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RESEARCH ARTICLE - HYDROLOGY AND HYDRAULICS

Quantifying future rainfall extremes in Türkiye: a CMIP6 ensemble approach with statistical downscaling

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Abstract

This study investigates the projected impacts of climate change on extreme rainfall events across Türkiye, utilizing a 6-high-performer-member ensemble of CMIP6 global climate models under two different shared socioeconomic pathways: SSP2-4.5 (Middle of the Road) and SSP5-8.5 (Fossil-fueled Development—Taking the Highway). We quantified and compared projected changes in the 5-year, 50-year, and 100-year return period values for daily maximum precipitation and examined their spatial and temporal variations. Our findings revealed a consistent intensifying extreme rainfall and increase in the quantile values under both scenarios, with significantly larger increases projected under the high-emission pathway. Under SSP5-8.5, the mean 100-year return level in the far future (2071–2100) is projected to be 30% higher than the historical baseline (1961–2014), reaching a mean of up to 130 mm compared with the historical 100 mm. Under SSP2-4.5, the increase was moderate to 15%, reaching a mean of approximately 115 mm across Türkiye. This difference between the scenarios highlights the importance of emission reduction efforts in mitigating extreme rainfall risks. We also observed intensifying extreme rainfall, with projected increases becoming more pronounced in the future. The percentage increase in return levels is generally larger for shorter return periods (5-year) than for longer ones, suggesting a greater relative increase in the frequency of more common, less extreme events. Additionally, coastal regions exhibited higher positive anomalies than inland areas, indicating greater vulnerability to intensified extreme rainfall. These findings highlight the urgent need for proactive and regionally specific adaptation measures to enhance infrastructure resilience, improve disaster preparedness, and ensure management of water resources critical for agriculture and urban areas in Türkiye.

Keywords Climate change · cmip6 · era5-land · Return period · Extremes · Dam management

Introduction

The Earth's warming climate causes alterations in extreme weather events, with a notable increase in the intensity and frequency of heavy rainfall. This trend is expected to continue as the global mean temperature rises, posing significant challenges for disaster prevention and mitigation, particularly in vulnerable regions, such as the Mediterranean (Mirza 2003; Vavrus et al. 2024).

A growing body of scientific literature demonstrates that human-induced climate change exacerbates the frequency and severity of climate-related disasters, including wildfires, floods, heatwaves, and droughts (Dey and Lewis 2021; Maslin 2021; Banholzer et al. 2014). These events have profound implications for human health, safety, water resource management, dam management, and societal well-being (Weilnhammer et al. 2021; Kundzewicz 2016). The scientific consensus, as reflected in the latest IPCC report (IPCC 2021),

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identifies global warming as the primary driver of this intensification of extreme weather. As temperatures continue to rise throughout the twenty-first century, these events are projected to become even more frequent and severe (Gumus et al. 2023; Heeter et al. 2023; Kouman et al. 2022; Fan et al. 2021; AghaKouchak et al. 2020).

Understanding the changing dynamics of extreme weather, particularly extreme rainfall, and its consequences are of paramount importance for effective climate change adaptation. This is especially crucial in regions such as Türkiye, which is located in the Mediterranean region, a climate hotspot, where the interaction of climate change with factors such as land-use change, population growth, and urbanization amplifies the challenges (Barati et al. 2023; Chai et al. 2022). Effective adaptation requires a multiscale understanding of climate extremes, from global and regional patterns to local implications (Wang et al. 2022a, b; Wudineh et al. 2022). This localized understanding is essential for planning and updating critical infrastructure, such as drainage and irrigation systems, to cope with evolving precipitation regimes (Dharmarathne et al. 2024; Parker et al. 2022; Ouali and Cannon 2018).

General circulation models (GCMs) are crucial tools for projecting future climatic conditions (Pierce et al. 2009; Randall et al. 2007)). The Coupled Model Intercomparison Project (CMIP) plays a key role in evaluating and comparing these models (Pierce et al. 2009). The latest iteration, CMIP6, utilizes advanced models with improved physical process representation, higher resolution, and advanced initialization techniques to enhance the accuracy of precipitation projections (Bağçaci et al. 2021; Wyser et al. 2020; Eyring et al. 2016). The integration of Shared Socioeconomic Pathways (SSPs) within CMIP6 (O'Neill et al. 2016) allows for the exploration of diverse greenhouse gas emission scenarios and their influence on future precipitation patterns, providing a deeper understanding of human-climate interactions.

Although GCMs provide valuable insights, their coarse resolution limits their ability to represent localized weather phenomena (Oruc et al. 2024; Gumus et al. 2023). Downscaling techniques such as Quantile Delta Mapping (QDM) (Cannon et al. 2015) are essential for bridging this gap by converting coarse-scale GCM outputs into fine-scale regional assessments. The QDM preserves essential precipitation statistics and enables more precise projections of extreme rainfall (Kim et al. 2021; Teutschbein and Seibert 2012), which are crucial for informing effective infrastructure planning and climate adaptation strategies.

The Coupled Model Intercomparison Project Phase 6 (CMIP6) has provided critical insights into the future of extreme rainfall patterns in Türkiye, indicating significant regional variations and trends. Bağçaci et al. (2021) stated that CMIP6 projections suggest a warming trend of up to 6.5 °C during summer months, indicating a substantial increase in extreme heat events across Türkiye. Türkiye is in the Eastern Mediterranean close to the Middle East, currently highly susceptible to humid heat, and hydrological extremes and climate simulations reveal that extreme precipitation incidents will become more intense with shorter return periods in the following decades (Donmez et al. 2023). However, the number of studies coupling CMIP6 and extreme precipitation is still limited. CMIP6 models indicate a decrease in heavy rain frequency but an increase in very heavy rains and total precipitation from very heavy rain days in Türkiye (Gumus et al. 2023). According to Kelebek et al. (2024), future simulations indicate intensified daily and subdaily extreme precipitation in Türkiye's Black Sea region, with maximum amounts exceeding 280 mm/day and a significant increase in autumn precipitation. Furthermore, despite numerous studies examining climate change impacts on water resources in this region, a comprehensive understanding of the long-term effects of extreme events under varying climate scenarios remains incomplete. This study addresses this gap by leveraging the highest-performing CMIP6 models for precipitation over the region, Türkiye, identified by Gumus et al. (2023); Gumus (2023). This detailed analysis of extreme rainfall offers updated insights into the region's resilience to climate change, a crucial novelty in comparison with previous research. The study's specific focus on the best-performing CMIP6 models (particularly HadGEM3-MM and EC-Earth family) for extreme precipitation in Türkiye represents a significant advancement in the field, and to the best of our knowledge, one of the first studies utilizes a selection based on extreme precipitation performance of GCM models.

This research undertakes a comprehensive investigation of projected future extreme rainfall patterns in Türkiye, employing an advanced CMIP6 multi-model ensemble and a high-resolution reference dataset for "near future" (2014–2040) to the "mid-future" (2041–2070) and "far future" (2071–2100). We utilize the QDM downscaling technique to enhance the spatial resolution of the GCM outputs and provide locally relevant projections. Our primary objective was to improve the understanding of the complex relationship between anthropogenic climate change and extreme rainfall events in the context of Türkiye's specific geographic and climatic conditions. This enhanced understanding is critical for developing robust climate adaptation strategies across multiple sectors.

