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Research Article

Harmonic Analysis of the Spatiotemporal Pattern of Thunderstorms in Iran (1961–2010)

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The current study aimed at investigating cycles and the spatial autocorrelation pattern of anomalies of thunderstorms in Iran during different periods from 1961 to 2010. In this analysis, 50-year periods (1961–2010) of thunderstorm codes have been collected from 283 synoptic stations of Meteorological Organization of Iran. The study period has been divided into five different decades (1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010). Spectral analysis and Moran's I were used to analyze cycles and the spatial autocorrelation pattern, respectively. Furthermore, in order to conduct the calculations, programming facilities of MATLAB have been explored. Finally, Surfer and GIS were employed to come up with the graphical depiction of the maps. The results showed that the maximum of positive anomalies mainly occurred in the northwestern and western parts of Iran due to their special topography, during all the five studied periods. On the other hand, the minimum of negative anomalies took place in central regions of the country because of lack of appropriate conditions (e.g., enough humidity). Moran's *I* spatial analysis further confirmed these findings as Moran's I depicts the positive and negative spatial autocorrelation patterns in line with negative and positive anomalies, respectively. However, in recent decades, this pattern has experienced a declining trend, especially in southern areas of Iran. The results of harmonic analysis indicated that mainly short-term and midterm cycles dominated Iran's thunderstorms.

1. Introduction

Thunderstorm is a climatic phenomenon that can have destructive effects on agriculture, civil facilities, structures, and economy [1]. In addition, thunderstorms are usually accompanied by other climatic phenomena (like hail, heavy rainfall, snow, and lightening), which can also claim the loss of numerous human lives [2, 3]. Although natural disaster cannot be prevented, its deleterious consequences can be predicted and minimized through studying thunderstorms over long-term periods. By so doing, the degree of the vulnerability of structures and civil facilities can be determined, leading to the construction of stronger structures in future. Furthermore, studying thunderstorms will reduce human causalities to a great extent [4, 5]. Many factors such as topography, land cover, and atmospheric processes are effective on the occurrence of thunderstorms [6]. Thunderstorms may be the result of severe gradient between two systems [7, 8]. A number of studies have indicated that height plays a significant role in the onset and evolution of storms [9]. However, several studies have been conducted in this field. For example, Davis investigated daily variations of thunderstorms in Heathrow airport, London. The results indicated that the majority of thunderstorms occurred in the afternoons. Also, some of them happened at midnights [10]. However, Callado and Pascual Berghaenel used different models to study the Mediterranean thunderstorms, and they argued that the high frequency of thunderstorms in Catalonia at the end of the spring and in summer can be attributed to local mountains and maritime influences [11]. Davolio et al. simulated the intense convective precipitation event of September 8^{th} and 9^{th}, 2002, in the southeast of France, and they believed that the existence of a midsize convective system before the approaching of cold front was responsible for this event [12]. Trentmann et al. concentrated on variations in convective precipitations of July 12^{th}, 2006, in Central Europe and found that the maximum amount of available convective energy for these precipitations was registered early afternoon, and they also concluded that topography played a significant role in the occurrence of these precipitations [13]. Kunz et al. studied the frequency trend of thunderstorm during 1974–2003 in southwest Germany, and they showed that the annual frequency of days with thunder and lightning had remained almost intact. However, the number of days with hail and its consequent damages had risen significantly [2]. Lin-Lin et al. focused on changes in thunderstorms within different decades and their annual distribution, and their results demonstrated that thunderstorm distribution varied in different seasons. That is, while in May, most of the thunderstorms happened in the north and in September, the majority of them occurred in the south [14]. Mohee and Miller used radar data and earth surface data in North Dakota in order to come up with the climatic features of thunderstorms, and their results supported the idea that thunderstorms mainly happened in the afternoon and early morning in June [15]. Loginov et al. studied the formation and variations of some thunderstorms in Belarus, and their results revealed that the thunderstorms had a lot of temporal and spatial variation [16]. Mic intended to find the reasons behind the occurrence of thunderstorms, and his findings showed that thunderstorms have a biannual cycle which has a weak correlation with the solar cycle. Furthermore, he discovered that the maximum number of thunderstorms happened in June [5]. Enno et al. used the Mann–Kendall test in order to analyze the frequency trend of thunderstorms in Baltic countries within the period 1950–2004, and his results indicated a 24% decline in the number of days in which thunderstorms happened. He recorded a rate of 0.9 day decline for each decade [17]. The similar research projects conducted by others (Yu and Lee, Abhilash et al., Lolis, and Mastrangelo et al.) are some other examples in this regard [18–21].

Iran is located on the way of different air masses, has different physiographic units, and encompasses various geographical latitudes [22–27]. Therefore, it has favorable conditions for the occurrence of thunderstorms. In Iran, the northwest and southwest of the Zagros mountain range experience two opposite conditions; that is, during the transition from cold to warm season, the number of lightning in the northwest of Iran is greater than that of the southwest. On the other hand, during the transition from warm to cold season, lightning in southwest outnumbers the one in northwest [28]. The majority of precipitation in Iran is influenced by the Mediterranean pattern [26, 27, 29–35]. When this pattern is combined with the Sudanese low pressure and faces the topography of southwest of Iran, forced convective climb and instability occur. Thus, the humidity of Arabian Sea moves toward southwest and conditions become favorable for thunderstorms [8, 33, 36]. At the same time, local instabilities during warm seasons, especially in higher areas, intensify rain showers. However, one cannot ignore the role of foreign cold front, which enters the country during the cold season, in creating lightning [2]. On the other hand, spatial changes of Azores High pressure have different influences on Iran's climate. More precisely, this system moves toward north and east, withdraws from the south because the polar trough low pressure advances in this area, and interacts with Gang low pressure. These phenomena cause instability and showers. Furthermore, the two cells of Sudanese low pressure and Mediterranean are combined over Kuwait and south of Iraq, with their troughs being extended to the northwest of Iran. Also, a low pressure cell is formed over the strait of Hormoz and the north of Arabian Peninsula. These phenomena cause warm weather and humidity of the Sea of Oman and the Persian Gulf to move over the region, hence making the conditions more favorable for instability and lightning [8]. Considering all these into account, various instability indices, such as SWEAT, TTI SOI, KI, SI, CIN, and CAPE, and the precipitation water (PW) index can provide good evaluations of thunderstorms. Among these indices, the Showalter index (SI) has yielded better results.

