Arabian Journal of Geosciences (2024) 17:49
https://doi.org/10.1007/s12517-023-11847-7

ORIGINAL PAPER

Tempo-spatial changes in the intensity of high extreme precipitation (HEP) in Iran

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Received: 2 July 2023 / Accepted: 24 December 2023 / Published online: 8 January 2024

Abstract

The intensity of precipitation, particularly high extreme precipitation (HEP), has always been responsible for numerous natural hazards, such as floods and landslides. Therefore, it is crucial to investigate the behavior change of precipitation intensity as a consequence of climate change. This research aims to investigate precipitation intensity, its decadal changes, and precipitation duration for all types of extreme precipitation in Iran. To this end, gridded data of precipitation from the hydrological year 1971–1972 through 2015–2016 was utilized, and the days of heavy (HP), very heavy (VHP), and extremely heavy (EHP) precipitation were extracted using the 90th, 95th, and 99th percentile thresholds, respectively. The investigation results indicated that the maximum intensity of the extreme precipitation types occurred mostly in the Zagros Mountains, the Iranian Coast of the Caspian Sea (ICCS), and parts of the coasts of the Oman Sea and the Persian Gulf. The correlation coefficient between precipitation intensity and spatial features revealed a strong and inverse relationship between precipitation intensity and geographic coordinates (i.e., longitude and latitude). Our findings revealed that the durations of rainy days for HP, VHP, and EHP were 1–8, 1–7, and 1–4 days, respectively. Furthermore, the most intense precipitation occurred in short-term durations (e.g., 1-day duration). The findings also exposed an increasing trend in precipitation intensity of short-term durations in mountainous regions. Moreover, the intensity of HP and VHP increased, while EHP decreased in large areas of the country. Decadal analysis revealed that the maximum intensity of all types of extreme precipitation occurred mainly in the second and third decades. Additionally, the heaviest precipitation events took place in the second decade, which coincided with the dominance of the positive North Atlantic Oscillation (NAO) phase.

Keywords Extreme precipitation · Heavy precipitation · Precipitation intensity · Precipitation duration

Introduction

Precipitation intensity is a critical aspect of precipitation, as it pertains to the temporal distribution of precipitation. The amount of precipitation received within a specific period determines the precipitation intensity, and the more significant the precipitation amount, the higher the intensity, compared to the same amount of precipitation received over an extended period (Alizadeh 2009). For instance, during the period of heavy precipitation from March 24 to 27, 2018, certain stations in the west of Iran recorded precipitation amounts equivalent to half of their annual precipitation (Hanafi and Asfandyar 2021), setting an unprecedented record for precipitation intensity since the beginning of Iran's recorded precipitation history.

The HEP is a crucial climatic phenomenon that has irreversible negative effects on natural and social environments, leading to social and economic disasters such as erosion, floods, and landslides (Hejazi Zadeh and Moghimi 2007). For instance, the HEP that caused floods in December 2012 in the southwest of the country (Halabian and Hossienalipour Jazi 2016) and the HEP on April 14, 2017, in the northwest of Iran (Khazaei and Abbasi 2019) damaged a considerable number of facilities. In addition, the HEP caused landslides and significant soil erosion in the northwest of Iran (Joybari et al. 2016; Zorati Pour and Arab Khedri 2016). Erosion is one of the primary factors that HEP can cause, which occurs in two ways. Firstly, during heavy downpours, soil cannot

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absorb water, resulting in increased runoff and ultimately leading to the formation of floods that carry a significant amount of surface soil with them. Secondly, the large drops of precipitation in an HEP event result in powerful kinetic energy that can cause erosion (Rafahi 2009). Landslides, which are a constant threat to human life, personal property, and infrastructure in mountainous areas (Rana et al. 2021), are also a consequence of HEP. However, in some cases, HEP can create hydrological formations that are beneficial, such as the Simara and Jaider lakes created by the Kabirkoh landslide event in west of Iran (Maghsoudi et al. 2015). Despite the negative impacts of HEP, its role in HEP in water supply should not be ignored. HEP provides reservoirs and underground water with significant volumes of water that can be utilized during times of water scarcity. As a result, HEP could prove to be beneficial for both urban and rural water management, as highlighted by Teymuri Poor and Molla Zadeh (2020), Saeidian (2021), and Tahmoureth (2021).

Compared to other regions of the country, the ICCS experiences a higher frequency of HEP. Through our analysis of the data, it was determined that the ICCS receives an average maximum annual precipitation of 560 mm due to HEP, distributed over an average duration of 14 days with rainfall. The Zagros Mountains also receive significant HEP. The distribution of HEP in the country appears to follow spatial features, with the majority of HEP occurring in the western and northern regions. In other words, HEP has an inverse correlation with longitude and a direct relation with latitude, as revealed by statistical correlation methods (Asakereh and Ashrafi 2023a, 2023b). In addition to the spatial variation of HEP, long-term temporal trends of days with HEP also exhibit specific features. The frequency of HEP in the Zagros Mountains, northwest, and northeast of the country is increasing. A study by Darand (2016) demonstrated an upward trend in the frequency of HEP in the western and southwestern half of the country, which raises concerns about flood damage in these areas (Raispour and Asakereh 2022).

The intensification of precipitation can be attributed to an increase in the speed of large-scale vertical movements in the atmosphere, as noted by Loriaux et al. (2016). De Vries et al. (2018) demonstrated the effectiveness of stratospheric potential vorticity and integrated water vapor transport structure in increasing precipitation intensity, particularly for the HEP in the Middle East. The formation of atmospheric instability due to the presence of the atmospheric cut-off and the polar front in the mid-level of the troposphere may have contributed to the emergence of extreme precipitation, leading to severe damage in affected areas, as discussed by Raispour and Asakereh (2022). Omidvar et al. (2013) pointed out that high specific/relative humidity, as well as moisture from water bodies penetrating the troposphere, also contributes to increased precipitation intensity. Furthermore, Hoseini Sadr et al. (2020) identified the rapid penetration of tropospheric moisture into the trough system as a significant factor in the formation of extreme precipitation, leading to floods. Mafakheri et al. (2019) attributed the rise of extreme precipitation to the increasing gradient of tropospheric height from north to south across the country.

Due to its impact on flooding and soil erosion, as well as its importance in predictive modeling, the intensity of precipitation has been the subject of much research by hydrologists and water resources engineers (Barry and Chorley 2003). However, the majority of the studies on the intensity of HEP in Iran (e.g., Behyar et al. 2013; Ghahreman 2003; Noori Gheidari 2012; Alavi et al. 2019a, 2019b) have focused on a small spatial (local) and temporal (hourly) scale, examining the intensity-duration relationship of individual precipitation events. The investigation of daily HEP intensity across the entire mainland of Iran from a climatological perspective has received less attention. Asakereh and Varnaseri Ghandali (2019) have conducted regional-scale research on this topic. Therefore, a climatological study that examines different types of HEP with varying durations and decadal changes is crucial.

This study aims to examine the intensity of various types and durations of HEP in Iran, as well as the decadal trends spanning from the hydrological year of 1971–1971 to 2015–2016. To achieve this objective, a statistical approach was employed on a daily precipitation-gridded database for conducting the analysis.

Data and methodology

Study area

Iran is situated in southwestern Asia, specifically on the arid planetary belt (Alizadeh 2009). Figure 1 illustrates Iran's location in the world and its topographic features. The distribution of moisture and precipitation in the country is significantly influenced by two primary mountain ranges (Asakereh et al. 2023): the Alborz Mountain range in the north (stretching from west to east) and the Zagros Mountain range in the west (extending from northwest to southeast). These mountain ranges impede the penetration of moisture (Alijani 1996). Consequently, the humidity varies significantly between the northern slopes of the Alborz mountain range (i.e., ICCS) and the western slopes of the Zagros mountain range and their respective opposite slops. The former receives more precipitation and is considered to be the rainiest area in the country, while the latter ranks second in terms of precipitation intensity. Furthermore, the Zagros region receives the highest amount of HEP, closely follows by the ICCS. The Caspian Sea in the north and the Oman Sea and

