The Relation between Atmospheric Teleconnection Patterns and Precipitation Extremes over Europe

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Abstract: Atmospheric correlations have profound importance for the perception of short-term and long-term variability in climate. The most important correlations are recognized as atmospheric teleconnection patterns which are instant correlations in the variations of large-scale atmospheric parameters at certain points on the Earth. These patterns may significantly lead to the variability in the climate and influence the extreme precipitation. Possible droughts and floods could originate as a consequence of excessive decrease or increase in precipitation amount and frequency.

The main aim of this paper is to obtain a better understanding of the relation precipitation extremes in the whole European domain that are relevant to the several representative atmospheric teleconnection pattern indices by applying various statistical approaches valid for consecutive 38 winter seasons. Relations were checked by means of Pearson and Spearman correlation methods for selected winter seasons. What is more, Multiple Linear Regression method was applied to determine the inter-connection between these atmospheric teleconnection patterns and the extreme precipitation frequencies exceeding thresholds settled. Then, according to the exceeding frequencies the determined critical values, most of the regions over Europe have a high negative and positive coefficients of these atmospheric teleconnection pattern indices with the precipitation totals and their frequencies valid for winter seasons (statistically significant at the 90%, 1 mm/day, 10 mm/day threshold levels).

1. Introduction

Our chaotic atmospheric system is the primary reason for naturally occurring atmospheric teleconnection patterns which is a reflection of internal atmospheric dynamics. Large-scale changes in the atmospheric waves could be triggered through atmospheric teleconnection patterns (ATP), and impact mesoscale storms and their location/intensity over wide areas. Severe and hazardous precipitation events are among the most devastating weather phenomenon since they are frequently followed by flash floods and sometimes accompanied by severe weather such as heatwaves, cold waves, drought, lightning, hail, and storms, etc. Hereby, the occurrence of extreme weather events in precipitation makes a growing interest in the scientific community due to their greater influences on society and economy. Understanding the variability of extreme precipitation frequencies and their association with atmospheric processes could assist to estimate the frequency and severity of extremes.

One of the remarkable atmospheric teleconnection patterns is the North Atlantic Oscillation (NAO) which plays a key role in the extra-tropical Northern Hemisphere winter, influencing precipitation, and atmospheric and oceanic circulation over a wide region (Hurrell, 1995; Hurrell, Van Loon, 1997). A convenient expression of NAO is commonly obtained by calculating the standardized sea level pressure (SLP) difference between the Azores high and Icelandic low for the 4-month (December-March) of the winter season (Hurrell, 1995). Through fluctuations in the strength of the Icelandic low and the Azores high, it controls the strength and direction of westerly winds and location of storm tracks across the North Atlantic. Thus, it indirectly changes the rainfall patterns of this vast region. A positive NAO index is often associated with higher precipitation across northern Europe by westerly winds across the middle latitudes of the Atlantic, across southern Europe and in the Middle East during the winter (Wallace, Gutzler, 1981). The inverse index, wind, and moisture patterns are associated with negative NAO index and, therefore, with the opposite effects on precipitation.

North Sea Caspian Oscillation (NCP) is another powerful climate phenomenon between Europe and Asia that may disrupt north hemisphere of atmospheric and oceanic circulation patterns and exert profound impacts on Eurasia. It refers to an upper-level atmospheric teleconnection between the North Sea and North Caspian at the level of 500 hPa geopotential height. NCP is defined as an upper-level atmospheric teleconnection between two regions centered between 0°, 55°N and 10°E, 55°N (North Sea) for its north-western pole and between 50°E, 45°N and 60°E, 45°N (Northern Caspian) for its southeastern pole (Kutiel, Benaroch, 2002). Winter and the transitional seasons are the most pronounced terms for NCP index (NCPi).

The climate in the Mediterranean region is mainly characterized by marked seasonality, with a wet season from October to March (Xoplaki, Gonzalez-Rouco, Luterbacher, Wanner, 2004). Especially, East European cities are affected by the pressure distribution which brings extreme wet and warm weather. Yet, there are two different versions of MOi. Here, we adopted the MOi calculated from normalized sea level pressure difference between Gibraltar's Northern Frontier (36.1°N, 5.3°W) and Lod Airport (32.0°N, 34.5°E) in Israel (Palutikof, 2003). In order to correctly examine East Europe weather conditions, this version (further north located) is preferred. Hence, MOi exhibits large scale variability of the Mediterranean climate by representing pressure anomalies between the east and west of the Mediterranean basin and the strength of the Rossby waves.