Accompanying thunderstorm (with lightning, tornado, hail, winds, heavy precipitations and hazardous atmospheric phenomena like turbulence, freezing, and wind sheering) makes considerable irrecoverable damages to natural and human environments. However, most of the studies in Iran have used different research methodologies to investigate thunderstorms in the northwest and southwest of the country. Until now, no comprehensive study has been conducted to include all areas of the country. As a result, the present study aimed at investigating changes in the spatial pattern of Iran's thunderstorms within the last five decades (1961–2010).

2. Methodology

In order to analyze spatial autocorrelation cycles and patterns of anomalies of Iran's thunderstorms, thunderstorm codes (91 to 99, 17, and 29) of a 50-year period were collected from 283 synoptic stations of Iran's Meteorological Organization (IRIMO). These data were prepared and validated by the IRIMO and have not been missing values during the studied statistical period.

(Figure 1 and Table 1). Moreover, in order to come up with a periodical analysis of thunderstorms, the study period was divided into five time intervals (1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010). When it comes to climate-related data, greater record lengths are more valid and reliable. Therefore, the researchers selected those stations which have the greatest record length (Figure 1).

First, with the aim of gaining a general understanding of thunderstorms, descriptive data were presented for each period. Then, in order to gain a detailed understanding, anomalies and center mean of thunderstorms for each period were analyzed. Average centers, which are the average gravity of spatial distribution, are defined by equations (1) and (2):

$$\overline{X}_c = \frac{\sum_{i=1}^{n} P_i X_i}{\sum_{i=1}^{n} P_i}, \tag{1}$$

$$\overline{Y}_c = \frac{\sum_{i=1}^{n} P_i Y_i}{\sum_{i=1}^{n} P_i}, \tag{2}$$

where P_i is frequency of thunderstorms and X_i and Y_i are latitude and longitude, respectively.

In order to have a more accurate analysis of thunderstorm changes within each decade, spectral analysis was utilized to analyze thunderstorm cycles for each period. The distribution of variance along all wavelengths of the time series is known as spectral analysis. In fact, the harmonic analysis technique entails analyzing the variance of a time series. In spectral analysis, time series are first converted to frequency functions (in the form of periodic functions with amplitude and frequency). In such functions, frequency indicates the time scale (cycles within a time unit) and amplitude represents variance in this time scale. Therefore, in this technique, each of the waves is extracted, and their contribution to the total variance is assessed. Then, after determining the variance, each of the waves is studied to see if they are statistically significant. In order to convert the time series to frequency and calculate the harmonics, first, two parameters should be calculated through equation (5) by equation (3) and equation (4) [37]:

$$a_i = \frac{2}{n} \sum_{t=1}^{n} x_t \cos\left(\frac{2\pi q}{n} t\right) \quad q = 1, 2, \ldots, \frac{n}{2}, \tag{3}$$

$$b_i = \frac{2}{n} \sum_{t=1}^{n} x_t \sin\left(\frac{2\pi q}{n} t\right) \quad q = 1, 2, \ldots, n, \tag{4}$$

where q is the number of harmonics. For even series, there will be $q = n/2$ harmonics, whereas for odd series, there will be $q = (n-1)/2$ harmonics.

The variance of each frequency (wave) was calculated through the following formula:

$$I(f_i) = \frac{n}{2}\left(a_i^2 + b_i^2\right). \tag{5}$$

In order to investigate dominant patterns of Iran's thunderstorms within decades, geostatistical methods of spatial autocorrelation (Moran's I) were used. This procedure helps discover whether the distribution pattern of the studied phenomenon follows a cluster or random pattern. In fact, in this procedure, Moran's I is calculated, and Z score and significance level are used to evaluate the calculated index. This type of analysis shows the regions in which the studied phenomenon has been clustered and has followed a significantly different pattern compared to the same phenomenon in the surrounding areas. As previously mentioned, the preassumption of this type of analysis is that the studied phenomena are weighed; hence, the clusters which have similar size can be easily identified. On the other hand, the patterns that do not form a cluster can be recognized too. Moran's I is calculated through equation (6) or equation (7). Z score is calculated by equation (8).

$$I = \frac{x_i - \overline{X}}{S_i^2} \sum_{j=1\ j\neq i}^{n} w_{i.j}\ (x_i - \overline{X}), \tag{6}$$

where x_i is the amount of phenomenon on the i_th cell, $\overline{X}$ is the mean of that phenomenon, and $w_{i.j}$ is the spatial weight between the two phenomena (i and j). Also,

$$S_i^2 = \frac{\sum_{j=1\ j\neq i}^{n} w_{i.j}}{n-1} - \overline{X}^2, \tag{7}$$

where n is the number of all phenomena. Standard z I_i is calculated through the following formula:

$$z_{I_i} = \frac{I_i - E[I_i]}{\sqrt{V[I_i]}}, \tag{8}$$

$$\text{And}: \ V[I_i] = E\left[I_i^2\right] - E[I_i]^2 \quad E[I_i] = -\frac{\sum_{j=1, j\neq 1}^{n}}{n-1}.$$

After conducting thunderstorms' cycle analysis and spatial pattern analysis, in order to determine the number of regions, cluster analysis is used. In fact, in this study, "Ward's Hierarchical Clustering" or the "method of minimum variance" analysis on average of thunderstorm occurrence was used for zoning and clustering Iran's thunderstorms. The method was used to group locations and their distributions based on their similarity. Ward's method looks at cluster analysis as a variance problem and computes

