DOI:10.28974/idojaras.2024.1.5

IDŐJÁRÁS

Quarterly Journal of the HungaroMet Hungarian Meteorological Service
Vol. 128, No. 1, January – March, 2024, pp. 75–98

Characteristics of annual and seasonal precipitation in North Macedonia: change analysis and correlation with the North Atlantic Oscillation (1951–2010)

Ivan Radevski[1,*], **Julia Hall**[2], **Svemir Gorin**[1], **Ana M. Petrović**[3]
Arse Kuzmanoski[1], **Emilija Manevska**[1], and **Pece Ristevski**[4]

[1]*Ss. Cyril and Methodius University*
Faculty of Natural Sciences and Mathematics, Institute of Geography,
Arhimedova 3, 1000 Skopje, North Macedonia

[2]*Interdisciplinary Centre for Complex System Science*
Meteoceanics Lisbon, Portugal

[3]*Geographical Institute "Jovan Cvijic" of the Serbian Academy of Sciences and Arts*
Djure Jakšića 9, 11000 Belgrade, Serbia

[4]*Military Academy "General Mihajlo Apostolski"*
Vasko Karangelevski bb, Skopje, North Macedonia

**Corresponding Author e-mail: radevskiivan3@gmail.com*

(Manuscript received in final form February 8, 2023)

Abstract— Studying the spatiotemporal precipitation characteristics in North Macedonia (1951–2010) is important as no spatially concurrent precipitation changes across the Balkan Peninsula have been identified. North Macedonia lies at the intersection between Mediterranean and continental climate zones and an improved understanding might help to better understand the regional precipitation patterns. The analysis shows a spatially consistent, high inter-annual variability, which makes trend detection difficult. Statistically significant decreasing trends were only found in seasonal precipitation at three stations. Changes in all other precipitation series were non-significant. Trends in winter, spring, and at annual scale are generally decreasing, whereas in summer are increasing. To better understand possible mechanisms behind the observed variability and change, correlations with the North Atlantic Ocsillation (NAO) were assessed. Significant and regionally concurrent correlations were detected. A strong correlation of the previous winter NAO-index with spring precipitation was found, which is valuable information for anticipatory water resources management in the region.

Key-words: precipitation; trends; Mann-Kendall; Sen's slope; NAO-index; North Macedonia

1. Introduction

Worldwide studies suggest a human influence on climate and hence on precipitation, which demands more advanced monitoring in the situation given the inherent climate uncertainty (*Alley et al.*, 2003). Precipitation is the primary input to our water resource system, and detailed knowledge is required for water resources management. Additionally, precipitation or the lack of it and its changes require detailed analysis, as precipitation is one of the main drivers of the extreme hydrological events such as floods and droughts in Europe (e.g., *Blöschl et al.,* 2017, 2019).

There are already numerous studies about the precipitation characteristics and their changes for almost all countries in Europe, but so far, a detailed assessment for the country North Macedonia is still missing. Hence this work aims to analyze and characterize changes in annual and seasonal precipitation time series in North Macedonia. To set the regional context for the current study, below the recent scientific findings of precipitation changes for the neighboring region of North Macedonia, located on the Balkan Peninsula, are briefly summarized below.

In Bulgaria, located in the east of North Macedonia, the observed seasonal precipitation trends for summer and spring are positive. This is opposite to the negative trends found for autumn and winter over the period 1901–2001, that was used for most of the investigated stations. No conclusive country-wide change signal was reported for total annual precipitation. The mountainous region of Rila and Pirin, the highest Balkan's mountains located close the North Macedonian border, are showing non-significant downward annual trends for annual precipitation sums (significance level of $\alpha=0.05$) (*Alexandrov et al.*, 2004).

A study in Romania shows mixed results for annual precipitation trends over 1961–2013, based on a significance level of $\alpha=0.1$. The three mountainous stations in the South Carpathians show a significant decreasing annual trend (*Marin et al.*, 2014).

A hydroclimatological change analysis in Greece (south of the study region) shows that most (15 out of 17) stations exhibit a non-significant downward trend in annual precipitation (only two are statistically significant), and 5 out of 17 gauges show a statistically significant decreasing trend in winter, for the period 1961-2006 (for both $\alpha=0.1$ and $\alpha=0.05$) (*Mavromatis* and *Stathis*, 2011).

The annual precipitation totals in Serbia (north of the study area) have a strong spatial gradient, and generally decrease from west to east (*Milovanović et al.*, 2017a). Research on temporal variability in annual precipitation in Serbia for 1961–2010 indicates a small number of gauges with a statistically significant trend ($\alpha=0.05$) between -5 and +5 mm/decade. The majority of stations in western Serbia shows positive trends in annual precipitation, whereas the trends in eastern Serbia are predominately mainly negative. Overall, there is an increasing trend in annual precipitation in Serbia, although not statistically significant ($\alpha=0.05$)

(*Milovanović et al.*, 2017b). The obtained decreases in annual precipitation near the border with North Macedonia and Bulgaria (southern Serbia) are moderate (mostly < -15 mm/decade).

The precipitation change pattern is different for seasonal and monthly changes in Serbia. Decreasing trends in monthly precipitation sums for February (-1.5 to -3 mm/decade) and June (-1.5 to -8 mm/decade) were detected in the southern part, near the border with North Macedonia (*Milovanović et al.*, 2017b). Additionally, a previous study investigating the seasonal changes in precipitation in Serbia (1961–2009), detected significant decreasing precipitation trends in winter (5/63 stations) and spring (7/63 stations), no statistically significant changes in summer, and significant increasing trends in autumn (9/63 gauges) (α=0.025). Overall, the study concluded that the majority of the precipitation changes are statistically non-significant (*Luković et al.*, 2014).

In Bosnia and Herzegovina (located northwest of the study region), *Popov et al.* (2019) identified three regions with different precipitation regimes using data over the period 1961−1990. A spatial gradient with a general decrease in annual precipitation from south and west towards the northeast was also determined. The same study also showed that two of the identified sub-regions, northwest, northeast, east, and the central part of country, have statistically non-significant positive decadal trends in annual precipitation for the period 1961–2018 (2.8 – 6 mm/decade), without information about the significance level. The third region located in the south of the country is characterized by strong negative precipitation trends (-40 mm/decade).

In Croatia (also located northwest of the study region at the coast of the Adriatic Sea), different seasonal precipitation changes were detected over the period 1961–2010. A significant decreasing trend can be found in annual precipitation totals in the mountainous region and in several other regions in summer, with α=0.05 (*Gajić-Čapka et al.*, 2015). The decreasing annual precipitation trends in the Mediterranean and the central part of Croatia are statistically non-significant. In the mountainous region, in summer, the trends are statistically significantly decreasing (-21 mm/decade), which is opposite to the continental region in the Pannonian Plain, which shows a statistically non-significant (α=0.05) increasing precipitation trend (*Gajić-Čapka et al.,* 2015).

Summarizing the above-mentioned studies (but not limited to these), it can be concluded that the mountainous parts of the Balkan Peninsula are affected by predominately decreasing precipitation trends. This is particularly true for western Bulgaria close to the Macedonian border for autumn, winter, and annual precipitation, Slovenia (winter), mountainous part of Croatia (summer), Southern Serbia (annual), and Greece (winter and annual).

Overall, the reviewed literature does not allow to discern any spatially consistent precipitation changes across the bordering regions of North Macedonia. This could be due to the fact that the Balkan Peninsula contains different climatic regions and are heavily modified by elevation and relief features.