In this study, spatial and temporal variability of extreme precipitation over Europe concerning these ATPs shown in Figure 1 are investigated over the European region for the winter period of 1979-2017.
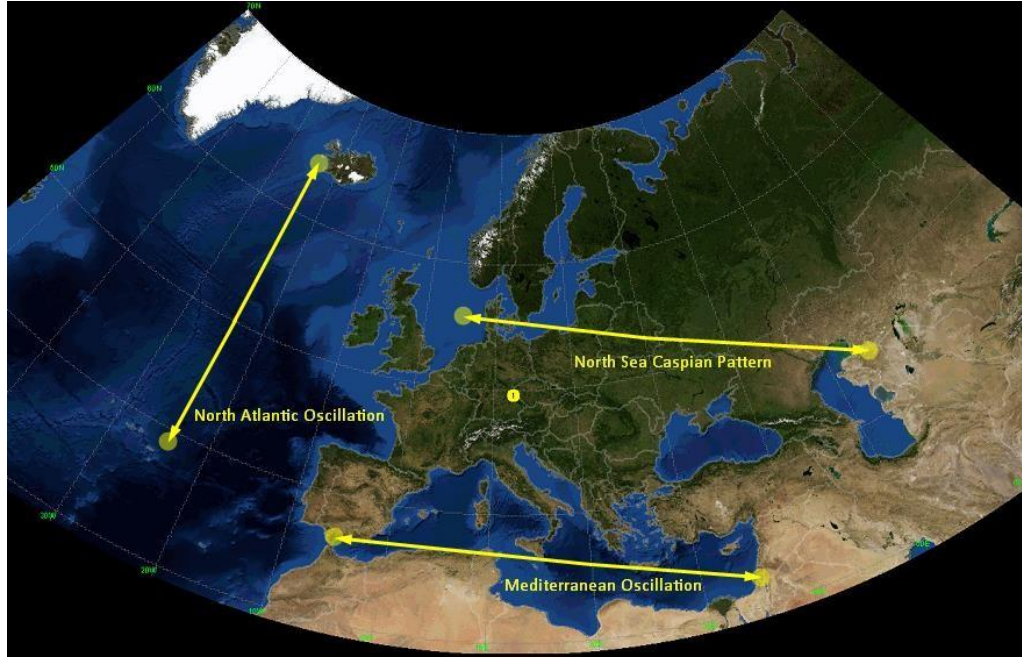

Figure 1. Atmospheric Teleconnection Patterns and their locations.

2. Data and Methodology

Daily precipitation data, E-OBS, collected by European Climate Assessment were used. The data cover the domain between 25.05 N - 71.45 N and 24.95 W - 45.45 E with 0.1° grid resolution.

NAO is simply part of the Arctic oscillation and varies over time with no particular periodicity. Monthly means indices normalized by the 1981-2010 climatological base period are obtained from Climate Prediction Center, NWS, NOAA.

According to hydrostatic equilibrium of atmosphere, geopotential unit must be in [m^2/s^2]. 500 mb geopotential of the ECMWF ERA-Interim data set is used to compute NCPi valid for the location (3) and was divided by the gravitational acceleration at the surface of Earth (g0), to convert the data set into a geopotential height by using the following equation (1)(2).

$$\Phi(z) = \int_0^z g\, \partial z \qquad (1) \qquad\qquad Z = \Phi(z)/g_0 \qquad (2)$$

$$NCP_i = \overline{Z}\,(0°,55°N; 10°E,55°N) - \overline{Z}\,(50°E,45°N; 60°E,45°N) \qquad (3)$$

The geopotential height data which is converted from the geopotential unit are standardized by the 1981-2010 climatological base period.

As the last ATP type, Mediterranean Oscillation Index (MOi) values are obtained as daily values from the Climate Research Unit at the University of East Anglia, Norwich, UK. Daily data are converted to monthly mean values which cover the period from 1979 to 2017. Then, the data set has also been standardized by the 1981-2010 climatological base period. December, January, February, and March are taken to represent the main months of the winter season of Northern Hemisphere.

Multiple linear regression (MLR), also known simply as multiple regression, is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. Multiple independent variables are related to a dependent variable. So that, once how these multiple variables relate to dependent variable are identified, all of the independent variables used to make accurate predictions. In essence, MLR is the extension of ordinary least squares regression that involves more than one explanatory variable. In the least squares regression analysis, the coefficients are selected so as to minimize the sum of the squared residuals (Wilks, 2011). We might let K denote the number of predictor variables (independent parameters). Simple linear regression is then the special case of $K = 1$. In general, the prediction equation becomes as

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_K \cdot x_K \tag{4}$$

These $K + 1$ regression coefficients often are called the regression parameters. In this study, there are three independent variables (NAOi, NCPi, MOi). Thus, $K = 3$ and the number of regression parameters is equal to 4.