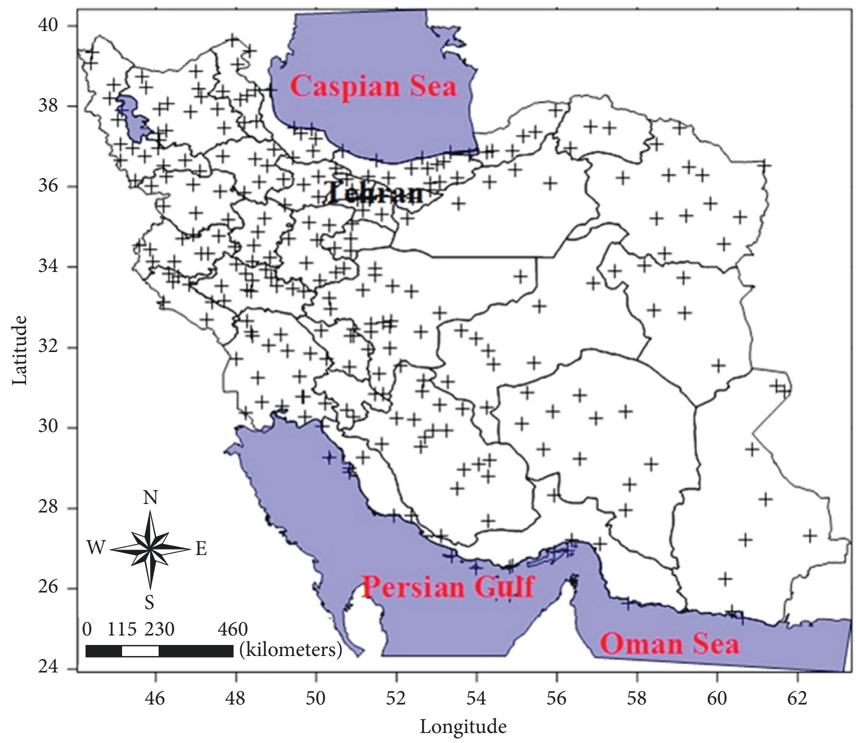

Figure 1: Distribution pattern of the studied stations.

Table 1: Thunderstorm's code and its description (source: WMO code 4677[1]).

Code	Description
17	Thunderstorm, but no precipitation at the time of observation
29	Thunderstorm (with or without precipitation) during the preceding hour but not at the time of observation
95	Thunderstorm, slight or moderate, without hail, but with rain and/or snow at the time of observation
96	Thunderstorm, slight or moderate, with hail at time of observation.
97	Thunderstorm, heavy, without hail, but with rain and/or snow at time of observation
98	Thunderstorm combined with dust/sandstorm at time of observation
99	Thunderstorm, heavy with hail at time of observation

Euclidean distances to evaluate dissimilarity between the clusters. Ward's algorithm, when implemented on a dataset, establishes groups by minimizing the dissimilarity or the total sum of squares. This algorithm calculates several clusters at a level when intergroup similarity is maximized while intragroup similarity is minimized [38–42].

3. Results

The salient statistical features of thunderstorm of Iran for different periods (1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010) have been extracted (Table 2). Accordingly, the greatest spatial mean (15.36 days) for thunderstorms happened in the fifth period (2001–2010). However, since variance is big, this period has the highest coefficient of variation. On the contrary, the lowest mean (6.86 days) belongs to the second period (1971–1980). Considering the periods and years, there are great differences between mean, mode, and median. This shows that thunderstorms followed dissimilar patterns in different times, hence not forming a normal distribution. The large difference of the quartile range further confirms this claim. Coefficient of skewness is positive for all periods, a phenomenon that shows the inclination of thunderstorms toward smaller values. This inclination has reached its peak during the first period (1961–1970). Kurtosis is used to describe the degree of sharpness (or flatness) of the curve. When the kurtosis coefficient is positive, the frequency of extreme values above the mean in the data is greater than the extreme values less than the mean. If kurtosis is close to zero, the curve will be sharp. As observed, kurtosis value is positive for all periods. Studying the 25, 50, and 75 percentile rank shows that the fifth period (2001–2010) experienced a greater value compared to other periods.

On the other hand, the maximum number of thunderstorms occurred in the same period (2001–2010), which indicates the wide range of differences in thunderstorms. It seems that the maximum number of thunderstorms has not randomly happened in this period; otherwise, it would not influence the center mean of this period (this period had the lowest mean). It can be concluded that, except the fifth period (2001–2010) in which a considerable increase can be observed in the number of thunderstorms, the dominant pattern of thunderstorms has experienced a rather stable mechanism in all the other periods.

Table 2: Spatial features of the frequency of Iran's thunderstorms for different periods.

Index	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	1961–2010
Average	7.7	6.8	10.5	13.6	15.3	10.9
Median	6.7	6.1	9.1	12.5	13.2	9.7
Mode	0.6	0.5	0.9	1.5	4.2	2.8
Variance	24.5	15.1	37.9	37.8	65	29
Standard	4.9	3.8	6.1	6.1	8	5.3
Coefficient	63.7	56.7	58.1	44.9	52.4	49.2
Range	31.1	20.1	30.3	32.5	34.9	28.3
Skewness	2.3	0.77	1	1	1	1.2
Kurtosis	9.9	2.8	3.3	3.7	3.3	4.3
Maximum	31.7	20.7	31.2	34.1	39.2	31.2
Minimum	0.6	0.5	0.9	1.5	4.2	2.8
Q1	4.5	3.6	5.8	9.5	9	7.1
Q2	6.7	6.1	9.1	12.5	13.2	9.7
Q3	8.9	9.5	13.2	16.2	19.9	12.6

3.1. Analyzing Anomalies and the Spatial Autocorrelation Pattern of Thunderstorms. In order to gain a more accurate understanding of the changing pattern of thunderstorm within each decade, mean, anomaly (the average of each year in different periods relative to the average annual value of the whole of the period), and center of gravity (center mean) were drawn for each period (Figure 2). The center of gravity focuses on the occurrence of climate phenomena in the studied area. For example, if the focus of the points is in the northwest of Iran, this indicates that the spatial center of gravity of the storms is in the northwestern part of Iran. In this procedure, for each period, thunder deviation from the normal distribution was calculated through the algebra map.

Some anomalies on earth are under the influence of random climate phenomena, while others are the consequence of a particular pattern [43, 44]. For example, positive anomalies of middle latitudes are the result of ocean currents and El Nino-Southern Oscillation (ENSO) [45]. Widespread cold anomalies may be a symptom of a severe winter. Some scientists use anomalies to identify normal and abnormal natural disasters. For instance, some scientists claim that environmental problems, such as flood, storm, and drought, are caused by climatic oscillations, especially exacerbated temperature anomalies on earth [46–51].

Analyzing anomalies of various periods shows that most of the positive anomalies belong to the northwest and southwest of the country (Figure 2). Alijani has demonstrated the occurrence of this maximum in his own study [33]. These positive anomalies may be the result of local conditions, especially topography [3, 52, 53], and/or dynamic and synoptic factors [54]. For example, some researchers attribute this maximum anomaly to anticyclone ridges over Russia that extend to the northwest of Iran and increases thermal gradient in the region. In addition, low pressure cells over the strait of Hormoz and the north of Arabian Peninsula, heat transfer, and humidity of the Sea of Oman provide necessary conditions for instability and lightning in the region [8]. One of the necessary conditions for the occurrence of thunderstorms is the availability of humidity [55]. Thus, it is observed that despite their high coefficient of variation, the central parts of Iran have negative anomaly because of low humidity and lack of convective climb. However, in the second period (1971–1980), positive anomalies significantly increased around 8% in comparison with the previous period, i.e., (1961–1970) (Table 2). As a result, the coastal areas of the Caspian Sea and the Persian Gulf experienced positive anomaly during this period, a condition that can be explained in the light of high humidity in these regions. In the same period (1971–1980), the spatial coefficient of variation of thunderstorms in the northwest of Iran had no significant change compared to the first period (Figure 2). It, however, experienced up to 20% increase in other areas, especially central parts of Iran. High coefficient of variation in these regions indicates that thunderstorms had a lot of oscillations in these areas. On the other hand, they become more or less stable toward the northwest of the country.

