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Extreme precipitation indices trend assessment over Thrace region, Turkey

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Abstract

The frequency and the severity of extreme weather events are increasing globally and will continue to do so in the coming decades as a consequence of our changing climate. Understanding the characteristics of these events is crucial due to their significant negative impacts on social, physical and economic environments. In this study, 14 extreme rainfall indices are determined and examined in terms of trends and statistical characteristics for the four meteorological stations located in the Thrace region of Turkey, namely Edirne, Tekirdag, Kirklareli and Sariyer (Istanbul). The results indicate that annual total precipitation has an increasing trend for the Kirklareli and Sariyer stations ($z = 1.730$ and $z = 2.127$) and a decreasing trend for the Edirne and Tekirdag stations ($z = -0.368$ and $z = -0.401$). However, the precipitation intensity indices (SDII) of all stations show increasing trends that are statistically significant for the Edirne and Kirklareli stations. The Kirklareli station tends to have more days with heavy, very heavy and extremely heavy rainfall events ($z = 2.241$, $z = 2.076$ and $z = 1.684$, respectively). It is also anticipated that maximum amount of rainfalls in daily and consecutive five- and ten-day time scales will probably increase at all stations. Moreover, rainfall from very wet days and extremely wet days and fraction of total wet day rainfall that comes from very wet days and extremely wet days indices also show increasing trend tendencies for all stations. The remarkable point is the decreasing total precipitation trend at the Edirne and Tekirdag stations, contrary to the Kirklareli and Sariyer stations, which indicates that the annual total precipitation does not necessarily depend on extreme precipitation for the analyzed period.

Keywords Climate change · Extreme indices · ET-SCI · Extreme rainfall · ClimPACT2 · Trend analysis

Introduction

Climate change projections show that extreme weather events will likely occur more frequently and intensely under future climates due to global warming (IPCC 2012, 2013, 2014a, 2014b). Although describing the processes behind extreme events is not easy, studies agree that climate change dominates and will dominate the severity and intensity of extreme events such as extreme precipitation (Keggenhoff et al. 2014; Myhre et al. 2019). Myhre et al. (2019) also showed that surface warming might double and even triple extreme precipitation events. Changes in the frequency and intensity of extreme rainfall can cause remarkable problems for human lives, agricultural production, economy and infrastructure design and management (Toros 2012; Yazid and Humphries 2015). It is expected that many sectors will be affected by the extreme precipitation events (Shiferaw et al. 2018). Hence, it is crucial to investigate the changes in extreme events and to quantify these changes coherently.

In this context, extreme precipitation has become the subject of interest in many studies. On the other hand, there was no consensus in terms of definition, calculation and methodology for the extreme events, particularly extreme indices (Abbasnia and Toros 2020). To ensure a uniform perspective in analyzing weather and climate extremes, expert team on climate change detection and indices (ETCCDI) has defined a core set of extreme indices (Alexander et al. 2006; Klein Tank et al. 2009; Zhang et al. 2011). In addition, the expert

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team on sector-specific climate indices (ET-SCI) has developed a number of climate indices for use in various sector applications such as water, agriculture or health (Alexander et al. 2013; Alexander and Harold 2016). The main purpose of all these indices is to measure and monitor the climate change and its variability in a uniform way.

Extreme precipitation indices have been subject of interest for historical and future periods by several researchers in the last decade to gain a better understanding of the behavior. Attogouinon et al. (2017) studied 11 precipitation indices for the upper Oueme River valley in Benin and did not found any significant trend. Harpa et al. (2019) analyzed future changes for five extreme precipitation indices in Romania and detected increases in heavy precipitation days, very heavy precipitation days and annual total wet day precipitation compared with the reference period. Keggenhoff et al. (2014) presented an increase in extreme precipitation over Georgia but they stated that all trends manifest a low spatial coherence. Türkeş (2012) showed that there is an increasing trend in annual total precipitation over the Tekirdag and Istanbul provinces in the Thrace region together with northern and eastern parts of the Black Sea region and the Central and Eastern Anatolia regions of Turkey. Yilmaz (2015) examined the Antalya province of Turkey and he indicated that the obtained results show that the region has the potential to face more intense rainfall events in the future. Sensoy et al. (2019) analyzed the sectoral climate indices for the Istanbul province of Turkey and notified the increasing risk on agriculture and water resources based on the indices and anthropogenic activities. Nigussie and Altunkaynak (2019) used both observed and projected rainfall series to analyze the effect of climate change on extreme rainfall events for the Olimpiyat meteorological station near the Ayamama watershed in Istanbul. Their results present significant differences between observed and future data-driven indices and highlight an increase in the flood risk for the region under the RCP8.5 scenario. Oruç (2020) studied the potential impacts of climate change on extreme precipitation for Tekirdağ station and found an increasing extreme daily rainfall magnitude at Tekirdağ Province. Abbasnia and Toros (2020) examined extreme temperature and precipitation indices for 71 meteorological stations across the coastal and non-coastal areas of Turkey. Their results reveal decreasing trends in the number of precipitation days and the volume of precipitation for the large majority of the stations. Tokgöz and Partal (2020) analyzed the annual precipitation and temperature data of the Black Sea region. Their results indicated a generally increasing trend for annual precipitations and temperatures in Black Sea region. Köyceğiz and Büyükyıldız (2019) investigated the temporal variability of extreme precipitation in Konya closed basin and found insignificant increasing and decreasing trends. In another study of Abbasnia and Toros (2018) covering the Marmara region of Turkey, while decreasing trends were observed in consecutive wet days for the Canakkale, Kocaeli and Sariyer meteorological stations, increasing trends were detected for the Yalova, Edirne, Bursa and Tekirdag stations. Moreover, maximum 1 day and 5 day precipitation amount indices presented significant increases for the Sariyer, Tekirdag and Edirne stations.

Knowledge about hydro-climatologic trends and diagnosis of extreme precipitation patterns are particularly important because underestimating these events can cause remarkable social and physical damages; on the other hand, overestimated extremes may lead to increases in infrastructure investment costs. Moreover, it is crucial for decision-makers to have all the necessary knowledge in order to implement appropriate climate change strategies and policies. However, it is unlikely to obtain spatial coherence when extreme precipitation is the subject; therefore, regional- and local-scale investigations of extreme precipitation characteristics have gained importance.

The selected area for this study is the Thrace region of Turkey representing the European side of the country (Fig. 1). This region plays an important role in the Turkish economy due to dense population, industrial activities and agricultural production. Due to the economic activities, the region has been exposed to anthropogenic impact besides natural effects. Moreover, with increasing pollution due to the intense industrial activities, managing the domestic and irrigational water demand has become more crucial for the region (Şaylan et al. 2011; Bagdatli and Belliturk 2016).

The objectives of this study are to compute the values of 14 specific ET-SCI extreme rainfall indices using ClimPACT2 software for the Edirne, Kirklareli, Tekirdag and Sariyer meteorological stations located in the Thrace region and to analyze the trend presence and relation for these indices in the historical period on annual and monthly basis. Although there are studies in the literature regarding extreme indices of the Thrace region (e.g., Sırdaş and Şen 2003; Acar et al. 2018; Abbasnia and Toros 2018), this study differentiates from the earlier studies by dealing with more sectoral precipitation indices, analyzing these indices not only annually but also in monthly temporal scale and investigating the correlations of indices among the stations.

