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SPATIALLY HETEROGENEOUS CHANGES IN THE FREQUENCY AND INTENSITY OF PRECIPITATION IN IRAN

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Abstract. The total precipitation trend has been investigated by many researchers in Iran. However, it is important to consider short-term and long-term precipitation separately. This study analyzed trends in 12 indices of precipitation, including 1-day precipitation frequency (1-DPF) to 6-day-and-more precipitation frequency (6-DMPF) and 1-day precipitation intensity (1-DPI) to 6-day-and-more precipitation intensity (6-DMPI) during 1968–2017 in Iran. Additionally, their relationships with the global mean surface temperature (GMST) trend were investigated. Trends were detected using the Mann–Kendall test and Sen's slope estimator. The ordinary least squares regression was used to calculate the percentage change in frequency and intensity of precipitation with increasing GMST. Several important findings emerged from this study: (1) the frequency of long-term precipitation has decreased in most regions of Iran, indicating a reduction in the length of precipitation periods; (2) the intensity of short-term and long-term precipitation has also decreased in most regions, suggesting that Iran's climate has become drier during this period; (3) changes in the frequency and intensity of precipitation are spatially heterogeneous, with a more significant decrease in the southern regions compared to the northern regions; (4) in higher latitudes of Iran, the contribution of long-term precipitation has decreased while the contribution of short-term precipitation (one-day and two-day) has increased. In contrast, all precipitation periods have decreased in lower latitudes; (5) 1-DPF and 2-day precipitation frequency (2-DPF) increase with global warming, with an average sensitivity of 2.6% K-1 and 2.7% K-1, respectively, while the other ten indices decrease with global warming. Therefore, most of the precipitation indices have decreased along with global warming in Iran.

Key words: precipitation frequency, precipitation intensity, long-term precipitation periods, short-term precipitation periods, global mean surface temperature, Iran

Introduction

Climate change has significantly affected human life, the ecosystem, water resources, the economy and agriculture. The global mean temperature increased by 1.07°C from 1850 to 2019 (IPCC 2022). This warming has changed other climatic elements, especially precipitation (Held, Soden 2006). Climate change has affected the frequency, intensity and duration of precipitation (IPCC 2022). An important effect of climate change is the intensification of extreme events (Kim *et al.* 2023). Changes in the frequency, intensity and duration of precipitation have increased natural hazards and endangered the sustainable development of human societies. According to the studies, the precipitation change pattern is not homoge-

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neous around the world. While the amount and intensity of precipitation have been increasing in humid regions, especially in tropical and temperate regions (Sun *et al.* 2022), the amount and frequency of precipitation have decreased in dry subtropical areas and most of the countries of the Mediterranean basin (Mathbout *et al.* 2018; Serrano-Notivoli *et al.* 2018; Acar, Gönençgil 2022; Li *et al.* 2022). Regional studies have reported increases in total annual precipitation and humid days in Europe (Myhre 2019), Australia (Fischer *et al.* 2018), and the United States (Li *et al.* 2022). The most recent findings show that consecutive dry days have increased dramatically in the dry regions of the world, indicating the lengthening of dry periods in dry regions (Sun *et al.* 2022).

Iran is located in the subtropics, where the increasing trends in temperature have been stronger than the global mean increase. Based on studies, the mean temperature of Iran will increase by 2.6°C in the coming decades (NCCOI 2014). The temperature increase is not homogenous in Iran. Sadeghinia *et al.* (2022) showed that the warming trends in the lowland areas of Iran are more intense compared to the high areas. Precipitation indices have often decreased, unlike temperature (Mansouri Daneshvar *et al.* 2019). The mean precipitation has decreased by 0.64 mm per year in Iran (Mohammadi 2011). Trends in R10mm, R20mm and PRCPTOT indices have been negative (Rahimi et al., 2018). The SDII index showed a weak increasing trend and the RX1day and Rx5day indexes showed a decreasing trend (Alavinia, Zarei 2021). Due to the increase in the number of dry days (CDD) (Mohammadi *et al.* 2017), Iran will experience longer dry periods. This occurrence is more probable in the southern regions of Iran (Ashraf Vaghefi 2019).

The frequency of heavy precipitation events has decreased in some areas of northwest, west and northeast Iran, while the number of precipitation events causing severe incidents has increased (Mahbod, Rafie 2021). Climate change and human-driven landscape development have led to significant reductions in water inflow (runoff from basins) to wetlands (Moshir Panahi *et al.* 2022). The increase in temperature and decrease in precipitation have contributed to the reduction of water in basins and the drying of lakes and wetlands in Iran.

Other studies have investigated additional factors affecting the distribution and amount of precipitation in Iran, such as changes in synoptic patterns and thermal properties of air masses. ENSO impacts Iran's rainfall (Bahrami *et al.* 2021). Summer patterns transport moisture from the southern seas, raising atmospheric levels (Jamalizadeh *et al.* 2019). Relative humidity trends are generally negative, except along the Caspian Sea and Persian Gulf, where specific humidity trends are positive (Katiraie *et al.* 2011). Synoptic patterns influence January temperatures, with cold air from the east Mediterranean causing anomalies, and with barotropic flows, weak ridges and troughs affecting geopotential height (Alijani *et al.* 2015).

Given that Iran's mean precipitation is one third of the global average, precipitation anomalies can lead to significant environmental issues such as droughts, floods, dust storms, drying up of lakes, and land subsidence (Ashraf Vaghefi 2019). Therefore, it is essential to identify the changes in Iran's precipitation more accurately. While there are many studies on the temporal and spatial changes of precipitation in Iran, there are fewer studies on changes in Iran's precipitation periods.