In all periods, the northeast areas of the country experienced negative anomaly (Figure 2). In other words, those areas had a fewer thunderstorms than the other areas. Some scientists believe that thunderstorms in this region occur because of its topography, high altitude above sea level, and the systems that enter the region from north and south [8]. However, in the third period (1981–1990), the intensity of positive anomalies reduced; hence, almost 75% of the country's area experienced negative anomaly (Table 3). But the amplitude of these anomalies oscillated between −14 and 16. Thus, moving from the four corners of Iran toward central parts, one can observe that the intensity of thunderstorms declines, but their distribution increases. This indicates that humidity plays a very important role in creating thunderstorms. As mentioned earlier, the second maximum intensity of thunderstorms in all the periods is observed in the south and southwest of the country. Some researchers believe that these thunderstorms are caused by combined patterns. More precisely, the stretch of a ridge on the northwest of Africa to Scandinavia creates cold air on the Mediterranean and deepens its trough. This phenomenon strengthens the low pressure center of the eastern Mediterranean. As a result, the increase of thermal gradient over the north of Africa and Red Sea strengthens the Sudanese system; hence, this system moves toward the north and is

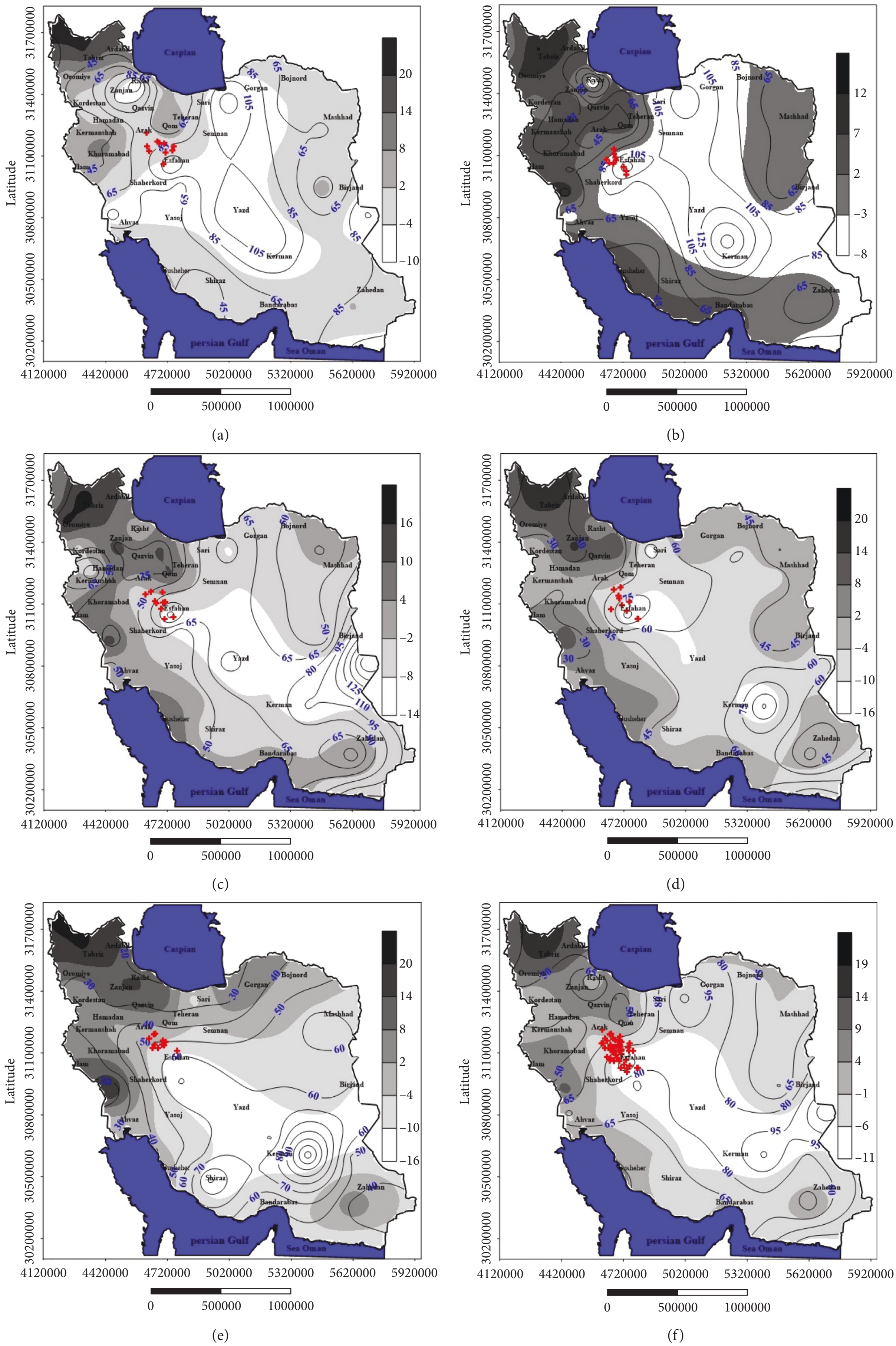

Figure 2: Spatial distribution of mean (contour), center of gravity (+), and anomalies (shaded) of Iran's thunderstorms in different periods. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, and (f) 1960–2010.

Table 3: The percentage of country's areas (studied stations) influenced by positive and negative anomalies of thunderstorms in different periods.