$$f(q) = \alpha + \beta \cdot I_1 + \gamma \cdot I_2 + \theta \cdot I_3 \tag{5}$$

Here the factors are expressed as,

f = frequency (number of days for specific threshold)

α = intercept
β = NAOi coefficient I_1 = Monthly NAOi
γ = NCPi coefficient I_2 = Monthly NCPi
θ = MOi coefficients I_3 = Monthly MOi

Throughout the paper, independent variables are represented as indices of ATPs. The dependent variable is represented by day number of frequencies over 90th percentiles, lower than the amount of 1 mm/day and greater than the amount of 10 mm/day of precipitation

3. Discussion and Results

Long-Term Variability of Atmospheric Teleconnection Patterns (ATPs)

It is critical to compare trends in winter seasons to determine the climatic effects of ATPs. Figure 2 illustrates the ATPs variability for winter months from December through March (DJFM). Negative and positive phases of NAOi were consecutively realized in the last seasons, especially. The situation is slightly different for NCPi. The positive phase of NCPi is dominant before the 21st century, while a more balanced mode is in the new century. For the MOi, the positive phases reached to most +2 levels, while the negative phases were strengthened and exceeded -3 values.

When the analysis of the averages of the months during winter seasons of the three ATPs is considered, the NAOi stayed on the positive phase for an average of 8 seasons in a row from 1987/88 winter season to 1994/95 winter season. NCPi had a higher positive average than the NAOi for 5 seasons in a row, corresponding to the same season range. In the same period, the seasonal averages of MOi have been in near neutral phase. Seasonal averages can provide insight into the pressure positionings and shed light on the potential rainfall or snowfall activities of that season. Particularly, the negative monthly phases of MOi lasts throughout the winter seasons from 2007 to 2012 that can be seen in Figure 2.
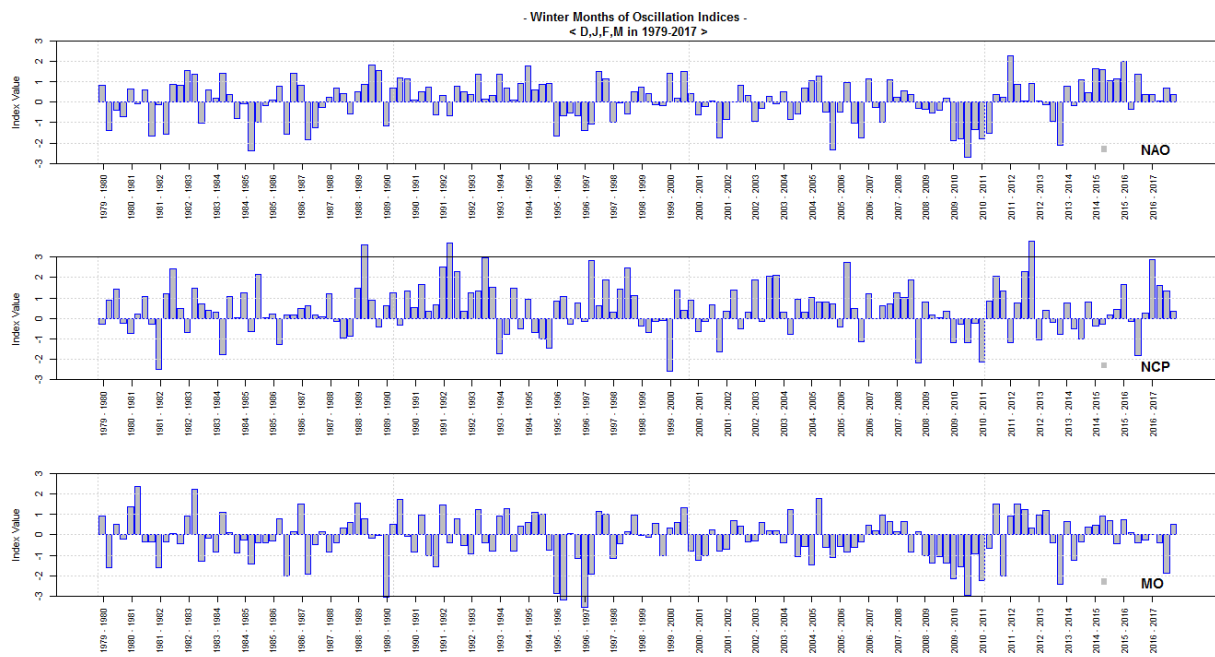