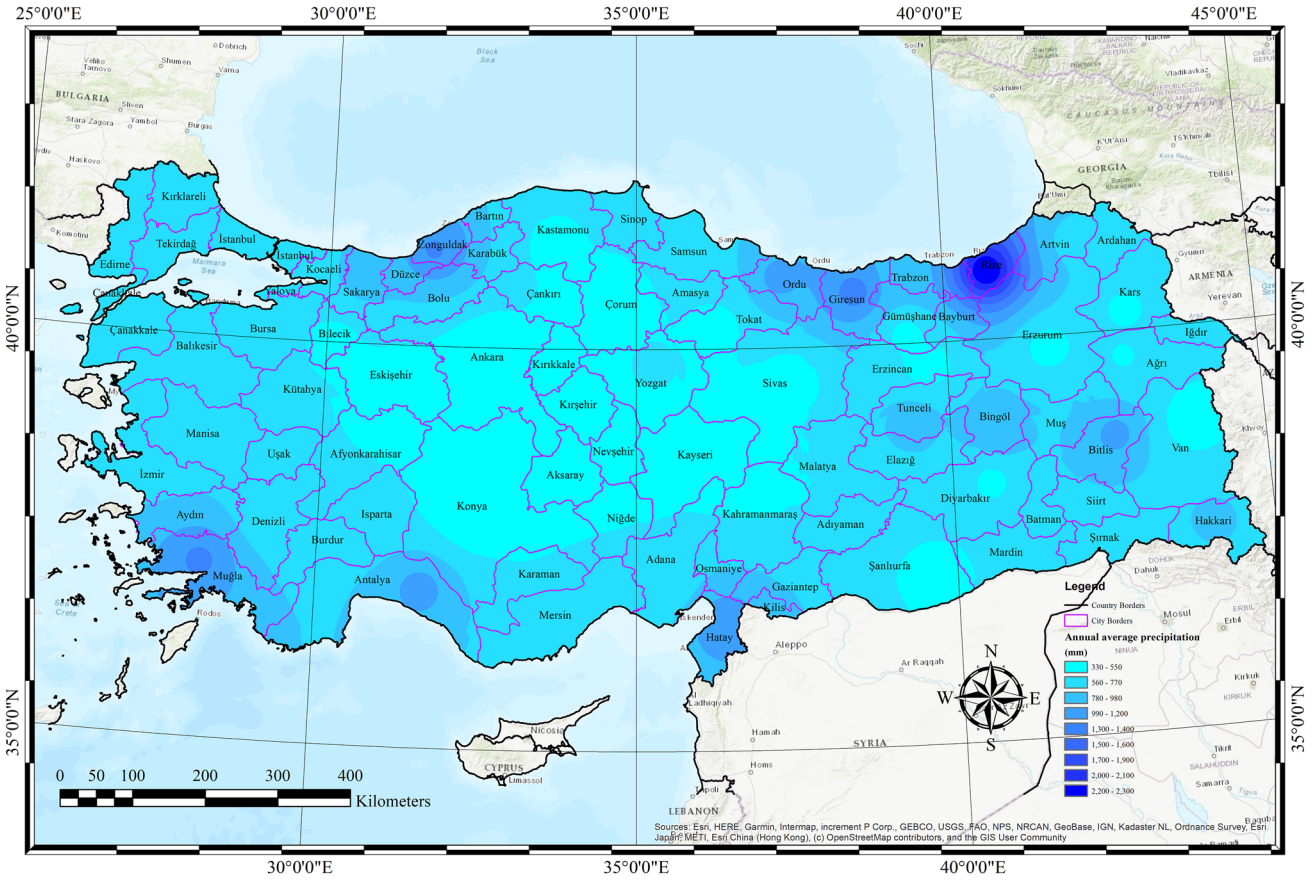


Fig. 1 Study area with precipitation heights

Data and methods

Study area

The geographical location and complex topography of Türkiye contribute to a diverse range of climatic conditions. Situated on the Anatolian Plateau in Western Asia, the country is bounded by the Black Sea, Aegean Sea, and Mediterranean Sea, encompassing a total land area of 783,562 km^2 (Fig. 1). While the Mediterranean climate predominates, regional variations arise because of the interplay of latitude, altitude, and proximity to large water bodies. Coastal areas experience milder conditions, whereas inland regions, particularly those shielded from maritime influences by mountain ranges such as the Taurus and Northern Anatolia, exhibit a more continental climate characterized by hot, dry summers, and cold winters. This climatic diversity is reflected in the precipitation patterns, with annual rainfall ranging from approximately 400 mm in Central Anatolia to over 2200 mm in the Black Sea region. Temperature variations were also pronounced, with the highest annual averages recorded in the Mediterranean and Aegean coastal regions and the lowest in Eastern Anatolia. National meteorological data for the period 1991–2020 indicate a mean annual temperature of 13.9 °C and average rainfall of 573.4 mm (GDM 2023).

Data

Reference data—ERA5-Land

In this research, the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5-Land dataset, a comprehensive reanalysis dataset for global climate and weather, serves as a reference source. The ERA5-Land dataset (Muñoz-Sabater et al. 2021; Muñoz Sabater 2019) offers data extending back to less than month from 1950 to the present. This dataset provides high-resolution hourly information on the land surface variables. Reanalysis integrates model data with observations around the world using the laws of physics to produce a complete and consistent dataset on a global scale. ERA5-Land is a tailored version of the ERA5 dataset that pertains to land area. The primary distinction between the original and this variant is that the horizontal resolution is 0.10° × 0.10° rather than 0.25° × 0.25°, which enables more precise scales. The temporal resolution

was hourly, similar to that of ERA5. This dataset was utilized to correct the bias of the GCMs and to evaluate the performance of the bias-corrected data.

Satellite precipitation datasets are known to present biases when compared to ground-based observations, especially in regions with complex terrain. Different satellite datasets may perform with varying degrees of accuracy depending on the specific characteristics of the study area. On the other hand, ERA5-Land is a reanalysis data set, which has been shown to perform well in capturing general precipitation trends and has higher resolution than many alternatives, and it is a valid choice for this study (Yilmaz 2023; Gumus et al. 2023; Gomis-Cebolla et al. 2023; Alexandridis et al. 2023).

CMIP6 GCMs

In this study, CMIP6 global climate models were employed as future projections. The 6th edition of the CMIP (CMIP6) is understood to have performed better than its predecessor, CMIP5. The factors contributing to these advancements can be summarized as assessing the extent of natural or human-caused radiation, accounting for aerosols, and factoring in land-use impacts (Bağçaci et al. 2021; Eyring et al. 2016; Lei et al. 2023; Li et al. 2020; Roesch et al. 2024). Despite the comparatively recent nature of CMIP6 data, there has been a noticeable increase in the utilization of the most current projections (Ma et al. 2024; Oruc et al. 2024; Gumus et al. 2023).

Various studies have provided differing results regarding the performance of CMIP6 and CMIP5 in different working regions. GCMs utilized in this study were selected based on the evaluation of Bağçaci et al. (2021), which compared the performance of CMIP6 and CMIP5 over Türkiye. Table 1 presents the names of the GCMs utilized in this study, along with data availability for different experiments (historical, SSP2-4.5, and SSP5-8.5) and spatial resolutions derived from the CMIP Phase 6 (CMIP6).

This study investigates the future climate under two scenarios: SSP5-8.5 and SSP2-4.5. Through examining these scenarios, the study presents a comprehensive understanding of future climate characteristics. SSP 5-8.5, with an anticipated radiative forcing of 8.5 W/m^2 by the late twenty-first century, describes a world driven by rapid economic growth, high energy use, and continued fossil fuel dependency, underscoring the pressing need to address this reliance and its potential risks. In contrast, SSP 2-4.5 envisions a more moderate socioeconomic path with a focus on sustainability, resulting in a radiative forcing of 4.5 W/m^2, emphasizing the role of sustainable development and emissions reduction to avoid severe climate impacts. The impacts projected under different scenarios often result in quantitative rather than qualitative differences, which means that while the magnitude of impacts may vary, the types of impacts remain consistent across scenarios. Therefore, using a moderate- and a high-emission scenario can effectively capture the range of potential future conditions without needing multiple intermediate scenarios (Burgess et al. 2023; Tebaldi et al. 2021). The comparison of these scenarios provides valuable insights into shaping climate policies, adaptation strategies, and promoting a more sustainable and resilient future, while deepening the understanding of how socioeconomic factors influence climate outcomes.

Table 1 CMIP6 GCMs utilized

Rank	CMIP 6 GCM	Spatial resolution
1	EC-Earth3 (Europe)	0.70 × 0.70
2	HadGEM3-GC31-MM (UK)	0.83 × 0.56
3	EC-Earth3-AerChem (Europe)	0.70 × 0.70
4	EC-Earth3-CC (Europe)	0.70 × 0.70
5	EC-Earth3-Veg-LR (Europe)	1.12 × 1.12
6	EC-Earth3-Veg (Europe)	0.70 × 0.70

To ensure consistency and facilitate fair comparison, a single ensemble member (named $r_ni_np_nf_n$, where r denotes realization, i denotes initialization, p denotes model physics, and f denotes forcing) approach was used. The outputs of the GCMs were primarily selected from the ensemble member r1i1p1f1.

Therefore, EC-Earth3 family models are members of r1i1p1f1 while HadGEM3-GC31-MM model is a member of r1i1p1f3 in this study.

Methodology

Bias correction

Diverse techniques have been extensively employed to downscale and correct the persistent bias in the mean and standard deviation of coarse-resolution climate model outputs. Assessing the local effects of climate change is a complex phenomenon due to the uncertainty associated with extracting data from global models with coarse resolution and converting it into information specific to the local area. As a result, techniques for downscaling and bias correction have gained widespread use in recent years to facilitate regional and local impact investigations. The literature contains a wide range of downscaling techniques; however, in this work, we concentrate on the quantile delta mapping (QDM) method, which has shown to perform better when handling extremes and used over the region successfully (Oruc et al. 2024; Gumus et al. 2023; Cannon et al. 2015).

