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Discussions

Recent trends in daily rainfall extremes over Montenegro (1951–2010)

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Abstract

More intense rainfall may cause a range of negative impacts upon society and the environment. In this study we analyzed trends in extreme ETCCDI (Expert Team on Climate Change Detection and Indices) rainfall indices in Montenegro for the period 1951–2010. Montenegro has been poorly studied in terms of rainfall extremes, yet it contains the wettest Mediterranean region known as Krivošije. Several indices of precipitation extremes were assessed including the number of dry days and rainfall totals, and their trends to identify possible changes. The results generally suggest that the number of days with precipitation decreased while rainfall intensity increased particularly in south-western parts of the country. A slight tendency towards intense rainfall events is suggested. Calculated trends for each index are spatially presented and examined using a *plotGoogleMaps* software package. This study also examined spatial pattern of relationship between extreme rainfall indices and North Atlantic Oscillation. Results suggested negative, mainly statistically significant correlations at annual, winter and autumn scale.

1 Introduction

Rainfall extremes in the Mediterranean region are of particular interest since they can have serious implications on the environment, society and economic sectors. Although annual rainfall in the Mediterranean region generally decreased during the second half of the 20th century (Raiser and Kutiel, 2010; Trenberth et al., 2007), the frequency of heavy rainfall generally increased (Alpert et al., 2002; Kostopoulu and Jones, 2005; Ducić et al., 2012). These intense periods of rainfall may have serious consequences including potential flooding, soil erosion and land degradation. Agricultural areas are sparsely distributed in this region and such hazards can significantly implicate farming.

Mediterranean region itself is characterized by complex pattern of inter-annual as well as intra-annual rainfall variability. Many authors therefore studied particular

NHESSD
3, 2347–2377, 2015

Mediterranean countries or stations in relation to rainfall extremes. Rodrigo and Trigo (2007) analyzed spatial patterns of rainfall extremes at annual and seasonal scales for whole Iberian Peninsula (1951–2002) using 15 stations. They noticed a significant (95 % confidence level) negative trend in daily intensity rainfall at annual level, between −2.00 and −5.76 mm day^{-1}, which was particularly pronounced in the Northern and Southern stations. Extreme rainfall (defined as 95th percentile of wet day amounts) did not reveal significant trends in most of the Iberian Peninsula. Authors also pointed out that result did not suggest clear spatial pattern. Focusing on spatial variability of rainfall extremes in Southern Portugal, Durao et al. (2009) showed a slight decrease in rainfall between 1960s and the end of the 20th century. Using observations from 105 stations they also concluded that indices of rainfall extremes (frequency of extremely heavy precipitation events and index characterizing flood events) have shown no significant temporal trends.

Other regions of the Mediterranean including the Italian Peninsula, Balkan Peninsula, Cyprus, and Israel despite tendency towards drier conditions also showed tendency towards extremity of rain events. Alpert et al. (2002) found for the Italian Peninsula (1951–1995) increasing trend in heavy-torrential categories (64–128 mm day^{-1}) and significant decrease in weaker categories (0–32 mm day^{-1}). They showed also that heavy to torrent contribution (32 up mm day^{-1}) increased from 23 % from the total rainfall in the 1950s to 31 % at the end of the study period. Significant percentage of the heavy rainfall events to total precipitation in Italy is confirmed later by Kostopoulu and Jones (2005). Same authors showed similar pattern for western coasts of Balkan Peninsula but with less significant results. In Israel and Cyprus no significant results are found for the period 1951–1995 (Alpert et al., 2002). Recent study of Ziv et al. (2014) on trends in rainfall regime over Israel (1975–2010) showed decrease in rain days in most of the stations located in wet and semi-arid parts but also increase in average rainfall amounts as well as heavy rainfall days (> 30 mm) in coastal areas (both statistically insignificant).

NHESSD
3, 2347–2377, 2015

Montenegro so far has been poorly studied in terms of rainfall extremes. Ducić et al. (2012) examined rainfall extremes in the wettest Mediterranean region Krivošije, Montenegro and their relationship to circulation types (1951–2007). Using only two stations Herceg Novi and Crkvice, their analyses of rainfall extreme indices showed that very extreme precipitation events significantly increased 1.8 % (95 % confidence level) annually despite having significant decreases (99 % confidence level) in the number of precipitation days (3.59 days annually for Crkvice and 2.97 days for Herceg Novi).

The aims of this study are examining of trends in rainfall extreme indices all over Montenegro as well as to better visualize their spatial pattern using web mapping techniques. Since recent study of Burić at al. (2011) indicated that North Atlantic Oscillation (NAO) may be correlated to rainfall in Montenegro we decided to examine to what extent the rainfall extreme indices are influenced by related teleconnection patterns (i.e. North Atlantic Oscillation-NAO).

In order to approach these research questions, this paper examines annual and seasonal trends in rainfall extreme indices in Montenegro during the period between 1951 and 2010. Introductory explanations including previous investigations are given in Sect. 1. A detailed description of the study area is given in Sect. 2. Data sets and a description of methodology are presented in Sect. 3. Results and a discussion are given in Sect. 4, and concluding remarks in Sect. 5.

2 Study area

The study area comprises Montenegro, which covers nearly 3 % of the Balkan Peninsula with the area of 13.812 km^2. It has diverse topography including a narrow Adriatic coastline stretching along the southwestern part, the karst region in the central parts and high Dinaric Mountains (above 2000 m) in the northern parts of the country (Fig. 1). The coastal region is characterized by a typical Mediterranean climate while a moderate-continental climate is present in its the northern parts. The average annual rainfall varies a great deal from about 800 mm in the northeast to above 4000 mm in mountainous areas in the west, which is the wettest part of the Mediterranean region (Ducić et al., 2012). The Crkvice meteorological station located on the southeastern slope of the Orijen Mountain presents the highest average annual rainfall extreme (4593 mm in the baseline period 1960–1990) found in Europe (http://wmo.asu.edu/maps/map.html). Such high annual rainfall is mostly due to orographic uplift (Radovanović et al., 2008).

3 Data and methodology

3.1 Data

The rainfall data include daily totals from 23 meteorological stations in Montenegro (1951–2010) provided by the Hydro-Meteorological Service of Montenegro. Metadata are quality controlled in terms of correction of misprints and relocation of the stations (WMO, 2004). There were no missing data.

