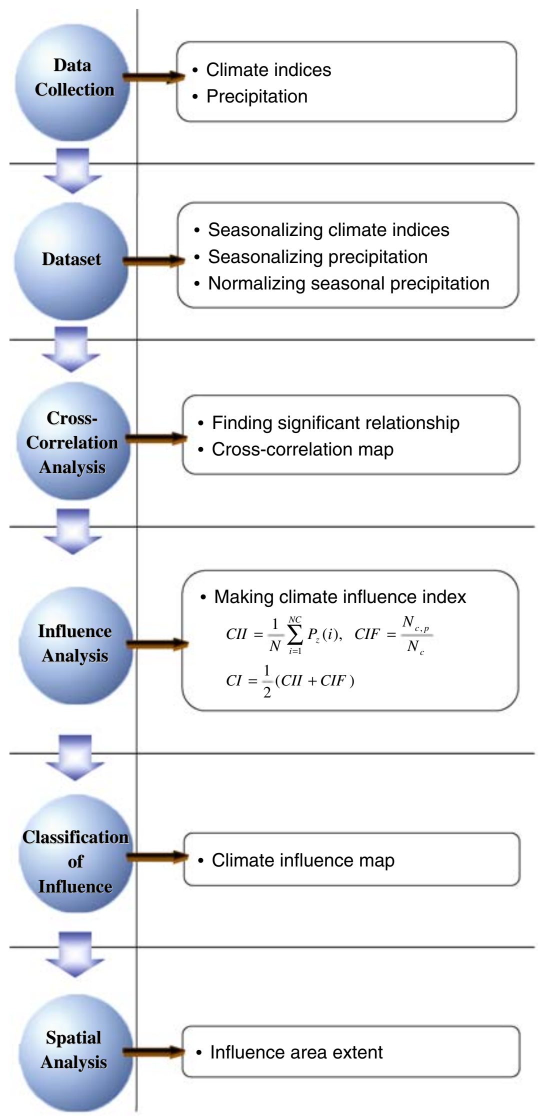

Fig. 1 Procedure of analyses for climate influence index

lion acres, and hydroelectric power for 11.5 billion kilowatt-hours (Pontius 1997), as well as controlling floods and droughts.

This study employed monthly precipitation data achieved from the National Climatic Data Center (http://www.lwf.ncdc.noaa.gov/oa/ncdc.html) and climate indices. Table 1 provides basic description of climate indices. A climate index is a simple measure developed to identify and characterize the large-scale climate circulation or the global climate change. The Southern Oscillation Index (SOI) represents the ENSO state by standardizing difference in SLP anomalies of Tahiti and Darwin (Ropelewski and Halpert 1986). The Equatorial SOI (ESOI) is the SLP difference between Indonesia and the eastern equatorial Pacific, which reflects well the La Niña condition. Ship Track 1 (ST1) is the ship-observed anomalies of the west coast of southern American SST, which has been used as an alternative ENSO index (Klein et al. 1999). The Pacific Decadal Oscillation (PDO) is a pattern of variability in the Pacific and overlying atmosphere having a characteristic cycle of 20–30 years (Mantua et al. 1997). The pattern resembles the interannual ENSO variability pattern. Streamflow, temperature, precipitation, and salmon abundance are clearly linked to this ENSO-like pattern over the last century (National Research Council 1998). The North Atlantic Oscillation (NAO) is an index representing the strength of the Icelandic climatological low and the central ridge of the Azores high. The amplitude and phase of NAO have intraseasonal to interdecadal cycles (National Research Council 1998). The average temperature of north hemisphere (ATNH) reflects the global warming trend. Another ENSO measurements are the Pacific equatorial SSTs observed in NINO12 (0°–10°S, 90°W–80°W), NINO3 (5°N–5°S, 150°W–90°W), NINO4 (5°N–5°S, 160°E–150°W), and NINO34 (5°N–5°S, 170°W–120°W).

Cordery and McCall (2000) showed that the strength of association between precipitation and climate variation varies with the data interval. The highest association between them is closely followed by three months. Therefore, hundreds of points of precipitation data and climate indices were analyzed based on seasonal values of winter (December–January–February), spring (March–April–May), summer (June–July–August), and fall (September–October–November) to evaluate and highlight the impacts of the climate variation on the Colorado River Basin in following sections.

