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RESEARCH ARTICLE - HYDROLOGY

Quantile trends of subhourly extreme rainfall: Marmara Region, Turkey

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Abstract
Global climate change will probably cause intensification of the hydrologic cycle, which can lead to alterations in extreme precipitation properties. In this study, we investigated the trend of 5-, 10-, 15-, and 30-min annual maximum rainfall series at 12 stations in the Marmara Region, Turkey, using quantile regression. The data ranges were from 46 to 71 years long. Five quantiles were used to examine the extreme rainfall series, and their quantile regression parameters were calculated. The results show that quantile regression is a powerful tool to compute trends with a more inferential context, which was validated with the notable differences between the trends at chosen quantiles and the classical ordinary least squares method. Concerning the problem of the analysis of climate trends, the quantile regression method seems to provide a perspective from a more detailed understanding of processes in the climate system in terms of characteristics of climate variability and extremity.

Keywords Marmara · Quantile regression · Trend · Extreme rainfall

Introduction

The frequency and intensity variations of extreme rainfall can cause significant problems for human society, including social, economic, and physical (Donat et al. 2016; Srivastava et al. 2020; Hosseinzadehtalaei et al. 2020; Gandini et al. 2020; Tabari et al. 2020). Therefore, it is crucial to consistently quantify these variations and gain a complete picture of changes such as intensification and frequency in extreme events. Myhre et al. (2019) showed that surface warming, on average 2K globally, would double and even triple the number of extreme precipitation events. Furthermore, climate change is expected to alter not only the mean variability but also the distribution of rainfall (Mohsenipour et al. 2020). On the other hand, the potential change in precipitation is not an easy process to predict. These changes can be analyzed in terms of inter-annual, seasonal changes, or variations in the mean and extreme properties. Changes in extreme rainfall events result in floods and droughts, which have become the primary components of catastrophic events all around the Globe (Uranchimeg et al. 2020). Climate change will likely have significant regional impacts; certain regions will experience more severe and intense events and become more vulnerable.

Climate variables are parameters that have direct or indirect effects in many areas. For this reason, the characteristics of these variables, how they behaved in the past, and how they will behave in the future have been a matter of curiosity and constitute the basis for many studies. Regionally and temporally differences of these variables led to the diversification of the studies on both spatial and temporal scales. While some of the studies dealt with the average behavior of these variables, some of them deal with the extreme values. Among these variables, rainfall and temperature were the most common because of both the widespread application and the impact area and the availability of long-term records. The temperature and precipitation over different time scales (annual, monthly, and daily) and periods in various parts of Turkey have been analyzed in many studies. Şenocak and Emek (2019) conducted a trend analysis of total monthly and annual rainfalls in the East Anatolia Region. Taylan and Aydın (2018) examined the monthly precipitation data of the Lakes Region located in the Middle Mediterranean

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Region in Turkey. Vaheddoost (2020) studied the monthly precipitation at the Bursa district in Turkey for the January 2005 to October 2018 period. Yurtseven and Serengil (2017) examined daily, monthly, seasonal, and annual precipitation for the selected stations at İstanbul. Türkeş et al. (2009) examined the monthly, seasonal, and annual precipitation considering the long-term changes and trends of 97 stations in Turkey.

Furthermore, the extreme conditions of temperature and precipitation have also been analyzed to further explore their potential impacts and identify the tendency of extremes based on the observed and future periods. Tosunoğlu (2017) evaluated the trends of daily maximum rainfall series in three different time scales of five stations located Çoruh Basin, Turkey. Demircan et al. (2017) investigated the future climate change for Turkey and its surrounding region with HadGEM2-ES, MPI-ESM-MR, and GFDL-ESM2M Global Circulation Models' RCP4.5 and RCP8.5 scenarios outputs. Abbasnia and Toros (2018) analyzed extreme temperature and precipitation indices at seven stations in the Marmara Region of Turkey for the period 1961–2016. Oruc (2021) analyzed the annual maximum rainfall data of 5-, 10-, 15-, and 30-min and 1-, 3-, 6-, and 24-h annual maximum rainfall series at 13 central stations in Central Anatolia, Turkey.

In the above-mentioned studies, the nonparametric Mann–Kendall trend test or linear regression methods were mostly applied to detect trends. However, these methods are not sufficient for the detection of variations of extremes or distributional changes and are sensitive to outliers (Shiau and Huang 2015). To address this problem, trend detection using quantile regression (QR) has emerged and has been used in studies for trend detection and exploring the characteristic patterns of extreme precipitation (Tharu and Dhakal 2020; Mohsenipour et al. 2020; Uranchimeg et al. 2020; Treppiedi et al. 2021). The QR method (Koenker and Basset 1978) enables detailed exploration of the structure of the climatic variable, unlike the ordinary least squares (OLS), which is based on the classical regression methods. Besides the trend in the mean, by using QR it is possible to detect the trends in the lower, median, and upper quantiles, which also allows a more complete picture of the properties of the variable of interest to be obtained (Li-jun 2014; Sterin and Lavrov 2020).

QR has been successfully applied in many recent studies. Wasko and Sharma (2014) applied the QR method to identify the scaling of extreme precipitation with temperature and revealed the efficacy of the method. Malik et al. (2016) explored the Indian summer–monsoon–extreme rainfall trends by QR and successfully represent the complex characteristics of the system. Amini et al. (2020) used a Bayesian QR model to study the teleconnections between drought and large oceanic–atmospheric indices in Iran. Pumo and Noto (2021) used quantile regression to identify the relationship between dew point temperature and extreme precipitation, whereas Zhang et al. (2020) analyzed the Arctic Sea ice using quantile regression-based approach to explore the impact of climate patterns. Sterin and Lavrov (2020) also investigated the temperature radiosonde observation trends with QR for several regions of the Northern Hemisphere. Most of the studies indicated that using QR enables the better understanding of the heterogeneous systems.

The Marmara Region, which represents the highest climate variability among the geographical regions of Turkey (Abbasnia and Toros 2018), has the highest economic activity and population density, making the region important and vulnerable to extreme events. These extreme events can cause excessive damage both in terms of loss of life, and loss of property, and bring along negative economic, social or environmental impacts over the region and the country. Extreme temperature and precipitation trends are also essential variables for decision making and design of public infrastructure, economic planning, and human health. For these reasons, in this paper we introduce the QR method to investigate trends in the Marmara Region of Turkey for the annual maximum rainfall data of subhourly storm duration (5–10–15–30 min) from 12 meteorological stations across the region with data of various length of at least 46 years. The calculated quantiles of the trends were also compared with the traditional ordinary least square (OLS) method. Furthermore, the MK trend test and the ITA method were also applied to detect average and categorical (trends in low, medium, or high data values in the time series) trends to compare and figure out any superiority of the QR method in practical applications.

Material and methods

Study area and data

The Marmara Region of Turkey is the center of industry and has the highest population among the seven geographical regions and the most densely populated region in Turkey (Toros and Abbasnia 2017). The region has a flat topography with a climate affected by the Mediterranean, Aegean, Black Sea, and inland continental climate. Summers are warm or hot, whereas winters are cold and wet. Although humidity can occur, dry summer seasons are also becoming one of the climatic conditions in the Marmara region (Abbasnia and Toros 2018).

According to Turkish State Meteorological Service statistics, the amount of annual precipitation in 2019 and 2020 was 565.5 and 546.7 mm, respectively, whereas the normal is 662.3 mm for the period of 1981–2010. Therefore, there has been a 17.5% decrease in precipitation compared with the normal and a 3.3% decrease compared with 2019 precipitation.

Based on the temperature analysis of the TSMS, the annual mean temperature in Marmara region is arround 14 °C; the long term mean temperature in the coldest month, January, is 5.1 °C; and the long term mean temperature in the hottest month, August, is 23.9 °C. The annual average relative humidity is approximately 75% and mild temperature values in the region are a result of coastal climate effects (TSMS 2021a,b; Baltaci 2019).

In this study, annual maximum rainfall data of subhourly storm duration (5–10–15–30 min) from 12 meteorological stations across the Marmara region were used (see Fig. 1) for the various study periods (Table 1). The subhourly annual maximum rainfall series of the stations that were collected through continuous approach were obtained from the Turkish State Meteorological Service (TSMS). These data were collected by both analog and automatic stations of the TSMS observation network.

Table 1 List of selected stations

Station	Lon	Lat	Elevation (m)	Data range
Balikesir	39.6326	27.9201	102	1957–2015
Bursa	40.2308	29.0133	100	1951–2015
Canakkale	40.1410	26.3993	6	1958–2015
Edirne	41.6767	26.5508	51	1949–2015
Florya (İstanbul)	40.9758	28.7865	37	1964–2015
Gokceada (Canakkale)	40.1910	25.9075	79	1970–2015
Kirklareli	41.7382	27.2178	232	1966–2015
Kocaeli	40.7663	29.9173	74	1945–2015
Sakarya	40.7676	30.3934	30	1962–2015
Sariyer (İstanbul)	41.1464	29.0502	59	1955–2015
Tekirdag	40.9585	27.4965	4	1963–2015
Yalova	40.6589	29.2796	4	1962–2015

Methods

Quantile regression

Quantile regression can be described as an extension of the traditional linear Eq. (1) and was introduced by Koenker and Bassett (1978):

$$y = a + bx + \varepsilon, \tag{1}$$

in which y and x are dependent and independent variables, respectively, and ε is the error term, whereas a and b are defined as the intercept and linear slope, respectively. Traditional linear regression framework assesses the regression parameters a and b using the method of ordinary least squares by minimizing the sum of squared errors (Eq. 2):