This research aims to answer the following questions:

- What are the frequency trends of short-term and long-term precipitation periods in different regions of Iran?
- What are the intensity trends of short-term and long-term precipitation periods in different regions of Iran?
- How do changes in the frequency and intensity of Iran's precipitation periods relate to changes in the global mean surface temperature (GMST)?

Data and method

Study area

Iran covers an area of ~1,648,000 km² and is located in Southwest Asia between latitudes 25° and 40°N and longitudes 44° and 63°E (Fig. 1). The Alborz and Zagros are the most important mountain ranges of Iran, extending from west to east and from northwest to southeast, respectively. These mountain ranges play an important role in the spatial heterogeneity of precipitation in Iran. The climate is warm and dry in most regions of Iran due to its location in the subtropical region. It is controlled by subtropical high pressure, especially in the warm season. Most of the precipitation is produced by Mediterranean and Sudanese systems entering Iran in the cold season from the west and southwest, respectively.

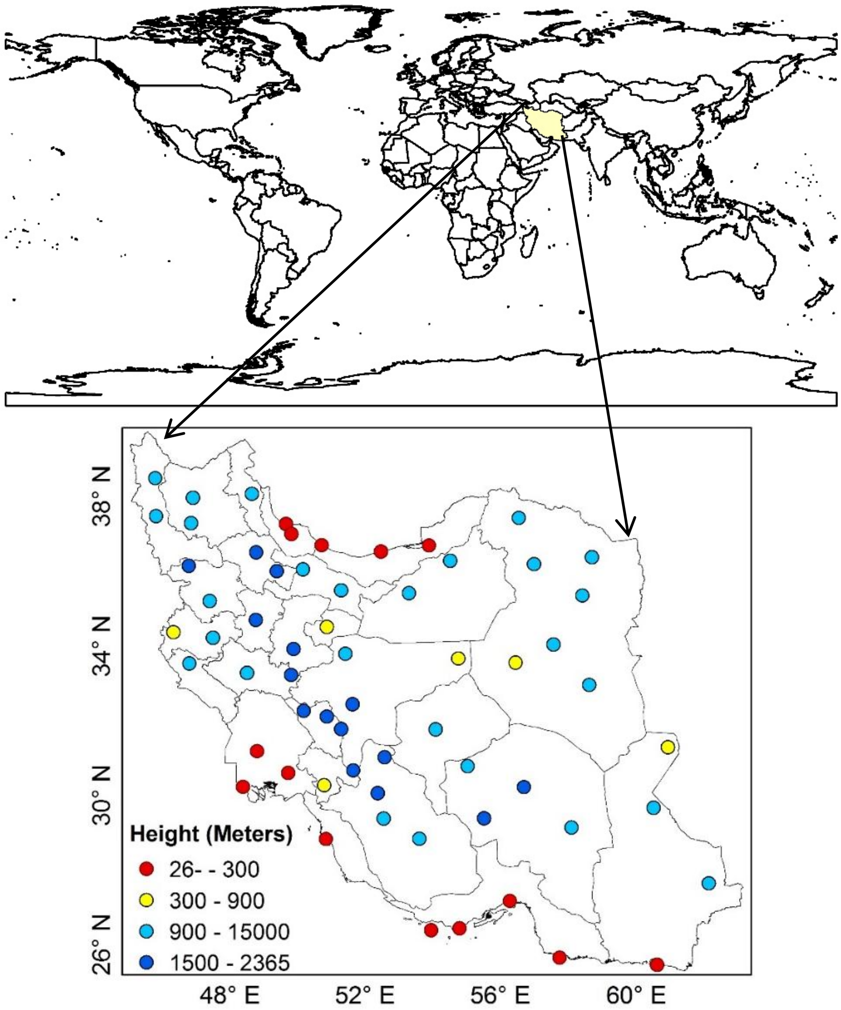

Fig. 1. Location map of stations with continuous daily records of precipitation over Iran

The climate is more humid on the Caspian Sea coasts and in the western mountainous regions of the country. However, it is extremely continental with hot and dry summers and cold winters, especially in the inner parts of the country. The mean precipitation is about 240 mm, with the highest occurring on the Caspian Sea coasts, amounting to 1800 mm. The amount of precipitation decreases to less than 100 mm in the interior plains of eastern and central Iran (Dinpanah *et al.* 2004; Raziei 2005).

Data

To investigate the trend of precipitation frequency and intensity, daily precipitation data were used from 62 synoptic stations that have reliable records from 1968 to 2017. The data were obtained from the National Meteorological Organization of Iran. Their homogeneity and change points were investigated and adjusted using the RHtests_dlyPrcp software package based on the transPMFred algorithm, developed by Wang and Feng (2013). For more details, refer to Wang (2008a, b) and Wang *et al*. (2010). In addition, we used the global mean surface temperature (GMST) data from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) (Hansen *et al.* 2010), expressed as temperature anomalies relative to the 1951–1980 mean (https://cdiac.ess-dive.lbl.gov/trends/temp/hansen/hansen.html).