Material and methods

Study area and data

The Thrace region lies in the northwestern part of Turkey (Fig. 1). In the north and west, Thrace has borders with Greece and Bulgaria. Kirklareli, Edirne, Tekirdag and part of Istanbul and Canakkale provinces are located in the Thrace region. The Black Sea and Balkan effects over

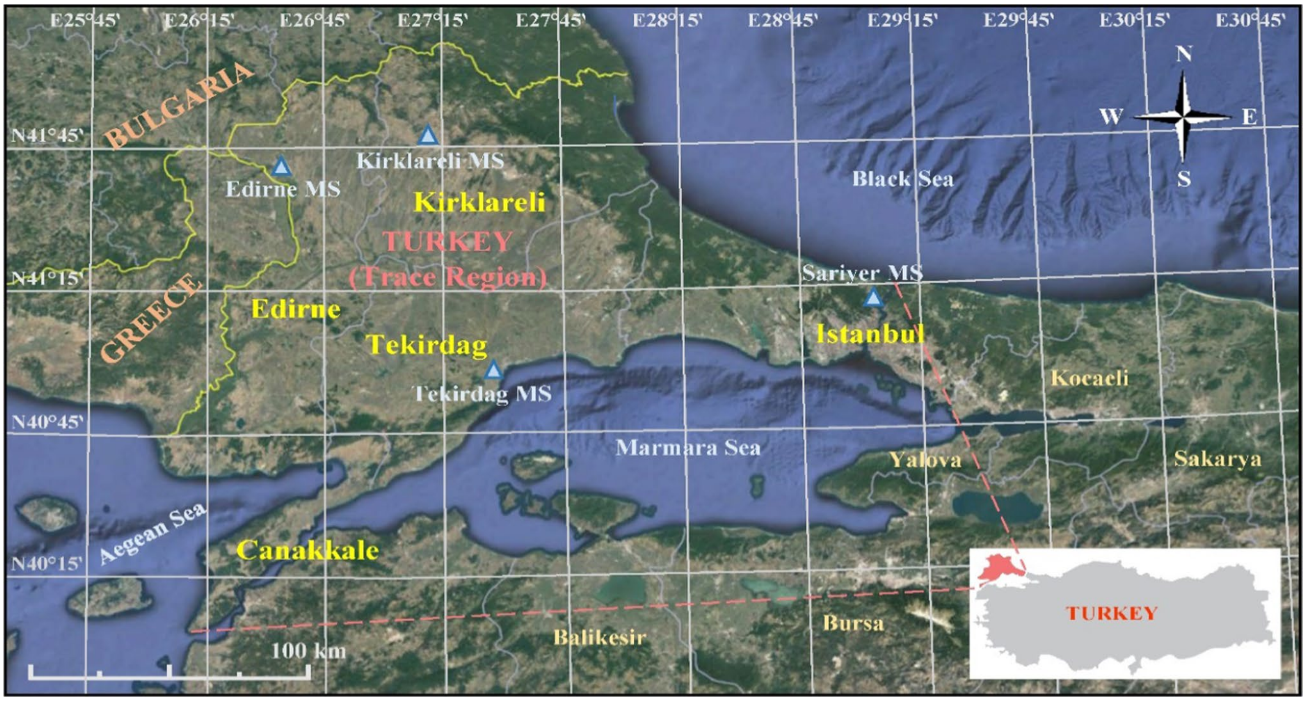

Fig. 1 Map of Thrace region and location of the meteorological stations

Table 1 Characteristics of the meteorological stations (MGM 2020)

Station	Longitude	Latitude	Elevation (m)	Data range
Edirne (17050)	26.55	41.68	51	1952–2016
Kirklareli (17052)	27.21	41.74	232	1981–2016
Tekirdag (17056)	27.50	40.96	4	1955–2016
Sariyer (17061)	29.05	41.15	59	1960–2016

Mediterranean climate lead to cold winters and warm summers in Thrace (Sırdaş and Sen 2003).

The daily historical precipitation records of several meteorological stations in the region are obtained from the Turkish State Meteorological Service. The Edirne (17050), Kirklareli (17052), Tekirdag (17056) and Sariyer (17061) stations are selected to be used for the historical period calculations due to their sufficiently long observation periods that allow the trend assessment of extreme precipitation indices over the region (MGM 2020). These stations are shown in Fig. 1 and are detailed in Table 1.

Trend tests

The Mann–Kendall (MK) trend test (Mann 1945; Kendall 1975) is a nonparametric rank-based test for identifying statistically significant trends in time series data (Gilbert 1987). It is among the most widely used nonparametric trend tests (e.g., Keggenhoff et al. 2014; Nigussie and Altunkaynak 2019; Wang et al. 2019; Militino et al. 2020). In this study, the MK trend test is used to detect if there is a monotonic upward or downward trend over time for the indices.

In the MK test, the null hypothesis (H_0) assumes that there is no trend and the alternate hypothesis (H_1) implies an increasing or decreasing trend over time. The mathematical equations for calculating MK test statistics S, variance of statistics $V(S)$ and standardized test statistics (Z) are given as follows:

$$S \geq \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} +1 & if\left(x_j - x_i\right) > 0 \\ 0 & if\left(x_j - x_i\right) = 0 \\ -1 & if\left(x_j - x_i\right) < 0 \end{cases} \tag{2}$$

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{m} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{3}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & ifS > 0 \\ 0 & ifS = 0 \\ \frac{S+1}{\sqrt{V(S)}} & ifS < 0 \end{cases} \tag{4}$$

In these equations, x_i and x_j are the values of sequence *i*, *j*; *n* is the length of the time series; t_p is the number of ties for *p*th value; and *m* is the number of tied values. A positive *Z* value indicates an upward trend, while a negative Z value indicates downward trend in the time series (Mann 1945; Kendall 1975; Ahmad et al. 2015; Chen et al. 2016).

It is known that serial correlation can affect the time series. Modified versions of the Mann–Kendall (M-MK) test are often used to justify original MK test results or to eliminate the influence of autocorrelation. One of these alternatives is the variance correction approach proposed by Hamed and Rao (1998). While this approach uses only significant lags of autocorrelation coefficients, Rao et al. (2003) suggested to use the first three autocorrelation coefficients. In this study, the variance correction approach is considered with the first three lags as an alternative to the MK test. The details of this approach can be found in Hamed and Rao (1998), Rao et al. (2003), Patakamuri and O'Brien (2020) and Patakamuri et al. (2020).

Expert team on sector-specific climate indices (ET-SCI)

The expert team on sector-specific climate indices (ET-SCI) of the WMO has been widely used to identify variability and trends in climate and sensitivity of various sectors according to these potential variations (Herold et al. 2018; Junk et al. 2019). In this study, ClimPACT2, a downloadable *R*-software package based on RClimDex software developed by ET-CCDI, is used to calculate sector-specific climate indices (Zhang and Yang 2004; Alexander and Herold 2016).

The period from 1961 to 1990 is suggested by WMO as a standard reference period for long-term climate change assessments (WMO 2017). Hence, while threshold-based indices are computed over the baseline period 1961–1990 for the Edirne, Tekirdag and Sariyer stations, the baseline period for the Kirklareli station is taken as 1981–1990 due to the lack of rainfall measurements.

The quality control of the rainfall time series is performed using the quality control functions of ClimPACT2 software and the *R*-based RHtests_dlyPrcp software (Wang and Feng 2013). According to the RHtests_dlyPrcp results, while the Edirne, Kirklareli and Sariyer stations show no change points, a change point is detected for the Tekirdag station. This problem is solved by revising the start of the observation period to 1955 for the Tekirdag station. After that, negative values, missing values and outliers are controlled manually.

After completing the required checks, ClimPACT2 is run to calculate extreme precipitation indices, listed in Table 2, using the daily rainfall time series. Trend analysis is conducted at annual scale on each of the 14 rainfall-based indices. In addition, the trends in PRCPTOT, CWD, R10mm, R20mm, R30mm, Rx1day, Rx5day and Rx10day indices are analyzed at monthly timescale.

