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RESEARCH ARTICLE

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Long-term change of summer mean and extreme precipitations in Korea and East Asia

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Abstract

The change of the precipitation characteristics over South Korea is investigated using long-term (60 years) hourly precipitation records from surface stations focusing on extended summer (June–September) and rainy season (Changma). The precipitation characteristics including extreme events (>30 mm·h^{-1} or >100 mm·day^{-1}) are also compared for the past (1961–1990) and recent (1991–2020) climatology. The amount of summer precipitation shows a notable increase over South Korea (2.6 mm·day^{-1}·century^{-1}) during the last 60 years (1961–2020) although it is smaller than recent 48-year trend measured in North Korea (9.7 mm·day^{-1}·century^{-1}). Precipitation amounts are significantly increased than past climatology particularly in 70–100 and 200 mm·day^{-1} intensity ranges. The frequency of extreme precipitation also exhibits an increasing trend (1.0 frequency·century^{-1}) during the last 60 years over South Korea. The frequency of extreme precipitation has been doubled in the recent climatology compared to the past climatology. Daily precipitations in top 1 percentile present clear increasing trends during the extended summer and Changma season in South Korea. Further investigation using gridded precipitation reveals that the similar mean and extreme precipitation increases are observed over the wider regions in East Asia, including central China and southern Japan. This result implies that the long-term precipitation change over South Korea is related to a large-scale circulation change in the East Asian summer monsoon.

KEYWORDS

climatology, extreme events, long-term trend, summer precipitation

1 | INTRODUCTION

According to the sixth assessment report of IPCC (IPCC, 2021), the average global temperature of the recent decade (2011–2020) has increased by approximately 1.09°C since the pre-industrial era and has most likely also enhanced the water cycle in the atmosphere (Trenberth et al., 2003, 2005). A rise in the water vapour content in the atmosphere particularly affects the water cycle, leading to either floods or severe droughts in certain regions. Recent studies reported that this climate change has a major impact on the summer monsoon in East Asia, causing heavy rainfalls and problems in water resources management (Cha et al., 2007b; Lee et al., 2014; Wang et al., 2021). Precipitation is one of the important climate factors that influence human life as well as socio-economic activities for a long term. In East Asia, where has a clear rainy season (summer monsoon;

Wang, 2006), summer precipitation serves as a crucial source of water for agriculture and industries. In addition, approximately 80% of the natural disasters in this region occur during the summer monsoon because it causes a large amount of rainfall in a short period of time (Wang, 2006; Webster et al., 1998).

The precipitation in the Korean Peninsula is largely controlled by the East Asian monsoon circulation and is characterized by a distinct rainy season in the summer (Choi et al., 2020; Kim et al., 2002; Li & Wang, 2005; Qian et al., 2002), which is known as "Changma" in Korea. The Changma is the major rainy period along with Mei-Yu in China and Baiu in Japan, usually lasting for about a month from late June to late July. The Changma precipitation accounts for approximately 30% (∼60% in June–September) of the total annual precipitation in the Peninsula, thus Changma is a very important period for water resource and disaster managements (KMA, 2011; Seo et al., 2011). It was recently reported that the characteristics of the East Asian summer monsoon (including Changma) have changed owing to the increase in water vapour content in the atmosphere as an outcome of global warming (e.g., Choi, 2015; Ha et al., 2005; Kwon et al., 2005, 2007; Moon et al., 2015). Kwon et al. (2007) for instance reported a significant change in the summer precipitation characteristics in East Asia during the 1990s. Min et al. (2015) showed that both the amount and frequency of heavy rainfall events have increased in South Korea relating to changes in East Asia summer monsoon. These changes in the summer precipitation characteristics could also cause a major impact on extreme weather related disasters.

Particularly, the summer precipitation changes in the Korean Peninsula have been reported in various studies. The recent change in summer precipitation over South Korea can be summarized by (1) an increasing trend of heavy rainfall with a decreasing trend in light rain and (2) increased intensity and intermittency of heavy rainfall in the rainy season (An et al., 2011; Choi et al., 2011; Hong et al., 2011; Jung et al., 2011). The change-point analysis using seasonal rainfall further revealed that these changes likely occur in the 1990s (Moon et al., 2015). Such change is assumed to be linked to the climate regime shift (Hong et al., 2014) in East Asia which appeared in the 1990s (Lee & Kwon, 2004; Moon et al., 2011). The climate regime shift occurs from the increase of sea surface temperature in the equatorial western Pacific. The inflow of water vapour into the Korean Peninsula increased due to the low-pressure rotation that occurred in the relatively warm western Pacific region (Hong et al., 2014; Moon et al., 2015).

Previous studies also have reported the long-term changes in precipitation amount and rainy season length. The Korean summer monsoon precipitation generally peaks twice, one in early July and the other in early September (Ha et al., 2012; KMA, 2011). However, Chang and Kwon (2007) reported that the amount of rainfall in the Korean Peninsula has increased mostly in August, causing an overall rise in the summer precipitation. Ho et al. (2003) suggested that there is a temporal change in the precipitation peaks, particularly a forward shift of the secondary peak. In addition, Changma (generally representing the primary peak) shows strong interannual variability (Ha et al., 2012; Ha & Lee, 2007; Seo et al., 2011).

The aforementioned studies have primarily focused on the characteristics of summer rainfall and their variability based on either pentad or monthly averages. However, the detailed characteristics and their change have not been well documented in hourly and daily timescales. The previously conducted hourly-based analyses also has too limited time span to draw clear conclusion in long-term trend in precipitation, particularly for extreme events. The present study compiled station-based hourly and daily precipitation data for 60 years focusing on the detailed precipitation changes in South Korea during extended summer and Changma seasons. Section 2 describes the data and method, and section 3 summarizes the characteristics of the summer precipitation (rain amount, rain rate, extreme events) over Korea and their changes from 1961 to 2020. Section 4 examines the spatial distribution of the precipitation characteristics. Finally, section 5 provides a summary and discussion of this study.

2 | DATA AND DEFINITION OF RAINY SEASON

2.1 | Data

This study utilized precipitation data obtained from regional Automated Synoptic Observing System (ASOS) stations operated by the Korea Meteorological Administration (KMA). Among about 100 ASOS stations, 15 stations have continuously recorded hourly precipitation from 1961 to 2020 (60 years) and enable long-term analyses on summer precipitation characteristics. The information and location of the stations are presented in Table 1 and Figure 1b. Additionally, daily precipitation data from 13 North Korean stations were also collected to better characterize the spatial structure of the rainfall in the Korean Peninsula. Then North Korean precipitation data were collected through the World Meteorological Organization (WMO) and provided by KMA. The North Korean data were available in daily average and for 48 years from 1973 to 2020. The North Korean data were used only for trend analysis to compare with South Korean precipitation trend.

Additional grid precipitation data were used to analyse the spatial features of the precipitation. The unified gauge-

TABLE 1 Latitude, longitude and elevation of the 15 stations in South Korea

Station	Latitude (°N)	Longitude (°E)	Elevation (m)
Seoul	37.58	126.97	85.5
Incheon	37.48	126.62	68.9
Gangneung	37.75	128.89	26.0
Chupungryeong	36.22	127.99	243.7
Pohang	36.03	129.38	3.9
Daegu	35.88	128.65	53.5
Jeonju	35.84	127.12	61.4
Ulsan	35.58	129.33	82.0
Gwangju	35.17	126.89	72.4
Busan	35.10	129.03	69.6
Mokpo	34.82	126.38	38.0
Yeosu	34.74	127.74	64.6
Ulleungdo	37.48	130.89	222.4
Jeju	33.51	126.53	20.5
Seogwipo	33.24	126.56	49.0