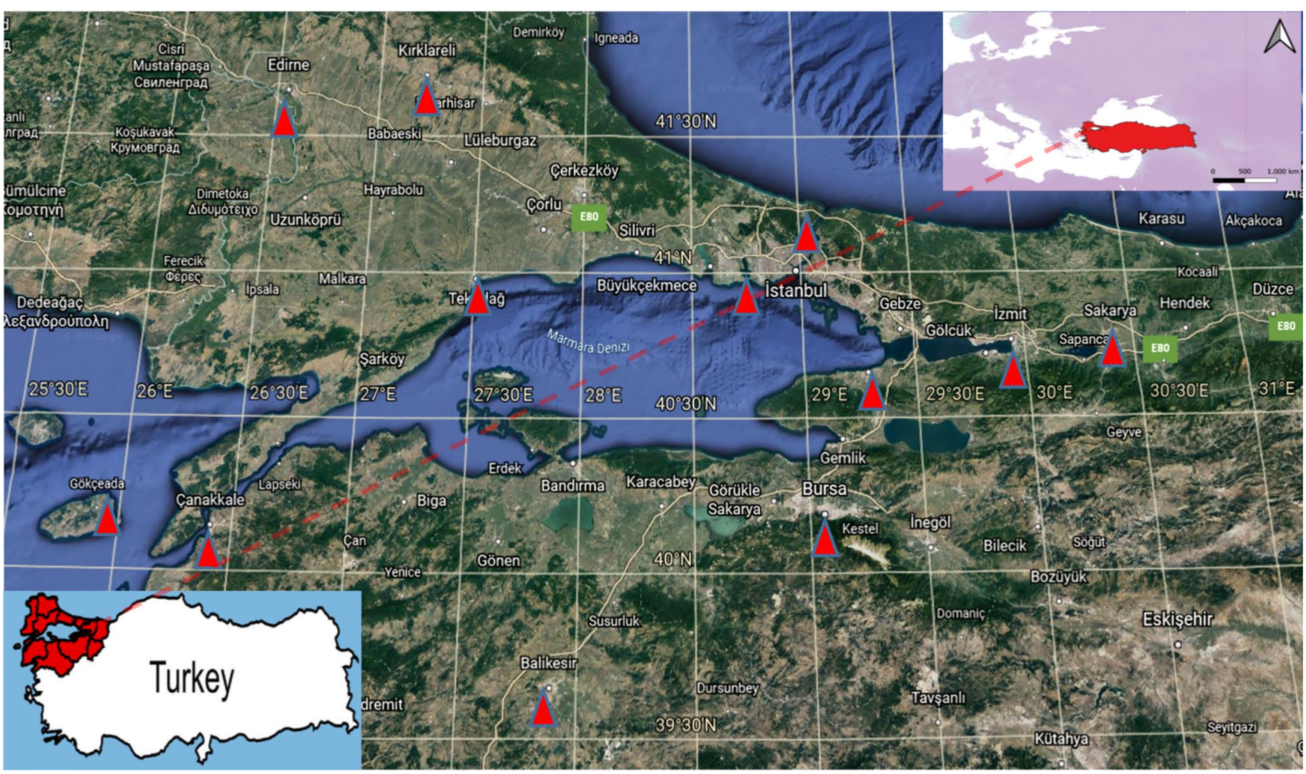


Fig. 1 Map of the selected stations in the study area

$$\min \sum_{i=0}^{n} \left(y_i - a - bx_i\right)^2. \tag{2}$$

The QR approach replaces the conditional mean function by a conditional quantile function. By doing this, the mean of the response variable is replaced by the quantile of the response variable (Eq. 3):

$$y = a_\tau + b_\tau x, \tag{3}$$

in which a_τ denotes the intercept for each quantile τ and b_τ denotes the slope of the quantile. The two coefficients can be derived by solving the problem of minimizing the sum of asymmetrically weighted absolute residuals for each desired quantile that ranges from 0 to 1, instead of squared residuals as in the classical least-squares method (Eq. 4):

$$\min \sum_{i=0}^{n} \rho_\tau\left(y_i - \left(a_\tau + b_\tau x_i\right)\right), \tag{4}$$

in which ρ_τ is the tilted absolute value function, which gives different weights to positive and negative residuals where tau is the quantile of interest that is 10th, 25th, 50th, 75th, and 90th quantiles in this study.

$$\begin{aligned} \rho_\tau &= \tau, && y_i \geq (a_\tau + b_\tau x_i) \\ \rho_\tau &= 1 - \tau, && y_i < (a_\tau + b_\tau x_i) \end{aligned} \tag{5}$$

A comprehensive explanation of the QR method can be found in (Koenker and Hallock 2001; Koenker 2005; Barbosa 2008; Li-jun 2014; Gao et al. 2020). In this study, y denotes the annual rainfall extremes for subhourly storm durations and x is the year of record. Computations are performed using quantreg software (Koenker 2021).

Trend tests

The Mann–Kendall (MK) trend test is a widely used nonparametric test to determine the trend for a desired period and one of the most preferred tests for the hydrometeorological variables (Mann 1945; Kendall 1975). In this study, the rank-based Mann–Kendall trend test is also applied to temperature indices for the analyses period in order to capture the potential trends.

Furthermore, Innovative Trend Analyses (ITA) method (Şen 2012) is used to visual inspection of trend and justify the MK test results. Details of this method can be found in (Şen 2012; Dabanli et al. 2016; Serencam 2019; Şisman and Kizilöz 2021). In this method, two halves of time series are used in ascending order and drawn on the horizontal (X) and the vertical (Y) axis and the positions of the two halves relative to 1:1 line of the diagram are used to explore the trend characteristics of the whole time series.

Results and discussion

QR estimates in the 10th, 25th, 50th, 75th, and 90th quantiles and the OLS for the 5–10–15–30-min time series at the Balikesir, Bursa, Canakkale, Edirne, Florya, Gokceada, Kirklareli, Kocaeli, Sakarya, Sariyer, Tekirdag, and Yalova stations are displayed in Figs. 2, 3, 4. The behavior of the 50th quantile can be depicted as the central tendency, whereas the 10th, 25th, 75th, and 90th quantiles indicate the higher and lower categories of the data, namely extremes of the data. Although similar trend tendencies were identified in the OLS and 10th, 25th, 50th, 75th, and 90th quantiles, significantly different slopes were detected for most of the time series (Figs. 2, 3, 4).

The behavior of the subhourly annual maximum observed time series at the Balikesir station is shown in Fig. 2a. Considering the 5-min annual maximum rainfall, all-quantiles showed decreasing trends. However, the slope of the quantiles differed from each other and from the OLS slope. Higher magnitude slopes were detected at quantiles 90th and 10th, whereas the slopes of the 50th and 75th quantile were smaller than the OLS. The 25th quantile exhibit a similar slope to the OLS. The 10-min rainfall series at the Balikesir station exhibited positive slopes for the 50th and 75th quantiles, whereas OLS showed a negative slope. The significant behavior is clearly shown by the 90th (− 0.08 mm/year) quantile, which had a significantly higher magnitude than the other quantiles. A positive slope was also observed for the 75th quantile of the 15-min rainfall data, which indicated an upward trend, whereas the OLS showed a negative slope. In comparison with the other quantiles and the OLS results, the 10th and 90th quantiles exhibited higher magnitudes of negative slope. The 25th and 75th quantiles and OLS of the 30-min time series indicated a positive trend. However, the 75th quantile showed a significantly higher positive slope (0.12 mm/year) among those with a positive slope. The other quantiles showed negative trends, which had higher values for the 10th and 5th quantiles. As inferred from the figure, the trends of the four annual maximum time series in the median slopes were not very close to the OLS results. Moreover, the upper and lower quantile trends demonstrated significantly different magnitudes from those of the mean calculated by OLS. Thus, the slope of the OLS may not be sufficient to describe the relation between subhourly annual maximum rainfall and time. The variations in the time series indicate the distribution change of the time series over time. The higher quantiles tend to decrease stronger than the mean and the median values.

The subhourly annual maximum observed time series at the Bursa station with quantile regression and OLS is

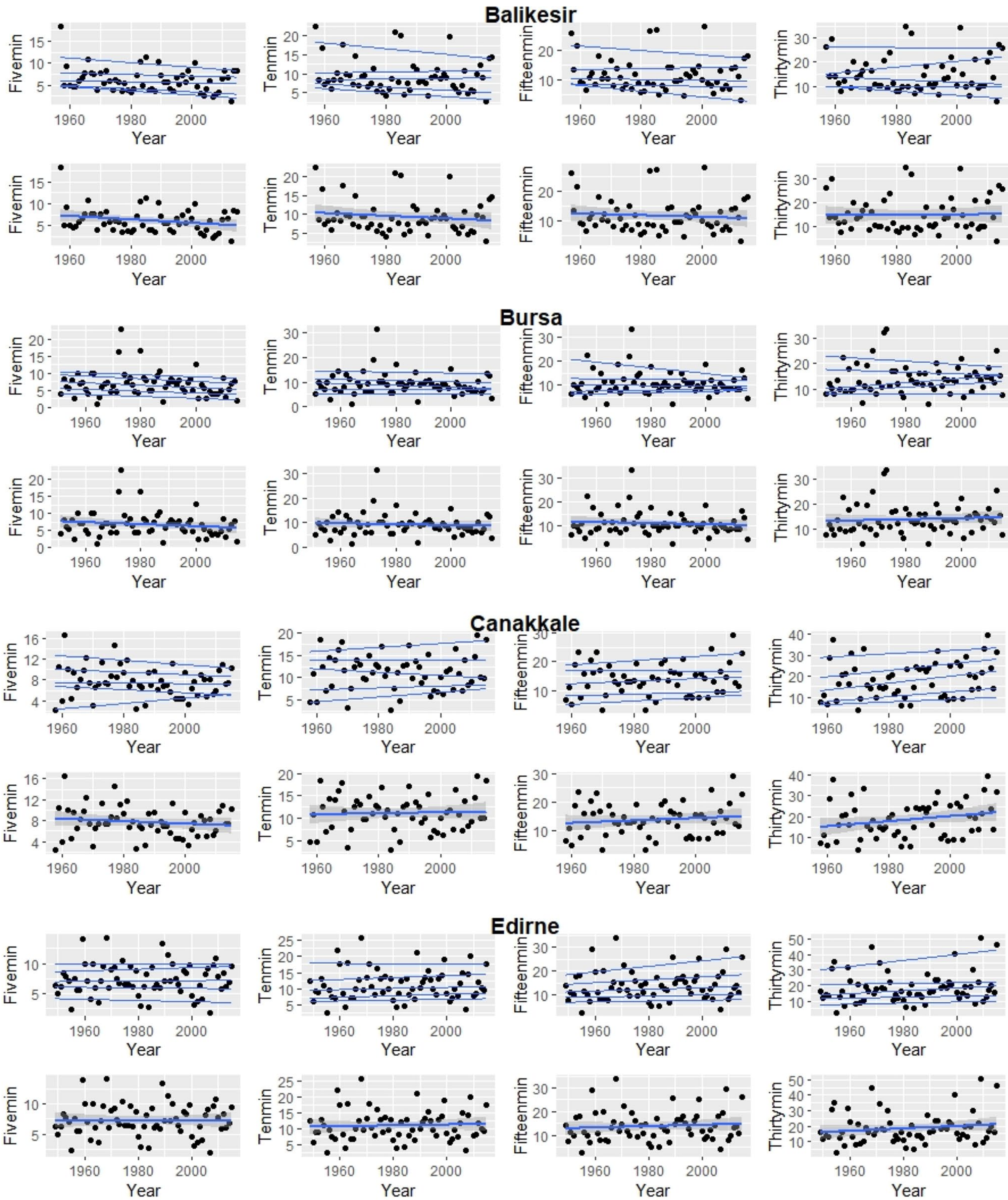


Fig. 2 10th, 25th, 50th, 75th, and 90th quantiles (upper bound) and the mean estimate by OLS (lower bound) for **a** Balikesir, **b** Bursa, **c** Canakkale, and **d** Edirne Stations