Table 1 Descriptions of climate indices

Name	Description	Period	Source
SOI	Southern Oscillation Index	1933–2001	CPC-NWS
ESOI	Equatorial Southern Oscillation Index	1958–2001	CPC-NWS
ST1	West Coast of American Sea Surface Temperature (Ship Track 1)	1951–2001	CPC-NWS
PDO	Pacific Decadal Oscillation	1900–2000	DAS-UW
NAO	North Atlantic Oscillation	1900–2000	CGD-UCARC
ATNH	Average Temperature of North Hemisphere	1856–2000	CPC-NWS
NINO12	Sea Surface Temperature at Nino1 and 2	1950–2001	CPC-NWS
NINO3	Sea Surface Temperature at Nino3	1950–2001	CPC-NWS
NINO4	Sea Surface Temperature at Nino4	1950–2001	CPC-NWS
NINO34	Sea Surface Temperature at Nino3.4	1950–2001	CPC-NWS

• Climate and Global Dynamic Division (CGD) of University Corporation for Atmospheric Research Center (UCARC) (http://www.cgd.ucar.edu/)

• Climate Prediction Center (CPC) of the National Weather Service (NWS) (http://www.cpc.ncep.noaa.gov/data/indices/)

• Department of Atmospheric Sciences (DAS) at University of Washington (UW) (http://www.atmos.washington.edu/~mantua/abst.PDO.html)

3 Cross-correlation

The cross-correlation analysis was performed between seasonal precipitation and climate indices to determine the time dependence and their linear relationship. Since climate variations play a causative role as a precursor to certain hydroclimatologic events, the lagged relationship was examined as well as the concurrent relationship. We attempted to capture the climate index along the preceding year (lagged analysis) and the same year (concurrent analysis) of the seasonal precipitation.

Recently, progressive research results were reported on the inherent nonlinearity of hydroclimatic systems (Elsner and Tsonis 1993; Hoerling et al. 1997; Sivakumar 2000, 2004). Their studies focused on the identification of nonlinearity (or choaticity) in the climate variation and the hydrologic variation, as well as the teleconnections between them. In order to detect the nonlinearity in the hydroclimatic time series, a vast number of data are necessary. Thus, data with a short time interval such as hourly streamflow or daily precipitation were mainly used in the chaotic studies. However, water resources managers are interested in the long-term prediction to operate or allocate water resources in a basin. So, this analysis focused on the seasonal anomalies of the climate index and precipitation. This is based on that the seasonal climate variation is a slowly progressive event and a low-frequency mode of atmosphere might play an important role in a long-range prediction (Kahya and Dracup 1994).

In order to evaluate the dependence between the precipitation and the climate variation, the correlation strength was defined as the absolute cross-correlation in this study. A special effort was made to find the climate index which has a prevalent effect on the seasonal precipitation in the Colorado River Basin. As the product of the effort, Table 2 shows the percentage of significant area, which has a higher correlation strength than 95% statistical significant levels ($\pm 2/\sqrt{N}$, where N is the number of data), for the concurrent and the lagged analysis in the basin. To focus on the linear dependence of the seasonal precipitation on the climatic variability, among ten climate indices, the climate index with the highest value in Table 2 was selected as a dominant and prevalent index for the scenario and the season. The selected index has the strongest relationship in time and space with the seasonal precipitation in the basin.

In the concurrent analysis, SOI, PDO, ST1, and SOI were selected as the dominant index for the winter, spring, summer, and fall precipitation, respectively. Their spatial distributions are shown in Fig. 2. For the lagged analysis, PDO, SOI, NAO, and NAO were selected as the dominant index for the winter, spring, summer, and fall precipitation, respectively. Their spatial distributions are also shown in Fig. 3. A remarkable seasonal relationship with SOI occurred in spring and fall for the concurrent analysis. Especially, the spring precipitation was significantly correlated with PDO in the area more than 50% of the basin. However, the summer precipitation had a relatively low relationship with climate indices due to its high interannual variability. It is noted that the dependences of the concurrent analysis were stronger than the lagged analysis in the strength and areal extent. The significant concurrent correlations exist in a wider range than the significant time-lag correlation in the basin..

4 Climate influence index

Kim et al. (1998) performed the composite analysis based on the standardization of hycroclimatological variables in order to quantify the influence of ENSO in Korea. They developed the influence index, which was used as a criterion to determine how El Niño or La Niña affects natural disasters in Korea. The influence index was calculated using the classified influence intensity and influence frequency. In this study, the influence index was modified to generalize the influence intensity and frequency based on Kim et al. (1998). The climatic influence intensity (CII) and the climatic influence frequency (CIF) are defined in Eqs. 1 and 2, respectively.

$$\mathrm{CII} = \frac{1}{N_C}\sum_{i=1}^{N_C} P_Z(i) \quad (1)$$

$$\mathrm{CIF} = \frac{N_{C,P}}{N_C} \quad (2)$$

where N_C is the number of years which belong to a specific climate phase, P_Z is the normalized seasonal precipitation in the climate phase year, and $N_{C,P}$ is the number of seasons which the seasonal precipitation belongs to a specific precipitation phase among the climatic phase years.