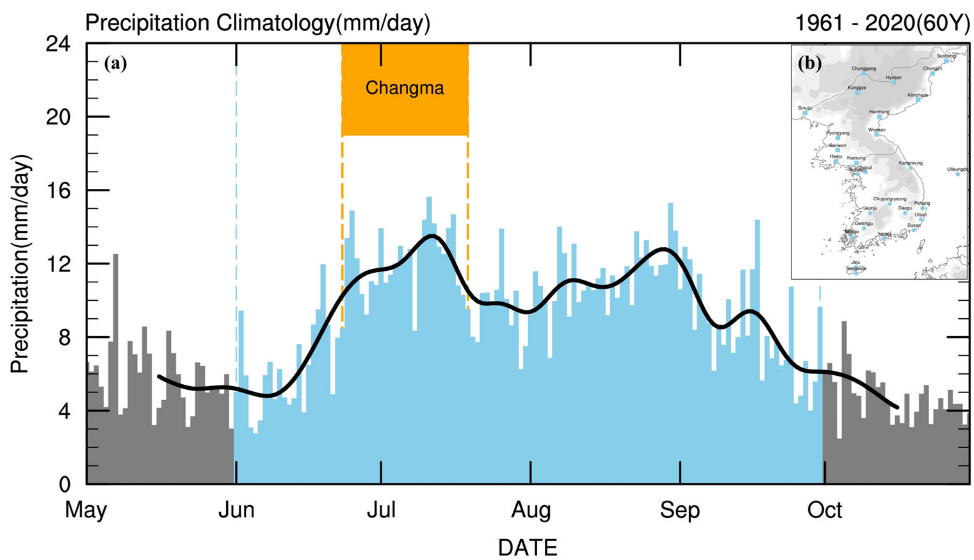

FIGURE 1 (a) Climatology (1961–2020) of daily rain rate (mm·day^{-1}) from stations in South Korea. The bars present daily, and the black curve indicates 10-day low-pass filtered values. (b) The map shows the locations of the 15 South Korean (KMA) stations. The 13 North Korean synoptic stations, which are used only for trend analysis, are also shown

based analysis (Xie et al., 2007) from NOAA (National Oceanic and Atmospheric Administration)/CPC (Climate Prediction Center) and APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation; Yatagai et al., 2012) data were adopted for the analysis. Both datasets were produced from surface precipitation measurements and provide daily record for the long period of time, that is, 1961–2005 for APHRODITE and 1979–present for NOAA/CPC. In order to make a direct comparison with station observations, APHTRODITE (1961–1978) and NOAA/CPC (1979–2020) data were merged for the analysis period (1961–2020). Because each precipitation dataset has a different spatial resolution (0.25° for APHRODITE and 0.5° for NOAA/CPC), APHRODITE was regridded into the NOAA/CPC 0.5° grid to merge two datasets.

2.2 | Definition of rainy season

Precipitation characteristics were analysed for extended summer from June to September (JJAS). The peak rainy season (Changma) was also defined to look into the precipitation change during the peak season. Because the onset date of rainy season varies each year (Ha et al., 2005; KMA, 2011; Oh et al., 2014; Seo et al., 2011), climatologically defined peak rainy season was used to conduct the analyses. The Changma season is fixed as climatological rainy period when the 27-day running average precipitation is the largest in the daily precipitation climatology (Figure 1). The climatologically defined Changma season is from June 23 to July 19, which matched well with the official records (June 24 to July 24) from Korea Meteorological Administration (KMA).

2.3 | Quantile regression

Quantile regression method is utilized to understand the behaviour of the extremes. Quantile regression estimate conditional quantile or percentile (Koenker & Bassett Jr, 1978; Koenker & Hallock, 2001) and allows better estimation for extreme values across a predictor variable, which is time in our analysis. A quantile regression model can be expressed as follow:

$$y_i = X_i\beta(\tau) + u_i, i = 1, 2, ..., n, \tau \in [0,1], Q_\tau(u_i|X_i) = 0,$$

$$Q_\tau(y_i|X_i) = X_i\beta(\tau) = \sum_i^n X_i\beta(\tau),$$

where y_i is the univariate response variable and X_i is the predictor variable, τ means the quantile level and has $\tau \in [0,1]$ values. β_τ represents the regression coefficient according to the quantile level and u_i is the error. The error term does not require an assumption of distribution, unlike ordinal least squares (OLS) method. $Q_\tau(y_i|X_i)$ represents the conditional quantile of y_i given X_i and quantile level(τ). Similar to the OLS method used for the traditional regression analysis, the regression coefficient estimator $\widehat{\beta}(\tau)$ for the quantile regression analysis is given as a solution to the following minimization problem,

$$\widehat{\beta}(\tau) = \min \sum_{i=1}^n \rho_\tau\left(y_i - X_i^T\beta\right), \text{where } \rho_\tau(\mathcal{Z}) = \mathcal{Z}(\tau - I(\mathcal{Z}<0)),$$

where n is the number of observation, $\rho_\tau(\mathcal{Z})$ is the loss function for a given quantile level (τ). We analysed daily precipitation measurements with $\tau = 0.95$ and 0.99 (referred as P95 and P99) to understand the trend of extreme precipitation.

3 | PRECIPITATION CHARACTERISTICS

3.1 | Trend in amount

The major characteristic of the precipitation in South Korea is the presence of the first rainy period in early July (Changma), followed by a second rainy period in early September with a relatively dry period in early August (Figures 1 and 2a). However, recent studies have reported sudden changes in this pattern (Choi et al., 2010). This change is also well observed in Figure 2. The traditionally known double-peak pattern is found during the early period (1961–1990s; blue curve in Figure 2b). However, after the mid-1990s, this pattern changed considerably. The climatologically dry season (early August) experienced substantial rain, particularly during the late 1990s and the early 2000s. Comparison of the first half (past 30 years) and the second half (recent 30 years) of the 60-year time series (Figure 2b) reveals these characteristics change clearly. Due to the increased precipitation in August, the dry season virtually disappeared. It is also noteworthy that the second rainy season began earlier in the recent climate comparing to the past one. In terms of rainfall amount, more rainfall is recorded from 1991 to 2020 (hereafter the recent climatology) than the one from 1961 to 1990 (hereafter the past climatology). The end of the second rainy season has notably delayed until late September (black line in Figure 2a is showing trend), while the onset date of the first rainy season presents no significant change. The end date was simply estimated as the day when precipitation falls below the yearly average based on the pentad precipitation (Figure 2a). This implies a longer and continuous wet season in the Korean Peninsula.

Figure 3 shows the time series of the daily rain rates and their trends averaged for summer (JJAS) and Changma period. Although the station data from North Korea have shorter records (48 years), it is also included to better understand the spatial distribution of the precipitation trends. The time series show gradual increases with relatively strong interannual variabilities. South Korea witnessed a gradual increase in the total precipitation, which is significantly manifested in the southern coastal regions. The precipitation change for South Korea is further summarized in Table 2. The average rain rate is 9.38 mm$\cdot$day^{-1} and the standard deviation is 1.56 mm$\cdot$day^{-1} for the past climatology. For the recent climatology, the average rain rate increases significantly to 10.31 mm$\cdot$day^{-1}, and its interannual variability also rises to 1.92 mm$\cdot$day^{-1}. Similarly, the average precipitation during Changma shows a significant jump from 11.45 mm$\cdot$day^{-1} in the past climatology to 12.95 mm$\cdot$day^{-1} in the recent climatology. This result shows significant rises in rain rate and its variability in recent climatology. North Korea also shows a significant increasing trend in precipitation in the past 48 years. It is noteworthy that the trend in North Korea is remarkably larger (9.7 mm$\cdot$day$^{-1}\cdot$century^{-1}) than that in the South Korea (2.6 mm$\cdot$day$^{-1}\cdot$century^{-1}), and the trend is significant at most stations.

3.2 | Intensity spectrum and extreme events

In addition to the amount of precipitation, the intensity change is further analysed by every 10 years using the 60-year hourly record in South Korea (Figure 4). The intensity is categorized into four levels, that is, light (<5 mm$\cdot$h^{-1}),

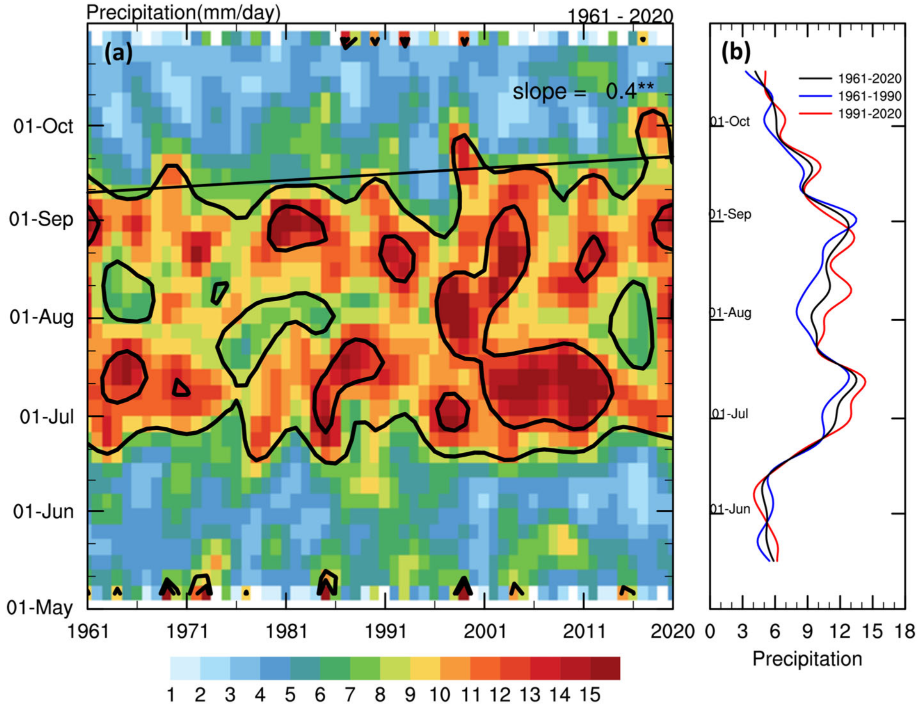

FIGURE 2 (a) Pentad-mean daily rain rate (mm·day^{-1}) averaged for the 15 South Korean stations as a function of year (*x*-axis) and day of year (*y*-axis). The straight line (day·year^{-1}) indicates the trend for the end date of the Post Changma. (b) 10-days low-pass filtered climatology for the past 30 years (1961–1990, blue), recent 30 years (1991–2020, red) and the total period (1961–2020, black)

