



A perturbation approach for assessing trends in precipitation extremes across Iran



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SUMMARY

Extreme precipitation events have attracted a great deal of attention among the scientific community because of their devastating consequences on human livelihood and socio-economic development. To assess changes in precipitation extremes in a given region, it is essential to analyze decadal oscillations in precipitation extremes. This study examines temporal oscillations in precipitation data in several sub-regions of Iran using a novel quantile perturbation method during 1980–2010. Precipitation data from NASA's Modern-Era Retrospective Analysis for Research and Applications-Land (MERRA-Land) are used in this study. The results indicate significant anomalies in precipitation extremes in the northwest and southeast regions of Iran. Analysis of extreme precipitation perturbations reveals that perturbations for the monthly aggregation level are generally lower than the annual perturbations. Furthermore, high-oscillation and low-oscillation periods are found in extreme precipitation quantiles across different seasons. In all selected regions, a significant anomaly (i.e., extreme wet/dry conditions) in precipitation extremes is observed during spring.

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1. Introduction

There is a general agreement that the global climate is undergoing a noticeable change, leading to intensified hydrological cycles due to increased atmosphere's moisture holding capacity (Trenberth, 2011). More frequent occurrences of extreme precipitation events over a large part of the land have been highlighted by the Intergovernmental Panel on Climate Change 4th and 5th Assessment Reports (IPCC, 2007, 2013). However, trends and patterns of precipitation vary substantially in different regions, with no clear and uniform trend across the globe (Sheffield et al., 2012; Damberg and AghaKouchak, 2014).

Study of precipitation extremes is of paramount importance for policymakers, as these events can result in devastating floods and droughts. Given the impacts of extreme precipitation events on human society and ecosystems, the variability and change in precipitation extremes have been increasingly studied on local and global scales (Kiktev et al., 2003; New et al., 2006; Di Baldassarre et al., 2006; Endo et al., 2009; Pal and Al-Tabbaa, 2011; AghaKouchak and Nasrollahi, 2010; Nyeko-Ogiramoi et al., 2013;

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Willems, 2013a, 2013b). At global scale, Frich et al. (2002) showed that heavy precipitation events have become more frequent in some parts of the world (i.e., southern Africa, southeastern Australia, western Russia, parts of Europe and eastern USA) during the second half of the 20th century. In another study, Alexander et al. (2006) found a widespread and significant increase in precipitation extreme and also a much less spatial coherency for precipitation changes compared with temperature changes. Zhang et al. (2005) showed that the trends in precipitation indices, including annual total precipitation, number of days with precipitation, and maximum daily precipitation, are generally weak and insignificant for the Middle East region, and there is no spatial coherence in the trends. Damberg and AghaKouchak (2014) analyzed wetting and drying trends across the globe and showed significant regional wetting and drying trends, but no significant trend in the average global precipitation.

Most previous studies on precipitation trends in Iran indicate insignificant trends across a wide range of spatial and temporal scales (Soltani et al., 2011; Tabari et al., 2011, 2012; Tabari and Aghajanjloo, 2013; Fathian et al., 2014; Dhorde et al., 2014), though Rahimzadeh et al. (2009) reported both negative and positive trends for precipitation-based indicators. Nevertheless, there is an evidence of a significant decreasing trend in precipitation over the northwestern regions of Iran (Tabari and Hosseinzadeh

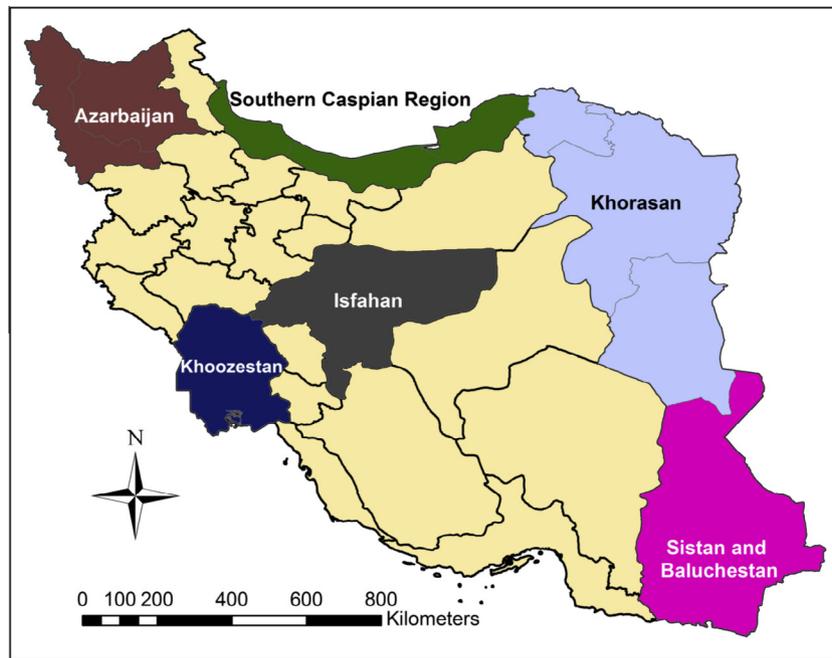


Fig. 1. Study areas in Iran Map.