Two conceptual climate phases were examined in this study. The positive climate phase is when the climate index is higher than the 75 percentile, while the negative climate phase is when the climate index is less than the 25 percentile. Seasonal precipitation was normalized from 0.0 and 1.0 preserving that the mean seasonal precipitation is 0.5. The normalization of seasonal precipitation dichotomizes the variation of precipitation into two phases; the increase phase and the decrease phase. When precipitation is higher than the mean, P_Z is higher than 0.5. So, P_Z higher than 0.5 represents the increase phase of precipitation. In the same way, P_Z less than 0.5 represents the decrease phase of precipitation. The value of $N_{C+,P-}$ means the number of years that the percentile of precipitation is less than 0.5 (the decrease phase of precipitation, P_{Z-}) during the climate index is higher than 75 percentile ($C+$).

Table 2 Percentage of significant area for the climate indices in the Colorado River Basin

Climate index	Concurrent analysis				Lagged analysis			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
SOI	37.24	41.94	5.87	45.75	3.23	28.45	1.76	1.76
ESOI	28.74	19.35	7.04	23.75	4.99	2.64	4.99	1.47
ST1	21.7	31.67	14.08	32.55	2.05	2.64	3.23	2.93
PDO	11.73	57.48	5.87	22.87	13.2	6.45	4.11	3.23
NAO	2.05	11.73	5.87	12.9	2.35	14.37	5.28	5.57
ATNH	13.2	15.54	2.05	1.17	3.81	2.35	2.93	2.35
NINO12	17.89	21.7	13.78	30.79	1.76	2.64	3.52	3.23
NINO3	12.02	30.21	10.85	34.02	2.35	3.52	2.05	1.17
NINO4	27.57	41.06	4.69	34.31	1.76	3.23	0.59	0.29
NINO34	20.23	43.99	7.04	34.90	2.64	0.29	0.88	0.29

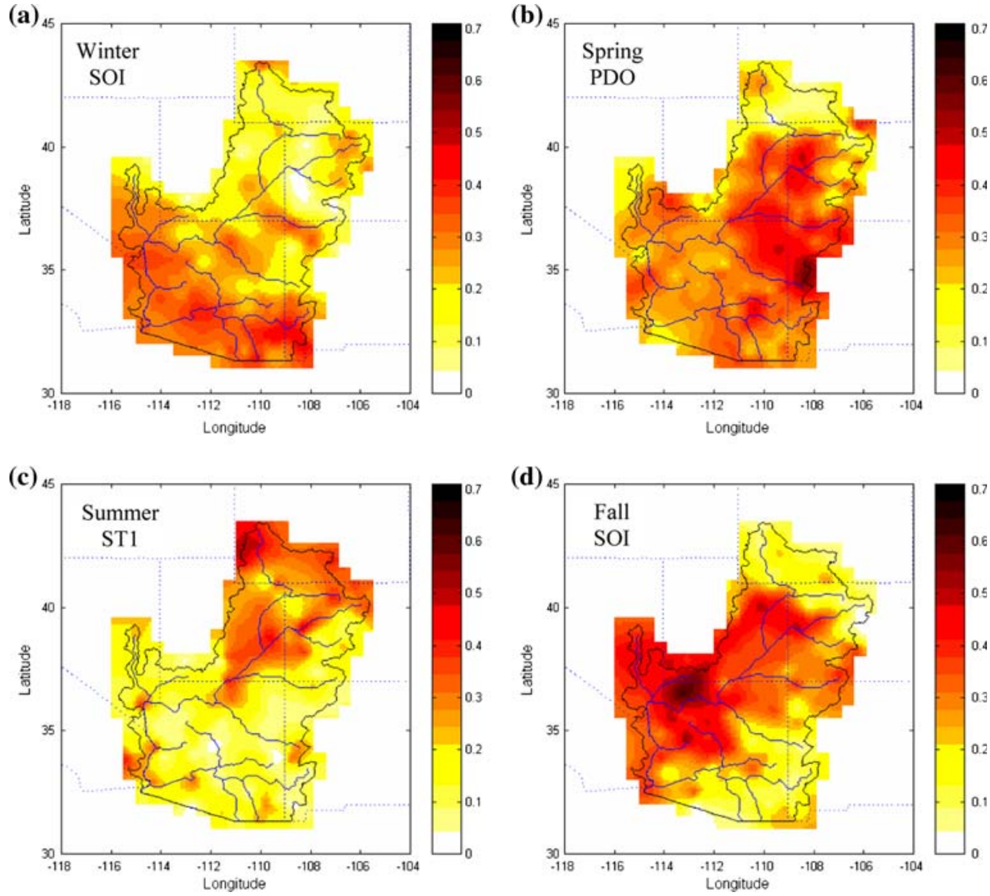

Fig. 2 Cross-correlation map for the concurrent analysis

The climate influence index (CI) is an arithmetic mean value of the influence intensity (CII) and the influence frequency (CIF), which measures how the climate variation affects the seasonal precipitation in both intensity and frequency. The CI is a non-dimensional index ranging from 0.0 to 1.0, and classified into five categories as shown in Table 3. Extreme decrease (ND) represents the case that, on the average, the amount of seasonal precipitation is less than 0.25 of the normal precipitation, and the probability of occurrence of increasing precipitation is less than 25% during the specific climate phase. Extreme increase (EI) indicates that, on the average, the amount of seasonal precipitation is more than 0.75 of the normal precipitation and the probability of occurrence of increasing precipitation is higher than 75% during the identified climate phase. If the amount of precipitation is large but the probability of occurrence of increasing precipitation is low, the influence index would be classified into NE (no effect).