Data homogeneity is a basic requirement when assessing changes in rainfall extremes. However, an advanced method for analyzing daily rainfall data homogeneity has not been developed yet (Toreti et al., 2010). In this study, data is carefully evaluated by applying a Multiple Analysis of Series for Homogenization (MASH v3.02) method. The MASH method was developed in the Hungarian Meteorological Service (Szentimrey, 1994, 1999, 2003); it is a relative homogeneity test that does not presume that the reference series are homogeneous (Costa and Soares, 2009). In this study, a version of MASHv3.02 extended for homogenization of daily rainfall data has been used. Portions of the timeseries with inhomogeneities were excluded from the analysis.

An Expert Team on Climate Change Detection and Indices (ETCCDI), supported by the World Meteorological Organization (WMO) Commission for Climatology, the Joint Commission for Oceanography and Marine Meteorology (JCOMM) and the Research Program on Climate Variability and Predictability (CLIVAR) developed the list of precipitation indices used in this study. We selected a set of five indices of rainfall

NHESSD
3, 2347–2377, 2015

extremes (Table 1) including the number of dry days and rainfall totals. Indices are defined in terms of the numbers of days that exceed either an absolute or percentile thresholds. Percentile-based indices allow spatial comparisons, as they sample the same part of the probability distribution of rainfall at each location. Day-count indices based on absolute thresholds are less suitable for spatial comparisons of extremes. The reason is that, over large areas, day-count indices based on absolute thresholds may sample very different parts of temperature distributions (Peterson et al., 2001; Klein-Tank and Konnen, 2003; Lucie et al., 2006; Gajić-Čapka, 2009; WMO, 2009; Caesar et al., 2011).

As a parameter of North Atlantic Oscillation, NAO index[1] is used, defined as an air pressure difference between Iceland and Azores.

3.2 Methodology

Percentile thresholds are determined empirically from the observed data series in the standard period of 1961–1990. The procedure ensures that extreme rainfall events can occur with equal probability throughout the year (WMO, 2009).

The statistical significance of the calculated trends of the indices was tested using a Mann–Kendall test. This method has been applied because it is more suitable for nonparametric distributions. The Mann–Kendall test is used for trend analysis in ETCCDI workshops (Zhang et al., 2005). Sen's (1968) slope estimator was used for estimating trends within the indices. This is a more robust approach for the estimation of trends in indices based on daily data (Salmi et al., 2002; Olofintoye and Sule, 2010; Šumenjak and Šuster, 2011; Mondal et al., 2012). Since the average annual rainfall in Montenegro varies a great deal from about 800 to above 4000 mm, rainfall trend for mean rainfall, SDII and R95TOT is given in percentage per decade (% dec^{-1}) using Normal 1961–1990.

[1]http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml

Depending on the data distribution, either the parametric or nonparametric method may be used for correlation detection. In general, nonparametric methods, like e.g. Kendall's tau test, perform better relative to their parametric counterparts for abnormal distributions. However, due to the fact that a preliminary analysis did not show the general presence of anomalies in our precipitation time series, the standard Pearson product-moment correlation coefficient has been applied.

We used a *plotGoogleMaps* (Kilibarda and Bajat, 2012) R software package in order to obtain better insight into the spatial distribution of calculated daily rainfall extremes trends as well as their correlations to NAO over Montenegro. All maps depicting annual and seasonal values of daily rainfall extremes trends as well as correlations between rainfall extreme indices and NAO are available as interactive maps in HTML format at the web page http://osgl.grf.bg.ac.rs/materials/mne.

4 Results and discussion

In order to analyze extreme rainfall in Montenegro five indices have been chosen. The analysis was performed for each of them at annual and seasonal scale. To better visualize their spatial pattern, trends of indices are depicted by bar graph using different colors for annual and seasonal scale (Figs. 2–8). Statistically significant trends at 95 % confidence level are outlined by black line.

Annual rainfall trend in Montenegro tends to decrease in south-western parts of the country mostly insignificantly (Fig. 2) since the only two stations (Budva $-3.6\,\%\,\mathrm{dec}^{-1}$ and Krstac $-2.8\,\%\,\mathrm{dec}^{-1}$) showed significant decrease. The winter significant decrease (between -4.8 and $-6.6\,\%\,\mathrm{dec}^{-1}$) is detected in the same parts of the country, suggesting slight tendency towards drier conditions. Those are mainly stations located in Mediterranean region of the country. In contrary, northern parts showed positive annual rainfall trends also significant at two stations. The autumn season revealed positive trends dominating all over the territory. Similar pattern with winter and spring decrease, and autumn increase in rainfall is shown by Luković et al. (2013) in their

NHESSD
3, 2347–2377, 2015

rainfall trend analysis for Serbia. Krichak and Alpert (2005) found that rainfall decline in western Mediterranean regions may be linked to positive trends in the North Atlantic Oscillation in last few decades. They also suggested that at the same time, the rainfall decrease over the Eastern Mediterranean could be explained by the positive trend in the East Atlantic Western Russia (EAWR) pattern.

Drier conditions are confirmed by consecutive number of dry days (DD) showing statistically significant increase at 13 stations (between 2.1 and 5 days dec^{-1}) at annual scale (Fig. 3) mainly distributed in SW parts of Montenegro. Similar results are found for winter season as well. Pronounced positive trends are found in coastal and central parts of Montenegro, highlighting the fact that Mediterranean areas may experience future drought (Brandt and Thornes, 1996). Other seasons showed low statistical significance and spatial coherence.

On the other hand, simple daily precipitation intensity index (SDII) revealed annual and seasonal increase (Fig. 4) particularly pronounced in SW parts of Montenegro during spring season (between 3.3 and 6.9 % dec^{-1}). Kostopoulu and Jones (2005) obtained similar results for Italian stations at annual and winter scale. Comparing to results found for Italian stations there is a lag of one season in Montenegro, pointing the strongest increase of SDII in Montenegro on spring.

Trends for Montenegro in number of days with rainfall above 75th percentile (R75p) revealed mostly negative annual values spread in southern and western parts of the country, statistically significant at four stations (Fig. 5). Positive annual trends are distributed in northern and eastern areas. Results on seasonal scale did not reveal strong change for R75p. However, an exception is summer season, showing an increase in R75p at all examined stations. However, none of them is being statistically significant. On the other side, days with rainfall events higher than 95th percentile (R95p) also show trend positive at annual scale mainly in central parts of Montenegro, statistically significant at seven stations. Winter season also revealed positive trend, significant at four stations concentrated in the same areas like the annual ones.