Talae, 2011; Shifteh Some'e et al., 2012; Golian et al., 2014). In a recent study, Madani (2014) highlights Iran's water crises including depleting groundwater levels, drying lakes, water supply, and extreme events. With nearly 85% of the country being in semi-arid and arid climates, the country faces both prolonged droughts, as well as floods. In the past two decades, floods have affected 11 million people in Iran and caused over 2600 fatal casualties (Madani, 2014; DOE, 2010). This highlights the importance of monitoring and assessing extreme precipitation across Iran.

Precipitation estimates over land areas are typically derived from surface rain gauge observations at automated or human-operated sites (Lockhoff et al., 2013). Rain gauges, although they provide longer records (Yatagai et al., 2009), are limited in sampling precipitation for continental and global applications (Nastos et al., 2013). In most regions of the world, rain gauges do not provide a reliable spatial representation of precipitation (Gruber and Levizzani, 2008), especially over oceans, deserts and mountainous areas. In addition, surface rain gauge observations are very inhomogeneously distributed in space and often suffer from substantial missing data, resulting in inadequate temporal and spatial sampling (Lockhoff et al., 2013) especially in developing countries. One of the main limitations of gauge-based trend analysis over Iran is that large areas of the country do not have sufficient observations (eastern, and southeastern Iran) in temporal and spatial scales.

On the other hand, global land-surface, land-atmosphere models, and satellite observations provide spatially and temporally homogeneous precipitation information at a quasi-global to global scale. In this study, precipitation data are obtained from NASA's Modern-Era Retrospective Analysis for Research and Applications-Land (MERRA-Land; Reichle et al., 2011), which is based on a fully coupled land-atmosphere that integrates satellite observations. Following the Intergovernmental Panel on Climate Change (IPCC, 2001) decadal analysis for climate change assessment, this study investigates decadal anomalies in extreme precipitation quantiles in several sub-regions of Iran during 1980–2010.

Previous studies for the trend analysis of hydrological variables have used mostly non-parametric tests such as Mann–Kendall and Spearman. These statistical tests are rank-based methods which

take the ranks of measurements into consideration rather than their actual values, and hence they are effective for hydrological records which are usually positively or negatively skewed (non-normally distributed). However, a limitation associated with these statistical tests is that their results are often influenced by serial correlation in the time series. Specifically, a positive serial correlation, that is likely the case for most hydroclimatological data, would increase the chance of incorrectly rejecting the null hypothesis of no trend or vice versa. Albeit several methods have been developed for removal of significant serial correlation from time series, it is helpful to use a method which does not depend on such restrictive assumptions. Thus, in this study, a rather novel approach named quantile perturbation method (QPM; Ntegeka and Willems, 2008; Willems, 2013a) which is not dependent on the above-mentioned assumptions is utilized for analyzing the anomalies. This approach is analogous to the frequency-perturbation method which has been applied in several climate change studies (e.g., Harrold et al., 2005; Chiew, 2006; Mpelasoka and Chiew, 2009; Willems and Vrac, 2011; Ntegeka et al., 2014) for construction of future climate change scenarios from climate models.

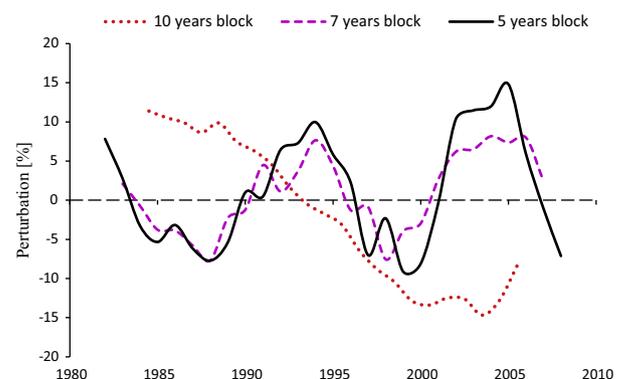


Fig. 2. Comparison between extreme precipitation perturbations of different block lengths in Azarbaijan region.

