



Deciphering the breaking points and spectral periodicities of mean air temperatures and precipitation sums in Montenegro

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Abstract

Using the Rescaled Adjusted Partial Sums (RAPS) and spectral analysis methods, the study aimed to extract subperiods (a break point analysis) based on data from 18 meteorological stations in Montenegro and determine the elementary periodicity using the Lomb periodogram of mean seasonal and annual air temperatures and precipitation totals for the period 1961–2020. Prior to this, trend calculations were performed, which showed a significant increase in mean seasonal and annual temperatures, with the most intense warming occurring in the summer (from 0.30 to 0.75 °C/decade). Trends in seasonal and annual precipitation totals are insignificant. According to RAPS values, two subperiods are clearly distinguished for temperatures, and a sudden increase in mean annual temperatures at 11 stations (61.1%) occurred only in 1997 and 1998. The year 1991 was a break point in 22.1% of cases. For seasonal and annual precipitation totals, a minimum of 4 subseries can be distinguished at all stations. According to the RAPS method, the years 2002 and 2003 most frequently appear as the last pivotal points leading to an increase in annual precipitation totals. In terms of precipitation, the most prominent periodicity observed is at 2.1 and 3.6 years, suggesting a quasi-biennial oscillation. Additionally, a 14.7-year periodicity is noted in winter precipitation, and a 3-year periodicity signals ENSO. Regarding average annual and seasonal temperatures, short-term (2–3 years), medium-term (4–5 years) and long-term (6, 8 and over 20 years) periodicities are distinguished. Only at two stations, was the Markowitz wave (MW) signal.

Keywords Temperature · Precipitation · Trend · RAPS · Periodicity · Montenegro

Introduction

In recent decades, analyzing the trends and periodicity of temperature and precipitation time series has become crucial for understanding contemporary and future climate changes (Ray et al. 2019). Global temperatures are on the rise (Paeth and Pollinger 2020; Burić and Penjišević 2023), and the prevailing consensus attributes this global warming to the anthropogenic greenhouse effect. Furthermore, Europe, including the Balkan region, is experiencing warmer conditions, with an increased frequency of heatwaves (Tomczyk

et al. 2019) and a decrease in frosty/cold days, as observed in Montenegro (Burić and Doderović 2022) and the neighboring states of Bosnia and Herzegovina (Popov et al. 2019) and Serbia (Milošević et al. 2017) respectively. Regarding changes in precipitation, there are significant regional variations. For instance, in Europe, the Mediterranean, and the Balkan Peninsula (which includes Montenegro), some regions are becoming drier, while others are getting wetter. For example, on the Balkan Peninsula (Montenegro, Serbia, Bosnia and Herzegovina) certain areas experience alternating periods of droughts and floods (Kutiel et al. 2015; Ionita and Nagavciuc 2021; Burić et al. 2021), but let's say in Serbia and Bosnia and Herzegovina, all major rivers register a trend of decreasing flow in the period 1961–2020 (Dimkić 2018; Gnjato et al. 2023).

Spectral analysis methods, along with simple harmonic analysis and the autoregressive method of moving averages, are commonly employed for estimating periodicity (Kotteroda et al. 2008). In addition to climatic variables, periodicity is often evident in the analysis of various hydrological

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time series (Ahmed et al. 2014). For the period 1850–1997, Pekarova et al. (2006) examined wet and dry periods of 18 major rivers in Europe and identified the presence of dry cycles lasting 13.5 and 28–29 years. The 28–29-year flow variability cycle is most prominently observed in the Neva River. The second most significant periodicity, at 3.6 years, may be associated with the quasi-biennial oscillation and is evident in the 100-year precipitation time series in neighboring Croatia, particularly in Zagreb and Crikvenica (Gajić-Čapka 1994). Oscillations of 4–5 years are also present in precipitation time series across Europe and the Mediterranean (Maheras et al. 1992), with shorter periods of 2–5 years noted in Central Europe (Brázdil et al. 2012).

Changes in precipitation and temperature are of fundamental importance from both a scientific and a practical perspective, as they are the two main components of the hydrological cycle (Mann and Gupta 2022). Montenegro, despite its relatively small size in terms of total land area, remains insufficiently investigated in the context of modern climate change. When it comes to trends in annual and seasonal precipitation and temperature, past research has primarily focused on data from the capital, Podgorica, and Kolašin for the period 1951–2018 (Doderović et al. 2020; Burić and Doderović 2021), neglecting calculations for the entire country. When it comes to the periodicity of temperature and precipitation, as far as is known, no one has dealt with this issue for Montenegro. Given Montenegro's complex topography, meteorology, and other physical-geographical factors, and its sensitivity to climate change as a Mediterranean region, this study marks the first attempt to estimate trends and periodicity of temperature and precipitation for the entire nation. The data for this analysis is sourced from 18 meteorological stations (MS) in Montenegro, covering the period from 1961 to 2020.

Data and methodology

The research focuses on Montenegro, a country covering an area of 13,812 km² with approximately 620,000 inhabitants residing within its borders. Geographically, it extends for about 100 km in straight line, opening onto the Adriatic Sea. Generally, Montenegro's landscape is characterized by a predominantly mountainous terrain, featuring numerous basins, karst fields, and deep river valleys. In addition to the rugged terrain and substantial variations in elevation, ranging from sea level (0 m above sea level) to the mountain peak of Zla Kolata in Prokletije, which stands at 2534 m above sea level, Montenegro's climate is significantly influenced by its geographical coordinates and its proximity to both the sea and different air masses associated with cyclonic and anticyclonic weather systems (Burić et al. 2013). According to the Köppen climate classification, based on the climate

data from 1961 to 1990, Burić et al. (2014) identified two primary climate types (C and D), consisting of three subtypes (Cs, Cf, and Df), and five specific subcategories (Csa, Csb, Cfb, Dfb, and Dfc).

Seasonal and annual temperature and precipitation values were acquired from the State Institute of Hydrometeorology and Seismology of Montenegro. For the purpose of this study, data from 18 meteorological stations (MS), spanning the years 1961 to 2020 (Fig. 1), were selected. To ensure the relative homogeneity of temperature and precipitation time series, the MASH method (Multiple Analysis of Series for Homogenization) was applied, following the approach detailed by Szentimrey (2003).

Based on data from the analyzed period spanning 1961 to 2020, the mean annual temperature exhibits considerable variation, with values ranging from 5.3 °C at MS Žabljak to 15.3–16.3 °C along the coastal regions and lowlands. Notably, within this relatively compact area, the absolute temperature extremes fluctuate between a frigid –32.0 °C at MS Rožaje and a scorching 44.8 °C at MS Podgorica. Furthermore, the precipitation levels show significant disparities. Over the same 1961–2020 period, MS Pljevlja records the lowest average annual rainfall at 799.3 mm. In contrast, MS Crkvice receives a substantial 4600.5 mm of precipitation on average each year.

