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Changes in Annual and Seasonal Extreme Precipitation over Southeastern Europe †

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Abstract: This study examined the association between precipitation indices and atmospheric processes in Southeast Europe using ERA5 land data from 1961 to 2020. The Rx1day intensity index showed predominantly positive trends in heavy precipitation events, resulting in more intense precipitation over fewer days in various parts of Southeast Europe, particularly during autumn. These findings highlight the potential increase in extreme precipitation frequency and intensity due to ongoing climate change, leading to an elevated risk of flood events. Such insights provide valuable information for policymakers and stakeholders to adapt to the impacts of extreme precipitation events.

Keywords: precipitation; extreme precipitation index; climate change; Southeast Europe

1. Introduction

Precipitation is a critical element in the study of hydrology, geomorphology, and the economy of a region, with extreme precipitation being of particular interest due to its significant impact on the area. The extremity of precipitation is generally classified into three main categories: severity, intensity, and rarity [1]. In recent years, climate fluctuations have led to devastating floods, droughts, and extreme rainfall in different parts of the world, significantly hindering socio-economic progress, especially in impoverished nations. The frequency and intensity of extreme weather events, such as destructive winds, lightning, and flooding, impact various essential areas, including agriculture, infrastructure, clean drinking water, and transportation, influencing policymaking decisions [2]. With the projected increase in extreme weather events in various regions globally, it is essential to gain more knowledge about the fluctuation of these events over different spatial and temporal scales [3]. Studying the characteristics of extremes generally involves analysing frequency and intensity indices. Although increased rainfall with climate change is expected to lead to pluvial flooding, historical evidence suggests a decrease in flood magnitude. Nevertheless, significant evidence shows that rainfall extremes are increasing [4], with over 7% of the world experiencing a statistically significant increase in the annual maximum 1-day rainfall [5,6]. Extreme precipitation trends are strongly influenced by climatic and non-climatic factors (e.g., anthropogenic greenhouse gas forcing) [7]. Thus, a regional approach that contemplates the large temporal and spatial variability is needed, as the previous studies were mostly focused on national levels. Therefore, the objective of this study was to offer an analysis of extreme precipitation changes that were observed over the whole of Southeast Europe (SEE).

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2. Materials and Methods

In this study, we analysed the trend of precipitation indices to understand the changes in SEE using the guidelines suggested by the joint WMO-CCl/CLIVAR Working Group on climate change detection. We analysed the highest one-day precipitation amount (Rx1day) index, which represents the maximum one-day precipitation amount in a given time period. We applied this index as it is commonly used to assess the severity and frequency of extreme precipitation events, which can lead to flooding and other types of weather-related damage. Understanding the patterns and trends in Rx1day is important for developing effective strategies for managing the risks associated with extreme weather events, such as improving infrastructure and emergency response systems. For that purpose, we used ERA5 land data from 1961 to 2020 with horizontal resolution of 9 km. ERA5-Land demonstrates higher ability than other reanalysis products across geographically diverse regions. This advocates that not only is enhancement of data assimilation remarkable, but also that higher spatial resolution is employed to reproduce extreme events [8]. The annual and seasonal Rx1day indices were calculated using xclim library in Python. The Mann–Kendall Trend Test was used for annual and seasonal Rx1day trend calculations. The maps were produced in ArcGIS Pro 3.1 software by interpolating trend values represented with a point mesh obtained from ERA5 Land pixel centroids, with a horizontal resolution of 9 km. The deterministic Radial Basis function (RBF) was used as a simple, balanced, and reliable interpolator [9]. The p values showing statistical significance were visualised with dots.

3. Results and Discussion

Of a selection of climate indices, broadly coincident with the most relevant ones, the selected index was maximum 1-day precipitation (Rx1day). The results indicate mostly positive trends in heavy precipitation events, which suggest more intense precipitation over fewer days in various parts of SEE. The Rx1day index, which has been found to be a good indicator of flood events in Europe, shows a statistically significant increase over the largest part of SEE, but especially over the middle parts of the Sava and Tisa rivers during autumn [10,11] as well as near the Danube River confluence into the Black Sea (Figure 1D). Similar statistically significant increases in precipitation intensity were reported for Central Europe [12,13]. These results indicate that autumn floods could become more common in parts of SEE.