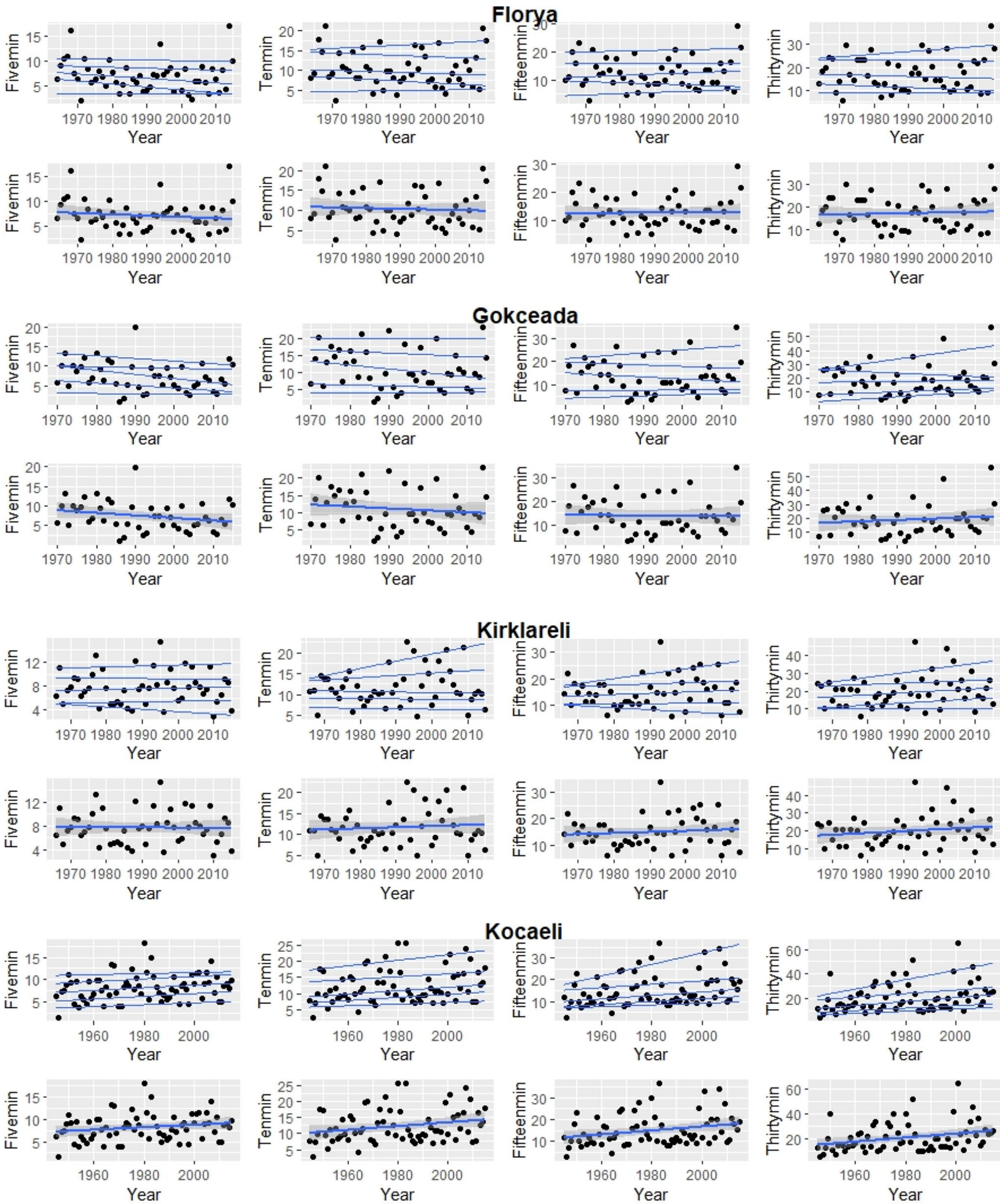


Fig. 3 10th, 25th, 50th, 75th, and 90th quantiles (upper bound) and the mean estimate by OLS (lower bound) for **a** Florya, **b** Gokceada, **c** Kirklareli and **d** Kocaeli Stations

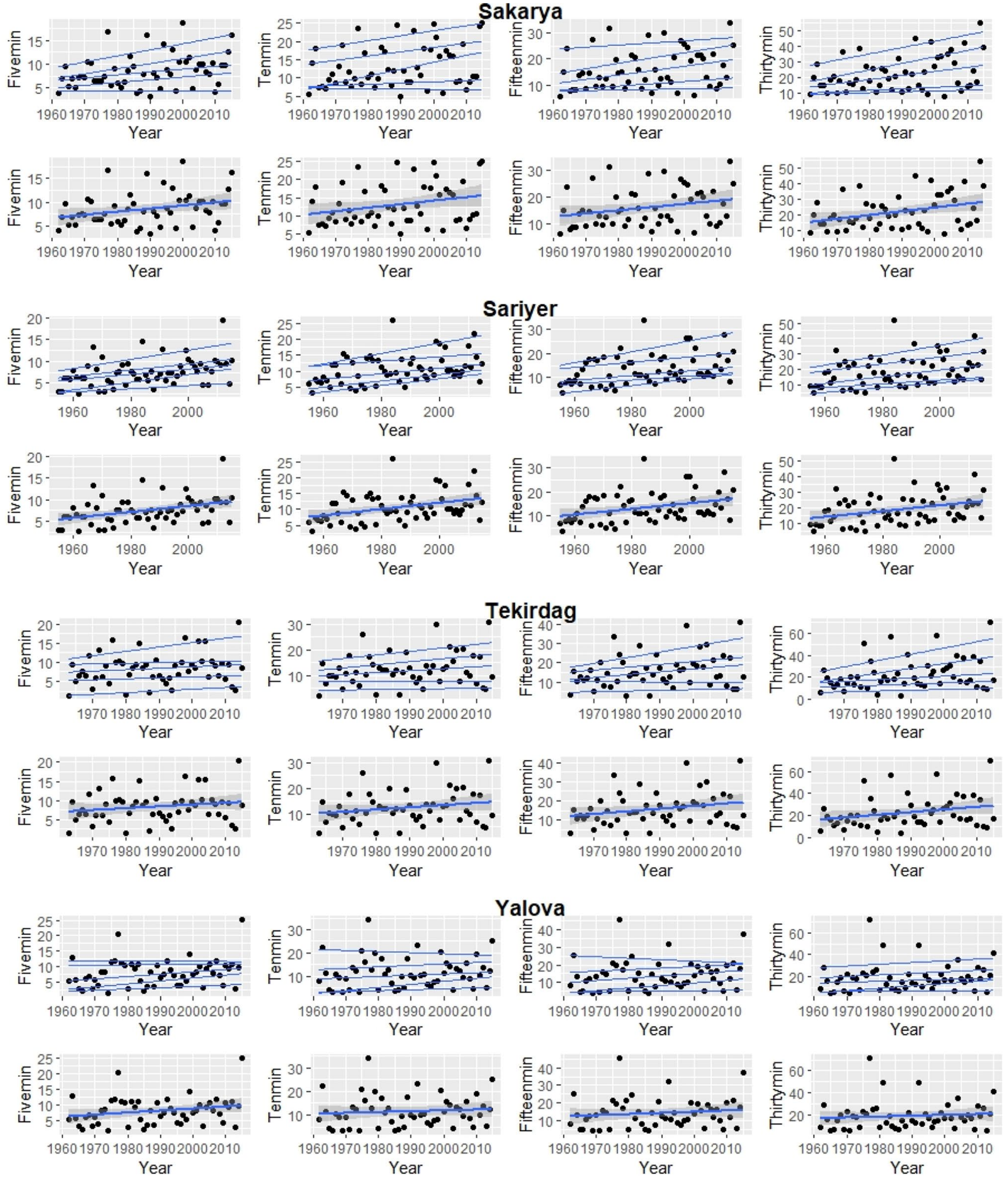


Fig. 4 10th, 25th, 50th, 75th, and 90th quantiles (upper bound) and the mean estimate by OLS (lower bound) for **a** Sakarya, **b** Sariyer, **c** Tekirdag, and **d** Yalova Stations

shown in Fig. 2b. The 5-min and 10-min annual maximum rainfall series exhibited similar behavior as their corresponding OLS results. On the other hand, the 90th quantile of the 15-min series (− 0.12 mm/year) and 25th, 50th, 75th, and 90th quantiles (0.06, 0.08, − 0.04, and − 0.07 mm/year) of the 30-min series exhibited significantly different trends from the OLS. These differences also exist for the sign of the slope among the quantiles. As shown in the figure, the higher extremes for the 15- and 30-min data decreased by a higher magnitude than the median quantile and the mean. Furthermore, the 30-min annual maximum time series showed an increasing trend even though the higher quantiles showed a decreasing trend tendency.

For the subhourly annual maximum observed time series at the Canakkale station in Fig. 2c, the 5-min annual maximum rainfall, all-quantiles showed decreasing trends, which was in accordance with the OLS results. The 10-min rainfall series at the Canakkale station exhibited positive slopes for the 10th, 25th, and 90th quantiles, whereas the 50th and 75th quantiles showed negative slopes. Significant behavior was shown by the 10th and 90th quantiles, which had significantly higher magnitudes (0.05 and 0.04 mm/year), and the median quantile, which had a significantly lower magnitude (− 0.04 mm/year) than the other quantiles. The 15- and 30-min duration data series exhibited closer values among their quantiles and the OLS, which mostly indicate an increasing trend. However, the 10th and 90th quantiles of 15-min data and the 50th and 75th quantiles of the 30-min data slopes were higher than the mean slope.

The behavior of the subhourly annual maximum observed time series at the Edirne station is shown in Fig. 2d. Considering the 5-min and 10-min annual maximum rainfall, all-quantiles showed similar trends. The slopes of that quantiles and the mean slope (OLS) were not dramatically different. On the other hand, the 90th quantile of the 15- and 30-min data revealed a considerable difference (0.12 and 0.19 mm/year) compared with the lower quantiles and OLS (0.03 and 0.08 mm/year). This significant increase in the slope can change the tail behavior of the rainfall series and distribution. According to the figure, more severe extremes are expected to occur at the Edirne station for the 15- and 30-min storm duration, but the frequency remains uncertain.

