Spatiotemporal Changes in Precipitation Concentration Indicators Over Iran

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1 Spatiotemporal Changes in Precipitation Concentration

2 Indicators over Iran

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9 **Abstract**

10 This study was conducted to investigate the spatiotemporal variability in precipitation concentration over Iran. For that
11 purpose, daily precipitation data with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ from the Asfazari database for the period
12 from 01/01/1962 to 31/12/2019 were used. Three indices including the precipitation concentration index (PCI),
13 precipitation concentration period (PCP), and precipitation concentration degree (PCD) were utilized for examination of
14 the variability in precipitation concentration over the country. The results demonstrated that the central, south-eastern,
15 and eastern parts of the country exhibited maximum temporal precipitation concentration, while the least precipitation
16 concentration could be observed over the Caspian coasts and the northern half of the country. The year 1998 was
17 selected as the change point due to the considerable difference in the values of the examined indices, and the long-term
18 statistical period was divided into two sub-periods before and after the change. During the sub-period after the change
19 point (1999-2019), precipitation concentration has increased in the western, central, eastern, and south-eastern parts of
20 Iran, according to PCI and PCD, and has decreased in the North and Northeast and along the northern coastline of
21 Oman Sea. Furthermore, there have been great spatial differences in the period of occurrence of precipitation along the
22 Northern coasts, according to PCP, varying from November, along the Caspian coasts, to August, along the northern
23 foothills of Alborz Mountains. The PCP index has increased during the sub-period after the change point along the
24 northern coastlines of Persian Gulf and Oman Sea and in parts of the North (along Alborz Mountains), indicating a shift
25 in the period of precipitation from winter to the warm seasons of spring and summer. Moreover, the decrease in PCP in
26 the Northwest and Northeast suggested that the period of occurrence of precipitation has shifted from the second half of

winter toward early winter and late fall. After the year of change point, the frequency of rainy days and precipitation have decreased, and PCI and PCD have increased.

29

Keywords: Variability, Precipitation Concentration, Index, Iran

31

1 Introduction

One of the most important climatic characteristics of any region, precipitation is, at the same time, one of the least sustainable variables that seriously affect the available water resources (Obot et al. 2010; Hu et al. 2017). Since 1900, land precipitation has increased by about 2 percent. The increase has exhibited no uniform spatiotemporal distribution, however (Qu et al. 2016). Studies demonstrate that there will be an increasing trend in extreme precipitation (Asadieh and Krakauer 2015). Moreover, the world is confronted with the issue of flood and drought due to climate change, and the daily prediction of severe precipitation can be effective in the planning to overcome the destructive effects of climate change (Shete and Patel 2015). Semi-arid regions in Iran have turned into arid ones over the past four centuries (Gholami et al. 2017). With a total greenhouse gas (GHG) emission of almost 741616 million tons of CO₂, Iran is the first country to be responsible for climate change in Middle East and the seventh in the world. Its high level of contribution to GHG emission is associated with the considerable production of oil and gas and rapid urbanization (Daneshvar et al. 2019). One of the most important responses of the Earth to the warming imposed on it involves variation in the water cycle. These include severe fluctuation in precipitation and its patterns, inappropriate spatiotemporal dispersal of rainfall, excessive evaporation and transpiration, significant increase in the occurrence of drought and flood and their frequency (IPCC 2014). Therefore, it seems necessary to use indices to express the variation in precipitation. They include Precipitation Concentration Index (PCI), Precipitation Concentration Period (PCP), and Precipitation Concentration Degree (PCD), used in precipitation studies around the world (Martin-Vide 2004; Li et al. 2011; Yeşilırmak and Atatanır 2016).

Raziei et al. (2008) investigated the variation in drought and precipitation in the western half of Iran in the 1965-2000 period using the precipitation concentration index. According to their findings, topography and latitude played the greatest roles in precipitation concentration fluctuation in the region. A long-term negative trend in precipitation concentration (a period of drought) was observed in the Northwest, along with a poor positive trend in the Southwest.