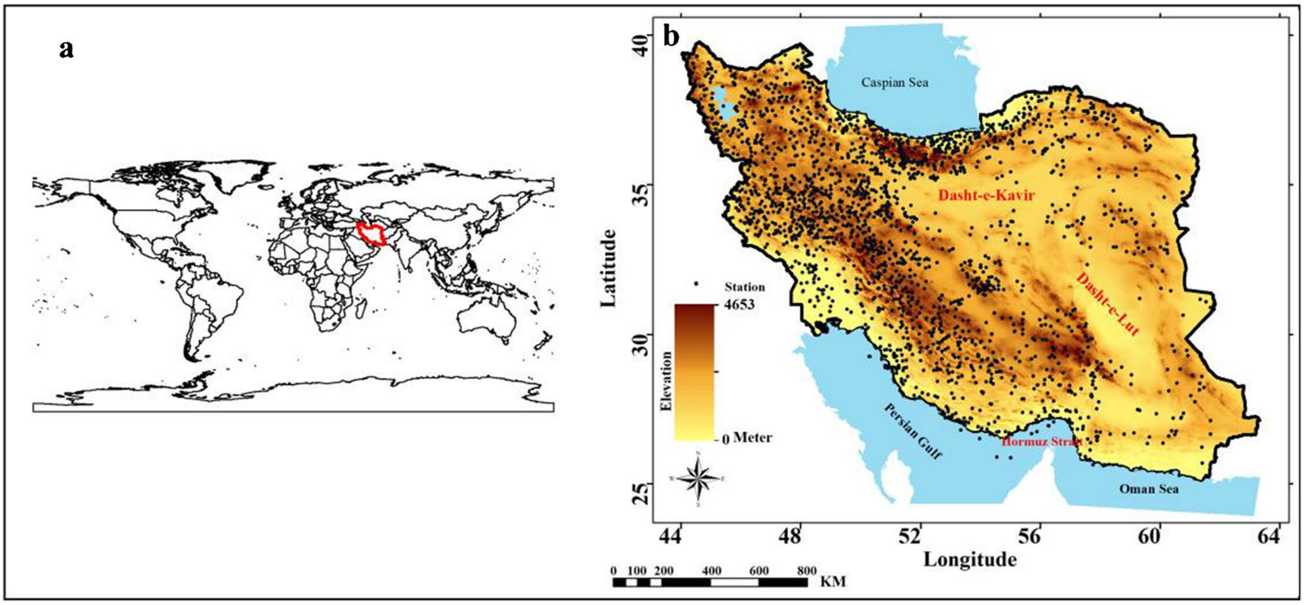

Fig. 1 (**a**) Iran's location in the world, and (**b**) its altitude (in meters), and spatial distribution of the stations used in the present research

the Persian Gulf in the south of the country are important local sources of moisture for the coasts. The coasts of the Oman Sea and the Persian Gulf experience sultry weather due to low latitude (STHP dominant) and high temperature (high moisture capacity) (Masoodian and kavyani 2008). However, the central and eastern regions of Iran receive very little precipitation due to the lee effects of the Alborz and the Zagros mountains and their considerable distance from moisture sources. Consequently, the desert in central part of the country, known as Dasht_e_Kavir, and the desert in eastern part, referred to as Dasht_e_Lut, have become extremely dry areas. These regions represent the driest parts of the country and are often the hottest during certain months.

In addition to the previously mentioned local factors, the amount and temporal-spatial distribution of precipitation in Iran are affected by numerous synoptic factors (Masoodian and Kavyani 2008). Moisture required for precipitation in most parts of the country is primarily supplied through systems such as westerlies passing through the Mediterranean Sea and the Red Sea. Precipitation in the western half of the country occurs mainly during autumn and winter, with some precipitation occurring in spring. Monsoon systems account for the precipitation in the southeastern part of the country through Gang's low pressure in the hot season (Alijani 1996). Figure 2a illustrates the spatial distribution of annual precipitation in Iran, with a spatial average of 249.2 mm. The maximum precipitation is observed along the Alborz and Zagros windward slopes. Asakereh et al. (2021b) reported that annual precipitation decreases from west to east and from north to south.

Data

In order to accomplish the research objectives, the third version of the Asfazari database (GAND) was utilized. This database is comprised of daily precipitation data collected from 2188 synoptic, climatic, and rain gauge stations (Fig. 1b), which are monitored by Iran's Meteorological Organization. These data were collected over a period of 46 years from March 21, 1970, to March 20, 2016, encompassing 16,801 days. The spatial resolution of the data is 10 km, and it was compiled by Masoodian (2019).

As can be seen in Fig. 1b, the spatial density of stations adopted by Masoodian (2019) decreases from west to east and from north to south. The spatial density of the station varies between zero and 4 stations per hundred square kilometers. Masoodian (2019) applied the trial and error method to estimate the minimum required stations and estimate the appropriate size of the pixels. Based on comprehensive studies assessing various interpolation methods for precipitation data in Iran, the Kriging method was identified as the appropriate interpolation technique. These investigations utilized the Lambert Conformal Conic Projection as the projection system for the database (Asakereh et al. 2023).

This dataset has been used by various researchers in several studies such as Montazeri and Masoodian (2013), Masoodian et al. (2016), Nasrabadi et al. (2013), Asakereh et al. (2021a), Asakereh et al. (2023), and Asakereh and Ashrafi (2023a and 2023b). In this research, the onset of the rainy season was considered to be September 23 (Asakereh et al., 2023), and therefore, the data arrangements were selected in a hydrological year format from 1970–1971 to 2015–2016.

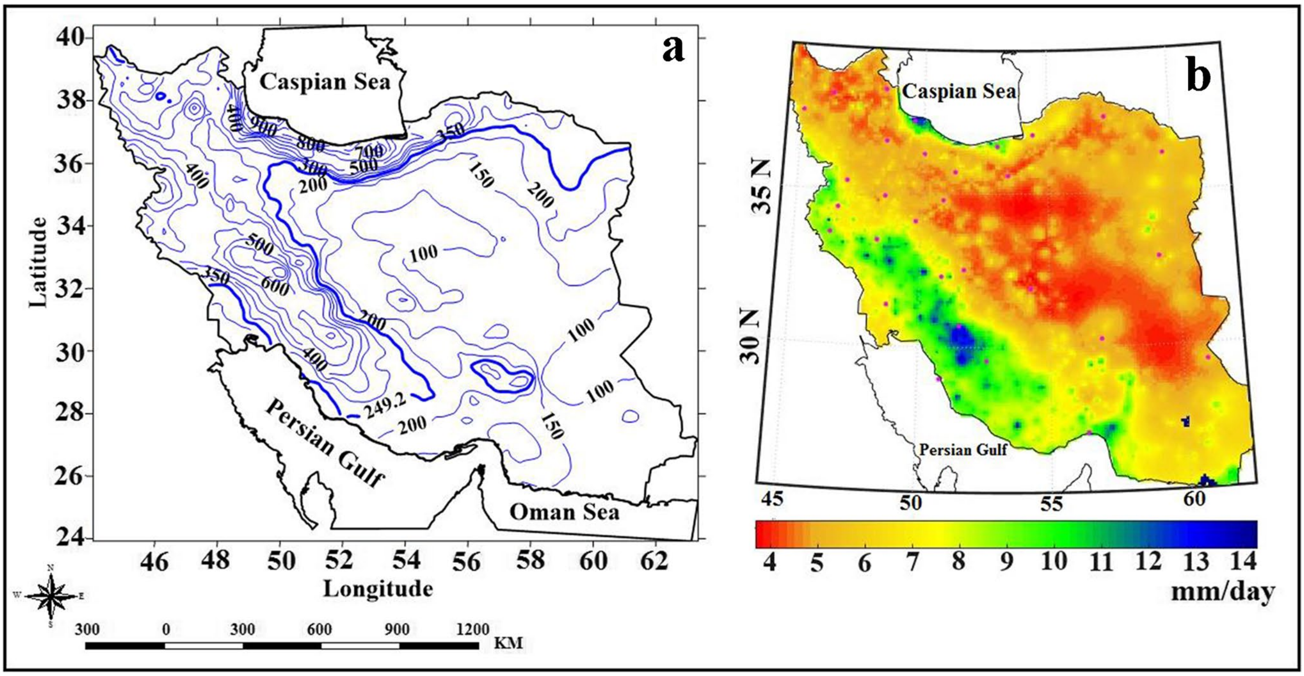

Fig. 2 Spatial distribution of (**a**) annual precipitation (mm) and (**b**) average of precipitation intensity

Methods

The present study investigates the climatology of the intensity of HEP (HP, VHP, and EHP) in Iran, as well as its decadal changes. To accomplish this objective, the following methodology was employed, wherein the analysis was performed on the pixel-level data derived from precipitation maps of Iran:

The identification of HEP is a commonly used method in many research studies, often accomplished through the use of a threshold. Asakereh (2011) suggested the use of quintiles to highlight the tail of the data frequency distribution. Percentile indices, such as the 90th percentile (R90p), 95th percentile (R95p), and 99th percentile (R99p), are utilized to identify HP, VHP, and EHP, respectively (Alexander et al. 2006). Rahim Zadeh et al. (2011) employed these indices to investigate changes in HEP. In this study, the 90th, 95th, and 99th percentiles of precipitation of precipitation on rainy days were calculated as indices of HP, VHP, and EHP, respectively, for all pixels of Iran's precipitation maps. Several previous studies have utilized similar methodologies to investigate EHP occurrences (e.g., Zhao et al. 2009; Rahim Zadeh et al. 2011; Ashrafi 2013; Jahanbakhsh Asl et al. 2022; Asakereh et al. 2021c). The World Meteorological Organization (WMO 2017) defines a day with precipitation exceeding 1 mm as a rainy day. Consequently, in our research, the aforementioned threshold was solely applied to days that recorded precipitation exceeding 1 mm. Days with precipitation below this threshold were omitted from the calculations. Hence, the days above the 90th, 95th, and 99th percentiles were identified as HP, VHP, and EHP days, respectively. Following identification of these HEP days, the intensity of precipitation for all three types of HEP was analyzed.