As highlighted by Maraun (2013) and Maurer and Pierce (2014), quantile mapping-based methods, such as QDM, can unintentionally exaggerate or diminish projected trends in

extreme precipitation. This issue is particularly pronounced in grid cells where the model does not adequately represent historical variance or where observational data exhibit a scaling behavior that differs from model outputs. Although concerns regarding the stationarity of biases and the potential underrepresentation of evolving precipitation extremes are justified, QDM provides a practical compromise between computational efficiency and accuracy, particularly when dealing with large-scale datasets across diverse climate scenarios (Maraun 2013; Maurer and Pierce 2014; Cannon et al. 2015).

The QDM method emerged to overcome and adjust systematic biases while maintaining the relative changes in the modeled quantiles of the variable being studied (Cannon et al. 2015). The fundamental equation of the quantile delta mapping method includes the bias-corrected value derived from the observational data and the relative change term sourced from the model data. This method differs from the detrended quantile mapping method in that it considers all modeled quantiles rather than solely focusing on the modeled mean.

The transfer function of regular quantile mapping is as follows:

$$\hat{x}_{m,p}(t) = F_{o,h}^{-1}\left\{F_{m,h}\left[x_{m,p}(t)\right]\right\}, \tag{1}$$

$F_{o,h}$ and $F_{m,h}$ represent the cumulative distribution functions (CDFs) of the reference (observed) and modeled data, respectively, for the historical period. $x_{m,p}(t)$ is the model value at time t from the projection period.

Initially, QDM calculates $\tau_{m,p}$, the nonexceedance probability associated with the value at time t, with the following equation:

$$\tau_{m,p}(t) = F_{m,p}^{(t)}\left[x_{m,p}(t)\right], \text{ where } \tau_{m,p}(t) \in \{0,1\}. \tag{2}$$

Then, the relative change in the model data over the historical and projection periods, $\Delta_m(t)$, can be calculated as follows:

$$\Delta_m(t) = \frac{x_{m,p}(t)}{F_{m,h}^{-1}\left[F_{m,p}^{(t)}\left\{x_{m,p}(t)\right\}\right]}. \tag{3}$$

The bias correction of the modeled $\tau_{m,p}$ quantile can be calculated as:

$$\hat{x}_{o:m,h:p}(t) = F_{o,h}^{-1}\left\{F_{m,p}\left[x_{m,p}(t)\right]\right\}. \tag{4}$$

Lastly, relative change $\Delta_m(t)$ is introduced to the bias-corrected model to obtain the bias-corrected future projection at time t,

$$\hat{x}_{m,p}(t) = \hat{x}_{o:m,h:p}(t) * \Delta_m(t). \tag{5}$$

The downscaling and bias correction are applied to each model individually, after which a multi-model ensemble mean is generated from the outputs to serve as the final dataset. In this study, Era5-Land data were used as a reference from 1961 to 2014 and models were bias-corrected based on this reference period.

Multi-model ensemble average

All Global Circulation Models (GCMs) were bias-corrected and downscaled to a 9 km × 9 km resolution before further analysis. Due to the varying resolutions and grids of the GCMs, a uniform grid system, specifically ERA5-Land, was used in this study. By using ERA5-Land as the reference dataset for bias correction and downscaling, consistency was ensured across all the downscaled models.

The multi-model ensemble average (MMEA) method is commonly employed in climate modeling studies to handle uncertainties arising from the parameterization, assumptions, and approximations of GCMs (Oruc et al. 2024; Gumus et al. 2023; Ahmed et al. 2019). While no universally accepted standard dictates the optimal number of GCMs for multi-model ensemble average (MMEA) analysis, research suggests that using the top-ranked three to ten GCMs is a common practice (Ahmed et al. 2019). However, some studies incorporate all available GCMs without ranking, which can lead to suboptimal MMEA performance. This is often due to the inadequate representation of crucial geographical features like orography (mountain ranges) or boundary structures in some lower-ranked models, affecting the accuracy of regional climate projections (Grose et al. 2020). Furthermore, incorporating a larger number of GCMs significantly increases the computational demands of the analysis, particularly when downscaling techniques are applied to enhance spatial resolution for local impact assessments. Therefore, it is crucial to determine the appropriate number of MME members by using this approach. In this study, we selected the aforementioned GCMs based on their performance evaluation by Gumus et al. (2023).

Extreme value analysis: employing the GEV distribution and block maxima approach

This study utilized extreme value analysis (EVA) to investigate meteorological extremes, a common approach for analyzing extreme weather events (Mtibaa 2024; Larrodera Baca et al. 2021; Wang et al. 2021; Makkonen and Tikanmäki 2019). Specifically, we employ the extreme value theory (EVT), which focuses on the statistical properties of distribution tails and provides methods for estimating the distribution of extreme values within a time series (Zorzetto et al. 2024; Nerantzaki and Papalexiou 2022). EVT utilizes

probabilistic distribution functions such as the generalized extreme value (GEV) or generalized Pareto distribution (GPD) to model extreme events, making it a valuable tool for engineering applications that deal with extreme conditions (Coles and Sparks 2006).

We have chosen the GEV distribution function to fit the block maxima (BM) of our data, an established method for characterizing the probability distribution of extreme values within the data blocks (Gilleland and Katz 2016).

$$G(z) = \exp\left(-\left\{1+\xi\left(\frac{z-\mu}{\sigma}\right)\right\}+-1/\xi\right), \quad (6)$$

where $z+ = \max\{z, 0\}$, $\sigma > 0$, and $-\infty < \mu, \xi < \infty$ (Coles et al. 2001).

The GEV distribution, defined by three parameters: location (μ), scale (σ), and shape (ξ)—given by Eq. (1) and depending on the sign of the shape parameter, ξ, three different distributions results, such as Fréchet from $\xi > 0$, Weibull when $\xi < 0$, and Gumbel from taking the limit as $\xi \to 0$ (Gründemann et al. 2023; Coles and Sparks 2006; Coles et al. 2001).

The Block Maxima (BM) approach was employed to analyze the probability distribution of maximum values within blocks of equal length (e.g., annual maximum daily precipitation) (Nerantzaki and Papalexiou 2022). The GEV distribution was then fitted to the obtained maxima series to estimate the exceedance probability, return periods, and corresponding return levels. It is important to note that the effectiveness of the BM approach depends on the block size and the number of blocks. If the number of blocks is small or the block size introduces biases, the distribution of the maximum series may not converge to the GEV distribution, as expected (Nerantzaki and Papalexiou 2022; Papalexiou and Koutsoyiannis 2013). In this study, annual blocks obtained from daily time series were used from 1961 to 2014 as reference period and from the 2015–2100 period for the future periods.

For parameter estimation of the GEV distribution, we used the maximum likelihood estimation (MLE) method. MLE is well-suited for this task because of its adaptability to model changes and advantageous asymptotic properties (Mahmoodian 2018). By maximizing the likelihood function, the MLE allows us to determine the optimal distribution parameters that best characterize the observed data.

Results

In this study, three future periods—near future (2015–2040), mid-future (2041–2070), and far future (2071–2100)—were evaluated and compared to the reference period using two distinct SSP scenarios, SSP2-4.5 and SSP5-8.5, for Türkiye.

The projections for future precipitation extremes indicate that they are likely to intensify in magnitude over land, surpassing historical extremes (Figs. 2, 4, and 6). This finding is strongly supported by consistent agreement across multiple models, regardless of the climate scenario or the frequency of extreme events (whether they occur every 5, 50, or 100 years), especially in projections for the distant future. The regions that are expected to experience the greatest increase in future extremes are primarily located around the coasts and just south of Eastern Anatolia. Although there are some locations in Central Anatolia and the inner Aegean regions where extreme precipitation is expected to decrease or remain unchanged in the near future, this is not the case for the majority of the study area.

The projected changes in 5-year return period values for extreme daily precipitation events across Türkiye were derived from a 6-member ensemble of GCMs under two contrasting SSPs: SSP5-8.5 (high-emission scenario) and SSP2-4.5 (moderate mitigation scenario) (Fig. 2).

Both scenarios projected a widespread increase in the 5-year return values, indicating the potential for more intense extreme precipitation events across Türkiye. However, the magnitude and spatial distribution of these changes differed significantly between the two scenarios.

SSP5-8.5 (high-emission scenario) exhibited a more pronounced and widespread intensification of extreme precipitation. The increases in 5-year return values are likely to be substantially larger compared to SSP2-4.5, particularly in the "Far Future" (2071–2100). For example, although coastal regions might experience increases of 15-25% under SSP2-4.5, these increases could escalate to 30–40% or even higher under SSP5-8.5. This highlights the amplified risks associated with the high-emission pathway. Considering SSP2-4.5 (moderate mitigation), while still projecting increases in extreme precipitation, the magnitude and spatial extent of these changes are less severe compared to SSP5-8.5.