54 Mondol et al. (2018) investigated precipitation concentration in Bangladesh during the 1980-2011 period using PCI. An
55 irregular, variable trend in precipitation concentration was found in that research to occur over the country. Moreover, a
56 significant increasing trend in temporal precipitation concentration was identified for the period after 2000 over most of
57 Bangladesh, which was consistent with the increase in the spatiotemporal irregularity of precipitation intensity and
58 duration as well as temporal precipitation concentration. Cortesi et al. (2012) analysed daily precipitation concentration
59 all around Europe during the 1971-2010 period. The results demonstrated that the highest daily precipitation density
60 occurred at the Western Mediterranean Sea basin, *i.e.* the coasts in Spain and France. In fact, latitude and distance from
61 the sea play major roles in the distribution of daily precipitation concentration in the region. It should also be noted that
62 the results of the Mann-Kendall's test did not exhibit a consistent series of precipitation distribution, and there was
63 seasonal and annual density only in parts of Northern and South-western France. In fact, the daily precipitation
64 concentration index ranges between 0.51 and 0.72 all around Europe, which is heterogeneous from the Northwest to the
65 Southeast. In general, the trend in the spatial distribution of precipitation is inconsistent all around Europe with the
66 global patterns.

67 Tolika (2019) analysed the temporal distribution of precipitation over Greece using the daily precipitation
68 concentration index in annual, seasonal, and monthly scale in regard to the atmospheric circulation patterns during the
69 1958-2000 period. The results indicated moderate precipitation concentration over Northern Greece and an increase in
70 the precipitation concentration index values toward the South. Over the southern and south-eastern regions,
71 precipitation was concentrated only in a few months, while there was slight precipitation over most of the year. The
72 precipitation concentration index value was moderate in winter and spring, but higher in summer, when less
73 precipitation coherence was exhibited. Precipitation concentration has increased all around Greece during the statistical
74 period in annual scale and in winter, spring, and fall, in that order. These variations have been associated to a large
75 extent with those in the atmospheric circulations over the country, reducing the frequency of rainy days. Yonglin et al.
76 (2016) made an analysis to identify a correlation between precipitation inconsistency and occurrence of natural events
77 and disasters such as flood and drought in China during the 1959-2014 period. They analysed the relationship between
78 18 stations in the study area using data on daily precipitation, the precipitation concentration index, and Spearman's
79 correlation coefficient. The results indicated close correlations between factors such as severity of drought, occurrence
80 of flood, and concentration of precipitation from the northwest to the southeast of the study area. In fact, high
81 consistency was observed in the research based on the findings on the indices between the type of precipitation
82 concentration in terms of spatiotemporal intensity and the above natural disasters.

83 A spatiotemporal investigation was made by Li et al. (2011) of the level and period of the precipitation concentration
84 index in Xinjiang Province, China during the 1961-2008 period. The results indicated that higher values of the
85 precipitation concentration index were observed at locations with less total annual precipitation and fewer rainy days.
86 Moreover, the northern regions of Xinjiang Province, which were associated with lower values of the concentration
87 index, involved precipitation dispersal over the year, while precipitation was largely concentrated in certain months in
88 the southern part of the province. Rahimi and Fatemi (2019) investigated the variation in heavy and moderate
89 precipitation in Iran. According to the results, decreasing trends have occurred in annual precipitation at most of the
90 stations during the 1960-2017 period, and the occurrence of heavy precipitation, rainy days, and severe wet periods has
91 been restricted to the Caspian coasts in the North and the Southern coasts. The purpose of this research was to analyse
92 the spatiotemporal variability in the different indices of precipitation concentration over Iran during the long-term 1962-
93 2019 period. The purpose of this research is to assess precipitation concentration and to analyze its period of occurrence
94 in monthly scale, the monthly precipitation distribution degree, and their trends. The hidden aspects of the temporal and
95 spatial behaviour of the turbulent variable of precipitation and its concentration can be manifested better through
96 application of precipitation network data with high spatial resolution over a long period of time and simultaneous
97 examination and comparison of the three indicators.

98

99 **2 Study area**

100

101 Figure 1 shows the altitudinal conditions of the study area, including two high-altitude zones over the country, one with
102 an altitude of more than 5000 meters along the Northern coastline and the other with an altitude of more than 4000
103 meters between 30°N and 35°N in the western half of the country along the central highlands of Zagros. The mean
104 altitude of the country is about 1250 meters, and the low-altitude areas include the Southern and Northern coasts and the
105 Southwest. The central parts of the country are also regarded as leeward low-altitude areas.

106

Fig. 1 Study area with height values and configuration of roughness

The long term mean of yearly precipitation during the 1962-2019 period is shown in Figure 2. It can be observed that the highest precipitation occurs along the south-western coasts of Caspian Sea, with an average annual precipitation of more than 1500 millimetres. The above rate amounts to more than 800 millimetres along Zagros Mountains in the western half of the country, located between 28°N and 34°N, and over the border highlands in the West. In the central parts of Iran, however, average yearly precipitation is minimized to 56 millimetres. In general, it can be stated that there are huge differences in monthly and annual precipitation around the country. Precipitation and its intensity have undergone quite clear variability as a result of that observed in the behaviour of precipitation-inducing weather systems over Iran in recent decades, arising from global warming and climate change according to researchers. This makes it necessary to analyse and scrutinize the variability in spatiotemporal precipitation behaviour.