Method

In this research, the Mann–Kendall test, Sen's slope estimator and ordinary least squares regression were used to analyze the data. The Mann–Kendall test is one of the most renowned methods for detecting trends in climate variables and has been utilized by various researchers (Li *et al.* 2022). A significant trend is identified using the Z value; positive values of Z indicate an increasing trend, while negative values indicate a decreasing trend. In this study, the significance of the trends was tested at the 5% significance level. Before applying the Mann–Kendall test, the pre-whitening method was implemented to remove the influence of autocorrelation in the time series (Yue *et al.* 2002). We applied Sen's slope estimator (Sen 1968) to assess the intensity of trends and used ordinary least squares regression to calculate the percentage change in precipitation indices in relation to the increase in GMST. The regression analysis generates an equation that characterizes the statistical relationship between the predictor variable (GMST) and the response variables (precipitation indices), enabling us to predict new observations. Our goal is to investigate how the distributions of precipitation indices change in response to variations in GMST. In this study, the percentage change in precipitation indices per 1 K increase in GMST is estimated, which we interpret as an indicator of the sensitivity of different precipitation indices to GMST change. This sensitivity value is calculated by determining the ratio of the linear trends of precipitation indices to GMST during the period 1987–2017. GMST, which refers to the average temperature of the Earth's surface, is commonly used in climate models and scientific studies to assess the impact of human activities on global climate. The GISS Surface Temperature Analysis version 4 (GISTEMP v4) provides estimates of global surface temperature changes. In this study, we used a gridded uncertainty ensemble of historical surface temperature anomalies from the Goddard Institute for Space Studies (GISS) Surface Temperature (GISTEMP) product (https://data.giss.nasa.gov/gistemp/) (Hansen *et al.* 2010).

Definition of indices

A review of the research background shows that most researchers have used the RR1 index (the number of days with precipitation ≥1 mm) and SDII (the simple precipitation intensity index) to examine changes in the number and intensity of rainy days in Iran. Although most researchers agree that the number of rainy days in Iran has decreased in recent decades, detailed information on changes in the length of rainy periods in Iran is lacking. In other words, which precipitation periods have been more affected by climate change: short-duration or long-duration precipitation events? A rainy period in Iran may last from one day to six days or more. This study considers whether the number or intensity of short-duration precipitation events (one day and two days) or long-duration precipitation events (three days to six days or more) has changed significantly. To address this, we defined 12 new indices to investigate changes in the duration and intensity of precipitation periods. Precipitation periods were first classified according to their duration (1-day precipitation period to 6-day precipitation period and more) and then examined separately. In this study, rainfall periods lasting one or two days are categorized as short-term precipitation, while those lasting three or more days are categorized as long-term precipitation. The names and characteristics of all indicators are presented in Table 1. The details of the calculation of each indicator are described below.

1-DPF: Represents the number of wet days in a year where precipitation lasted for only one day. For example, the Ahvaz station recorded 15 such one-day precipitation occurrences in 1968.
2-DPF: Represents the number of wet days in a year where precipitation lasted for exactly two days.
3-DPF: Represents the number of wet days in a year where precipitation lasted for exactly three days.
4-DPF: Represents the number of wet days in a year where precipitation lasted for exactly four days.
5-DPF: Represents the number of wet days in a year where precipitation lasted for exactly five days.
6-DMPF: Represents the number of wet days in a year where precipitation lasted for six days or more.
1-DPF= **1-DPF** represents the number of wet days during a year that lasted only one day.
For instance, the Ahvaz station recorded 15 such one-day precipitation occurrences in 1968.
1-DPI= Let RR_{wj} be the daily precipitation amount during a year, provided the precipitation period lasts only one day (RR≥1mm) in period j. If W represents the number of wet days during a year that lasted only one day, then the 1-DPI is calculated as:

$$1 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} \mathrm{RR}_{wj}}{W} \quad (1)$$

Table 1

Precipitation indices used in this study

Description	Index	Unit
1-day precipitation frequency	1-DPF	days
2-day precipitation frequency	2-DPF	days
3-day precipitation frequency	3-DPF	days
4-day precipitation frequency	4-DPF	days
5-day precipitation frequency	5-DPF	days
6-day or more precipitation frequency	6-DMPF	days
1-day precipitation intensity	1-DPI	mm
2-day precipitation intensity	2-DPI	mm
3-day precipitation intensity	3-DPI	mm
4-day precipitation intensity	4-DPI	mm
5-day precipitation intensity	5-DPI	mm
6-day or more precipitation intensity	6-DMPI	mm

Example: for the Ahvaz station in 1968, the 1-DPI index is calculated as follows:

$$1 - DPI = \quad (2)$$

$$= \frac{(1+1+7+13+1+1+29+1+3+22+5+5+37+19+2)}{15} = 9.8$$

2-DPI: Let RR_{wj} represent the daily precipitation amount during a year, provided the precipitation period lasts exactly two days (RR≥1mm) in period j. If W represents the number of wet days during a year that lasted exactly two days, then the 2-DPI is calculated as:

$$2 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \quad (3)$$

3-DPI: Let RR_{wj} represent the daily precipitation amount during a year, provided the precipitation period lasts exactly three days (RR≥1mm) in period *j*. If *W* represents the number of wet days during a year that lasted exactly three days, then the 3-DPI is calculated as:

$$3 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \quad (4)$$

4-DPI: Let RR_{wj} represent the daily precipitation amount during a year, provided the precipitation period lasts exactly four days (RR≥1mm) in period j. If *W* represents the number of wet days during a year that lasted exactly four days, then the 4-DPI is calculated as:

$$4 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \quad (5)$$

5-DPI: Let RR_{wj} represent the daily precipitation amount during a year, provided the precipitation period lasts exactly five days (RR≥1mm) in period j. If *W* represents the number of wet days during a year that lasted exactly five days, then the 5-DPI is calculated as:

$$5 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \quad (6)$$

6-DMPI: Let RR_{wj} represent the daily precipitation amount during a year, provided the precipitation period lasts six or more days (RR≥1mm) in period j. If *W* represents the number of wet days during a year that lasted six or more days, then the 6-DMPI is calculated as:

$$1 - \mathrm{DPI} = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \quad (7)$$