For the purposes of the study, the following methods were used: trend analysis, Rescaled Adjusted Partial Sums (RAPS), and spectral analysis. The trend analysis was conducted using the Sen method, and the statistical significance of the trends was assessed via the Mann–Kendall test at various significance levels, including $p < 0.001$, 0.01, 0.05, and 0.1. Precipitation trends are expressed as a percentage per decade (% per decade), rather than in millimeters (mm per decade). This is due to the significant variation in precipitation amounts in Montenegro caused by orographic characteristics and the influence of moist air masses during their forced upward movement. Therefore, relative trend values (in %) serve as a more reliable indicator of precipitation variability compared to absolute values (in mm). For instance, a 10 mm variation along the trend line in Pljevlja (an area with low precipitation) can be considered significant, while in Crkvice (an area with high precipitation), the mentioned trend is relatively insignificant. Regarding temperature, the trend is expressed in degrees Celsius per decade (°C per decade).

The RAPS method was used to determine the breakpoints, or the onset of changes in mean temperatures and precipitation totals. This method is applied for the analysis of time series of hydroclimatic variables (temperature, precipitation, river flow, and others). A graphical representation based on RAPS transformation enables a clear insight into the breakpoint years, identifying sudden jumps or drops in values, irregular fluctuations, determination of subperiods with similar characteristics

Fig. 1 Map of Montenegro showing the locations and altitudes of meteorological stations



within the entire series, and other features (Đurin et al. 2022; Šrajbek et al. 2023). RAPS is calculated using the following equation (Eq. 1):

$$RAPS_N = \sum_{i=1}^N \frac{Y_i - \bar{Y}}{S_Y} \tag{1}$$

where: Y_i is the individual value of the given member, $i = 1, 2, \dots, n$, \bar{Y} is the average value of the time series, S_Y is the standard deviation of the time series, N is the counter during the summation process (Garbrecht and Fernandez 1994).

Spectral analysis of elementary periodicity plays a pivotal role in identifying and assessing the strength of periodic components across a range of frequencies within different time series. In this study, the Lomb periodogram method was employed for this purpose. To mathematically define the classic periodogram, the analysis starts with the discrete Fourier transform equation, as outlined by VanderPlas (2018). The free software package *PA*leontological *ST*atistics (*PAST*) provides the Lomb periodogram. Before conducting the analysis, the data undergoes automatic detrending. Periodicity (p_y , measured in years) is calculated using the following formula (Eq. 2):

$$p_y = 1 \cdot (\text{frequency} \cdot \text{basic time unit}^{-1})^{-1} \tag{2}$$

Each unit on the abscissa of the Lomb periodogram corresponds to one year, a crucial detail given that our data operates on a fundamental time unit of precisely one year. The frequency (measured in years) is depicted on the x-axis of the Lomb periodogram and is calculated with the following relation: $1/(x_{\text{unit}} - 1)$. On the y-axis, the power axis is represented in units that are proportional to the square of the sinusoidal amplitudes found within the data. When interpreting ‘ p_y ,’ the analysis considers values from 2 to $n/2$, which, in our case, amounts to 30 for a dataset spanning 60 years. To conduct the elemental periodicity analysis in this study, we utilized *PAST* version 4.11 (*Past4.11*) software.

Results and discussion

Precipitation and temperature trend

Based on obtained results, it can be concluded that changes in annual and seasonal precipitation in Montenegro are generally insignificant. The annual precipitation trend (January–December) ranges from -5.4 to 1.9% per decade. At the seasonal level, the precipitation trends are as follows: in winter (DJF) from -8.0 to 1.1% per decade, in spring (MAM) from -5.2 to 2.7% per decade, during summer (JJA)

from -6.8 to 1.8% per decade, and in the autumn (SON) season from -4.6 to 3.4% per decade (Fig. 2).

Only two stations record significant trends in precipitation changes. MS Krstac shows a statistically significant decrease in annual precipitation at a significance level of 0.01 (99% level of confidence), and the decrease in winter, spring, and summer precipitation is significant at a lower significance level of 0.05 (95% level of confidence), while autumn precipitation shows an insignificant decrease at this location. A significant negative trend in summer precipitation is recorded at MS Crkvice (-6.8% per decade), according to the Mann–Kendall test at a significance level of 0.05. Therefore, changes in annual and seasonal total precipitation are generally insignificant, except in the two cases mentioned. It is worth noting that the majority of Montenegro exhibits a negative trend, indicating a slight tendency towards drier conditions.

Unlike precipitation, where changes are found to be insignificant, mean seasonal and annual temperatures exhibit a positive trend at all observed stations, with the majority being statistically significant. The mean annual temperature increases at a rate ranging from $0.12\text{ }^{\circ}\text{C}$ per decade (MS Tivat) to $0.51\text{ }^{\circ}\text{C}$ per decade (MS B.Polje). The annual warming trend is significant at two MS at the 0.01 level, and at the highest risk level ($p < 0.001$) for the other 16 MS (Table 1). The positive trend in mean seasonal temperatures falls within the range ($^{\circ}\text{C}$ per decade): winter $0.01\text{--}0.46$, spring $0.10\text{--}0.47$, summer $0.30\text{--}0.75$, and autumn $0.01\text{--}0.47$. Out of the 18 observed stations, statistically significant warming is present in 14 MS during winter and 13 MS during autumn. In spring and summer, all 18 observed stations register a significant warming trend, predominantly at the highest level of acceptance of the hypothesis ($p < 0.001$ or 99.9% confidence level). The trend results indicate that the

