THE INFLUENCE OF ATMOSPHERIC OSCILLATIONS, CONSIDERED THROUGH LARGE-SCALE INDICES, ON THE PRECIPITATION FIELD IN THE DANUBE BASIN

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The aim of the present study is to compare the influence of two large-scale atmospheric circulation indices on precipitation in the Danube basin. One of the indices is the well-known North Atlantic Oscillation index (NAOI) and the other one Greenland Balkan Oscillation index (GBOI).
From all the investigations regarding the significance of the influence of the two at large scale atmospheric indices on the climate in the Danube basin so far, it has highlighted that GBOI compared to NAOI has a much higher statistically significant influence on the climate variability in southeastern Europe.
The novelty of the present study consists in investigating the influence of the two atmospheric indices on the occurrence of maximum monthly precipitation by applying the extreme values theory (EVT).
From this preliminary investigation, only for the spring season, it emerged that although GBOI has a greater importance for the occurrence of precipitation extremes in southeastern Europe, the influence of NAOI is not negligible.

Keywords: precipitation, climate indices, wavelet coherence, generalized extreme value.

1. INTRODUCTION

The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric circulation variability in the North Atlantic sector and exerts a strong influence on European winter weather and climate (Hurrell *et al.* 2003).

As shown in McKenna and Maycock (2022), there is much dispute regarding the spatiotemporal influence of the NAO on precipitation in Europe, taking into account observational data and an uncertainty related to the results of scenarios regarding changes in 21st century European winter precipitation, due to simulated NAOI trends.

From the investigations carried out by various researchers on observational data, a significant influence of the NAO on the occurrence of precipitation in the northern and southwestern parts of Europe has been clearly found. Some of these investigations are mentioned in McKenna and Maycock (2022).

Considering that the NAO does not have a clear influence on the climate of southeastern Europe, the authors of this paper (Mareş *et al.* 2013) proposed to look for another atmospheric index that can more significantly influence precipitation in this part of Europe, either singly or in combination with other atmospheric indices. Thus, an atmospheric index was calculated that takes into account the sea level pressure (SLP) gradient between Greenland and the Balkan Peninsula, the so-called Greenland Balkan Oscillation index, and thus the effectiveness of the influence of this atmospheric index on the climate of southeastern Europe was tested.

The influence of several climate indices on the overall state of precipitation or on other climate variables such as Palmer drought indices or on the discharge of the Danube in the lower basin has also been investigated in various publications by the authors, of which we mention (Mareş *et al.* 2019, 2025).

A testing of the combined influence of large-scale atmospheric factors with indicators of solar variability on the climate of southeastern Europe was also attempted (Dobrică *et al.* 2018; Mareş *et al.* 2021a,b, 2023a,b).

As regards the significance of the influence of the two atmospheric indices on the climate in

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the Danube basin, it has emerged, from all investigations so far, that GBOI has a much higher statistically significant influence on the climate variability in southeastern Europe compared to NAOI.

In general, the comparative analyses of the influence of the two climate indices on the climate of southeastern Europe carried out in the papers mentioned above. There were some minor exceptions (Dobrică *et al*. 2018; Mareş *et al*. 2023b, 2025) where such analyses have been performed for the total precipitation values, that reflect the average moisture state at the level of the Danube basin.

However, from separate analyses per station developed in a recent study (Mareş *et al.* 2025), it emerged, as we expected, that there are differences between the areas of the Danube basin. Therefore, a differentiation between GBOI and NAOI per station was emphasized in the present paper.

Furthermore, because the state of the Danube discharge has great socio-economic importance during especially the spring season, in terms of the occurrence of abundant/few precipitation, we tried to achieve an analysis of precipitation extremes for two meteorological stations: Novi Sad and Arad.