Result and discussion

Changes in 1-day precipitation frequency and intensity

Figure 2a shows the spatial distributions of the trends of 1-DPF in Iran. The significance of the trend of all indices has been tested at the 0.05 level. The 1-DPF increased at 60.7% of the stations and decreased at 39.3% during 1968–2017. The 1-DPF increased in the range of 0.03–0.108 days/year, at most stations located in the west, northwest, northeast and southwest of Iran. Meanwhile, it decreased in the range of 0.03–0.2 days/year at most stations located in the southeastern and central region and parts of the Caspian Sea coast. The average slope of the trend in different regions of Iran implies that 1-DPF increased significantly in the west, northwest and northeast of Iran from 1968 to 2017 (Tab. 2). Our findings confirm the results of Asakereh and Ashrafi (2023) regarding the increase in the frequency of short-term precipitation.

Pearson's correlation coefficient was calculated to identify the relationship between 1-DPF and latitude and longitude in Iran (Tab. 3). The results show a significant positive relationship (0.26) between 1-DPF trends and latitude, indicating a positive trend in most stations in high latitudes and a negative trend in most stations in low latitudes. In addition, the correlation coefficient between longitude and 1-DPF (-0.27) shows a positive trend is often observed in the western stations and a negative trend in the central and eastern stations (Tab. 3). Similar findings have been reported by other researchers, indicating a general decline in the frequency of precipitation events across Iran. For example, Rahimi and Fatemi (2019) noted a significant increase in extreme precipitation values and precipitation frequency in the southwestern regions and the coasts of the Persian Gulf. As Asakereh and Ashrafi (2023) pointed out, our findings indicate that latitude and longitude have a significant effect on 1-DPF trends in Iran.

Table 2

Average slope of trends for analyzed indices in different regions of Iran

Indices	West	Northwest	Southwest	South coast	Southeast	Caspian Sea Coast	Northeast	Center
1-DPF	**0.081***	**0.046***	0.065	0.018	-0.055	-0.024	**0.043***	-.0074
2-DPF	**-0.033***	**-0.028***	**-0.018***	.022	**-0.046***	**-0.05***	**-0.022***	-0.006
3-DPF	0.03	0.006	0.043	-0.061	-0.06	0.021	0.0014	-0.065
4-DPF	-0.01	**-0.081**	0.031	-0.048	-0.088	-0.041	-0.041	0.0063
5-DPF	-0.042	0.009	-0.005	**-0.1**	0.026	-0.04	-.0004	-0.033
6-DMPF	-0.01	-0.017	0.02	-0.04	-0.05	-0.047	-0.04	-0.021
1-DPI	-0.005	0.094	-0.03	-0.001	-0.012	-0.0004	-0.03	-0.02
2-DPI	-0.053	-0.03	-0.04	-0.014	-0.008	-0.072	-0.032	-0.036
3-DPI	0.002	0.016	-0.04	-0.026	0.01	0.044	-0.018	-0.026
4-DPI	-0.01	-0.03	-0.001	-0.05	0.01	-0.01	-0.054	-0.01
5-DPI	-0.022	0.21	-0.004	-0.023	-0.003	0.19	-0.015	0.02
6-DMPI	0.014	-0.013	-0.068	-0.027	-0.015	-0.008	-0.004	-0.01

*Significant at the 95% confidence level

Table 3

Correlation coefficients between precipitation indices and geographical factors (Latitude and Longitude) for the 62 stations across Iran in the 1968–2017 period

	1-DPF	1-DPI	2-DPF	2-DPI	3-DPF	3-DPI
Latitude	**0.26***	-0.20	**0.28***	**-0.35***	**0.34***	-0.08
Longitude	**-0.27***	0.03	-0.23	0.15	0.05	-0.14

*Significant at the 95% confidence level

In the case of 1-DPI, there is a significant negative trend at ~42% of stations and a non-significant negative trend at ~35% of them (Fig. 2b). Additionally, a non-significant increasing trend is observed at 23% of the stations. Based on the average slope (Tab. 2), the 1-DPI has generally decreased in Iran. The 1-DPI decreased significantly in stations located on the Caspian Sea coast, southeast, west, northwest, northeast and southwest of Iran, in the range of 0.006–0.072 mm/year. The negative correlation between 1-DPI and latitude (-0.2) shows that 1-DPI decreased more strongly in northern regions compared to southern and central regions (Tab. 3). These findings confirm the results of Alavinia and Zarei (2020). Other studies have also reported a decline in precipitation intensity, particularly in the central and eastern regions of Iran. For instance, Pazhoh and Darand (2024) found that precipitation concentration index (CI) values have increased, indicating a higher concentration of precipitation in specific areas.

Changes in 2-day precipitation frequency and intensity

There is no widespread statistically significant decreasing or increasing trend in the 2-DPF over Iran (Fig. 2c). Although the number of stations showing statistically non-significant increasing or decreasing trends in 2-DPF is equal, their spatial distribution is different. The 2-DPF has increased non-significantly in the range of 0.02–0.18 days/year in the western, southwestern, northeastern and northwestern regions and parts of the Caspian Sea coast (the Babolsar and Gorgan). Conversely, it has non-significantly decreased in the range of 0.054–0.2 days/year in the central and southeastern regions and the coasts of the Persian Gulf and the Oman Sea. There is a statistically significant positive correlation (0.28) between 2-DPF and latitude (Tab. 3). The correlation analysis implies that, during 1968–2017, 2-DPF increased in the northern regions of Iran and decreased in the southern regions. Our findings confirm the increasing trends of 2-DPF in the northern parts of Iran (Asakereh, Ashrafi 2023).