The Florya station data for the subhourly storm durations is shown in Fig. 3a. The 5-min annual maximum rainfall data showed decreasing trends for all-quantiles with different slopes. The 10-min rainfall series at the Florya station exhibited negative and similar trends for the mean and the median quantiles. On the other hand, the 90th quantile revealed a positive trend with a positive slope (0.04 mm/year). The 15-min series showed an almost similar trend direction except for the 25th quantile (− 0.04 mm/year). Also, the magnitudes of the quantile slopes were mostly higher than the OLS (0.01 mm/year). Considering the 30-min data, the OLS and the 90th quantile results exhibited increasing trends, whereas the other quantiles indicated negative slopes. A comparison of the positive slope of the OLS and the 90th quantile indicated that the 90th quantile had a much higher magnitude (0.11 mm/year). The difference in magnitude and the direction of the slopes indicate the possible insufficiency of the OLS to capture the change of the annual maximum data over time at Florya station.

The Gokceada station data shown in Fig. 3b also exhibited considerable differences among the quantiles and the OLS results for most of the storm durations. The 10th and 90th quantile slopes were almost parallel, which suggested no significant change for the variability in the extreme quantiles of the 10-min storm duration, whereas the OLS results indicated a decreasing mean variability. Besides, all the time series exhibited divergent slopes from their corresponding OLS results. The 15- and the 30-min data of the station stood out, with significantly increasing 90th quantiles (0.13 and 0.39 mm/year).

The behavior of the subhourly annual maximum observed time series at the Kirklareli station Fig. 3c stood out with a higher increasing trend of the 90th quantiles compared with those for the 10-, 15-, and 30-min storm durations (0.17, 0.19, and 0.26 mm/year), whereas the 10th quantile of all the durations showed negative trends except for the 30-min data series. On the other hand, all the higher quantiles, such as the 75th and 90th, exhibited positive trends except for the 75th quantile of the 5-min storm duration. The median quantile and the OLS showed closer values for the 15- and 30-min data, whereas different signs were revealed for the 5- and 10-min data. The higher quantiles had more influence on the behavior of the mean trend at Kirklareli station for the 10-, 15-, and 30-min series.

The data from the Kocaeli station is shown in Fig. 3d, which revealed analogous features to that of the Kirklareli station, but there were no negative slopes for any of the quantiles and the OLS at Kocaeli station. The effect of higher quantiles increased with increasing storm duration, and the slope values tripled and doubled for the 15- and 30-min storm durations (0.27 and 0.38 mm/year) compared with their corresponding OLS results (0.09 and 0.16 mm/year). The median quantiles and mean values (OLS) were almost exhibited similar slopes, which suggested variability in the time series can be captured with mean results, but the trends in the upper quantile (90th) were significantly higher than the others.

As shown in Fig. 4a, there was a clear increasing trend at Sakarya station. Most of the quantiles and the OLS exhibited an increasing trend except for the 10th quantiles of the 5- and 10-min data. Additionally, the 75th and 90th quantiles of the 5-, 10-, and 30-min series revealed significantly higher magnitudes when compared with the OLS results. The 10-min data indicated the highest slopes (0.19 mm/year) for the median quantile, whereas the rest of the rainfall series of storm durations represented higher magnitudes of the slope for the upper quantiles, such as the 75th or 90th quantiles.

The QR results at the Sariyer station are shown in Fig. 4b. According to the results, most of the storm durations at all quantiles represent increasing trends. Temporal variation of these rainfall series behaves similarly in terms of trend direction. Moreover, the upper quantiles exhibited a higher magnitude of trend, whereas the lower quantiles behaved similarly to the OLS results and revealed consistent patterns with OLS.

The behavior of the subhourly annual maximum observed time series at the Tekirdag station is shown in Fig. 4c. Considering the storm durations and the quantiles, only the 25th quantiles of the 10 and 15 min rainfall series indicated negative trends. On the other hand, higher quantiles of 15- and 30-min series showed a significant increasing trend. Both Sariyer and Tekirdag station time series exhibited a general increasing trend with increasing quantiles. Furthermore, the magnitude of the slope of the quantiles increased with increasing storm durations such as 0.16 and 0.14 mm/year for 10-min rainfall series at Sariyer and Tekirdag stations, respectively, and 0.23 and 0.29 mm/year for the 15-min series and 0.32 and 0.58 mm/year for the 30-min data at the same stations.

The QR results at the Yalova station are shown in Fig. 4d. Unlike most of the time series, the 90th quantile of the rainfall series exhibited the opposite direction according to OLS results except for the 30-min storm duration. Moreover, the highest magnitudes of the slope were detected for the 25th and median (50th) quantiles. Besides the upper quantile of 90th, the rainfall series exhibited coherent results in terms of direction and slope magnitude for the quantiles and OLS.

The quantile slopes were calculated by quantile regression for 10th to 90th quantiles, and the variations that were depicted for trends of the selected quantiles are displayed in Tables 2, 3, 4 and 5 for 5–10–15–30-min rainfall series, respectively. The uncertainty bands of the quantile slopes and the confidence bands of the OLS are provided in "Appendix". There was an increasing trend for quantile 90th (the upper quantile) for most of the rainfall series of 15 and 30 min, which indicated that extreme rainfall events might become more extreme. In contrast to the OLS, QR revealed a more comprehensive inference for the distribution change of the annual maximum values of four subhourly storm durations at the 12 stations.

Moreover, when the change of sign of the quantiles investigated, it was depicted that negative slopes change to

Table 2 The quantile regression and OLS coefficients for 5-min storm duration

Station	$q=0.1$	$q=0.25$	$q=0.5$	$q=0.75$	$q=0.9$	OLS
Balikesir	−0.05	−0.04	−0.01	−0.02	−0.05	−0.04
Bursa	−0.03	−0.03	−0.04	−0.04	−0.03	−0.03
Canakkale	0.05	−0.03	−0.00	−0.03	−0.04	−0.02
Edirne	−0.01	−0.00	0.00	0.01	−0.00	−0.00
Florya	−0.00	−0.06	−0.04	−0.02	−0.01	−0.03
Gokceada	−0.01	−0.06	−0.11	−0.02	−0.07	−0.07
Kirklareli	−0.04	0.01	0.01	−0.00	0.02	−0.00
Kocaeli	0.02	0.03	0.03	0.03	0.01	0.03
Sakarya	−0.00	0.06	0.06	0.11	0.13	0.06
Sariyer	0.04	0.09	0.06	0.07	0.11	0.07
Tekirdag	0.04	0.03	0.04	0.02	0.12	0.05
Yalova	0.04	0.10	0.08	0.01	−0.00	0.07

Table 3 The quantile regression and OLS coefficients for 10-min storm duration

Station	$q=0.1$	$q=0.25$	$q=0.5$	$q=0.75$	$q=0.9$	OLS
Balikesir	−0.05	−0.04	0.01	0.01	−0.08	−0.04
Bursa	−0.00	−0.00	−0.03	−0.03	−0.02	−0.02
Canakkale	0.05	0.02	−0.04	−0.00	0.04	0.01
Edirne	0.01	0.02	0.02	0.03	−0.00	0.01
Florya	0.01	−0.05	−0.03	−0.03	0.04	−0.02
Gokceada	0.01	−0.03	−0.11	−0.05	−0.01	−0.06
Kirklareli	−0.01	−0.01	−0.01	0.05	0.17	0.03
Kocaeli	0.03	0.05	0.05	0.04	0.09	0.06
Sakarya	−0.01	0.03	0.19	0.12	0.14	0.10
Sariyer	0.10	0.10	0.09	0.07	0.16	0.10
Tekirdag	0.02	−0.00	0.08	0.12	0.14	0.09
Yalova	0.04	0.13	0.05	0.06	−0.05	0.04

Table 4 The quantile regression and OLS coefficients for 15-min storm duration

Station	$q=0.1$	$q=0.25$	$q=0.5$	$q=0.75$	$q=0.9$	OLS
Balikesir	−0.10	−0.02	−0.01	0.02	−0.07	−0.03
Bursa	0.02	0.02	−0.00	−0.01	−0.12	−0.02
Canakkale	0.06	0.03	0.04	−0.01	0.07	0.04
Edirne	0.02	0.02	0.03	0.06	0.12	0.03
Florya	0.04	−0.04	0.05	0.00	0.03	0.01
Gokceada	0.05	0.02	−0.09	−0.06	0.13	−0.01
Kirklareli	− 0.08	0.01	0.05	0.04	0.19	0.04
Kocaeli	0.04	0.07	0.08	0.08	0.27	0.09
Sakarya	0.02	0.09	0.16	0.20	0.08	0.12
Sariyer	0.13	0.08	0.10	0.11	0.23	0.12
Tekirdag	0.04	−0.01	0.15	0.15	0.29	0.14
Yalova	0.02	0.15	0.13	0.09	−0.08	0.07

Table 5 The quantile regression and OLS coefficients for 30-min storm duration

Station	$q=0.1$	$q=0.25$	$q=0.5$	$q=0.75$	$q=0.9$	OLS
Balikesir	−0.09	0.01	−0.06	0.12	−0.01	0.01
Bursa	–	0.06	0.08	−0.04	−0.07	0.02
Canakkale	0.06	0.12	0.16	0.15	0.08	0.12
Edirne	0.04	0.03	0.09	0.02	0.19	0.08
Florya	−0.00	−0.06	−0.04	−0.00	0.11	0.03
Gokceada	0.17	0.11	0.03	−0.13	0.39	0.10
Kirklareli	0.00	0.12	0.11	0.07	0.26	0.10
Kocaeli	0.09	0.10	0.16	0.14	0.38	0.16
Sakarya	0.05	0.09	0.26	0.41	0.40	0.24
Sariyer	0.16	0.12	0.22	0.23	0.32	0.19
Tekirdag	0.07	0.11	0.16	0.43	0.58	0.25
Yalova	0.02	0.22	0.08	0.14	0.16	0.08

positive with increasing storm duration. This was especially obvious for the Canakkale, Edirne, Gokceada and Kirklareli stations while Bursa, Florya and Balikesir stations also exhibited similar behavior but not as significant as the others. The reason behind this change can not only be the general climate drivers of the region but also local conditions since the stations that exhibited this behavior distributed over the region randomly.

