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Temporal-Spatial Variability of the Severest Dry Spells in the North-West of Iran

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Abstract

The variability of temperature and precipitation is regarded as one of the main characteristics of the climate. Precipitation and its results, especially results such as droughts, vary on different temporal and spatial scales. The purpose of this paper is to determine the frequency of the inter-annual variability of the driest month in north-west Iran. In order to obtain the best results, we used 11 synoptic weather stations and included 30 years of continuous data records (1977-2006). Initially, the driest months were determined using the Standardized Precipitation Index (SPI); thereafter, the harmonic method was applied for closer examination and demonstration of the frequency of precipitation. The results derived from the harmonic method showed that the highest percentage of variance distribution (approximately 80%) is found in the central sections of the region according to the first harmonic of the Zanjan station. In these sections, the inter-annual changes of in the driest months typically fit a semi-annual pattern during the examined period. In the northern parts, higher harmonics are required to explain variance, which implies a higher variability and a lack of consistency in the occurrence of the driest month in these regions. The lowest PVR1 value (nearly 28%) was registered by the Ardebil station. Therefore, in Zanjan station, the inter-annual changes of the examined component have more homogeneity owing to the high PVR value of the first harmonic, while the level of variability in the driest months was higher in stations like Ardebil. Higher harmonics are required to explain this variance.

***Keywords*:** Variability; Harmonic; Drought; Variance; North-West of Iran

1. Introduction

Precipitation is commonly considered one of the most important factors of the climate. For the most part, it varies based on temporal-spatial scales. The time variability and spatial distribution of precipitation along various scales are regarded as the main causes of floods and droughts, and can bring about enormous financial damages. As a result of the importance of precipitation's temporal-spatial variability, and its role in Communication and economic disasters, it has attracted the attention of many researchers (Rodriguez *et al*., 1998; Ochola & Kerkides, 2003; Baigorria *et al*., 2007; Jianting *et al*., 2009; Nastos & Zerefos, 2009).

It is difficult to explain drought because many variables are directly and/or indirectly involved, and for this reason a comprehensive and appropriate description has not yet been proposed for use by all researchers (Farajzadeh, 2005). Droughts result in severe economic and social consequences, and for this reason droughts have been studied comprehensively through the examination of the duration of dry months (Nastos & Zerefos, 2009). In recent years, issues related to droughts have attracted much attention and planning for drought has become an inevitable political issue for governments.

Kulshreshtha and Klein (1989) examined the effects of the agricultural drought model. The model they used in their research, i.e., the ADIEM, consists of four components: a

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hydrology crop simulation model, a model simulating the business activity of a farm, a regional inlet-outlet model and an occupation model. Hisdal and Tallaksen (2003) studied the climatic characteristics of drought in Denmark. Through simulating the precipitation and comparing the drought's attributes, they showed that hydrological droughts in non-homogeneous regions are less frequent and have longer durations as compared to climatic droughts. Hejazizadeh and Shirkhani (2003), through studying droughts and short dry periods in Khorasan, Iran, demonstrated the probability and frequency of dry periods. Sanaeinejad *et al*. (2003) studied dry spells in Mashhad. According to this research, the trend of dry spells shows that the frequency and stability of these spells are increasing but their intensity is decreasing.

Besides putting forward various methods to study drought, Farajzadeh (1994) has studied the time and spatial characteristics of drought in Iran. In the long term, he found that the concurrence of drought in the northern and southern regions is higher in relative terms than that of the eastern and central parts of the country. Through SPI and Markov chain calculations, Alizade and Ashgar Toosi (2008) predicted the 2008 climate based on a 30-year statistical period (1977-2007). The SPI index results based on a short-term scale (three months) showed that the Khorasan-e-Razavi province stations had the highest occurrence of mild-wet conditions, followed by mild-drought ones.

By comparing the various predictive methods of the SPI index, Eyvazi *et al*. (2009) came to the conclusion that an artificial nervous system (MLP) is able to predict SPI values and drought conditions more accurately than an artificial nervous system (RBF). Bronini *et al*. (2001) showed that the Standardized Precipitation Index can be very useful for quantification in the study of drought. They have also found that this index and water equilibrium equations are both suitably correlated on the monthly scale. In addition, they showed that by combining the SPI index and water equilibrium equations, it is possible to change the cultivation time of each plant and alter the shortage and abundance of humidity in different processes for each plant appropriately, so as to protect plants against drought.