In the subsequent stage, the duration of precipitation for all three types of HEP was analyzed. The investigation revealed that days associated with HEP thresholds at the 90th, 95th, and 99th percentiles had durations of up to 8, 7, and 4 days respectively. For greater durations, the areas covered by precipitation were negligible from a climatological standpoint. This feature can be attributed to local precipitation forcing (Asakereh et al. 2021b). To distinguish between local and large-scale precipitation, we employed trial-and-error criteria aimed at identifying spatially continuous precipitation patterns that extended over at least 10% of the country's territory. Therefore, all durations of HEPs were examined to determine their association with large-scale synoptic justifications. For instance, days with precipitation characterized by atmospheric instability were categorized as instances of widespread precipitation. Specifically, these were days when continuous areas covered a minimum of 10% of the country. As the duration of precipitation events increased, there was a reduction in the coverage of the affected areas, along with spatial discontinuities, indicating a diminished influence of macro-scale climatic forcing. Consequently, we selected durations of 4, 3, and 2 days to investigate HP, VHP, EHP, respectively, in order to exclude local, infrequent, and fragmented HEPs.

The intensity of precipitation was calculated for all three types of HEP in the current study. Specifically, the intensity of HEP was determined by calculating the ratio of the total HEP to the total number of days associated with HEP for each year. To explore the relationship between the intensity of HEP and several spatial factors, including longitude, latitude, and altitude, Pearson correlation and partial correlation analyses were conducted. These analyses were performed separately for the entire country and for mountainous regions. According to Alaie Taleghani (2017), the average elevation of Iran is approximately 1300 m above sea level. To establish criteria for delineating mountainous regions, it was decided that areas exceeding this threshold would be considered mountainous. This threshold corresponds to the Alborz, Zagros, Northwest, and Northeast regions of the country.

To assess decadal changes in precipitation intensity, the study period was divided into four decades, and each decade was analyzed for the intensity of HEP types. The first 5 years of the statistical period were excluded, and the remaining 40 years was divided into four 10-year intervals. Thus, the first decade spanned from 1976–1977 to 1986–1985; the second decade covered 1986–1987 to 1995–1996; the third decade included 1997–1996 to 2006–2005; and the fourth decade consisted of 2006–2007 to 2015–2016.

The trend of the maximum frequency of durations was evaluated through a least squares error regression analysis. As such, the linear function defining the trend is expressed as follows (Box et al. 2016):

$$T_t = \alpha + \beta\, t$$

where T_t is the amount of HEP (mm), t is time (1, 2, 3, …, n). α and β are intercept and slope (amount of change per unit of time), respectively.

In order to investigate the impact of teleconnection indices on HEP (heavy precipitation events) intensity, several teleconnection indices were analyzed. Amongst all the indices examined, NAO (North Atlantic Oscillation) showed the highest correlation. The relevant data was retrieved from https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh. The effect of these indices on precipitation intensity was also studied.

Results and discussion

Climatology of intensity of HEP

Figure 3 depicts the average long-term intensity of HP, VHP, and EHP in millimeters per day. The highest intensities of all three types of precipitation are found in the Zagros mountains, particularly in the southern part of Zagros Mountains and the southwestern coast of the Caspian Sea. Masoodian and Karsaz (2015) attribute the HEP in southern Zagros to the enrichment of the Mediterranean trough in the Zagros region, which is due to the mountain's role in saturating low-pressure systems with moisture that enters the country through this area. Asakereh and Ashrafi (2023b) demonstrated that the maximum HEP in the ICCS was due to the proximity of the Alborz mountains to the sea in this part of the Caspian coast. The mountains' close proximity to the sea causes the lifting of a large amount of humid air mass, resulting in precipitation in a relatively small area.

In addition to the previously mentioned areas, the coasts of the Oman Sea to the east of the Strait of Hormuz also

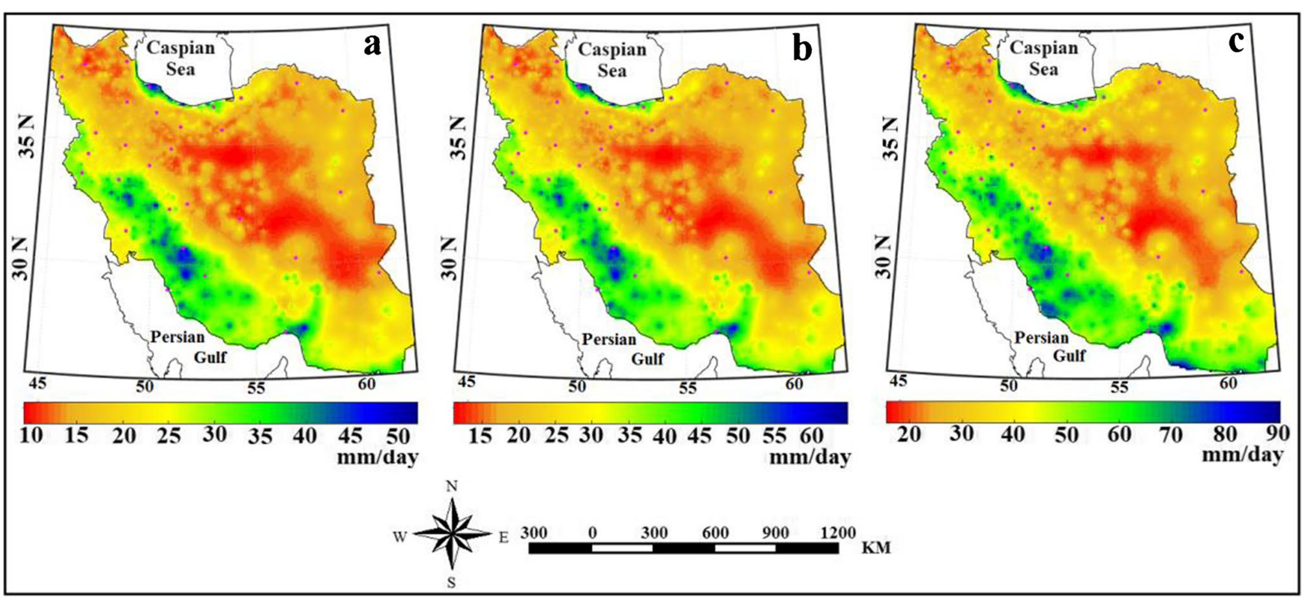

Fig. 3 Long-term intensity average of (**a**) HP, (**b**) VHP, and (**c**) EHP

exhibit the maximum intensity in the HEP. Monsoon systems affect these areas at certain times of the year (Saligheh 2006; Alijani et al. 2012; Mahoutchi 2018), leading to HEP. Access to the moisture of the water bodies in the south of the country strengthens these systems (Rezaei et al. 2018). Precipitation events often occur in a few days, resulting in HEP. Lashkari and Khazaie (2014) suggest that high-pressure systems passing over the Bay of Bengal and the Arabian Sea contain a high amount of moisture for HEP in the southeast of the country.

In contrast, the central dry regions, namely Dasht-e-Lut and Dasht-e-Kavir, exhibit the lowest intensities across all three types of HEP. This characteristic can be attributed to the region's location and the arrangement of the surrounding mountains. The central part of the country is located far away from western moisture sources such as the Mediterranean Sea, and it is relatively distant from northern and southern water bodies. Moreover, the presence of the Zagros Mountain range in the west and the Alborz Mountain range in the north acts as a barrier to sufficient moisture reaching this region. It appears that the role of the Zagros Mountain range is more prominent since its northwest-southeast direction hinders westerlies and Sudanese systems, which are the primary precipitation resources for Iran, from accessing this area. As a result, according to Asakereh and Ashrafi (2023b), the moisture from these systems gets discharged in the west of Zagros, leading to the weakening of rain-producing systems in the eastern part of Zagros, ultimately resulting in the reduction of HEP intensity in the central dry regions.