According to Baltaci (2019), nonsignificant increasing trends occur for the precipitation extremes of the Marmara Region based on Man-Kendall and OLS methods. In our study, the OLS of 34 of 48 subhourly time series exhibited an increasing trend at the 12 stations located in Marmara Region. Abbasnia and Toros (2018) found an increasing trend for the 1-day and 5-day precipitation amounts, which was supported by the results of Sensoy et al. (2013), who indicated an increasing maximum 1-day precipitation at all the stations except Southeastern Anatolia. In our study, we also observed increasing trends, especially for the upper quantiles of the time series, with increasing storm duration, which can be depicted as a signal of intensification at the stations. Aziz and Yucel (2021) revealed increasing return level values up to 25% when nonstationarity was considered at the Marmara Region and indicated more intense precipitation, which could be one of the reasons that the OLS mean slope is not sufficient to define the complete trend of the time series and support the hypothesis that more detailed analyses are needed. Furthermore, when subhourly time series were examined, the differences among the quantiles indicate the distribution change of the extreme rainfall series over time, which is one of the main indicators of the nonstationary theory. Abbasnia and Toros (2020) also predicted the possibility of stronger and shorter precipitation extremes in the future, especially for the coastal areas, and Sarış (2020) stated that more frequent extremes are expected for the north-east Black Sea region and from the south-west to the south-east Mediterranean coasts. The results of our study also indicate the intensification and stronger extremes, but it is not reasonable to conclude anything about the frequency of these extremes. Furthermore, the results of our study also indicate that the intensification is not only limited to the coastal regions but that most of the stations, whether they are coastal or inland, exhibited higher magnitudes of slopes for the upper quantiles. Lolis and Türkeş (2016) reported that there is a difference between the mechanisms that are dominant for the occurrence of extreme rainfall during the cold and hot periods of the year. This might be one of the reasons for the differences between the stations and the storm durations. It will be vital to examine the annual maximum time series in terms of the precipitation time over the year. Furthermore, the published studies mentioned above mostly used a daily timescale for the analyses, which is a coarse scale for comparison of those results with our results, in which we used subhourly extreme rainfall data, which is essential input for the urban infrastructure system design and flash flood events.

Besides, for every selected station, MK trend test and the ITA method were also performed to determine and compare the behavior of the rainfall time series with QR results. Balikesir station showed a clear decreasing trend for the storm durations when the ITA graph was examined (Fig. 5a). This behavior was mainly dominated by the medium and high data values of the annual maximum series. The accumulation of the medium-level values around the 1:1 line indicates the insignificance of the detected trends especially for low and medium values according to the ITA results. However, the negative trend behavior was detected for the highest values of all the rainfall durations at Balikesir station.

Considering Bursa station (Fig. 5b), mostly station, the subhourly rainfall data points fell below or accumulated near the 1:1 line, whereas the 30-min data low and medium values mostly fell over the 1:1 line which can be one of the reasons that MK results revealed increasing trend for this storm duration. On the other hand, no significant trend was observed for the values that were smaller than the medium ones.

Contrasting tendencies were also observed for Canaklae station (Fig. 5c). The 5-min rainfall data exhibited a clear downward trend and 30-min data exhibited a clear upward trend, whereas the remaining rainfall time series exhibitted different trend characteristics for their corresponding low, medium, and high data values which in general revealed no significant trend. The ITA results displayed a clear downward trend for medium and high values of 5-min rainfall data. The 15- and 30-min data points mostly fell above the 1:1 line, implying an overall upward trend.

The Edirne station rainfall series showed different trend patterns in terms of low, medium, and high values (Fig. 5d). However, almost all the rainfall series high values deviated from the 1:1 line while remaining medium and low values accumulated around or above the 1:1 line. Only the 30-min time series showed an upward trend, and the rest of the rainfall series had no clear trend tendency whether upward or downward. However, the upward trend of rainfall series was not demonstrated for all the data points.

At Florya station (Fig. 6a), the ITA results showed no significant trend in general, but the 5-min rainfall series displayed slightly different trend tendencies than the others. The 5-min rainfall data points fell below the 1:1 line, whereas the remaining rainfall series points stayed both along, below, and above the line with minor drifts from the 1:1 line that does not allow interpretation of the trend except few high values of 5, 15, and 30 min.

The ITA method results for the data from Gokceada station showed a downward trend for 5-, 10-, and 15-min and an upward trend of the medium values for 30-min rainfall series (Fig. 6b). Low-level data points were generally positioned above the 1:1 line. High-level values exhibited similar trend behavior with their corresponding medium-level data points for 5 and 10-min rainfall series. However, the high category values of 15- and 30-min series represented opposite direction with their corresponding medium values.

Trend results obtained for Kirklareli station (Fig. 6c) indicated upward trends for all the medium and high values, which were generally positioned around or above the 1:1 line. However, low data values of the rainfall series except the 30-min series accumulated on or below the 1:1 line that indicate no or downward trend. On the other hand, all the high data values of the rainfall series except the 5-min rainfall series clearly showed an upward trend.

The Kocaeli station rainfall series showed a consistent upward trend (Fig. 6d). All low, medium, and high rainfall data values were positioned above the 1:1 line with a few exception points for the medium values. Low- and medium-level values were closer to the 1:1 line, whereas the high values showed a strong upward trend and were located farther from the 1:1 line compared with the low and medium values at Kocaeli station.

The Sakarya, Sariyer, Tekirdag, and Yalova (Fig. 7a–d) stations rainfall series mostly showed similar patterns that indicate upward trend. Almost all the rainfall series high values deviated from the 1:1 line for Sakarya (Fig. 7a) and Tekirdag (Fig. 7c) stations positively. Only a few numbers of low values for Sakarya station and high values of Sariyer (Fig. 7b) and Yalova (Fig. 7d) stations showed a downward trend. However, the upward trend of rainfall series was not demonstrated with the same level for all the data points. For example, the medium values of the 10-, 15-, and 30-min rainfall series were accumulated on the 1:1 line for Yalova station, which indicated no trend. Furthermore, the higher values of the Tekirdag station 5 min rainfall series considerably departed and fell above the 1:1 line, whereas the rest of the data points were closer to the 1:1 line, and it was not easy to find any evidence of a trend for such a series.

Furthermore, Mann–Kendall test results were also obtained, and the results revealed various trend tendencies (Table 6). In this table, the numbers presented in bold show significant trends at 0.05 significance level. For instance,

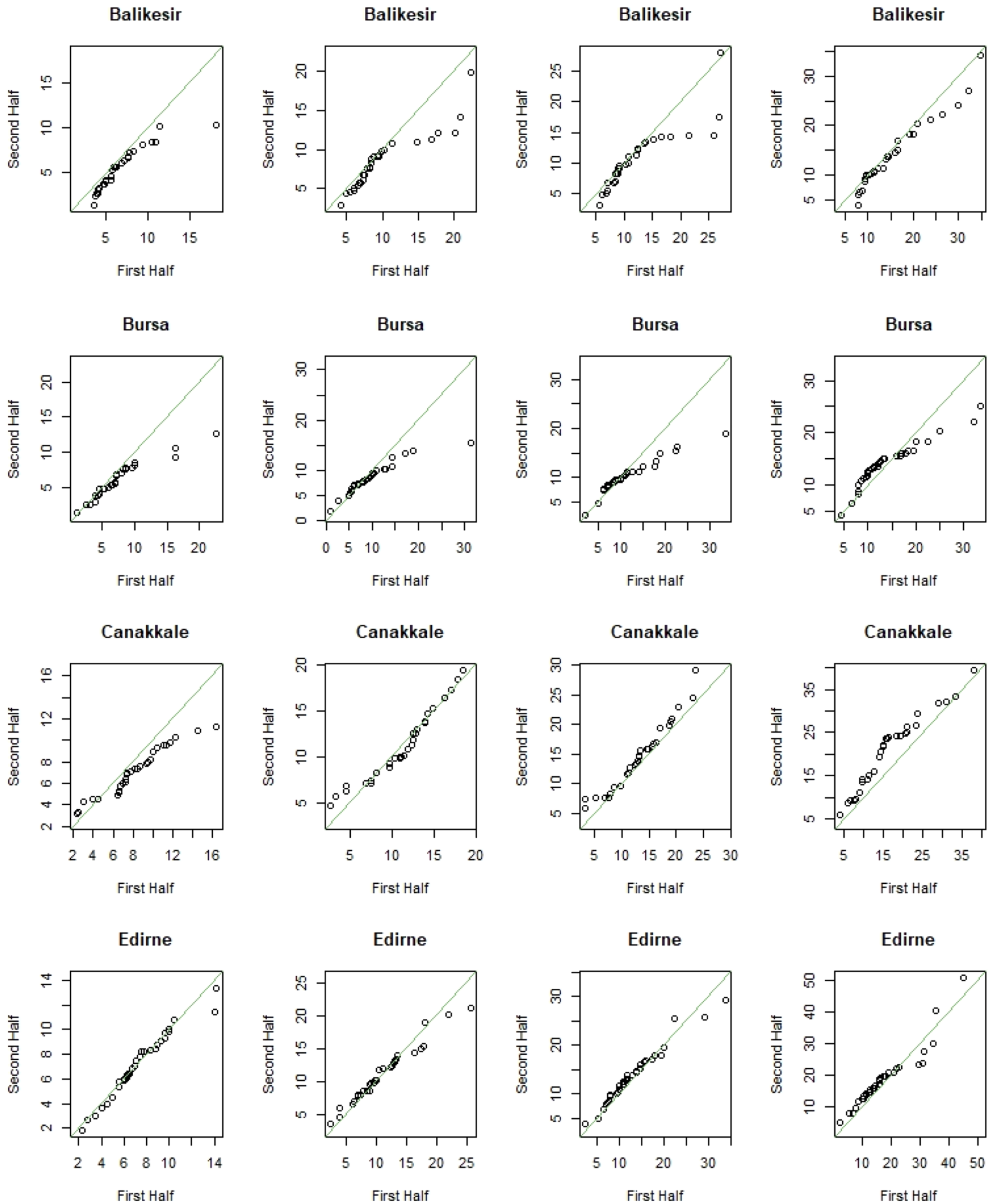


Fig. 5 ITA results (5 min (left) to 30 min (right)) for **a** Balikesir, **b** Bursa, **c** Canakkale, and **d** Edirne Stations