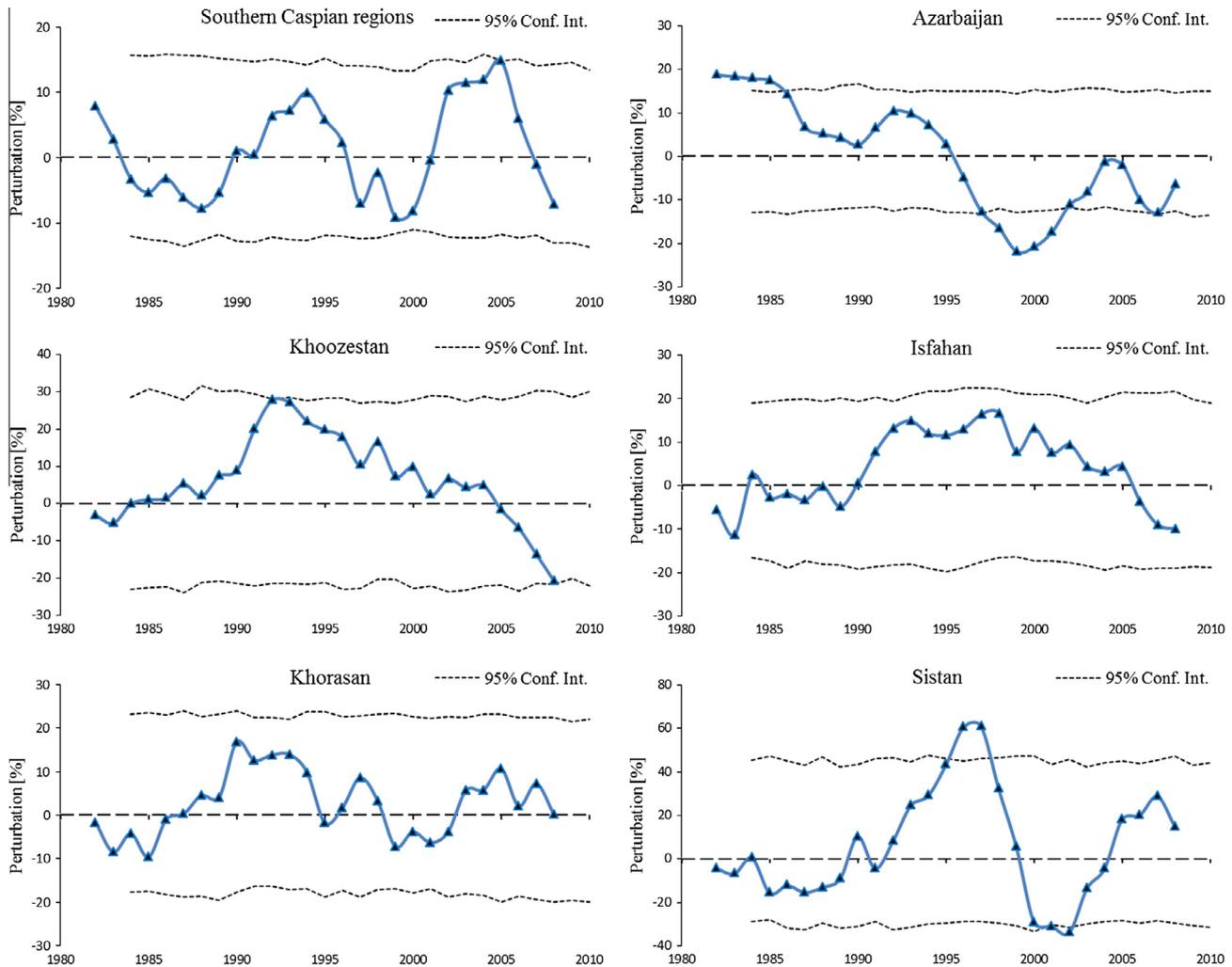


Fig. 3. Extreme precipitation perturbations using 5-year blocks together with 95% confidence intervals to define statistically significant perturbations.

2. Materials and methods

2.1. Data

This study analyzes temporal oscillations in precipitation series in several sub-regions of Iran over a 31-year period (1980–2010). The sub-regions are chosen from different regions (Fig. 1) with distinct climatic conditions. The climate of the country is strikingly influenced by the Alborz and Zagros mountain ranges and two great deserts called Dasht-e Lut (Emptiness Desert) and Dasht-e Kavir (Great Salt Desert). The northern part of the country (southern coasts of the Caspian Sea) has a humid climate. In this region, air temperatures rarely fall below freezing during winter and the region remains humid for the rest of the year. Adversely, an arid/hyper-arid climate is dominant over the southeastern part of the country. Indeed, this part is one of the driest regions of Iran, and the world. The central and northeastern parts are characterized by arid and semi-arid climate conditions, while the northwestern part being in a mountainous region has a cold semi-arid climate. The northwestern part is generally the coldest region of the country, with heavy snowfall and subfreezing temperatures during December and January. The climate of the southwestern part is generally hot and occasionally humid.

For this study, precipitation data were obtained from the MERRA-Land dataset. MERRA data are generated based on an updated modeling and assimilation system that ingests data from many

modern observing systems and focuses on historical analyses of the hydrological cycle on a broad range of weather and climate time scales. MERRA-Land precipitation forcing is based on merging a gauge-based data product from the NOAA Climate Prediction Center with MERRA precipitation (Reichle, 2012). MERRA-Land provides hydrologic and land-surface data at a horizontal resolution of $2/3^\circ$ longitude by $1/2^\circ$ latitude from 1 January 1980 onwards. MERRA data has been widely used in both research and operational systems (Bosilovich et al., 2011; Rienecker et al., 2011; Hao et al., 2014). In this work, monthly averaged MERRA-Land data were used for the anomaly analysis.

2.2. Decadal anomaly of precipitation extremes

The quantile perturbation method is used to analyze decadal anomalies in precipitation extremes. The method initially considers the frequency aspect of time series which focuses on the frequency of occurrence of a quantile (time series values for given empirical probabilities being exceeded or for given mean recurrence intervals), and then the perturbation aspect which determines the relative magnitudes of quantiles based on a certain baseline. By compounding the two aspects, the method provides the opportunity to analyze changes in the time series values for a particular return period. In other words, this method calculates anomalies in extreme value quantiles between the full time series (a 31-year monthly precipitation series in our case) as a baseline

period and a selected subseries of the full historical period (hereafter, a block period). The calculation of the perturbation factor of the QPM method for the time series involves the following steps:

1. Derive subseries from the full time series.

For this study, block periods of 5, 7 and 10 years with a sliding window of 1 year were selected. For a baseline period of 1980–2010 and given a 5-year block length, the following subseries are considered: 1980–1984, 1985–1989, 1990–1994, . . . With a sliding window of one year, the following subseries are produced: 1981–1985, 1986–1990, 1991–1995. . .