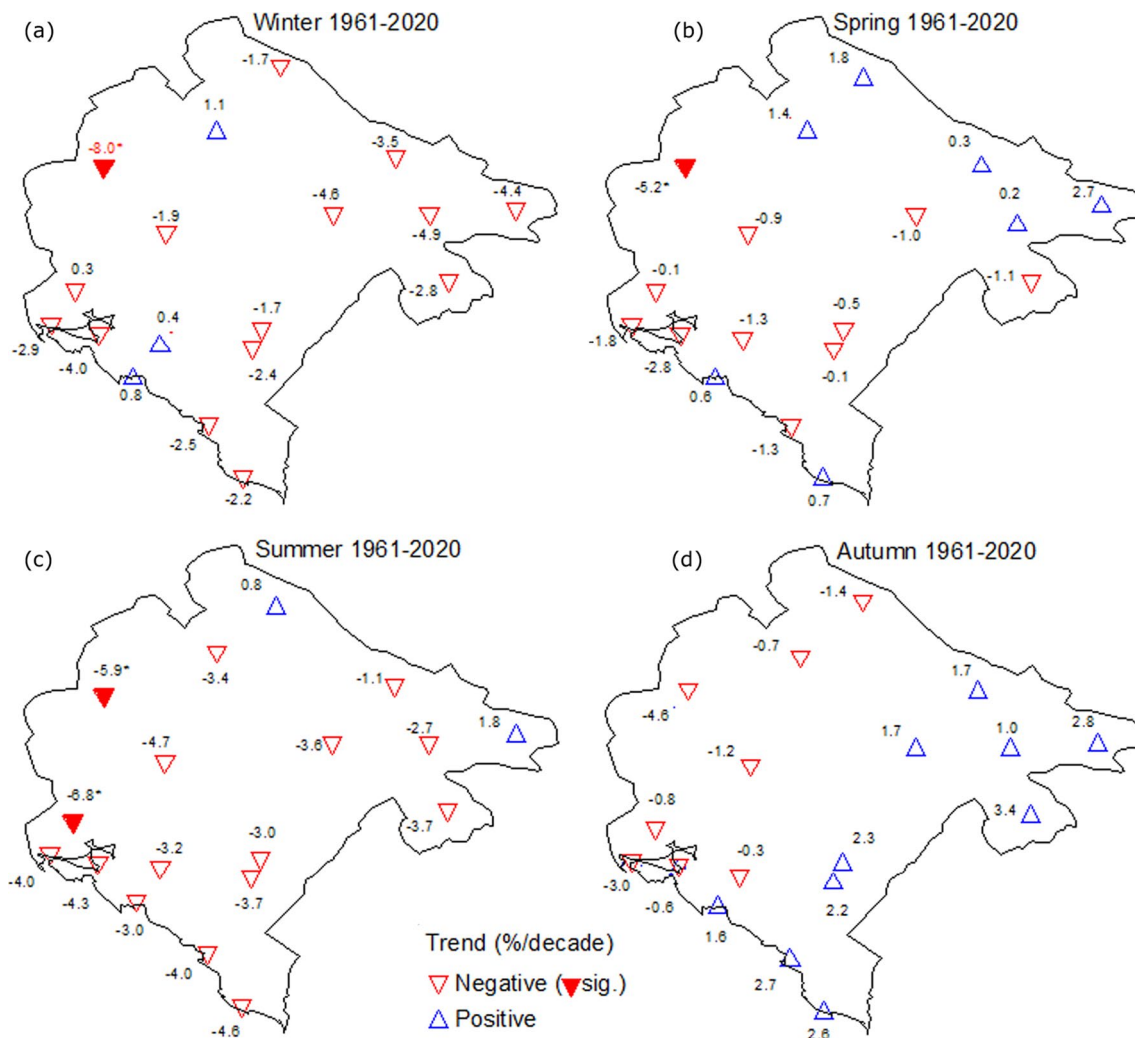


Fig. 2 Seasonal precipitation trends in the territory of Montenegro for the period 1961–2020: **a** Winter, **b** Spring, **c** Summer and **d** Autumn (Significance levels: ** for $p < 0.01$, * for $p < 0.05$)

Table 1 Trend of mean annual and seasonal temperatures (°C per decade) in Montenegro in the period 1961–2020

MS	Year	Winter	Spring	Summer	Autumn
Ulcinj	0.19***	0.06	0.22***	0.39***	0.01
Bar	0.36***	0.16*	0.35***	0.62***	0.25***
Budva	0.33***	0.11 ⁺	0.31***	0.60***	0.22**
Tivat	0.12**	0.01	0.10*	0.30***	0.04
H.Novi	0.22***	0.04	0.20***	0.44***	0.11
Golubovci	0.32***	0.18*	0.31***	0.53***	0.11
Podgorica	0.36***	0.25**	0.37***	0.56***	0.18*
Cetinje	0.25***	0.13	0.19**	0.34***	0.19*
Crkvice	0.43***	0.18 ⁺	0.42***	0.68***	0.40***
Nikšić	0.30***	0.17 ⁺	0.25***	0.49***	0.15 ⁺
Krstac	0.20**	0.21 ⁺	0.21*	0.32***	0.08
Plav	0.50***	0.37**	0.35***	0.75***	0.47***
Kolašin	0.32***	0.21 ⁺	0.31***	0.53***	0.23**
Žabljak	0.38***	0.32**	0.38***	0.53***	0.27**
Rožaje	0.50***	0.46***	0.37***	0.66***	0.38**
Berane	0.47***	0.42***	0.40***	0.63***	0.40***
B.Polje	0.51***	0.40**	0.47***	0.75***	0.42***
Pljevlja	0.33***	0.34*	0.25**	0.46***	0.20*

Significance levels: ***p < 0.001, **p < 0.01, *p < 0.05, +p < 0.10

most pronounced warming in Montenegro during the period 1961–2020 occurs in summer.

The analysis further reveals a regional regularity in terms of the increase in average temperature, with a discernible trend moving from the southwest to the northeast and east of the country, particularly during winter and summer (Fig. 3). This general pattern is also observed in the precipitation trend. The most significant decrease in precipitation is observed in the western and southwestern parts of Montenegro, while as we move inland, the negative trend not

only diminishes but also changes direction. Consequently, the extreme northeastern part of the country experiences a slight tendency toward increased precipitation over the observed period. In other words, the regions in Montenegro closest to the sources of moisture, such as the Adriatic and Mediterranean Seas and the Atlantic, show the most substantial decrease in precipitation (Mediterranean region) and the smallest increase in temperature. Conversely, the more continental parts of the country exhibit a trend of increasing precipitation and the most pronounced warming. This paradox suggests that changes in both precipitation and temperature, aside from being influenced by greenhouse gas emissions, may also be linked to variations in air masses, such as teleconnections. It should be mentioned that the condensation level in Montenegro is at an altitude of about 1000–1200 m (Burić et al. 2013), and under warmer climate conditions, it is very likely that this level is now at a higher elevation. This could be one explanation for the slight upward trend in precipitation in the highest mountainous part of Montenegro (northeastern region). On the other hand, the reasons for the lesser (attenuated) increase in temperature along the coast, in the south, and southwest of the country could also be related to the influence of the sea, but this requires further research.