Both scenarios projected significant increases in 5-year return values along the Aegean, Mediterranean, and Black Sea coasts (Fig. 3). However, the increases were likely to be more pronounced under SSP5-8.5, exacerbating the risks of flooding, coastal erosion, and impacts on coastal communities and infrastructure. The spatial patterns of change in inland regions are likely to be more complex, with variations among western, central, and eastern Anatolia. While some areas might experience increases in extreme precipitation under both scenarios, others might see decreases or a combination of both.

In the near future (2015–2040), both the SSP2-4.5 and SSP5-8.5 scenarios will project relatively minor changes in the 5-year extreme rainfall events, with anomalies generally below 10% across most of Türkiye (Fig. 3). However, some localized increases of up to 20% were evident in the southeastern regions under the SSP5-8.5. As we move into

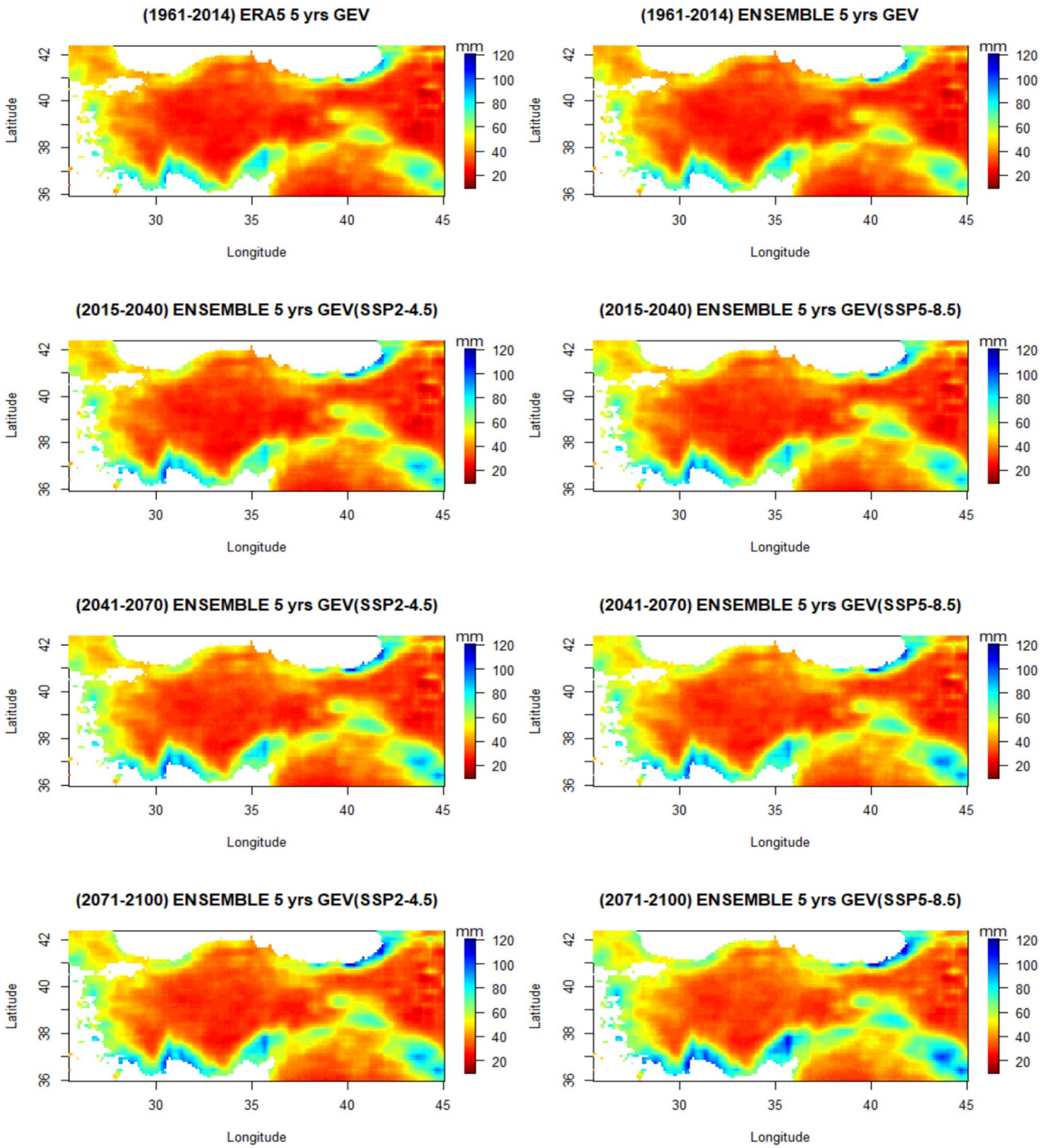


Fig. 2 Five-year return level

the mid-future (2041–2070), the distinction between scenarios becomes more pronounced. Under SSP2-4.5, increases remained moderate, mostly below 20%, while SSP5-8.5 shows more widespread and significant increases, particularly along the coasts and in the southeast, with anomalies reaching 30-40%. In the far future (2071–2100), the intensification of 5-year extreme rainfall events will continue, with both scenarios projecting larger increases. While SSP2-4.5 anomalies generally range from to 20–40%, SSP5-8.5 projections show a further escalation, with widespread

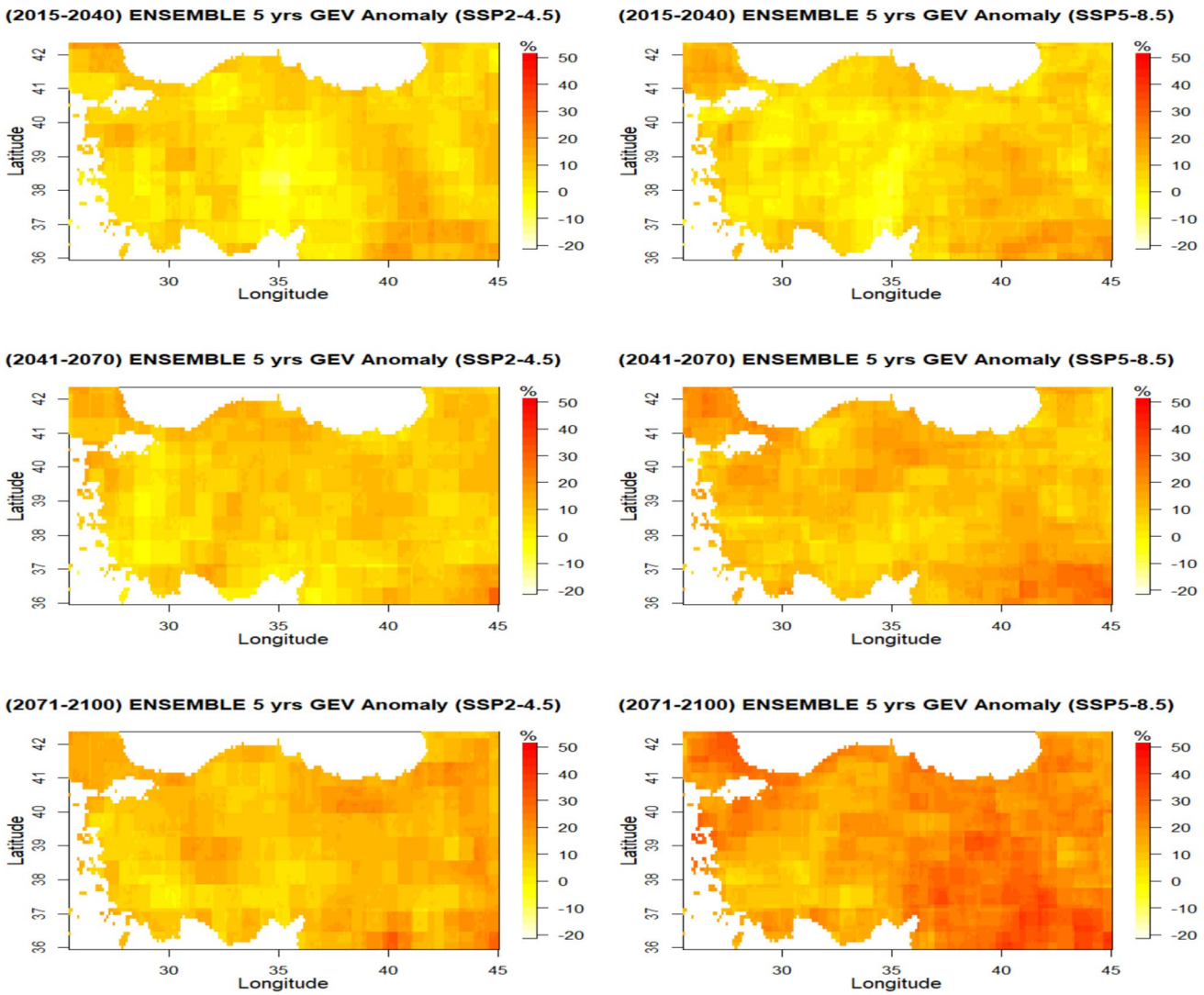


Fig. 3 Five-year return level anomaly

areas exceeding 40% and some regions approaching a 50% increase along the coasts (Fig. 3).