Table 1 presents the regions classified by different levels of precipitation intensity extracted from Fig. 3. It can be observed that areas with low precipitation intensities have a more extensive coverage compared to higher intensities. The geographical coverage associated with precipitation decreases as its intensity increases. Precipitation intensities that have wide-ranging impacts often occur in the central, eastern, northwestern, and northeastern parts of the country. In contrast, areas with low precipitation intensities are typically limited to the Zagros Mountains and certain parts of the ICCS region.

Table 2 presents correlation coefficients and partial correlation coefficients between various types of HEP (HP, VHP, and EHP) and spatial parameters (longitude, latitude, and altitude) for both the entire country and the Alborz and Zagros Mountain ranges. The findings reveal an inverse relationship between latitude, longitude, altitude, and precipitation intensity across the entire country. Specifically, an elevation in latitude and longitude causes rain-producing systems, especially westerlies and Sudanese systems, to move far from moisture sources, resulting in a decrease in precipitation intensity (Asakereh et al. 2021b). Nevertheless, it is important to note that the higher temporal distribution of precipitation in the northern regions of Iran also contributes to a reduction in precipitation intensity. Figure 6 demonstrates that HEP frequency is higher in higher latitudes, particularly in the ICCS. The correlation coefficients and partial correlation coefficients of all three spatial parameters with HEP across the entire country are significant with 95% confidence. Nonetheless, the role of geographical coordinates is more prominent.

In Fig. 4, precipitation intensity is depicted for varying durations of HP, VHP, and EHP. The maximum precipitation intensity was observed in the Zagros mountains, due to

Table 1 The areas (%) of the country covered by different intensity classes of HEP

HEP	Intensity of precipitation (mm/day)									
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
HP	0.88	59.37	24.42	13.79	1.54	0.01	0	0	0	0
VHP	0	43.87	27.04	17.51	10.09	1.44	0.04	0	0	0
EHP	0	4.02	39.53	18.64	13.75	13.56	8.42	1.97	0.10	0.006

Table 2 Correlation coefficients of the spatial factors with the intensity of HP, VHP, and EHP

Location	Local factor	Correlation coefficients			Partial correlation coefficients		
		Heavy	Very heavy	Extremely heavy	Heavy	Very heavy	Extremely heavy
All parts of the country	Longitude	−0.219	−0.426	−0.118	−0.540	−0.542	-0.549
	Latitude	−0.204	−0.448	−0.127	−0.610	−0.625	-0.653
	Altitude	−0.186	−0.482	−0.133	−0.107	−0.113	-0.112
Alborz and Zagros Mountain	Longitude	−0.137	−0.131	−0.137	−0.453	−0.462	0.5
	Latitude	−0.395	−0.411	−0.438	−0.571	−0.587	-0.626
	Altitude	0.188	0.186	0.174	0.123	0.12	0.102

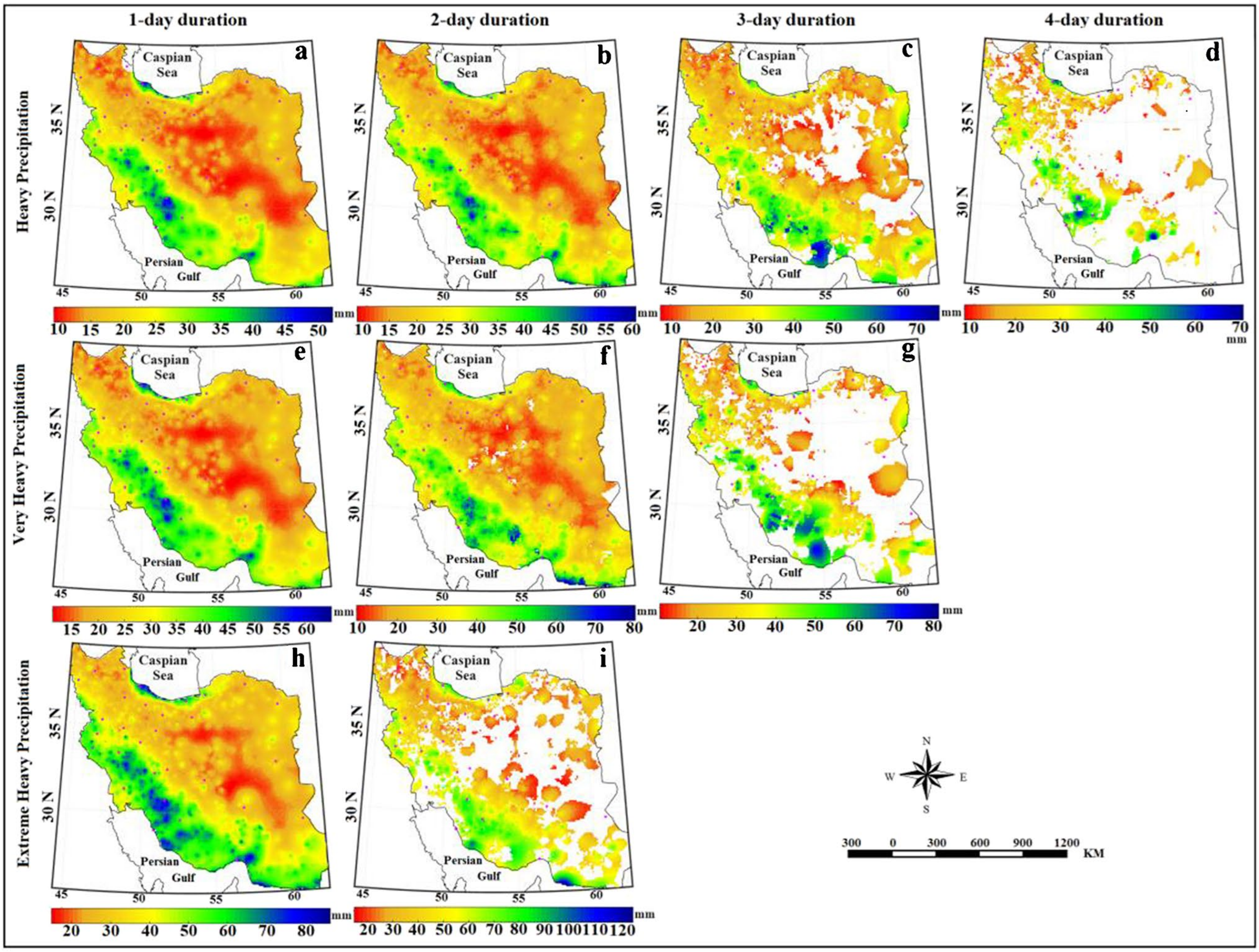

Fig. 4 Intensity of HP, VHP, and EHP with different durations. That first, second, and third rows of the figure represent HP, VHP, and EHP, respectively. (**a**) One-day duration, (**b**) 2-day duration, (**c**) 3-day duration, and (**d**) 4-day duration. (**e**) One-day duration, (**f**) 2-day duration, and (**g**) 3-day duration. (**h**) One-day duration and (**i**) 2-day duration

the orographic effects, as previously mentioned. Similarly, the southwest coast of the Caspian Sea also recorded the highest precipitation intensity resulting from advection of cold high pressures, such as the Siberian high pressure and Black Sea high pressure, which absorb ample moisture while traversing the Caspian Sea (Masoodian and Kavyani 2008). The Oman Sea coasts exhibited the maximum intensity of the 1-day duration of EHP, attributed by Rezaei et al. (2018) to the strengthening of the moisture of the westerlies and Sudanese systems passing through the Persian Gulf and the Sea of Oman.