RAPS method analysis

Using the aforementioned Eq. (1), RAPS values were calculated with the aim of determining the highest/lowest peak to define the breakpoint year of changes. For the sake of brevity, a graphical representation of the RAPS method for the MS Podgorica is provided here, but the same procedure was applied to other MS as well. The obtained RAPS values of mean summer temperatures for Podgorica indicate that two subseries can be distinguished: 1961–1991 and 1992–2020. Thus, according to

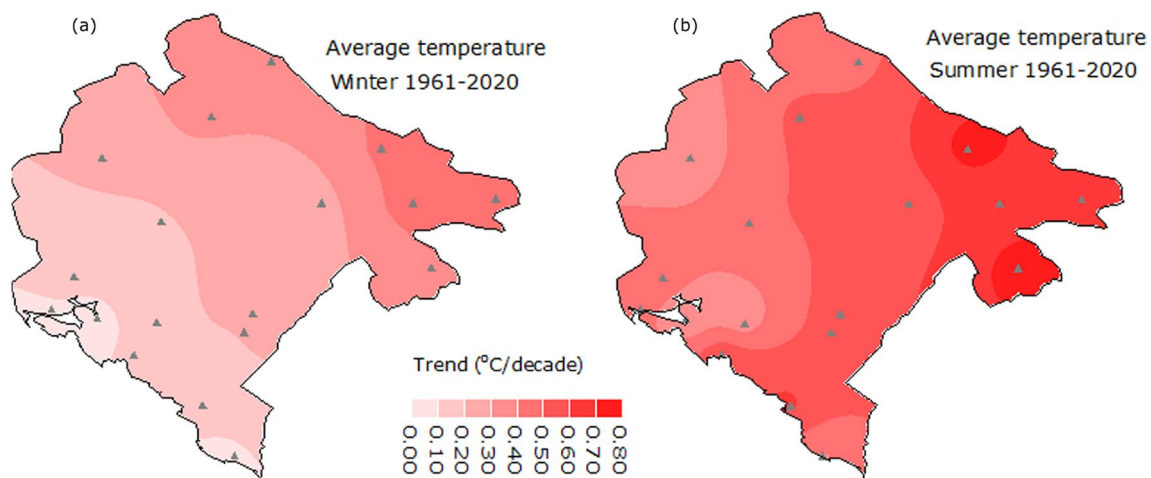


Fig. 3 Spatial distribution of mean **a** Winter and **b** Summer temperature trends in Montenegro (1961–2020)

RAPS values, a sudden increase in mean summer temperatures in Podgorica occurred in 1992. For the period 1961–2020, the years of abrupt changes for the winter and spring seasons are 1993 and 1998, while for the autumn season, three subseries with different thermal properties can be identified: 1961–1968, 1969–1997, and 1998–2020, with 2 years of abrupt changes: 1969 and 1998 (Fig. 4a). Fluctuations are noticeable in seasonal and annual precipitation totals, which is consistent with the variable nature of this parameter, allowing several breakpoints to be identified. The last breakpoint for winter is 2002, for spring 2011, and for autumn, it is the year 1990, when an increase in precipitation occurred from the mentioned years. For summer precipitation totals, the last breakpoint year is 2009, but from this year onwards, precipitation decreases (Fig. 4b). According to RAPS values, a sudden increase in mean annual temperatures in Podgorica occurred only in 1997, while for annual precipitation totals, at least 4 subseries can be distinguished: 1961–1969, 1970–1980,

1981–2002, and 2003–2020, with a sudden increase in annual precipitation totals generally observed from 2003 onwards (Fig. 4c).

In Table 2, the last years when abrupt changes in mean seasonal and annual temperatures and seasonal and annual precipitation totals occurred are listed. It should be emphasized that the last RAPS value in the series must be 0. For all MS in Montenegro, for all temperature and precipitation time series, the final RAPS value was indeed 0, confirming the correctness of the calculations. According to the RAPS method, in 94.4% of MS (17 MS), the abrupt increase in mean winter and mean spring temperatures began in 1993 and 1998, respectively. The breakpoint years for the onset of rapid warming in summer are 1991 and 1992 in most cases (77.8% of MS). In the majority of cases (72.2% of MS), the abrupt increase in mean autumn temperature also began in 1998.

Due to the Mediterranean precipitation regime, the influence of intricate orography, the interplay of maritime

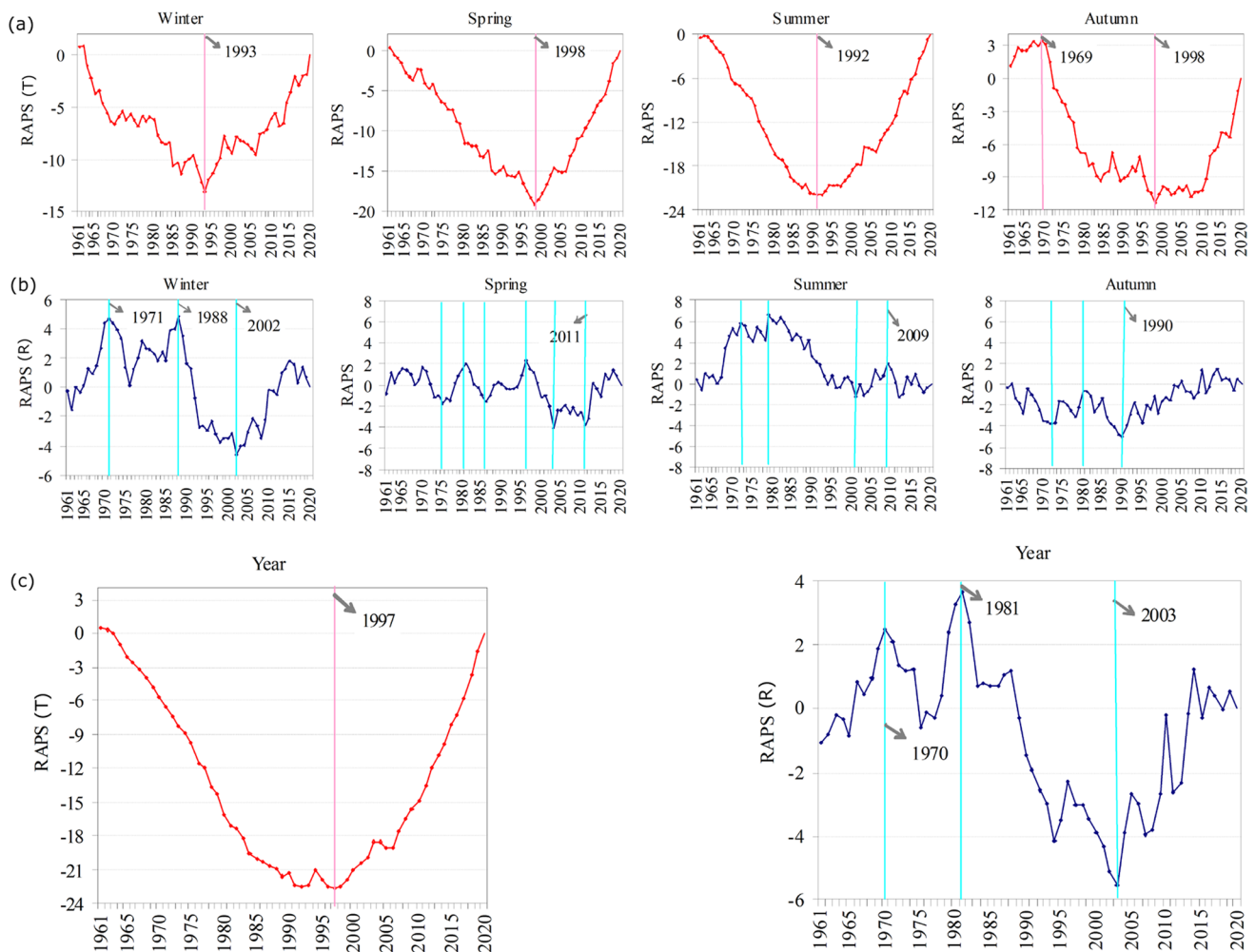


Fig. 4 RAPS values of mean seasonal temperatures (a) and seasonal precipitation totals (b), as well as mean annual temperatures and annual precipitation totals (c) in Podgorica for the period 1961–2020