moderate (5–20 mm·h^{-1}), heavy (20–30 mm·h^{-1}) and extreme (>30 mm·h^{-1}) rain. Precipitation exceeding 30 mm·h^{-1} or 100 mm·day^{-1} is often used for the definition of extreme events in South Korea (Cha et al., 2007a; Jo et al., 2020; Jung et al., 2011; KMA, 2011). Our station data analysis (Figures S1 and S2, Supporting Information) confirms that the 30 mm·h^{-1} and 100 mm·day^{-1} criteria correspond to the 99.54th and 97.71th percentiles, respectively. Although there is slight difference in frequency, the 30 mm·h^{-1} and 100 mm·day^{-1} criteria are used for hourly and daily extreme following previous literature to facilitate comparison. During the summer and Changma period, the frequency and amount of light rain tend to decrease, whereas those of the moderate, heavy, and extreme rain generally increase. In particular, the extreme rain rate with exceeding 30 mm·h^{-1} clearly shows increases in both frequency and amount. This is a meaningful indicator that the characteristic of summer precipitation in the Korean Peninsula has been shifted to convective rain, which can cause flash flood events. The Changma period shows similar but relatively weaker trends, and the rise in the intensity is more pronounced during the post-Changma period (figure is not shown), whose time span become complex and longer (refer to Figure 2a).

The precipitation intensity change is further summarized by comparing the past and recent daily climatology (Figure 5). Similar to the results from the hourly precipitation (Figure 4), weak rain (0–50 mm·day^{-1}) decreases in the recent climate while moderate and heavy rain (>50 mm·day^{-1}) increases significantly compared to the past climatology. Particularly, the extreme rainfall over 100 mm·day^{-1} increased by 30% in amount. From the perspective of the ratio to total precipitation during summer, the rainfall less than 50 mm·day^{-1} declined by 6.3%, and the rainfall of 50–100, 100–150, 150–200 and over 200 mm·day^{-1} increased each 2.9, 1.1, 0.6 and 1.6%, respectively.

This feature is clearly revealed in the precipitation spectrum (rain amount as a function of rain rate; Figure 6). The increase in the precipitation amount in the recent climatology is most noticeable for the precipitation events of 70–100 mm·day^{-1}, which are observed throughout the summer. Similar to the results shown in Figure 5, a decrease of rainfall amount is observed at the intensity range of 20–40 mm·day^{-1} in the recent climatology (Figure 6). Daily precipitation in North Korea shows similar results as in South Korea (Figure S3). The summer rainfall in 70–120 mm·day^{-1} range increases in the recent climatology compared to the past, while the amount in less 30 mm·day^{-1} range significantly decrease. The hourly precipitation shows significant increases in the intensity levels of 10–14, 22–32 and 34–38 mm·h^{-1} (Figure S4). The rainfall with an intensity greater than 30 mm·h^{-1}, which is considered as extreme precipitation that might cause flash floods, increases significantly by 39% in JJAS and 52% in the Changma period. Such an increase in precipitation intensity is consistent with previous studies that used relatively short precipitation records (e.g., Choi et al., 2010; Ho et al., 2003). It is noteworthy that, during the Changma period, the amount of rainfall increases in the most of the intensities in the recent climatology. These characteristics are summarized in Table 3.

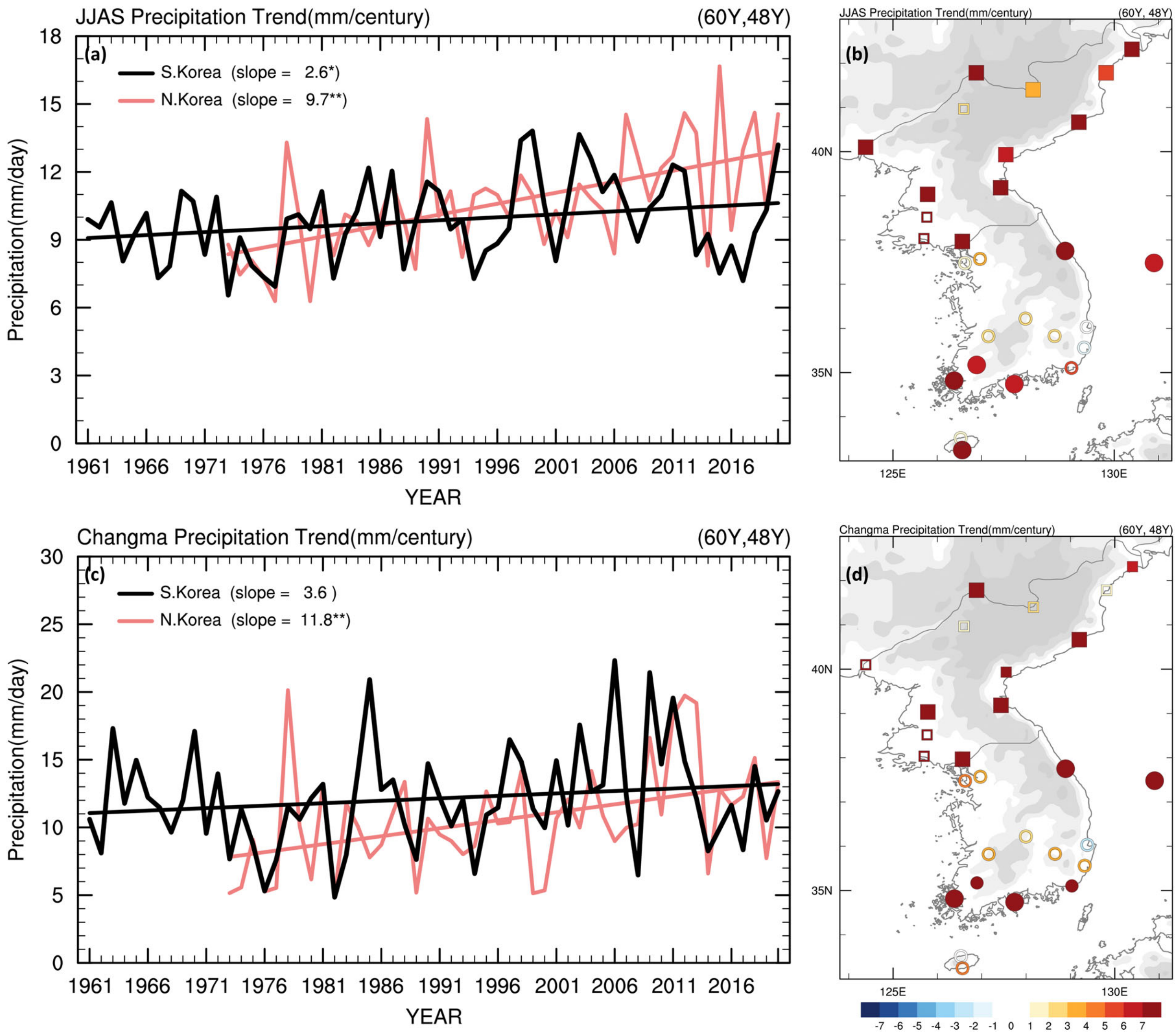

FIGURE 3 (a, c) Annual time series of daily rain rate (mm·day^{-1}) averaged for (a, b) JJAS and (c, d) Changma seasons observed in South (black) and North Korea (red) stations, and (b, d) their trends. The filled large and small circles (square mean station of North Korea) present significant values at 95% and 90% confidence levels, respectively

TABLE 2 Mean and standard deviation of seasonally averaged daily precipitation rate (mm·day^{-1}) for JJAS and Changma

Period	Unit (mm·day^{-1})	Past 30 years	Recent 30 years	Difference
JJAS	Mean	9.38	10.31	0.93*
	Standard deviation (interannual variation)	1.56	1.92	0.36
Changma (23 June–19 July)	Mean	11.45	12.95	1.5*
	Standard deviation (interannual variation)	3.56	3.85	0.29

Note: Asterisk (*) denotes significant value at 95% confidence levels.