The concurrent and lagged cases were examined, and Figs. 4, 5, 6 and 7 show the climate influence map for four seasons, respectively. The text in the first line indicates the phase of climate index, and the text in the second line means the case of analysis. For example, ''Negative'' and ''Concurrent'' in Fig. 4a means the negative phase of SOI (the dominant index in winter for the concurrent analysis is the SOI) and the concurrent analysis, while ''Positive'' and Lagged'' in Fig. 4d means the positive phase of PDO (the dominant index in winter for the lagged analysis is the PDO) and the lagged analysis (refer to Table 2). Each influence map displays the area extent according to the influence class in Table 3.

Noticeable decreases of precipitation occur concurrently in winter for positive SOI phase (Fig. 4c), and in fall for positive SOI phase (Fig. 7c). Winter precipitation tends to decrease concurrently with a positive SOI with a large areal extent (Fig. 4c). The negative PDO in fall decreases winter precipitation as well (Fig. 4b). The positive phase of SOI (the La Niña condition) tends to enhance the effect of the negative phase of PDO to decrease precipitation in winter as shown in Fig. 4b and c.

In the spring, precipitation is apt to decrease for the negative PDO in the same year (Fig. 5a) and increase for the negative winter SOI (Fig. 5b). In the summer, precipitation in a north region increases in the positive phase of summer ST1 (Fig. 6c), and in some area precipitation decreases with the positive phase of spring NAO (Fig. 6d). In the fall, precipitation has a tendency to increase with the negative

Fig. 3 Cross-correlation map for the lagged analysis

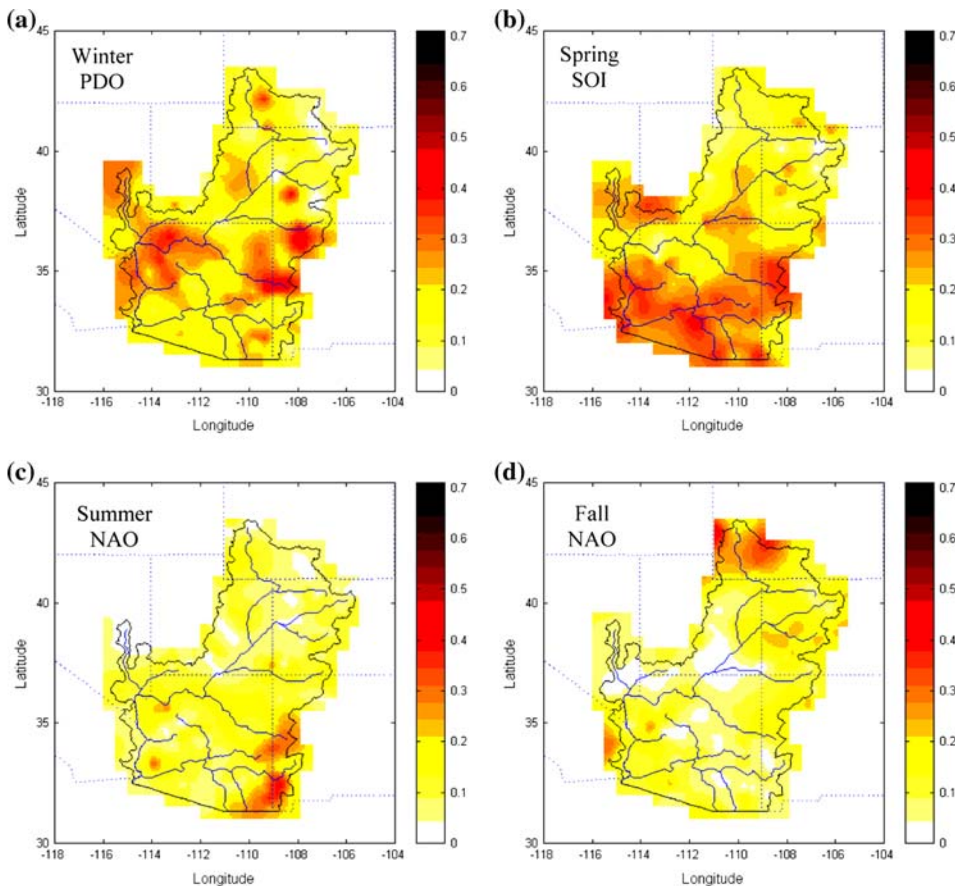

Table 3 Classification of climate influence

Class	Range of index	Note
ED	$0 \le CI < 0.25$	Extreme decrease
MD	$0.25 \le CI < 0.4$	Moderate decrease
NE	$0.4 \le CI < 0.6$	No effect
MI	$0.6 \le CI < 0.75$	Moderate increase
EI	$0.75 \le CI \le 1.0$	Extreme increase

phase of SOI and decrease with the positive phase of SOI in the same year (Fig. 7a, c). Especially, fall precipitation decrease extremely when the SOI is in a positive phase in the same year with large areal extent. The results confirm that El Niño (negative SOI phase) and La Niña (positive SOI phase) affect precipitation in the distinctly antithetic way in the Colorado River Basin.