Table 2 Initial year of the last subperiod with abrupt increase in mean temperatures and changes in precipitation sums at 18 meteorological stations (MS) in Montenegro according to the RAPS method for the period 1961–2020

MS	Temperature					Precipitation				
	Year	Winter	Spring	Summer	Autumn	Year	Winter	Spring	Summer	Autumn
Ulcinj	1991	1993	1998	1991	1981	2008	2008	2011	2012	2008
Bar	1997	1993	1998	1992	1998	2003	2002	2011	2006	2008
Budva	1997	1993	1998	1992	1998	2003	2005	2011	2003	2008
Tivat	1996	1993	1998	1992	1998	2008	2008	2011	2001	2008
H.Novi	1997	1993	1998	1992	1998	2008	2008	2011	1983	1985
Golubovci	1997	1993	1998	1992	1998	2003	2008	2011	2003	1990
Podgorica	1997	1993	1998	1992	1998	2003	2002	2011	2009	1990
Cetinje	1998	1993	1998	1992	2007	2002	2002	2011	1979	1989
Crkvice	1997	1993	1998	1997	1998	2002	2002	2003	1979	1995
Nikšić	1991	1987	1998	1991	2008	2002	2002	2011	1979	1990
Krstac	1998	1993	1999	1997	2009	1980	1987	1988	1976	1980
Plav	1998	1993	1998	1997	1998	2008	2008	2008	1979	2008
Kolašin	1991	1993	1998	1991	1998	2002	2008	2012	1989	1990
Žabljak	1997	1993	1998	1991	1998	2002	2002	2012	1983	1995
Rožaje	1993	1993	1998	1990	2007	2008	2002	1994	2012	1995
Berane	1991	1993	1998	1991	1998	1994	2002	1993	1995	1995
B.Polje	1998	1993	1998	1997	1998	2002	2002	2012	2004	2005
Pljevlja	1993	1993	1998	1991	1998	2003	2002	2008	2003	2010

The bolded years indicate the initial year of the last subseries from which precipitation totals decrease

influences from the south and continental influences from the north, and the presence of different air masses, the situation with precipitation is much more complex compared to temperature because it is a climatic element that is highly variable in time and space. Graphical representations of RAPS values have shown that for all 18 MS, there are a minimum of 4 shorter or longer time subseries within the 60-year series. However, in 61.1% of cases (11 MS), the years 2002 and 2003 represent the beginning of an increase in annual precipitation totals in the last identified subperiod, and in 5 MS, it is 2008. In the summer season, the last subseries in most cases (66.7% of MS) is characterized by the separation of the initial peak of RAPS values, so the indicated year (bolding year in Table 2) represents the beginning of a decrease in precipitation.

Based on the results obtained using the RAPS method within the time series (1961–2020) of mean temperatures, two subperiods are clearly distinguished for all MS, both seasonal and annual. A sudden increase in mean annual temperatures occurred only in 1997 and 1998 at 11 MS (61.1%), while 1991 was pivotal in 22.1% of cases (4 MS). In the neighboring country of Croatia, Bonacci (2010) mentions precisely the year 1997 for the Crikvenica MS when there was a sudden increase in mean annual air temperatures. For the other 25 MS in Croatia, the pivotal points for mean annual temperature were mostly in 1988 and 1992.

Spectral analysis of precipitation and temperature periodicity

The results of spectral analysis for elementary periodicity in the 60-year (1961–2020) time series of precipitation (R) and temperature (T) for central MS Podgorica are presented below. To maintain clarity and avoid excessive data presentation, the results for the other locations (17 MS) will be presented in tabular format, highlighting only the single strongest peak with its associated frequency.

Analyzing the results of elementary periodicity calculations for annual precipitation in Podgorica over the 60-year period (1961–2020), five prominent peaks have been identified. The strongest peak exhibits a frequency with a peak power of 3.7, corresponding to a cycle length of approximately 3.6 years. This periodicity can be associated with a quasi-biennial oscillation, a pattern observed in 100-year precipitation time series in neighboring Croatia (Gajić-Čapka 1994). The second peak has a power of 3.2, indicating a period of around 4.3 years (Table 3 and Fig. 5). The third most prominent peak, with a power of 3.1, corresponds to a period of about 8.7 years. Walanus et al. (2022) have highlighted the significance of this periodicity in annual precipitation across Europe. The fourth peak, with a power of 2.3, corresponds to a period of approximately 2.9 years, which can be associated with the quasi-biennial oscillation. The fifth power peak, at 1.9, corresponds to a period of about 3.2 years. Periodicities of 3 to 4 years are clear indicators

Table 3 Length cycles (in years) of the five most significant peaks of the time series of annual and seasonal precipitation for MS Podgorica (1961–2020)

Year		Winter		Spring		Summer		Autumn	
Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)
3.7	3.6	4.4	14.7	5.1	2.8	4.2	3.7	5.0	2.3
3.2	4.3	3.7	2.9	4.1	8.7	3.6	3.3	3.6	6.0
3.1	8.7	3.1	8.9	3.6	4.3	3.5	2.3	3.6	4.3
2.3	2.9	2.6	22.5	2.5	2.5	2.6	9.3	2.8	2.4
1.9	3.2	2.6	3.1	2.3	2.0	2.6	2.7	2.0	3.2

of the El Niño-Southern Oscillation (ENSO), while the primary periodicity of the Southern Oscillation Index (SOI) corresponds to a cycle lasting 3.5 years (Karagiannidis et al. 2008). The periodicity in the time series of seasonal precipitation in Podgorica reveals fluctuations with shorter cycles in the spectral range of 2–5 years, as well as longer-term cycles ranging from 6.0 to 14.7 years, and even exceeding 20 years (22.5) in general. Türkeş et al. (2002) reported that long period fluctuations of 14 and 21 years were found in winter precipitation in Turkey.

In the case of the mean annual temperature (T-Year) in Podgorica for the period 1961–2020, the analysis of elementary periodicity has identified the five most significant cycles of 4.1, 5.1, 6.5, 8, and 26.2 years. These five strongest peaks are clearly visible on the graphical display and are tabulated for both the mean annual and mean seasonal temperatures (see Table 4 and Fig. 6) in Montenegro's capital, Podgorica.