Similar results are found for index R95pTOT which is a measure of very extreme precipitation events. It showed statistically significant positive trend at annual scale for nine stations in Montenegro (Fig. 7). Kostopoulu and Jones (2005) found similar results for Balkan Peninsula in their study. The analysis at the seasonal scale shows that the trends are mostly weak and less significant. However, certain spatial pattern is noticed for spring season between western and eastern parts of the country, presenting opposite trends.

Extreme rainfall increased in many parts of the world (IPCC, 2013). In Montenegro number of days with heavy rainfall (≥ 20 mm) decreased in south-western parts, while increase is detected in north-eastern parts of the country (Fig. 8). Results in this paper showed that stations in Mediterranean parts of the country, which receive high annual totals, are indicating negative trends. At the other hand, northern stations with less rainfall totals are indicating positive trends.

Figures 9–15 show spatial pattern of correlations between extreme rainfall indices including rainfall totals and number of dry days, and NAO index significant at the probability level of 95 %.

All stations showed statistically significant negative correlations in rainfall amounts at annual level and during winter season (Fig. 9). At autumn season majority of stations also showed statistically significant negative correlations. Since a higher correlation is revealed in winter than other seasons in previous literature (Caloiero et al., 2011), many studies, while analyzing NAO impact, concentrate mainly on this season (Fearari et al., 2013). This control exerted by NAO on the rainfall during winter is related to corresponding changes in the associated activity of North-Atlantic storm tracks that affect most of western Europe (Osborn et al., 1999; Goodess and Jones, 2002) and the Eastern Mediterranean such as in Turkey (Türkeş and Erlat, 2005). None of stations provided significant correlations for spring and summer rainfall.

Number of dry days (DD) showed significant positive correlations with NAO in all stations at annual and winter level (Fig. 10). The autumn season also suggested significant positive correlations. Krichak and Alpert (2005) found for Mediterranean

NHESSD
3, 2347–2377, 2015

region that NAO-positive periods are wetter than normal weather over West Europe but drier than normal weather in Mediterranean, which positive correlations between DD and NAO for Montenegro certainly confirms.

Simple daily precipitation intensity index (SDII) showed negative annual and winter correlations mainly concentrated in central and eastern parts of the country (Fig. 11). Very similar pattern is noticed in R95p (Fig. 12). On the other hand quite similar distribution with significant negative correlations at annual scale as well as during winter and autumn season is noticed in R75p (Fig. 13) and R20 mm (Fig. 14) indices. The index R95pTOT (Fig. 15), apart from significant negative correlations on winter season, did not reveal any specific spatial pattern.

5 Conclusions

In this paper we have studied trends in indices of rainfall extremes in Montenegro as well as their relation to North Atlantic Oscillation for the period 1951–2010, using observations from 23 stations. This research was focused on the spatial pattern analysis of rainfall extreme indices using web-mapping tools.

Results suggested dominant decrease in annual rainfall amounts followed by increase in number of dry days. Tendencies towards drier conditions are mainly pronounced in south-western parts of the country. Despite suggested drier conditions, precipitation intensity increased all over the country. Very extreme precipitation events indicated particular increase in south-western parts of the country. Such tendencies in Mediterranean part of Montenegro towards increase in precipitation intensity on wet days are suggested in IPCC (2013) reports under the scenarios of future climate change.

Spatial pattern of trend in extreme rainfall indices suggested opposite tendencies in southwestern (central and coastal areas) and northeastern parts of Montenegro (mountains). While implicating more extreme but generally drier conditions in SW parts, eastern parts showed slight tendency towards wetter conditions. Apart from different response in terms of opposite trend shown between these two areas of Montenegro, they are also characterized by different rainfall regime. South western parts of the country experience Mediterranean climate while north eastern parts have continental climate. For that reason, Kutiel et al. (2014) included north eastern Montenegrin stations into analysis of Serbian stations while analyzing rainfall regime and its uncertainty in Serbia and Montenegro.

Results on relationship between extreme rainfall indices and North Atlantic Oscillation over Montenegro during investigated period seemed to be directly linked to changes in one of the major large-scale circulation modes such as NAO pattern, particularly during the winter season. This is the reason why some studies are mainly focused only on winter part of the year (Ferrari et al., 2013) sometimes including March (Trigo et al., 2002). That is why some authors use a wet season concept between October and March in their analysis (Xoplaki et al., 2004).

Detailed rainfall analysis in Montenegro is of particular importance, taking into account recent floods (2010, 2012, and 2013) causing serious damage (Burić et al., 2013, 2014). The country is highly dependent on rainfall, since tourism is one of the main economic strategies including hydro-electric production.

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NHESSD
3, 2347–2377, 2015
Recent trends in daily rainfall extremes over Montenegro
D. Burić et al.

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NHESSD

3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Table 1. Definitions and abbreviations of the ETCCDI indices of precipitation extremes used in this study.

Index	Definition	Unit
SDII	Simple daily precipitation intensity index (annual total/number of days with precipitation ≥ 1 mm day^{-1})	mm dec^{-1}
R20 mm	Number of days with heavy precipitation amount above 20 mm	days dec^{-1}
R75p	Number of days with precipitation amount above a site specific threshold value for moderate days, calculated as the 75th (R75 %) percentile of the distribution of daily precipitation amounts at days with Rd ≥ 1 mm in the 1961–1990 baseline period.	days
R95p	Number of days with precipitation amount above a site specific threshold value for very wet days, calculated as the 95th (R95 %) percentile of the distribution of daily precipitation mounts at days with Rd ≥ 1 mm in the 1961–1990 baseline period	days
R95pTOT	Fraction of annual total precipitation due to events exceeding the 1961–1990 95th percentile	%

Definitions including formulas are available from ETCCDI website http://www.climdex.org/indices.html.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