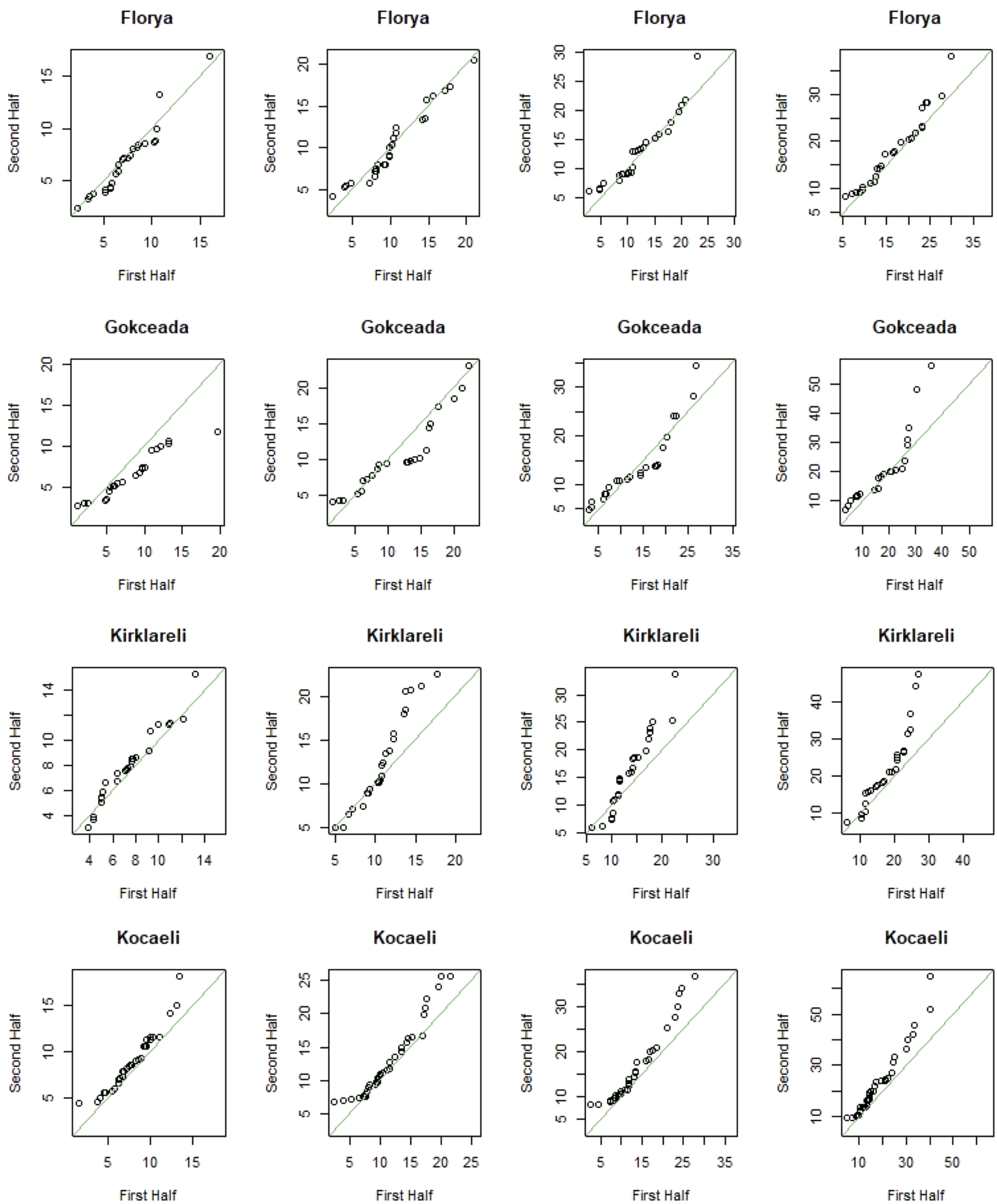


Fig. 6 ITA results (5 min (left) to 30 min (right)) for **a** Florya, **b** Gokceada, **c** Kirklareli and **d** Kocaeli Stations

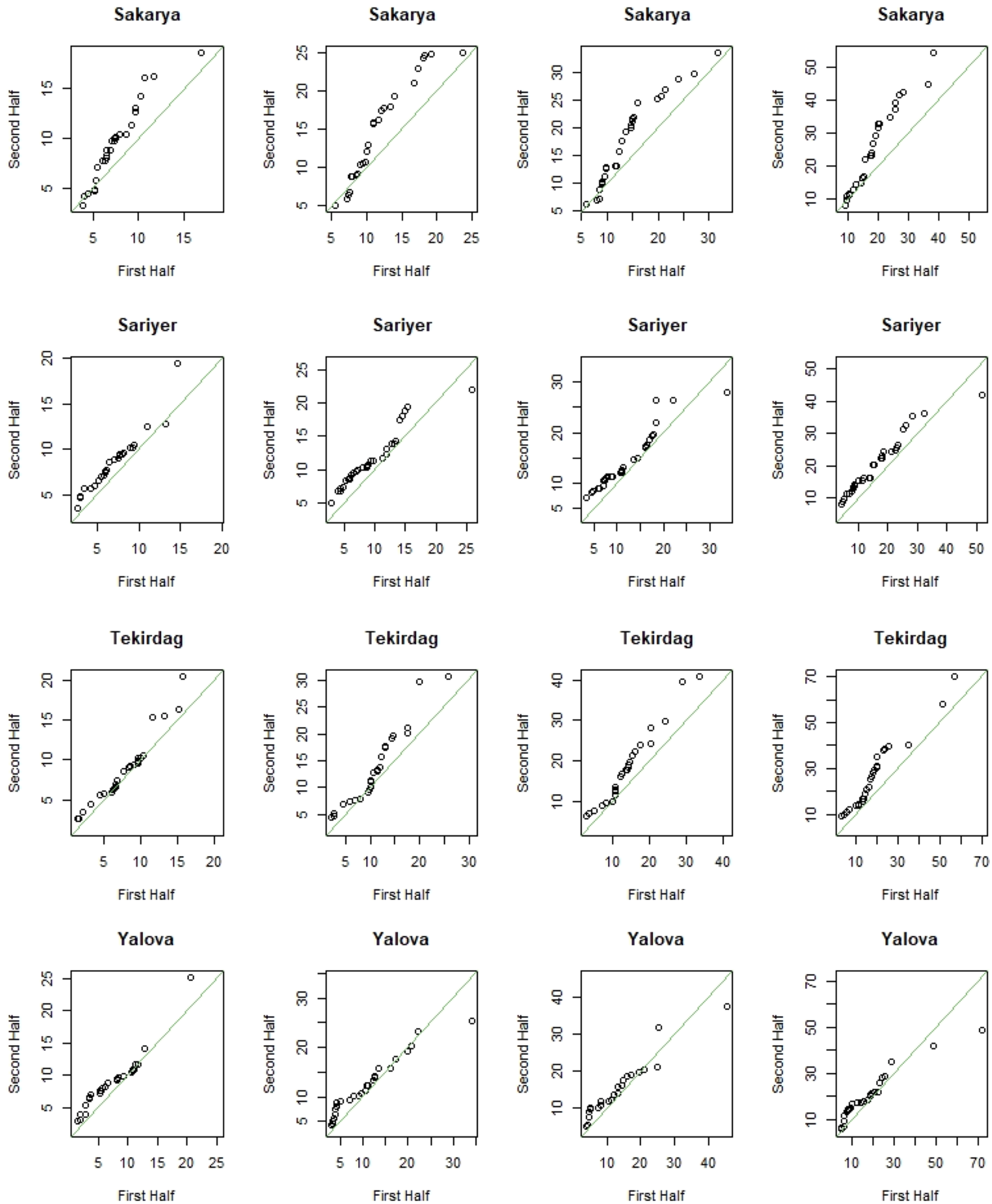


Fig. 7 ITA results (5 min (left) to 30 min (right)) for **a** Sakarya, **b** Sariyer, **c** Tekirdag, and **d** Yalova Stations

Table 6 The Mann–Kendall test statistics

Station	5 min	10 min	15 min	30 min
Balikesir	− 1.426	− 0.824	− 0.504	− 0.013
Bursa	− 1.354	− 0.742	− 0.210	1.416
Canakkale	− 0.879	− 0.020	0.644	**2.000**
Edirne	0.189	0.688	0.785	1.348
Florya	− 1.177	− 0.813	− 0.174	− 0.055
Gokceada	− 1.572	− 0.795	− 0.313	0.436
Kirklareli	0.109	0.000	0.703	0.962
Kocaeli	1.773	**1.916**	**2.343**	**3.043**
Sakarya	**2.142**	1.850	**1.978**	**2.201**
Sariyer	**3.288**	**2.957**	**2.895**	**2.782**
Tekirdag	0.952	1.189	1.488	1.757
Yalova	1.605	1.097	1.239	1.395

Balikesir, and Florya stations exhibited decreasing trend for all storm durations while Edirne, Kirklareli, Kocaeli, Sakarya, Sariyer, Tekirdag and Yalova stations showed no decreasing trends. Among the 12 stations only Bursa, Canakkale and Gokceada stations revealed both increasing and decreasing trend. 30-min storm duration of Bursa and Gokceada stations and 30- and 15-min storm duration of Canakkale stations showed increasing trends. However, the trends were mostly not significant. The stations and storm durations that exhibited significant increase or decrease at the 0.05-significance level were Canakkale station for 30-min storm duration with increasing trend, Kocaeli station for 10-, 15-, and 30-min data with increasing trends, Sakarya station for 5-, 15-, and 30-min data with increasing trends and Sariyer station with increasing trends for all the storm durations. It is also worth to say that all significant trends were observed for increasing tendencies. Moreover, the stations with increasing trends were mostly located in the northern part of the region.

Quantile regression, MK test and ITA results were also compared. While ITA and QR imply the similar trend tendency in general, quantiles slopes of QR cannot be depicted from the ITA graph in some cases. For instance, 5-min data of Balikesir station had similar slopes for 10th, 25th and 90th quantiles while this result cannot be obtained from the ITA graph directly. Furthermore, the decreasing trend of high values at Bursa station for the 5- and 10-min data did not follow the same pattern for the QR results of the same duration at the same station since the QR results exhibit similar slope values. Canakkale and Edirne stations showed similar results for QR and ITA. Florya station also indicated that ITA results coincide with QR. At the Gokceada station, QR results indicated variations between the QR slopes and ITA results for the 5-min series, yet the rest of the series imply consistency between QR and ITA. Kirklareli and Kocaeli stations revealed consistent behavior for the 10-, 15-, and 30-min data, but differences were explored for the 90th quantile slope QR and the high values of ITA for the 5-min data which was also valid for Yalova station. In addition, while the distance of the values to the 1:1 line did not change considerably the QR slopes that indicate the trend of the quantiles change remarkably. For example, Sakarya, Sariyer, and Tekirdag stations ITA graphs exhibit similar positions for the data points however, the quantile slopes indicate different values among each other such as 0.13, 0.11 and 0.12 for 5-min and 0.40, 0.32, and 0.58 for 30-min 90th quantile values.

The analyses revealed that, in general, the extreme and average trends agree in terms of the sign, but they were not necessarily agree in terms of significance and magnitude. When the rainfall series examined, for some cases, an overall or categorical trend is not easy to detect with the ITA method to compare with QR results. One of the reasons for this could be the different statistical properties of the time series. Also, the visually detected low, medium, and high categories of the ITA did not exactly match the quantiles of the time series.