The frequency of the strongest peak corresponds to a cycle length of 26.2 years for the mean annual temperature. This spectral range (20–70 years) corresponds to the Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO) (Deser et al. 2010; Newman et al. 2016). The second most prominent peak, with a power of 3.2, indicates a periodicity of approximately 4.1 years. Oscillations in the range of 2–6 years have been observed in the North Atlantic Oscillation (NAO) index (Zhang et al. 2011), along with periodicities of 2–8 years associated with El Niño-Southern Oscillation (ENSO) (Turner 2004). The third strongest peak, with a power of 2.7, corresponds to a period of about 5.1 years. Similar to the second peak, the periodicity within this spectral range can be detected in the ENSO and NAO indices.

The fourth power peak, with a value of 2.6, represents a period of approximately 6.5 years. This medium-term oscillation in temperature time series has been observed in the Nišava river basin in southeastern Serbia and is associated with the Mediterranean Oscillation Index (MOI) (Martić-Bursać et al. 2017). The fifth strongest peak in Podgorica corresponds to a period of about 8 years. Plaut et al. (1995), in their analysis of temperature changes in central England over a 335-year period, identified a cycle of

7–8 years. Similar results, indicating a climatic oscillation of 7–8 years in ground temperature, have been obtained by other researchers in various locations across Europe and the Mediterranean (Brázdil et al. 2012). It's worth noting that this periodicity of 7–8 years has also been detected in the North Atlantic Oscillation (NAO) index by researchers such as Jajcay et al. (2016).

At the seasonal level, all identified oscillations can be categorized into three groups: short-term, medium-term, and long-term fluctuations. When analyzing winter temperature series, longer-term fluctuations of 19.7 and 9.1 years are observed. The 19.7-year fluctuation can be associated with the Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO). Short-term periodicities of 2.2 and 3.0 years can be linked to El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) teleconnections, while the medium-term periodicity of 6.1 years is indicative of the Mediterranean Oscillation Index (MOI). Or, variations in the mean summer temperature series for MS Podgorica are primarily characterized by medium and long-term cycles of 4.1, 5.0, 7.6, 9.3, and 24.8 years, which can be linked to confirmed periodicities, including NAO, ENSO, MOI, PDO, and IPO teleconnections. The influence of these and other teleconnections on temperature and precipitation changes and cyclic fluctuations in Montenegro warrants further in-depth examination. For example, Doderovic and Buric (2015) determined that the Atlantic Multidecadal Oscillation (AMO) significantly affects summer temperature parameters in Montenegro.

Elementary periodicity calculations were also performed for the other 17 MS, and the results are presented in a table. For both the time series of precipitation (Table 5) and temperature (Table 6), only the single strongest peak with its associated frequency is included. The analysis reveals a high degree of compatibility between the results of MS Podgorica and the other 17 MS in general. An exception is observed at two stations on the Montenegrin coast (MS Herceg Novi and MS Ulcinj), where the primary long-term oscillation of 29.5 years was identified in the annual temperature series. This 29.5-year periodicity, also known as the Markowitz wave

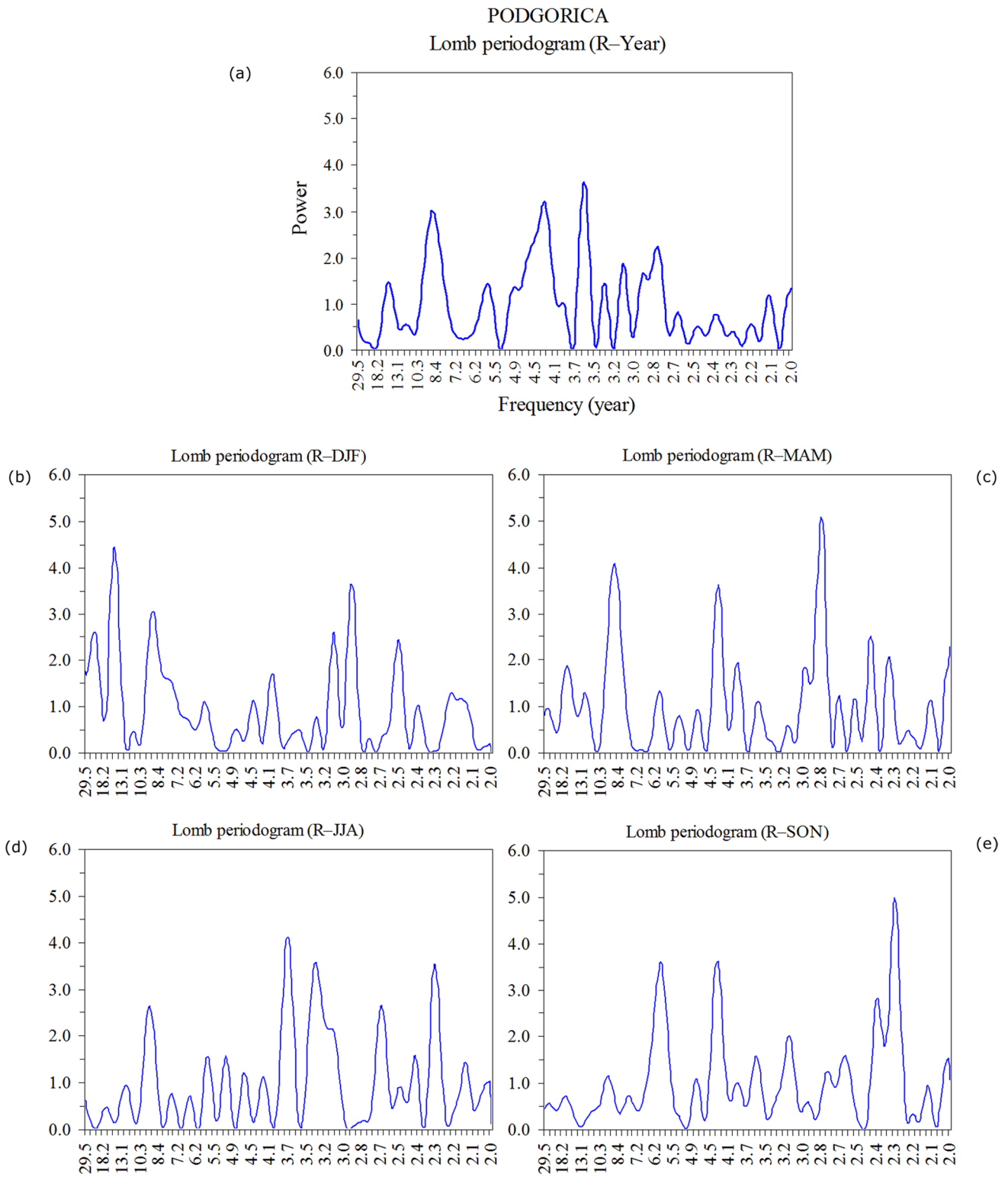


Fig. 5 Lomb periodogram of precipitation at the MS Podgorica (1961–2020) for **a** Year, **b** Winter, **c** Spring, **d** Summer and **e** Autumn

Table 4 Length cycles (in years) of the five most significant peaks of the time series of mean annual and seasonal temperatures for MS Podgorica (1961–2020)

Year		Winter		Spring		Summer		Autumn	
Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)	Power	Frequency (year)
3.7	26.2	4.0	6.1	4.3	8.1	3.8	5.0	5.0	26.2
3.2	4.1	3.3	2.2	3.8	2.2	2.8	4.1	3.9	6.3
2.7	5.1	2.4	9.1	3.7	3.5	2.0	24.8	2.5	17.5
2.6	6.5	2.3	3.0	2.6	5.6	1.8	7.6	2.0	9.3
2.1	8.0	2.0	19.7	2.2	2.7	1.6	9.3	1.8	2.4

(MW), was obtained for cosmic rays by Pérez-Peraza et al. (2012). This intriguing coincidence warrants further in-depth research to determine whether there is a connection between the 29.5-year MW oscillation and the annual temperature at these two mentioned MS.