North Macedonia lies at the intersection between the Mediterranean and continental climate regions. A detailed analysis of the precipitation characteristics and the observed changes in the region will fill the spatial gap and might help to provide a better context for the observed regional changes on the Balkan Peninsula.

Additionally, to improve the understanding of the drivers of observed precipitation characteristics, precipitation amounts have been correlated with the North Atlantic Oscillation (NAO) in several studies for the European region. For example, close to the current study region, North Macedonia, past research has shown that precipitation sums (over the period 1900-2010) and NAO-index have a negative correlation in Italy and Greece, as well as most of the Mediterranean gauges (some of which were statistically significant at $\alpha=0.05$) (*Philandras et al.,* 2011). In Romania, winter precipitation shows a strong negative correlation with the NAO-index (*Bojariu* and *Paliu*, 2001). A study about the Vojvodina province in northern Serbia shows a statistically significant negative correlation between precipitation totals and the NAO-index for winter ($\alpha=0.1$), and statistically significant negative correlations ($\alpha=0.05$) for annual and autumn precipitation sums with their respective NAO-index (*Tošić et al.,* 2014). A broader study of the main Mediterranean mountains (Atlas, Pyrenees, Alps, Apennines, Dinaric Alps, Balkan Mountains, Taurus) by *López-Moreno et al*., (2011) found a general statistically significant negative correlation ($\alpha=0.05$) between the winter NAO-index and winter precipitation for the Balkan Mountains, to which the mountains of North Macedonia belong to. However, for the entire country of North Macedonia, a detailed investigation is still missing. Such an analysis might provide better context of the observed larger regional precipitation variability and changes.

1.1. Study area

The country of North Macedonia is located in Southeastern Europe (*Fig. 1*), more specifically in the central part of the Balkan Peninsula and covers an area of 25 713 km^2. The relief is predominantly hilly-mountainous, and the elevation ranges from 54 m a.s.l. (in the Gevgelija Basin) to 2 764 m a.s.l. (peak Golem Korab on the Korab Mountain), with almost 30 plains and only a few less mountain ridges.

With the help of the geographical latitude and relief conditions, North Macedonia can be roughly divided into a larger region with mainly continental climate and 2 smaller regions with sub-Mediterranean climate located in the south-eastern and southwestern parts of the country. Additionally, areas with elevation above 1 100 m a.s.l. with high mountainous climate can be found embedded in the larger region with continental climate. Generally, the climate transitions from continental to high mountainous with increasing elevation around 1 100 m a.s.l. (*Kendrovski* and *Spasenovska,* 2011; *Radevski* et al., 2018).

The larger region where the continental climate can be felt encompasses the Prespa Plain, Kichevo Plain, Kumanovo Plain, Pijanec and Slavishte Plains, Polog Plain, and the country largest Pelagonia Plain. In general, the precipitation regime of the continental climate region has two distinct precipitation maxima in late spring and middle autumn, and several minima, with a primary minimum in summer and a secondary minimum and less pronounced winter minimum. The smaller sub-Mediterranean region covers the Gevgelija-Valandovo, Dojran Plain, and Ohrid-Struga, where the Mediterranean climate influences are strongly felt. During some years, the Mediterranean influences are suppressed in certain areas, but there are also years when the Mediterranean influences are even felt along the valley of the river Vardar to Skopje, along the valley of the river Strumica in the Strumica-Radovish Plain.

The regions with mountain climate can be found in the country's highest mountains, the Shar, Korab, Jablanica, Baba, and Jakupica Mountains, which are all located in the western part of North Macedonia in parallel with the plains. In the interior of the mountain region with elevations over 2 250 meters, an alpine climate can be detected. The regions with mountain and alpine climate have the highest precipitation, generally higher than 1 000 mm/year on the highest country mountains (*Zikov*, 1995). The mountainous regions experience a precipitation maximum in winter and a precipitation minimum in late summer.

Generally, with increasing elevation the climate regimes found at the precipitation gauging stations change from sub-Mediterranean over a continental to high mountainous climate with the exception of Ohrid (station 11), located in the southwestern part of the country at the large Ohrid Lake, where even at a higher elevation a sub-Mediterranean climate can be detected.

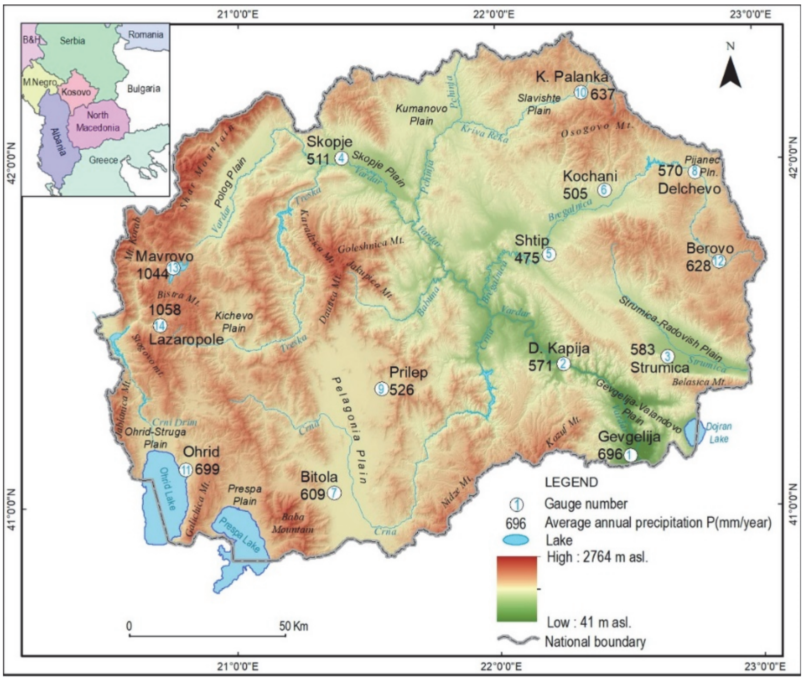

Fig. 1. Topographical map of North Macedonia showing the location of the precipitation gauges and their annual average precipitation for 1951–2010.

1.2. Data

For North Macedonia, instrumental precipitation measurements are only available for a few gauges for the first part of the 20th century. Systematic precipitation measurements are only available for a higher number of gauges after the Second World War. For the analysis, 14 precipitation gauges belonging to the Northern Macedonian National Hydrometeorological Service have been chosen that have complete data for 60 years (1951–2010). The stations were selected to ensure the best geographical coverage possible, whilst also aiming to include measurements from precipitation gauges located at a variety of different elevations and good coverage of the three climates regions in North Macedonia described above (see also *Table 1*).

Table 1. Characteristics of precipitation gauges ordered by increasing elevation

No.	Gauge	Latitude	Longitude	Elevation [m.a.s.l.]	Climatic Region
1	Gevgelija	41°09’00”	22°30’00”	59	sub-Mediterranean
2	D. Kapija	41°25’00”	22°15’00”	125	sub-Mediterranean
3	Strumica	41°26’00”	22°39’00”	224	sub-Mediterranean
4	Skopje	42°01’00”	21°24’00”	302	continental
5	Shtip	41°44’00”	22°12’00”	322	continental
6	Kochani	41°55’00”	22°25’00”	345	continental
7	Bitola	41°03’00”	21°22’00”	586	continental
8	Delchevo	41°58’00”	22°46’00”	630	continental
9	Prilep	41°21’00”	21°33’00”	661	continental
10	K. Palanka	42°12’00”	22°20’00”	691	continental
11	Ohrid	41°07’00”	20°48’00”	760	sub-Mediterranean
12	Berovo	41°42’16”	22°51’13”	827	continental
13	Mavrovo	41°42’00”	20°45’00”	1 240	high mountainous
14	Lazaropole	41°32’00”	20°42’00”	1 332	high mountainous

The 14 precipitation gauges used in this study are located at elevations ranging from 59 m a.s.l. to 1 332 m a.s.l. These gauging stations are shown in *Fig. 1,* and their main characteristics are listed in *Table 1*. The set of precipitation stations analyzed includes 2 mountain stations (>1 000 m a.s.l.) located on Bistra Mountain in the western part of the country (Lazaropole and Mavrovo).