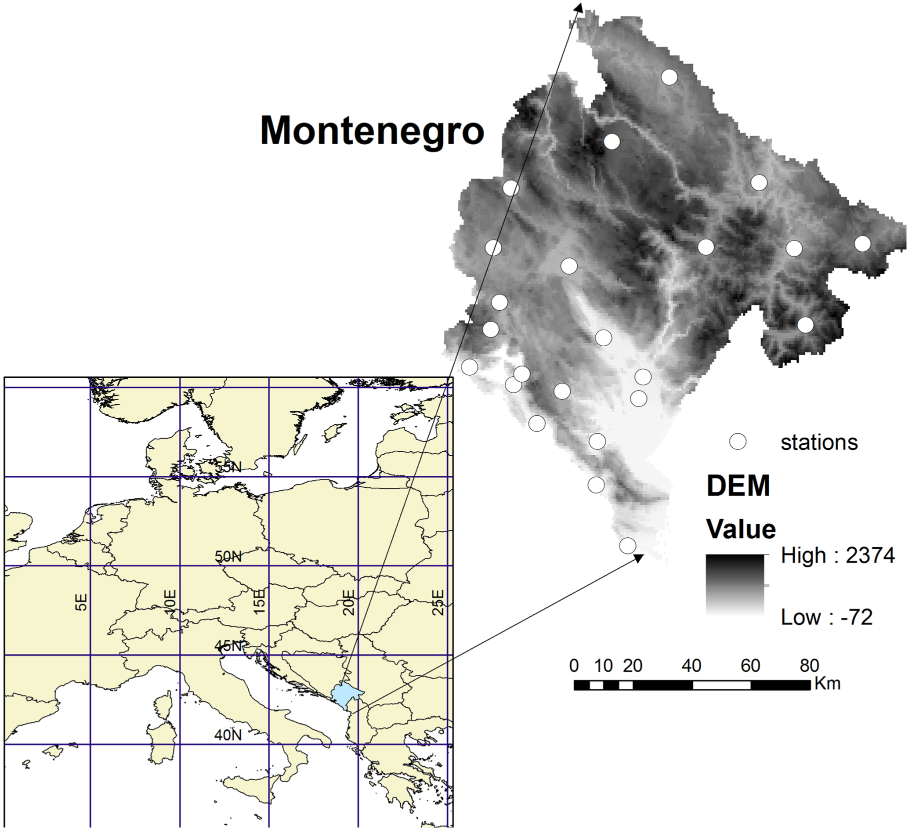

Figure 1. Locations of the stations.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

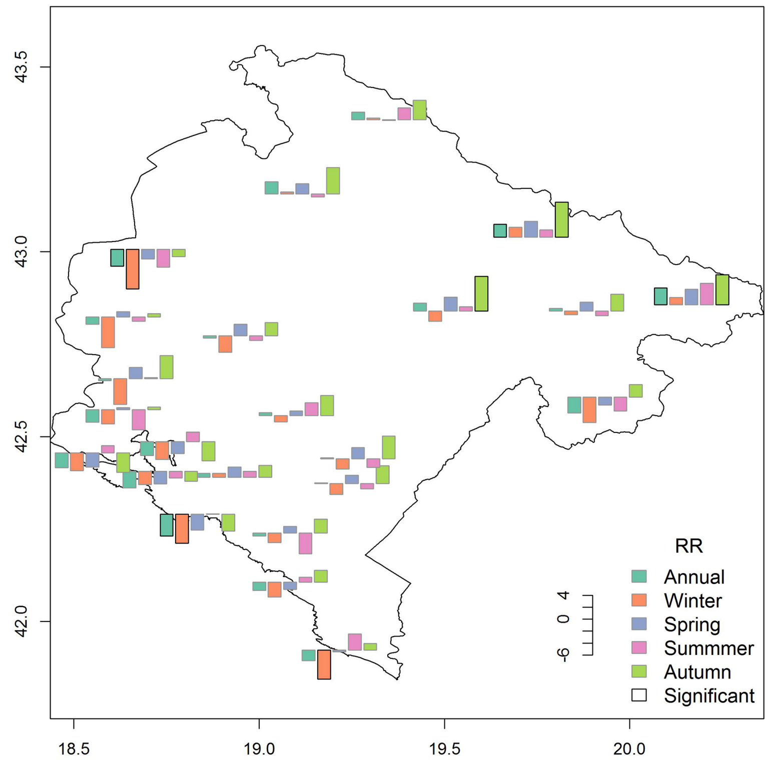

Figure 2. Decadal trends in the annual and seasonal mean precipitation (RR) in % dec^{-1}.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

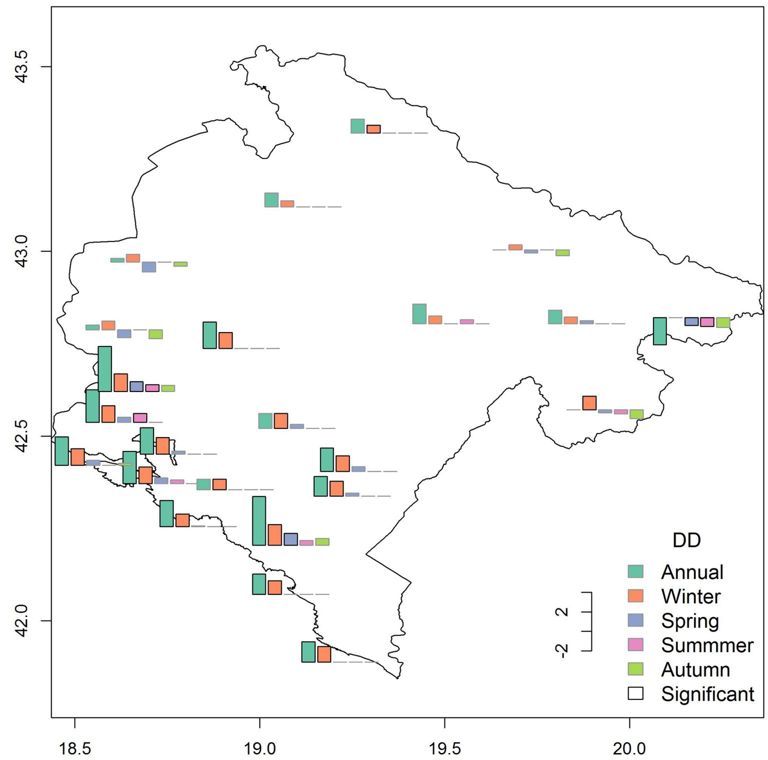

Figure 3. Decadal trends in the annual and seasonal number of dry days (DD) in days dec^{-1}.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