Mishra and Desai (2005) used linear probability models such as ARIMA and SARIMA with the Standardized Precipitation Index (SPI) to predict drought. Their research results confirmed that statistical models give appropriate outcomes in the form of short-term predictions of drought (up to two months). Engelbrecht et al. (2006), considering dry spells in the wet season in a tropical forest, discovered that short dry spells in the wet season differentially affect seedling survivorship of pioneer species. Fischer *et al*. (2013), by applying a Markov-based method in the Makanya catchment, Tanzania, conclude that the length of dry spell occurrence is highly variable in space, even over relatively short distances, in this region.

Given that in north-west Iran agriculture plays an important role in economics, and given the occurrence of several droughts in this region, familiarity with the behaviour of droughts is absolutely essential. Thus, the main objective of the present research is to find the dominant pattern of inter-annual alternation in the driest monthly spells during the examined period.

2. Materials and methods

The main focus of this paper is investigating the inter-annual oscillations of the driest monthly spell during the examined period. First, based on the Standardized Precipitation Index (SPI), the severity of droughts will be determined. Then, through harmonic analysis, extreme droughts will be analysed. In order to study the severest dry spells in north-west Iran, precipitation data for 30 years (1977-2006) from 11 synoptic stations in north-west Iran have been used (Table 1 and Fig. 1).

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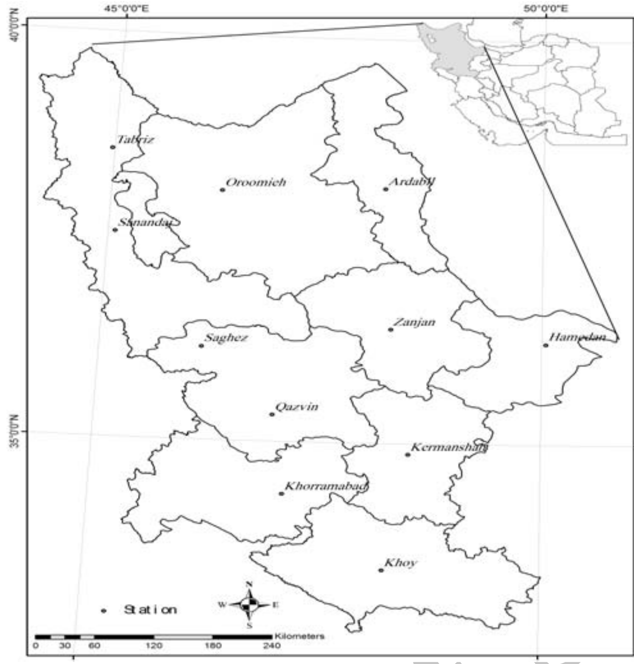

Fig. 1. Situation of weather stations under study

Table 1. Studied weather stations

NO.	Stations	Longitude	Latitude	Elevation(m)
1	Ardebil	29-48	36-41	1663
2	Oromiyeh	45-05	37-32	1315.9
3	Tabriz	46-17	38-05	1361
4	Khoramabad	47-17	33-26	1147.8
5	Khoy	44-58	38-33	1103
6	Zanjan	48-17	38-15	1332
7	Saqez	46-16	36-15	1522.8
8	Sanandaj	47-00	35-20	1373.4
9	Qazvin	50-03	36-15	1279.2
10	Kermanshah	47-09	34-21	1318.6
11	Hamedan	48-32	34-52	1741.5