The trend of 2-DPI during 1968–2017 is presented in Figure 2d. Generally, 2-DPI has decreased in Iran. It can be seen that a statistically significant (29%) and non-significant (51.6%) decrease has occurred in the range of 0.001–0.14 mm/year in almost all regions of Iran. Additionally, 2-DPI has increased in the range of 0.002–0.078 mm/year, significantly in about 1.6% and non-significantly in about 17% of stations. There is a negative correlation (-0.23) between 2-DPI and latitude (Tab. 3). Spatially, the majority of stations that experienced a statistically significant decrease in 2-DPI are located in the northern half of Iran, especially in the northwest and north-east. An interesting result of our research is the strong negative correlation between 2-DPI and latitude. This confirms previous studies (e.g., Hejazizadeh *et al.* 2020) that reveal significant changes in precipitation indices in the western and northwestern regions of Iran.

Changes in 3-day precipitation frequency and intensity

The 3-day precipitation frequency (3-DPF) has decreased in most regions of Iran (Fig. 2e). A significant decreasing trend is observed in 12.9% of the stations, while a non-significant decreasing trend is found in 48.4% of the stations. In contrast, only 1.6% of the stations show a significant increasing trend. The 3-DPF has decreased by 0.071–0.24 days per year in most regions of Iran, according to Sen's slope. It has increased very slightly only in the northwest and southeast of Iran. There is a positive correlation coefficient (0.34) between 3-DPF and latitude, significant at the 5% level. Thus, the 3-DPF has decreased more strongly in the southern and central regions of Iran compared to the northern regions. Based on the regional average slope, significant decreasing trends have been observed only in the southern coasts of Iran (Tab. 2). These findings suggest that global warming may lead to spatially heterogeneous trend patterns, a phenomenon observed in other studies on precipitation indices (Alavinia, Zarei 2020; Mahbod, Rafiee 2021).

The spatial pattern of change in the 3-day precipitation intensity (3-DPI) is shown in Figure 2f. This index shows a decreasing trend in about 77% of the stations, with a significant trend at 14.5% of stations and a non-significant trend at 63.1%. A significant increasing trend is observed in only 1.6% of the stations. The 3-DPI has decreased by 0.003–0.19 mm per year in most regions of Iran. The strongest decreasing trends have occurred in the southeast, the Caspian Sea coast, the northeast and the Persian Gulf coast (Tab. 2). In general, the trends of 3-DPF and 3-DPI indicate that both indicators decreased during 1968–2017.