Considering the MK test results and QR slopes; significant MK test results mostly explored from the time series that revealed higher magnitude of QR slopes for the 90th quantile except Sakarya station 15-min data. Sensitivity of MK test results to the outliers can be one of the reasons for this. However, it cannot be concluded as higher QR slopes lead to increasing significance. The sign of the MK test results, and the quantile slopes exhibited consistent results in general. On the other hand, 5-min data of Edirne and Kirklareli stations, 10-min data of Edirne station, 15-min data of Florya station, and 30-min data of Balikesir and Florya stations MK test results showed different sign from the OLS.

Lastly, the variation of the distribution of precipitation maxima was investigated through the absolute difference between 25 and 75% quantiles in Tables 2, 3, 4, and 5. In this regard, every standard maximum precipitation series were analyzed for all stations in itself. The largest difference for the five-minute series was found for the Yalova station as 0.09. Following the Yalova station, Sakarya, Floya, and Gokceada stations also exhibited larger differences among the other stations (0.05, 0.04, and 0.04). Considering the ten-minute precipitation series Tekirdag station revealed the highest absolute difference, 0.12, while Yalova and Sakarya stations together with Kirklareli station further showed similar behavior that is higher absolute difference between 25 and 75% quantiles. When fifteen- and thirty-minute maximum precipitation considered, Tekirdag and Sakarya stations exhibited the highest differences, 0.16 and 0.11 for fifteen-minute data, and 0.33 and 0.32 for thirty-minute data, respectively. Besides these stations, Gokceada and Yalova stations for the fifteen-minute data and Gokceada station for the thirty-minute data indicated higher difference among the other stations. The difference of the quantiles can be interpreted as the signal of standard deviation of the precipitation series which increases with a larger difference. Thus, the stations and storm durations that displayed higher absolute difference can also have higher standard deviation values.

Conclusions and remarks

In this study, the trends of subhourly annual maximum time series at 12 stations were investigated by using a QR-based method and results were also compared with Mann–Kendall test and ITA method. At least 45-year-long data from 12 stations in the Marmara Region, Turkey, were examined over time to obtain a better inference of the extreme rainfall behavior. Five quantiles (10th, 25th, 50th, 75th, and 90th) were selected, and the results of these quantiles were compared with ordinary least-squares slopes of the same rainfall series.

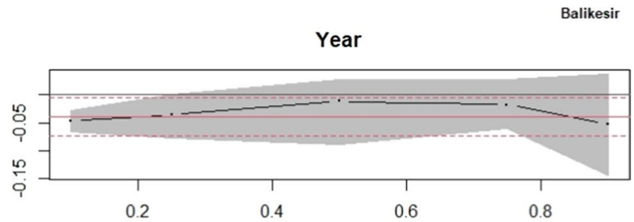
Regarding the extreme rainfall, the QR-based method revealed more detailed information in terms of trend analysis and the impact of the independent variable, which was time in this study, which allows a more complete inference to be made about the relationship. Besides, the relationship between the frequency and extreme rainfall events is easier to detect using QR. This is particularly important for the impact studies and long-term infrastructure designs that are based on the stationary assumption.

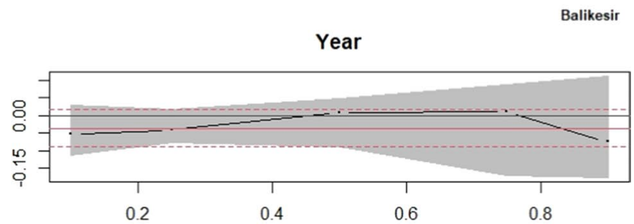
Moreover, a better understanding of the temporal behavior was obtained, which cannot be obtained by the characteristics of the mean. In addition, outliers of the data set have higher impact over the mean and the mean that is obtained by the classical methods are also more sensitive to the outlier effect. As the quantiles increased, a more significant increasing trends were observed. Furthermore, the most significant differences compared with the classical method were observed for the 90th quantile of the rainfall series.

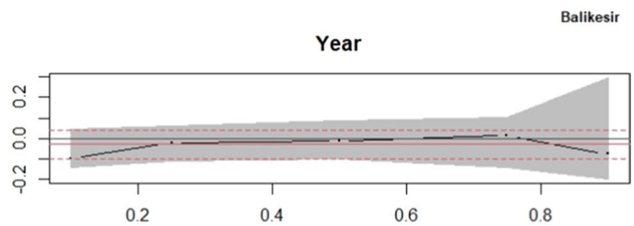
The slopes of the upper, middle, and lower quantiles and the mean displayed various slope values among the stations and the durations that indicate the change in the distribution of different quantiles. The change in the lower and upper quantiles revealed valuable information, and therefore, the QR method can be used to explore and study the long-term climatic variability. Since the frequency and the magnitude of the quantiles differ, QR method enables to explore their change in time.

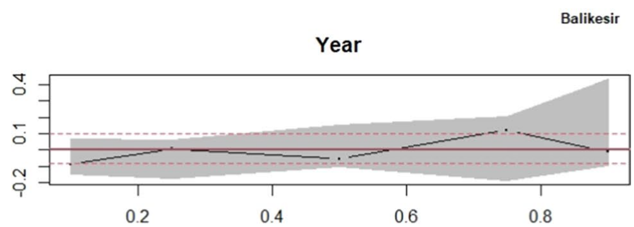
Furthermore, the rate of change of the extreme conditions can be detected with the QR method compared to mean that enables to understand whether extreme conditions become more extreme or not which is not an easy process with the alternative trend analyses methods.