2.1. Standardized Precipitation Index (SPI)

This index, introduced by McKee *et al*. (1993), is based on investigating the effects of precipitation's shortage on ground waters, surface water resources and soil humidity, which are computable for various timescales. The SPI index is applied for each region based on a long-term record of precipitation, as well as on short-term (one-, three-, six- and nine-month) and long-term (12-, 18-, 24-, 48- and 72-month) intervals (Shahian *et al*. 2009). The index can be very useful for early warning and for helping to evaluate drought severity (Mosaedi *et al*. 2009). Evaluation of this index requires the fitting of the most suitable probability distribution to the time series of long-term precipitation data for each station. Gamma distribution is usually the best type, and after the required computations and determination of the relevant parameters, the SPI index is computed as follows (Eyvazi *et al*. 2009):

$$Z = \frac{X - \bar{X}}{S}$$

$$Z = SPI = -\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad t = \sqrt{\ln\left[\frac{1}{H(x)^2}\right]} \quad 0 < H(x) \le 0/5$$

$$Z = SPI = +\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad t = \sqrt{\ln\left[\frac{1}{(1 - H(x))^2}\right]} \quad 0/5 < H(x) \le 1$$

H(x) is the cumulative probability function and the values of C_0, C_1, C_2, d_1, d_2 and d_3 in the above equations are as follows:

$C_0 = 2.51557$, $d_1 = 1.432788$
$C_1 = 0.802853$, $d_2 = 0.189269$
$C_2 = 0.010328$, $d_3 = 0.001308$

The Standardized Precipitation Index (SPI) is an index based on the probability of rainfall for any timescale and can assist in assessing the severity of drought. The SPI can be calculated at various

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timescales which reflect the impact of the drought on the availability of water resources.

The SPI calculation is based on the distribution of rainfall over long periods of time. The long-term rainfall record is fit to a probability distribution, which is then normalized so that the mean (average) SPI for any place and time period is zero. SPI values above zero indicate wetter periods, and values less than zero indicate drier periods (Table 2). After computing the SPI value in each time interval, the humidity condition is divided into several classes. A positive SPI value indicates that the amount of precipitation exceeds the average, and a negative value indicates the contrary.

Table 2. Standardized Precipitation Index (SPI) classification (McKee *et al*. (1993)

Humidity Condition	SPI Value
No Drought	SPI ≥ 0
Mild Drought	0 / -0.99
Moderate Drought	-1 / -1.49
Severe Drought	-1.50 / -1.99
Extremely Severe Drought	SPI≤ -2

In order to study the inter-annual variability of the driest spells for each month, harmonic analysis technique has been applied. A synopsis of harmonic analysis technique and an explanation are presented below.

For the number of examined frequencies f_t harmonic analysis may be presented as follows (Panofsky & Brier 1958):

$$f_t = \bar{f} + \sum_{k=1}^{n/2}\left(A_k \cos\frac{2\pi}{n}kt + B_k \sin\frac{2\pi}{n}kt\right)$$

Here, A_k and B_k are the harmonic's coefficients (K= 1, 2…). These coefficients are written as follows (Lamb 1990; Wilks 2006; Wyszynski 2006):

$$A_k = \frac{2}{n}\sum_{t=1}^{n} f_t \cos\left(\frac{2\pi}{n}kt\right)$$

And,

$$B_k = \frac{2}{n}\sum_{t=1}^{n} f_t \sin\left(\frac{2\pi}{n}kt\right)$$

Here, f_t shows the frequency of different occurrences. Each harmonic's amplitude, C_k, is obtained through the following formula (Jenkins & Watts 1980):

$$C_k = \left[{A_k}^2 + {B_k}^2\right]^{1/2}$$

Each harmonic's variance can be derived from the following function (Livada *et al*. 2008):

$$V_k = \frac{C_k^2}{2}$$

The percentage of variance (PVR) for each harmonic is obtained from the following ratio:

$$PVR(k) = {V_k}/{\sum_1^6 V_k}$$

The phase angle of each harmonic, Φ_k, can also be calculated through the following function (Wilks 2006):

$$\varphi_k = \begin{cases} \tan^{-1}(B_k/A_k), & A_k > 0 \\ \tan^{-1}(B_k/A_k) \pm \pi, or \pm 180^\circ, & A_k < 0 \\ \frac{\pi}{2}, or\ 90^\circ, & A_k = 0 \end{cases}$$

Finally, the occurrence time of each harmonic's maximum, T_k, will be derived from the following equation (Livada *et al*. 2008):

$$T_k = \left(\frac{12}{360}\right)\Phi_k$$

The first harmonic indicates an annual cycle with the highest amplitude as compared to other harmonics. The second harmonic shows a semi-annual change, while the third harmonic implies the seasonal changes of the four months in more detail, and is also an index of inter-annual patterns of examined frequencies. Finally, the values of T_k show the temporal motion of the maximum frequency along the time axis (Table 3).