During the 2-day duration of HP, the Zagros exhibited the highest intensity, attributed to the persistence of atmospheric instability caused by the reduced speed of the air mass passing through the mountain range. However, the coverage area of this duration decreased compared to the 1-day duration, potentially due to the decrease in energy forcing the precipitable systems. In small areas, such as those in the north of the Hormuz Strait, the Oman Sea coasts, and the southwest of the Caspian Sea, the intensity of HP was also high, attributed by Saligheh (2006) to the influence of southeastern mountains preventing the moisture of the Oman Sea. The southwest of the Caspian Sea recorded the maximum intensity of HP due to frequent occurrence of showers, as indicated by Rezaei and Roshani (2010). Asakereh and Varnaseri Ghandali (2019) similarly reported that the west of the Caspian Sea had the highest intensity of precipitation. During the 2-day duration of VHP, the highest intensity was observed east of the Strait of Hormuz on the coast of the Oman Sea, with high intensity also recorded in the Zagros. The 2-day duration of EHP exhibited the maximum intensity east of the Strait of Hormuz on the coast of Oman, with moderate intensities experienced by the Zagros. In central parts of Iran, the distance from moisture sources and the Zagros Lee effect (Alijani 2008; Masoodian and Kavyani 2008) resulted in low intensity of the 2-day duration of EHP.

During the 3-day duration of the HP event, the location of maximum intensity shifted westward in comparison to the 2-day duration of HP. The maximum intensity was observed near the coast of the Persian Gulf, west of the Strait of Hormuz. Ghazipor et al. (2021) attributed the short durations of HP in these regions to Sudanese systems. The maximum intensity of precipitation in the Zagros occurred in scattered areas. The 3-day duration of VHP showed a similar distribution of maximum precipitation intensity areas to that of the 2-day duration of HP. However, the area covered by VHP was more extensive than that of HP. In the case of the 4-day duration of HP, the maximum area of precipitation was located in the north of the Hormuz Strait, approximately 28 N, with a significant distance from the coastline, followed closely by the Zagros region in terms of intensity ranking. Furthermore, the southwestern coast of the Caspian Sea also experienced significant precipitation intensity.

As previously mentioned, the HEP exhibited varying intensities over different durations, with shorter durations showing higher precipitation intensity. As the HEP persisted, the precipitation intensity decreased. For instance, the maximum intensity of HP was recorded at 52 mm in 1 day, 61 mm in 2 days, 73 mm in 3 days, and 70 mm in 4 days. However, the average precipitation intensity over the 2 days was approximately 30.5 mm per day. Similarly, the average precipitation intensities for the 3-day and 4-day durations were 24.3 mm and 17.5 mm per day, respectively. Thus, it can be inferred that short-term durations are associated with the highest intensity of HEP, as a large amount of precipitation occurs in a shorter period, which is consistent with the findings of Ghazipor et al. (2021).

Decadal changes in intensity of HEP

Figure 5 depicts the average precipitation intensity for three types of HEP, namely HP, VHP, and EHP, over four studied decades. The figure illustrates that the maximum precipitation intensity in HP (located on the left column of the figures) is concentrated in the elevated regions of the Zagros, the southwestern part of the Caspian Sea, certain areas along the coasts of the Persian Gulf, and the northeastern part of the Strait of Hormuz. The average precipitation intensity was found to be higher in the second and third decades compared to the first and fourth decades (Table 3). Conversely, the lowest intensity occurred in the low-elevated interior regions. The spatial distribution of the maximum and minimum values of VHP intensity regions was similar to that of HP; however, VHP intensity values were higher than those of HP. The third decade recorded the highest intensities of VHP, followed closely by the second decade. During the fourth decade, although the precipitation intensity was higher than in the first decade, the frequency of occurrence of VHP decreased compared to the first decade (as shown in Fig. 6). The maximum coverage of EHP was slightly different from the other HEP types. In the first decade, the maximum areas covered with HEP were located in south Zagros, east and northeast of the Strait of Hormuz, and to some extent in the southwest of the Caspian Sea. However, in the second decade, only a maximum area was observed on the coast of the Oman Sea, east of the Strait of Hormuz. The spatial distribution of the maximum coverage of EHP in the second decade differed significantly from that of the first decade, which can be attributed to changes in the strength and frequency of precipitable systems entering the country. In the third decade, the maximum intensities occurred again in the Zagros, parts of the coast of the Persian Gulf, the northeast of the Strait of Hormuz, and the southwest of the Caspian Sea. Gandomkar (2010) associates HEP on the coast of the Persian Gulf with the Sudanese low-pressure system that enters the region from the south and southwest, along with the presence of local convective conditions. Moreover, his findings indicate that if the Mediterranean trough spreads over Iran simultaneously with the Sudanese low pressure, HEP increases in both amount and intensity. Asakereh and Khojasteh (2021) found that although the frequency of cyclones was lower during the third decade, their precipitation was higher in comparison to the previous decade, a feature confirmed by Ashrafi (2019) and Jahanbakhsh et al. (2021). Alijani et al. (2011) reported that monsoon lows increased in both intensity and number during summer in the southeast of the country. These lows have been identified as having the highest intensity in the entire country. Khosravi (2019) attribute HEP in the southeast of the country to the pressure gradient between Pakistan's low pressure and Tibet's high pressure. In the fourth decade, the spatial distribution of intensity was similar to that of the third decade, but the maximum-intensity areas had less coverage. Table 3 shows that the maximum intensity of HEP in the second decade was greater than those in other decades. Previous studies have attributed this event to a positive and relatively strong North Atlantic Oscillation (NAO) phase during this decade. Asakereh et al. (2017) also found that precipitation in the country was high during the positive phase of the NAO. Mahmoodabadi et al. (2018) reported a significant relationship between HEP in the southeast of the country and the NAO.

The analysis of Figs. 6 and 7 indicates that the total precipitation over the two decades under study was influenced by the frequency of EHP events. This finding is consistent with the study conducted by Mehrzad et al. (2019), which reported an upward trend in the frequency of EHP events in the southern region of the country. Asakereh and Ashrafi (2023b) further corroborated this observation by demonstrating an increase in the frequency of EHP events across a significant portion of the country.

Figure 7 reveals that during the initial decade, the ICCS exhibited the highest concentration of precipitation intensity.

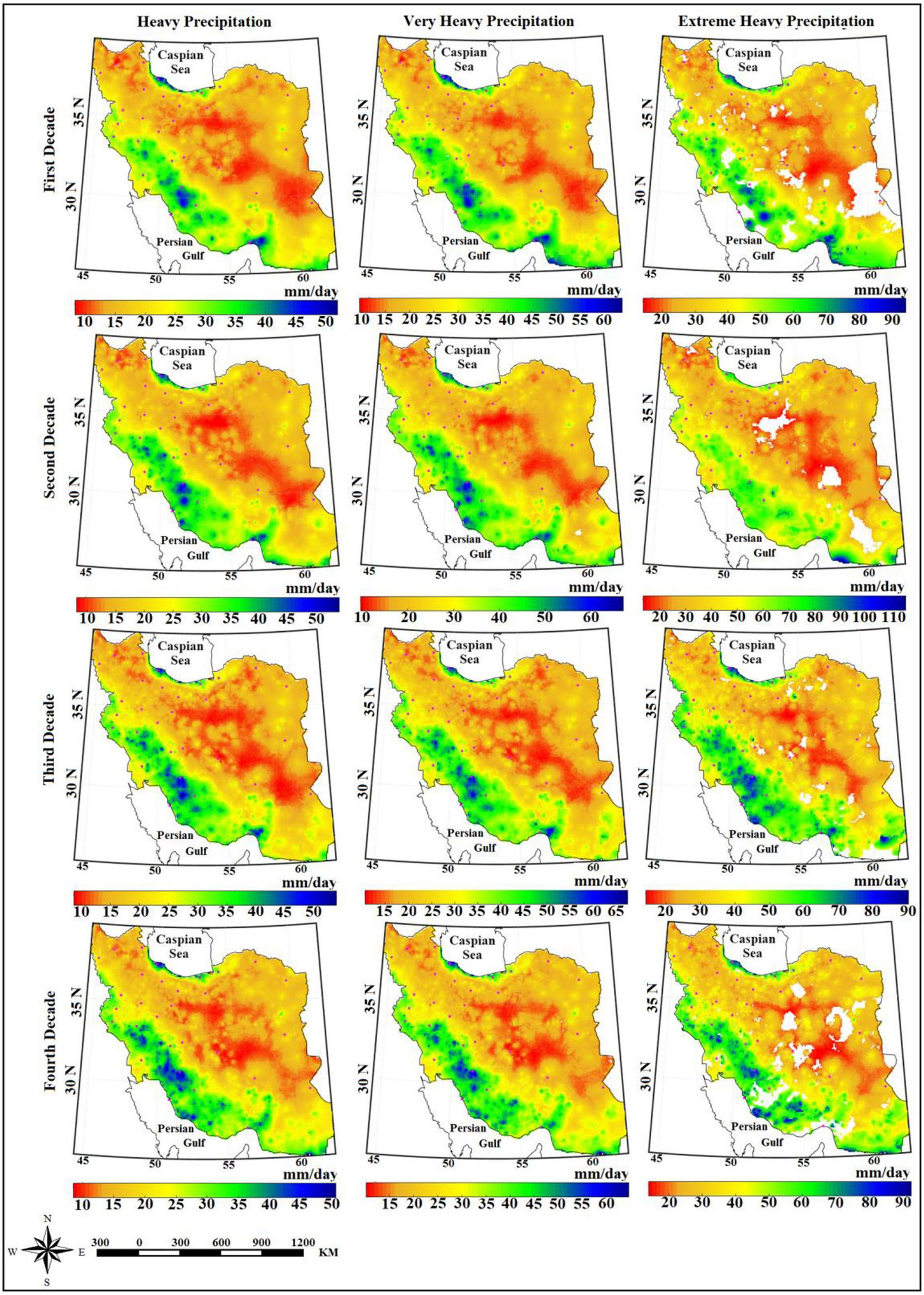

Fig. 5 The average intensity of HEP over the studied decades

Table 3 Descriptive characteristics of the average intensity of HEP over the studied decades