2. Methodology

2.1. Analysed precipitation variables

As this study aims to identify precipitation characteristics and long-term changes, five different types of precipitation sum (PS) series were analyzed as indicated in *Table 2*. Note that for the calculation of the winter the precipitation totals, precipitation from the December of the previous year was used, hence the winter precipitation sum (WiPS) series start only a year later (1952).

Table 2. Analysed precipitation variables, their abbreviations as used in this study and analysis period with months and years.

Precipitation series	**Abbreviation**	**Period**
Annual precipitation sum	APS	1951–2010
Winter precipitation sum	WiPS	XII-II (1952–2010)
Spring precipitation sum	SpPS	III-V (1951–2010)
Summer precipitation sum	SuPS	VI-VIII (1951–2010)
Autumn precipitation sum	AuPS	IX-XI (1951–2010)

2.2. Test for autocorrelation

Before analyzing the changes in precipitation records, all the time series were checked for autocorrelation, as the existence of either positive or negative autocorrelation in a time series can confound the change detection, and hence it can lead to a false detection of a statistically significant trend where none may exist (*Yue* 2002). To evaluate the presence of a lag-1 serial correlation, the correlation structure of each series used in the trend assessment was assessed using plots of autocorrelation function (*ACF*) at a 10% significance level (α=0.1) (not shown).

2.3. Temporal change

Following the well-established methodology used in previous published studies on precipitation, trends were analyzed, using the widely used non-parametric Mann-Kendall (MK) trend test (*Mann*, 1945; *Kendall*, 1975) to detect monotonic trends and to assess their significance. For the basic significance testing of the trends, a significance level (α) of 0.1 was used. Increasing and decreasing trends were detected according to the sign +/- of the statistics *S*. Further details of the MK test can be found in the Appendix.

The trend slope β over the precipitation series is estimated with the nonparametric Theil–Sen method, which is suitable to detect a nearly linear trend in the variable *x* and is also less affected by non-normal data and outliers (*Sen,* 1968, *Hirsch et al.* 1982). The slope is computed between all pairs *i* of the variable *x*:

$$\beta_i = \frac{x_j - x_k}{j - k} , \tag{1}$$

where $j>k$, $j=2,\dots n$, $k=1,\dots, n-1,$ and $i=1\dots N$. For *n*-values in the precipitation series *x*, it will result in $N = n(n-1)/2$ values of β (which is the median over all the combinations of record pairs for the dataset). The Sen's slope β is presented in mm per decade, with sign + for increasing and – for decreasing trend.

2.4. Temporal variability

Knowledge on the temporal variability of a time series helps in the interpretation of the trend detection results. If there is high inter-annual variability, the signal to noise ratio in the series is large, and hence trend detection needs a long time series to allow the detection of statistically significant trends (*Wilby*, 2006; *Murphy et al.,* 2013), or a strong change signal.

Here the temporal variability of the precipitation series is statistically described using the coefficient of variation (*CV*) and, for the ease of interpretation, expressed as a percentage of the mean of the series, thereby showing the long-term variability from the mean value:

$$CV = \frac{\sigma}{\mu} * 100 , \tag{2}$$

where σ is the standard deviation and μ is the mean of the record of the PS series.

To evaluate the overall temporal evolution and variability of all PS series despite their differences in absolute values, the time series were standardized and expressed as standardized precipitation sum anomalies (*SPSA*):

$$SPSA = \left(\frac{ps_I - \mu}{\sigma}\right) \tag{3}$$

where PS_i is the precipitation sum (mm) aggregated over annual or seasonal timescales for an individual year (*i*), μ is the mean of the record of the PS series, and σ is the standard deviation of the PS series.

Positive/negative values of *SPSA* indicate above/below mean precipitation sum quantities for the series. For visualization purposes, the *SPSA* series were smoothed using a centered 4-year moving average. Additionally, the changes in resulting trends calculated in Section 3.2 and their statistical significance were evaluated by varying the start and end date of the time series. If the trends changed considerably, such changes are reported in Section 3.

2.5. Atmospheric influences

As previous studies outside the study region have already shown a possible influence of the North Atlantic Oscillation (NAO) on streamflow (*Birsan*, 2015), possible connections between the different precipitation sums within the study region and the station-based North Atlantic Oscillation Index (NAOI) by Hurrell (*Hurrell*, 2018) are explored over the period 1951–2010 using the Spearman correlation. For both, annual, and seasonal analyses (for both PS and NAOI series), calculations are based on the seasonal mean values calculated from the monthly time series, which are used as input for the correlation analysis.

The NAOI has been defined as the difference in the sea level pressure between the tropical Azores high and polar Icelandic low. The index is expressed with two different phases to represent the changes in the atmospheric situations. Positive NAO phases are characterized by higher pressure differences between the Azores high and Icelandic low and are, on average, responsible for drier conditions in Southern Europe. Negative phases characterize a weaker pressure gradient between the Azores and Iceland. During this phase, storm tracks move southwards towards the Mediterranean Sea, leading to higher precipitation levels in Southern Europe (*Wallace* and *Gutzler*, 1981).

Additionally, lagged correlations (i.e., non-matching seasons) between the different seasonal NAOI and different seasonal precipitation were performed. After initial testing (not shown), the results of the correlations of the winter NAOI and the following seasonal precipitations are assessed here in detail, as winter is the season with the strongest and most clearly defined NAO patterns.

3. Results

3.1. Seasonal precipitation variations

For most of the stations (Table 3) there is no strong seasonal variations in the annual precipitation totals with no season contributions of more than 32% to the annual budget. Spring season has generally an average contribution to the annual precipitation totals with around 25%. Summer is the driest season, with the lowest contribution percentage of ~13%, except in the northeastern part of the country, where an above average precipitation contribution can be measured. The wettest season on average is autumn, with exception of the mountainous areas that have the highest seasonal precipitation contribution in winter.

Table 3. Mean annual and mean seasonal precipitation totals in mm. Seasonal values are expressed as % of the annual values. Underlined/bold letters indicate the driest/wettest seasons, respectively.

N	Gauge	Annual total	Winter %	Spring %	Summer %	Autumn %
1	Gevgelija	696	28.75	25.44	16.10	**29.61**
2	D. Kapija	571	**29.92**	26.25	17.50	26.42
3	Strumica	583	25.72	25.72	20.24	**28.30**
4	Skopje	511	25.42	25.22	22.88	**26.40**
5	Shtip	475	21.04	26.93	23.77	**28.19**
6	Kochani	505	22.17	26.13	24.94	**26.72**
7	Bitola	609	28.26	25.63	17.58	**28.42**
8	Delchevo	570	20.36	26.16	**26.68**	**26.68**
9	Prilep	526	23.59	26.64	20.93	**28.92**
10	K. Palanka	637	20.87	**27.30**	26.83	25.11
11	Ohrid	699	30.91	24.33	13.16	**31.62**
12	Berovo	628	22.46	**26.28**	25.96	25.32
13	Mavrovo	1044	**31.32**	25.19	14.08	29.50
14	Lazaropole	1058	**30.62**	24.57	14.46	30.34

3.2. Temporal change and variability

The characteristics of the annual precipitation sum (APS) and the results of the trend analysis are shown in *Table 4*. All trends obtained are non-significant (at a significance level of α=0.1). Non-significant trends range from -17.4 mm/decade at Mavrovo to + 9.8 mm/decade at Lazaropole, which are the precipitation gauges having the highest mean APS (mean > 1000 mm/year) and being located at the highest elevation in this study. However, when examining the total change observed in relation to the mean APS, the gauge at Prilep experiences the strongest negative change (-16.15%) and Mavrovo exhibits only the second strongest negative trend (-10.02% of the mean), whereas Lazaropole still shows the strongest positive trend (+5.57%). Overall, negative trends are dominating (79%).