4 | SPATIAL CHARACTERISTICS

4.1 | Precipitation trend

The daily gridded rainfall data are analysed to get an insight into the spatial distribution of precipitation in the Korean Peninsula and surrounding East Asian regions. The average precipitation in South Korea is about 5–8 mm·day^{-1} during summer and 7–10 mm·day^{-1} during Changma (Figures 7a,c and S5), which is approximately 30% lower than the precipitation records from the stations (compare Figures 3 and 7). This discrepancy is likely due to gridding processes and spatial representation issue. However, the long-term trend and interannual variability of the grid data match well with those of the stations, indicating that the gridded data are suitable for the trend analysis.

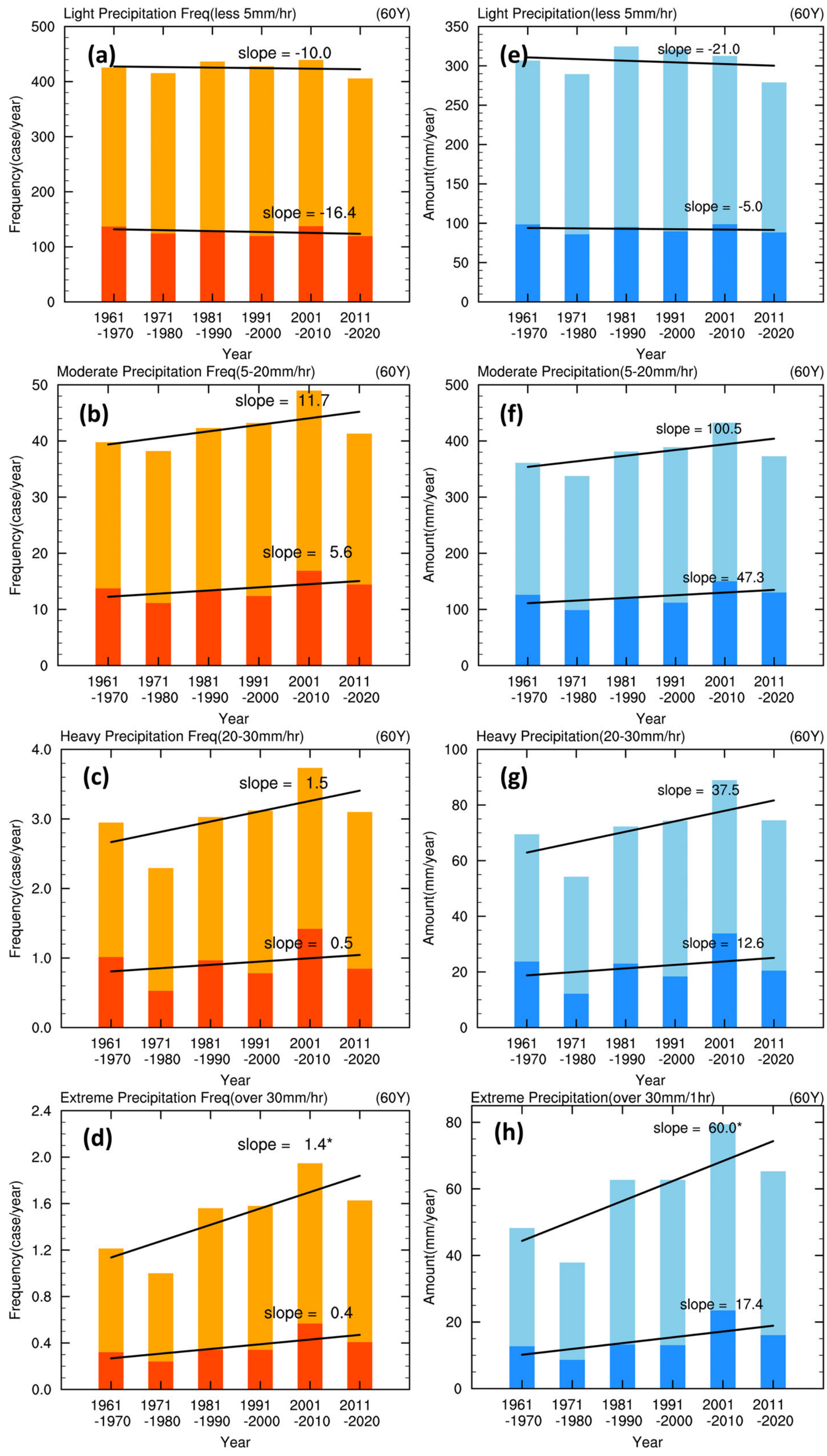

FIGURE 4 (a–d) Annual frequency and (e–h) amount of (a, e) light (<5 mm), (b, f) moderate (5–20 mm), (c, g) heavy (20–30 mm), and (d, h) extreme (>30 mm) hourly rainfall during JJAS (light colours) and Changma (dark colours) averaged for South Korea stations from 1961 to 2020. The trend (frequency or amount·century^{-1}) is computed using yearly data applying 10-year running mean, but units are changed to frequency (or amount) per decade for clarity. Asterisk represents significant values at 90% confidence level

During the Changma period, the Korean Peninsula experiences a large amount of rain along with central China and southern Japan (Figure S5). Although rainy season in China (Mei-Yu) and Japan (Baiu) usually starts 1 or 2 weeks earlier than the Korean Changma, the spatial distribution explains a large amount of precipitation in

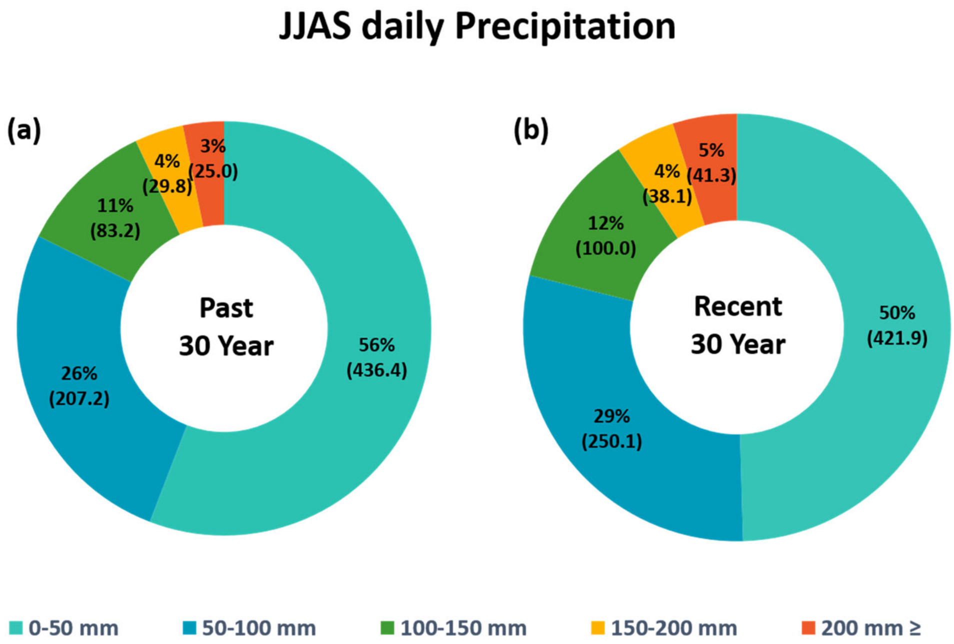

FIGURE 5 The amount of daily rainfall during JJAS obtained from South Korean stations and their intensity (50 mm interval) for the (a) past and (b) recent 30 years. The values in parentheses denote amount of rainfall in mm

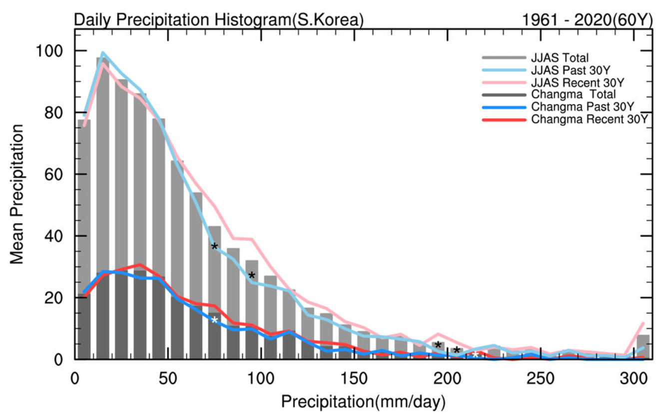

FIGURE 6 Histograms of rainfall amount (mm·period^{-1}) as a function of daily rain rates (mm·day^{-1}) from the South Korean stations. Interval of the rain rates is 10 mm. Values of the past and recent 30 years are presented in blue and red, respectively. Light and dark colours represent JJAS and Changma seasons. Black (white) asterisks present significant values in the difference between recent and past in JJAS (Changma) period at 90% confidence level

central China and southern Japan as the wet seasons of these three countries largely overlap in time (Wang, 2006).