2. Sort the time series values in descending order for each block period.
3. Calculate empirical return periods according to the ranks of the values (n/i , where n and i are the length of block period and rank, respectively; $i = 1$ for the highest value).
4. Perform steps 2 and 3 for the baseline period.
5. Calculate relative change as the ratio of the extreme value in the block period to the extreme value in the baseline period with the same return period.
6. Calculate perturbation factor for each block period as the average of all relative changes; Then, obtain anomaly values for the return periods above an extreme threshold (a threshold above which the values are considered as “extreme”).

The threshold used in this study will select three highest precipitation values in each year.

The above mentioned procedure was applied to examine anomaly in precipitation extremes for each region separately. Moreover, the analysis was done for the extreme values in each season. In this seasonal analysis, given block periods are restricted to the months of each season.

2.3. Statistical significance of precipitation anomaly

The significance of the perturbation factors in extreme quantiles is tested using the non-parametric bootstrapping method. The confidence intervals are computed to check the perturbation factors in which periods are statistically significant under the null hypothesis of randomness. The perturbation factors between the upper and lower limits of the confidence interval (the region of acceptance of the null hypothesis) are considered insignificant, whereas those outside the region of acceptance of the null hypothesis are defined as statistically significant. For the calculation of the confidence intervals, the values in the full time series at each site are randomly resampled to make a new series with different sequence, and the anomalies are recalculated for the resampled series based on the QPM method. The anomaly calculations are repeated 1000 times, leading to 1000 anomaly values for each block period. After ranking of the 1000 anomaly factors, the 25th and 975th values define the 95% confidence intervals for each block period.

3. Results and discussion

The selection of an appropriate block length is the first step for application of the QPM method. Our preliminary analysis indicated that a block length of 5 years can represent a better illustration of oscillation patterns (high & low) in precipitation extremes in comparison to longer blocks lengths (Fig. 2). Hence, a 5-year block was chosen in this study.

The quantile perturbations of precipitation extremes are shown in Fig. 3. The perturbation factors for the 1980s are within the confidence interval limits for all regions except Azarbaijan, indicating

insignificant anomalies in precipitation extremes in this period. For the 1990s, higher perturbations as well as lower perturbations are found for the southern Caspian regions, Azarbaijan and Khorasan. Further, precipitation extremes in Khoozestan, Isfahan and Sistan reveal a positive anomaly in the 1990s. These positive anomalies are statistically significant only for Sistan, in which the extreme precipitation quantiles are around 61% higher than those based on the full time series (Table 1). In addition, a low oscillation period is observed for Azarbaijan during the late 1990s and the early 2000s, with a significant change of 22%. There is also a significant negative anomaly in extreme precipitation quantiles in the 2000s for Sistan. The magnitude of this negative anomaly is 34%. The country has experienced the driest years for the last 50-year period during 1999–2001 and the mean surface water flow in the water years of 1998/9 and 1999/2000 showed a decline of 41.5 and 55.5%, respectively (Abbaspour and Sabetraftar, 2005; Golian et al., 2014). Another noteworthy anomaly is a near significant positive anomaly in the precipitation extremes in the 2000s for the southern Caspian regions. In recent years, the southern Caspian regions experienced several devastating floods. For instance, the destructive flood in August 2001 on the southeastern Caspian regions caused around 300 human casualties and \$ 60 million damage (Panahi et al., 2010). In the remaining regions, the anom-

Table 1
Characteristics of highest anomaly in the considered regions.

Region	Magnitude of highest anomaly (%)	Sign of highest anomaly	Time of highest anomaly
Southern Caspian regions	14.83	Positive	2000s
Azarbaijan	21.91	Negative	1990s
Khoozestan	27.65	Positive	1990s
Isfahan	16.63	Positive	1990s
Khorasan	16.78	Positive	1990s
Sistan	60.78	Positive	1990s

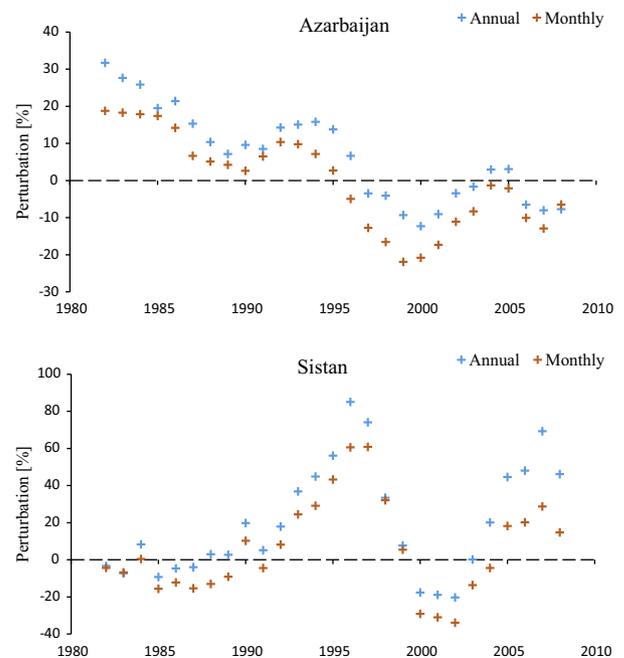


Fig. 4. Comparison between extreme precipitation perturbations for monthly and annual aggregation levels using 5-year blocks together with 95% confidence intervals to define statistically significant perturbations.