The paper is structured as follows: The data and the methods are presented in Section 2. In Section 3, a comparative analysis of the GBOI and NAOI influence on the precipitation expressed by First principal component PC1-PP of the Empirical Orthogonal Functions (EOF) development for each season is presented, through simple correlation analyses. Then, the GBOI signal is highlighted in comparison with NAOI using Partial wavelet coherency PWC. This is followed by an analysis for each station of the GBOI signal compared with NAOI for the winter and spring seasons. For the spring season, a Generalized extreme value GEV modeling of the maximum monthly precipitation in March, April and May is performed for the Arad and Novi Sad stations. Section 4 is dedicated to the concluding remarks.

2. DATA AND METHODS

For a period of 120 years (1901–2020), daily precipitation values from the 15 stations (Fig. 1) were extracted from the dataset of the European Climate Assessment & Dataset (ECA&D) project (Klein Tank *et al*. 2002) through the website www.ecad.eu. From the daily values, the monthly total and then the total precipitation for each season from the respective stations were then obtained.

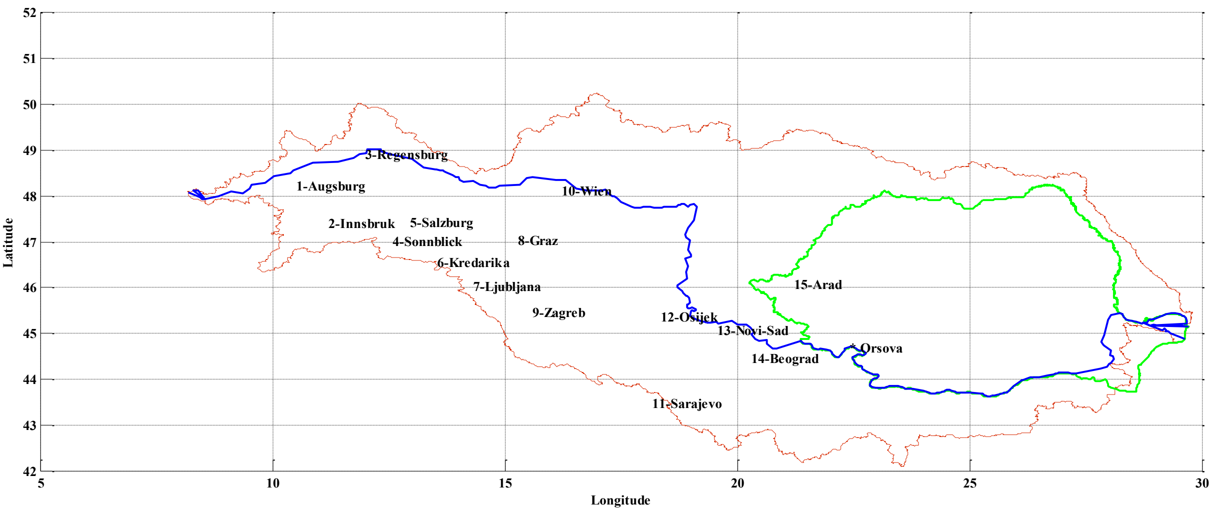

Figure 1. Localization of 15 stations in the Danube basin.

The GBOI was introduced by Mareș *et al.* (2013) to reflect the baric contrast between the Balkan and the Greenland zones. The GBOI's definition started from the analysis of the correlations (Fig. 2) between each grid point of the sea level pressure and the first principal component (PC1) of the development in the empirical orthogonal functions (EOFs) of the precipitation from 15 stations in the Danube basin (Fig. 1).

This index was calculated as the difference between the normalized sea level pressure at Nuuk and Novi Sad. The monthly GBOI values for the period 1901–2020 are presented in the *Supplementary Information* in the study of Mareș *et al.* (2025).

As regards the NAOI, was obtained from the Hurrell Station-Based Monthly NAO Index (Hurrell and Phillips 2023) (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).

As for the ***methods*** applied, first, representations in Empirical Orthogonal Functions (EOFs) were used to characterize the overall state of precipitation along the Danube basin, considering only the first principal component (PC1).