Table 2 Explanations of the expert team on sector-specific climate indices (ET-SCI) (Alexander and Herold 2016)

ID	Name	Definition	Unit
Rx1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
Rx*d*day	User-defined consecutive days precipitation amount (*10-day in this study*)	Monthly maximum consecutive *d*-day precipitation	mm
SDII	Simple precipitation intensity index	Annual total precipitation divided by number of wet days (defined as PRCP ≥ 1.0 mm) in the year	mm/day
R10mm	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	day
R20mm	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	day
R*nn*mm	User-defined extremely heavy precipitation days (*30 mm in this study*)	Annual count of days when PRCP ≥ *nn* mm	day
CDD	Consecutive dry days	Maximal number of consecutive days with RR < 1 mm	day
CWD	Consecutive wet days	Maximal number of consecutive days with RR ≥ 1 mm	day
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
R95pTot	Contribution from very wet days	Fraction of total wet day rainfall that comes from very wet days	%
R99pTot	Contribution from extremely wet days	Fraction of total wet day rainfall that comes from extremely wet days	%
PRCPTOT	Annual total wet day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

Table 3 Basic statistical parameters for the Edirne station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
Mean	589.30	8.42	39.71	5.31	19.28	6.80	2.79	46.22	77.16	96.88	151.40	25.06	53.12	8.28
Std. dev	119.39	1.28	13.13	1.42	4.98	2.64	1.84	14.87	21.79	26.47	80.55	10.85	61.51	8.34
Skewness	0.80	0.59	1.06	0.70	0.40	0.08	0.71	1.51	1.38	0.75	0.58	− 0.21	1.58	0.92
Kurtosis	0.44	0.14	0.93	− 0.10	− 0.44	− 0.58	0.33	4.31	4.22	0.50	0.23	− 0.67	2.76	0.35

Table 4 Basic statistical parameters for the Kirklareli station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
Mean	541.90	8.30	42.64	5.03	17.67	6.42	2.53	48.21	72.75	91.82	137.90	24.37	49.07	8.59
Std. dev	147.50	1.38	12.65	1.32	6.03	3.41	1.66	15.02	23.59	27.07	82.00	10.17	50.54	7.86
Skewness	0.76	0.21	0.98	0.17	0.71	0.84	0.86	0.65	1.02	0.82	0.85	0.24	0.96	0.38
Kurtosis	0.26	− 0.71	0.41	− 0.81	− 0.08	0.16	− 0.08	− 0.85	1.26	1.20	− 0.31	− 0.96	0.32	− 1.01

Table 5 Basic statistical parameters for the Tekirdag station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
Mean	576.30	8.55	46.68	5.23	18.58	6.44	2.76	53.52	84.05	104.80	155.10	25.36	58.65	9.03
Std. dev	129.05	1.29	15.48	1.34	4.85	2.26	1.97	21.81	30.14	35.97	96.29	11.72	67.69	9.67
Skewness	0.48	0.51	0.61	0.36	0.34	0.26	0.46	1.38	0.85	0.64	0.68	0.06	1.09	0.78
Kurtosis	− 0.61	− 0.19	− 0.61	− 0.60	− 0.33	0.06	− 0.59	2.68	0.28	− 0.34	− 0.38	− 0.89	0.51	− 0.22

Table 6 Basic statistical parameters for the Sariyer station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
Mean	813.50	8.73	37.84	7.53	26.61	9.39	3.83	56.35	95.27	120.50	201.10	23.36	74.73	8.13
Std. dev	158.80	1.21	12.25	2.19	5.68	3.22	2.26	22.28	35.68	33.66	120.80	11.05	86.55	8.63
Skewness	0.48	0.24	0.89	1.63	0.37	0.45	0.58	1.03	1.92	1.43	0.47	− 0.08	1.32	0.81
Kurtosis	− 0.27	− 0.85	0.16	4.66	0.04	0.18	0.27	0.47	5.41	3.47	− 0.64	− 1.13	1.86	− 0.07

Results and discussion

Index statistical inference and trends on an annual basis

Fourteen extreme rainfall indices are calculated using the daily rainfall series recorded in the concerned observation periods at the Edirne, Kirklareli, Tekirdag and Sariyer meteorological stations. Basic statistical characteristics of these indices are presented in Tables 3, 4, 5 and 6 for the Edirne, Kirklareli, Tekirdag and Sariyer stations, respectively. The Sariyer station has the highest mean and standard deviation values of PRCPTOT, and the mean value of CDD for this station is the smallest one among the four stations. The Sariyer station has the highest mean and standard deviation values of the maximum 1-, 5- and 10-day precipitation indices (i.e., Rx1day, Rx5day and Rx10day). Considering the percentile indices (i.e., R95p, R99p, R95pTot and R99pTot), while the Kirklareli station has the smallest mean values of R95p and R99p, the Sariyer station has the smallest mean values of R95ptot and R99ptot. Moreover, the Rx1day, Rx5day and R99p indices of the Edirne station, Rx1day index of the Tekirdag station and CWD, Rx5day and Rx10day indices of the Sariyer station indicate the presence of extreme values.

Furthermore, positively and highly positively skewed values exist such as for CDD, CWD, Rx1day, Rx5day, Rx10day and R99p indices at all stations. Considering the kurtosis values, presence of outliers is more remarkable for Rx1day, Rx5day and R99p for the Edirne station, Rx1day for the Tekirdag station and CWD, Rx5day and Rx10day for the Sariyer station that indicates a heavy tail for these indices.

MK and M-MK tests are used for the trend detection of extreme rainfall indices considered in this study. Significance level is accepted as 0.05 in these analyses and the results of the MK and M-MK tests are presented in Tables 7 and 8, respectively. In these tables, the numbers presented in bold show significant trends at 0.05 significance level.

The results in Table 7 show that in general, there are increasing trends in most of the indices. On the other hand, the PRCPTOT index of the Edirne station, the PRCPTOT, CDD and R10mm indices of the Tekirdag station and the CDD index of the Sariyer station show decreasing trends. Toros (2012) found a general decrease in the annual total precipitation during the last decades for individual stations of Turkey and stated that while 34% of the stations have negative trends with only 12% of them at significant level, 22% of the stations have positive trends with only 4% of them at significant level. There is no negative trend detected for the Kirklareli station although Gönençgıl (2012) found that the meteorological stations of the Thrace region are dominated with decreasing trend in annual precipitation amounts which started in the year 1975 and gradually became evident during the 1990s. The detected trends for the Edirne and Kirklareli stations are not statistically significant, except for SDII, R95p and R95ptot for the Edirne station, SDII, R10mm and R20mm for the Kirklareli station. Considering the Sariyer station, 50% of the indices (i.e., 7 of 14) show statistically significant increasing trend tendencies. While all significant trends are positive for the Edirne, Kirklareli and Sariyer stations, there is no significant trend (neither negative nor positive)

Table 7 Mann–Kendall (MK) test: z-statistics and p values of annual rainfall indices

	Edirne		Kirklareli		Tekirdag		Sariyer	
	z-value	p value	z-value	p value	z-value	p value	z-value	p value
prcptot	− 0.368	0.713	1.730	0.084	− 0.401	0.689	**2.127**	0.033
sdii	**2.282**	0.023	**2.929**	0.003	1.166	0.244	1.852	0.064
cdd	1.774	0.076	0.560	0.575	− 0.024	0.981	− 0.662	0.508
cwd	0.478	0.632	0.308	0.758	0.840	0.401	1.684	0.092
r10mm	0.818	0.413	**2.241**	0.025	− 1.609	0.108	0.677	0.499
r20mm	1.462	0.144	**2.076**	0.038	0.787	0.432	1.763	0.078
r30mm	1.125	0.260	1.684	0.092	1.162	0.245	**2.745**	0.006
rx1day	1.636	0.102	1.471	0.141	1.585	0.113	**2.292**	0.022
rx5day	1.523	0.128	1.117	0.264	1.537	0.124	1.535	0.125
rx10day	1.393	0.164	1.566	0.117	1.282	0.200	0.991	0.322
r95p	**2.185**	0.029	1.294	0.196	1.112	0.266	**2.733**	0.006
r95ptot	**3.001**	0.003	0.422	0.673	1.640	0.101	**2.843**	0.004
r99p	1.634	0.102	1.719	0.086	1.397	0.162	**2.601**	0.009
r99ptot	1.599	0.110	1.411	0.158	1.606	0.108	**2.608**	0.009

Table 8 Modified Mann–Kendall (M-MK) test: corrected z-statistics and new p values of annual rainfall indices

	Edirne		Kirklareli		Tekirdag		Sariyer	
	***z*-value**	p value	z-value	p value	z-value	p value	z-value	p value
prcptot	− 0.368	0.713	1.730	0.084	− 0.401	0.689	**2.127**	0.033
sdii	**2.282**	0.023	**2.928**	0.003	1.166	0.244	1.852	0.064
cdd	1.774	0.076	0.560	0.575	− 0.024	0.981	− 0.662	0.508
cwd	0.478	0.632	0.308	0.758	0.840	0.401	1.684	0.092
r10mm	0.818	0.413	**2.241**	0.025	− 1.609	0.108	0.964	0.335
r20mm	**2.261**	0.024	**2.076**	0.038	0.787	0.432	1.763	0.078
r30mm	1.125	0.260	1.684	0.092	0.873	0.383	**2.745**	0.006
rx1day	1.636	0.102	1.471	0.141	1.254	0.210	**2.292**	0.022
rx5day	1.523	0.128	1.117	0.264	1.537	0.124	1.535	0.125
rx10day	1.393	0.164	1.566	0.117	1.282	0.200	0.991	0.322
r95p	**2.185**	0.029	1.294	0.196	1.112	0.266	**2.733**	0.006
r95ptot	**3.001**	0.003	0.422	0.673	1.640	0.101	**2.843**	0.004
r99p	1.634	0.102	1.719	0.086	1.143	0.253	**2.601**	0.009
r99ptot	1.599	0.110	1.411	0.158	1.606	0.108	**2.608**	0.009

at 0.05 significance level for the Tekirdag station on the annual base.