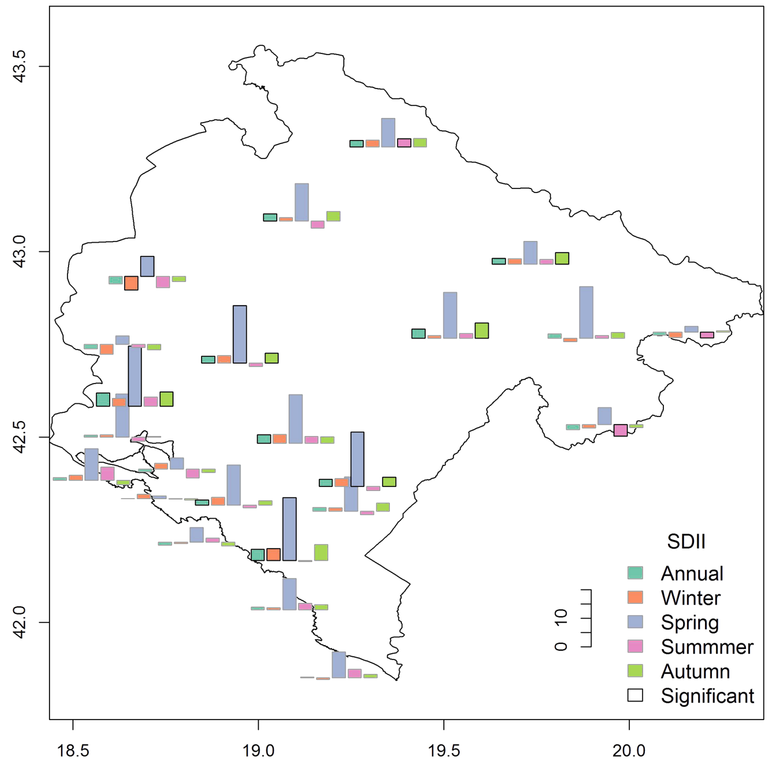

Figure 4. Decadal trends in the annual and seasonal simple daily precipitation index (SDII) in $\% \, \mathrm{dec}^{-1}$.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

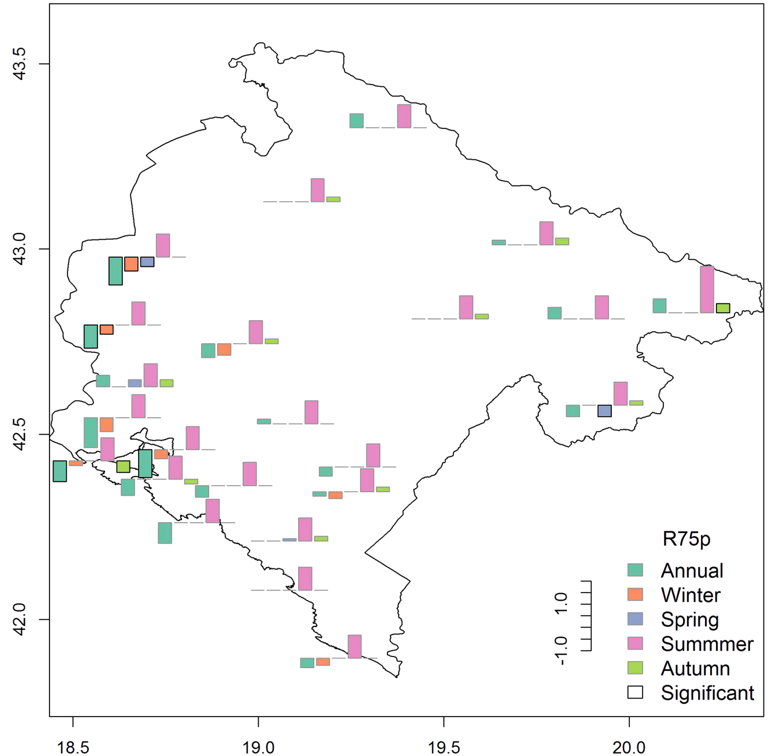

Figure 5. Decadal trends in the annual and seasonal rainfall above 75th percentile (R75p) in day dec^{-1}.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

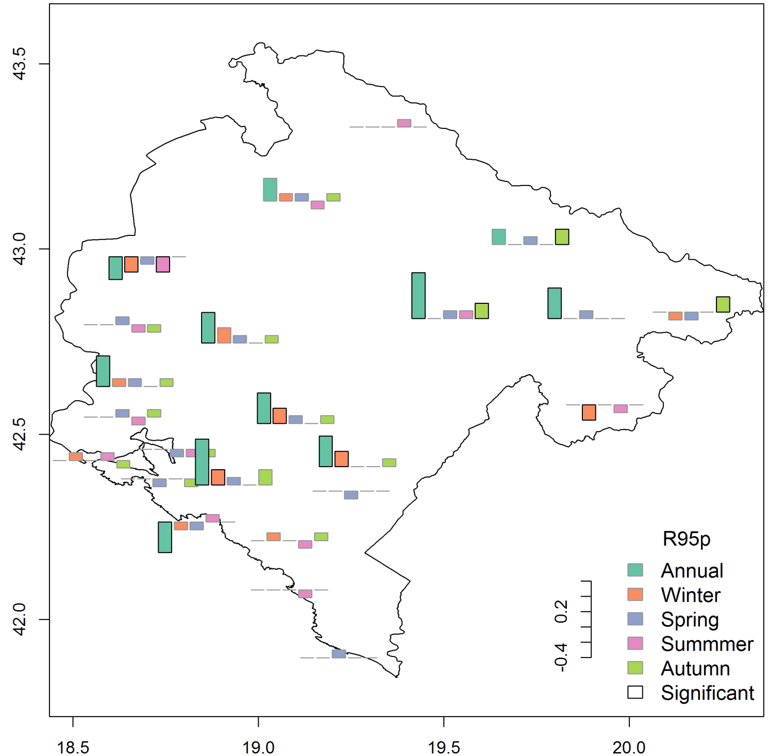

Figure 6. Decadal trends in the annual and seasonal rainfall above 95th percentile (R95p) in day dec^{-1}.