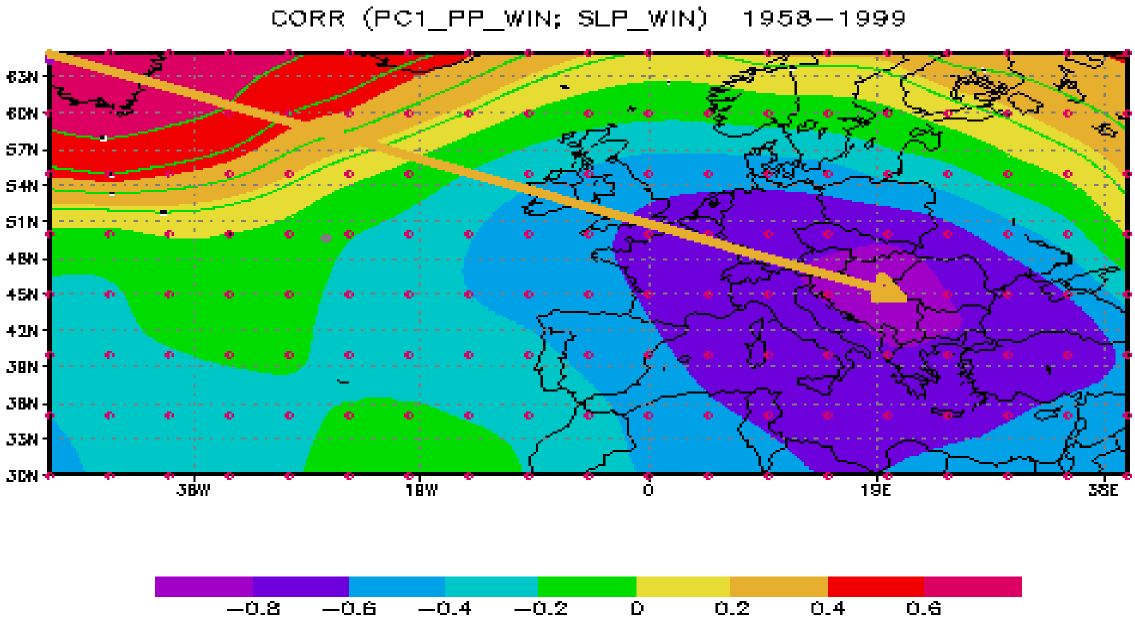

Figure 2. Map of correlations between PC1-precipitation for the 15 stations in the Danube basin and SLP during winter. The arrow starts from the highest positive correlation (Nuuk, Greenland) and proceeds to the highest negative correlation (Novi Sad, Serbia).

In order to find the degree of coherence in the time-frequency domain between the atmospheric indices and the precipitation field, different variants of the wavelet transform theory were used (Grinsted *et al.* 2004; Schulte *et al.* 2016; Hu and Si 2021).

Also, a modeling of maximum daily discharges for each month by means of generalized extreme value (GEV) and the introduction as covariates the two climate indices (GBOI and NAOI) was applied (Gilleland and Katz 2016).

3. RESULTS AND DISCUSSION

In the following, some of the most relevant results related to the comparative influence of the two atmospheric indices on the overall state of precipitation in the Danube basin will be presented, considering only the first principal component of the development in EOFs of the precipitation field, denoted here by PC1-PP.

Table 1

The correlations coefficients (R) between PC1-PP in the Danube basin and the two climate indices (CIs), GBOI and NAOI, for each season (1901-2020). The 99% confidence levels (CLs) correspond to R >=0.232 and CL = 95% for R = 0.178.

CIs/Season	WIN	SPR	SUM	AUTUMN
GBOI	**0.7868**	**0.4984**	**0.3149**	**0.5859**
NAOI	**-0.2997**	-0.0680	0.0201	**-0.2332**

From Table 1, it can be seen that the GBOI has an impact with high statistical significance in all seasons, with the highest values in the winter season. In the winter season, the NAOI presents the most important significant influence, as already shown in several publications including Mareş *et al.* (2016, 2025) for the eastern part of the middle Danube basin, this influence can also be observed in the autumn season; by contrast, in the spring and summer seasons, it has no influence that can be taken into consideration.

Considering only the winter season, details in the time-frequency domain will be obtained by applying partial wavelet coherence (PWC) analyses. Hu and Si (2021) improved the PWC method so that the PWC could reveal the relation of two variables after removing the influence of multiple variables.