Only 3 gauges showed a statistically significant (α=0.1) positive lag-1 serial correlation (Prilep, Ohrid, and Mavrovo), no statistically significant trends were detected in the APS series. The temporal precipitation variability found at all gauges can be classified as moderate and ranges from 17.9% at (K. Palanka) to 23.2% at Mavrovo. In the case of stronger interannual variability, the detection of statistically significant trends could be confounded.

Table 4. Annual precipitation sum series characteristics and trend analysis: mean annual sum, Theil–Sen slope β in mm/decade, total change in % of mean, and variability as in % of mean.

N	Gauge	Mean annual sum	*β* [mm/decade]	% Change	% Variability
1	Gevgelija	696	-6.6	-5.7	22.2
2	D. Kapija	571	-7.2	-7.57	21.6
3	Strumica	583	-8.1	-8.32	21.5
4	Skopje	511	0.4	0.41	20.9
5	Shtip	475	-6.5	-8.17	22.1
6	Kochani	505	-5.4	-6.36	19.0
7	Bitola	609	5.2	5.14	20.5
8	Delchevo	570	0	-0.02	21.3
9	Prilep	526	**-14.1**	**-16.15**	**22.8**
10	K. Palanka	637	-2.7	-2.57	17.9
11	Ohrid	699	-0.7	-0.64	21.4
12	Berovo	628	-8.6	-8.18	18.4
13	Mavrovo	1044	**-17.4**	**-10.02**	**23.2**
14	Lazaropole	1058	**9.8**	**5.57**	**18.5**

None of the seasonal PS series analyzed displayed a statistically significant (α=0.1) positive lag-1 serial correlation, hence one can assume that the detected trends are not confounded by autocorrelation.

The characteristics and possible changes in seasonal precipitation sums are listed in *Table 5*. For the WiPS, most of the trends are negative (~71%). Only the gauge at Shtip shows a statistically significant negative trend of -6.4 mm/decade or over the entire period of record a decrease of 38.91% respective to the long-term winter mean precipitation sum. This percentage change is the highest seasonal change value, as in Shtip (*Fig. 2*), the lowest winter precipitation totals are measured. Detecting such change is of importance for the region, as winter in Shtip is already the driest season, which is becoming increasingly drier. Similarly to the annual change results, Mavrovo again has the highest absolute change value (-14 mm/decade), however, the WiPS trend is not statistically significant. The positive trends in the WiPS series at a few gauges are weak and do not exceed 8.3% of the long term-mean. The interannual variability in WiPS is very high ranging from 37.5 to 55%.

Table 5. Seasonal precipitation sum characteristics and trend analysis: mean seasonal sum, Theil–Sen slope β in mm/decade, total change in % of mean, and variability as in % of mean. Trends that are statistically significant (α=0.1) are shown in bold.

N	Gauge	WiPS			SpPS			SuPS			AuPS		
		Mean sum	β	**% Change**	**Mean sum**	β	**% Change**	**Mean sum**	β	**% Change**	**Mean sum**	β	**% Change**
1	Gevgelija	200	-4.4	-13.27	177	-7.2	-24.52	112	0.2	1.28	206	-1.8	-5.13
2	D. Kapija	167	-0.7	-2.39	150	-2.9	-11.43	100	-0.1	-0.44	151	0.1	0.40
3	Strumica	149	0.1	0.60	150	**-4.6**	-18.30	118	3.3	16.84	165	-3.7	-13.55
4	Skopje	128	1.8	8.26	129	-4.8	-22.32	117	5.9	30.04	135	-1.5	-6.57
5	Shtip	99	**-6.4**	-38.91	128	-3.2	-14.82	113	2.7	14.54	134	-1	-4.29
6	Kochani	111	-1.7	-9.20	132	**-6.4**	-28.79	126	0.4	1.69	135	4.1	17.99
7	Bitola	172	1.2	4.15	156	1.5	5.93	107	0.2	0.89	173	3.7	12.83
8	Delchevo	116	-1.8	-9.39	149	2.0	7.97	152	1.0	3.86	152	0.6	2.27
9	Prilep	123	-6.2	-30.12	140	-3.9	-16.73	110	2.8	15.40	152	-0.5	-1.84
10	K. Palanka	132	-1.6	-7.36	174	-2.4	-8.14	171	4.3	15.15	160	4.3	16.13
11	Ohrid	216	-3.7	-10.38	170	4.4	15.42	92	1.7	11.06	221	2.6	7.00
12	Berovo	140	-3.9	-16.82	165	-3.7	-13.57	163	2.5	9.29	159	-0.8	-2.87
13	Mavrovo	326	-14	-25.83	263	-1.0	-2.30	147	-1.1	-4.52	308	-2.9	-5.63
4	Lazaropole	323	0.1	0.17	260	0.5	1.17	153	4.4	17.44	321	8.6	16.0

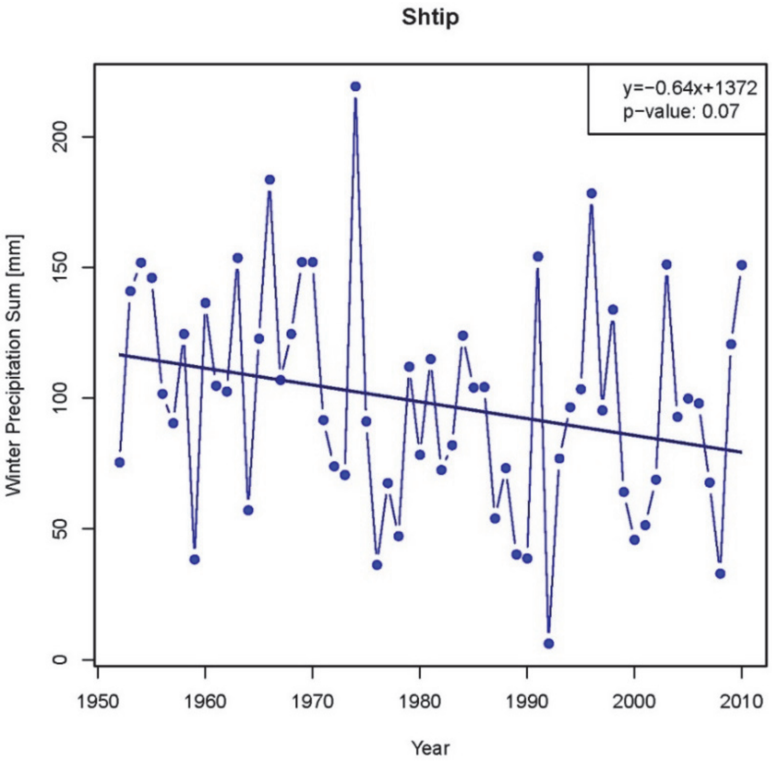

Fig. 2. WiPS series for Shtip with a statistically significant trend, Sen's slope estimate, and p-value.