Recent research studies undoubtedly indicate a strong correlation between the variable star Sun and its activity, and the Earth's climate (Tinsley 2023; Zharkova et al. 2023). Both short-term and long-term periodicities in solar activity have been observed, and we have taken into account those correlating with the results shown in our own research. In 1843, Schwabe detected the 11-year periodicity in sunspot numbers, and in 1908, Hale discovered the complete solar cycle spanning 22 years. The 11-year Schwabe periodicity in sunspot numbers has been shown to display distinct high variability from 8 to 15 years. Thus, the duration of the Schwabe cycle is anticorrelated to its amplitude (Waldmeier's rule). Long-term periodicities in solar motion and activity range from 25 to 250 years (Charvátová and Střeščík 1992). A 16-year periodicity is a signature of solar wind (Prabhakaran Nayar 2006), and pronounced power peaks of 1.2–2.5 years are indicative of solar activity (Kilcik et al. 2009). Vecchio and Carbone (2009) have found the temporal modulation of quasi-biennial periodicity in the signature of 1.5–4 years. Regarding the aforementioned solar activity periodicities and our own results, on the yearly level, the strongest peaks in average temperature for MS Podgorica have shown some short-term (4.1), mid-term (8.0), and long-term (26.2) periodicities, indicative of the temporal modulation of quasi-biennial periodicity, Schwabe cycle, and long-term periodicity in solar motion and activity. On the seasonal level, the strongest spring (8.1) and autumn (26.2) power peaks are indicative of the Schwabe cycle and long-term periodicity in solar motion and activity, while the second strongest summer power peak (4.1) and winter (2.2) are indicative of the temporal modulation of quasi-biennial periodicity. Comparing the results obtained at MS Podgorica with those at the other 17 MS included in the analysis, we conclude that there is a high degree of compatibility both on annual and seasonal levels.

Conclusions

The paper presents the results of trends, the RAPS method, and elementary periodicity of temperature and precipitation in Montenegro for the period 1961–2020. The trend of changes in annual and seasonal precipitation is generally insignificant, ranging from approximately –5% to about 3% per decade. On the other hand, mean seasonal and annual temperatures exhibit a positive trend at all observed stations, with many being statistically significant. The average annual temperature increase ranges from 0.12 to 0.51 °C per decade. RAPS values have shown that abrupt increases in mean winter and mean spring temperatures occurred at 17 MS (94.4%) starting from 1993 and 1998, respectively, while abrupt warming in summer and autumn began in 1991 and 1992, respectively, and in 1998, at 13 MS each. Unlike mean temperatures, where two subseries are distinguished within the observed period (1961–2020), precipitation exhibits four or more subperiods. Regarding the last subseries, winter precipitation totals show an increase from 2002 and 2008 at 16 MS, while spring totals show an increase from 2011 and 2012 at 12 MS. According to the RAPS method, for autumn precipitation totals, the breakpoint years in the last subseries are most frequently 1995 and 2008. In the case of summer precipitation totals, no predominant year is observed as a breakpoint, likely due to frequent convective rainfall during this season. At MS Podgorica, periodicity is visually demonstrated using the Lomb periodogram. A table is also provided, showing the lengths of cycles (in years) for the five most significant peaks in the sum of precipitation and temperature. The results obtained at MS Podgorica exhibit a significant resemblance to those obtained at other monitoring stations (MS), suggesting a harmonious relationship between these cycles. In the examined time series of precipitation sums in Podgorica and the other 17 MS, oscillations were observed, which can be linked to well-established periodicities occurring in Europe and the Mediterranean, such as the NAO, ENSO, and the quasi-biennial oscillation. The most noteworthy periodicities are at 2.1 and 3.6 years, indicative of the quasi-biennial oscillation. Additionally, there is a 14.7-year periodicity observed in winter precipitation and