Figure 8 shows the climate influence area extent in the Colorado River Basin. In general, NE dominates a large area, but a significant increase of precipitation is shown in spring (negative lagged case), summer (positive concurrent case), and fall (negative concurrent case). A large area in a basin is subjected to a decrease of precipitation in winter (negative lagged case), spring (negative concurrent case), summer (positive lagged case), and fall (positive lagged case).

5 Discussions

Several empirical studies have been conducted to provide explicit evidence that there are inherent nonlinearity in the climate anomalies and their interaction with the regional hydrologic variations (Elsner and Tsonis 1993; Hoerling et al. 1997; Sivakumar 2000, 2004). Due to present technical difficulties such as sampling and downscaling problems, however, the nonlinear component of the climatic response has not been explored throughout the world. The comfortable way in practice to understand the inter-relationship between the climate and the regional hydrologic variation is to consider the dominant linear component. Although the idealized linear relationship may forfeit the sensitivity of the hydrologic response to the climate variation, the linearity is still useful in the construction of a forecasting model in practice for the management of regional water resources (Chiew et al. 1998; Liu et al. 1998; Piechota et al. 1998; Hamlet and Lettenmaier 1999; Pie-

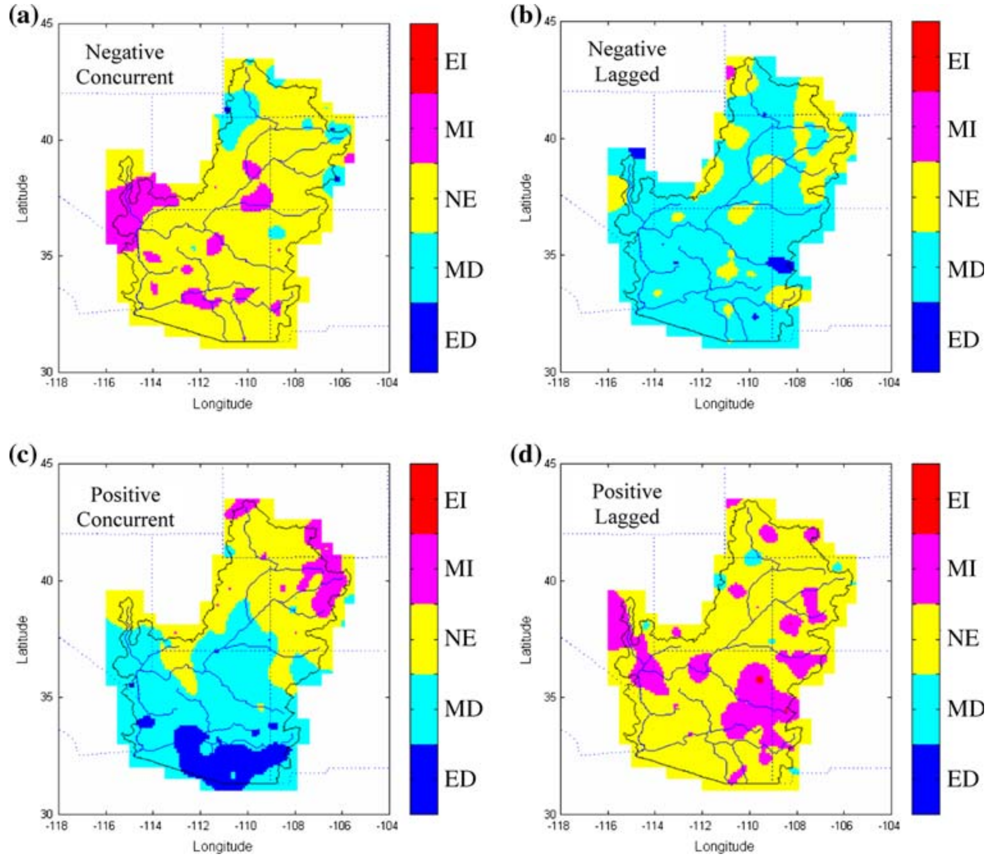

Fig. 4 Climate influence map for winter

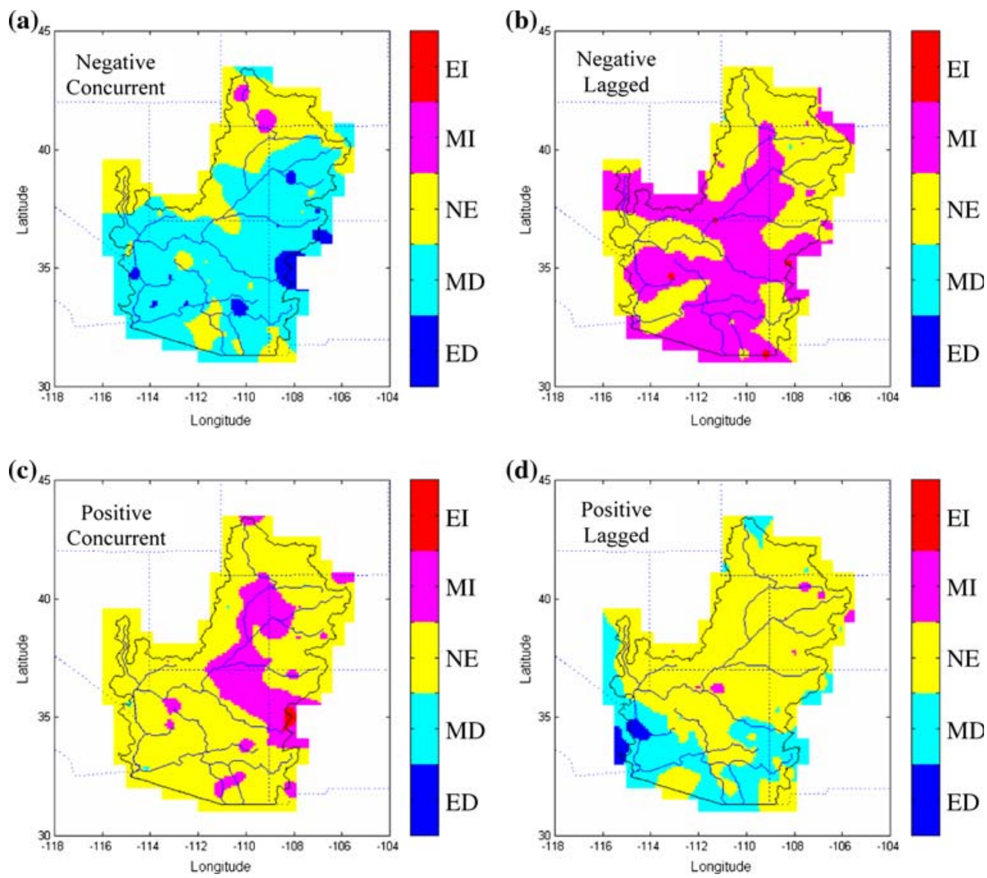

Fig. 5 Climate influence map for spring

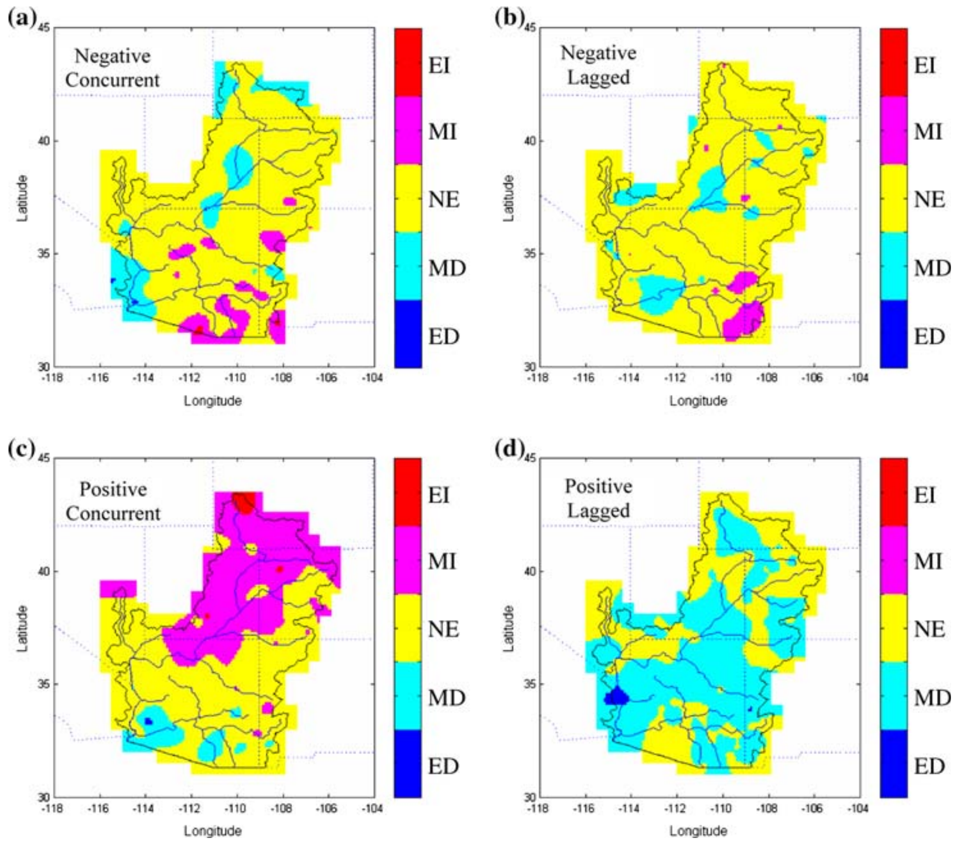