In the SpPS series, two statistically significant negative trends were detected at Strumica and Kochani (*Fig. 3*). Although the two gauges do not exhibit the strongest negative trend (-4.6 and -6.4 mm/decade, respectively), which can be found at Gevgelija with -7.2 mm/decade, they show one of the highest changes relative to the long-term mean (-18.3% and -28.79% respectively). The strong decrease in Kochani is of importance, as it has the 3rd lowest spring precipitation total of the country. The non-statistically significant trends at other gauges range from -7.2 to +4.4 mm/year and from -24.52 to +15.42% of the long-term spring sum mean. Most of the trends across the country are negative (~71%) with particularly gauges that are located at lower elevation (<500 m) showing all negative trends (including the two statistically significant trends).

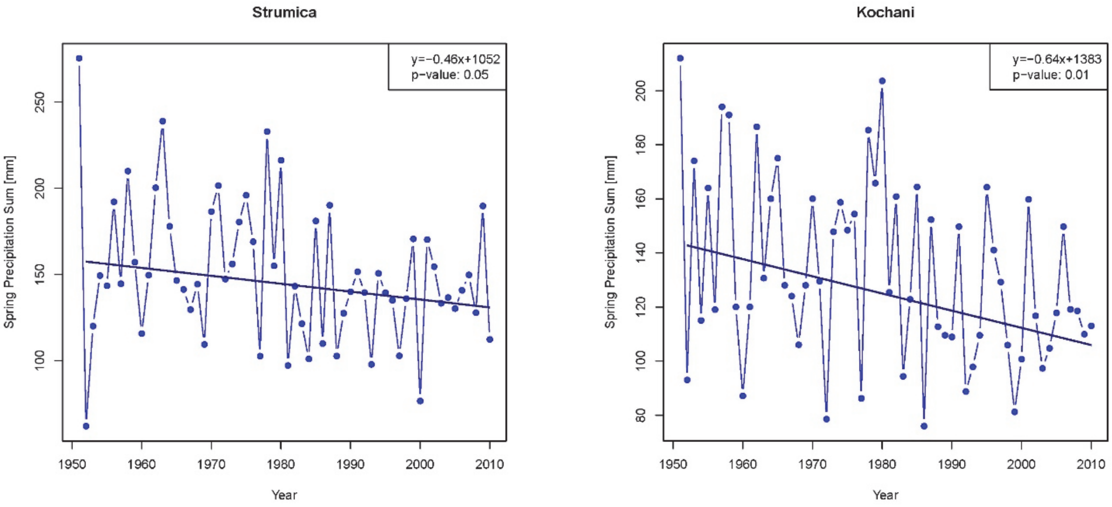

Fig. 3. SpPS series and statistically significant trends for Strumica and at Kochani with Sen's slope estimate and p-value.

In the SuPS series there are no statistically significant increasing or decreasing trends. Overall, the trends are predominately increasing (~86%), which is opposite to the WiPS and SpPS. The trends in the SuPS series range from -1.1 to +5.9 mm/year. When relating the changes to the long-term mean, the negative/positive trends have the smallest/highest percentage of change (-4.52 %, +30.04%, respectively). These results indicate, that in general there is a pattern of increasing precipitation in summer, the driest season on average, although no statistically significant trends could be detected yet. The lack of statistical significance could be partly caused by the high temporal variability found in the SuPS series (39.7 – 62.4% of the long-term mean), which is the highest found in all seasonal series.

Changes in the AuPS series are inconclusive with no statistically significant trends and half of the gauges showing increasing and the other half showing decreasing trends. However, the positive trends appear to be slightly stronger both in terms of the absolute values and in terms of the relative changes. As the analysis of individual precipitation trends in North Macedonia showed predominately inconclusive results, the temporal evolution of the seasonal precipitation series across the country are evaluated and shown in *Fig. 4*.

The temporal evolution of the SPSA series across all series (*Fig. 4*) shows the high variability of the seasonal PS series over time, which concurs the reported statistical results and high variability of the series as listed in *Table 5*.

Additionally, from *Fig. 4*. it is also apparent that the period of record chosen has a high influence on the trends obtained (and their statistical significance), which is elaborated below (results of the detailed analysis are not shown). All examples of statistical significance refer to the significance level of α=0.1. For example, if the APS series had been analyzed until the early 2000s, statistically significant negative trends would have been detected at Gevgelija, Kapija, Strumica, Shtip, Prilep (significant until ending 2009), K. Palanka, Berovo, and Mavrovo (until 2008).