Figure 2. Monthly means of NAOi NCPi, MOi between 1979-2017 for DJFM. Months of winter seasons (DJFM) between 1979 and 2017 are included.
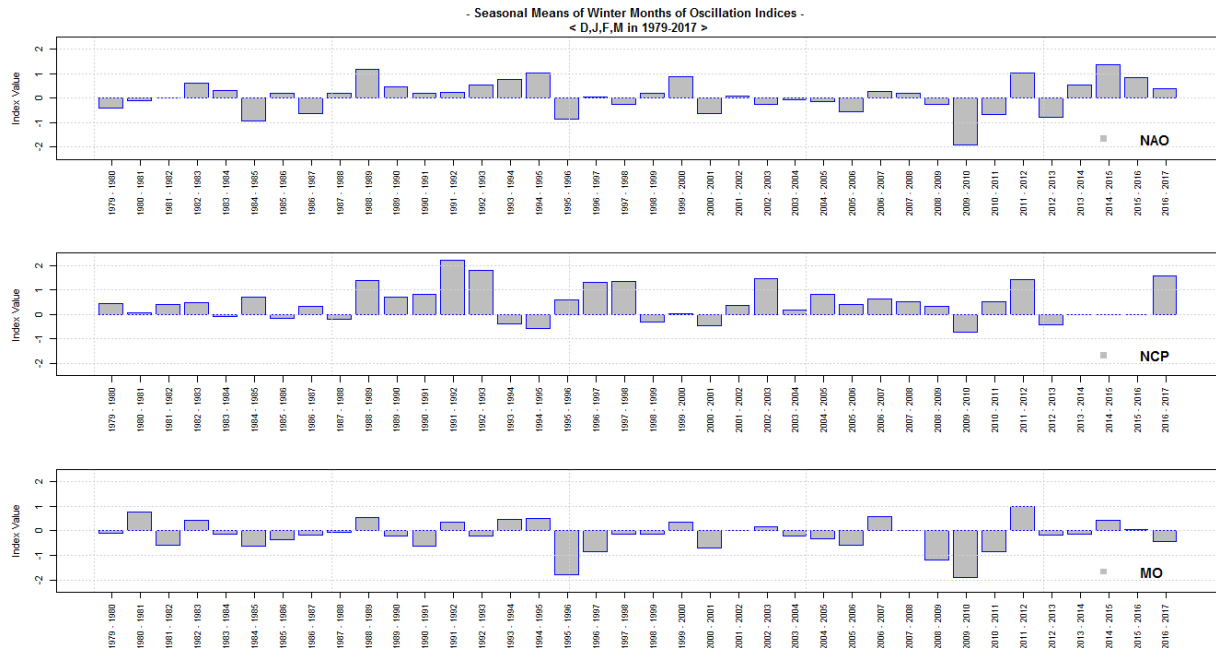
Figure 3. Multiple time series representation of seasonal means of NAOi, NCPi, MOi between 1979-2017. Months of winter seasons (DJFM) between 1979 and 2017 are included.

Evaluating of 90th Percentiles of Precipitation

In order to acquire the thresholds of daily precipitation extremes, the 90th percentile of precipitation data were calculated. The variation from the daily value of the precipitation total at a certain location during a specific time period has a strong influence because low rainfall is identified as drought, while too much rain may be associated with floods. In meteorology, the threshold values of 80% and above are used to find the region representing the severe and farthest endpoints of a normally distributed data set. While specifying 90th percentiles of each grid based on winter seasons between 1979 and 2017, two separate approaches are applied. In the first approach, the threshold value at a certain point is estimated by including all days while in the second approach, only wet (precipitative) days are considered.
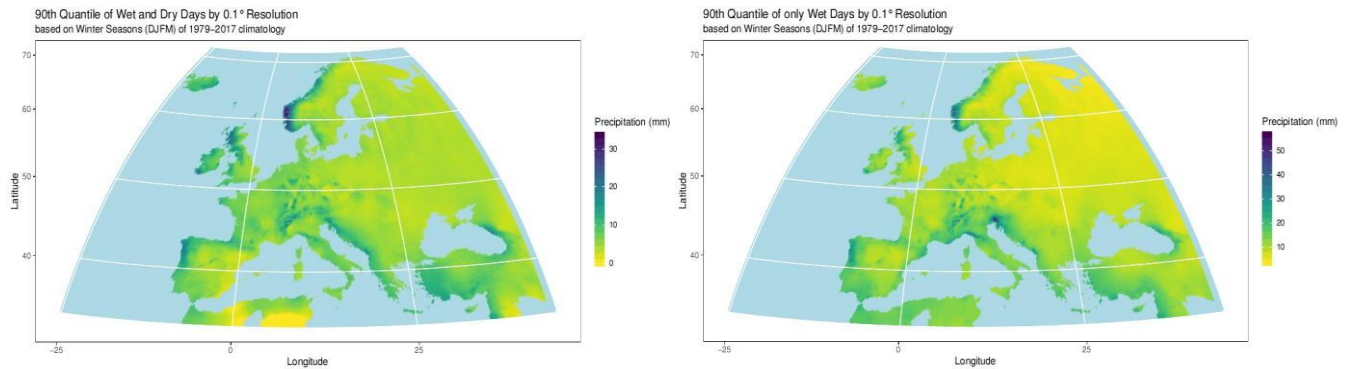

Figure 6. Europe domain map of the 90th threshold for each grid valid for all days/only precipitative days of 38 winter seasons.