3. Results and Discussion

The relative frequency was extracted based on the repeated number of minimum occurrences of the monthly SPI value for each month of year (Fig. 2). Through separating the data into orthogonal components in the form of a harmonic, the inter-annual changes in the data can be explained. The four typical stations of Zanjan, Tabriz, Qazvin and Khoy were chosen in order to show the harmonic behaviour of the dry spells, since the first to fourth harmonic plays the most important role in the explanation of variance for each station, respectively.

In Zanjan station, the first harmonic plays the most important role in the explanation of variance. Therefore, the drought behaviour pattern of this station consists of a regular pattern manifested inter-annually during the examined period. In the other stations, the first harmonic's amplitude is reduced and higher harmonics explain the data variance (Tables 3 to 7).

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Table 3. The relationship between T_k and the most probable time occurrence

Time Intervals	Months	Value T_k		
1	January	0.5	0.5	-11.5
15		1	1	-11
1	February	1.5	1.5	-10.5
15		2	2	-10
1	March	2.5	2.5	-9.5
15		3	3	-9
1	April	3.5	3.5	-8.5
15		4	4	-8
1	May	4.5	4.5	-7.5
15		5	5	-7
1	June	5.5	5.5	-6.5
15		-6	6	-6
1	July	-5.5	6.5	-5.5
15		-5	7	-5
1	August	-4.5	7.5	-4.5
15		-4	8	-4
1	September	-3.5	8.5	-3.5
15		-3	9	-3
1	October	-2.5	9.5	-2.5
15		-2	10	-2
1	November	-1.5	10.5	-1.5
15		-1	11	-1
1	December	-0.5	11.5	-0.5
15		0	12	0

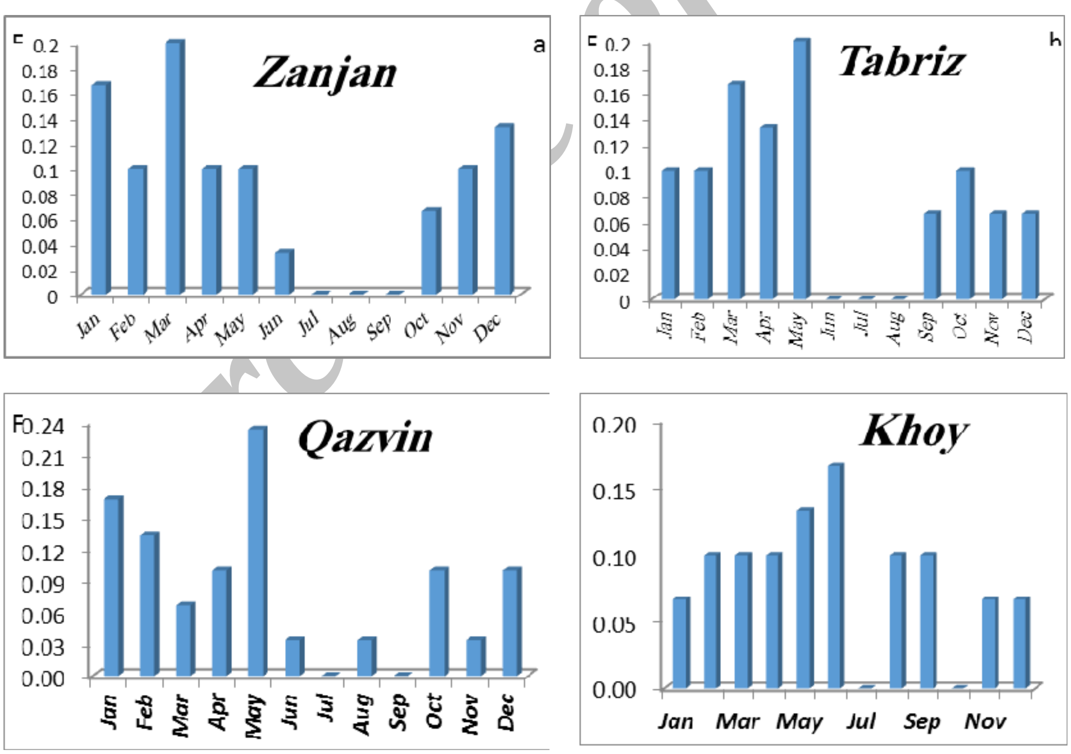

Fig. 2. Relative frequency of each month in relation to monthly minimum SPI in the selected stations