Fig. 6 Climate influence map for summer

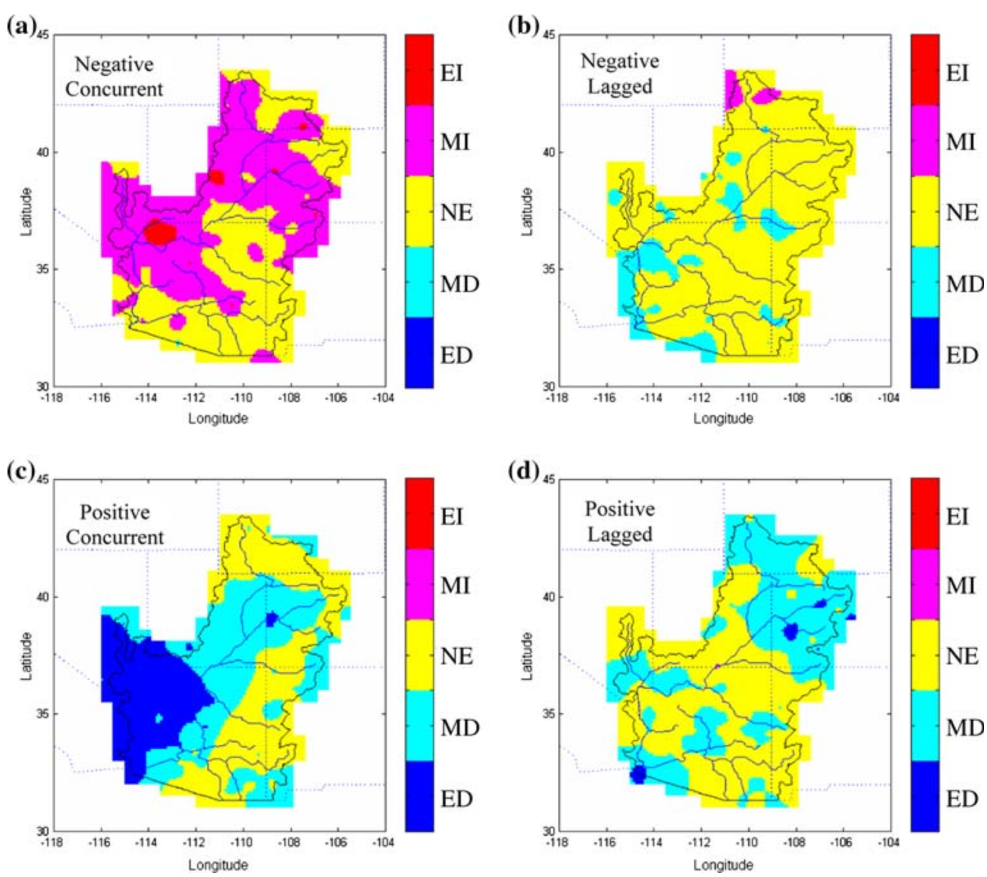

Fig. 7 Climate influence map for fall

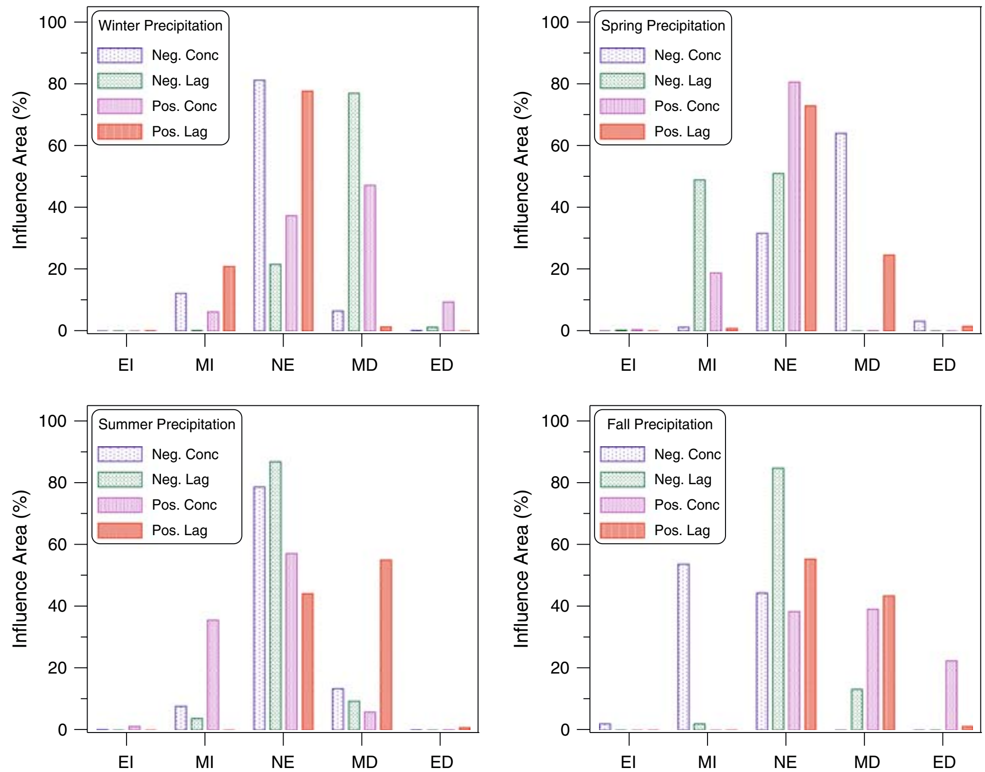

Fig. 8 Percentage of influence area in the Colorado River Basin

chota and Dracup 1999; Cordery and McCall 2000; Gutiérrez and Dracup 2001; Pulwarty and Melis 2001).

Based on the assumptions that the linear relationship between the climate and the regional hydrologic variations prevails in the Colorado River Basin, Kim et al. (2006) proposed the climate influence index to quantify the strength of linkage between the large-scale climatic patterns and the regional precipitation in the basin. Kim et al. (2006) employed the SOI and the PDO to represent the large-scale climatic variability. Although there are many studies to illustrate that the SOI and the PDO are mainly teleconnected with the precipitation variability in the USA (Ropelewski and Halpert 1986; Kahya and Dracup 1993, 1994; Dracup and Kahya 1994; Mantua et al. 1997; Cayan et al. 1999; Hu and Feng 2001; Pulwarty and Melis 2001), it is still necessary to investigate the influence of other climate indices. In this study, ten types of climate indices were gathered and analyzed their influences on the seasonal variability of precipitation in the basin. The results confirm that the Colorado River Basin is subjected to the climate patterns represented by the SOI and the PDO. It is also necessary to consider the climate pattern which is at times represented by the combination of plural climate indices (Kim et al. 2006). Since we concerns extreme climate phases like El Niño and La Niña, however, the historical record is too short to fully evaluate various climate patterns at a time. In addition, the empirical approach using the short historical measurements gives rise to a problem of reliability. The Monte Carlo simulation technique is one of practical solution to this problem (Zhang et al 2004).