Orographic effects could lead to more pronounced increases in mountainous regions than in lowland areas, regardless of the emission scenario. However, the magnitude of these increases was likely amplified under SSP5-8.5. The intensification of extreme precipitation continues in both scenarios, with a wider spatial extent and larger magnitude of increase under SSP5-8.5. The most significant increases in 5-year return values are projected for the "Far Future," with the difference between SSP5-8.5 and SSP2-4.5, becoming even more evident. This emphasizes the long-term consequences of emission choices.

Considering the projected changes in 50-year return values for extreme precipitation events across Türkiye, derived from a 6-member ensemble of GCMs under the SSPs SSP2-4.5 (moderate mitigation scenario), reveals a tendency of intensification throughout the twenty-first century (Fig. 4). While the entire country is expected to experience an increase in the magnitude of these rare but impactful events, the analysis highlights the significant spatial and temporal variability in the projected changes.

Coastal regions, particularly along the Aegean and Mediterranean Sea coasts, emerge as hotspots of intensification, exhibiting consistently high increases in 50-year return values across all future time periods. This suggests the potential for more frequent and severe extreme precipitation events in these areas, posing significant challenges for coastal infrastructure, urban planning, and resilience of coastal communities. For instance, projections may indicate increases ranging from 10 to 30% or even higher in

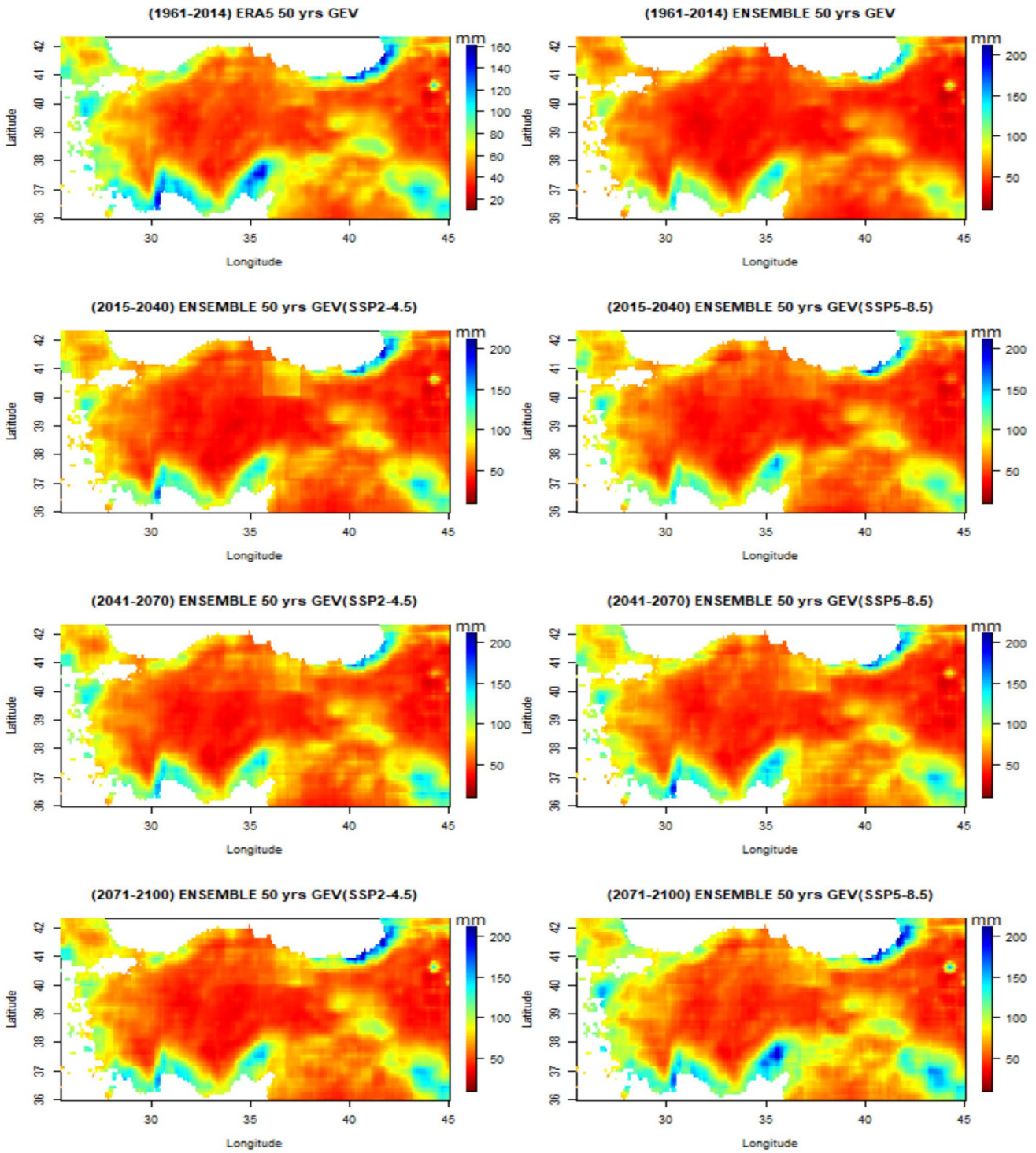


Fig. 4 50-year return level

certain coastal areas compared with the historical baseline, emphasizing the need for targeted adaptation measures.

In contrast, the interior regions of Anatolia displayed more complex spatial patterns. Central Anatolia exhibits a mixture of increases and decreases, with some areas potentially experiencing a decline in extreme precipitation events. This heterogeneity underscores the importance of region-specific adaptation and water resource management strategies. Mountainous regions, influenced by orographic effects, are likely to experience more pronounced