NHESSD
3, 2347–2377, 2015

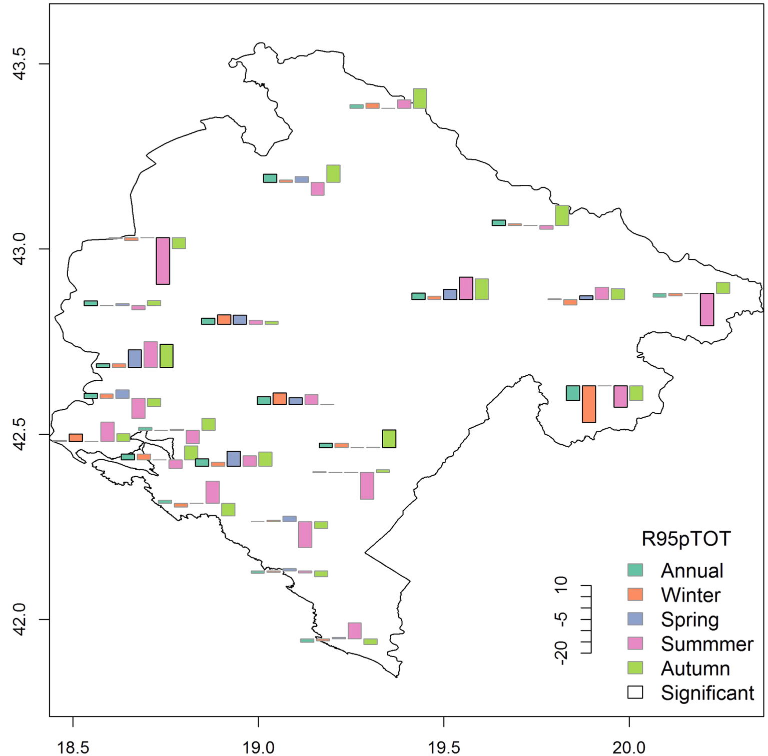

Figure 7. Decadal trends in the annual and seasonal precipitation fraction due to very wet days (R95TOT) in $\% \, \mathrm{dec}^{-1}$.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

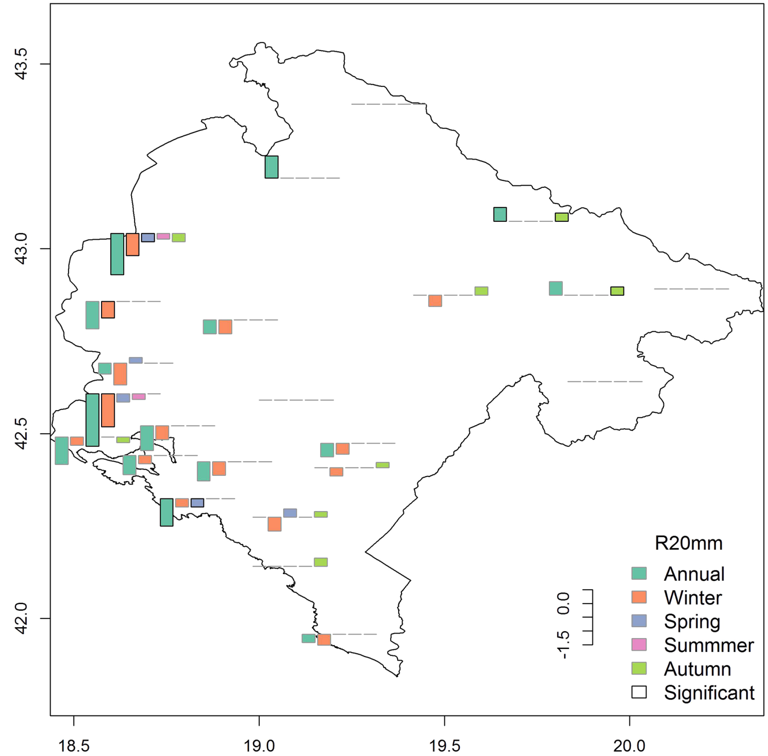

Figure 8. Decadal trends in the annual and seasonal number of days with heavy precipitation (R20 mm) in days dec^{-1}.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

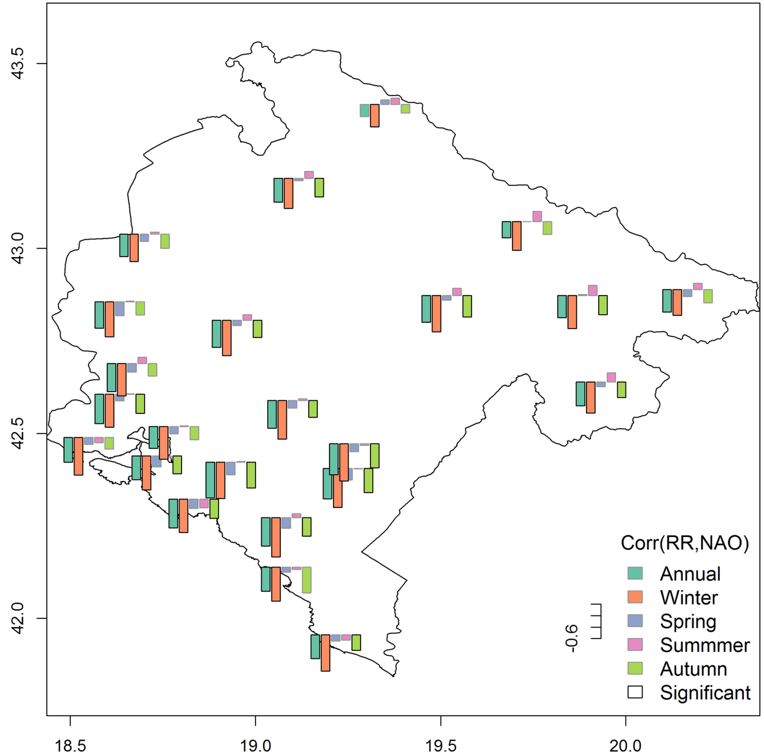

Figure 9. Mapped correlation between annual and seasonal mean precipitation (RR) and NAO index.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