Fig. 2 Long term mean of yearly precipitation over Iran

120
121
122

123 **3 Data and Methods**

124 **3.1 Data**

125 For this study, daily gridded precipitation data from the Asfazari database during 01/01/1962 to 31/12/2019 were used.
126 The database has been interpolated over Iran using the Kriging geostatistical method at spatial resolution of 0.25×0.25
127 degrees.

128 3.2 Methods

129 3.2.1 Precipitation Concentration Index (PCI)

130 In this research, the inconsistency in monthly precipitation was calculated using the precipitation concentration index.
131 The index was first presented by Oliver (1980) and then adjusted and modified by De Luis et al. (2012). According to
132 Michiels et al. (1992), this index is an indicator of the erodibility of precipitation, and represents the relationship
133 between variability and the monthly distribution of precipitation (De Luis et al. 2012). The modified version of the
134 index is as follows (Eq.1):

$$135 \quad PCI = 100 \times \frac{\sum_{i=1}^{12} P_i^2}{(\sum_{i=1}^{12} P_i)^2} \quad (1)$$

136 where P_i is the amount of precipitation in the i^{th} month, separately calculated for each year during the period of
137 analysis for each of the spatial cells. In general, the lower the amount of annual precipitation, the greater the variation
138 exhibited by the amount of monthly precipitation. Consequently, the higher the value of the index, the greater the above
139 variation (Oliver 1980). In other words, a greater portion of annual precipitation occurs during a small number of
140 precipitation events.

141 The value of the precipitation concentration index varies between 8.3 and 100. According to Oliver (1980) broad
142 classification, index values between 8.3 and 10 indicate uniform distribution of monthly precipitation throughout the
143 year (low precipitation concentration), values between 10 and 15 denote moderate precipitation concentration, and those
144 between 15 and 20 signify irregular, seasonal distribution (irregular precipitation concentration). Index values more
145 than 20 represent climatic conditions with considerable, fundamental variation in monthly precipitation and plenty of
146 irregularity in its distribution (high precipitation concentration) (De Luis et al. 2011).

147

148 3.2.2 Precipitation Concentration Period (PCP) and Precipitation Concentration Degree (PCD)

149 The indices known as the precipitation concentration period and the precipitation concentration degree were presented
150 by Zhang and Qian (2003). They convert the values of the scalar variable of precipitation to vectors to specify the
151 annual distribution of precipitation correctly. These indices are also powerful tools for investigation of the climatic
152 hazards of drought and flood. They are calculated based mainly on vector analyses. Let us assume the values of monthly
153 precipitation as a directed vector and a full year as a cycle, a 360° circle, where each month equals a 30° angle,
154 specifying the direction of that month in the year. In that case, the angle corresponding to the 15th (middle) day in each

month will be assumed as its direction angle, with a different value from those of the other months (Li et al. 2011). The PCD and PCP indices can be calculated easily based on the above assumptions. First, the angle in question needs to be calculated and considered as basis. Each month's precipitation is assumed to be a vector that is decomposed into two, horizontal and vertical, components. Each group of components are then summed to obtain the corresponding total values (represented as R_x and R_y). In the next step, the PCD index is assumed to be the absolute value of the two totals divided by total annual precipitation. Therefore, the value of PCD correctly reflects the level of precipitation concentration over a certain period in a year. If annual precipitation occurs in only one month of the year, for instance, the ratio of the combinatorial component to annual precipitation will be 1, and the value of PCD will be maximized. By contrast, if monthly precipitation is the same throughout the year, the pairwise totals of the combined components will be summed separately along the horizontal and vertical axes, until they amount to zero, and the value of PCD is minimized. Yonglin et al. (2016) proposed a classification for a more accurate specification of concentration in terms of PCD values, as follows (table 1).

Table 1 Evaluation and classification of PCD values

Classification	Type	PCD values
1	High concentration	$PCD > 0.8$
2	Medium concentration	$0.721 < PCD \leq 0.8$
3	Low concentration	$0.647 < PCD \leq 0.721$
4	normal	$0.476 < PCD \leq 0.647$
5	Low distribution	$0.384 < PCD \leq 0.476$
6	Medium distribution	$0.27 < PCD \leq 0.384$
7	High distribution	$PCD < 0.27$

On the other hand, the PCP index involves the direction of the angle of the combinatorial component. In fact, it simply represents the overall effect of monthly precipitation and the mean angle of the total vector. It also indicates what month of the year maximum precipitation occurs in.