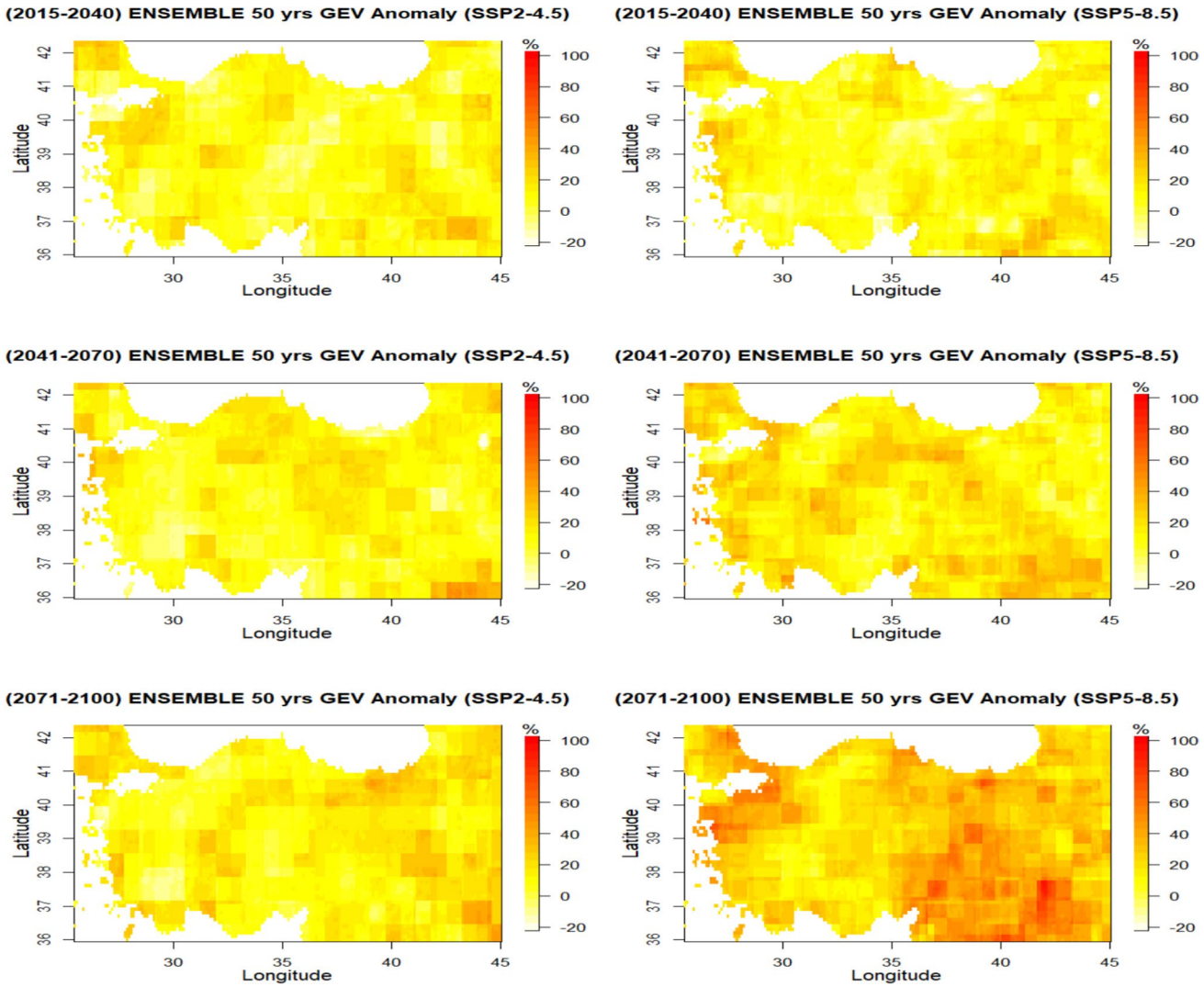


Fig. 5 50 years return level anomaly

increases than lowland areas, further emphasizing the need for nuanced, location-specific climate adaptation planning.

The analysis reveals a clear temporal tendency of intensifying extreme precipitation as we move from the "Near Future" (2014–2040) to the "Mid Future" (2041–2070) and "Far Future" (2071–2100) (Fig. 5). While the "Near Future" projections show early warning signs, particularly along the coasts, the "Far Future" paints a picture of a significantly wetter climate with substantially more intense extreme rainfall events.

For the 50-year return period, which represents more extreme events, the projected changes were more substantial (Fig. 5). In the near future, both scenarios will show noticeable increases, particularly in the southeast and along the coasts, with anomalies ranging from 10 to 30% under SSP2-4.5 and 20 to 40% under SSP5-8.5. The mid-future projections indicate further intensification, with widespread anomalies exceeding 20% under SSP2-4.5, and 40% under SSP5-8.5. Notably, the Aegean and Mediterranean coasts as well as southeastern Türkiye exhibited the most pronounced increases under both scenarios. In the future, 50-year return period anomalies will become even more significant. While SSP2-4.5 projections show increases reaching 40-60% in many areas, SSP5-8.5 anomalies often exceed 60%, with localized hotspots surpassing 80% along the coasts and in the southeast.

Visual examination of the maps revealed intensification in extreme precipitation events. In most cases, the projected 100-year return values show an increase compared to the historical baseline, particularly in the "Far Future" and under the high-emission scenario (SSP5-8.5). This suggests that rare extreme precipitation events are expected to intensify in the future. Changes in extreme precipitation appear to exhibit spatial variability, with

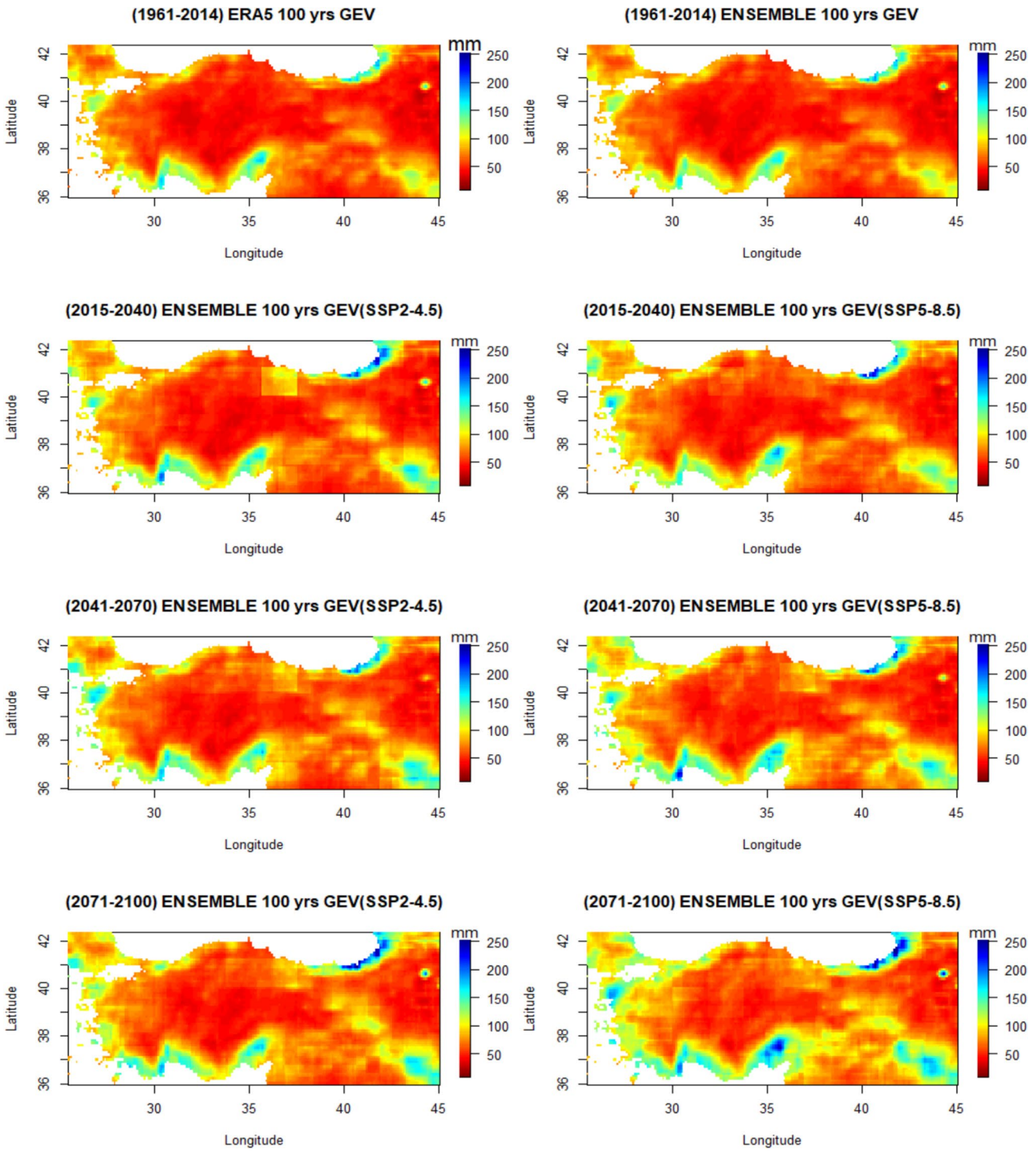


Fig. 6 100 years return level

some areas experiencing more significant increases than others.

Analyzing the 100-year return period values of the daily annual maximum precipitation provides specific insights into the changing behavior of the most extreme rainfall events (Fig. 6). The projected increases in the 100-year return values suggest the potential for both an increased frequency and intensity of extreme precipitation events. This implies that events that were historically considered rare (occurring once