We would argue that some benefits can accrue in using the classification of climate influence. The climate influence was classified in this study based on the value of the climate influence index in Table 2. Kim et al. (2006) used the standardized precipitation index (SPI) to represent standardized precipitation anomalies. The wetness condition in the basin was expressed by the SPI values in the influence maps in their study. This is nice to analyze the influence phenomenon classified based on the SPI values. However, a decision maker needs explicit classification criteria to determine the allocation of the limited water resources in a basin. The influence maps constructed in this study provide a spatial distribution of the climate influence conditions classified into 5 categories. The maps provide valuable information to the decision makers for the water resources management in the basin.

6 Summary and concluding remarks

This study sought to develop a conceptual statistical framework for the analysis of the climate influence on seasonal precipitation in the Colorado River Basin. Cross-correlation maps were constructed to examine the general trend of relationship between the seasonal climate index and precipitation. Based on the constructed cross-correlation maps and hypothesis that the climate pattern is the causal factor to the seasonal variability of precipitation, statistically conceptual influence index was developed and examined in the Colorado River Basin. No index exists to dominate the seasonal variability of precipitation in the whole basin. However, the strength of the seasonal response of precipitation to the climate pattern varies significantly in different locality in the basin.

The negative PDO condition reduces the extent of decrease in the winter precipitation associated with the La Niña condition. Increases in the summer precipitation are combined with the positive ST1 index, while decreases in the summer precipitation were affected by the positive NAO condition. Increases in the spring precipitation are led by El Niño-like variability, and the fall precipitation is affected by ENSO fluctuations. The phases of SOI affect the fall precipitation in opposite direction. These results indicate that there are no persistent influences of the teleconnections variation on the seasonal precipitation in the Colorado River Basin, but they provoke the controversy over the influence of teleconnections on the precipitation variations, of which researches have been concentrated on the effect of ENSO on summer and winter precipitation.

The analysis methods used in this study were proposed in the hope that the structured pattern of variations in the long-term dynamics of climate system is used to explain enhanced and depressed frequency of seasonal precipitation. It is noteworthy to point out that a predictive framework for precipitation conditioned climate state can be developed based on correctly capturing the role of teleconnections. In this case, it would be useful for flood and drought control planning and their risk assessment for large basins.

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