Let us assume that precipitation in each month of the year is decomposed into two, horizontal and vertical, components, represented by the sine and cosine axes, respectively. Thus (Equations 2 and 3):

$$r_{xi} = r_i \sin \theta_i \quad (2)$$

$$r_{yi} = r_i \cos \theta_i \quad (3)$$

where r_i indicates monthly precipitation, and θ_i denotes the angle corresponding to each month. Therefore, the vector for precipitation in the twelve months of the year is decomposed into two combinatorial horizontal and vertical components, which can be shown as follows

$$R_x = \sum_{i=1}^{12} r_{xi} = \sum_{i=1}^{12} r_i \sin \theta_i \quad (4)$$

$$R_y = \sum_{i=1}^{12} r_{yi} = \sum_{i=1}^{12} r_i \cos \theta_i \quad (5)$$

Moreover, the total is defined as follows (Eq.6):

$$R = \sqrt{R_x^2 + R_y^2} = \sqrt{(\sum_{i=1}^{12} r_i \sin \theta_i)^2 + (\sum_{i=1}^{12} r_i \cos \theta_i)^2} \quad (6)$$

Similarly, the PCD (C_n) index is written as follows (Eq.7):

$$C_n = \frac{R}{\omega} = \frac{\sqrt{(\sum_{i=1}^{12} r_i \sin \theta_i)^2 + (\sum_{i=1}^{12} r_i \cos \theta_i)^2}}{\sum_{i=1}^{12} r_i} \quad (7)$$

where ω is the total value of precipitation over the year.

Since the ratio of the horizontal combinatorial component to the vertical one is the tangent of the vector angle, the PCP (D) index is defined as follows (Eq.8).

$$D = \tan^{-1} \left(\frac{R_x}{R_y} \right) \quad (8)$$

Equations 7 and 8 concern the PCD (D) and PCD (C_n) indices, respectively, and are far more accurate and useful than the method of vector representation. It was stated above how to define the range of variation in the vector angle for precipitation in each month of the year, but the middle angle for each month, θ_i , has not yet been specified. Table 2 shows the θ_i angle separately for each month.

Table 2 The range of the precipitation vector angle of each month of the year and the middle angle of each month θ_i (units are in degrees)

Month	Angle range	Angle in the middle of the month
January	15 to 345	0
February	15 to 45	30
March	45 to 75	60
April	75 to 105	90
May	105 to 135	120
June	135 to 165	150
June	165 to 195	180
August	195 to 225	210
September	225 to 255	240
October	255 to 285	270
November	285 to 315	300
December	315 to 345	330

Figure 3 separately shows the distribution of the angle ranges concerning each month of the year and the median angles of each month. It can also be observed in the figure how the monthly precipitation vector is decomposed into two components, horizontal and vertical. For instance, two monthly precipitation components, horizontal and vertical, can be defined for February as vectors $\overrightarrow{BA}$ and $\overrightarrow{OB}$. The size of the vector indicates precipitation concentration intensity, and its direction suggests the period in which precipitation is concentrated.

Figure 3 Distribution of the angle range of each month of the year and the corresponding angle in the middle of each month

As shown in Figure 3, however, the vertical component of precipitation can be observed only in January and July, and the horizontal one only in April and October. Therefore, there are equations simpler than Equations 7 and 8 (Equations 9 and 10) for calculation of C_n and D in cases other than those mentioned above that can replace the calculation of the sine and cosine values of the angles corresponding to each month, as follows.

$$C_n = R/\omega = \sqrt{R_x^2 + R_y^2 / \sum_{i=1}^{12} r_i} = \quad (9)$$

$$D = \tan^{-1} \left[\frac{R_x}{R_y} \right] = \quad (10)$$

$$\left[\frac{\frac{1}{2}(r_2 + r_6 - r_8 - r_{12}) + \frac{\sqrt{3}}{2}(r_3 + r_5 - r_9 - r_{11}) + (r_4 - r_{10})}{\frac{1}{2}(r_3 - r_5 - r_9 + r_{11}) + \frac{\sqrt{3}}{2}(r_2 - r_6 - r_8 + r_{12}) + (r_1 - r_7)} \right]$$

215

216 The above method is accurate and clear, where each day of the month should encompass the same angle (30°) over
 217 the circle if periods are considered in terms of months, although not all months contain the same number of days.