alies in the extreme precipitation quantiles in the 2000s are not statistically significant. Overall, there is an evidence of significant anomalies in precipitation extremes in the northwest and southeast regions of Iran. This is in line with the long-term trends reported for ground-based precipitation observations in these regions (Tabari and Hosseinzadeh Talaei, 2011). It is also worthwhile to note that the highest perturbation factor for almost all regions is observed in the 1990s (Table 1).

In order to explore the effect of aggregation level on the detected anomalies, the anomalies in precipitation extremes for the monthly aggregation level are compared to those for the annual level as shown in Fig. 4 for two selected regions. A similar behavior is observed for both aggregation levels, though the perturbations for the monthly aggregation level are generally lower than the annual perturbations. This is not consistent with results of Ntegeka and Willems (2008) where they found that the perturbations of daily ground-based precipitation extremes are lower than those of 10-min precipitation extremes.

The anomalies in extreme precipitation quantiles are also identified for each season (Figs. 5–8). From Fig. 5 it is evident that, there are significant anomalies for the winter period (DJF) over the southern Caspian regions, Azarbaijan and Khorasan. The high oscillation period in the late 1980s in the northern part of Iran (southern Caspian regions) is also seen in the northeastern part (Khorasan). The late 1990s show a dominance of significant

negative anomalies over the southern Caspian regions with changes up to around 40%. Shifteh Some'e et al. (2012) also found that a significant decreasing trend in in-situ precipitation observations over southern Caspian regions started in the 1990s. The significant positive anomaly of precipitation extremes in the 1990s over Azarbaijan remained significant when only the extreme values in the DJF period are considered, although the pattern changed. Moreover, the positive anomaly of precipitation extremes over Khorasan in the late 1990s became significant when only the extreme values in the DJF period are considered. For Sistan, the confidence interval bounds are wide for DJF and the anomalies are statistically insignificant. Regarding the extreme precipitation anomalies in the DJF period for Khoozestan and Isfahan, the most relevant observation is the absence of significant anomalies. Although a limited number of significant trends were reported for Iranian precipitation, but the highest number was obtained for the winter season (Tabari and Hosseinzadeh Talaei, 2011; Shifteh Some'e et al., 2012).

For the spring period (MAM), all surveyed regions indicate significant oscillations with changes up to 200% (Fig. 6). In the 1980s, high oscillation in precipitation extremes is only found to be significant over Azarbaijan. The anomalies in extreme precipitation quantiles show a dramatic positive change over Khoozestan, Isfahan and Sistan during the 1990s. A significant low perturbation is observed in extreme precipitation over southern Caspian regions