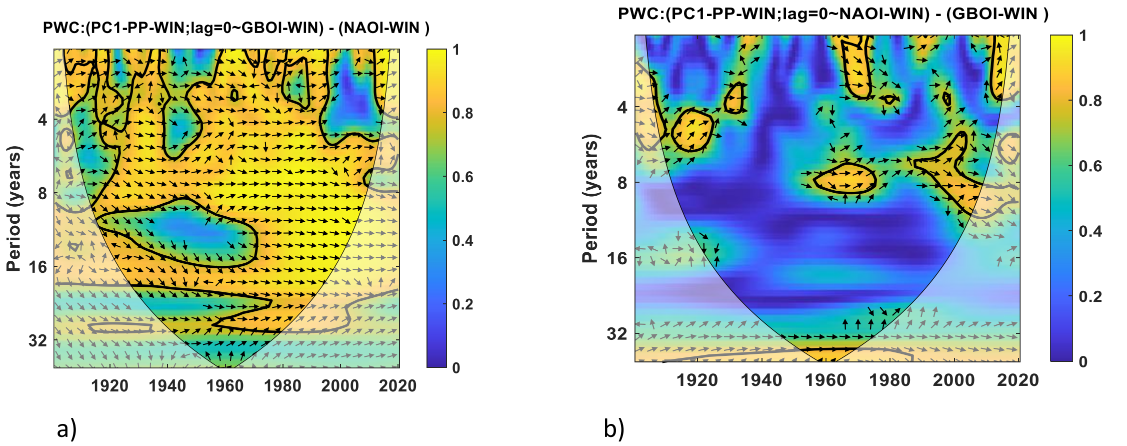

Figure 3. Partial wavelet coherence (PWC) for PC1-PP winter with a) GBOI, excluding NAOI, and b) NAOI, excluding GBOI..

The Figure 3 presents the results obtained using PWC. Figure 3a shows the relationship between PC1-PP and the GBOI, eliminating the NAOI, while Figure 3b shows the relationship between PC1-PP and the NAOI, eliminating the GBOI.

It can be seen from Fig. 3a that there is a significant coherence between GBOI and PC1-PP for a large area within the cone of influence. The arrows indicate that the two variables are in phase, that is, they are positively correlated.

Figure 3b reveals that after removing the GBOI from the NAOI coherence with precipitation, the area of the influence of the NAOI on precipitation is narrowed. It is worth mentioning that, in the coherence field between PC1-PP and the NAOI, a relatively significant coherence appears inside the cone of influence, around periods greater than 32 years, which can be associated with the 33-year solar cycle (Brüuckner cycle). A more detailed discussion of the results indicated by Fig. 3 is found in Mareş *et* al. (2025), also taking into account the wavelet coherence (WTC) between the two atmospheric indices.

To see if there are any differences between the influences of the two climate indices on certain stations in the Danube basin, correlation analysis will be tested through a Pearson correlation coefficient, presented in Fig. 4, for the winter season. As can be seen from Fig. 4, the precipitation from stations located in the eastern part of the middle basin and in the lower Danube basin are correlated with the GBOI with a CL higher than 99%, while for the NAOI, there are only five stations for which the CL is clearly > 99%.

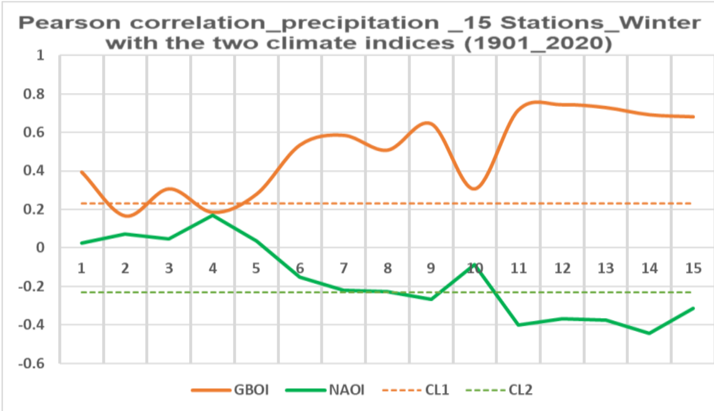

Figure 4. The winter season correlations coefficients between precipitation and GBOI and NAOI, at the 15 stations in the Danube basin, for the period 1901–2020 (solid lines). The dotted lines represent the 99% confidence level (CL).