The main goal here is to create two different threshold values for each point. Threshold values generated from only rainy days are quantitatively higher than the threshold values taken into account for all days. North Africa and the Arabian Peninsula have a threshold value of 5mm and below, while Norway, West England and Northern Portugal have a threshold value of 25 mm and above. In Turkey, coastal areas have a higher threshold than that inland. The 90th threshold, which is a critical value for extreme rainfall, ranges from Scandinavia to the Mediterranean basin.

It should be noticed that the air that gained moisture on the North Atlantic caused severe rainfall on the western shores of Europe due to the influence of dominant westerly flows in the mid-latitudes. Therefore, the 90th threshold in these regions is relatively high. Along the coastline of Western Europe, it has a huge precipitative range of 20 mm or more from Portugal to Norway. Besides, Southern Europe and the Mediterranean basin have a moderate threshold value of 13-15 mm, whereas Eastern European countries have a low threshold. In this way, with topographical, frontal and convective effects may create the cyclones and troughs that bring rainfalls and snowfalls on Europe.

Frequencies exceeding the 90th Percentiles year by year over Europe

When the frequency map exceeding the 90th threshold value for the winter season of 1994/95 and 1995/96 are examined as example winter season. On the seasonal average, in the winter of 1994/95, while NAOi and MOi were in the negative phase, NCPi was in a positive phase. The western part of the Mediterranean has frequencies lower than 5 days. On the contrary, Northwest Europe has received more than 25 days of extreme precipitation range. In addition, other European regions have moderate frequency values. The 1995/96 season has the opposite effects.
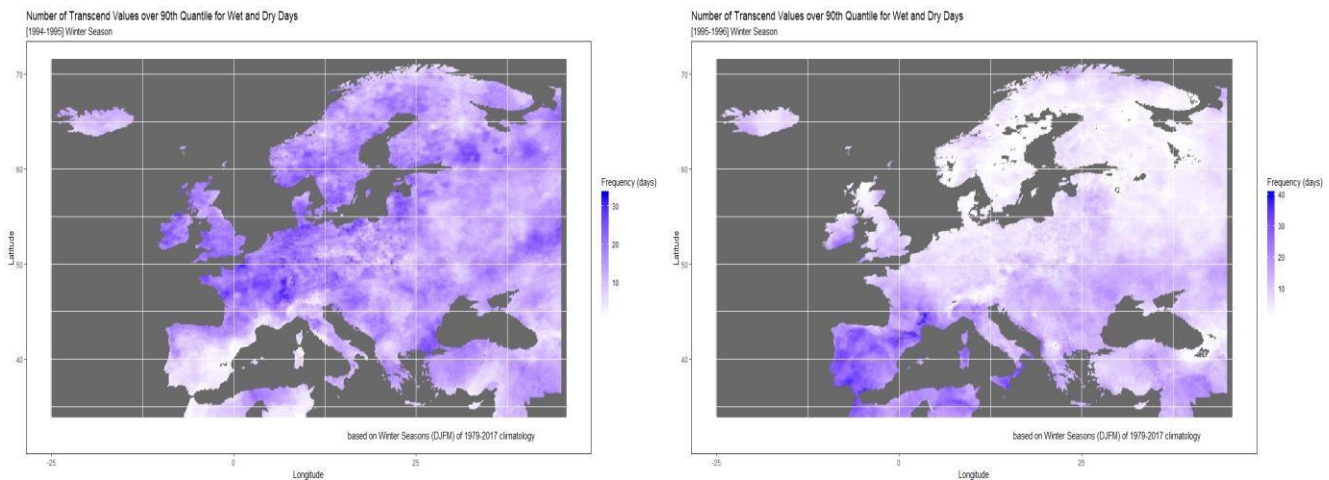

Figure 5. Example frequency maps of Europe for 1994/95 and 1995/96 winter season. 90% thresholds are based on only precipitative days of 1979-2017 winter seasons.