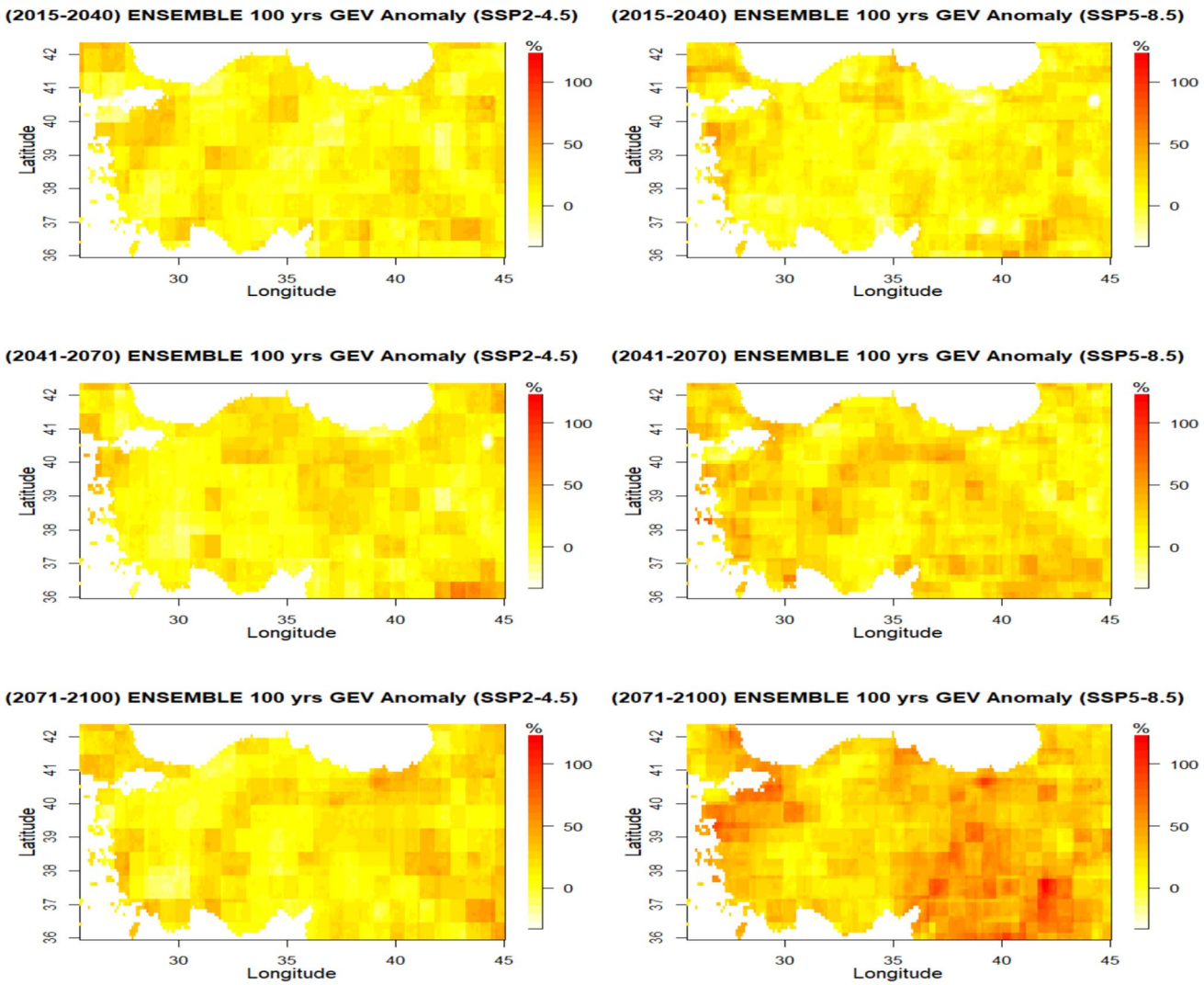


Fig. 7 100 years return level anomaly

every 100 years, on average) might become more frequent in the future, and their magnitude could also be greater.

The 100-year return period anomalies, which represent the most extreme rainfall events, revealed the most dramatic changes (Fig. 7). Even in the near future, both scenarios project significant increases, particularly along the coasts in southeastern Türkiye and around the Sea of Marmara. Under SSP2-4.5, anomalies range from 20 to 40% in these regions, whereas SSP5-8.5 shows even larger increases, exceeding 40% in many areas. By the mid-future, intensification is widespread, with SSP2-4.5 anomalies reaching 40–60% across much of Türkiye, while SSP5-8.5 projections show a more widespread and intense increase, with anomalies frequently exceeding 60% and reaching 80–100% at certain locations. In the far future, the projected changes are striking, with SSP2-4.5 anomalies reaching 60–80% in many areas and SSP5-8.5 exceeding 80% across much of Türkiye, with some regions experiencing anomalies of over 100%. This underscores the potential for events previously considered extremely rare to become significantly more frequent and intense under high-emission scenarios.

While the overall tendency points toward intensification of extreme precipitation, it is important to recognize that regional and local variations are likely (Fig. 7). The maps may reveal specific areas within the region that experience more pronounced changes than others due to factors such as topography, proximity to coastlines, and large-scale atmospheric circulation patterns. Analyzing these spatial variations can help prioritize adaptation and mitigation efforts in the most vulnerable areas.

Discussion and recommendations

In the extreme precipitation projection, CMIP6 was used to investigate the extreme precipitation change by means of the GEV and two different scenarios, SSP2-4.5 and SSP5-8.5, for 5-50-100 years return periods on Türkiye. Several recent studies have employed similar methodologies as this study (Crévolin et al. 2023; Martel et al. 2021; Cannon and Innocenti 2019).

Crévolin et al. (2023) conducted a study using CMIP5 and CMIP6. More frequent storms with an average increase of approximately 30–40% in their intensity are projected in the far future; the Authors find, as mentioned above. One of the most important impacts of a future warmer climate is the projected increase in the frequency and intensity of extreme rainfall events. Martel et al. (2021) stated that the intensification of extreme rainfall in a warmer climate is a settled scientific issue. While we obtained some decreasing values in the near future, we generally predicted increasing values in mid- and far-future forecasts. Cannon and Innocenti (2019) studied the projected intensification of sub-daily and daily rainfall extremes using the GEV to project extreme precipitation values. According to their results, there are spatially coherent yet relatively low increases in dispersion, the ratio of scale and location parameters of the GEV distribution, observed across more than half of the domain, offering some evidence for the return period dependence of future changes in extreme rainfall.

Considering our study, the results obtained from these studies were similar to those obtained in this study. Regardless of the scenarios, that is, both SSP2-4.5 and SSP5-8.5, it is clear that GEV results with far future changes are sharper than those in the near- and mid-future which might be a because of the radiative forcing of the GCMs increases over time for these two scenarios.

The maps highlight distinct regional variations in the projected changes. Coastal areas consistently exhibited higher anomalies across all return periods and timeframes, underscoring their heightened vulnerability to intensified extreme rainfall. This vulnerability is likely linked to warmer sea surface temperatures, increased atmospheric moisture, and potential changes in the storm tracks (Salarieh et al. 2023; Fernández-Alvarez et al. 2023; Cheng et al. 2022; Mure-Ravaud et al. 2019). Southeastern Türkiye also experienced substantial increases, potentially owing to shifts in large-scale atmospheric circulation patterns, moisture transport (Ciric et al. 2018; Barcikowska et al. 2018; Schicker et al. 2010) or potential climate zone shifts (Bayar et al. 2023). Central Anatolia, however, shows a more mixed picture, with some areas experiencing increases, while others show smaller changes or even decreases, emphasizing the need for more localized assessments to understand regional nuances in climate change impacts. Gumus et al. (2023) investigated precipitation and temperature extreme indices over Türkiye considering the CMIP6 models for two different scenarios and stated increasing SDII, decreasing total precipitation, and displayed dry day conditions and their spatiotemporal variations which may be one of the reasons of the increasing intensity for the selected return periods of this study. Sensoy et al. (2013) conducted a study on extreme climate indices across 109 stations in Türkiye, covering the period from 1960 to 2010. The findings indicated an increase in heavy precipitation days for the majority of the stations, with the exception of those located in the southeastern Anatolia and Aegean regions. Furthermore, most stations exhibited an increasing trend in maximum 1-day precipitation, with the exception of the southeastern Anatolia region, which is inconsistent with our findings. Touhedi et al. (2023) demonstrated that a dominant increasing trend is observed across Türkiye, particularly concentrated in the Black Sea, Marmara, and Aegean regions. There was an observed increase in medium- and long-duration rainfall, whereas short-duration rainfall showed a tendency to decrease. Albayrak (2021) noted that the high spatial variability of extreme precipitation leads to both decreasing and increasing relative changes across different regions. By the end of the century, however, the effects of annual extreme precipitation in the regions become significantly more pronounced. In their study, Abbasnia and Toros (2020) conducted an analysis of extreme temperature and precipitation indices across 71 meteorological stations in Türkiye, which includes both coastal and non-coastal regions, from 1961 to 2016. The study's findings indicate a shift in precipitation extremes toward shorter-duration, higher-intensity rainfalls. It was noted that increased atmospheric humidity in coastal areas is anticipated to result in more intense rainfall, particularly at higher latitudes. Furthermore, Gönençgil and Acar (2021) noted that the rising trend of consecutive dry days alongside the declining trend of consecutive wet days may serve as a signal that severe precipitation events will become more frequent in the annual total precipitation. These findings support our findings which also highlighted the costal regions that will be prone to extreme precipitation. Another study, Acar and Gönençgil (2022), investigated the extreme precipitation indices over Türkiye and revealed trends in the SDII index that generally display a trend toward an increase for the observation data which aligns with the results of our findings. Gumus (2023) also stated that the values derived from the GCM simulations suggest that the frequency and intensity of extreme precipitation events could rise in the future, particularly under the SSP5-8.5 scenarios, which is also supported by this study' results.

These studies underscore the urgency of incorporating climate change considerations into the infrastructure design, flood risk management, and disaster preparedness planning

in Türkiye. The significant differences between the SSP2-4.5 and SSP5-8.5 scenarios highlight the critical importance of global efforts to mitigate greenhouse gas emissions and follow a more sustainable path to minimize the risks associated with these increasingly extreme rainfall events.