218 For the PCD index, the sum of the horizontal components (R_x) indicates the difference in precipitation between the
 219 first half of the year (January to June) and the second half (July to December), while the vertical components suggest
 220 the difference in precipitation between the cold winter half of the year (October to March) and the hot summer half
 221 (April to September). In general, the PCP index represents the period (month) in which total precipitation is
 222 concentrated throughout the year, and PCD signifies the degree and concentration of total precipitation during the 12
 223 months of the year.

224

225 3.2.3 Mann-Whitney test

226 The nonparametric Mann-Whitney test was presented by Mann and Whitney in 1947. It was used in this research to
 227 verify the significance of change points in the time series of indices. The change points were identified using the
 228 homogeneity test of cumulative deviations and Worsley's test of maximum likelihood for the analyzed indices, and their
 229 significance was verified using the Mann-Whitney test at three confidence levels, 90, 95, and 99.

230 If a time series is broken into two sets $\{X_1, X_2, \dots, X_T\}$ and $\{X_{t+1}, X_{t+2}, \dots, X_T\}$ such that the numbers N_1 and N_2 are
 231 equal to N , the series of the two sets can be sorted to obtain a new series Z_i :

$$232 \quad U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} + R_1 \quad (11)$$

$$233 \quad U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \quad (12)$$

234 where R_1 and R_2 are the sums of the ranks of the individuals in the first and second samples, respectively. The Mann-
 235 Whitney test statistic is observed for samples larger than 20 and calculated using the following equation, and it follows
 236 standard normal distribution (Asakereh, 2011).

$$237 \quad Z_0 = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{(n_1)(n_2)(n_1+n_2+1)}{12}}} \quad (13)$$

238 The calculated test statistic Z_0 is compared to the normal distribution table. If Z_0 is greater than the value in the Z
239 table, the null hypothesis (that the two series separated based on a change point are equal) is not retained, and the time
240 series exhibits different behavior before and after the change point. By contrast, if Z_0 is less than the value in the Z table,
241 the null hypothesis (that the two series separated based on a change point are equal) is retained. For samples with fewer
242 than 20 observations, the critical U is extracted from the table particular to the test and compared to the smaller U in the
243 above equations.

244

245 **4 Results**

246 **4.1 Precipitation Concentration Index**

247 One of the indices used in this research for identification of precipitation dispersal over the year was the precipitation
248 concentration index, which is shown for Iran in Figure 4. As can be observed, precipitation concentration has gradually
249 increased from the North to the South, amounting to more than 25 % all over the southern half of the country,
250 approximately to the south of 35°N, and maximized along the Southern coasts to 45 %, indicating that the majority of
251 rainy days, total precipitation supply, and extreme irregularity have occurred in these regions within a short period over
252 the year. The value of PCI has decreased, however, in regions with higher latitudes and closer to the westerly's winds
253 and in the North and the West, where high Alborz and Zagros Mountains are located, respectively. Minimum
254 precipitation concentration can be observed along the Caspian coasts. This region has had the highest frequency of rainy
255 days over the country each year, occurring in a fully dispersed form in the different seasons of the year. Therefore, an
256 inverse correlation is observed over the country between PCI and the frequency of rainy days and latitude. Longitude,
257 however, has been directly related to PCI, which indicates the higher precipitation concentration in arid, low-
258 precipitation, and low-altitude regions over the country (Table 3).

259

260

Fig. 4 Spatial distribution of PCI over Iran

Table 3 Area-average correlation between precipitation concentration index (PCI) with spatial characteristics, precipitation and rainy days

index	Shorthand	R
Longitude	Lon	0.535
latitude	Lat	-0.913
precipitation	P	-0.53
rainy days	RD	-0.868

It was found through an analysis of the mean PCI values in Iran during the long-term period from 1962 to 2019 that precipitation concentration over the country has gradually increased significantly ever since 1998. Therefore, the period