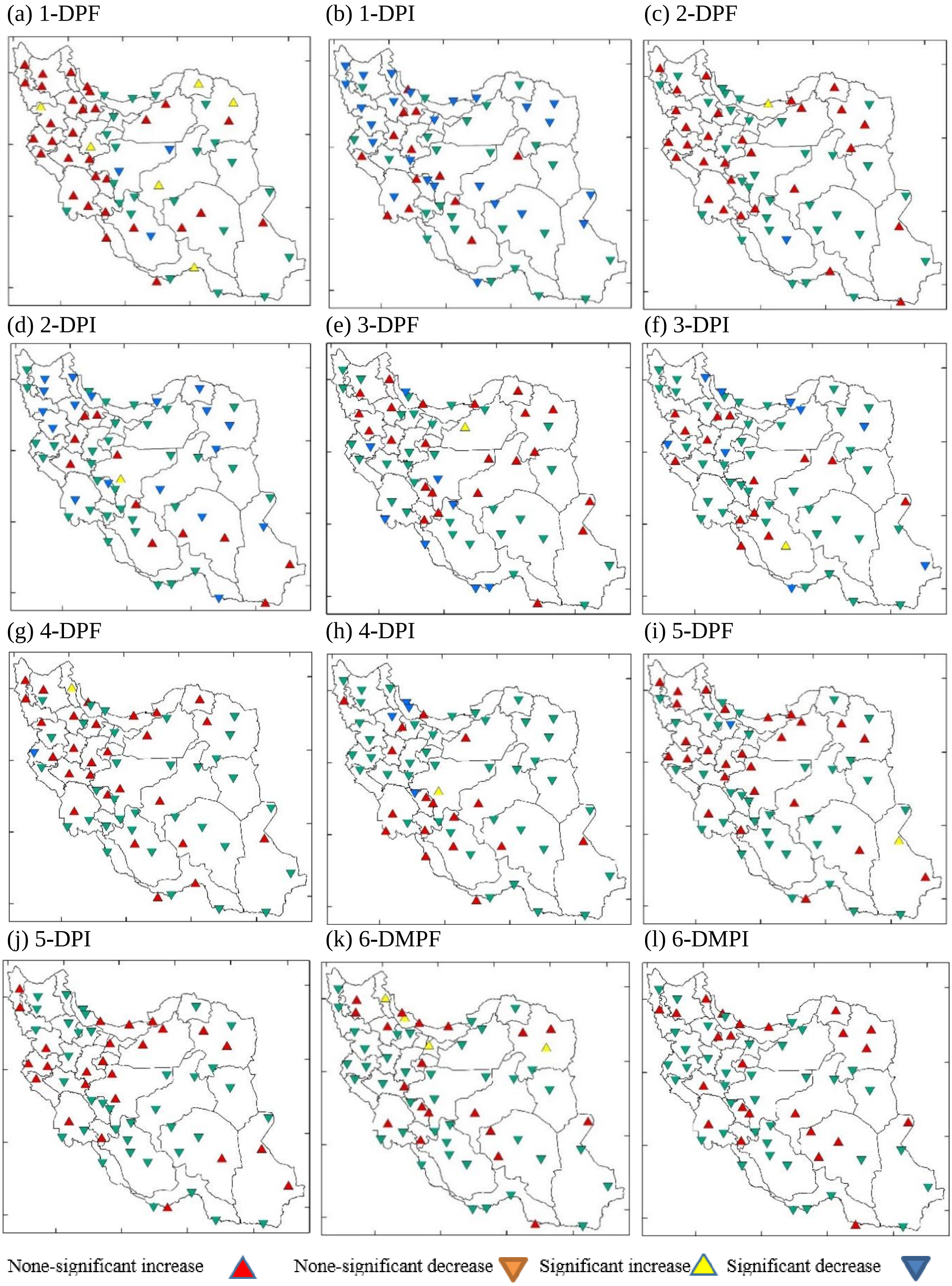

Fig. 2. Summary of Mann–Kendall trend analyses for the period 1968–2017
Explanations: (a), (b), (c) (d), (e), (f), (g) (h), (i), (j), (k) and (l) are maps of trends for 1-DPF, 1-DPI, 2-DPF, 2-DPI, 3-DPF, 3-DPI, 4-DPF, 4-DPI, 5-DPF, 5-DPI, 6-DMPF and 6-DMPI, respectively.
Red and green triangles indicate non-significant increasing trends and non-significant decreasing trends, respectively.
Yellow and blue triangles indicate statistically significant increasing and decreasing trends by a two-sided test at the 5% level.

Changes in 4-day precipitation frequency and intensity

The spatial distribution of the 4-day precipitation frequency (4-DPF) trend shows a significant increase only at the Ardebil station and a significant decrease only at the SarPol Zahab station (Fig. 2g). A very weak decrease (53.5%) and increase (43.8%) have been observed in other stations. Spatially, increasing trends are mostly observed in the northern half of Iran, particularly in the northwest (Tab. 2), while there is no specific spatial concentration for the decreasing trends. The trend is very weak and close to zero, except for Ardebil (0.2), Sarpol Zahab (-0.36), Kohrang (-0.26), and Ilam (0.195) stations. Therefore, according to the average slope of the trend (-0.001), the 4-DPF has not significantly changed in most regions of Iran. However, there is a positive correlation coefficient between the 4-DPF and latitude (0.2).

The trend of 4-day precipitation intensity (4-DPI) in Iran (Fig. 2h) shows that the percentage of stations with a decreasing trend (71.6%) is much higher than those with an increasing trend (28.4%). There is a significant decreasing trend at 6.5% of the stations (Anzali, Rasht, Zanjan and Kohrang) and a significant increasing trend at 1.6% (Isfahan). In general, 4-DPI has weakly decreased in most parts of Iran. There is a negative correlation coefficient (-0.28) between 4-DPI and latitude, significant at the 5% level (Tab. 4). Consequently, there is a decreasing trend at most stations located in the northern half of Iran (above 32.5°N). According to the average slope of the trend (Tab. 2), the decreasing trend is more pronounced along the Caspian Sea coasts, west, northwest and center compared to other regions. This important finding indicates that both the frequency and intensity of 4-day precipitation have decreased over the last five decades in Iran. These changes have led to an increase in the length of dry periods and a decrease in the length of wet periods in Iran, as noted in other studies (Toulabi Nejad *et al.* 2021).

The increasing length of dry periods and decreasing length of wet periods in a region already prone to aridity can have several severe consequences, including water scarcity, agricultural impact, ecosystem stress, economic strain and health issues.

Table 4

Correlation coefficients between precipitation indices and geographical factors (latitude and longitude) for the 62 stations across Iran in the 1961–2017 period

	4-DPF	4-DPI	5-DPF	5-DPI	6-DMPF	6-DMPI
Latitude	0.2	**-0.28***	0.18	-0.061	0.21	0.04
Longitude	-0.07	0.06	0.02	0.136	0.06	0.23

*Significant at the 95% confidence level

Changes in 5-day precipitation frequency and intensity

At Zahedan station, the change in the 5-DPF has shown a significant increase, whereas at Qazvin station, it has significantly decreased (Fig. 2i). This is consistent with the heterogeneous nature of precipitation patterns observed in other regional studies, where spatial variability is influenced by topographical and climatic factors. A non-significant decreasing trend is observed at 54.8% of the stations, primarily situated along the southern coast and central regions of Iran, while 41.9% of the stations, mainly in the northern half of the country, exhibit a non-significant increasing trend (Tab. 2). The average slope indicates that the decreasing or increasing trends of the 5-DPF are generally very weak and close to zero at most stations (Tab. 2). Overall, it can be concluded that the 5-DPF has not undergone a significant change in Iran. Studies in similar semi-arid regions have noted that precipitation frequency does not change uniformly and is often influenced by local atmospheric conditions and elevation.