Figure 7 shows the average rain rate in South Korea. APHRODITE and CPC show good overlap between 1979 and 2006, allowing us to merge them. The precipitation trend of South Korea shows 2.7 mm·day^{-1}·century^{-1} during summer and 5.0 mm·day^{-1}·century^{-1} during Changma period, which are significant at 95% and 90% confidence intervals, respectively. Although the trend of summer rainfall is similar to the measurements from the stations, precipitation trend in Changma period is slightly stronger than the station values (3.6 mm·day^{-1}·century^{-1}). The gap between the grid and station data can be attributed to different sampling of the data because the trend varies with location (Figure 3d).

The increase in summer precipitation in the Korean Peninsula is also observed over central China and southern Japan (Figure 7b). A similar, but stronger trend is observed during the Changma period (Figure 7d). Particularly, the shape of the trend is similar to that of the climatological rain band during the Changma period (Figure S5b), which leads to the speculation that the increased precipitation may be related to an enhancement of large-scale flow pattern forming the monsoon front. Qian and Lin (2005) and Liu et al. (2005) suggested an increase in the precipitation intensity in the eastern regions of China based on 40-year (1961–2000) precipitation data. Becker et al. (2006) also reported positive precipitation trends in the Yangtze River basin of China and attributed it to the increased moisture transport. Zhou

TABLE 3 (a) Daily and (b) hourly precipitation amount (mm) in South Korea

(a)	JJAS daily precipitation				Changma daily precipitation			
	60 years	Past 30 years	Recent 30 years	Diff	60 years	Past 30 years	Recent 30 years	Diff
0–50 mm	429.2	436.5	421.9	−14.5	132.7	131.1	134.3	3.2*
50–100 mm	228.7	207.2	250.1	42.9*	73.1	67.6	78.7	11.2*
100–150 mm	91.7	83.2	100.1	16.9*	30.2	27.0	33.5	6.4*
150–200 mm	33.9	29.8	38.1	8.3*	9.3	9.2	9.5	0.3
≥200 mm	33.2	24.9	41.3	16.3*	6.9	4.6	9.2	4.6*
(b)	**JJAS hourly precipitation**				**Changma hourly precipitation**			
	60 years	**Past 30 years**	**Recent 30 years**	**Diff**	**60 years**	**Past 30 years**	**Recent 30 years**	**Diff**
0–10 mm	504.8	497.4	512.1	14.6*	156.9	153.5	160.2	6.7*
10–20 mm	180.1	169.3	191.0	21.7*	58.9	54.8	63.2	8.4*
20–30 mm	72.3	65.3	79.3	14.0*	21.9	19.6	24.2	4.6*
30–40 mm	32.8	27.6	38.0	10.4*	8.0	6.5	9.5	2.9*
≥40 mm	26.6	21.9	31.1	9.2*	6.53	5.0	8.1	3.0*

Note: The past 30 years and recent 30 years values and their differences are provided for JJAS (left) and Changma (right) seasons. Asterisk (*) denotes significant values at 95% confidence level, respectively.

and Wang (2006) showed that the increasing summer precipitation along the Yangtze River is positively related to warm sea surface temperature (SST) anomaly over the Indian Ocean and south China sea which is strongly affected by the strengthened Hadley circulation. In addition, the southwest expansion of the North Pacific subtropical high and the resulting changes in water vapour transport (Allan & Ansell, 2006) could cause this trend. Endo (2011) explains that precipitation in southwestern Japan tends to decrease overall during the early Baiu (1 June–20 June) period and increase during the late Baiu (11 July–31 July) period. For the precipitation trend in Japan, Endo (2011) described that the Baiu front became more persistent during the late Baiu period (mid to late July) producing more precipitation in southern Japan. Preethi et al. (2017) suggested that the increasing summer rainfall over Korean–Japan has a significant positive correlation with increasing trend in SST over Indian Ocean (e.g., Roxy et al., 2014). However, the physical mechanism is not fully understood.

4.2 | Characteristics of the trend

Similar to Lu et al. (2016) and Li et al. (2018), relative contributions of rainfall intensity (I) and frequency (F) on the summer and Changma total precipitation are evaluated using a linear regression model. The linear regression model $R = c_0 + c_1F^* + c_2I^* + \epsilon$ is computed based on the 60-year data with each element defined as follows: during the predefined periods of each year (summer and Changma period), the number of days with daily precipitation more than 1 mm is defined as frequency (F); the amount of precipitation for F days as R; the average precipitation during F days defined as intensity ($I = R/F$). The standardized frequency ($F^* = F/\sigma_F$) and intensity ($I^* = I/\sigma_I$) are used for the calculation, thus the coefficients c_1 and c_2 represent relative importance.

The variability and trend of the summer precipitation (R) are well explained by the frequency and intensity, and the regression model reveals that the summer precipitation is generally more sensitive to the intensity (c_2 = 127.7 mm) than a frequency (c_1 = 83.9 mm) change over the Korean Peninsula. Figure 8 presents the time series of c_1F^* and c_2I^* separately for 60 years. It shows that the interannual variability and trend are better represented by intensity than the frequency. In addition, the intensity explains stronger trend (339.8 mm·century^{-1}) than the frequency (80.8 mm·century^{-1}). The JJAS precipitation (R) trend is 340 mm·century^{-1} (equivalent to 2.8 mm·day^{-1}·century^{-1}) which is largely explained by the intensity trend.

The spatial distributions of c_1 and c_2 are further analysed over East Asia (Figure S6). Along with the Korean Peninsula, central China and southern Japan have 1.5–2 times higher coefficient for intensity (c_2) than the frequency (c_1) suggesting that the precipitation intensity is more important than the frequency in these regions. The spatial distribution of large c_2 values generally coherent with the region of increasing precipitation trend (Figure 7b). This result implies that the precipitation trend is related to the intensity increase of the precipitation. The middle to southern regions of Japan