For the other seasons, in terms of the results regarding the influences of the two climate indices considered simultaneously with precipitation in the same season, we can mention the autumn (not shown here), and spring seasons. In the autumn season, the correlations with the GBOI are statistically significant with a CL > 99% for all the stations considered, while for the NAOI's influence, CL > 99% was obtained only for a few stations located in the transition area from the middle to the lower Danube basin.

For the spring season, except for three stations in the upper basin, the influence of the GBOI was significant, with CL ≥ 99%, and for the NAOI only precipitation at the Arad station indicates a significant relationship (Fig. 5).

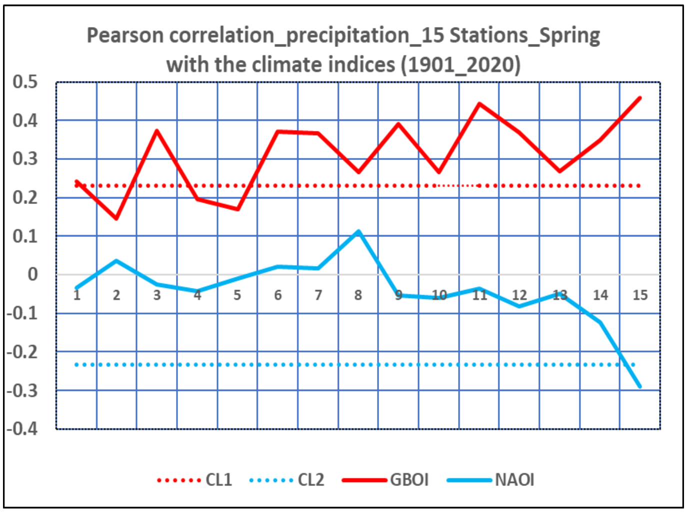

Figure 5. Same as Fig 4, but for Spring season.

The influence of the two atmospheric circulation indices on precipitation in the lower Danube basin during spring (simultaneously or with certain lags) is of particular importance. Knowledge of the evolution of precipitation during the spring season has an important impact on the evolution of the Danube discharge at the entrance to Romania, the discharge state influencing important socio-economic areas.

Therefore, in the following, some of the preliminary results obtained by applying methods from the EVT field for the maximum monthly precipitation in the spring months will be presented.

By means of GEV and by inserting as covariates the two climate indices (GBOI and NAOI), the maximum monthly precipitation is modelled. From the period 1901–2020 were selected maximum monthly precipitation in spring months (March, April, May) at two meteorological stations in the middle and lower Danube basin: Novi Sad (Serbia) and Arad (Romania).

The results of applying GEV without covariates are presented in Figures 6 and 7, where the red line indicates the amounts of precipitation of 150 mm, which are estimated, at a return period of 100 years for the ARAD station, and 50 years for the Novi Sad station. The top panels of these figures show: left - the quantile-quantile plot (empirical versus modeled GEV) of the extremes; right – the quantile-quantile plot simulated with the GEV model according to the empirical situation in which the regression line (thin solid line) and the 95% significance level band are plotted. The bottom panels display, on the left, the probability density of the empirical data (solid line) and that (dashed line) of the model-adjusted data, and, on the right, the return level (mm) with the 95% confidence interval band depending on the return period (years).