The winter season (December–January–February) was highlighted by positive precipitation trends over upper part of the Vardar River in North Macedonia (Figure 1A). It is important to highlight that the three most severe floods that occurred in this region were recorded in 1979, 1996, and 2016; all three occurred during January and February. The Central Peloponnese Region is facing decrees of extreme precipitation events during winter. In the spring season, (March–April–May), a statistically significant positive trend can be observed over the western parts of North Macedonia, southern parts of Serbia, and southwestern parts of Albania over the Vjosa River basin (Figure 1B). Southeastern parts of Greece also show statistically significant changes over central parts of Euboea Island and the Attica peninsula. During the summer months (June, July, and August), a statistically significant decrease in extreme precipitation was observed along the Adriatic Sea coast (Dinaric mountains) from Slovenia to Albania (Figure 1C). Different studies across Europe pointed out that annual and seasonal trends in extreme precipitation are more significant than changes in mean precipitation [14,15]. The results of the seasonal indices of Rx1day trends indicate that the northern part of the region reflects the characteristics of the Central European regime, while in the south of the region, the trends reflect the characteristics of the Mediterranean regime. The increase in the intensity of precipitation over most of SEE can be credited to global warming and the Clausius–Clapeyron relation, which explains how a warmer atmosphere holds more water vapour, which in turn causes more intense precipitation [14]. A similar study reported that the water-holding capacity of the atmosphere has increased by 7% due to global temperature increase [16].