Rainfall is one of the most important components of water resource management for decisionmaking and planning in the region having agriculture-based economy, and the increasing trend of CDD for the Edirne and Kirklareli stations needs attention in this context. Especially the increasing trend and magnitude of CDD with decreasing total precipitation at the Edirne station is worth to focus as a signal of water scarcity in the near future. On the other hand, CWD indices also show increasing trends for all stations but none of these trends are significant.

While annual total precipitation (i.e., PRCPTOT) shows a decreasing trend for the Edirne and Tekirdag stations, increasing trends are detected for the Kirklareli and Sariyer stations. Although negative trends are detected for total precipitation indices of the Edirne and Tekirdag stations, SDII indices of these stations show positive trends with a significant one for the Edirne station. Sensoy et al. (2013) investigated the extreme climate indices in Turkey for 109 stations and for the period from 1960 to 2010 and they found that heavy precipitation days increase for most of the stations except the ones in the Aegean and southeastern Anatolia regions. Furthermore, in most of the stations, maximum 1-day precipitation followed an increasing trend, apart from southeastern Anatolia. Regarding R10mm, R20mm and R30mm indices, a positive trend is found for most of the stations, supporting the results of other studies, while it is observed that R10mm index has a negative trend for the Tekirdag station. In addition, Rx1day, Rx5day and Rx10day indices show an increasing trend during the study period for all stations. Abbasnia and Toros (2018) also revealed significant increasing trends of Rx1day and Rx5day indices for the Edirne and Tekirdag stations which support the results of this study.

Regarding the percentile indices, while R95p, R99p, R95pTot and R99pTot values of all four stations show an increasing trend, R95p and R95pTot indices of the Edirne station and all percentile indices of the Sariyer station have significant positive trends. R95pTot and R99pTot represent the percentage of annual precipitation that comes from very wet days and extremely wet days, respectively. Hence, these indices can be used to investigate the possibility that there may have been a greater change in extreme precipitation events than in total amount. Accordingly, for the Kirklareli and Sariyer stations, it can be expected that extremes are going to change more rapidly when increasing total precipitation and very wet days/extremely wet days indices are considered. However, for the Edirne and Tekirdag stations, the decreasing trend of total precipitation indicates that the very wet days and extremely wet days are less affected by the trend in the total precipitation. Abbasnia and Toros (2020) examined the extreme temperature and precipitation indices for 71 stations across Turkey from 1961 to 2016, covering the Thrace region and also R95p and R99p indices. When compared their findings with the present results, it is seen that there are differences in terms of trend tendency and significance that could be due to the duration of data, chosen baseline period and chosen significance level.

Furthermore, for the Kirklareli station, both consecutive dry days (i.e., CDD) and annual total precipitation (i.e., PRCPTOT) indices show positive trends with a higher magnitude for total precipitation. This can be interpreted as daily rainfall events with relatively stable CWD compared to annual precipitation may expose an increase in the frequency and/or intensity of heavy rain.

The M-MK tests are utilized to justify the results of MK tests, as stated before. The values in Table 8 show that the results of the M-MK tests are, in general, consistent with those of the MK tests in the direction and significance of trend. However, the R20mm value of the Edirne station, R30mm, Rx1day and R99p values of the Tekirdag station and R10mm value of the Sariyer station are corrected by the results of the M-MK tests. Considering these modifications, the corrected R20mm value of the Edirne station indicates a significant increasing trend while the MK test results yield insignificant trend for this index. The rest of the results show consistent z-statistics and p values for the indices.

The relationships between annual rainfall indices are calculated in a 14×14 matrix for the Edirne, Kirklareli, Tekirdag and Sariyer meteorological stations, as presented in Tables 9, 10, 11 and 12, respectively. The results show that the maximum 1-, 5- and 10-day precipitation indices (i.e., Rx1day, Rx5day and Rx10day) have better relationships with the percentile indices (i.e., R95p, R99p, R95pTot and R99pTot). The results also reveal that the threshold indices (i.e., R10mm, R20mm and R30mm) have better relationships with SDII and PRCPTOT indices while PRCPTOT has a stronger relationship than SDII. Moreover, CDD and CWD indices have the worst correlations with other indices for all stations. In addition, fairly good correlations are observed between R30mm, R95p and R95pTot indices and between Rx1day, R99p and R99pTot indices. Although both positive and negative correlations are detected among the annual values of the rainfall indices, positive relationships exhibit stronger correlations while the negative correlation values are not as strong as the positive ones.

Index statistical inference and trends on a monthly basis

In order to detect the changes in extreme precipitation at a shorter time scale, the monthly trends of PRCPTOT, CWD, R10mm, R20mm, R30mm, Rx1day, Rx5day and Rx10day indices are computed using the MK and M-MK tests for all stations. The results of the MK and

Table 9 Correlation matrix of annual rainfall indices for the Edirne station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
prcptot	1.00	0.66	-0.09	0.05	0.87	0.70	0.64	0.36	0.38	0.44	0.65	0.29	0.59	0.44
sdii	0.66	1.00	0.16	-0.16	0.63	0.71	0.71	0.49	0.49	0.53	0.78	0.63	0.63	0.56
cdd	-0.09	0.16	1.00	0.03	-0.15	-0.02	0.01	0.09	0.09	0.26	0.09	0.17	0.12	0.13
cwd	0.05	-0.16	0.03	1.00	-0.06	-0.00	-0.02	0.09	0.09	0.09	0.00	0.01	-0.03	-0.02
r10mm	0.87	0.63	-0.15	-0.06	1.00	0.56	0.41	0.13	0.21	0.35	0.41	0.07	0.36	0.21
r20mm	0.70	0.71	-0.02	-0.00	0.56	1.00	0.71	0.23	0.28	0.35	0.74	0.59	0.38	0.30
r30mm	0.64	0.71	0.01	-0.02	0.41	0.71	1.00	0.55	0.48	0.48	0.91	0.79	0.67	0.61
rx1day	0.36	0.49	0.09	0.09	0.13	0.23	0.55	1.00	0.78	0.61	0.64	0.60	0.81	0.86
rx5day	0.38	0.49	0.09	0.09	0.21	0.28	0.48	0.78	1.00	0.82	0.57	0.53	0.69	0.73
rx10day	0.44	0.53	0.26	0.09	0.35	0.35	0.48	0.61	0.82	1.00	0.53	0.46	0.60	0.61
r95p	0.65	0.78	0.09	0.00	0.41	0.74	0.91	0.64	0.57	0.53	1.00	0.90	0.74	0.67
r95ptot	0.29	0.63	0.17	0.01	0.07	0.59	0.79	0.60	0.53	0.46	0.90	1.00	0.56	0.58
r99p	0.59	0.63	0.12	-0.03	0.36	0.38	0.67	0.81	0.69	0.60	0.74	0.56	1.00	0.97
r99ptot	0.44	0.56	0.13	-0.02	0.21	0.30	0.61	0.86	0.73	0.61	0.67	0.58	0.97	1.00