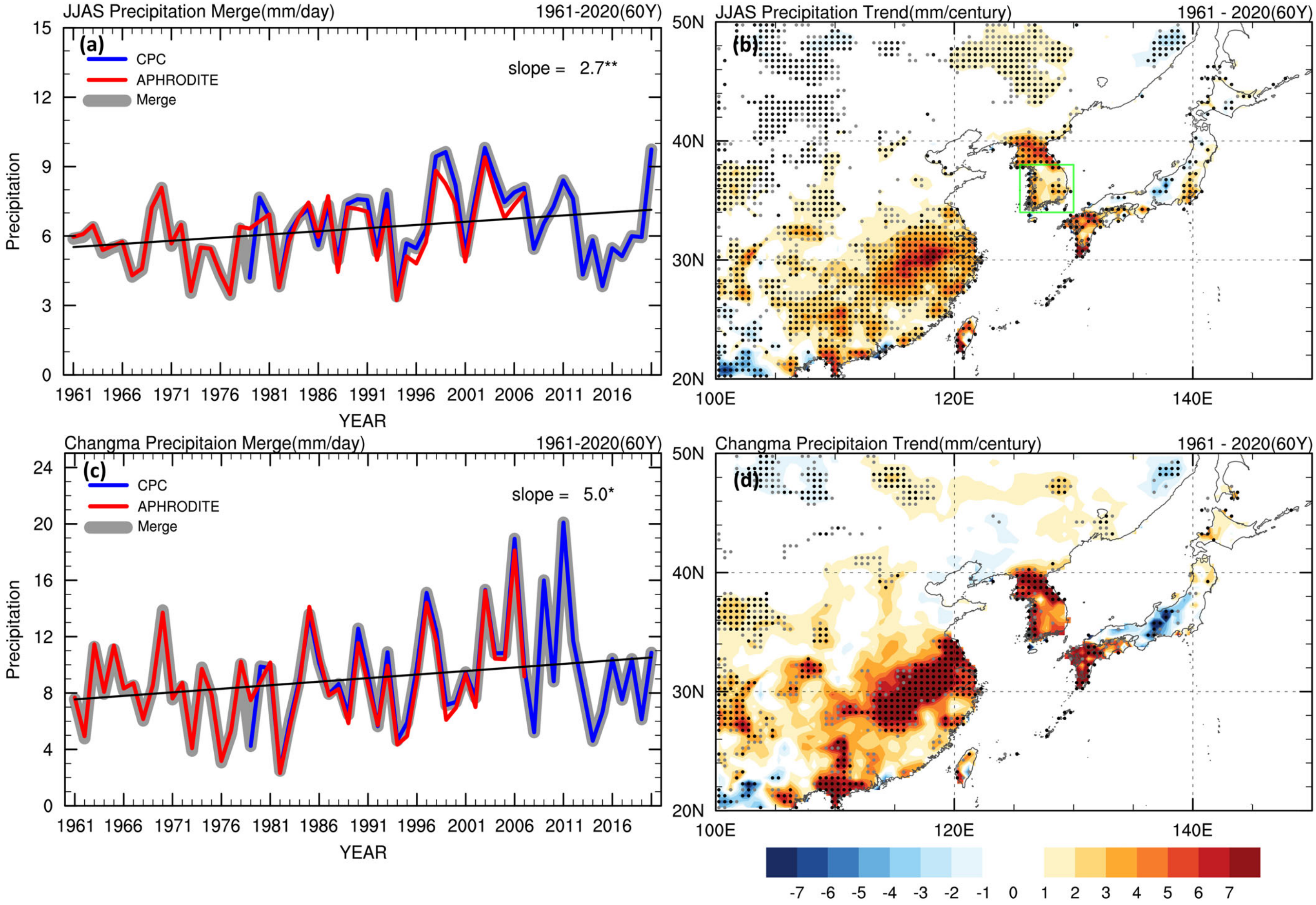

FIGURE 7 (a, c) Annual time series of seasonal mean rain rate (mm·day^{-1}) averaged over South Korea for (a, b) JJAS and (c, d) Changma season. (b, d) Their trend (mm·century^{-1}) maps are also presented in the right panel. The black and grey dots represent significant values at 95% and 90% confidence levels, respectively. The green box shows the averaged area of the (left panel and Figure 8) time series

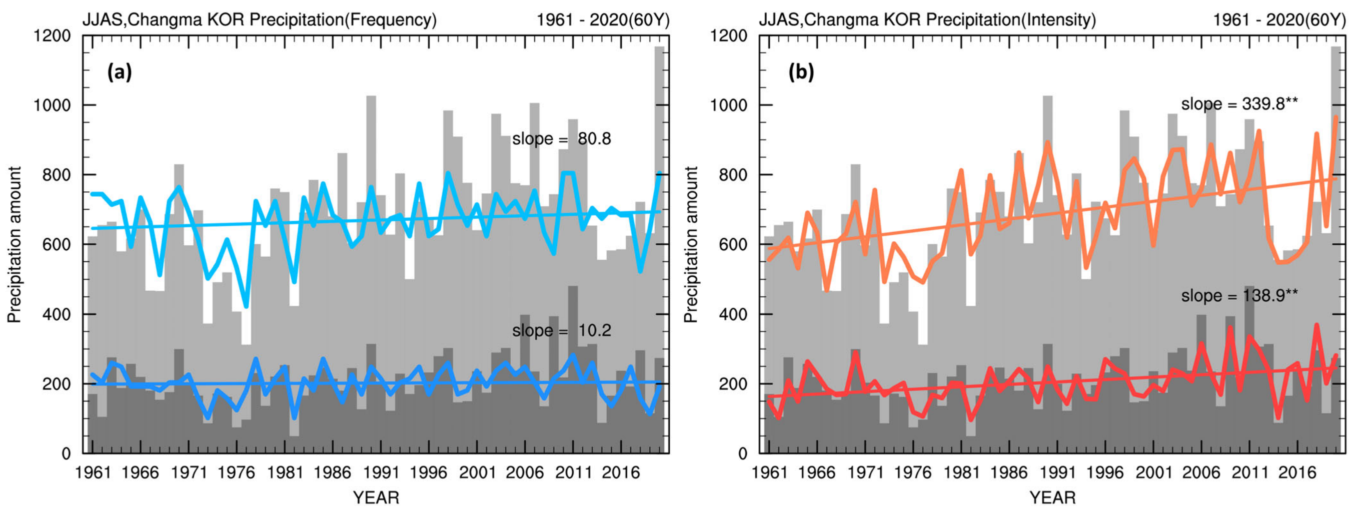

FIGURE 8 Annual time series of rainfall amount (mm·period^{-1}) are represented by terms of rain (a) frequency and (b) intensity parameters over South Korea (blue and red solid line, respectively). The actual rainfall amount (mm·period^{-1}) during JJAS and Changma are also shown as light and dark bars, respectively. The intercept values are added for both rain days and intensity for visual clarity, while slope is the necessary information

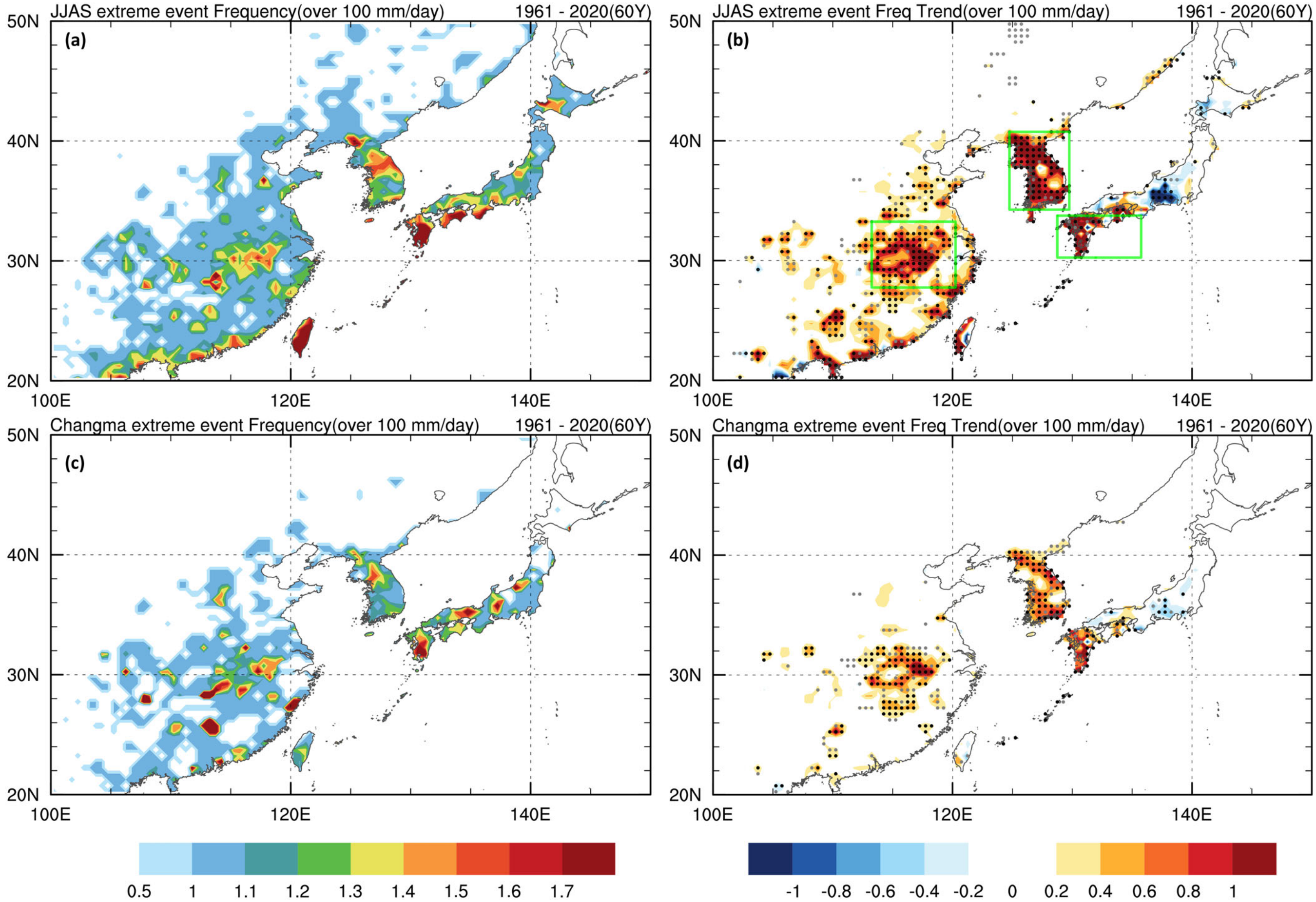

FIGURE 9 (a, c) Averaged frequency of heavy rainfall (>100 mm·day^{-1}) and (b, d) their trends (number·century^{-1}) for (a, b) JJAS and (c, d) Changma. The black and grey dots on the trend represent significant values at 95% and 90% confidence levels, respectively. The green boxes show the averaged area of Figures 10 and 11 time series

are remarkably sensitive to the intensity, while the enhanced precipitation is confined only in southern regions. Such a characteristic reflects Japan's upward trend of extreme precipitation, which will be further discussed in the next section.