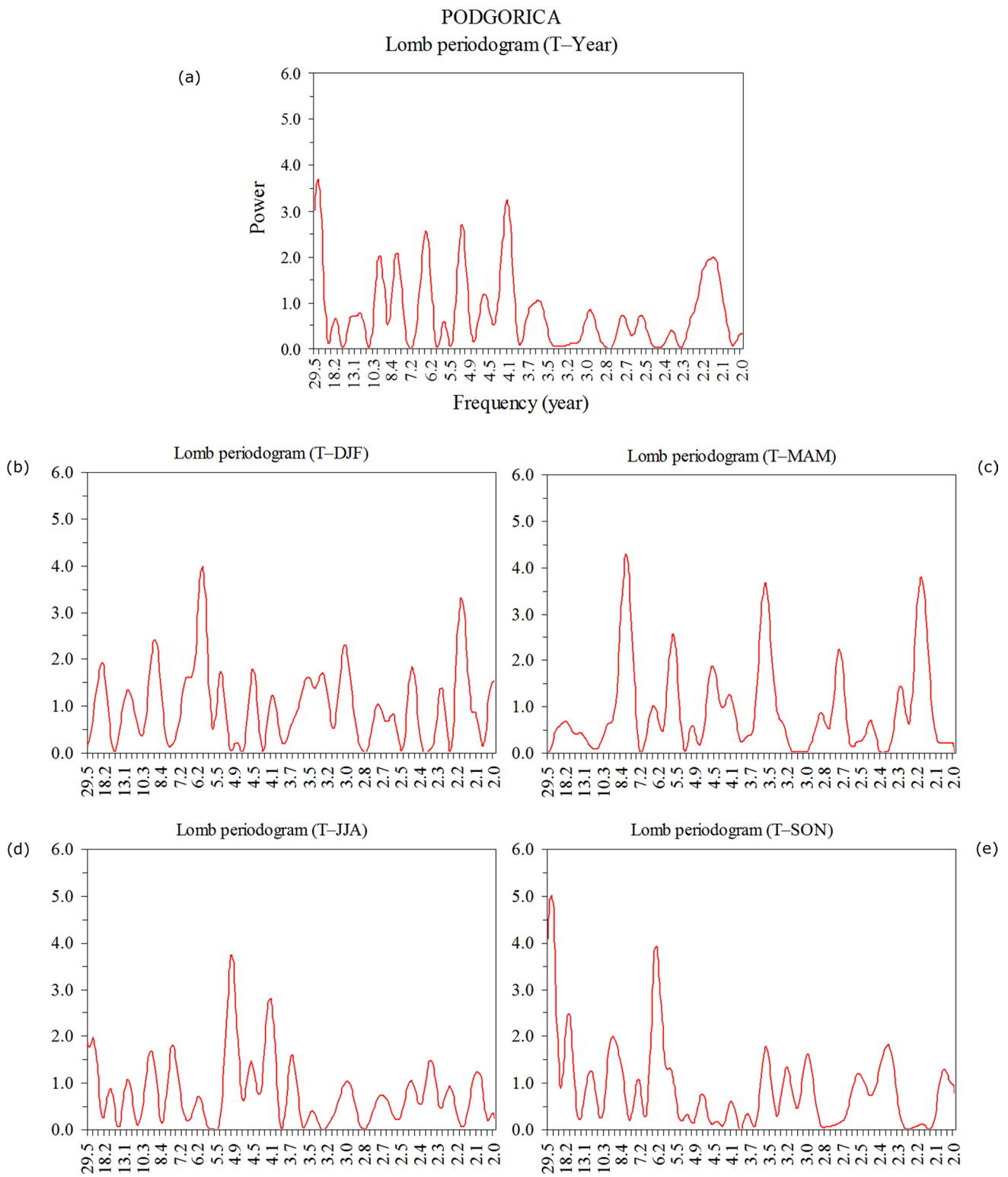


Fig. 6 Lomb periodogram of average temperatures at the MS Podgorica (1961–2020) for: **a** Year, **b** winter, **c** spring, **d** summer and **e** autumn

3-year periodicities signaling ENSO. Regarding average annual and seasonal temperatures, the analysis of elementary periodicity reveals short-term (2–3 years), medium-term

(4–5 years), and long-term (6, 8, and over 20 years) oscillations. Future research should concentrate on examining the factors that have driven changes in temperature and

Table 5 Length cycles (in years) of the strongest peaks of the time series of annual and seasonal precipitation at the MS in Montenegro (1961–2020)

MS	Year		Winter		Spring		Summer		Autumn	
	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)
Ulcinj	3.1	2.9	4.8	14.7	6.0	2.8	3.9	3.3	3.7	2.3
Bar	3.8	8.6	5.0	14.7	4.4	2.9	6.4	3.3	4.3	5.9
Budva	2.6	4.4	4.2	23.6	2.7	5.4	3.8	4.6	4.9	2.3
Tivat	3.6	2.7	6.3	14.7	4.9	8.6	5.6	3.8	4.3	2.3
H.Novi	4.1	29.5	5.5	14.7	4.3	8.6	4.4	3.3	4.7	2.3
Golubovci	3.6	3.6	4.9	14.7	5.1	2.8	4.1	3.3	4.9	5.9
Podgorica	3.7	3.6	4.4	14.7	5.1	2.8	4.2	3.7	5.0	2.3
Cetinje	4.0	4.6	4.9	14.7	5.9	8.4	6.8	3.8	5.3	5.9
Crkvice	2.8	4.4	3.7	21.4	4.1	4.3	5.8	3.7	3.6	2.3
Nikšić	4.4	5.0	4.2	2.9	5.4	2.8	6.9	3.3	4.1	2.3
Krstac	3.9	4.9	4.4	13.9	3.3	4.4	4.4	3.8	4.6	2.3
Plav	5.8	29.5	5.8	26.2	6.4	27.8	4.7	3.3	4.3	3.5
Kolašin	3.5	3.6	4.3	15.2	4.2	4.2	5.1	3.2	3.4	2.3
Žabljak	3.5	2.1	4.2	8.3	3.9	2.9	4.5	3.8	2.9	5.6
Rožaje	3.2	8.0	3.8	2.9	3.6	8.4	5.6	3.2	4.5	8.6
Berane	4.8	2.1	4.1	15.7	6.1	4.0	3.9	3.1	3.8	2.2
B.Polje	3.7	8.6	4.1	22.5	7.5	8.6	4.5	3.2	3.6	6.1
Pljevlja	5.1	2.1	4.1	15.2	3.1	2.5	4.3	2.5	3.6	26.2

Table 6 Length cycles (in years) of the strongest peaks of time series of mean annual and seasonal temperatures at the MS in Montenegro (1961–2020)

MS	Year		Winter		Spring		Summer		Autumn	
	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)	Power	Fre- quency (year)
Ulcinj	6.2	29.5	3.1	6.1	4.8	8.3	3.1	7.6	3.7	9.1
Bar	3.2	18.2	3.5	2.2	3.1	8.4	3.1	5.1	4.7	6.3
Budva	3.1	17.5	3.2	2.2	4.7	3.5	4.1	4.4	4.3	27.8
Tivat	3.9	27.8	4.7	8.7	4.3	8.1	3.3	5.1	3.9	6.2
H.Novi	5.1	29.5	3.4	8.9	4.0	2.2	3.1	5.1	4.7	6.3
Golubovci	3.7	4.1	3.6	6.1	4.2	3.5	3.7	4.1	5.1	6.3
Podgorica	3.7	26.2	4.0	6.1	4.3	8.1	3.8	5.0	5.0	26.2
Cetinje	5.5	24.8	5.0	2.2	5.3	2.2	3.6	23.6	6.1	26.2
Crkvice	3.4	12.8	4.0	3.1	3.0	2.2	3.6	23.6	5.5	24.8
Nikšić	2.9	5.1	4.3	6.1	4.1	3.5	3.4	5.1	5.1	26.2
Krstac	3.8	6.6	4.0	9.1	5.3	2.2	3.9	5.1	5.3	6.5
Plav	3.5	13.5	3.4	6.1	6.0	8.1	3.8	3.7	4.4	26.2
Kolašin	3.2	24.8	4.1	6.1	4.3	8.1	3.5	5.1	4.1	26.2
Žabljak	2.9	5.1	4.0	6.1	3.9	8.0	3.9	8.1	4.1	6.4
Rožaje	6.5	24.8	3.6	2.2	3.4	2.7	2.8	5.1	6.6	26.2
Berane	3.7	5.2	3.9	6.1	4.1	8.1	3.1	5.1	6.1	26.2
B.Polje	3.6	24.8	3.9	6.1	4.0	8.1	3.5	4.1	5.8	26.2
Pljevlja	3.1	5.1	5.2	6.1	4.4	8.1	4.2	5.1	4.2	27.8

precipitation, especially the impact of anthropogenic greenhouse effects and their correlations with variations in atmospheric and oceanic oscillations.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by DB, JM, JL, BJ and JD. The first draft of the manuscript was written by DB and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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