Table 10 Correlation matrix of annual rainfall indices for the Kirklareli station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
prcptot	1.00	0.77	-0.06	0.13	0.91	0.93	0.67	0.41	0.65	0.56	0.71	0.40	0.49	0.23
sdii	0.77	1.00	0.18	-0.26	0.75	0.81	0.67	0.55	0.61	0.58	0.73	0.56	0.62	0.45
cdd	-0.06	0.18	1.00	-0.37	-0.04	-0.03	0.07	0.35	0.11	0.05	0.06	0.11	0.32	0.40
cwd	0.13	-0.26	-0.37	1.00	-0.00	0.14	-0.14	-0.06	0.16	0.07	0.00	-0.03	-0.04	-0.12
r10mm	0.91	0.75	-0.04	-0.00	1.00	0.81	0.54	0.29	0.53	0.50	0.53	0.21	0.39	0.15
r20mm	0.93	0.81	-0.03	0.14	0.81	1.00	0.71	0.45	0.68	0.56	0.80	0.56	0.56	0.30
r30mm	0.67	0.67	0.07	-0.14	0.54	0.71	1.00	0.46	0.48	0.48	0.90	0.80	0.59	0.42
rx1day	0.41	0.55	0.35	-0.06	0.29	0.45	0.46	1.00	0.77	0.76	0.60	0.55	0.88	0.86
rx5day	0.65	0.61	0.11	0.16	0.53	0.68	0.48	0.77	1.00	0.89	0.65	0.51	0.66	0.52
rx10day	0.56	0.58	0.05	0.07	0.50	0.56	0.48	0.76	0.89	1.00	0.59	0.48	0.66	0.57
r95p	0.71	0.73	0.06	0.00	0.53	0.80	0.90	0.60	0.65	0.59	1.00	0.91	0.69	0.51
r95ptot	0.40	0.56	0.11	-0.03	0.21	0.56	0.80	0.55	0.51	0.48	0.91	1.00	0.61	0.55
r99p	0.49	0.62	0.32	-0.04	0.39	0.56	0.59	0.88	0.66	0.66	0.69	0.61	1.00	0.93
r99ptot	0.23	0.45	0.40	-0.12	0.15	0.30	0.42	0.86	0.52	0.57	0.51	0.55	0.93	1.00

Table 11 Correlation matrix of annual rainfall indices for the Tekirdag station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
prcptot	1.00	0.78	-0.13	0.33	0.83	0.83	0.77	0.65	0.69	0.69	0.81	0.60	0.67	0.54
sdii	0.78	1.00	-0.06	0.17	0.70	0.80	0.79	0.62	0.65	0.65	0.81	0.73	0.64	0.57
cdd	-0.13	-0.06	1.00	-0.31	-0.10	-0.10	-0.12	-0.04	-0.21	-0.23	-0.12	-0.10	-0.08	-0.06
cwd	0.33	0.17	-0.31	1.00	0.14	0.30	0.25	0.09	0.22	0.29	0.25	0.20	0.19	0.16
r10mm	0.83	0.70	-0.10	0.14	1.00	0.70	0.51	0.35	0.47	0.50	0.51	0.29	0.37	0.25
r20mm	0.83	0.80	-0.10	0.30	0.70	1.00	0.73	0.43	0.54	0.59	0.74	0.62	0.48	0.40
r30mm	0.77	0.79	-0.12	0.25	0.51	0.73	1.00	0.66	0.67	0.67	0.93	0.88	0.67	0.60
rx1day	0.65	0.62	-0.04	0.09	0.35	0.43	0.66	1.00	0.75	0.63	0.77	0.70	0.90	0.86
rx5day	0.69	0.65	-0.21	0.22	0.47	0.54	0.67	0.75	1.00	0.86	0.76	0.70	0.76	0.71
rx10day	0.69	0.65	-0.23	0.29	0.50	0.59	0.67	0.63	0.86	1.00	0.71	0.65	0.64	0.59
r95p	0.81	0.81	-0.12	0.25	0.51	0.74	0.93	0.77	0.76	0.71	1.00	0.94	0.82	0.74
r95ptot	0.60	0.73	-0.10	0.20	0.29	0.62	0.88	0.70	0.70	0.65	0.94	1.00	0.76	0.73
r99p	0.67	0.64	-0.08	0.19	0.37	0.48	0.67	0.90	0.76	0.64	0.82	0.76	1.00	0.97
r99ptot	0.54	0.57	-0.06	0.16	0.25	0.40	0.60	0.86	0.71	0.59	0.74	0.73	0.97	1.00

M-MK tests are presented in Tables 13, 14, 15 and 16 and Tables 17, 18, 19 and 20 for the Edirne, Kirklareli, Tekirdag and Sariyer stations, respectively. In these tables, the numbers presented in bold show significant trends at 0.05 significance level.

At the monthly scale, the PRCPTOT index of the Kirklareli station shows a significant increasing trend in January, September and October. In addition, the CWD index of the Edirne station significantly decreases in February. While there is no significant negative or positive

Table 12 Correlation matrix of annual rainfall indices for the Sariyer station

	prcptot	sdii	cdd	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day	r95p	r95ptot	r99p	r99ptot
prcptot	1.00	0.86	- 0.04	0.33	0.87	0.82	0.82	0.61	0.58	0.62	0.84	0.65	0.72	0.64
sdii	0.86	1.00	- 0.02	0.19	0.69	0.80	0.83	0.62	0.61	0.68	0.86	0.76	0.68	0.64
cdd	- 0.04	- 0.02	1.00	- 0.21	- 0.01	- 0.14	- 0.17	0.11	0.21	0.25	-0.05	-0.05	- 0.02	- 0.01
cwd	0.33	0.19	- 0.21	1.00	0.34	0.16	0.26	0.14	0.15	0.27	0.16	0.08	0.12	0.10
r10mm	0.87	0.69	- 0.01	0.34	1.00	0.67	0.58	0.33	0.29	0.45	0.55	0.32	0.40	0.29
r20mm	0.82	0.80	- 0.14	0.16	0.67	1.00	0.73	0.44	0.45	0.45	0.74	0.62	0.49	0.42
r30mm	0.82	0.83	- 0.17	0.26	0.58	0.73	1.00	0.61	0.64	0.65	0.93	0.86	0.78	0.73
rx1day	0.61	0.62	0.11	0.14	0.33	0.44	0.61	1.00	0.80	0.67	0.76	0.74	0.73	0.76
rx5day	0.58	0.61	0.21	0.15	0.29	0.45	0.64	0.80	1.00	0.88	0.72	0.71	0.68	0.69
rx10day	0.62	0.68	0.25	0.27	0.45	0.45	0.65	0.67	0.88	1.00	0.69	0.64	0.60	0.59
r95p	0.84	0.86	- 0.05	0.16	0.55	0.74	0.93	0.76	0.72	0.69	1.00	0.95	0.85	0.82
r95ptot	0.65	0.76	- 0.05	0.08	0.32	0.62	0.86	0.74	0.71	0.64	0.95	1.00	0.78	0.79
r99p	0.72	0.68	- 0.02	0.12	0.40	0.49	0.78	0.73	0.68	0.60	0.85	0.78	1.00	0.98
r99ptot	0.64	0.64	- 0.01	0.10	0.29	0.42	0.73	0.76	0.69	0.59	0.82	0.79	0.98	1.00

Table 13 Monthly Mann–Kendall (MK) test z-statistics for the Edirne station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	0.136	0.127	0.386	– 0.094	0.857	0.062	0.306	0.017
Feb	– 0.317	**– 2.070**	0.349	1.124	1.252	–	0.459	0.702
Mar	0.357	1.013	0.017	1.293	0.993	0.866	0.906	0.510
Apr	– 1.144	– 0.265	– 0.733	– 1.059	–	– 0.566	– 1.348	– 0.702
May	– 0.628	– 0.766	– 0.141	1.051	0.674	0.164	– 0.781	– 0.555
Jun	– 1.223	– 0.161	– 1.440	– 0.784	– 1.180	– 1.478	– 1.251	– 0.311
Jul	1.353	0.219	1.319	1.232	1.147	1.557	1.665	1.523
Aug	0.091	– 0.922	0.037	– 0.402	0.338	0.102	0.408	0.481
Sep	0.561	– 0.048	1.265	1.404	1.594	0.600	0.283	0.221
Oct	0.770	0.969	1.226	1.631	– 0.076	1.172	0.674	0.679
Nov	– 0.470	– 1.443	0.481	– 0.575	– 1.303	0.062	– 0.243	0.108
Dec	– 0.396	0.567	– 0.438	1.133	1.656	0.453	0.906	0.878