The Link between Teleconnections and the Frequency of Days with Extreme Precipitation

Regional interpretation can be made on a mesoscale or synoptic scale about extreme drought and extreme rainfall regimes with the support of the MLR coefficients. With using of ATP indices, MLR coefficients are considered in three parts. The first one is the rainy (precipitative) days frequency that exceeds the 90th percentile value. The second of all is the production of coefficients based on the frequencies which are less than 1 mm. Third, new coefficients are derived from the number of daily precipitation with more than 10 mm.

In Figure 6, when the ATP coefficients were analyzed for the number of days exceeding the threshold value of the 90th percentile, extreme rainfall has occurred in the northern sections of the 50°N latitude while the NAOi and MOi are in positive phase; the NCPi is in the negative phase. This result verifies the positive correlation between NAOi and MOi based on Spearman-Pearson correlation methods. Even though there is no significant relation between any other indices of ATPs and NCPi, the positive phase of NCPi brings severe extreme rainfall to the western Atlantic coast of Norway. In the positive phase of the NAOi, jet streams pass through a further north latitude and affect the precipitation in Scandinavia with strong coefficients. Except northern side of the 55°N latitude and the North Atlantic region, Eastern Europe and southern Spain experience a lower number of days with extreme precipitation during the NAOi positive phase.
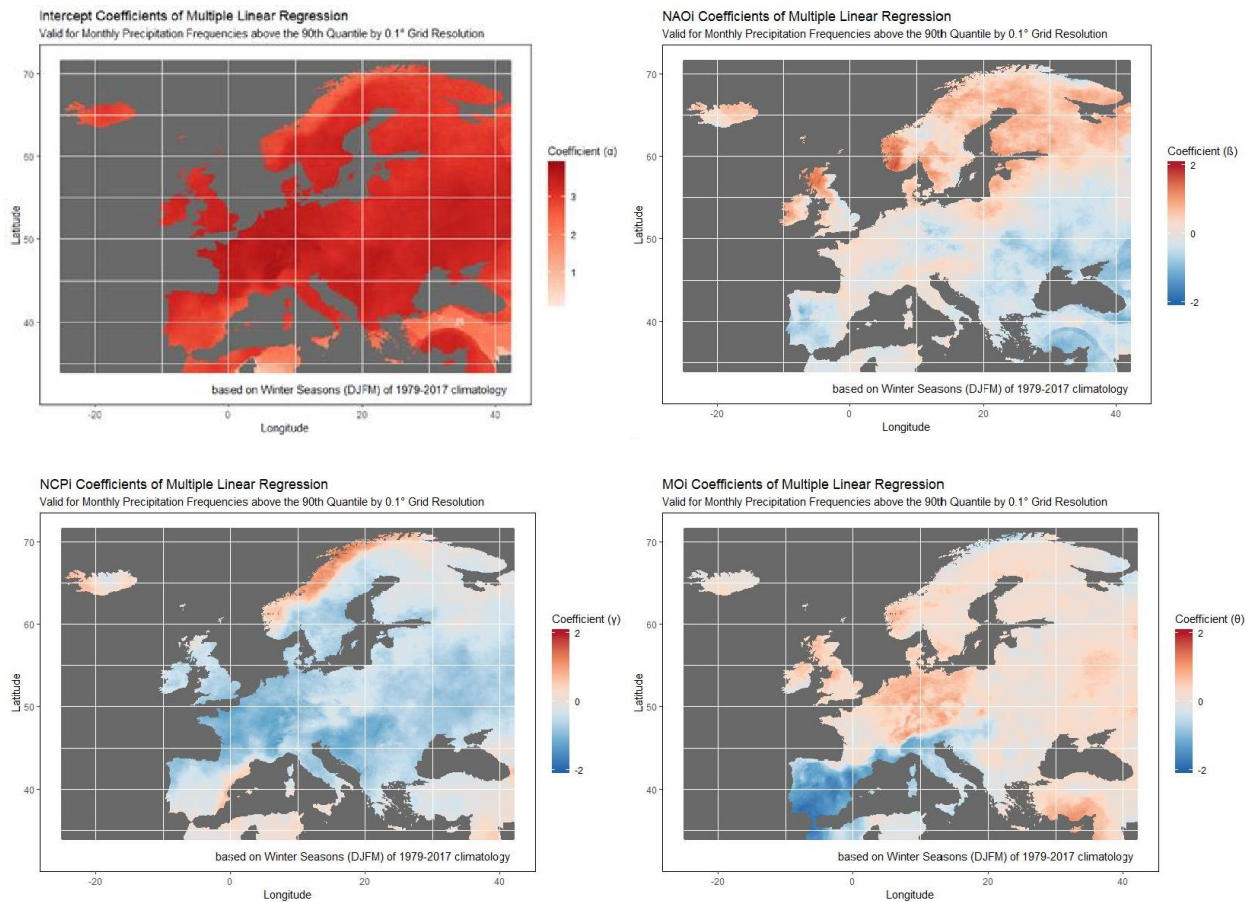

Figure 6. Distribution of MLR coefficients α, β, γ, θ for the monthly frequencies above 90th percentiles of precipitation based on winter seasons (DJFM) between 1979 and 2017.