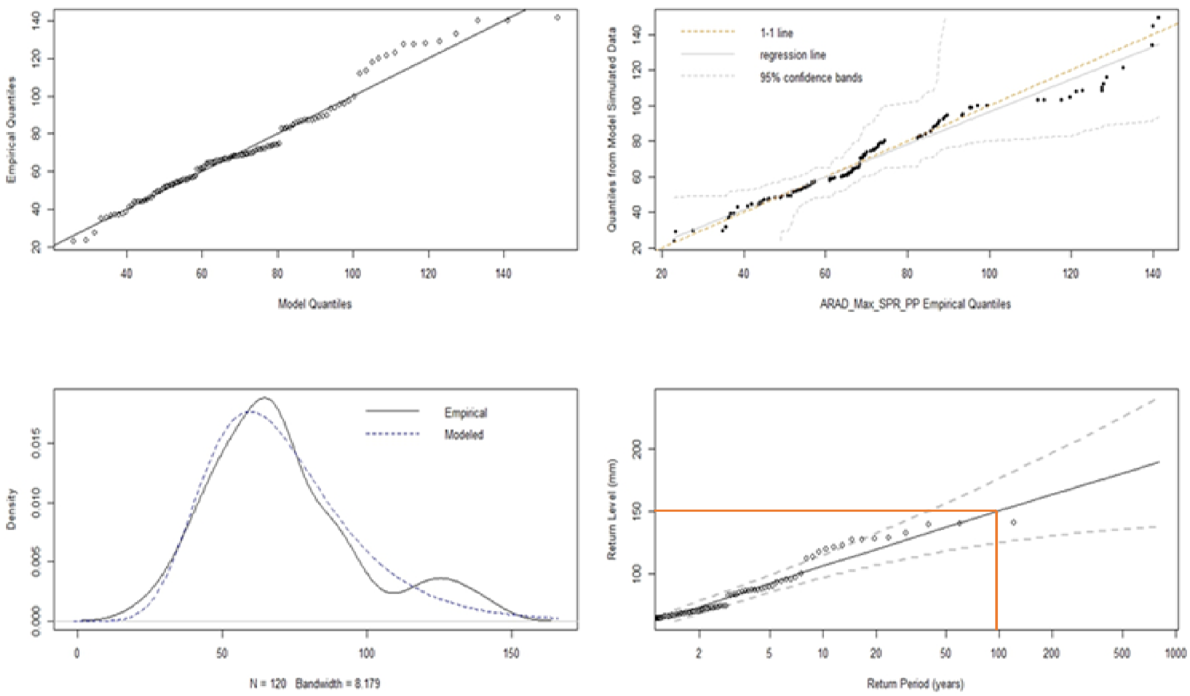

Figure 6. GEV fit diagnostics for maximum monthly precipitation in spring (March, April, May) in period 1901–2020 at Arad (Romania).

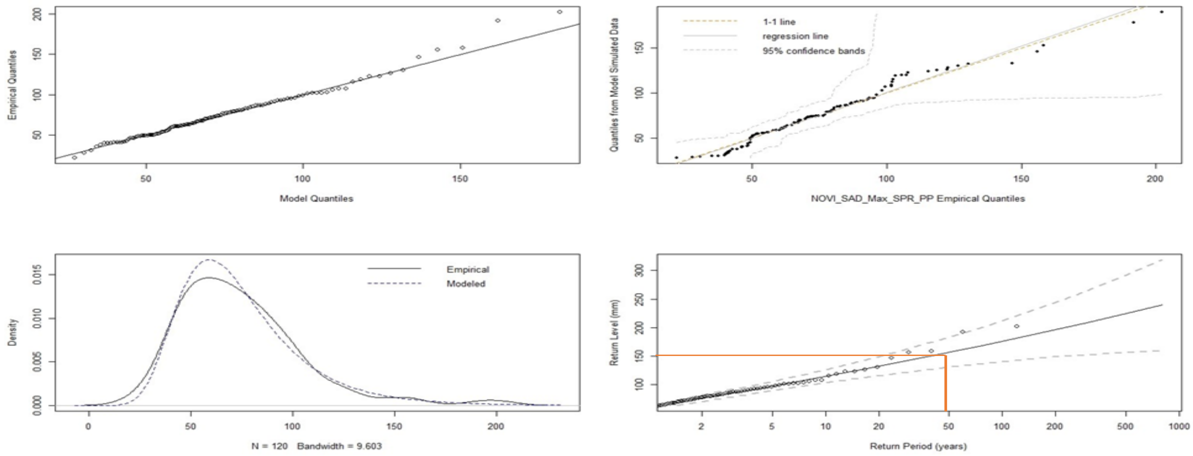

Figure 7. GEV fit diagnostics for maximum monthly precipitation in spring (March, April, May) in period 1901–2020 at Novi Sad (Serbia).