On the other hand, the projected increases in extreme precipitation may be subject to uncertainties due to the stationarity assumption in QDM. It is vital to acknowledge this limitation that might affect the interpretation of the findings of this study, especially concerning the magnitude of projected extremes.

Regarding the number of selected GCMs, while selecting six CMIP6 models based on regional performance provides valuable insights regarding the future climate projections, relying on a limited ensemble may not fully encompass the full spectrum of uncertainties inherent in these projections. Yet, the chosen models were selected for their ability to replicate historical climate patterns over Türkiye, with a focus on spatial resolution, representation of key climatic variables, and performance in simulating extreme precipitation events. Although this criterion enhances regional relevance, it may also constrain the representation of the full range of model uncertainties. IPCC AR6 WGI Report (2021) provides comprehensive insights into uncertainties in climate projections, the importance of large ensembles and the perspective they offer on projection uncertainties. Knutti et al. (2010) further emphasized the value of multi-model ensembles for quantifying projection uncertainties while also indicating that averaging model outputs can, in some cases, lead to a loss of signal. In this regard exploring ensemble weighting schemes that incorporate model performance metrics can be a solution to optimize model skill and ensemble diversity, thereby a more robust future climate characterization can be obtained.

The CMIP6 models selected in this study offer comprehensive and high-quality data for SSP2-4.5 and SSP5-8.5. This ensures consistency through analysis and enhances the reliability of projections. Using these widely adopted scenarios allows for better comparability with other studies and facilitates meta-analyses in future research such Gumus et al. (2023), Oruc et al. (2024). Including SSP1-2.6 (a low-emission scenario consistent with ambitious climate mitigation efforts to limit warming to below 2 °C) and SSP3-7.0 (a scenario with high challenges to mitigation and adaptation due to regional rivalry and nationalism) could provide a more comprehensive picture of potential future climates. SSP1-2.6 could illustrate the potential benefits of aggressive mitigation and inform strategies aiming for sustainable development while SSP3-7.0 might shed light on the risks associated with limited cooperation and fragmented policies, which could be particularly relevant in certain geopolitical contexts. We discuss how the inclusion of these scenarios could potentially affect our results and interpretations, especially in terms of the range of projected extreme rainfall changes.

Applying the GEV distribution to annual maxima assumes that the statistical properties of extreme precipitation events remain stationary over time while, under significant climate change, the frequency and intensity of extreme events may evolve in ways that deviate from historical patterns, potentially violating the stationarity assumption (Wehner et al. 2024). This could introduce biases in our long-term projections and affect the reliability of our results. Aziz and Yucel (2021) also indicated that CORDEX-based precipitation projections revealed that the effects of non-stationarity over the projection period varied in size and type from those observed during the historical period across various locations in Türkiye. Non-linear changes in extreme precipitation under SSP5-8.5 could impact the validity of the stationary GEV assumptions because of more pronounced biases under higher warming levels due to amplified changes in atmospheric dynamics and moisture content. There are methods that modify GEV to capture the changes in extremes such as change-permitting extreme value models (Prosdocimi and Kjeldsen 2021). Tabari (2021) studied the selection of either the BM or POT methods is significant for assessing the impact of climate change on global flooding and extreme precipitation. He disclosed that the difference between the BM and POT results fluctuate based on variable, event extremity, season, and space. Despite its limitations, the GEV distribution remains a widely used tool for analyzing extreme events due to its solid theoretical foundation and ease of application. The use of the GEV distribution in this study is also consistent with standard practices in climatology but this study also acknowledges the necessity of considering non-stationarity in the context of significant climate change.

Besides, there are some points that need to be considered as recommendations. First, future studies could explore bias correction methods that account for non-stationary biases, such as those incorporating dynamic scaling factors or model output statistics to adjust for changing climate conditions. Additionally, the use of ensemble approaches that combine multiple bias correction methods could be beneficial to capture the range of uncertainties in extreme precipitation projections.

Regarding future scenarios, exploring SSP1-2.6 and SSP3-7.0 would provide valuable insights into the impacts of aggressive mitigation efforts and the risks posed by socioeconomic fragmentation, respectively. Therefore, future studies should include a broader range of SSP scenarios to capture the full spectrum of uncertainties as well as potential outcomes.

Moreover, advanced statistical techniques, such as Bayesian hierarchical models or machine learning approaches, can more effectively capture the complexities of changing

climate, particularly its extreme events. Future research should further explore non-stationary extreme value models and consider additional covariates that may affect extreme precipitation events, thereby defining the underlying patterns better.

Future studies should consider using larger ensembles of climate models to capture a wider range of uncertainties. For instance, incorporating additional CMIP6 models or using ensembles from multiple modeling centers could offer a more comprehensive evaluation. Employing ensemble weighting schemes based on selected model performance metrics can help balancing model skill and ensemble diversity is one method to do this. Lastly, performing sensitivity analyses to examine how different ensemble sizes and compositions affect the projections of extreme precipitation would further enhance the accuracy and robustness of the study results.

Conclusions

This study delves into the potential impacts of climate change on extreme rainfall events in Türkiye. A quantitative and comparative analysis of projected changes in 5-year, 50-year, and 100-year return values for daily maximum precipitation, depicted in Figs. 2, 3, 4, 5, 6, and 7, reveals crucial insights. Using downscaled CMIP6 projections under two SSPs (SSP2-4.5 and SSP5-8.5), this study examined these changes across different time periods, emission scenarios, and return periods, comparing them against a historical baseline (1961–2014).

The analysis consistently shows that the high-emission scenario (SSP5-8.5) projects significantly larger increases in extreme rainfall than the moderate mitigation scenario (SSP2-4.5). This disparity is evident across all time and return periods. For instance, the mean 100-year return level in the far future (2071–2100) under SSP5-8.5 is projected to be 130 mm, a 30% increase from the historical baseline of 100 mm. Under SSP2-4.5, the mean reached 115 mm, which was an increase of 15%. A similar pattern is observed for the 5-year return period in the far future, where the mean increases by 37.5% under SSP5-8.5, compared to a 20% increase under SSP2-4.5.

Furthermore, a clear temporal trend emerges: projected increases become more pronounced as we move from the near future (2021–2040) to the mid-future (2041–2070) and finally to the far future (2071–2100). This acceleration is evident under both scenarios but is more pronounced under SSP5-8.5. For instance, the mean 100-year return level under SSP5-8.5 increases from 110 mm (a 10% increase over historical) in the near future to 120 mm (a 20% increase) in the mid-future and finally to 130 mm (a 30% increase) in the far future.

Interestingly, the analysis reveals that the percentage increase in the return levels is generally larger for shorter return periods than for longer returns, regardless of the scenario or time period. For example, in the far future under SSP5-8.5, the 5-year return level experiences a 37.5% increase, while the 50-year and 100-year return levels show increases of 30% and 30%, respectively. This suggests that while the magnitude of more extreme rainfall events is projected to increase, the frequency of less extreme events (such as those with a 5-year return period) may experience a more significant relative increase compared with rarer, more extreme events.

Spatial variations in these projected changes were also evident in the anomaly maps (Figs. 3, 5, and 7). Coastal regions consistently exhibited higher positive anomalies than inland areas, indicating greater vulnerability to intensified extreme rainfall. The maximum anomalies, reaching up to 60 mm for the 100-year return level in the far future under SSP5-8.5, were concentrated along the coasts. Central Anatolia, on the other hand, shows smaller increases or even some negative anomalies, particularly for the 50-year and 100-year return periods under SSP2-4.5. This spatial heterogeneity underscores the importance of considering the regional differences in adaptation planning.

These quantitative findings highlight the substantial impact of climate change on the extreme rainfall patterns in Türkiye. Choosing a high-emission pathway will drastically increase the risk compared with a moderate mitigation pathway. The projected increases, particularly the amplified increases for shorter return periods and vulnerability of coastal regions, necessitate immediate action to enhance infrastructure resilience, improve disaster preparedness, and ensure sustainable water management. This analysis provides crucial quantitative data for understanding the implications of climate change on extreme rainfall in Türkiye and emphasizes the need for informed policy decisions, targeted adaptation investments, and continued research to refine projections and inform more effective risk management strategies.

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Author contribution SO did conceptualization and supervision; SO and BG done data curation; SO, BG, and TT performed formal analysis; SO and TT investigated the study; SO, BG, TT gave the methodology and did writing—original draft and writing-review and editing; BG gave software; BG and TT visualized the study. All authors have read and agreed to the published version of the manuscript.

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Data availability Publicly available datasets were analyzed in this study and model performance obtained from the acknowledged project**.**

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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