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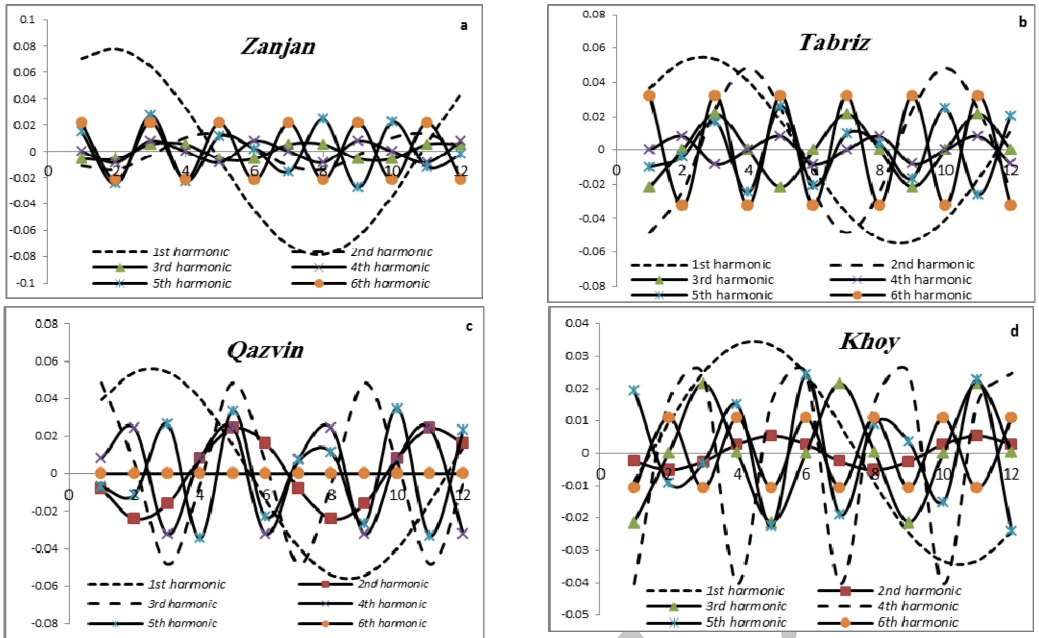

Fig. 3. Harmonic patterns of four chosen stations in the region under study

Table 4. First to sixth harmonic's components in Zanjan station

K	A_k	B_k	C_k	V_k	PVR_k	$CPVR_k$	Φ_k	T_k
1	0.0448	0.0643	0.0784	0.0031	80	80	55	1.8
2	0.0027	-0.0140	0.0142	0.0001	3	83	-79	-1.3
3	0.0054	-0.054	0.0076	0.0000	1	83	-45	-0.5
4	0.0081	0.0047	0.0093	0.0000	1	84	30	0.3
5	-0.0018	0.0271	0.0271	0.0004	10	94	94	0.6
6	-0.0215	0.0000	0.0215	0.0002	6	100	180	1.0

Table 5. First to sixth harmonic's components in Tabriz station

K	A_k	B_k	C_k	V_k	PVR_k	$CPVR_k$	Φ_k	T_k
1	0.0115	0.0536	0.0458	0.0015	39	39	78	2.6
2	-0.0242	-0.0419	0.0484	0.0012	31	70	240	4.0
3	0.0000	0.0215	0.0215	0.0002	6	76	-90	-1.0
4	-0.0081	-0.0047	0.0093	0.0000	1	77	210	1.7
5	0.0208	0.0163	0.0265	0.0003	9	86	38	0.3
6	-0.0323	0.0000	0.0323	0.0005	14	180	180	1.0