The performance of introducing the GBOI and NAOI in winter and spring as covariates into the location parameter of the GEV distribution of maximum precipitation during the spring months was tested by the Akaike Information Criterion (AIC) (Akaike, 1974) and Bayesian Information Criterion (BIC), introduced by Schwarz (1978), and also by the value of the parameter of confidence *p*. (Figures 8 and 9). The values of AIC and BIC are represented in the graphs against a reference value of 1100 units, for ease of visualization. The p-value for each entered covariate is specified under each predictor variable. The lowest value of *p* (0.00048) is for the GBOI in spring. The influence of NAOI is significant in spring with a **p** = 0.02.

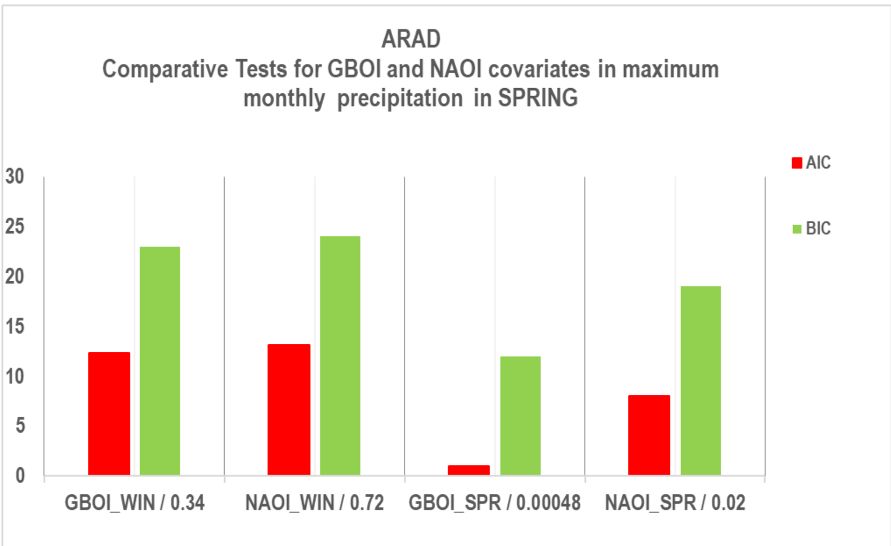

Figure 8. AIC and BIC values in the case of introducing as covariates of the winter averages of GBOI and in the location parameter of the GEV distribution for modeling of the maximum monthly precipitation in spring (March, April, May) in period 1901–2020 at Arad (Romania).

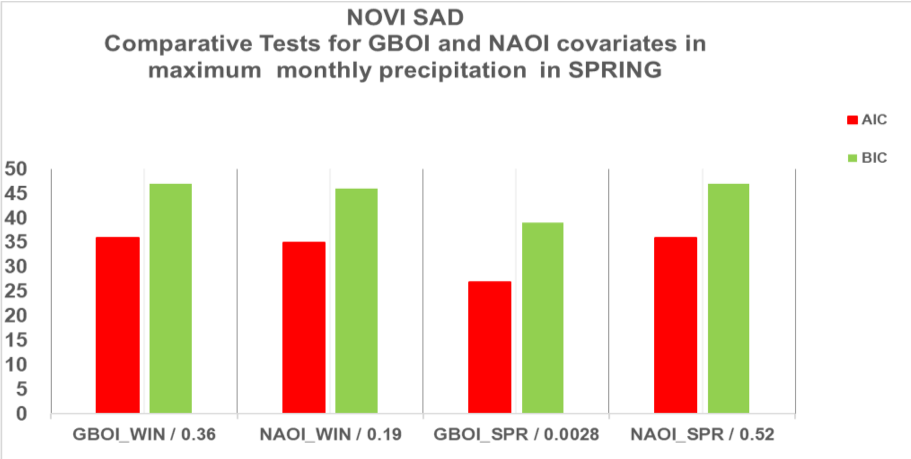

Figure 9. Same as Fig. 8 but for Novi Sad station.