under investigation was divided into two sub-periods, one before the change point (1962-1998) and the other thereafter (1999-2019), and the mean values and trends in the index were compared. According to Figure 5a, the spatial dispersal of PCI values during the first period has been consistent with long-term mean PCI all over the statistical period, with the regions with maximum and minimum PCI located along the Southern and Northern coasts, respectively. Low precipitation concentration (less than 25 percent) has proceeded from the Northwestern corner to areas to the south of and along Zagros Mountains, in the western half of Iran. During the first sub-period, a wider area in the country has undergone low precipitation concentration, and regions such as Lalehzar Mountains, in the South at 30°N 57°E, and the central and eastern parts of Iran have been characterized by lower precipitation concentration intensity, *i.e.* higher temporal dispersal of rainy days, over the year. Regions with concentration values higher than 40 percent are observed within a small part of the Southern coasts. During the second sub-period, however, regions with high precipitation concentration values have been extended significantly over a wider range toward higher latitudes, in areas including the Southwest, Center, and eastern half of the country. Moreover, concentration intensity has amounted to more than 50 percent over certain regions such as the south-eastern corner of the country. The point to be noted is that the PCI value has significantly decreased in the second sub-period along the northern coastline of Oman Sea, which can be associated with climate change and global warming, in turn increasing the mean trend in factors such as Oman Sea surface temperature and land surface temperature (Bahri and Khosravi 2020; Pionkovski et al. 2014), specific humidity (Darand et al. 2019), and fall precipitation in the South and Southeast in recent years (Mosaffa et al. 2020) (Fig. 5b). Figure 5c shows the difference between the significant changes in PCI over the country before the change point and those thereafter. It is clearly observed in the figure that the value of PCI has significantly increased during the second sub-period over the West, centre, and East and in certain dispersed areas adjacent to the Caspian coasts. This indicates an increase in precipitation irregularity and the occurrence of rainy days within a particular short period of the year over these regions. By contrast, the value of PCI has decreased at a significance level of 0.001 along Alborz Mountains in the North, between 35°N and 37°N, and the northern coastline of Oman Sea.

294
 295 **Fig. 5** Spatial distribution of PCI over Iran **a:** In the pre-change point period (1962-1998), **b:** After the change point period (1999-
 296 2019), **c:** Significance of their differences in different confidence levels over Iran

297 Figure 6 shows the area-averaged of yearly time series of PCI, frequency of rainy days, and mean precipitation over
 298 Iran during the 1962-2019 statistical period. According to the figure, PCI has gradually increased after 1998. Inverse
 299 relationships can also be observed between PCI and the other two variables above. Thus, the frequency of rainy days
 300 and precipitation have decreased over the country as PCI has increased during the examined statistical period,
 301 particularly after 1998. The inverse relationship between PCI and the former variable (-0.602) has been severer than that
 302 between PCI and the latter (-0.559), suggesting that the frequency of rainy days has been more effective on the variation
 303 in the PCI rate over Iran.

Fig. 6 Area-averaged of PCI time series, frequency of rainy days and annual precipitation in Iran

4.2 Precipitation Concentration Period (PCP)

The precipitation concentration index was used for specification of precipitation concentration in different months of the year (Fig. 7). Figure 7 shows the spatial distribution of PCP. The period of precipitation concentration over Iran exhibits highly significant spatial variability, where minimum PCP has varied from less than 50° in the West, centre, and East to more than 300° along the southern Caspian coastline. The latest time of occurrence of precipitation has varied as precipitation concentration from November along the Caspian coastline to August along the northern foothills of Alborz Mountains. The wide variety in the period of occurrence of precipitation in the coastal and adjacent regions actually indicates the roles of topography, distance from the sea, and difference in synoptic and local-scale systems in the occurrence of precipitation. Like the Caspian coasts, the northern coasts of Persian Gulf and those on the Southwest exhibit long maximum precipitation periods, with PCP values varying between about 90° and 160° , corresponding to the months from March to July. Another class has involved regions in the Northwest and Southeast, where precipitation has occurred from April to July. Over a large part of the country, however, there has been precipitation in winter, particularly in February and March.

Fig. 7 Spatial distribution of PCP over Iran on a daily time scale

The analysis of variability in PCP during the examined periods demonstrates that the spatial dispersal of PCP over Iran in the sub-period before the change point has been closely similar to the mean for the entire long-term period (Fig. 8a). In the sub-period after the change point, however, PCP has decreased over different regions including the Northwest and Northeast, located between 35°N and 37°N, and small areas to the east of Zagros Mountains (Fig. 8b),

indicating the temporal variation in the occurrence of precipitation from the second half of summer toward late fall and early winter. However, there are wider regions where mean monthly PCP has increased than ones with decrease in PCP. The former regions are dispersed all along the southern coasts, in the Southwest, and to the north of the central regions of the country, with PCP values amounting from about 10°- 80° during the sub-period before the change point to 130°- 250° during the sub-period thereafter. In fact, the increase in the value of PCP over these regions indicates the temporal shift in precipitation from winter to mid-spring up to late summer. The maximum increase in PCP during the second sub-period has amounted to about 225° over a small part of the northern coasts of Persian Gulf in mid-July. Figure 8c shows the difference between the values of PCP in both sub-periods before and after the change point in terms of the Mann-Whitney test significance, well indicating the significant variability in the precipitation concentration period over these regions.