HEP type	Decade	Min (mm/day)	Max (mm/day)	Mean (mm/day)
HP	First	8.25	52.03	19.37
	Second	8.11	54.04	20.3
	Third	8.73	53.89	20.33
	Forth	8.48	50.66	20.37
VHP	First	9.6	63.79	24.46
	Second	9.7	67.09	25.49
	Third	10.52	67.46	25.48
	Forth	10.14	64.64	25.38
EHP	First	13.93	94.5	36.7
	Second	13.55	115.32	38.6
	Third	14.06	90.4	37.5
	Forth	13.9	92.6	37.24

However, in the subsequent two decades, the Zagros Mountains also experienced substantial precipitation. In numerous regions across the country, the precipitation intensity was not significant throughout all three decades. It is important to acknowledge that the intensity of precipitation in a given region is contingent upon the prevailing climate, and thus, it is not appropriate to compare the intensity of precipitation between regions with dissimilar levels of precipitation.

Table 4 displays the correlation between spatial factors and the average intensity of the three different types of HEPs over four decades. The results indicate an inverse relationship between the intensity of HP events and spatial factors during this period. However, in the third decade, EHP exhibited a weak direct relationship with altitude. This can be attributed to the fact that cyclones that entered the country during this time had less power in terms of precipitation generation, but the orographic forcing mechanism in the Zagros allowed them to produce relatively more intense precipitation (Asakereh and Khojasteh 2021). In the first decade, the relationship between longitude and HP and VHP intensity was weaker compared to the other three decades, while it was stronger for EHP, particularly in the third decade. During this decade, the intensity of precipitation had an inverse relationship with latitude, which was due to the formation of cyclones in the dry areas of Iraq and Arabia that entered Iran in the last few decades. These cyclones carried a small amount of moisture that formed precipitation in the Zagros due to orographic forcing mechanisms (Masoodian 2012). The correlation between latitude, HP, and VHP was higher in the first and fourth decades. Furthermore, EHP in the second and third decades had a higher correlation with latitude, whereas the correlation with altitude was stronger in the first decade.

Long-term trend of HEP intensity

Figure 8 illustrates the trend of HEP intensity during the studied period. The results indicate an increasing trend in HP and VHP intensity in scattered areas of western and southern Iran. The most significant increases in HP intensity were observed in the Zagros Mountains, a part of the Persian Gulf coast, and a small portion of southern central Iran. Meanwhile, areas with the highest VHP intensity trends were distributed in small spots within the same regions. On the other hand, EHP intensity experienced a decreasing trend throughout almost the entire country, with scattered stationary trends in some areas. This type of HEP was associated with a reduction in total precipitation amount and a decrease in occurrence frequency during the third and fourth decades (as shown in Figs. 5 and 6). The decline in EHP intensity, amount, and frequency may be attributed to the location where cyclones are formed upon entering the country. Jahanbakhsh et al.'s (2021) study indicates that the formation of cyclones over Arabia and Iraq has slightly increased compared to the past, resulting in the entry of dry or less humid air into Iran. Additionally, Masoodian's (2012) research suggested the emergence of a cyclone center over Iraq.

Figure 9 depicts the trend of the intensity of HEP with varying durations over the studied period. The intensity of HP has been observed to increase in a broad area across the country. Specifically, in the south Zagros and Persian Gulf coasts for the 1-day duration, and in the southeast of Iran for the 2-day duration, the increasing trends were stronger, while declining trends were scattered across different regions. In terms of VHP with different durations, a wide area of the country exhibited a weakly increasing trend. However, for the 1-day duration in high parts of Zagros and the coasts of the Persian Gulf, a stronger increasing trend was observed, while other durations showed a mix of stronger increasing and decreasing trends in small scattered regions. For the 1-day duration of EHP, a considerable portion of the country saw a decreasing trend, which was more prominent around the Strait of Hormuz, whereas the increasing trend occurred sporadically in different regions. The 2-day duration witnessed an increasing trend in many parts of the country, including a very strong increase in a small area of the middle Zagros. Precipitation in these areas is typically supplied by Sudanese systems. Lashkari and Mohammadi's (2019) study suggests that the shortening of the activity period of Sudanese systems in these areas is responsible for the observed increasing trend of short-term precipitation.

Figure 9 illustrates the trend of HEP intensity with varying durations during the studied period. The intensity of the HP has been observed to increase in a wide area of the country. Specifically, the 1-day duration in the south Zagros and Persian Gulf coasts and the 2-day duration in the southeast of Iran exhibited stronger increasing trends, while the