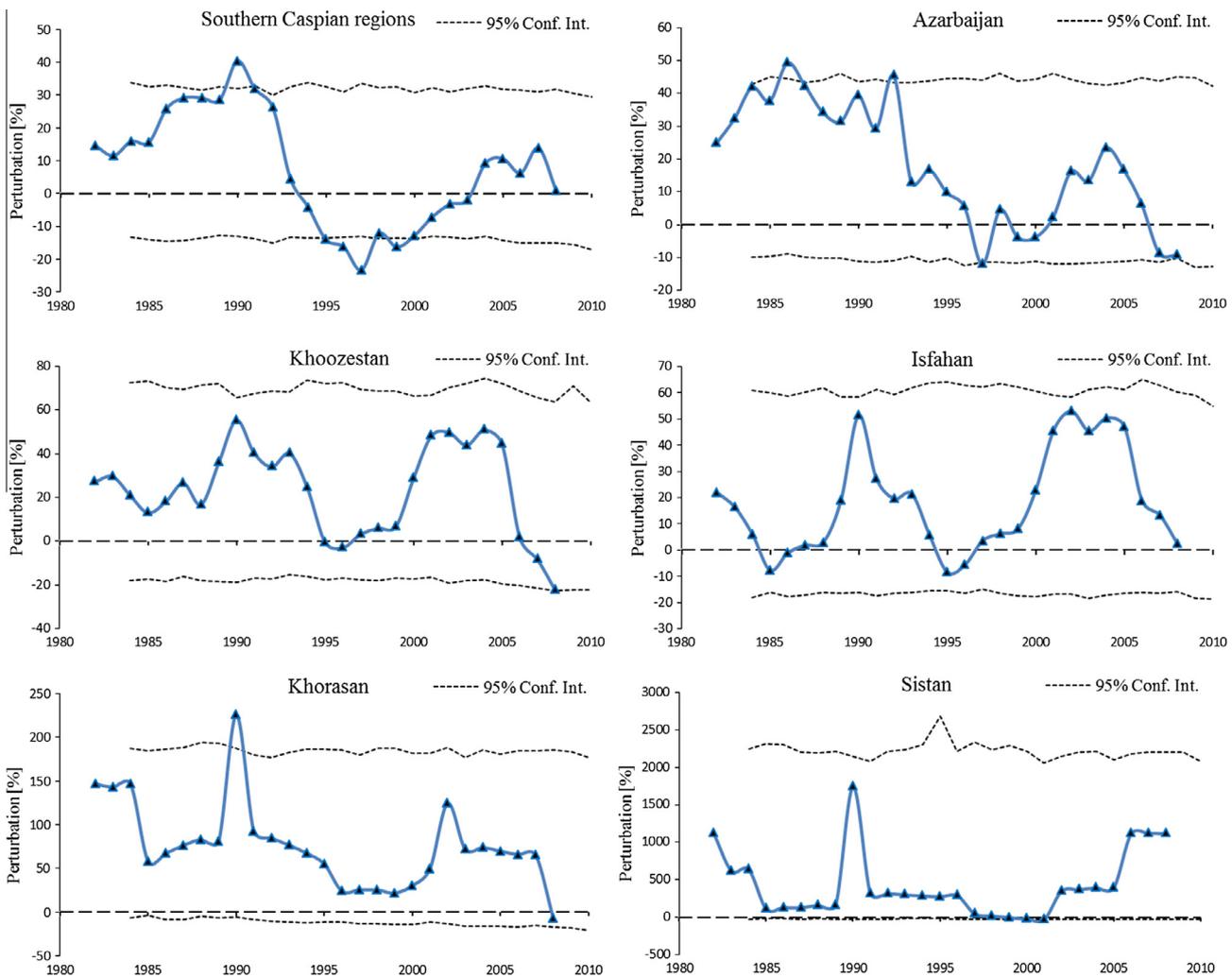


Fig. 5. Extreme precipitation perturbations using 5-year blocks for winter period (DJF) together with 95% confidence intervals to define statistically significant perturbations.