Taking into consideration Figure 7, prominent coefficients could be highlighted numerically in many coastal areas. The phase effects of NAOi bring drastic perturbation to Europe in the north-south direction in terms of drought and cause non-precipitative effects to be carried to the Mediterranean. Besides, in the positive phase of the MOi, the west of the Mediterranean basin (Spain, Italy, southeastern France, etc.) has a considerable amount of rainy days under 1 mm/day and it has a severe dry winter period recorded (Figure 7). In the positive phase of the NCPi, Central-Western European countries have severe arid days, nevertheless; as moving towards Scandinavia, NCPi has a sharp opposite effect.
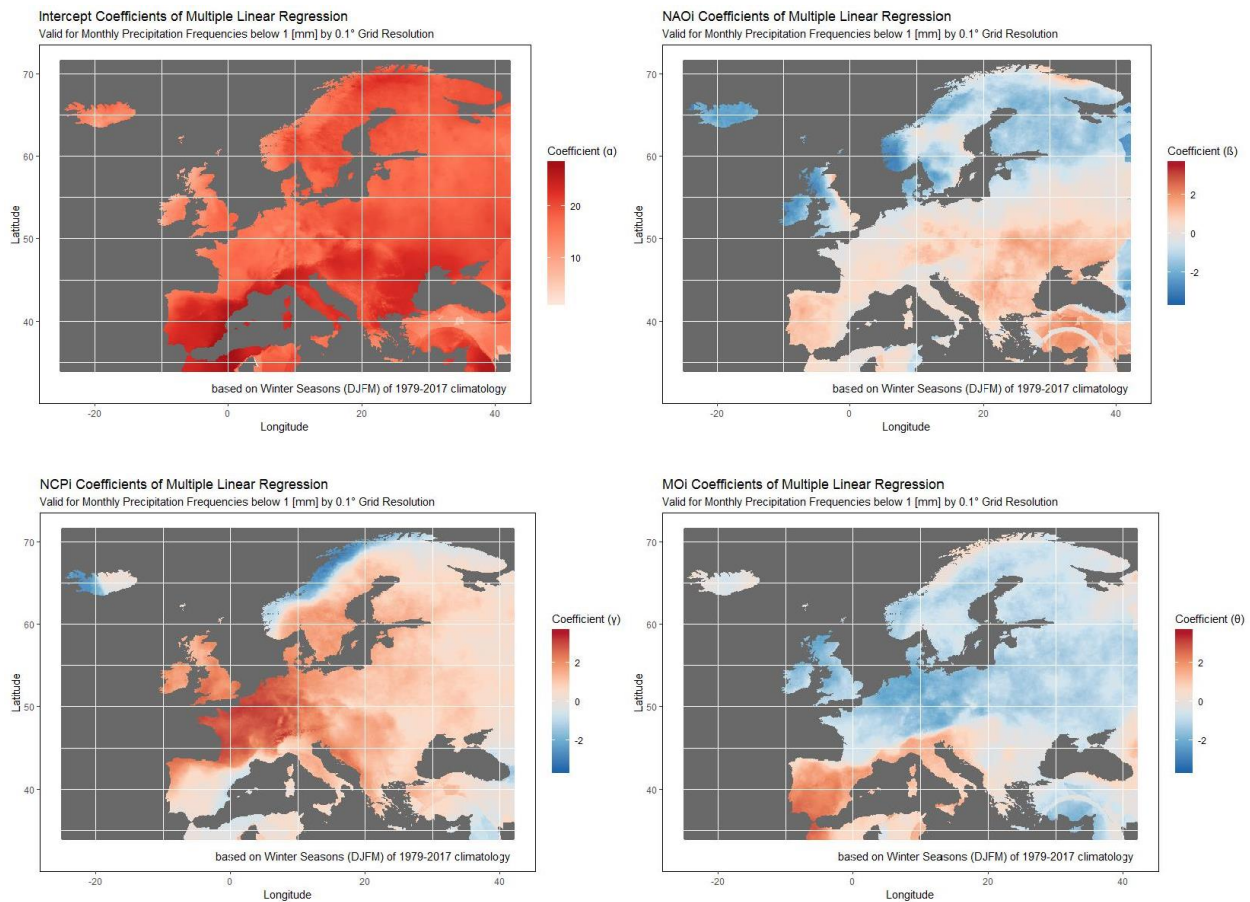

Figure 7. Distribution of MLR coefficients α, β, γ, θ for the number of days with precipitation above 10 mm for winter seasons (DJFM) between 1979 and 2017.