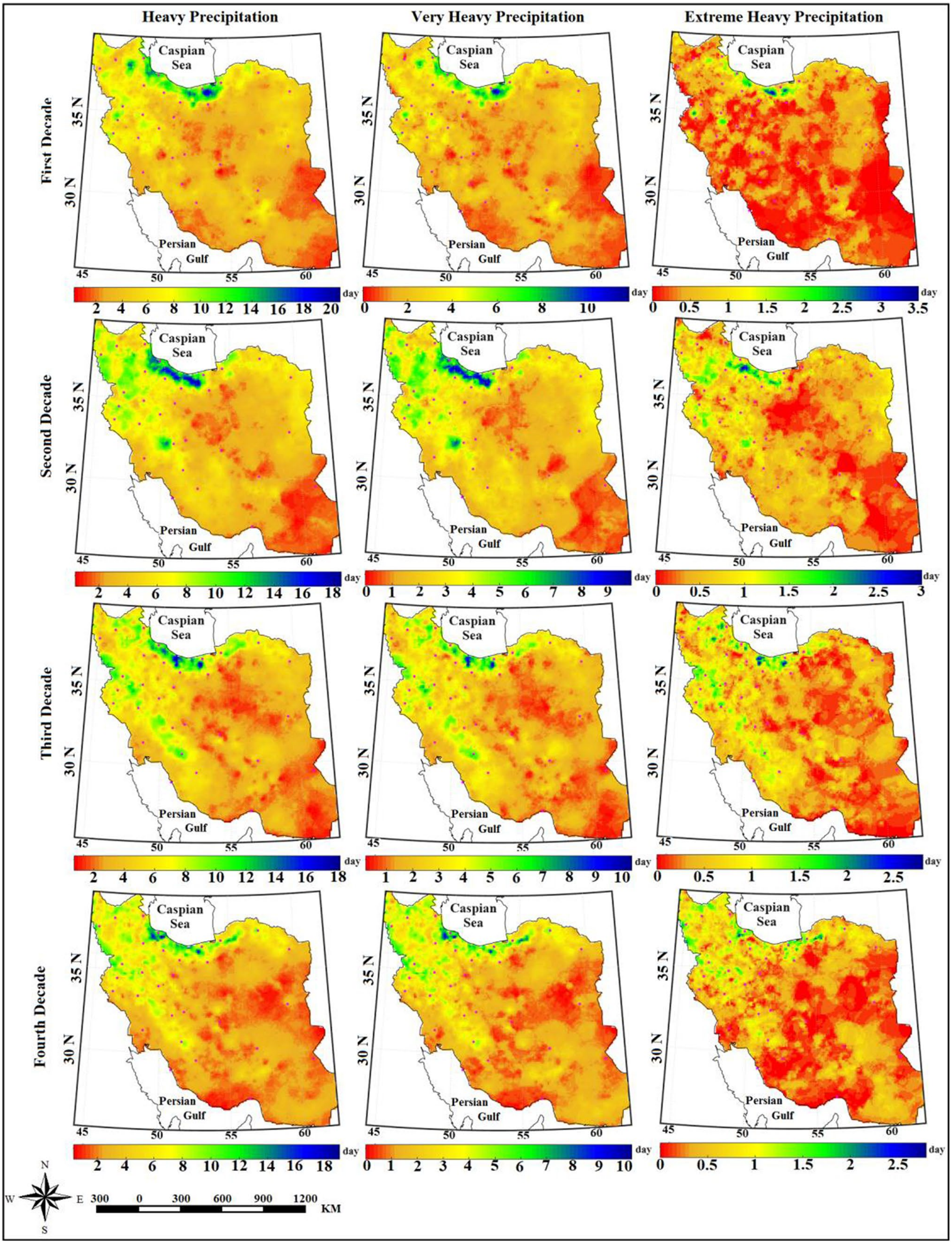

Fig. 6 The frequency of HEPs over the studied decades

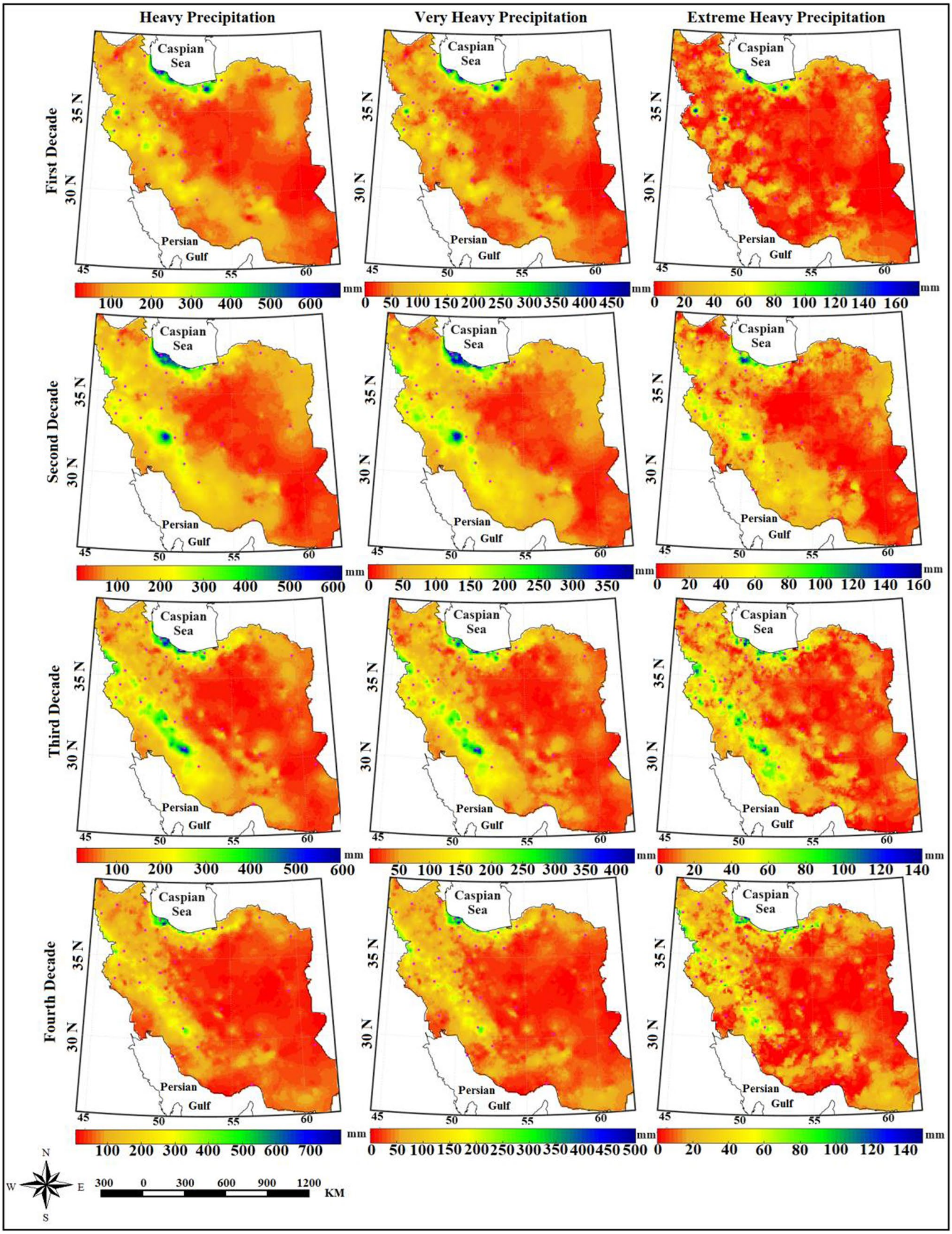

Fig. 7 The average of total precipitation resulted from HEP over the studied decades

Table 4 Correlation coefficients of the spatial factors with intensity of HP, VHP, and EHP for four study decades

HEP type	Local factors	First decade	Second decade	Third decade	Forth decade
HP	Longitude	−0.185	−0.229	−0.258	−0.210
	Latitude	−0.430	−0.405	−0.395	−0.436
	Altitude	−0.149	−0.106	−0.082	−0.133
VHP	Longitude	−0.169	−0.204	−0.243	−0.206
	Latitude	−0.456	−0.436	−0.413	−0.439
	Altitude	−0.169	−0.116	−0.09	−0.127
EHP	Longitude	−0.194	−0.188	−0.245	−0.185
	Latitude	−0.269	−0.379	−0.326	−0.269
	Altitude	−0.152	−0.088	0.004	−0.04

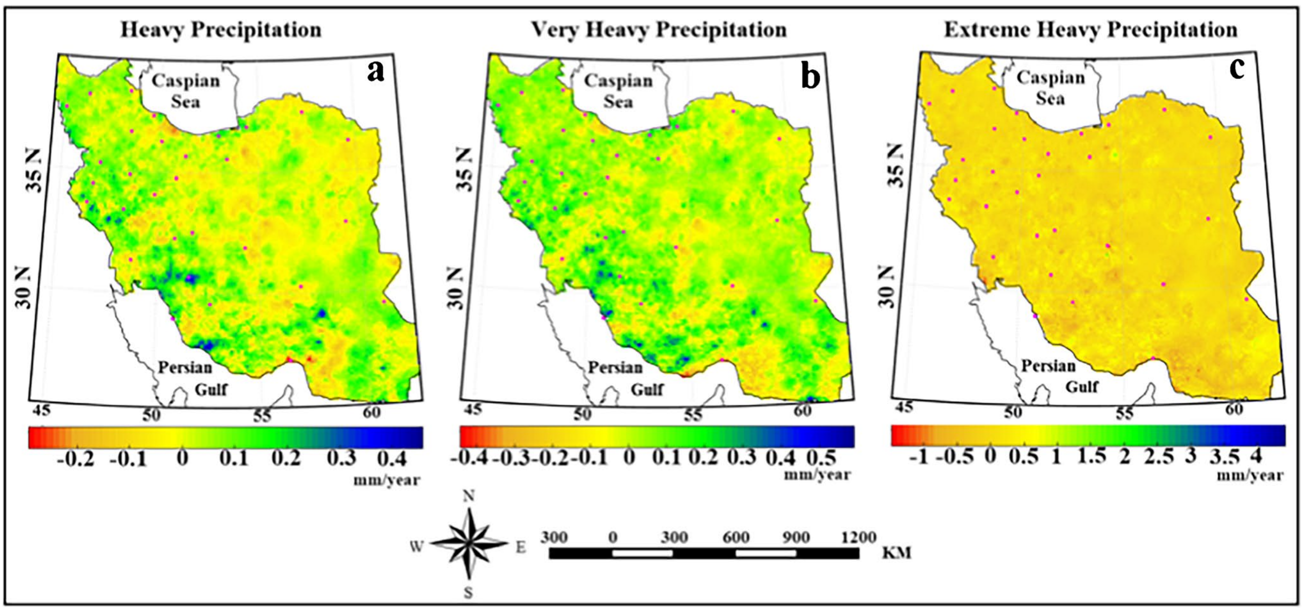

Fig. 8 Trends of intensity of HEP ((**a**) HP, (**b**)VHP, and (**c**) EHP)

declining trends were scattered in different parts of the country. In terms of VHP with different durations, a wide area of the country experiences a weak, increasing trend. However, the 1-day duration in the high parts of Zagros and the coasts of the Persian Gulf have had a stronger increasing trend. Other durations depicted a mix of stronger increasing and decreasing trends in small, scattered regions. For the 1-day duration of, a large area of the country had a decreasing trend, which was more prominent around the Strait of Hormuz, while the increasing trend took place sporadically in different parts of the country. During the 2-day duration, there was an increasing trend in many parts of the country, with a very strong increase observed in a small area of the middle Zagros. Precipitation in these areas is often supplied by the Sudanese systems. According to the study of Lashkari and Mohammadi (2019), the observed increasing trend of short-term precipitation was due to the shortening of the activity period of the Sudanese system in these areas.