Index	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	1961–2010
Negative	77.2	70	75.1	73.4	71.5	76.7
Positive	22.8	30	24.98	26.6	28.5	23.3

combined with the Mediterranean low pressure, thus causing instability and thunderstorms over Iran [8, 36]. Some other researchers believe that these thunderstorms happen because of the front nature accompanying the advection of warm air in lower parts of the atmosphere, which happens in cyclone centers of 500 HPa [56]. Therefore, in the third, fourth, and fifth periods (1981–1990, 1991–2000, and 2001–2010), anomalies have had more or less similar conditions (Table 3). However, in the fourth period, spatial coefficient of variation of thunderstorms experienced fewer changes. For example, compared to the third period (1981–1990), the thunderstorm coefficient of variation in the southwest of the country experienced 40% decline in the fourth period (1991–2000) (Figure 2). These changes had less oscillation in the south, southwest, and northwest of the country (compared to other regions) during all the five periods. This can be explained in the light of the appropriate conditions of these regions for the occurrence of thunderstorms. The center of gravity was drawn for thunderstorms in order to identify their spatial behavior and regularity of occurrence (Figure 2). These centers are highlighted with gray spots. As indicated, the direction and inclination of thunderstorms' centers of gravity has a direct relationship with positive anomalies on the scale of both periods and years. That is, since in all the periods the maximum intensity of anomalies is located in the northwest and west of the country, the centers of gravity are located on the northwest of Iran (Figure 2). The density of these centers on a single location during all periods shows that they follow a regular pattern. The density and regularity of these centers are so important that even a small change in their location represents significant changes in thunderstorms.

In order to display the dominant pattern of spatial distribution of Iran's thunderstorms during various periods, Moran's I was employed (Figure 3). The results of this data analysis procedure indicate that whether the phenomena are randomly distributed or are clustered around a single point. If the value of Moran's I is positive, it shows that the studied phenomenon is surrounded by similar phenomena and it is part of that cluster. On the other hand, if the value of Moran's I is negative, it means that the studied phenomenon is surrounded by dissimilar phenomena, which do not form a cluster. This index is calculated based on a standardized score and interpreted in the light of the significance level.

In this procedure, HH represents clusters with high values (i.e., positive spatial autocorrelation), LL shows clusters with low values (i.e., negative spatial autocorrelation), HL indicates lack of any cluster (i.e., a high value is surrounded by lower values), and LH shows that a low value is surrounded by high values. For this type of analysis, the p-value is set at 0.05. The results of Moran's I analysis are presented in Figure 3.

Studying changes in anomaly patterns on both periodical and annual scales show that according to Moran's model, the maximum intensity of anomalies forms a positive spatial autocorrelation. In other words, it is surrounded by high value phenomena. On the other hand, the negative spatial autocorrelation pattern matches the minimum of negative anomalies. However, except the first period (1961–1970) in which this pattern has been insignificant, the pattern experienced almost similar conditions in other periods. For instance, in the first period, only 9.9% of the country's area (mainly the northwest of Iran and southwest of the Caspian Sea) had positive spatial autocorrelation (Table 4). At the same time, during this period, less than 3% of the country's area formed low clustering pattern (Table 4). Thus, in none of the periods, HL (i.e., high values surrounded by low values) and LH (i.e., low values surrounded by high values) patterns can be observed. Since the second period (1971–1980), the area dominated by positive and negative spatial autocorrelation increased, hence experiencing little oscillation in other periods. The most dominant positive spatial autocorrelation pattern (around 20%) can be observed during the second period (1971–1980) (Table 4). Since then, high clustering pattern experienced a significantly downward trend, which moves from the north to the south of Iran. In contrast, negative spatial autocorrelation experienced some oscillations Figure 3. The same findings have been obtained by Araghi et al., hence verifying the results of this study [57]. In general, thunderstorms do not follow any particular pattern in the largest area of the country.

3.2. Analyzing Oscillations and Cycles of Thunderstorms. In order to gain a more accurate understanding of thunderstorm changes within each decade, spectral analysis was used to assess cycles that dominate each period. In spectral analysis, changes in time series are divided into parts that have frequencies. This procedure of data analysis is used to extract and analyze explicit and implicit oscillations with various wavelengths. Figure 4 shows the spatial distribution of variances and cycles of thunderstorms. In this figure, cycles are identified by colorful spectra and variances are shown in the form of contours.

It is observed that in all the periods, mainly short cycles of 2 to 4 years dominate Iran's thunderstorms (in 95 percent level of significant). For example, in the first period (1961–1970), almost 75% of the country's area had thunderstorms with 2-year to 4-year cycles (Table 5). Most of the