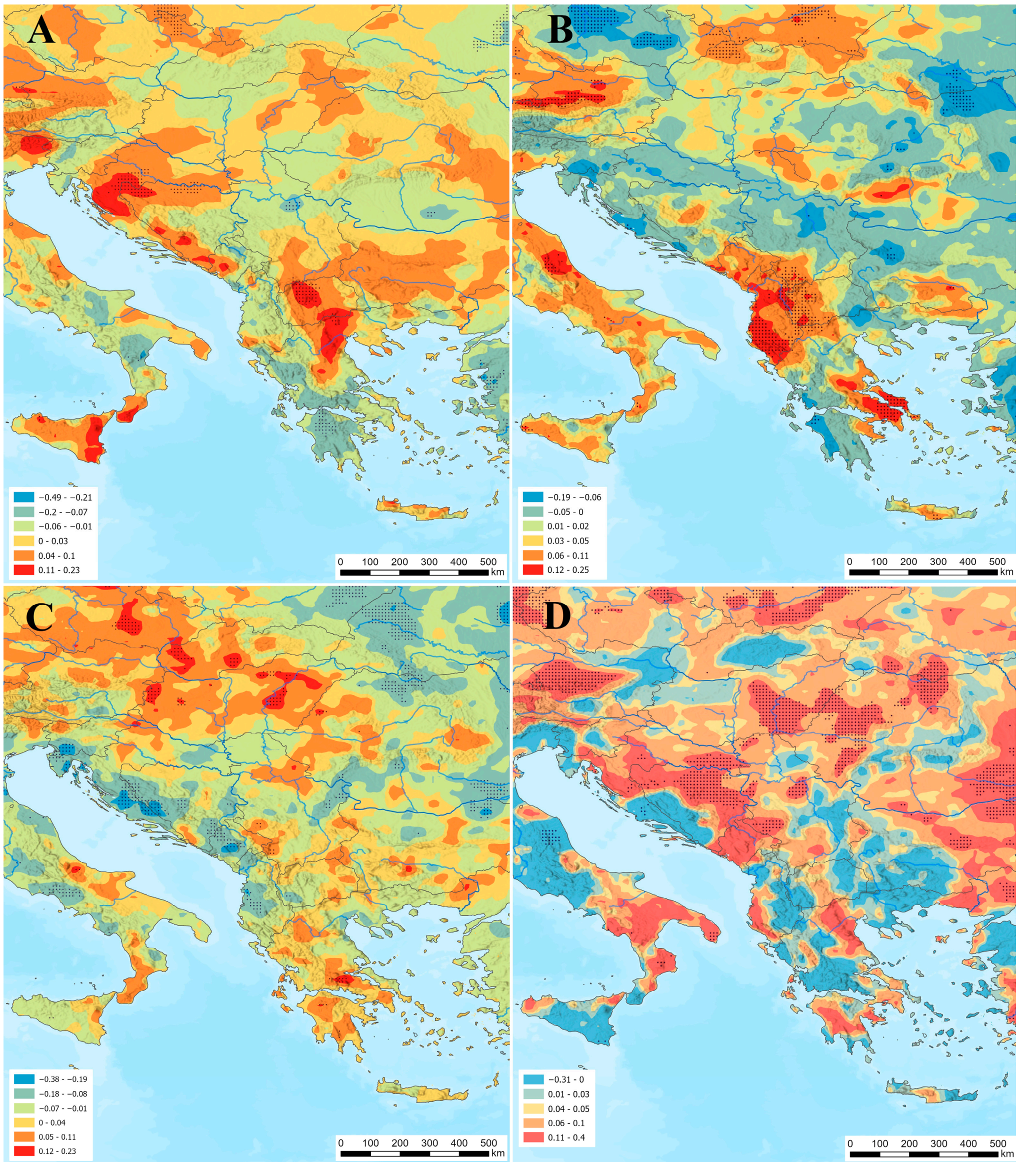

Figure 1. Seasonal trends of Rx1day with statistical significance (shaded areas), (**A**). December–January–February; (**B**). March–April–May; (**C**). June–July–August; (**D**). September–October–November.

Therefore, it can be concluded that, most probably, human influence contributed to the global tendency towards increases in the amount, intensity, and frequency of extreme precipitation [17]. Also, variability in precipitation over Europe is mainly predisposed by variability in the atmospheric circulation. This relationship is particularly strong during the colder period of the year, as many studies have provided evidence for the influence that changes in the North Atlantic oscillation (NAO) and other circulation indices have over the changes in precipitation in Europe [18]. During warmer periods, this relationship is weaker and other factors in addition to circulation also play important roles [19]. Even at relatively short distances (<500 km), positive and negative trends in Rx1day are found over SEE. One of the explanations for this incoherence could be the large extreme precipitation gradients at the local level [20]. This becomes particularly evident in regions transitioning from wetter to drier conditions, suggesting that any future increase in extreme precipitation could be dampened [21,22]. Seasonal trends of Rx1day show that we can expect a shift in flood events from the spring to autumn period and heavy precipitation events may become more frequent now and in the future as global air temperatures rise [12,23].

4. Conclusions

In conclusion, this study highlights the critical role of precipitation indices, mainly Rx1day, in hydrology. Climate fluctuations have resulted in devastating floods, droughts, and intense rainfall, negatively impacting socio-economic progress, especially in impoverished nations. The increasing frequency and intensity of extreme weather events pose significant challenges and influence policymaking decisions in various sectors. The results reveal predominantly positive trends in heavy precipitation events, indicating more intense rainfall over shorter periods. Notably, the Rx1day index exhibits a significant increase, suggesting an increased likelihood of autumn floods on the Sava and Tisa Rivers. The variability of precipitation also varies across different regions, including plains, hills, and mountains. These findings support the expectation of an increased frequency of heavy precipitation events with rising global air temperatures. Overall, the variability of precipitation also varies between different regions, including plains, hills, and mountains. This research contributes valuable insights to the understanding of precipitation extremes and their implications for Southeast Europe, aiding policymakers and stakeholders in developing strategies to mitigate the impacts of extreme precipitation events. In the coming decades, the expected continuation of increasing trends in more intense and frequent droughts, heavy precipitation, and heat extremes will pose a significant challenge to our society and economy, given their numerous negative impacts.

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