Regarding the 5-DPI, there have been no significant changes at any of the stations (Fig. 2j). Around 60% of the stations display a non-significant decreasing trend, while 40% exhibit a non-significant increasing trend. Based on the regional average slope, the 5-DPI has weakly declined in most regions of Iran. Spatially, most stations with a non-significant increasing trend are located in the northern half of Iran, in contrast, those with a non-significant decreasing trend are predominantly in the southern half. Our findings that the 5-DPI has not changed significantly at any station mirror results from other regional studies indicating that, while the intensity of individual precipitation events might show variability, overall long-term changes are not pronounced. Our analysis of non-significant trends in 5-DPF and 5-DPI adds to the understanding of how different durations of rainfall events are affected by seasonal and climatic variations.

Changes in 6-day-or-more precipitation frequency and intensity

Figure 2k illustrates the spatial pattern of the 6-DMPF trend across Iran. The analysis indicates significant increasing trends at ~6.4% of stations, insignificant increasing trends at 30.6% and insignificant decreasing trends at 63%. Specifically, the trend has increased in the provinces of Gilan, Mazandaran, Ardabil, Tehran and East Azerbaijan, while it has decreased in other provinces. Notably, all stations with a significant increase (Tehran, Torbat Heydarieh, Rasht and Ardabil) are located above 38 degrees latitude. According to Kendall's Z-scores and Sen's slope estimates, the increasing trends are more intense but confined to a smaller geographic range (limited to a few provinces), whereas the decreasing trends, though weaker, span a broader geographic area.

Figure 2I demonstrates that the 6-DMPI does not exhibit any significant increase or decrease across Iran. A non-significant decreasing trend is observed at 63.3% of the stations, while a non-significant increasing trend is seen at 37.3%. There is a non-significant increasing trend in the provinces of Mazandaran, Gilan, Ardabil, Zanjan, Qazvin, Chaharmahal and Bakhtiari, as well as in North and Central Khorasan. Conversely, a decreasing trend is evident at stations located in the western provinces (such as Kurdistan, Kermanshah, Hamadan, Lorestan and Ilam), most central regions (including Isfahan, Fars, Central, Semnan and South Khorasan provinces), Golestan province and along the Persian Gulf coast.

Our findings align closely with the research conducted by Javari (2017) and Kaboli *et al.* (2021). For instance, Javari *et al.* (2017) identified a downward trend at most stations, with significant decreases observed in eastern and central Iran and increases noted in western and northern regions. Our detailed spatial analysis of the 6-DMPF and 6-DMPI trends builds on this high-resolution approach, offering additional insights into regional precipitation patterns.

General analysis of precipitation trends

Based on the results provided for various precipitation durations (1-day, 2-day, 3-day, 4-day, 5-day, and 6-day-or-more), what follows is a comprehensive analysis of the similarities and differences in the trends of frequency and intensity of these precipitation events in Iran.

- Significance of trends: Shorter duration events (1-day to 2-day) show more significant trends compared to longer durations (3-day to 6-day or more). The increasing length of dry periods and decreasing length of wet periods suggest potential water scarcity, agricultural impacts and ecosystem stress in arid regions.
- Regional patterns: Northern regions tend to exhibit more positive trends in frequency, while southern and central regions show more negative trends.
- Predominant decline in intensity: Across all durations, there is a general trend of decreasing intensity, especially in the northern regions.
- Latitude correlation: Positive correlation with latitude for frequency trends and negative correlation for intensity trends, indicating regional variations.
- Spatial variability: Significant trends in specific regions for different durations, highlighting local climatic influences.

Responses of frequency and intensity indices of precipitation to global warming

Correlation analysis reveals a significant negative correlation between GMST (Global Mean Surface Temperature) and the indices 2-DPI, 3-DPF, 3-DPI and 4-DPI (see Tab. 5). Furthermore, regression analysis shows that both 1-DPF and 2-DPF increase with global warming, exhibiting mean sensitivity values of 2.6% K^{-1} and 2.7% K^{-1}, respectively. In contrast, 3-DPF, 4-DPF, 5-DPF, and 6-DMPF all show a decrease with global warming, with mean sensitivity values of 5.5% K^{-1}, 2.9% K^{-1}, 5.4% K^{-1}, and 1% K^{-1}, respectively. Additionally, 1-DPI, 2-DPI, 3-DPI, 4-DPI, 5-DPI, and 6-DMPI all demonstrate a decrease with global warming, with mean sensitivity values of 5% K^{-1}, 5.8% K^{-1}, 5.7% K^{-1}, 6% K^{-1}, 5% K^{-1}, and 4% K^{-1}, respectively. These results suggest a clear association between global warming and a reduction in precipitation intensity and frequen-

Table 5

Correlation coefficients between precipitation indices and GMST in the 1968–2017 period

GMST	1-DPF	1-DPI	2-DPF	2-DPI	3-DPF	3-DPI	4-DPF
	0.06	-0.23	0.1	**-0.42***	**-0.4***	**-0.31***	-0.05
GMST	4-DPI	5-DPF	5-DPI	6-DMPF	6-DMPI		
	-0.3*	-0.16	-0.12	-0.1	-0.2		

*Significant at the 95% confidence level

cy over time, though the exact mechanisms and broader implications require further investigation. The observed decreases in intensity and frequency indices suggest a trend towards more sporadic precipitation events, consistent with global warming scenarios discussed in recent literature (Jones, Lee 2021; Smith *et al.* 2022).

Conclusion

This study investigated spatially heterogeneous trends in the frequency and intensity of precipitation using new indices from 1968–2017 in Iran. We analyzed changes across various precipitation periods (1 to over 6 days), made it possible to make several key findings.