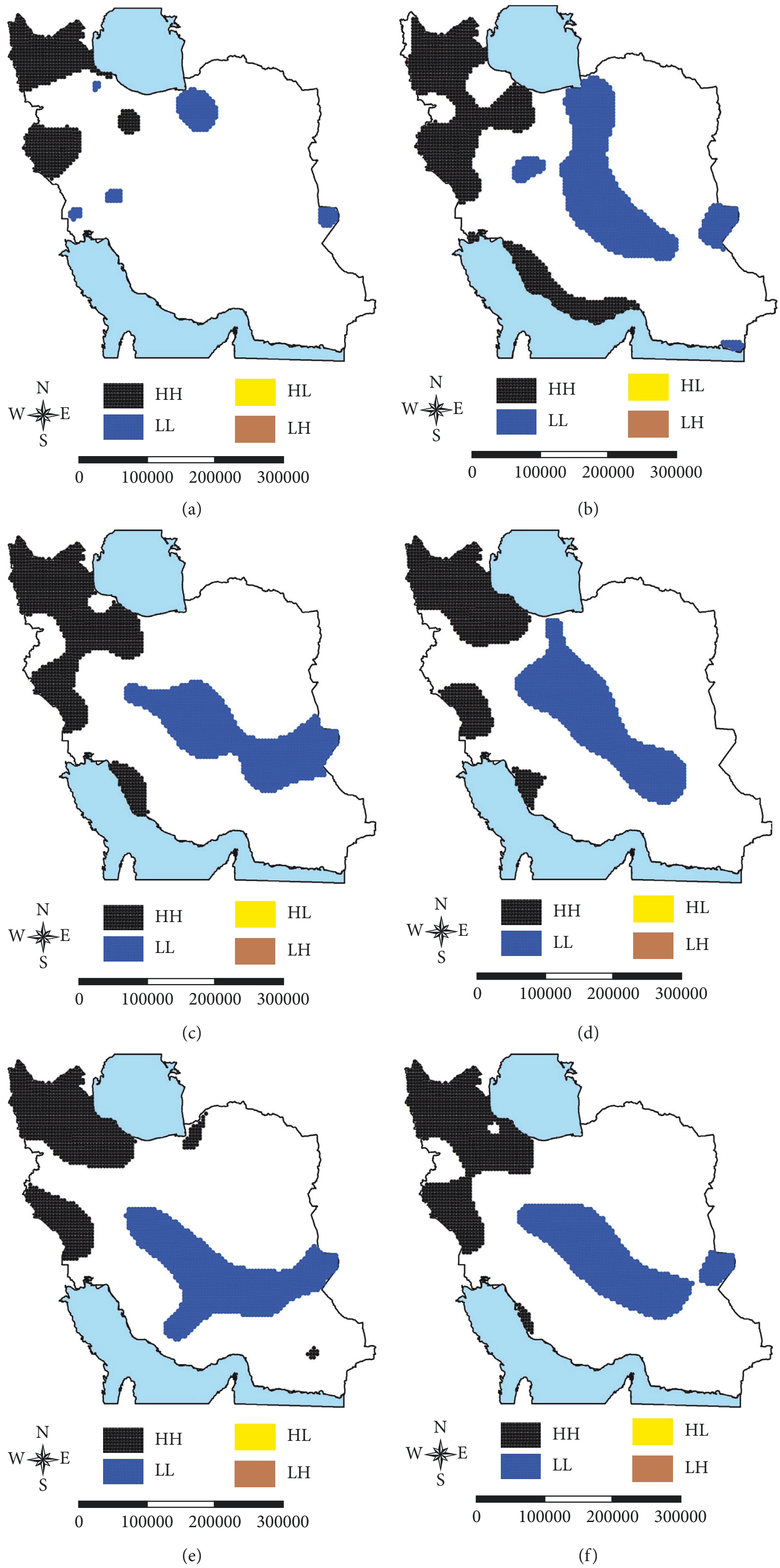

Figure 3: Spatial distribution of autocorrelation pattern of Iran's thunderstorms based on Moran's I^2. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, and (f) 1960–2010.

Table 4: The coverage percentage of spatial autocorrelation pattern of Iran's thunderstorms based on Moran's I.

Pattern	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	1961–2010
HH	9.9	19.07	16.01	17.19	14.58	15.66
LL	2.79	16.014	13.7	14.34	15.04	15.61
HL	—	—	—	—	—	—
LH	—	—	—	—	—	—

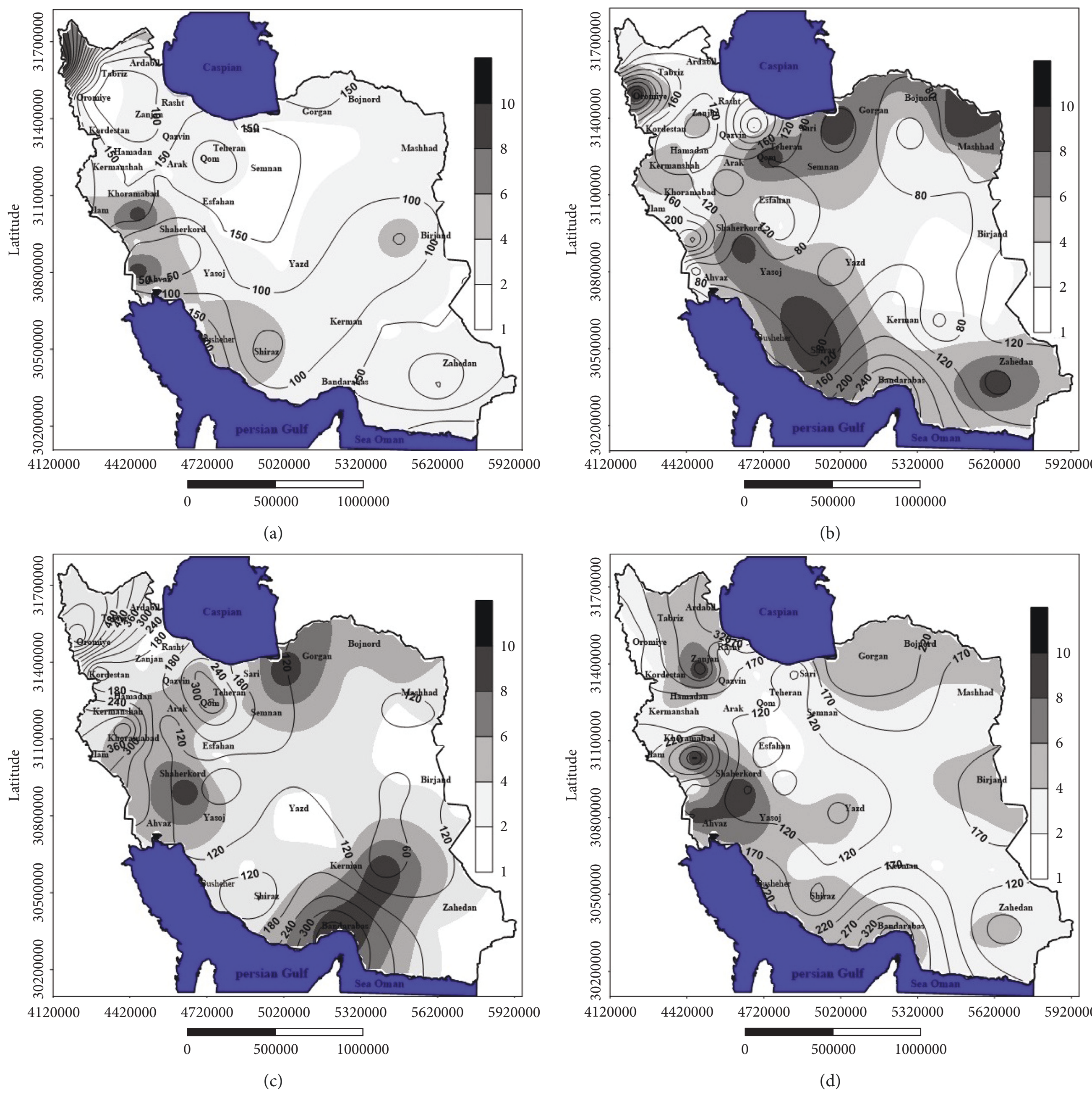

Figure 4: Continued.