Fig. 8 Spatial distribution of PCP over Iran **a**: In the pre-change point (1962-1998), **b**: Post-change point (1999-2019), **c**: Significance of their differences in different confidence levels

348 4.3 Precipitation Concentration Degree

349

350 Another indicator of the precipitation concentration is the precipitation concentration degree, where is calculated based
351 on the daily precipitation data (Fig. 9). Minimum PCD can be observed along the Northern Caspian coastline with a rate
352 of less than 0.3, indicating the high dispersal of rainy days over the year. Toward the southern latitudes, the
353 precipitation concentration degree has gradually increased; thus, regions located along Alborz Mountains, in the North,
354 and Zagros Mountains, in the Northwest, exhibit moderate precipitation, with the index value lying between 0.35 and
355 0.45. In the other regions, including the West, South, and centre and the eastern half of the country, concentration
356 degree has been more than 0.6, indicating the occurrence of most rainy days within a small period of the year (winter
357 mainly) and the lack of precipitation in most of the year's months. It is only in the south-eastern corner of the country
358 that precipitation concentration degree exhibits desirable conditions, with a value of 0.4, indicating the greater dispersal
359 of rainy days over the year than in the adjacent regions in the South.

360

361

362

363

364
365 **Fig. 9** Spatial distribution of PCD over Iran

366 Mean PCD during the sub-periods before and after the change point and the difference between the values of the index
367 in the two sub-periods are given in figure 10. As can be observed, PCD has decreased in the sub-period after the change
368 point over the south-eastern Caspian coasts, the northern parts of the central region, corresponding to Alborz
369 Mountains, and Northern Zagros Mountains, in the Northwest between 35°N and 37°N (Fig. 10a). Moreover, the index
370 has increased in the above sub-period over small areas adjacent to the Caspian coasts particularly the south-western
371 ones and in the Northwest, which can indicate the alarming conditions of water resources in such regions despite their
372 small areas. Thus, the decreasing trend in precipitation in certain Northern and North-western regions (Pour et al. 2020;
373 Fathian et al. 2020) has destructive effects on the available water resources. According to Dehghanipour et al. (2020),
374 water level has significantly lowered at Lake Urmia, in North-western Iran, during the 1996-2016 period. By contrast,
375 PCD has increased in the Southeast, centre, and East. The greatest increase in PCD can be observed along the South-

376 eastern coasts, amounting from about 0.6 in the sub-period before the change point to 0.8 in the sub-period thereafter
 377 (Fig. 10b). However, the greatest change can be observed along the northern coastline of Oman Sea, in Southern Iran,
 378 where PCD has decreased from 0.7 during the sub-period before the change point to less than 0.4 in the sub-period
 379 thereafter, indicating the significant increase in the temporal dispersal of rainy days over the year in this region and the
 380 decrease in seasonal precipitation concentration. Figure 10-c shows the significance levels of the difference in PCD
 381 values over Iran.

383

384

385 **Fig. 10** Spatial distribution of PCD over Iran a: In the pre-change point period (1962-1998), b: In the post-change point period (1999-
386 2019) and c: the significance of their differences in different confidence levels

387

Figure 11 shows the area-averaged yearly time series of PCD and PCP indices with respect to the frequency of rainy days and mean precipitation over Iran during the period of analysis. There have been inverse relationships between the examined indices and the above precipitation parameters during the long-term period. Thus, the indices have increased in the years when the frequency of rainy days and mean precipitation have decreased, where the former parameter exhibits a closer relationship. The increasing trend in the indices during the sub-period after the change point is totally clear, indicating an increase in precipitation concentration or a decrease in temporal dispersal of rainy days over the year. The increasing trend in precipitation concentration over Iran has been correlated with the increase in drought intensity and the decreasing trend in precipitation in recent years (Nouri and Bannayan 2018; Sharafi and Mir Karim 2020). Moreover, an inverse relationship can be observed between PCP and PCD, suggesting that the rainy days in the precipitation peak season, *i.e.* winter, have shifted to other seasons including spring and summer as the precipitation concentration period has increased over Iran, resulting in a decrease in the precipitation concentration degree over the country. The findings indicating a change in the precipitation season in Iran from winter to spring are consistent with those of Salehi et al. (2020), suggesting that the trend in precipitation has become significantly decreasing after the 1990s, and a change can be observed in the precipitation season at certain stations in different regions around the country.