4.3 | Extreme event

The frequency and trend of heavy rainfall are analysed to understand the spatial characteristics of the extreme events in East Asia (Figure 9). Based on the criterion of 100 mm·day^{-1}, the average number of extreme events in South Korea is 0.89 times a year in JJAS and 0.76 times a year during Changma. The extreme events are more frequently observed in central and southern coastal parts of the Korean Peninsula. In the next order, the frequency is high in the southwest, and the southeast area is observed with a lower frequency due to topographical characteristics. The trends of the extreme events show a similar distribution. In China, extreme rainfall is frequent over southern coastal regions and central China, particularly over the Yangtze River, but significant positive trends are mainly observed over the Yangtze River. In Japan, the wide area of the south Japan is affected by extreme events, while increasing trend is confined to the southwestern Japan on the windward side of summer mean flow. These trends in extreme events reminiscent of the trends in summer precipitation (Figure 7b) implying that extreme events may contribute a significant portion of the summer precipitation trends in these regions as their precipitation is strongly affected by intensity (refer to Figure S6). The spatial distribution of the trend is similar during the Changma period. This result is not very sensitive to the selection of the threshold.

The time series of the extreme events is further investigated over the three regions (Korean Peninsula, central China and southern Japan; denoted by the green box in Figure 9b) where clear increasing trends are observed (Figure 10). Korea and China show a steady increase in extreme events from the 1960s to the present with a significant trend of 1.0 and 0.5 frequency·century^{-1},

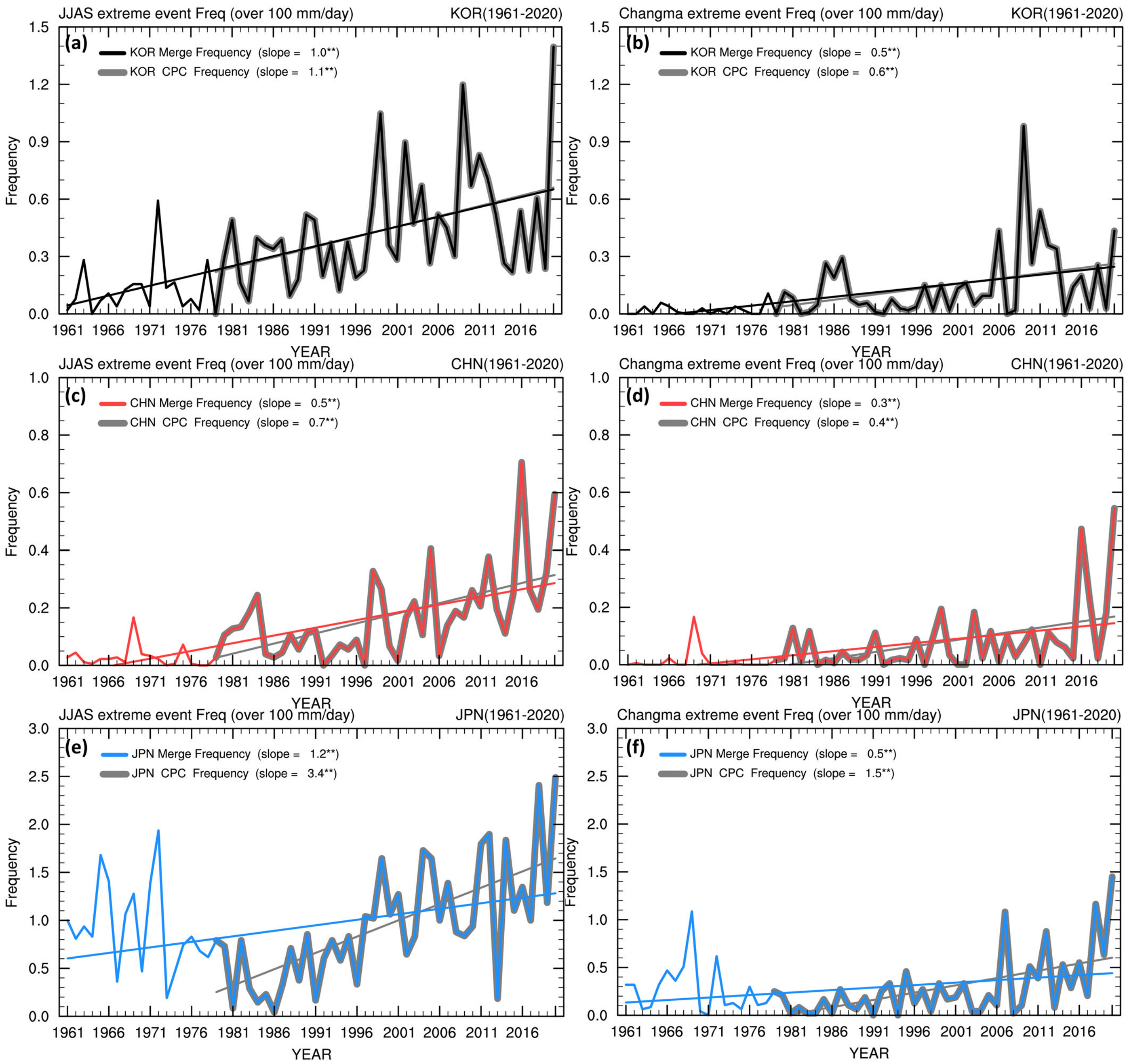

FIGURE 10 (a, c, e) Average frequency of heavy rainfall (>100 mm·day^{-1}) in JJAS and (b, d, f) Changma for (a, b) Korean Peninsula (black), (c, d) central China (red), (e, f) Southern Japan (blue). The straight line (number·century^{-1}) indicates the trend of frequency and grey line represents trends of frequency about only CPC data. Asterisk (**) denotes significant values at 95% confidence levels

respectively. Japan presents a slightly decreasing trend until the mid-1980s, but the frequency increases afterward showing a significant rising trend of 1.2 frequency·century^{-1}. Ohba et al. (2015) also reported the increase of heavy rains in Japan during Baiu Season and attributed it to the increase in water vapour transportation along the boundary of the North Pacific High. Duan et al. (2015) also suggested that the PDO (Pacific Decadal Oscillation) can affect the variability of the extreme events in recent decades. This result is consistent with the increase in strong precipitation in station observation over South Korea (Figure 6). With only CPC time series covering recent 42 years (1979–present), the trends are 1.1, 0.7 and 3.4 frequency·century^{-1} in summer over Korea, China and Japan, respectively (grey curve in Figure 10). The change of number of station used to CPC is not significant in East Asia from 1978 to 2003. During the Changma season, the three regions show slightly stronger trends than during the summer and present larger interannual variabilities than the summer.