Table 6. First to sixth harmonic's components in Qazvin station

K	A_k	B_k	C_k	V_k	PVR_k	$CPVR_k$	Φ_k	T_k
1	0.0142	0.0543	0.0561	0.0016	37	37	75	2.5
2	0.0161	-0.0186	0.0246	0.0003	7	44	-49	-0.8
3	-0.0054	0.0484	0.0487	0.0012	28	72	96	1.1
4	-0.0323	-0.0093	0.0336	0.0006	13	85	196	1.6
5	0.0235	0.0264	0.0353	0.0006	15	100	48	0.3
6	0.0000	0.0000	0.0000	0.0000	0	100	90	0.5

Table 7. First to sixth harmonic's components in Khoy station

K	A_k	B_k	C_k	V_k	PVR_k	$CPVR_k$	Φ_k	T_k
1	-0.0242	0.0247	0.0346	0.0006	30	30	134	4.5
2	0.0027	-0.0047	0.0054	0.0000	1	30	-60	-1.0
3	0.0000	0.0215	0.0215	0.0002	11	42	-90	-1.0
4	0.0242	-0.0326	0.0406	0.0008	41	82	-53	-0.4
5	-0.0242	-0.0032	0.0244	0.0003	15	97	188	1.3
6	0.0108	0.0000	0.0108	0.0001	3	100	0	0.0

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3.1. The First Harmonic

When investigating the inter-annual variations, if the first harmonic plays a stronger role in the variance's distribution, this will indicate the more regular variability of the examined component. Spatial distribution of the first harmonic's components (Fig. 4) illustrates the following:

- The highest PVR1 value belongs to middle and southern parts of the region.
- The PVR1 value reduces from the middle sections towards the outer sections.
- The spatial pattern of the first harmonic shows the driest annual spells during the examined period. Apart from the central parts of the region, the inter-annual variability of these spells is very high.
- The spatial pattern of T1 values (Fig. 4b), which indicates the apex time of the first harmonic's occurrence, represents values from (~2) to (~4), indicating a temporal period of around February to May.
- The climax time of the first harmonic's occurrence in the southern sections of the region is almost in February, whereas in the northern parts, especially around Khoy station, it is almost in April.
- The C1 value in the southern sections of the region is higher, indicating higher spectral power of the first harmonic in these regions.

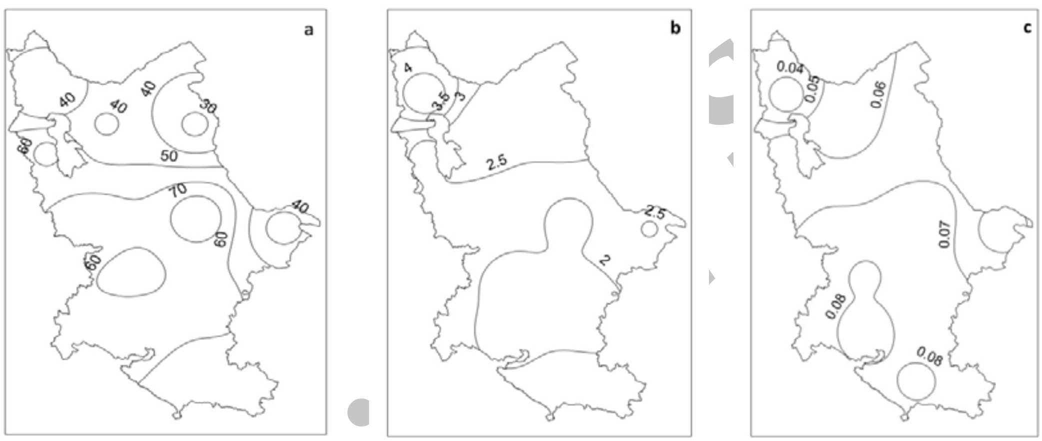

Fig. 4. Spatial distribution of PVR1 (a), T1 (b) and C1 (c) values of the driest spells in the region under study

3.2. The Second Harmonic

The spatial pattern of PVR2 indicates that its value is much lower than PVR1 in all the sections (Fig. 5a). The highest PVR2 value is observed in the northern sections of the region, around Tabriz station. The T2 value has a very high irregular distribution such that it varies from (~-1) to (~4). This form indicates time intervals of around November to April, i.e., the second harmonic's climax with an alternation of six months. The size of the second harmonic's amplitude is also lower in the western sections.