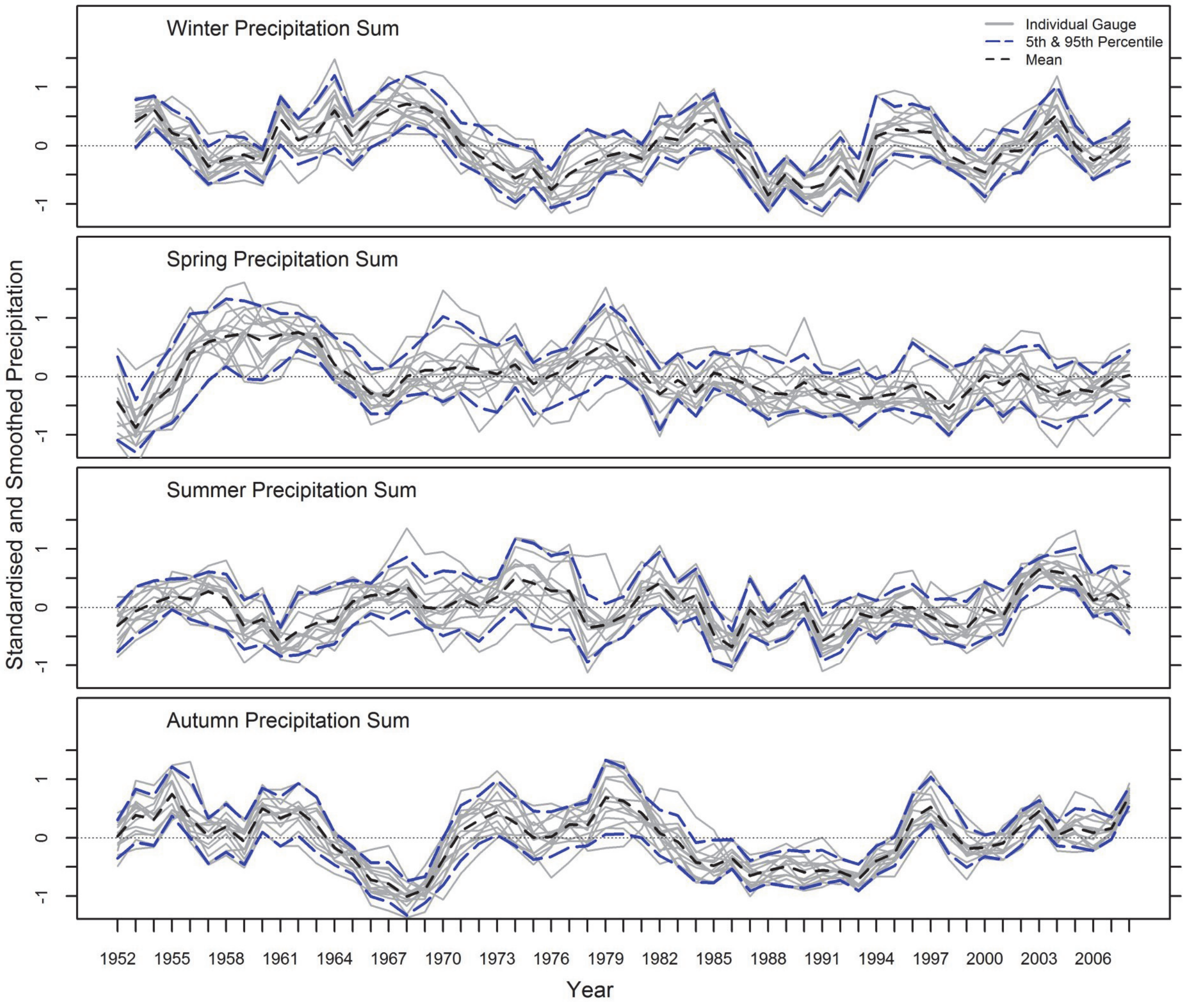

Fig. 4. Standardized and smoothed seasonal precipitation sums (SPSA). Light grey lines are the standardized and smoothed 4-year moving average series for individual gauges, blue dashed lines are the 5th and 95th percentiles of the standardized and smoothed series, and black dashed line is the average across all series.

Similar results can be obtained for the WiPS series at Prilep and Mavrovo. If the time series had been analyzed until 2009, the detected trend would have been statistically significant. The same applies to the SpPS starting 1952 at Skopje (ending 2009) and Shtip (ending 2008). If SpPS trends would had analyzed from ~1960, Gevgelija, Strumica, Skopje, Shtip, Kochani, Prilep, Berovo Marovo, and Lazaropole would have been showing statistically significant negative trends, and the analysis period would have ended in 2009 or 2010. For the SuPS series non-significant trends would have been obtained unless for few series beginning in1970 and ending around 2000 (e.g., D. Kapija, K. Palanka, and Berovo), which indicated significant negative trends for that period. Similarly, if the AuPS series had been analyzed until 1995, significant negative trends would have been found at Gevgelija, Strumica, and Mavrovo. Hence the trend results (and their statistical significance) obtained from the longest available study period, might not be representative of the shorter-term variability apparent in the data.

Furthermore, *Fig. 4* shows that (apart from a few gauges and individual years) the seasonal precipitation sums at the individual stations follow a common coherent pattern of high and low precipitations for each year and season. This indicates that there is a likely common driver behind the coherent inter-annual variability of the precipitation records.

3.3. Atmospheric influences

As discussed earlier, a possible driver of the coherent precipitation change over time could be the North Atlantic Oscillation (NAO), which in turn could cause the associated shifts in spatial and temporal precipitation patterns. For the full PS series, the relationships between the monthly NAO index (NAOI) and monthly PS series are assessed using Spearman correlations, as depicted in *Figs. 5*. and *6*. Here, negative or positive correlation between precipitation sums and NAOI series indicates a lower or higher NAOI, respectively, associated with higher precipitation values.

The correlations between the precipitation and NAOI at an annual scale are predominately negative (except for the very weak non-significant positive correlation at Bitola). Six out of the seven gauges that are located above an elevation of 600 m a.s.l. show a statistically significant negative correlation (except for Prilep, which is non-significant), with Lazaropole having the strongest Spearman's rank correlation, *rho* (*rho*=-0.114). All stations below 500 m indicate a weaker, non-significant correlation. Additionally, most of the stations with a significant negative correlation have a high mean annual PS (>620 mm) and a continental climate. The exception is Gevgelija, located in the southeast, which is the lowest lying station with a pronounced sub-Mediterranean climate.

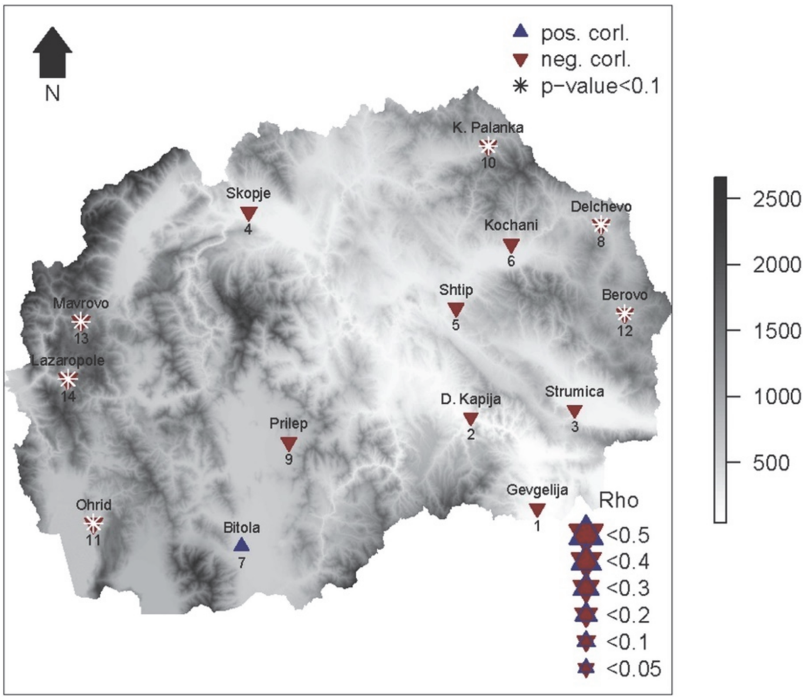

Fig. 5. Spearman's rank correlation (*rho*) between the mean of the monthly PS series and the mean of the monthly NAOI evaluated at an annual timescale. Elevation is shown in m a.s.l., blue/red color represent positive/negative correlations. Size of triangles indicates magnitude of correlations (based on upper and lower absolute correlation value), significant correlations (α=0.1) are shown by white stars.

In the seasonal correlation analysis (*Fig. 6*), the absolute correlation values are much higher than in the annual evaluation. Winter, summer, and autumn show a consistent spatial correlation pattern, having the same correlation sign countrywide. In winter and autumn, the correlations are all negative (9 and 7 gauges, respectively, are statistically significant), whereas in summer all correlations are positive (12 significant). Spring season has a more spatially distinct pattern of positive (non-significant) correlations in the central and negative correlations on the eastern and western sides of the country (3 of which are significant). As a general pattern, one can also observe that in spring, the correlations between precipitation totals and the NAO change with increasing elevation from statistically non-significant positive to significant negative correlations.

In winter, statistically significant negative correlations can be found at higher elevations. For many of these stations, winter is the season with the lowest percental precipitation (% of annual total) with exception of the stations in the western part which receive the highest amount of precipitation. In lower lying areas the correlations are non-significant. In autumn, the low-lying stations located in the centre of the country with low seasonal precipitation show a statistically significant negative correlation, although negative correlations are also found in the rest of the country.