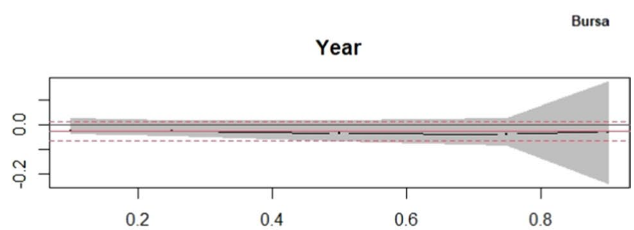
Appendix

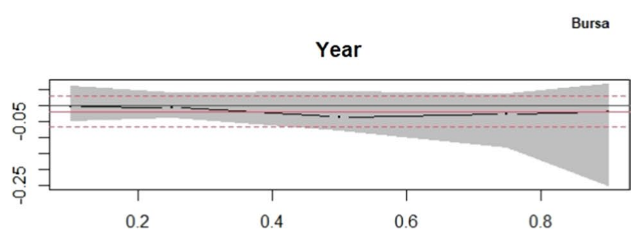


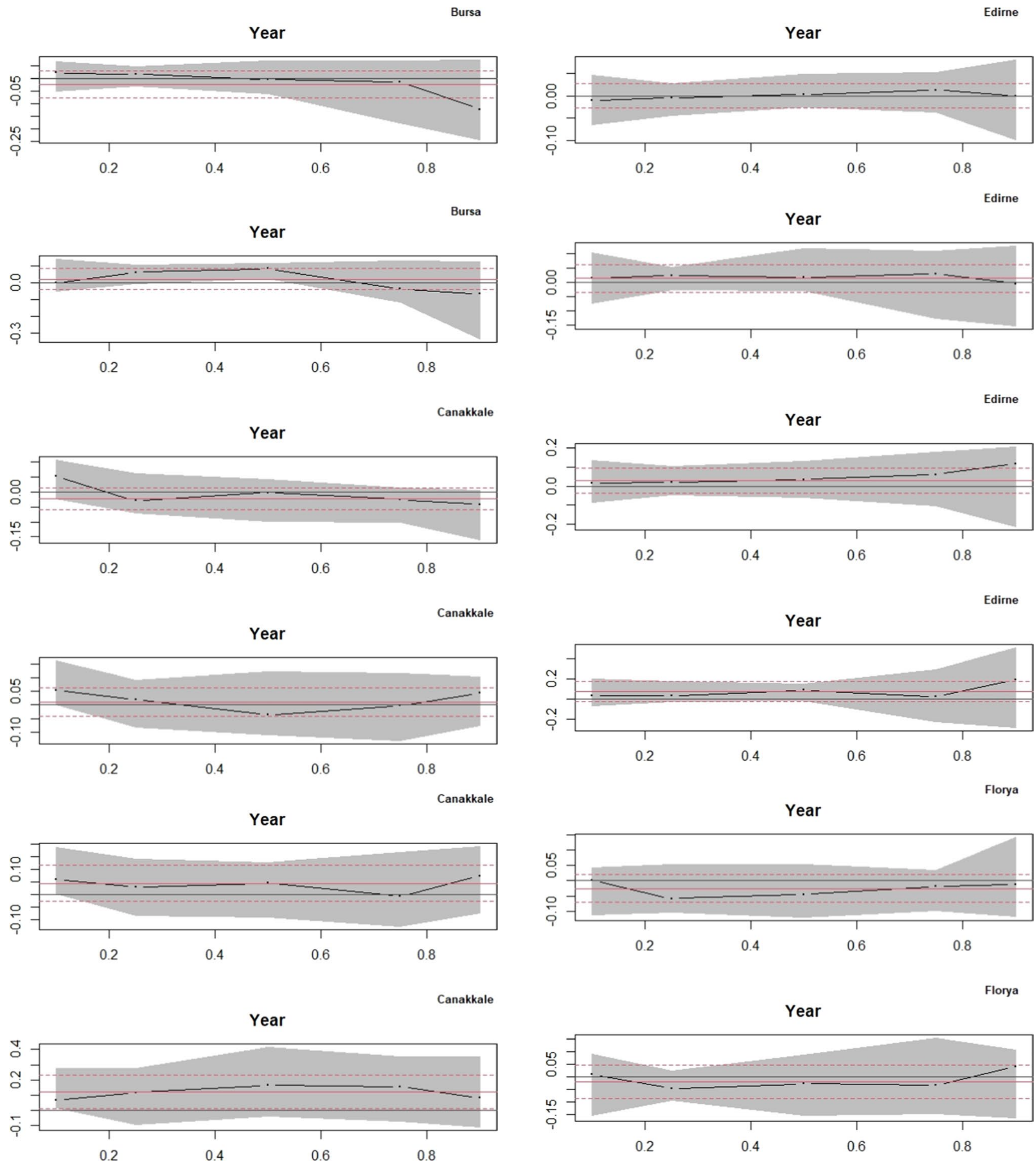








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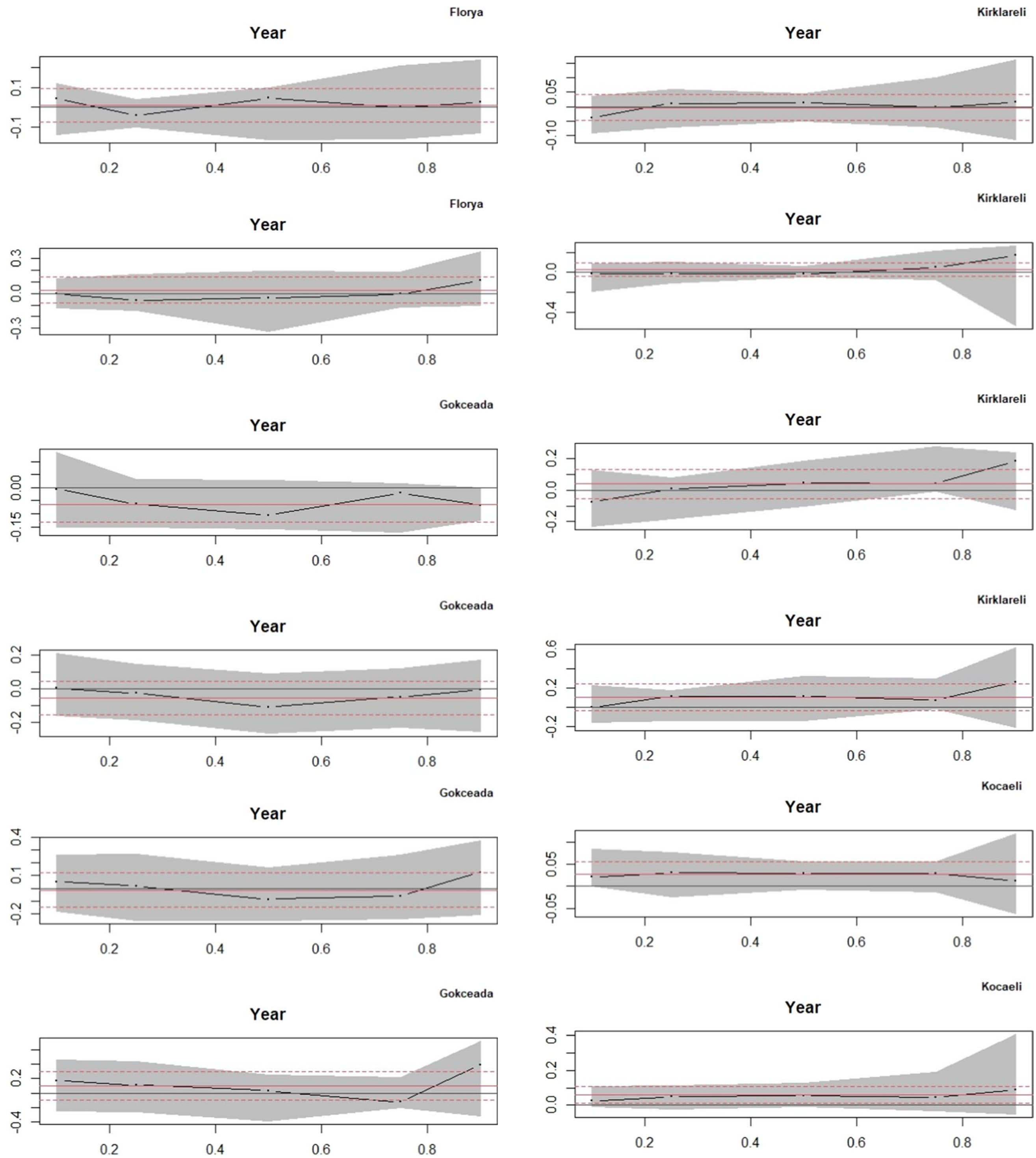
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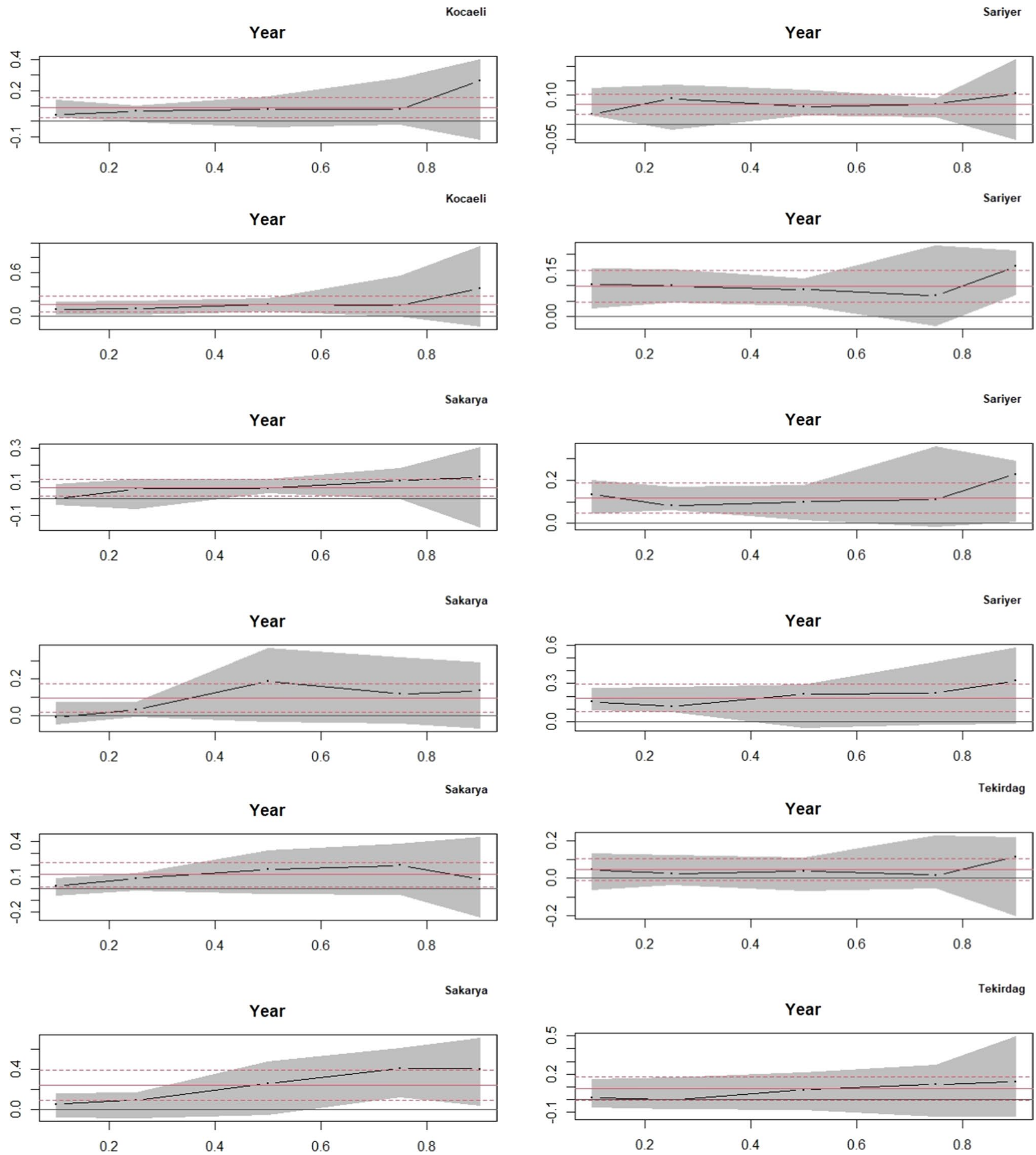
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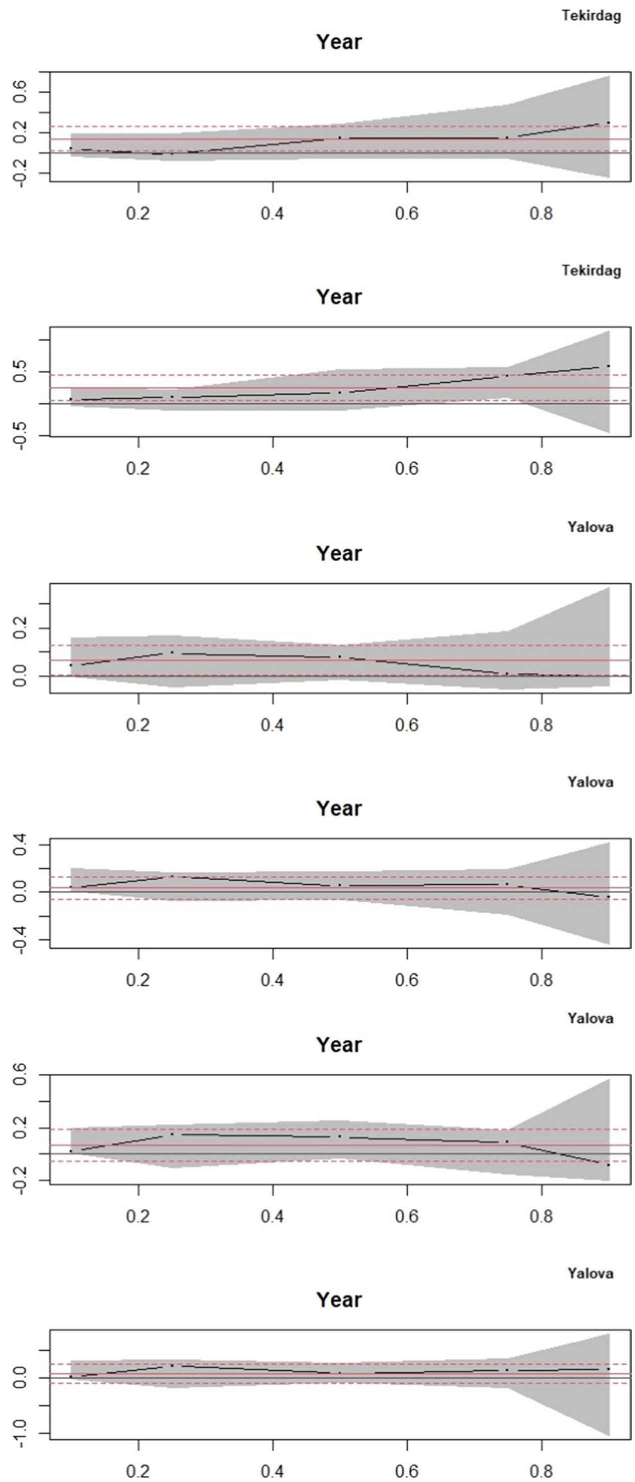

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Declarations

Conflict of interest The author declares no conflict of interest.

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