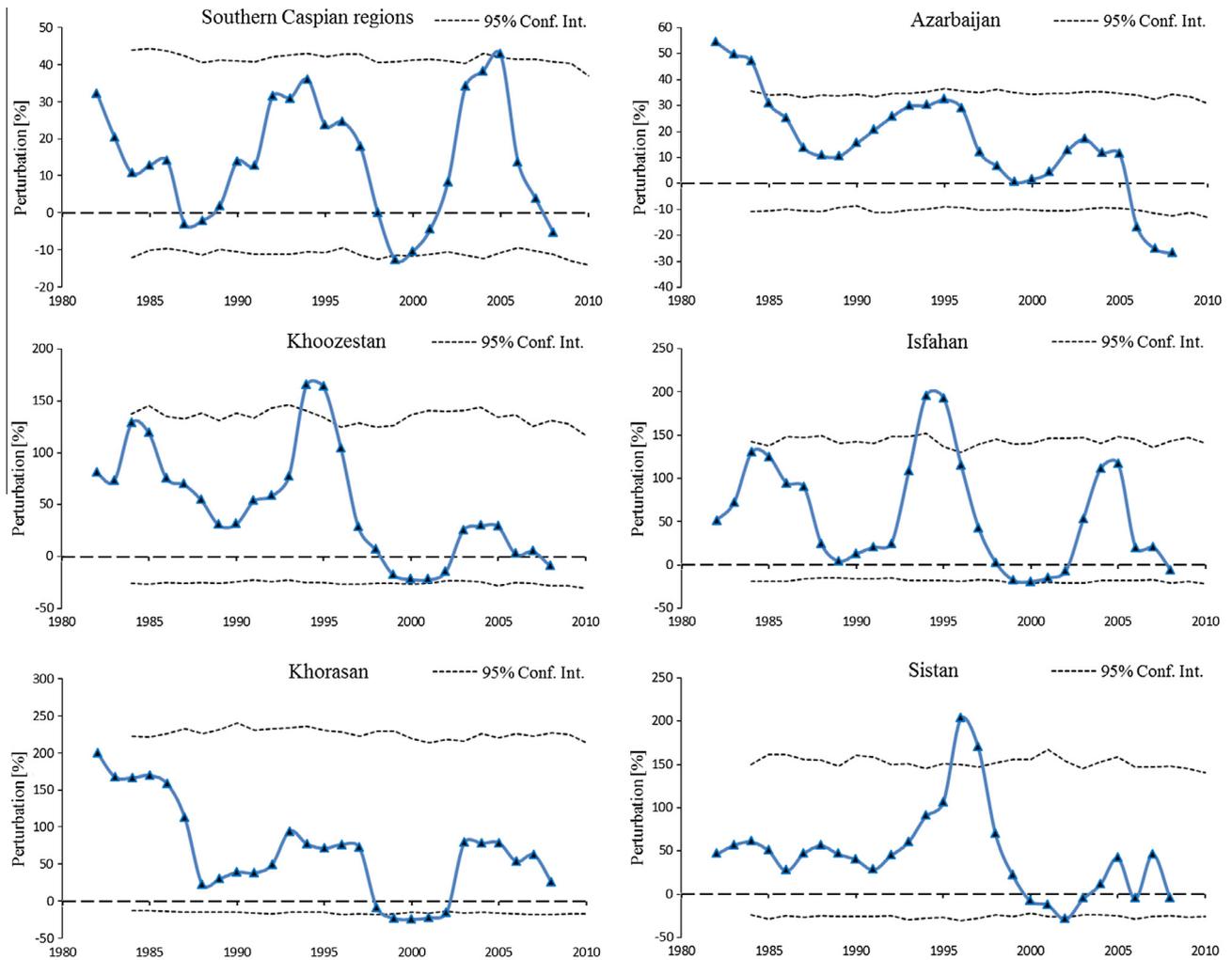


Fig. 6. Extreme precipitation perturbations using 5-year blocks for spring period (MAM) together with 95% confidence intervals to define statistically significant perturbations.

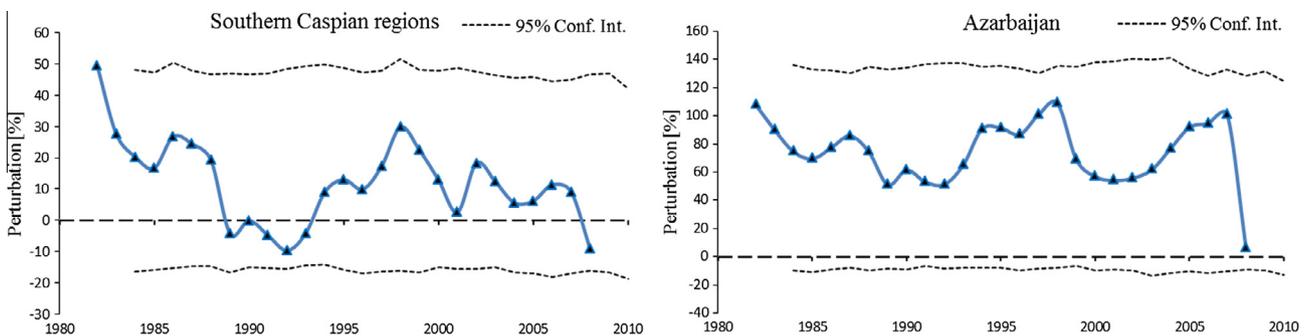


Fig. 7. Extreme precipitation perturbations using 5-year blocks for summer period (JJA) together with 95% confidence intervals to define statistically significant perturbations.

and Khorasan in the late 1990s and the early 2000s. In the 2000s, the plots of the QPM method also exhibit a significant negative anomaly over Azarbaijan, a near significant negative anomaly over Isfahan, Khoozestan and Sistan and a near significant positive anomaly over southern Caspian regions. As a whole, it can be stated that the anomaly pattern in spring extreme precipitation quantiles in the central part of the country (Isfahan) is very similar to that in the southeastern part (Khoozestan).

The anomaly in extreme precipitation quantiles for the summer period (JJA) is only studied over southern Caspian regions and Azarbaijan which have enough non-zero precipitation values for the analysis. As it becomes evident in Fig. 7, there is no significant anomaly in precipitation extremes for the JJA period over the two mentioned regions with the exception of a significant positive anomaly in the early 1980s over southern Caspian regions.