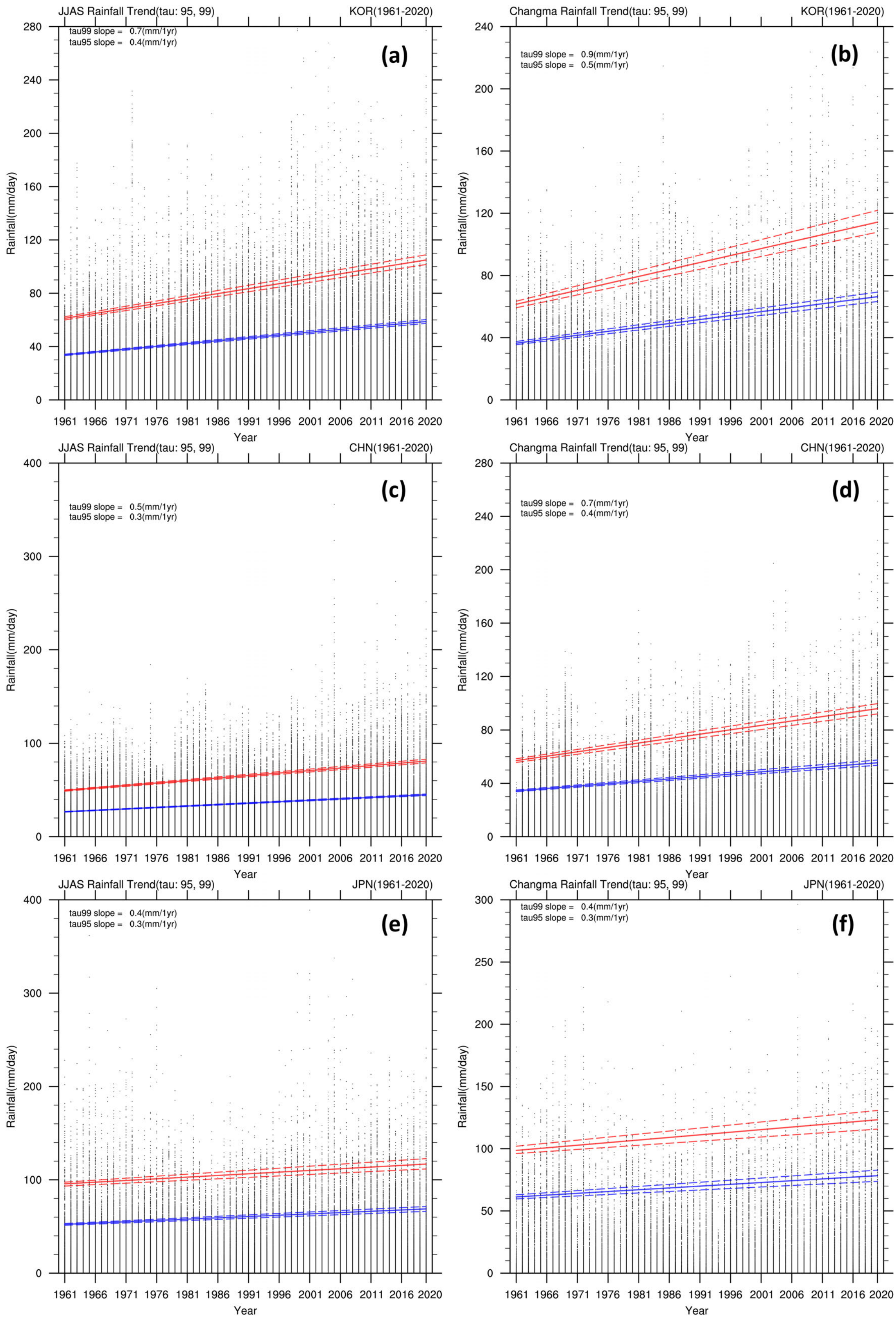

FIGURE 11 Time series of daily precipitation in (a, c, e) JJAS and (b, d, f) Changma for the period of 1961–2020 over (a, b) Korean peninsula, (c, d) Central China, (e, f) Southern Japan. Daily precipitation indicated by black dots, and linear slopes of P95 (blue) and P99 (black) showed by straight line. Dashed lines denotes significant interval at 95% confidence levels

The trend of extreme precipitation is further analysed for the Korean Peninsula, central China, and southern Japan using quantile regression. Top 1% (P99) and 5% (P95) daily precipitation are particularly examined during the summer and Changma season for the three regions (Figure 11). The P95 and P99 show clear rising trend for the three regions consistently with previous analysis (Figure 10). The average P99 value in southern Japan is about 100 mm·day^{-1} and the largest among the three regions. The P99 values in the Korean peninsula and central China show slightly lower average at ~80 mm·day^{-1}, however they show stronger trend than southern Japan. Particularly, P99 value in Korea shows a sharp trend of 0.9 mm·year^{-1}, which is roughly equivalent to 10% intensity increase per decade. These results clearly demonstrate that extreme events have been more frequent and stronger in East Asia.

5 | SUMMARY AND DISCUSSION

This study investigates the characteristics and long-term variability of summer precipitation and extreme event in South Korea using 60-year hourly record from surface stations. Gridded daily precipitation data are also used to understand the precipitation change in South Korea in connection to the precipitation change over East Asia. The summer precipitation climatology of South Korea exhibits distinct two peaks in early July and late August. This characteristic is well observed from 1961 to the mid-1980s. However, it is disturbed from the 1990s showing a large interannual variability. The end date of the rainy season presents a significant delay, whereas the beginning of the rainy season presents no significant trend. This implies that a rainy season in South Korea is lengthened. The rainfalls during summer and Changma period show significant upward trends in the Korean Peninsula with a remarkably larger increase in North Korea.

The comparison of the past and recent hourly precipitation climatology shows significant increases in moderate, heavy and extreme rainfall. Particularly, the frequency of the extreme rainfall (exceeding 30 mm·h^{-1}) presents a significant increase from 1 to 1.8 times during the recent 60 years. It is a clear indicator that the characteristic of summer precipitation in South Korean has been shifted to entail intense rain in a short period of time. The Changma season shows a similar trend with summer, but the increase is gentle and not significant yet. In precipitation intensity, significant increases are observed for the precipitation events of the 10–14, 22–32 and 34–38 mm·h^{-1} range suggesting a higher risk of localized flash flood over South Korea. During Changma, precipitation amount decreases in 0–2 mm·h^{-1} range and increase in the other ranges. Particularly, precipitation in the 10–12, 28–32 and 38–42 mm·h^{-1} range significant increase.

In the recent climatology, the daily precipitation slightly decreases in the 0–50 mm·day^{-1} strength (weak rainfall) and substantially increases in the other strengths (>50 mm·day^{-1}). From the perspective of the ratio to total amount, the rainfall over 50 mm·day^{-1} increased by 6.3%, of which maximum range is 50–100 mm·day^{-1}, and the ratio is 2.9%. The amount of extreme rainfall over 100 mm·day^{-1} increased by 3.3% to the total amount, which is ~18% increase from its past climatology. This daily rainfall increase is notably large in the precipitation intensity of 70–100 and 190–220 mm·day^{-1}, which could cause heavy and flash flood events. Daily precipitation in North Korea shows similar results to South Korea, which increase 70–120 mm·day^{-1} range in the recent climatology. However, the less 30 mm·day^{-1} range significantly decrease, and does not show increase about 200 mm·day^{-1} range.

The increasing precipitation trends appear across the East Asian region, including central China and southern Japan, forming a shape of monsoon rain belt. This pattern suggests that the large-scale monsoon front may be related to the monsoon precipitation increase. Further analysis reveals that the intensity increase is more responsible for the precipitation increase than the frequency increase. The spatial distribution of extreme precipitation (>100 mm·day^{-1}) presents a good coherence with the distribution of summer rainfall. However, its increase is more locally organized over the Yangtze River, Korean Peninsula and southwestern Japan likely forming the shape of a monsoon front. The frequency of extreme events steadily increases over central China and the Korean Peninsula, while it shows a gentle minimum in the mid-1980s before a strong increase over Japan. The extreme events (P99 and P95) show intensifying trends in East Asia, particularly where the summer monsoon is active. The increase is largest over South Korea during the Changma season. This result supports the idea that precipitation intensity strengthens in summer and Changma, and this likely causes more extreme events.

The summer precipitation in East Asia is affected by many factors such as the intensity of North Pacific High (e.g., Ha & Lee, 2007; Wang, 2006), frequency of synoptic cyclones (Park et al., 2021), moisture transport (Kamae et al., 2017; Mundhenk et al., 2016) and the location of subtropical westerly jet (Yokoyama et al., 2017; Zheng-Bin et al., 2014). The remote influence can also modulate the summer precipitation over East Asia: AO (Gong et al., 2011; Gong & Ho, 2003), ENSO (Wang et al., 2008; Weller et al., 2016) and Indo-Pacific warm pool SST (Roxy et al., 2014; Ueda et al., 2015). Recent studies reported that a strengthened monsoon front and moistening of lower troposphere are potential cause of the precipitation increase over

East Asia (Becker et al., 2006; Preethi et al., 2017). However, the fundamental cause of the increases in precipitation and reliable mechanisms are still open questions. Further studies based on long-term analysis and modelling will be beneficial for better understanding the causal relation.

AUTHOR CONTRIBUTIONS

Hyeon-Seok Do: Formal analysis; software; visualization; writing – original draft. **Joowan Kim:** Conceptualization; software; writing – review and editing. **Eun-Jeong Cha:** Data curation; formal analysis. **Eun-Chul Chang:** Data curation; investigation. **Seok-Woo Son:** Conceptualization; methodology; writing – review and editing. **Gyuwon Lee:** Methodology; writing – review and editing.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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