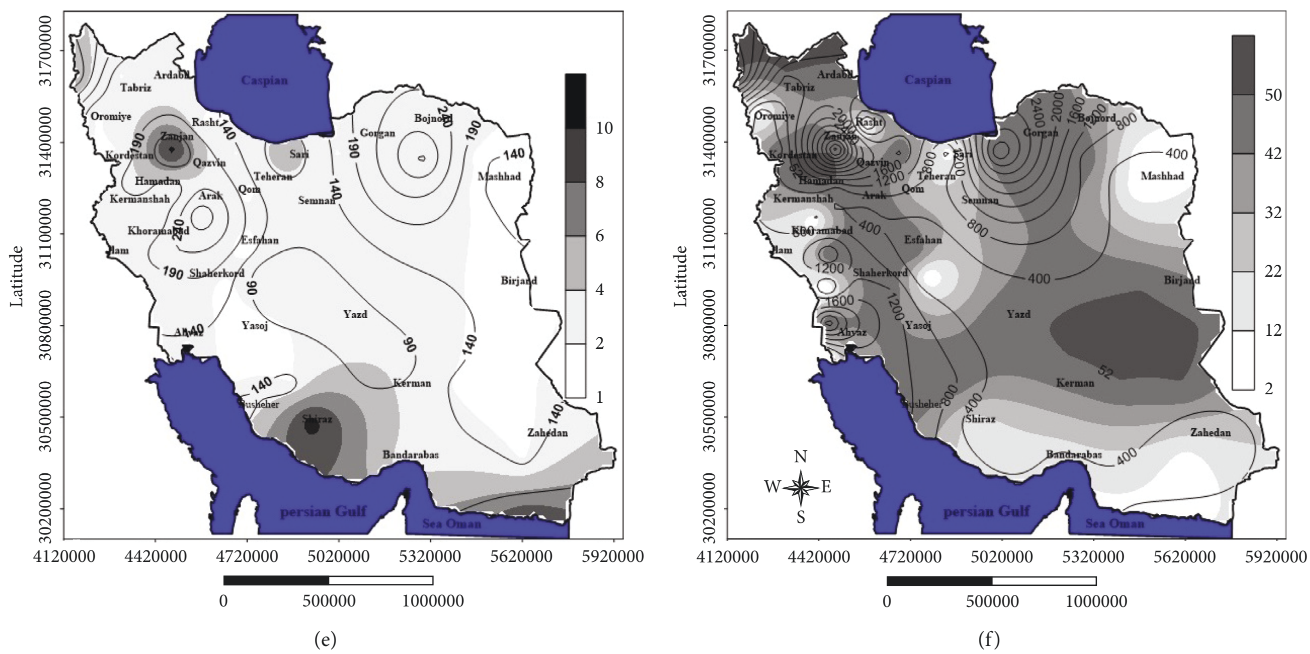

Figure 4: Spatial distribution of variance (contour) and cycles (shaded) of Iran's thunderstorms during various periods. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, and (f) 1960–2010.

Table 5: The area covered by Iran's thunderstorms during different periods.

Cycle (year)	1961–1970 (percent)	1971–1980 (percent)	1981–1990 (percent)	1991–2000 (percent)	2001–2010 (percent)	Annual	
						Cycle (year)	1961–2010 (percent)
1–2	9	7.6	8.7	1.7	12.6	0–10	3.2
2–4	74.6	33.6	49.2	52.7	69.5	10–20	14.9
4–8	15	50.7	37.2	43.5	15.2	20–30	14.1
8–10	1.4	8.1	4.8	2.1	2.7	30–40	18.5
						40–50	49.3

scientists have attributed these 2-year to 4-year cycles to El Nino-Southern Oscillation (ENSO), Quasi Binomial Oscillation (QBO) of the large-scale atmospheric circulation pattern, orbital currents, and other climatic-oceanic processes [58, 59].

Cycles in which the return period is as long as the studied period indicate the existence of a trend. These cycles can be observed in the form of black spots in all the periods (Figure 4). For example, in the first period (1961–1970), 1.4% of the country's area (which is mainly located in the west) has a trend, while in the second period (1971–1980), 8.1% of the area of the country has this trend (Table 5). Following short-term cycles, midterm cycles of 4 to 8 years dominate the analysis scale of periods (Table 5). In the second period (1971–1980), these cycles form a strip and cover 50.7% area of the country, mainly located in the inner parts. This is the highest coverage of the cycle among all the five periods (Figure 4). Moving toward the fourth and fifth periods (1991–2000 and 2001–2010), one can observe that the number of short-term cycles decline and midterm cycles become dominant, instead. In total, around 15% of the country's area had thunderstorms with midterm cycles of 10 to 20 years (Table 5). Jahanbakhsh and Edalatdoust believe that these cycles are the result of sunspot activities and the North Atlantic Oscillations (NAO) [60].

Taken together, in some regions of Iran, thunderstorms are influenced by many factors and indicate various patterns. In other parts, they follow a limited number of patterns. For instance, there is no dominant pattern in the southern and central parts of the country. Also, in all the five studied periods, a great deal of variety can be observed in thunderstorms' number of cycles. On the other hand, western and northwestern parts of the country experienced various cycles during the five periods. Thus, in addition to external factors, the topography of this part (western and northwestern) of the country played a significant role in the type of cycles. Nevertheless, Figure 3 (the map related to analyzing the annual cycles) shows that almost half of the country has a cycle which is similar to the studied period. As a result, in terms of both spatial and temporal scales, although thunderstorms have experienced oscillations, they have also had some trends. In all the periods, the highest variance is observed in the place where the length of the cycle is equal to that of the studied period.