Discussion

In Iran, hydrologists have primarily conducted studies on precipitation intensity on an hourly scale, with a few investigations conducted over longer periods. Additionally, the study of precipitation intensity has been limited to small spatial scales, such as watersheds, and has been overlooked at the national level. Therefore, the objective of the current study is to investigate the precipitation climatology and changes in the intensity of heavy precipitation in Iran across various durations. The study conducted indicates that heavy precipitation is most intense in wet regions of the country with short durations. Tabari (2020) noted an increase in the intensity of heavy precipitation across all climate zones, with greater increases observed in wet areas. Asakereh and Varnaseri Ghandali's (2019) study also found that the intensity of precipitation was highest in the wettest parts of the ICCS, with an increasing trend in the intensity of heavy precipitation over short-term

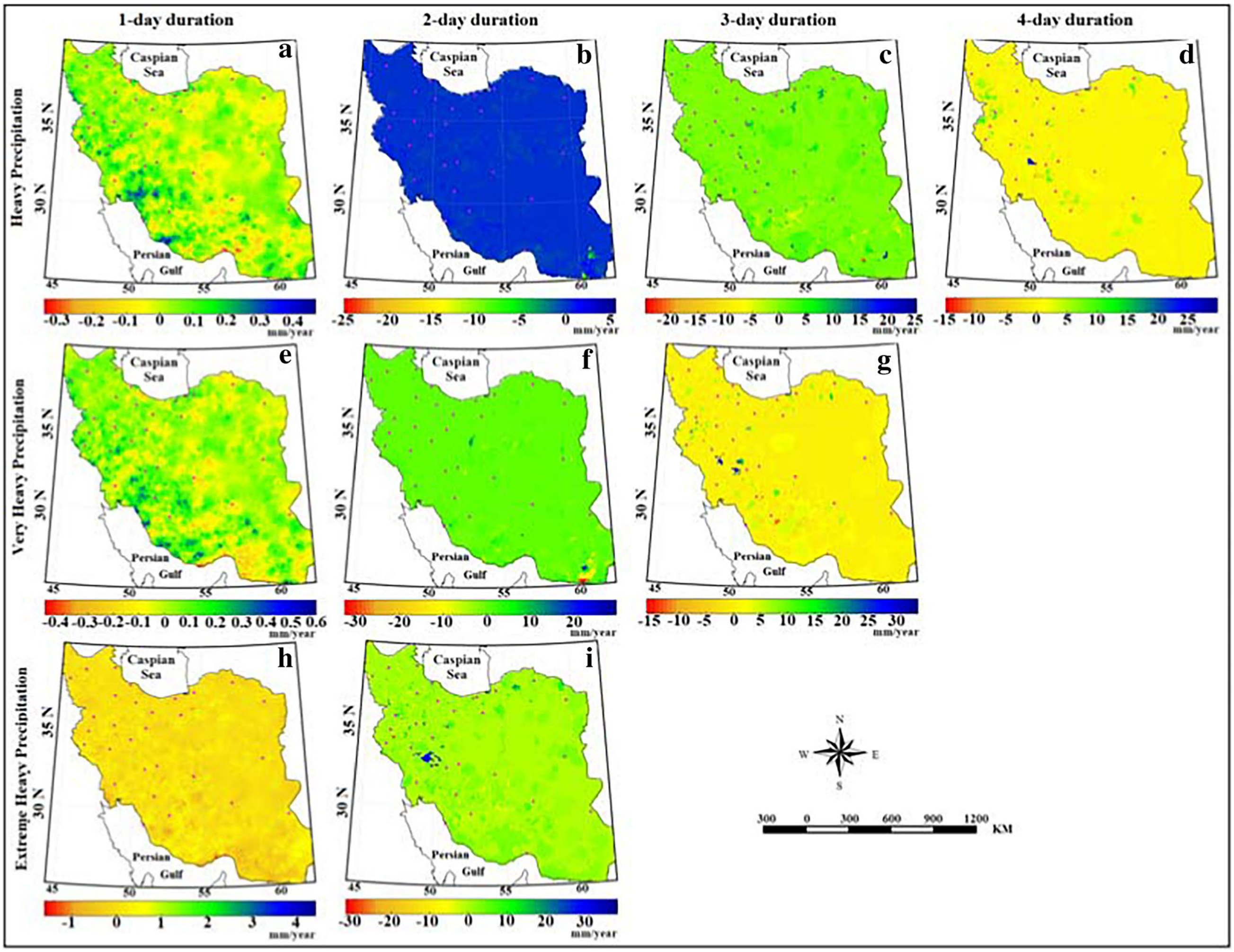

Fig. 9 Trends of average intensity of different durations of HEP. (**a**) One-day duration, (**b**) 2-day duration, (**c**) 3-day duration, and (**d**) 4-day duration. (**e**) One-day duration, (**f**) 2-day duration, and (**g**) 3-day duration. (**h**) One-day duration and (**i**) 2-day duration

durations. These results were confirmed by the study conducted by Lashkari and Mohammadi (2019), as well as the findings of Zeybekoğlu and Keskin (2020) in Turkey. Myhre et al. (2019) demonstrated that the intensity of precipitation doubles with every 1-degree increase in temperature, with a stronger increase observed in extreme precipitation. However, the intensity of EHP in the country has decreased. Gallego et al. (2006) also showed a decrease in the intensity of precipitation on the Iberian Peninsula.

Our study, conducted over a decade, revealed that the intensity of all types of heavy precipitation reached its maximum in the second and third decades, with the heaviest precipitation occurring in the second decade. This observation coincides with overcoming the positive phase of the North Atlantic Oscillation (NAO), as demonstrated by Mahajan et al. (2018), who found a strong relationship between heavy winter precipitation in Western Europe and the NAO index. As it is mentioned in the literature (e.g., Asakereh et al. 2017), the NAO determine the westerlies and associated cyclones track bringing precipitation for Iran.

Conclusion

To conduct this research, the Asfazari dataset covering the hydrological years spanning from 1971–1972 to 2015–2016 was utilized. HEP was extracted based on the 90th, 95th, and 99th percentile thresholds as HP, VHP, and EHP, respectively, using the time series of rainy days. The analysis focused on the intensity of HEP and its changes. The findings revealed that the Zagros region, as well as the southern and southwestern coasts of the Caspian Sea, experience the highest intensity of HP. Longitude and latitude were found to be the primary factors inversely affecting the intensity of HP. Additionally, short (1-day) durations exhibited higher precipitation intensity compared to longer durations, indicating that short durations experienced more intense HP. Over the studied period, the intensity of HP and VHP increased in most areas of the country, while the intensity of EHP decreased widely across Iran. Notably, an increasing trend in the intensity of precipitation during short-term durations of HP and VHP was observed, particularly in the Zagros region. Given the intensifying trend of HP and VHP, it is likely that the intensity of precipitation will surge in the future. The results of a related study by Zarrin and Dadashi-Roudbari (2022) also confirmed more intense precipitation throughout the country in the future. Increased precipitation intensity will result in torrential precipitation and consequent flood occurrences, leading to soil erosion. Therefore, the rise in HP intensity will increase the risks associated with this precipitation.

Author contribution We, the authors, contributed to the research. Hossein Asakereh performed the study conception, design, data collection, and material preparation. Data analysis was performed by Saeideh Ashrafi. The first draft (in Persian) of the manuscript was written by Saeideh Ashrafi. The final version of the manuscript (in English) was written by Hossein Asakereh.

Data availability The data of daily precipitation was provided from Islamic Republic of Iran Meteorological Organization (IRIMO) which have been described in details under the heading of "data" in this manuscript.

Declarations

Ethics approval The manuscript is original and is not submitted to another journal for simultaneous consideration neither has been published elsewhere in any form or language (partially or in full). Results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. No data, text, or theories by others are presented as if we are the author's own.

Patient consent We, the authors, understand that any information we submit for this study will be treated as confidential, and that we have all contributed to the research.

Consent for publication We, the authors, provide our consent for this research to be published *in Climatic Change Journal*, which include maps and information within the text.

Competing interests The authors declare no competing interests.

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