405 **Fig. 11** PCD index yearly time series, PCP, frequency of rainy days and annual received precipitation in Iran

406 **5 Conclusion**

407 In the current study, three indices, including PCI, PCD, and PCP, were used for analysing of spatiotemporal
408 precipitation concentration variability over Iran during a long-term period. Moreover, the decreasing and increasing
409 rates of the above indices during the periods of investigation were tested at different confidence levels based on the
410 Mann-Whitney test. The results demonstrated that maximum PCI and PCD have occurred in the lowest-precipitation
411 regions over the country, in the centre, East, and Southeast, and the minimum values of these indices can be observed in
412 those with the highest precipitation, including the southern Caspian coasts and the northern half of Iran, indicating the
413 high distribution of rainy days over the year in these regions. The comparison of the two sub-periods before the change
414 point, period (1962-1998) and thereafter (1999-2019) demonstrated that precipitation concentration has increased in the
415 western and central parts and the eastern half of the country, and it has decreased in the northern and north-eastern parts
416 and the northern Oman Sea coasts. Moreover, the annual time series of the precipitation characteristics demonstrated
417 that the frequency of rainy days and precipitation have decreased after the change point, and there have been inverse
418 relationships with the analysed indices, indicating an increasing trend in precipitation irregularity and a decrease in the
419 dispersal of rainy days over Iran in recent years. The indices under investigation have been most closely related to the
420 frequency of rainy days and latitude. Latitude has been effective on the spatiotemporal variability in precipitation
421 concentration over the country through variation in factors such as synoptic systems, topographic characteristics, and
422 highland configuration.

423 The PCP index, however, indicates temporal difference in the precipitation core throughout the year over the country.
424 Mean PCP varies between 15° (in January) in the eastern and western parts of Iran and 315° (in December) along the
425 southern Caspian coasts. Over most parts of Iran, maximum precipitation has occurred in winter, mainly concentrated in
426 February and March. However, the relevant period includes November along the southern Caspian coasts and October
427 along the northern coasts of Persian Gulf. Spatially, the greatest temporal variation in precipitation cores can be
428 observed in the North, from the Caspian coasts to the northern foothills of Alborz Mountain, indicating an increase in
429 the diversity of the factors and elements effective on the occurrence of precipitation in these regions. In the sub-period
430 after the change point, precipitation over the country has shifted in temporal terms toward precipitation out of season,
431 consistently with the increase in precipitation concentration. Thus, PCP has increased in the Southwest and along the

432 northern coasts of Persian Gulf and Oman Sea, indicating the shift in the occurrence of precipitation from winter toward
433 the warm seasons of spring and summer. In the western and north-eastern parts of Iran, however, PCP has decreased,
434 suggesting that precipitation period has shifted from the second half of winter toward early winter and late fall.

435 In summary, it can be stated that precipitation concentration has been high over most of Iran's area, according to PCI
436 and PCD, and the country has become more arid with greater spatial difference in precipitation after the change point,
437 as the frequency of rainy days and precipitation have decreased. In other words, Iran has been confronted not only with
438 a shortage but also with an unequal geographical distribution of precipitation. On the other hand, the variety of
439 precipitation sources around the country has caused the amount and period of rainfall to be different in each region
440 (Darand and Pazhoh 2019; Roustaei et al. 2017). The increasing trend in drought years frequency and the decreasing
441 trend in precipitation amount can also be observed in different parts of the world, including the middle latitudes of the
442 Northern Hemisphere (Adler et al. 2017), Asia, Africa, and Australia (Khan and Gilani 2021), Northern Ethiopia
443 (Asfaw et al. 2017), Sardinia, Italy (Caloiero et al. 2019), Cauca River, South-western Columbia (Ávila et al. 2019),
444 Aegean, and Western Turkey (Bacanli 2017). The increasing trend in global warming has played an important role in
445 the changes in elements and occurrence of extreme climatic phenomena over different parts of Iran (Karimi et al. 2018;
446 Alizadeh et al. 2010; Daneshvar et al. 2019). It is highly undesirable for such a low-precipitation country as Iran to shift
447 toward a concentrated system of precipitation, where most of the precipitation occurs within a few months, and a major
448 part of the year passes without precipitation, and exploitation of water under such climatic conditions requires
449 extremely powerful water management.

450

451 **Declarations**

452 **Ethics approval** This article does not contain any studies with human or animal participants performed by any of the
453 authors.

454 **Consent to Participate** All authors consent to participate in the research.

455

456 **Consent to Publish** All authors consent to publish the research findings.

457

458 **Availability of data and materials** The datasets generated during and or analyzed during the current study are
459 available from the corresponding author on reasonable request.

460

Authors Contributions Mohammad Darand: study and worked on Conceptualization, methodology, writing—original draft, writing—review and editing, Farshad Pazhoh: worked on formal analysis, data collection, conceptualization, analysis. All authors read and approved the final manuscript.

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