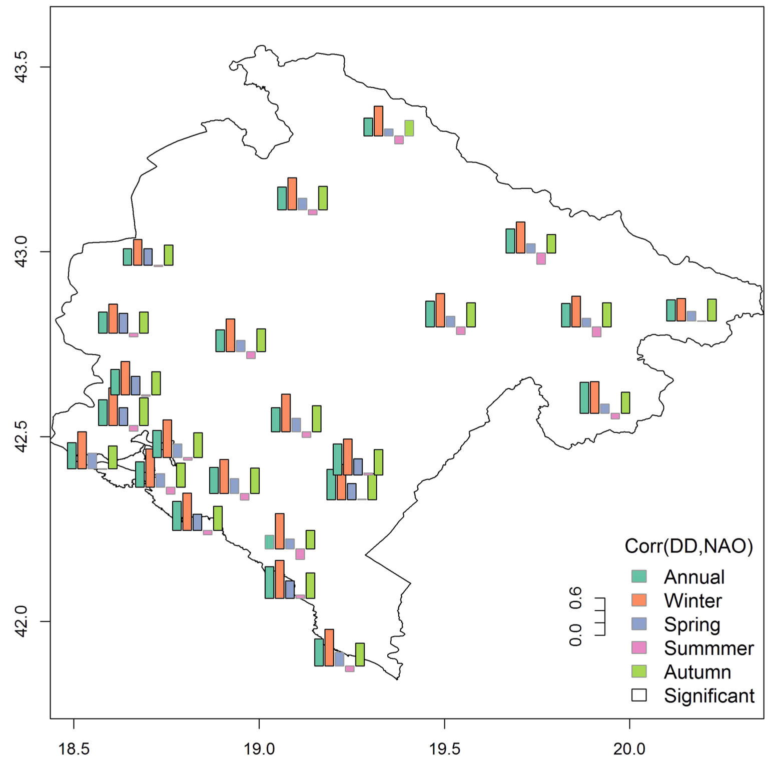

Figure 10. Mapped correlation between annual and seasonal DD and NAO index.

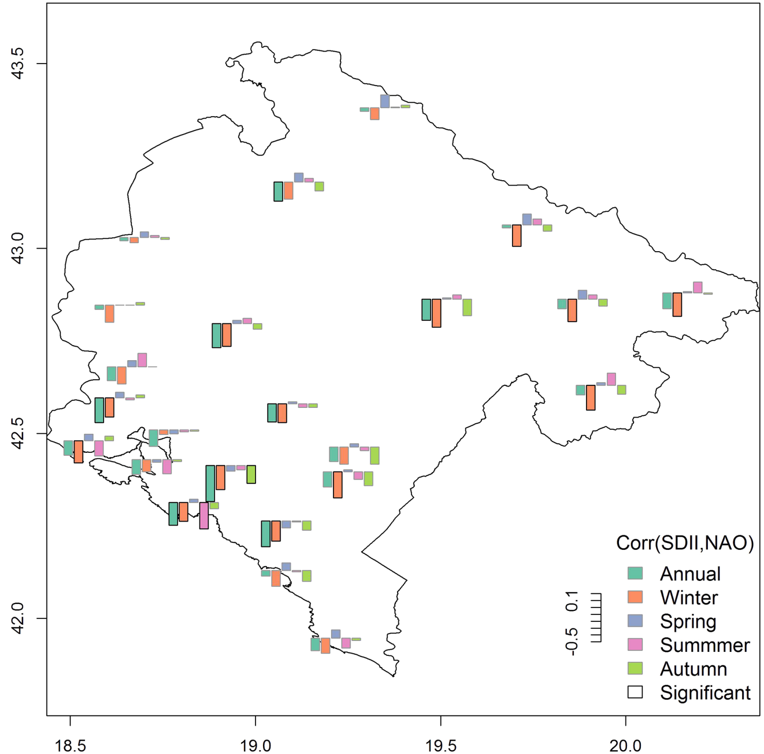

Figure 11. Mapped correlation between annual and seasonal SDII and NAO index.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

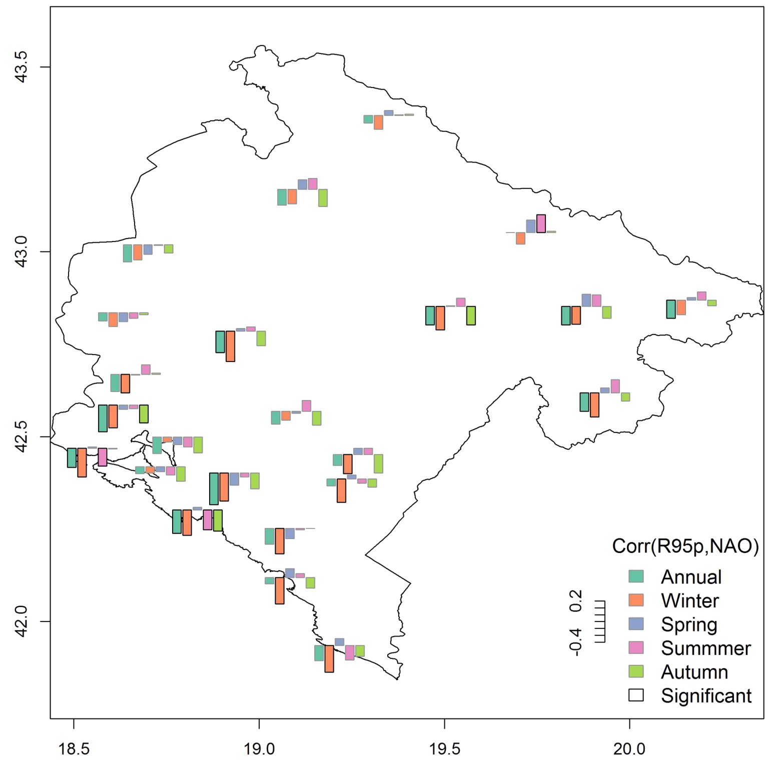

Figure 12. Mapped correlation between annual and seasonal R95p and NAO index.

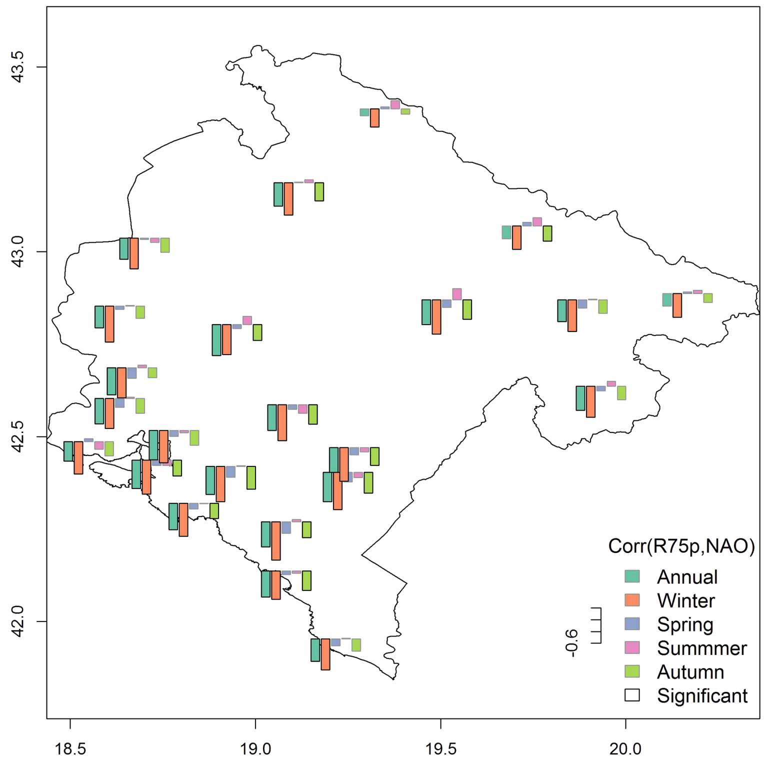

Figure 13. Mapped correlation between annual and seasonal R75p and NAO index.