3.3. The Third Harmonic

The spatial pattern of PVR3 shows that only in the eastern sections of the region does it possess a relatively high value, while in other parts it reduces to a large extent (Fig. 6a). The T3 value also indicates values between (~-1) and (~2), which implies time periods of November to February. Furthermore, the C3 value is higher in eastern and north-eastern parts of the region.

4. Conclusion

The main purpose of the present paper is to investigate the inter-annual variability of the driest months obtained by the SPI method in north-west Iran. To do so, we used the harmonic analysis method. Using harmonic analysis as a domain frequency method, which is very efficient for studying the variability patterns of the inter-annual variations of the driest months obtained by SPI, we showed that the first harmonic has the highest percentage of variance distribution, especially in the middle and southern sections of the region. Therefore, the prevalent pattern of the inter-annual variations of the driest months in this section is annual. The most prominent station is Zanjan station, with the highest PVR1 value of around 80%. By contrast, Ardebil station possesses the lowest value, at around 28%. Harmonic analysis

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indicates that inter-annual variability of the driest spells have an annual pattern in the study region. On the one hand, the longer the first harmonic's amplitude, the more homogeneous the study component would be. On the other hand, this signals a low variability. With respect to the higher explanatory power of the PVR1 value and the longer amplitude of the first harmonic (C1), the temporal variability values for the driest months are more homogeneous and exhibit a more obvious pattern in the central sections, especially in Zanjan station. Meanwhile, in places where the power value of the first harmonic decreases, the first harmonic's role also decreases in variance distribution, and the role of higher harmonics increases.

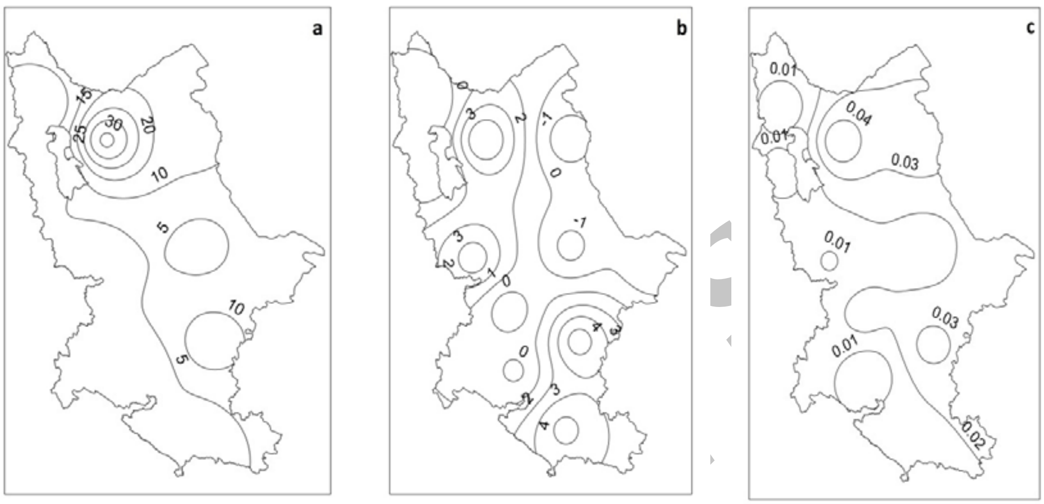

Fig. 5. Spatial distribution of PVR2 (a), T2 (b) and C2 (c) values for the driest spells in the region under study

Fig. 6. Spatial distribution of PVR3 (a), T3 (b) and C3 (c) values for the driest spells in the region under study

Overall, from harmonic analysis of the inter-annual variations of the driest months in north-west Iran, the following results were obtained:

● Of 11 examined stations, approximately seven stations have a PVR value of more than 50%, indicating that the inter-annual variability pattern of the driest months is definitely annual.

● The first harmonic pattern has a south-north geographic form; the effect of the first harmonic on variance distribution decreases from south to north.

● The sections where the first harmonic's role is most obvious are located in the central sections of the region.

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● In some regions, especially Ardebil station, the first harmonic's share in variance distribution is very low, indicating that the driest month's variation does not follow a regular pattern, so that higher harmonics are required to explain the variance.

● The first harmonic's climax time (T1) varies between 1.7 and 4.5 in most regions.

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