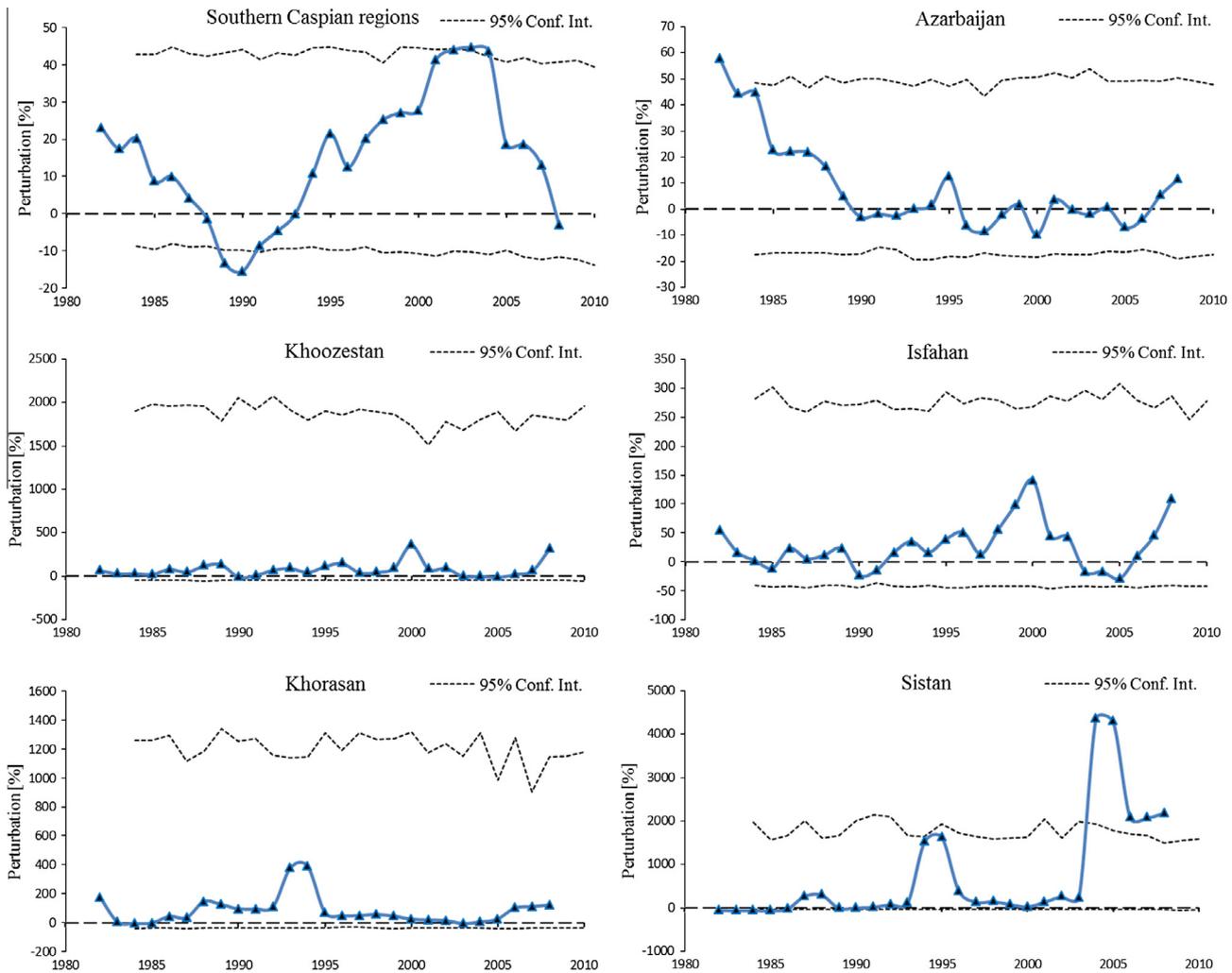


Fig. 8. Extreme precipitation perturbations using 5-year blocks for autumn period (SON) together with 95% confidence intervals to define statistically significant perturbations.

The derived perturbations for precipitation extremes in the autumn period (SON) reveal both high and low perturbations (Fig. 8). The precipitation extremes do not show any significant perturbation in SON over Khoozestan, Isfahan and Khorasan. On the other hand, the analysis reveals a substantial increase in extreme precipitation quantiles in the 2000s over Sistan. Moreover, it becomes apparent from Fig. 8 that there is a significant anomaly in the extremes over southern Caspian regions in the late 1980s and the early 1990s. Further, a significant positive anomaly over Azarbaijan in the 1980s and over southern Caspian regions in the 2000s can be identified from the results.

Whether similar or different anomaly patterns are found for a given season in comparison with all seasons combined depends on the contribution of precipitation extremes of that season in all seasons' extremes. For instance, if the highest extreme values occur mainly in the summer season, the anomaly pattern for summer will be similar to that for all seasons combined.

Overall, extreme precipitation in all surveyed regions reveals a significant anomaly in spring period. Moreover, extreme precipitation in the central and southeastern regions (Isfahan and Khoozestan) indicates significant anomalies only in spring period. The anomalies in these regions are mostly positive, implying a strong threat of flash floods in the mentioned regions. In addition, significant anomalies are dominant in northern Iran (southern Caspian regions) in all the periods considered, which is consistent with the frequent floods observed in recent years in those regions.

4. Conclusions

In this study, temporal oscillations in precipitation extremes were examined for several sub-regions of Iran using the QPM method. Precipitation data were obtained from MERRA-Land for the period 1980–2010. The results showed an evidence of significant perturbations in extreme precipitation quantiles (i.e., significant changes in extreme conditions) over the northwest and southeastern parts of the country. The 1990 decade was the period in which almost all regions experienced highest perturbation factors (i.e., most extreme wet/dry conditions). Among the considered regions, a substantial increase was observed in extreme precipitation quantiles in the 1990s over Sistan in which the quantiles were around 61% higher than those based on the full time series. Albeit the perturbations for the monthly precipitation extremes are generally lower than the annual perturbations, the pattern is similar. The identified anomalies for different seasons indicated that the sign and significance of the anomalies in extreme precipitation quantiles in different regions vary with season substantially. Practically, this methodology offers a framework for monitoring changes in seasonal extremes. Numerous studies argue that in a changing climate weather patterns in different seasons may shift depending on the region (e.g., earlier snowmelt, shorter snow season, and longer rainfall season). The results show that this method can be used to assess how extremes in different seasons have changed in historical observations. The methodology can also

be used with the climate model simulations of the future to assess changes in extremes in response to different emission scenarios.

The recent progress in global land–atmosphere modeling and satellite remote sensing techniques makes it possible to analyze precipitation variability in remote places of the world where rain gauge networks are sparse or not available, mainly due to the huge costs of establishment and maintenance. It is acknowledged that satellite observations and model simulations have their own biases and uncertainties (Reichle et al., 2011). However, numerous studies show that they provide valuable information (Sorooshian et al., 2011; Robertson et al., 2011). Thus, conducting similar studies in ungauged catchments particularly in developing countries will lead to a better understanding of the trends and pattern of the anomalies in extreme precipitation, where other means of observations are not available.

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