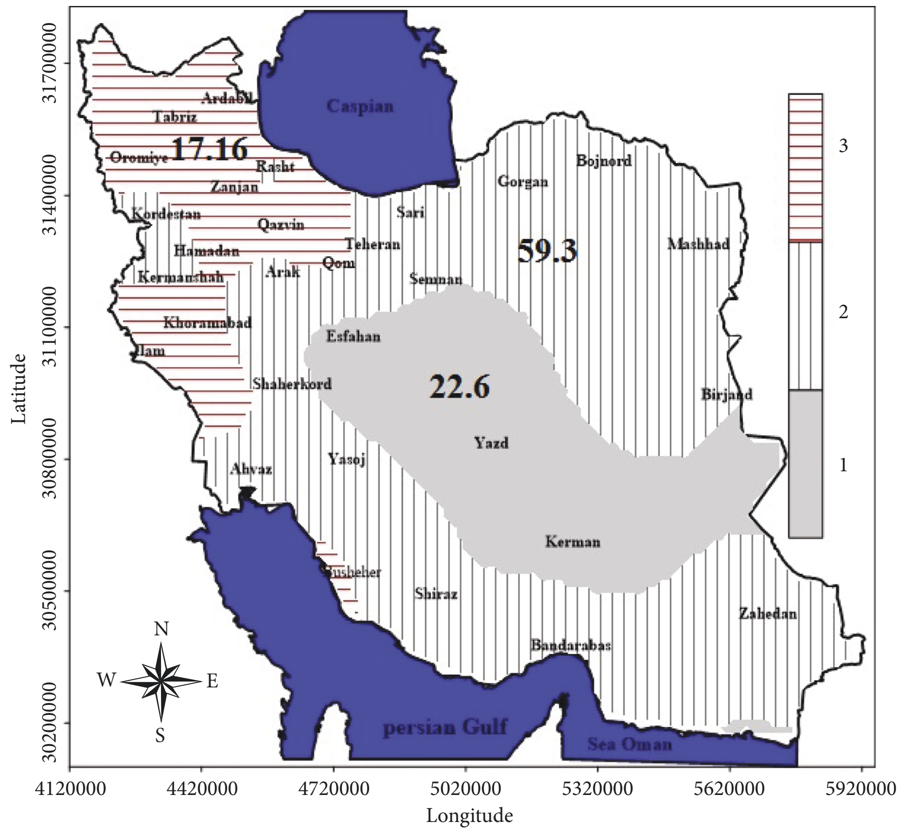

Figure 5: Regions influenced by Iran's thunderstorms during the past 50 years based on cluster analysis (percent).

Table 6: Descriptive statistics for regions influenced by Iran's thunderstorms based on cluster analysis.

Index	Frequency of the region which had few thunderstorms and high coefficient of variation (region 1)	Frequency of the region which had a mid-number of thunderstorms and low coefficient of variation (region 2)	Frequency of the region which had a great number of thunderstorms and low coefficient of variation (region 3)
Mean	5.3	10.3	20.6
Standard	0.8	2	3.8
Coefficient	25.6	19.8	12.6
Maximum	6.9	15.7	31.2
Minimum	2.8	6.9	15.8
Skewness	0. 3	0.5	−0.02
Kurtosis	2	2.6	2.5
Range	4	8.8	15.4
Median	5.3	10	19.4

3.3. Analyzing Thunderstorms in Each Region. Cluster analysis was utilized in order to investigate the regions that were influenced by thunderstorms. The results yielded three regions that indicate the regions covered by each cluster (percent) (Figure 5). The first region mainly includes central parts of Iran, especially the Loot Desert. The second region mostly encompasses the south, southeast, and northeast of the country. As indicated in Table 6, this region had an average thunderstorm occurrence of 10.3 days. Finally, the third region includes some northwestern regions and parts of coastal area of the Persian Gulf. This region has positive spatial autocorrelation and the maximum intensity of anomalies. It also has the highest average occurrence of thunderstorms (20.6 days) (Table 6). On the other hand, the highest coefficient of variation (25%) belongs to the first region (this region has few thunderstorms and high coefficient of changes). Table 6 indicates that there is an insignificant difference between the mean and mode of thunderstorms in these three regions, a phenomenon that shows the normal distribution of thunderstorms in the three regions. Skewness is positive in the first and second regions. Furthermore, for a large area of these two regions, the average occurrences of thunderstorms are 5.3 days and 10.3 days, respectively. Nonetheless, for the largest area of the third region, the mean of thunderstorm occurrence is 20.6 days.

4. Conclusion

Thunderstorms, which constitute a climatic component, are a key element in water cycle and atmospheric electricity. They reflect the unusual manifestation of solar energy and consist of different dimensions. In most of the cases, thunderstorms have limited power. However, sometimes, they are influenced by humidity, convective pattern, integration pattern, and atmospheric instabilities, hence causing large cyclonic storms which spread over thousands of square kilometers of areas and/or strong and destructive tornadoes [1, 61]. This study focused on thunderstorms that had been recorded between 1961 and 2010 in 98 synoptic stations, and this period was divided into five decades (1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010).

In all the five periods, thunderstorms mainly occurred in the southwest and northwest of Iran. The same findings have been obtained by Salahi and Ghavidel et al. [52, 62]. The occurrence of thunderstorm in the western coasts of the south of Iran has higher frequency than the central and the eastern regions, making it a potential area in this region for storm formation [63]. In the west part of the country, especially in northwest (Tabriz, Oroomieh, and Zanjan stations) and west, thunderstorms have higher frequencies [62]. Nevertheless, in the third and fourth periods, the intensity of these thunderstorms increased in the southern regions of the country. At the same time, central parts of Iran had negative anomaly, a finding that verifies the results of the study of Ghavidel et al. [62].

The occurrence of thunderstorms has experienced a rising trend toward recent decades; however, it has had a lot of oscillations, most of which have occurred along mountains, especially in the northwest topographies of Iran. These findings are in line with those of Ahmadi et al., who concentrated on thunderstorms in the province of Khuzestan [64].

The results of data analysis indicated that in recent decades, positive autocorrelation pattern of thunderstorms has had a significant increase. On the contrary, negative autocorrelation pattern of these thunderstorms has had little oscillation. However, the positive pattern has experienced a declining trend in the southern areas of the country. The same findings were obtained by [61]. Changes that occurred in the climate and water resources of Iran during the past years and their consequences (e.g., warming, precipitation reduction, frequent droughts, and the decline of groundwater levels) indicate that climate change deserves more serious attention.

The results of analyzing thunderstorm cycles during various periods showed that short-term cycles of 2 to 4 years dominated thunderstorms. Most of the scientists attribute these cycles to ENSO, QBO of the large-scale atmospheric circulation pattern, orbital currents, and other climatic-oceanic processes. For example, Kane and Teixeira believed that 2- to 3-year cycles of precipitation in Massachusetts could be attributed to QBO [65]. The same claim was proposed by Hartman et al. for 2- to 3-year cycles of precipitation in China and Lana et al. for 4.6-year and 2.1-year cycles of precipitation in Fabra in the northeast of Spain [58, 66]. Furthermore, Hartman et al. believed that 9.1 year and 5.5 year cycles of precipitation could be explained in the light of the NAO and cycles of 11.8 years could be attributed to sunspot activities [58]. Phase oscillations were observed in thunderstorm cycles of mountainous areas of the country; nonetheless, these regions have experienced high coefficient of variation in different periods. Thus, while planning for industrial activities, experts must consider these issues into account.

The results of thunderstorm cluster analysis yielded three regions: the first region mainly includes central parts of Iran, especially the Loot Desert. The second one mostly encompasses the south, southeast, and northeast of the country. And, the third region covers the northwest of Iran and some small coastal areas of the Persian Gulf.

Data Availability

The meteorological data used to support the findings of this study can be found in http://aerology.ir/ and are available from the corresponding author upon request. The data given in figures and tables which are used to support the findings of this study are also available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

All authors contributed equally to this article.

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