Table 14 Monthly Mann–Kendall (MK) test z-statistics for the Kirklareli station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	**2.289**	1.804	1.876	1.027	1.289	1.757	**2.411**	**2.806**
Feb	0.885	0.214	1.242	1.385	**2.036**	1.008	1.308	1.934
Mar	0.204	0.395	0.313	-1.326	– 0.503	0.191	-0.054	0.041
Apr	– 0.136	– 0.190	0.245	0.906	0.483	0.777	0.163	– 0.014
May	0.654	1.105	1.144	0.201	– 0.438	0.409	0.504	0.627
Jun	0.627	–	1.414	– 0.225	– 0.070	0.817	1.076	1.199
Jul	0.423	– 0.860	0.668	1.541	1.202	0.545	0.558	0.736
Aug	0.451	0.906	0.465	0.686	1.001	1.091	1.090	0.763
Sep	**2.942**	0.737	**3.344**	**2.509**	1.873	**3.570**	**2.166**	1.839
Oct	**2.193**	1.222	**2.167**	1.654	0.704	1.076	**2.193**	**3.283**
Nov	– 1.485	– 1.070	– 1.301	– 1.113	– 1.033	– 1.526	– 0.804	– 0.599
Dec	– 0.313	–	– 0.223	1.408	– 0.319	– 0.232	0.286	– 0.082

trend in the R10mm, R20mm and R30mm indices of the Edirne station, these indices show significant increasing trends for the Kirklareli station (e.g., R10 mm and R20 mm in September and R30mm in February). On the other hand, the R20mm and R30mm indices of the Tekirdag station indicate significant negative trends in November. The maximum 1-, 5- and 10-day precipitation indices (i.e., Rx1day, Rx5day and Rx10day) of the Kirklareli station increases significantly in January, September and October. For the Sariyer station, the monthly MK test z-statistics

Table 15 Monthly Mann–Kendall (MK) test *z*-statistics for the Tekirdag station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	− 1.166	− 0.324	− 1.547	− 1.532	0.714	− 0.389	− 1.264	− 1.002
Feb	1.264	0.012	1.615	1.047	1.504	1.264	1.185	1.008
Mar	− 0.213	0.572	− 1.001	− 0.283	− 0.703	− 0.079	− 0.620	− 0.024
Apr	− 0.553	–	− 1.277	0.328	1.536	0.085	− 0.237	0.808
May	0.146	0.144	− 0.823	0.032	0.874	0.249	− 0.298	− 0.298
Jun	− 0.371	− 0.312	− 0.788	0.561	–	− 0.316	− 0.565	− 0.419
Jul	− 0.961	− 1.881	− 0.316	0.176	0.044	− 0.468	− 0.334	− 0.279
Aug	0.267	0.607	0.196	1.141	0.620	0.049	− 0.116	− 0.852
Sep	0.986	0.854	1.607	1.482	1.435	0.869	1.762	1.555
Oct	1.452	0.857	1.570	1.157	1.286	1.288	1.731	1.500
Nov	− 1.549	0.225	− 1.496	**− 2.081**	**− 2.132**	**− 2.351**	− 0.620	− 0.292
Dec	− 0.942	− 0.839	− 0.745	− 0.340	− 0.510	− 0.559	0.182	− 0.152

Table 16 Monthly Mann–Kendall (MK) test *z*-statistics for the Sariyer station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	− 0.695	− 0.070	− 0.992	− 1.106	0.337	− 0.509	− 0.702	− 0.964
Feb	1.308	1.158	0.372	1.889	**2.226**	1.866	0.805	0.867
Mar	0.620	1.210	0.219	0.395	− 0.634	0.248	0.076	0.241
Apr	− 0.482	− 1.297	0.357	− 0.315	− 0.916	0.241	− 0.709	− 0.213
May	0.145	− 1.509	0.889	0.927	0.434	1.129	0.675	0.647
Jun	1.818	0.567	1.899	1.730	1.445	1.287	1.941	1.101
Jul	− 0.165	− 0.893	− 0.168	− 0.320	0.594	− 0.145	0.200	0.138
Aug	0.911	0.917	0.953	− 0.109	0.808	1.005	1.342	1.067
Sep	1.281	0.893	0.702	0.060	1.732	0.227	0.647	1.611
Oct	**1.996**	1.625	1.555	1.695	1.292	1.797	**2.120**	**2.237**
Nov	1.040	**3.269**	− 0.420	0.370	0.760	1.053	0.668	1.336
Dec	− 1.143	1.260	− 1.061	− 0.894	0.732	0.151	0.337	− 0.475

Table 17 Monthly modified Mann–Kendall (M-MK) test *z*-statistics for the Edirne station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	0.111	0.127	0.308	− 0.094	0.857	0.050	0.306	0.017
Feb	− 0.317	**− 2.070**	0.349	1.124	1.252	0.006	0.459	0.702
Mar	0.540	1.013	0.027	1.293	0.993	1.637	1.398	0.772
Apr	− 1.614	− 0.265	− 1.040	− 1.059	0.011	− 0.566	− 1.882	− 0.702
May	− 0.628	− 0.766	− 0.197	1.051	0.674	0.164	− 0.781	− 0.777
Jun	− 1.223	− 0.229	− 1.440	− 0.784	− 1.180	− 1.478	− 1.251	− 0.311
Jul	1.353	0.219	1.319	1.232	1.147	1.557	1.665	1.523
Aug	0.091	− 0.922	0.037	− 0.402	0.338	0.102	0.408	0.481
Sep	0.561	− 0.048	1.265	**2.066**	1.594	0.600	0.283	0.221
Oct	0.770	0.969	1.226	1.631	− 0.076	1.172	0.674	0.679
Nov	− 0.470	− 1.443	0.480	− 0.575	− 1.303	0.062	− 0.243	0.108
Dec	− 0.396	0.567	− 0.438	1.133	1.656	0.453	0.906	0.878

show no significant decreasing trend for any of the indices while significantly increasing trends are observed for PRCPTOT in October, CWD in November, R30mm in February and Rx5day and Rx10day in October.

While both increasing and decreasing trends are detected at monthly scale, some months are dominated with solely negative or positive trends. For the Edirne station, the indices in April, May, June and November show mostly decreasing trends

Table 18 Monthly modified Mann–Kendall (M-MK) test *z*-statistics for the Kirklareli station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	**2.289**	1.804	1.876	1.027	1.289	1.757	**2.411**	**2.167**
Feb	0.885	0.214	1.242	1.385	**2.036**	1.008	1.308	1.934
Mar	0.204	0.395	0.313	− 1.326	− 0.503	0.191	− 0.054	0.041
Apr	− 0.136	− 0.147	0.245	0.906	0.483	0.777	0.163	− 0.014
May	0.654	1.105	1.144	0.201	− 0.438	0.409	0.504	0.627
Jun	0.627	0.000	1.414	− 0.225	− 0.070	0.817	1.076	1.199
Jul	0.423	− 0.860	0.668	1.541	1.202	0.545	0.558	0.736
Aug	0.451	0.906	0.465	0.686	1.001	1.091	1.090	0.763
Sep	**2.942**	0.737	**3.344**	1.862	1.873	**3.570**	**2.166**	**2.798**
Oct	**2.193**	1.222	**2.167**	1.654	0.704	1.076	**2.193**	**5.506**
Nov	− 1.536	− 1.070	− 1.301	− 1.113	− 0.840	**− 2.862**	− 0.804	− 0.599
Dec	− 0.313	0.000	− 0.223	1.408	− 0.319	− 0.232	0.286	− 0.082