Taking into account the magnitudes of these criteria, it emerged that the highest performance was obtained for simultaneous connections, GBOI having a statistical significance with a higher confidence level than NAOI, both for Arad and Novi Sad. For the climate indices in the winter season on the extreme precipitation, the influence of NAOI at the Novi Sad station can be mentioned, but with a not very high level of confidence.

4. CONCLUDING REMARKS

From the correlative analyses between the precipitation in the Danube basin expressed by PC1 of the EOFs decompositions and the two climate indices (GBOI and NAOI) for the period 1901–2020, it emerged that for the winter season both indices have an influence at the overall level of the Danube basin during this season with a CL of 99%, with the mention that for GBOI the relationship (R) is quantified by a value of approximately 0.79 while for NAOI it is approximately -0.30. For the other seasons GBOI presents a CL > 99%, with the lowest values during the spring season. Regarding the influence of NAO, this is significant, considering a CL > 99% only in the autumn season. In the spring and summer seasons the influence of NAO is at a negligible level of significance.

By representing the relationship between GBOI and PC1-PP in the winter season by means of PWC, eliminating the influence of the NAO weather phenomenon, a large area of significant coherence was obtained in the time-frequency domain. Applying the same for the winter season, this time between PC1-PP and NAOI, eliminating the contribution of GBOI, the area of significant coherence appears only in limited areas. Consequently, the significant signal of GBOI compared to NAOI on the overall precipitation field during winter was highlighted.

To see what happens with the spatial influence on precipitation of the two climatic indices, the relationships between the two indices for each station in the winter and spring seasons were analyzed. During the winter season, the precipitation from stations located in the eastern part of the middle basin and in the lower Danube basin are correlated with the GBOI with a CL higher than 99%, while for the NAOI, there are only five stations for which the CL is clearly > 99%. For the spring season, except for three stations in the upper basin, the influence of the GBOI was significant, with CL ≥ 99%, and for the NAOI, only precipitation at the Arad station indicates a significant relationship.

If for the influence of GBOI and NAOI on PC1-PP, the conclusions are very clear, for the influence of the two indices on extreme precipitation, the results are less remarkable. The GEV modeling was performed without covariates and with the introduction of the two climate indices during the winter and spring seasons in the location parameter of the GEV distribution.

The tests performed through AIC and BIC led to the following remarks:

– The most significantly high result of the GEV modelling was obtained by introducing the GBOI during spring as a covariate in the location parameter of the maximum precipitation in spring months at the Arad station; for this case, the wavelet coherence also revealed a significant connection in the band of periods of approximately 22 years for the interval 1920–1980. The coherence of the variables is in phase, that is, high values of GBOI determine the occurrence of precipitation above normal values.
– Also, for simultaneous relationships between extreme precipitation and the two climate indices during spring, with a less low significance, the influence of GBOI on precipitation at the Novi Sad station and of NAOI on precipitation at the Arad station was obtained;
– Regarding the testing of the influence of GBOI and NAOI in winter on the maximum precipitation in spring, from the investigations in this study, no statistically significant results were obtained. The best result was for the influence of NAOI in winter on the maximum precipitation in spring in Novi Sad, but with a confidence level of only 80%.

These less significant results obtained regarding the signal of the two climate indices on the occurrence of extreme precipitation in the Danube basin during the spring season, lead to the need to continue investigations related to finding an optimal combination of atmospheric or extra-atmospheric factors that would determine the prediction (estimation) with a higher probability of this extreme precipitation.

In the case of combining the influence of the two indices, it is necessary to eliminate redundancy, and thus an expansion of the area of simultaneous synergistic influence of the NAO and GBO phenomena is expected, which will be the subject of a future investigation.

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