1. The 3-DPF, 4-DPF, 5-DPF and 6-DMPF decreased at 61.3%, 55.1%, 56.2% and 63% of stations, respectively, indicating a reduction in the duration of precipitation periods in most regions of Iran. This reduction could be related to the decreased durability or number of precipitation systems in the Iranian plateau. Previous studies (Alavinia, Zarei 2020; Hejazizadeh *et al.* 2020; Toulabinejad *et al.* 2021; Asakereh, Ashrafi, 2023) have reported similar trends, but our study adds new insights into both short-term and long-term precipitation changes. This trend suggests a shift towards shorter precipitation events, which can affect water availability and agricultural productivity. Policies aimed at water conservation and efficient irrigation practices will be crucial in mitigating the impacts of these changes (Mahadevan *et al.* 2024).

2. The intensity of both short-term and long-term precipitation has decreased in most regions of Iran. Specifically, the 1-DPI, 2-DPI, 3-DPI, 4-DPI, 5-DPI and 6-DMPI have shown declines at 77%, 80.6%, 77%, 71.6%, 60% and 60.3% of stations, respectively. This indicates a drop in the expected amount of precipitation per event over recent decades, aligning with the findings of decreasing precipitation intensity in the subtropical, Middle East and Mediterranean regions (Trenberth *et al.* 2011; Scheff *et al.* 2012; He, Soden 2017; Held, Soden 2017; Tuel, Eltahir 2018; Brogli *et al.* 2019; Tuel, Eltahir 2020). Reduced precipitation intensity could lead to lower groundwater recharge rates, affecting water supplies for domestic and agricultural use. Adaptation strategies such as rainwater harvesting and improved water management systems will be necessary to address these challenges (Kambala *et al.* 2017).

3. Precipitation trends vary by region within Iran, with significant differences between high and low latitudes. The southern and central regions have experienced a general decrease in the frequency and intensity of all precipitation periods, whereas northern regions show weaker trends. High latitude regions such as the west and northwest have seen increases in short-term events but decreases in long-term events, indicating a shift in the contribution of different precipitation types. These trends are more pronounced in the desert and semi-desert regions, corroborating other studies on dry period prolongation in arid areas (Mohammadi *et al.* 2018; Doostan, 2020; Toulabinejad *et al.* 2021; Sun *et al.* 2022). These regional variations highlight the need for region-specific adaptation strategies. For instance, areas experiencing more short-term events may need infrastructure improvements to handle intense rainfall and prevent flooding, while regions with prolonged dry periods will require measures to combat drought and ensure sustainable water supplies (Visser *et al.* 2024).

4. There is a significant correlation between the frequency and intensity of certain precipitation periods and geographic factors like latitude and longitude. For example, the 1-DPF shows a positive correlation with latitude (0.26) and a negative correlation with longitude (-0.27). This implies increased short-term precipitation in northern and western Iran and decreases in the south, center and east. The correlations for 2-DPF and 3-DPF with latitude (0.28 and 0.34, respectively) are significant at the 5% level. This demonstrates the heterogeneous nature of precipitation changes across

different regions. Other studies (Sadeghinia *et al.* 2022; Asakereh, Ashrafi 2023) have also reported significant correlations between precipitation indices and geographic factors in Iran. Understanding these correlations can help in predicting future precipitation patterns and preparing region-specific climate adaptation plans. This is vital for infrastructure planning, disaster risk reduction and agricultural practices (Stokes, Howden 2010).

5. Changes in the intensity of short-term and long-term precipitation show regional variability. For instance, the 1-DPI has decreased more significantly along the Caspian Sea coast and in the southwest and west of Iran. The 2-DPI has shown greater decreases in the northwest, southeast, and southern coast. A significant negative correlation (-0.28) exists between the 4-DPI trend and latitude, with most stations located in northern Iran exhibiting decreasing trends. While changes in 6-DMPI are not significant at any station, increasing trends are more apparent in certain provinces (e.g., Mazandaran, Gilan, Ardabil). The intensity of short-term rainfall events has generally increased, leading to potential flash floods and other hazards. Increased intensity of short-term rainfall events highlights the need for enhanced flood management systems and urban planning to mitigate flash floods and other hazards. Additionally, regions with declining long-term precipitation intensity will need to focus on drought preparedness and water resource management (Muzammil *et al.* 2023).

6. The 1-DPF and 2-DPF increase with global warming, with average sensitivity values of 2.6% K^{-1} and 2.7% K^{-1}, respectively, while other indices (10 in total) decrease. This strong correlation between rising global temperatures and changing precipitation patterns underscores the need for policies to adapt to climate change and mitigate its impacts, particularly in arid and semi-arid regions of Iran. Higher global mean surface temperatures (GMST) can increase atmospheric moisture capacity, leading to more intense rainfall events and altered atmospheric circulation patterns, resulting in extreme weather events. Climate change adaptation policies must account for the increased variability and intensity of precipitation. This involves investing in resilient infrastructure, enhancing water management practices, and developing early warning systems for extreme weather events (Jenelle *et al.* 2022).

This analysis underscores the intricate nature of precipitation trends in Iran, highlighting the necessity for localized studies to comprehend regional variations and impacts. Our findings align with global research that shows spatial heterogeneity and regional variations in precipitation trends (Wood *et al.* 2021). However, other studies emphasize the complexity and variability of these trends on a global scale (Darand *et al.* 2015; Doostan 2020; Jamali *et al.* 2022).

These insights are crucial for developing policies to adapt to climate change and mitigate its impacts, particularly in arid and semi-arid regions of Iran. Understanding these localized variations is essential for effective agricultural planning, water resource management and policy-making (Arkeh, Hamzawy 2024).

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