Table 19 Monthly modified Mann–Kendall (M-MK) test *z*-statistics for the Tekirdag station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	− 0.894	− 0.324	− 1.193	− 1.532	0.714	− 0.300	− 1.264	− 0.803
Feb	1.263	0.012	1.615	1.047	1.504	1.263	1.185	1.008
Mar	− 0.213	0.572	− 1.001	− 0.283	− 0.703	− 0.079	− 0.620	− 0.024
Apr	− 0.553	0.005	− 1.277	0.328	1.536	0.085	− 0.237	0.808
May	0.146	0.144	− 0.823	0.032	0.874	0.249	− 0.298	− 0.298
Jun	− 0.371	− 0.312	− 0.788	0.561	0.000	− 0.316	− 0.565	− 0.419
Jul	− 0.961	− 1.880	− 0.316	0.176	0.044	− 0.468	− 0.524	− 0.377
Aug	0.267	0.607	0.196	1.140	0.620	0.049	− 0.116	− 0.852
Sep	0.986	0.854	1.607	1.482	1.435	0.869	1.762	1.555
Oct	1.206	0.857	1.295	1.156	1.286	1.064	1.433	1.500
Nov	− 1.549	0.225	− 1.496	**− 2.081**	**− 2.132**	**− 2.351**	− 0.620	− 0.292
Dec	− 0.765	− 0.839	− 0.745	− 0.340	− 0.420	− 0.458	0.251	− 0.152

Table 20 Monthly modified Mann–Kendall (M-MK) test *z*-statistics for the Sariyer station

Month	prcptot	cwd	r10mm	r20mm	r30mm	rx1day	rx5day	rx10day
Jan	− 0.531	− 0.070	− 0.771	− 0.827	0.272	− 0.391	− 0.540	− 0.759
Feb	1.308	1.158	0.372	1.573	**2.226**	1.866	0.805	0.867
Mar	0.620	1.210	0.322	0.395	− 0.634	0.248	0.113	0.000
Apr	− 0.482	− 1.855	0.357	− 0.431	− 0.916	0.241	− 0.709	− 0.213
May	0.145	− 1.177	0.889	0.927	0.434	1.129	0.675	0.647
Jun	1.817	0.567	1.899	1.730	1.445	1.287	1.941	1.101
Jul	− 0.165	− 0.893	− 0.168	− 0.320	0.594	− 0.145	0.200	0.138
Aug	0.911	0.917	0.953	− 0.109	0.808	1.005	1.342	1.067
Sep	1.281	0.893	0.702	0.060	**2.551**	0.227	0.647	1.611
Oct	**1.996**	1.625	1.555	1.695	1.292	1.797	**2.120**	**2.237**
Nov	1.039	**3.268**	− 0.420	0.370	0.760	1.053	0.668	1.335
Dec	− 1.143	1.260	− 1.061	− 0.894	0.732	0.213	0.337	− 0.475

and increasing trends are observed for rest of the months. It is worth to say that these trends are nonsignificant except CWD index in February which has a significant decreasing trend. Considering the Kirklareli station, mostly negative trends are observed in November and December. Negative trends of the monthly indices are not significant; however, positive trends with significantly high values exist especially in January, September and October. For the Tekirdag station, decreasing trends are dominated in January, March, June, July, November and December and positive trends are observed in February, September and October. The only month with indices having significant trends, namely R20mm, R30mm and Rx1day, is November for the Tekirdag station. For the Sariyer station, negative trends are generally dominant for the indices in January, April, July and December while increasing trend tendencies are observed in rest of the months for most of the indices.

When the results of the monthly M-MK and MK tests are compared, it is observed that the z-statistics of the M-MK tests show variations in terms of significance for some months and indices. Considering the M-MK test results, the R20mm index of the Edirne station has a significant increasing trend in September, while the MK test results reveal an insignificant trend for this index. The Rx10day and Rx1day indices of the Kirklareli station approach significance in the months of September and November, respectively, according to the M-MK test results. Moreover, the magnitude of the Rx10day index of this station increases considerably in October. Although there are some differences between the MK and M-MK test results of the Tekirdag station as for the PRCPTOT, R10mm and Rx1day indices of January and the Rx1day and Rx5day indices of the months of October and December, these differences do not change the significance or direction of trends. The monthly M-MK test results exhibit differences from the ones of the MK tests for the Sariyer station, too, but the only significant difference is detected in the R30mm index of September.

The relationships between four stations in terms of monthly PRCPTOT, CWD, R10mm, R20mm, R30mm, Rx1day, Rx5day and Rx10day indices are analyzed as presented in Table 21. To be able to obtain consistent comparisons, the period from 1981 to 2016 is considered for all stations. The results show that the indices of the Edirne and Kirklareli stations are better correlated than the indices of other stations on monthly basis. January, February, September and October are the months that the indices of the Edirne and Kirklareli stations exhibit fair correlations. The PRCPTOT indices of these stations are also showed better correlations in most of the months except July and August. The indices of the Kirklareli and Tekirdag stations, except CWD and R20mm, show better correlations in September than in other months. Regarding the Tekirdag and Edirne stations, it can be said that September, October and December are the months that the PRCPTOT, CWD and R10mm indices show closer relationships. The Sariyer station has a better relationship with the Tekirdag station that may be due to the effect of their similar locations by the sea.

Conclusions

This study assesses the 14 sector-specific ET-SCI precipitation indices in terms of statistical characteristics, trends using the nonparametric MK and M-MK tests and correlations between each other in both annual and monthly temporal scales for the four meteorological stations located in the Thrace region of Turkey, namely Edirne, Tekirdag, Kirklareli and Sariyer. Within this scope, the basic statistical characteristics of the extreme rainfall indices are determined at first and the calculated values indicate significant differences between most of the extreme indices. The trend tendencies of extreme rainfall indices are detected using the nonparametric MK and M-MK tests on annual and monthly bases. The indices mostly do not have significant trends in most of all the stations, and the insignificant trends are mostly positive.

At the annual scale, total precipitation shows increasing trend for the Kirklareli and Sariyer stations and decreasing trend for the Edirne and Tekirdag stations. However, all of the precipitation intensity indices (SDII) show increasing trends that are significant for the Edirne and Kirklareli stations. Decreasing total precipitation and increasing daily intensity trends might be a signal of decrease in the wet days for the Edirne station. This situation is also supported by the increase in the consecutive dry days and, hence, could be considered as a warning both for increasing intense precipitation and drought conditions. The Kirklareli station tends to have more days with heavy, very heavy and extremely heavy rainfall events. It is also anticipated that maximum amount of rainfalls in daily and consecutive five- and ten-day time scales will probably increase at all stations. Moreover, rainfall from very wet days and extremely wet days and fraction of total wet day rainfall that comes from very wet days and extremely wet days indices also show increasing trend tendencies for all stations, especially Sariyer. Above all, the remarkable point that has to be emphasized is the decreasing total precipitation trend at the Edirne and Tekirdag stations indicating that the annual total precipitation does not necessarily depend on extreme precipitation for the analyzed period. When the relationships between annual rainfall indices are analyzed for each station separately, it is observed that the maximum 1-, 5- and 10-day precipitation indices seem to be correlated with the percentile indices. The correlation analyses also reveal that the threshold indices have better relationships with SDII and PRCPTOT indices that are more evident at the Kirklareli and Sariyer stations which have the same trend direction for the total precipitation and threshold indices. In addition, while CDD and CWD indices have the worst correlations with other indices for all stations, fairly good correlations are observed between R30mm, R95p and R95pTot indices and between Rx1day, R99p and R99pTot indices. Moreover, mixed positive and negative trends are seen only for the total precipitation and consecutive dry days indices while the rest of the indices show positive trends whether significant or not.