NHESSD
3, 2347–2377, 2015

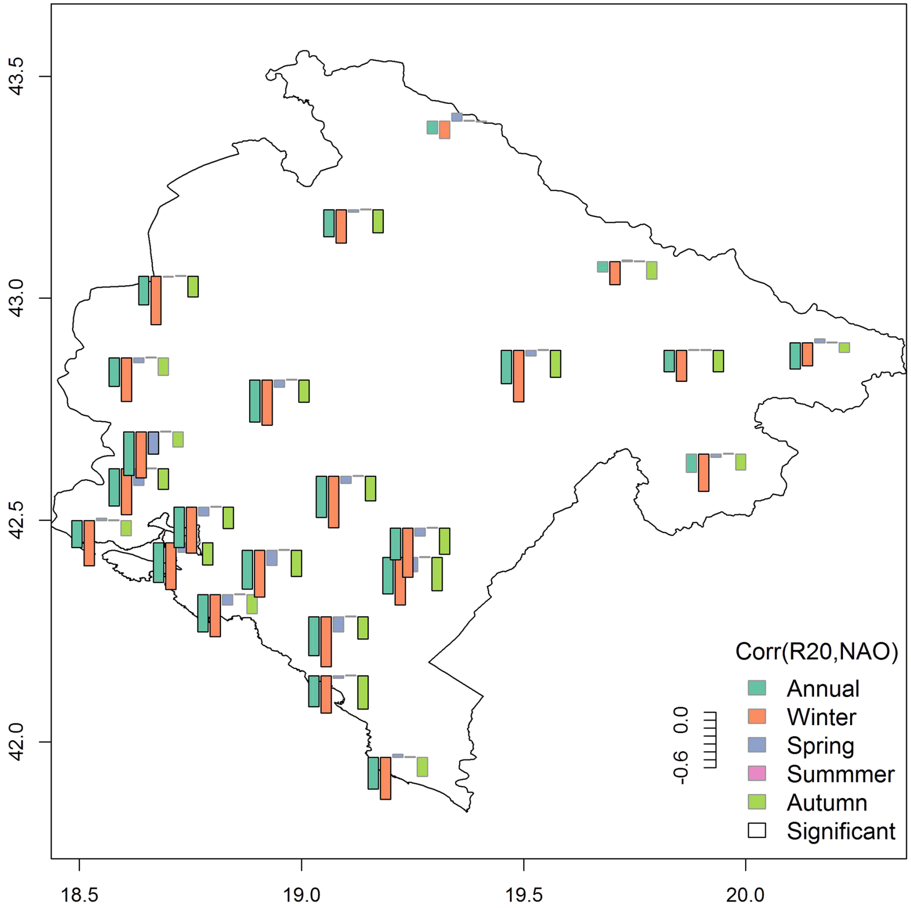

Figure 14. Mapped correlation between annual and seasonal R20 mm and NAO index.

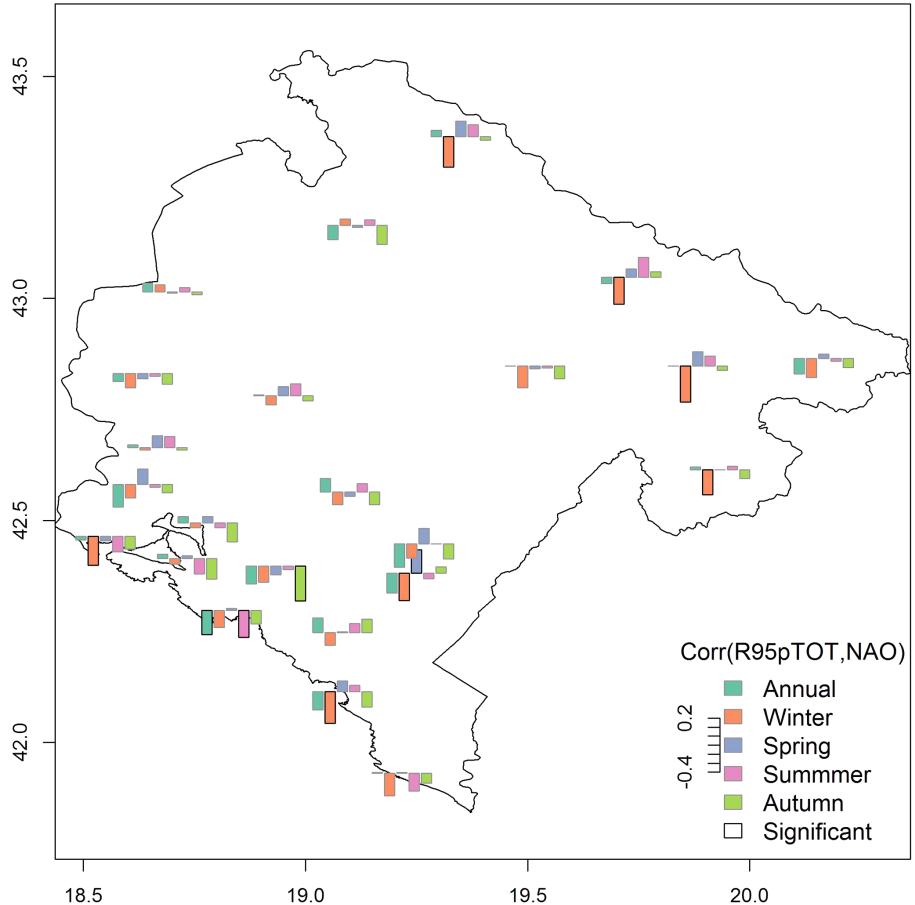

Figure 15. Mapped correlation between annual and seasonal R95pTOT and NAO index.

NHESSD
3, 2347–2377, 2015

Recent trends in daily rainfall extremes over Montenegro

D. Burić et al.