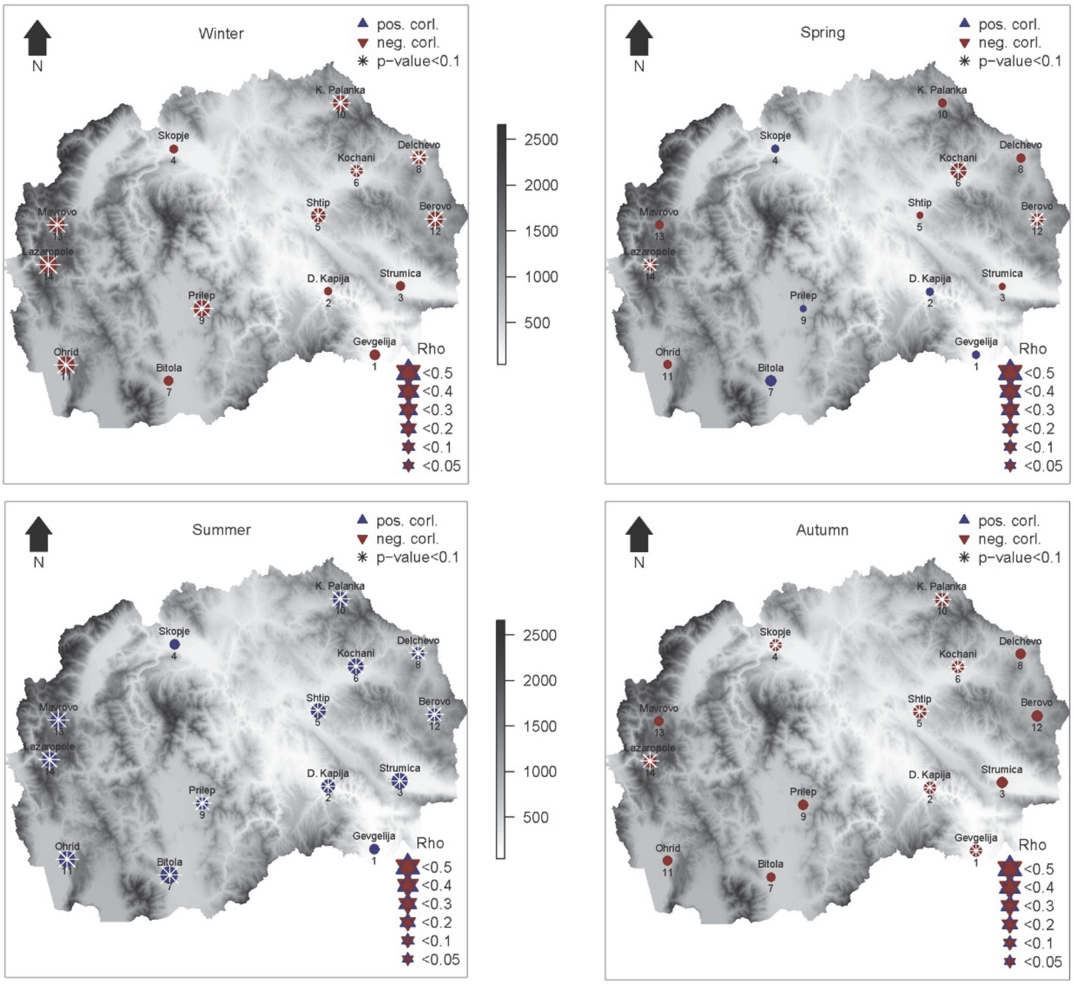

Fig. 6. Spearman's rank correlation between the mean of the monthly PS series and the mean of the monthly NAOI evaluated at a seasonal timescale. Symbols and elevation are as in *Fig. 5*.

In summer, which is generally the driest month, all correlations are positive (most of which are statistically significant). It should also be noted that at Bitola, the summer precipitation-NAOI correlation value (*rho*=0.495) is the highest obtained among all stations and seasons. Hence, the contribution of summer is strongly reflected on an annual scale leading to a positive correlation as shown in *Fig. 5*.

When performing lagged correlations, i.e., correlating the previous NAOI with the seasonal precipitations (i.e., with spring, summer and autumn), the correlation results only improve for the spring season (*Fig. 7*). Instead of having mixed spatial correlations across the study region in spring (when correlated with the same season NAOI), now spatially consistent negative correlations emerge. Also, the number of gauges showing statistically significant trend increases to 11. Overall, the strength of correlation also increases, apart from the 2 gauges (Kochani and Lazaropole) that had strong and statistically significant correlations when spring precipitation is correlated with the same season NAOI. Lazaropole (gauge located at the highest elevation) does not show a significant correlation with the NAO anymore

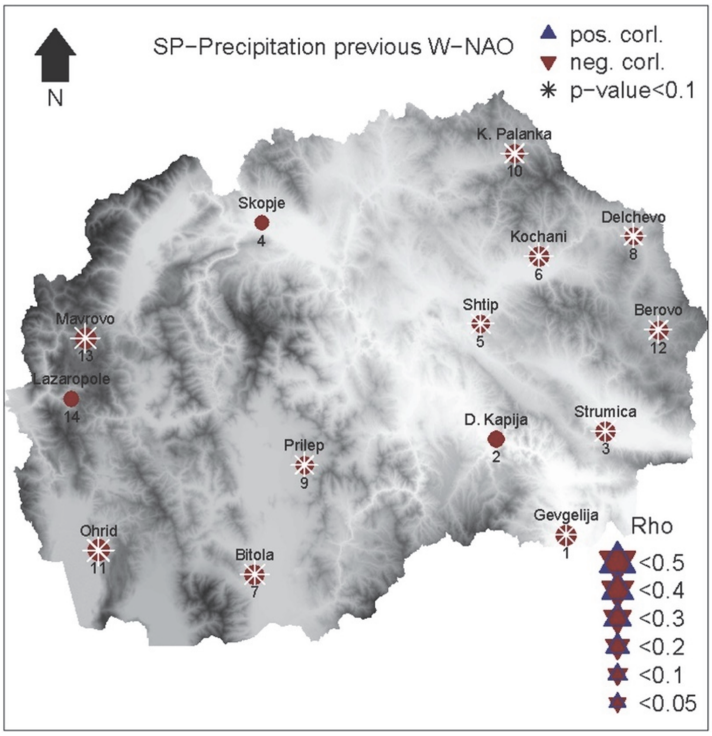

Fig. 7. Spearman's rank correlation between the mean of the monthly SpPS series and the mean of the previous monthly winter NAOI (1952–2010). Symbols and elevations are as in *Fig. 5*.

4. Discussion

The results obtained for the detailed analysis of annual and seasonal precipitation sums for the study region North Macedonia show that in the analyzed 60-year period (1951–2010), precipitation trends in North Macedonia have a spatially non-coherent pattern of predominantly significant or non-significant downward trends (except for the summer season with increasing trends) (*Tables 3* and *4*).

This outcome for North Macedonia concurs with the results of existing regional studies around the study region. This is particularly evident for the decreasing trends in annual precipitation in Croatia, Serbia, and Greece.

The study of the Mediterranean (*Philandras et al.,* 2011) shows also decreasing trend in annual precipitation sums, especially in Southern Europe. There is no spatial similarity with the other neighboring countries, especially for annual precipitation in Bulgaria and Romania, where the trend results are of mixed direction (*Marin et al*., 2014). Comparing our annual change results with those of Serbia (*Milovanović et al.,* 2017b), near the North Macedonia border, the trends are non-significantly decreasing in both countries.

The downward annual precipitation tendencies found in the southeastern moderate Mediterranean stations Gevgelija, Demir Kapija, and Strumica, correspond to the majority of negative trends found in Greece (*Mavromatis* and *Stathis,* 2011).

This seasonal study results of North Macedonia, and a previous research of a wider region predominately have a negative trend in winter (although mostly not statistically significant), which was also noted in Romania (*Marin et al*., 2014), Bulgaria (*Alexandrov et al*., 2004), Serbia (*Luković et al.,* 2014), Dalmatia-Croatia (*Gajić-Čapka et al.,* 2015), and Greece (*Mavromatis* and *Stathis,* 2011). The spring trend results are predominantly positive in Bulgaria (*Alexandrov et al*., 2004) and Greece (*Mavromatis* and *Stathis*, 2011), negative in North Macedonia and Serbia (*Luković et al*., 2014), while predominantly positive summer trends are detected in Bulgaria (*Alexandrov et al.,* 2004) and North Macedonia, and negative trends in Croatia (*Gajić-Čapka et al.,* 2015) and Serbia (*Luković et al.,* 2014). The autumn results are miscellaneous trends in North Macedonia, positive in Serbia (*Luković et al.,* 2014), and negative in Bulgaria (*Alexandrov et al*., 2004).