At the monthly scale, PRCPTOT index shows a significant increasing trend for the Kirklareli station in the months

Table 21 Monthly correlations of indices for the Edirne (E)-Kirklareli (K), Edirne (E)-Tekirdag (T), Kirklareli (K)-Tekirdag (T), Edirne (E)-Sariyer (S), Kirklareli (K)-Sariyer (S) and Tekirdag (T)-Sariyer (S) stations

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
prcptot												
E-K	0.91	0.89	0.81	0.70	0.71	0.76	0.66	0.46	0.80	0.81	0.74	0.80
E-T	0.69	0.67	0.67	0.55	0.54	0.52	0.46	0.21	0.76	0.69	0.63	0.77
K-T	0.66	0.67	0.76	0.67	0.53	0.54	0.34	0.36	0.83	0.74	0.59	0.76
E-S	0.58	0.53	0.37	0.42	0.58	0.32	0.30	0.32	0.59	0.21	0.15	0.48
K-S	0.47	0.57	0.55	0.47	0.47	0.27	0.21	0.60	0.67	0.24	0.26	0.54
T-S	0.69	0.58	0.58	0.85	0.66	0.38	0.45	0.38	0.47	0.55	0.59	0.81
cwd												
E-K	0.74	0.56	0.54	0.63	0.66	0.59	0.49	0.61	0.80	0.68	0.70	0.65
E-T	0.56	0.40	0.51	0.35	0.45	0.53	0.30	0.51	0.68	0.79	0.41	0.71
K-T	0.66	0.28	0.58	0.59	0.37	0.56	0.59	0.61	0.62	0.69	0.66	0.54
E-S	0.35	0.52	0.25	0.34	0.41	0.27	0.37	0.53	0.34	0.26	- 0.02	0.16
K-S	0.41	0.27	0.23	0.31	0.38	0.30	0.17	0.50	0.42	0.14	- 0.05	0.04
T-S	0.34	0.45	0.14	0.36	0.51	0.44	0.18	0.50	0.54	0.36	- 0.00	0.45
r10mm												
E-K	0.78	0.77	0.56	0.63	0.63	0.72	0.48	0.38	0.84	0.73	0.53	0.48
E-T	0.67	0.68	0.53	0.25	0.40	0.33	0.24	0.33	0.80	0.70	0.59	0.75
K-T	0.52	0.55	0.54	0.19	0.43	0.42	0.07	0.04	0.79	0.55	0.54	0.47
E-S	0.44	0.58	0.19	0.17	0.37	0.40	0.35	0.07	0.64	0.34	0.10	0.54
K-S	0.34	0.53	0.29	0.10	0.25	0.56	0.19	0.41	0.59	0.25	0.20	0.40
T-S	0.76	0.52	0.44	0.57	0.56	0.33	0.31	0.30	0.63	0.49	0.60	0.66
r20mm												
E-K	0.47	0.70	0.42	0.64	0.46	0.21	0.39	0.01	0.47	0.63	0.32	0.43
E-T	0.31	0.12	0.12	0.02	0.11	- 0.11	0.23	- 0.11	0.48	0.44	0.38	0.30
K-T	0.25	0.04	0.45	0.21	0.05	0.30	0.30	- 0.04	0.64	0.57	0.29	0.50
E-S	0.36	0.21	- 0.10	0.16	0.06	- 0.01	0.19	0.09	0.51	- 0.01	0.02	0.22
K-S	0.09	0.19	0.16	0.25	0.07	- 0.06	0.11	0.10	0.43	- 0.01	- 0.01	0.19
T-S	0.50	0.25	0.05	0.36	0.13	0.49	0.31	0.17	0.24	0.37	0.64	0.57
r30mm												
E-K	0.56	0.37	0.25	- 0.06	0.12	0.47	0.25	- 0.11	0.47	0.42	0.38	0.48
E-T	0.15	0.03	0.24	0.13	- 0.13	0.08	0.32	- 0.13	0.51	0.48	0.17	0.22
K-T	0.06	0.12	0.52	0.16	- 0.16	- 0.12	0.11	- 0.07	0.82	0.37	0.24	0.57
E-S	0.24	0.25	0.32	0.24	- 0.08	- 0.13	0.11	0.25	0.35	- 0.10	- 0.05	0.19
K-S	0.04	0.27	0.38	- 0.06	- 0.09	- 0.13	- 0.15	0.34	0.31	- 0.06	0.12	0.34
T-S	0.07	0.29	0.21	0.30	- 0.05	- 0.04	0.45	- 0.15	0.17	0.33	0.23	0.49
rx1day												
E-K	0.87	0.74	0.58	0.51	0.27	0.59	0.66	0.22	0.71	0.78	0.43	0.53
E-T	0.31	0.19	0.39	0.21	0.17	0.17	0.54	0.03	0.76	0.36	0.42	0.38
K-T	0.36	0.29	0.48	0.44	0.06	0.06	0.19	0.05	0.80	0.43	0.20	0.55
E-S	0.34	0.36	0.22	0.05	0.11	0.16	0.08	0.16	0.49	- 0.13	- 0.07	0.18
K-S	0.29	0.48	0.42	0.12	0.07	0.02	0.05	0.15	0.53	- 0.04	0.02	0.37
T-S	0.45	0.51	0.25	0.48	0.22	0.17	0.27	0.20	0.38	0.38	0.39	0.44
rx5day												
E-K	0.87	0.69	0.76	0.63	0.54	0.78	0.54	0.17	0.73	0.85	0.50	0.58
E-T	0.44	0.46	0.50	0.31	0.26	0.26	0.46	0.05	0.66	0.59	0.31	0.45
K-T	0.47	0.40	0.58	0.55	0.19	0.42	0.15	0.02	0.81	0.61	0.43	0.63
E-S	0.33	0.36	0.21	0.22	0.20	0.20	0.17	0.38	0.58	0.04	- 0.14	0.20
K-S	0.38	0.50	0.52	0.20	0.15	0.14	0.05	0.27	0.65	0.09	- 0.01	0.37
T-S	0.38	0.50	0.26	0.57	0.39	0.30	0.35	0.11	0.43	0.35	0.41	0.60
rx10day												
E-K	0.82	0.81	0.80	0.69	0.61	0.77	0.48	0.26	0.75	0.85	0.58	0.64
E-T	0.58	0.49	0.54	0.40	0.29	0.17	0.38	0.21	0.63	0.66	0.42	0.48
K-T	0.52	0.52	0.53	0.52	0.23	0.34	0.26	0.19	0.77	0.68	0.60	0.59
E-S	0.45	0.46	0.24	0.28	0.39	0.13	0.15	0.49	0.53	0.12	- 0.04	0.30
K-S	0.42	0.56	0.46	0.27	0.29	0.13	- 0.00	0.54	0.63	0.12	0.09	0.42
T-S	0.47	0.54	0.27	0.71	0.40	0.36	0.33	0.16	0.38	0.36	0.45	0.66

of January, September and October and for the Sariyer station in October. The CWD index of the Edirne station significantly decreases in February, while a significant increase is observed for this index of the Sariyer station in November. The threshold indices of the Kirklareli station have significant increasing trends as in September for R10mm and R20 mm and in February for R30mm. In addition, while the R30mm index of the Sariyer station shows an increasing trend in February and September, the R20mm and R30mm indices of the Tekirdag station indicate significant negative trends in November. The Rx1day, Rx5day and Rx10day indices of the Kirklareli station increase significantly in September and October and the Rx5day and Rx10day indices of the Sariyer stations have significant increasing trends in October. Moreover, according to the correlation analyses performed among the four stations at the monthly time scale, there are considerable correlations between the indices of the Edirne and Kirklareli stations, especially for total precipitation.

Annual and monthly extreme precipitation trends are important indicators of what might happen in the near future for the sectors such as agriculture, infrastructure and water supply. Potential changes in precipitation characteristics have direct impact over water availability and surface runoff and, hence, over the above-mentioned sectors. Regarding the agriculture sector, crop type, irrigation pattern and even insurance rates are determined according to the characteristics of extreme events. The Thrace region is one of the agricultural basins in Turkey so impacts over product variety and growing season directly affect the regional and national economy. This study depicts a quantitative base with the detection of annual and monthly trends of extreme precipitation indices and demonstrates the basic relationship patterns of these indices for the Thrace region. The results of this study notice not only the extreme precipitation but also the significant differences for the extreme precipitation indices within the region.

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