Overall, the analysis of the temporal evolution of precipitation changes in North Macedonia show that there is strong inter-annual variability that has the potential to statistically influence the trend detection. Hence, one should not focus on one single time period to assess trends and their statistical significance. This strong variability could also explain why it is currently difficult to identify larger scale similarities in observed precipitation changes, when comparing with neighboring countries, as different time periods were used for the assessment. Additionally, trend signals obtained (although they are not statistically significant) should be taken into consideration, particularly if the entire country shows a spatially concurrent same sign of change, when analyzed with different start and end years.

The detailed analysis has shown that although relatively close to each other (13 km distance) and similar in mean annual and seasonal precipitation totals, the two mountainous stations (Mavrovo and Lazaropole) exhibit a very different precipitation change patterns. The only significant difference between these two mountain gauges is the direction in which the slope of the mountain faces. The mountain side on which Mavrovo station is located faces northward and Lazaropole station faces southward. The difference in slope direction and hence different climatic drivers could be the reason why different change signs and magnitudes have been detected at these stations. However, the detailed reasons for this phenomenon are beyond the scope of the current study, and should be investigated in future research. The current study also found that the North Atlantic Oscillation (NAO) seems to have an influence on the annual and seasonal precipitation sums in the region, based on the correlations obtained. To the authors knowledge, there is no study directly investigating the effects of the NAO to precipitation in the broader region in which the study region is located. However, in a study in Romania (*Birsan*, 2015), strong negative correlations between the NAOI and the mean annual streamflow have been found in western and southern parts of the country. Positive correlations were found in plain lowland stations and no significant correlations were found for mountain gauges.

At an annual scale, the correlation of the NAOI and precipitation sums can be classified as a weaknegative correlation, which is strongest at the stations located at higher altitude (above 600 m), except Bitola, which is positively correlated. Winter and autumn are negatively correlated with the NAOI for all stations, summer is positively correlated for all stations in the country, whereas the results for spring are variable. With increasing elevation, the climate regime changes from sub-Mediterranean to mountainous. Similarly, the detected negative correlations with the NAOI become stronger in annual and winter precipitation sums and change from statistically not significant to significant. Similar change with increasing elevation can also be seen in spring, were the correlations change from statistically non-significant positive to statistically negative. In summer, there is no change across the climate regions, and all correlations are significantly positive. The negative correlations of the NAOI with winter precipitation obtained in this study are in line with previous results obtained at mountain gauges in the Mediterranean region (*López-Moreno et al.,* 2011). This is likely due to the fact that the winter NAO is stronger than that of the other seasons, which has already been pointed out in previous studies (*Hurrell*, 1995). This indicates stronger contribution of winter and autumn correlations in shaping the picture or the annual correlations.

The analysis also discovered a strong influence of the winter NAO even on the spring precipitation in North Macedonia (negative correlations) which means that for anticipating spring precipitation, the previous winter NAO might be a valuable source of information. This should be further explored in future studies.

5. Summary and conclusion

This study has provided an analysis of annual and seasonal precipitation characteristics and their changes in North Macedonia. The results are generally concurrent with the past studies for the southeastern and Mediterranean regions and time periods of study, with a few exceptions that might be due to different methods or time periods used for the different analyses.

One of the important findings is the strong, statistically significant, decreasing trend (-6.4 mm/decade) in Kochani (spring precipitation) and in Shtip (winter), as the gauges are located in the most arid mid-eastern part of the country, and low seasonal precipitation is becoming even lower. Apart from this important finding, no overarching large-scale changes could be detected. Hence, an overarching study across all the Balkan states using similar data and consistent methodology with the aim of identifying and better understanding of the precipitation characteristics and their spatiotemporal changes in the wider region will be needed. Such a larger scale study might also allow for better insights, if the predominant statistically non-significant changes identified in this study are just locally non-significant (e.g., due to high inter-annual variability in the records at specific gauges), or if the lack of significant trends due to the high variability in precipitation is part of a larger scale regional picture. Additionally, the lack of large-scale consistent change signal could also be caused by the high variability of landscape features, which results in strong spatial gradients in the climatology of the area (three different climate regimes), making it impossible to obtain a concurrent spatial change signal. Therefore, a lack of spatial consistency in trends should not be interpreted as a lack of actual changes, but rather highlights the importance of further research in this topic.

The decreasing precipitation trends found in most of the seasons over the period 1951–2010 in North Macedonia highlight the need for improved water management lead by the state authorities, especially in the central and the eastern arid parts of the country. Future studies should hence focus on a more detailed analysis of change in additional precipitation indices (e.g., extremes and spells) to better understand the possible effects of a changing climate. Additionally, further studies are needed for informing water management and agricultural plans. Moreover, planning for new water infrastructure, to store water in winter and spring for the drier summer season is very important because of decreasing precipitation in the arid parts of the country.

This study has also shown that the annual and seasonal precipitation sums in North Macedonia show a high correlation with the North Atlantic Oscillation. A strong correlation of the previous winter NAOI with spring precipitation was also found, which indicates the possibility for anticipating the magnitude of spring precipitation one season ahead. This lagged correlation with the NAOI might be a valuable source of information for water resource management, but it needs to be further explored. However, for such future work, a wider network of meteorological stations is needed, reflecting the variety of climatological regimes in the study region. Unfortunately, the number of working meteorological stations is decreasing since the 1990s. To allow future research on this important topic, the re-establishing of the meteorological and precipitation gauging network in North Macedonia for obtaining high-quality climatological data is needed.

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Appendix

The Mann-Kendall (MK) test allows testing two hypotheses: H0 - There is no significant trend in the time series and Ha - there is a significant trend in the time series. To test the hypotheses the computation of MK S statistics is required, which is determined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(T_j - T_i\right) , \quad (1)$$

where

$$\mathrm{sgn}\left(T_j - T_i\right) = \begin{cases} 1 \, if \; T_j - T_i > 0 \\ 0 \, if \; T_j - T_i = 0 \\ -1 \, if \; T_j - T_i < 0 \end{cases} . \quad (2)$$

In the formula T_j and T_i are the time series of annual/seasonal values of precipitation sums in years *j*=*i*+1, *i*+2, *i*+3, and *i*=1, 2, 3,…, *n*-1, where *j*>*i*, and *n* is the last year of the time series. A positive value of *S* indicates an increasing trend and a negative value indicates a decreasing trend in the precipitation time series.

$$Z = \begin{cases} \frac{s-1}{\sigma} \; or \; S > 0 \\ 0 \; or \; S = 0 \\ \frac{s+1}{\sigma} \; or \; S < 0 \end{cases}, \tag{3}$$

where Z is normalized/standard test statistics, $\sigma 2$ is the variance of a near normally distributed statistics S for $n \geq 10$. For measuring the significance of the precipitation trend, the p-value was computed (significance level α=0.1). Hence, if the p-value is lower than 0.1 Ha is accepted, and a positive or negative trend is considered to be statistically significant. If p>0.1, H0 is accepted, which means there is no statistically significant monotonic trend in the precipitation time series.

$$p = [1 - f\,(Z)]\,. \tag{4}$$