There are various local effects in Europe in terms of extreme rainfalls and snowfalls exceeding 10 mm. In Figure 8, for NAOi and MOi in the positive phases, the northern part of the United Kingdom (Scotland) and the western region of Scandinavia such as Norway have inclined to exceed 10 mm/day precipitation. These indices also create different effects over Turkey and the Western Mediterranean countries. Moreover, in the negative phase of NCPi, the Alpines have values exceeding 10mm.
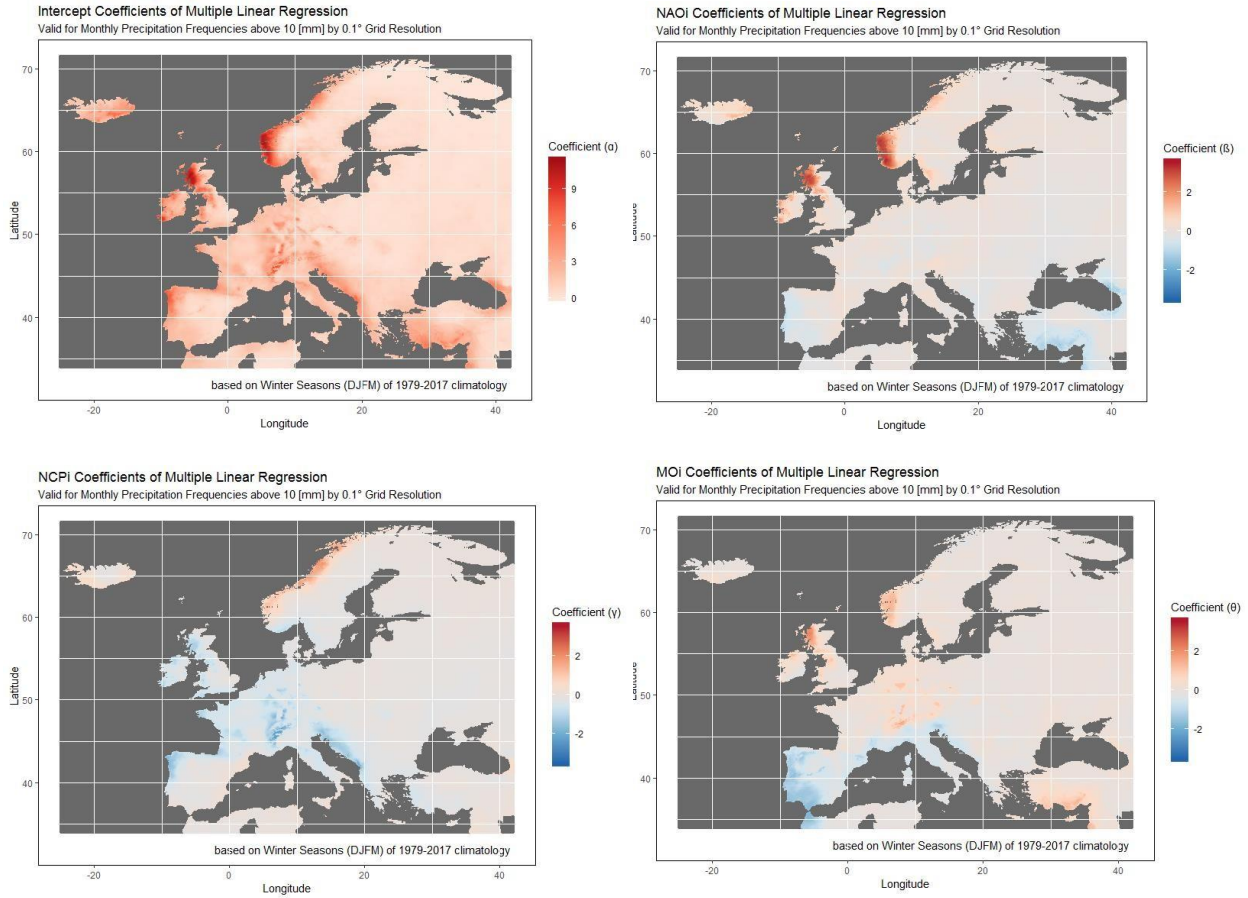
Figure 8. Distribution of MLR coefficients α, β, γ, θ for the number of days with precipitation lower than 1 mm for winter seasons (DJFM) between 1979 and 2017.

4. Conclusions

To sum up, the relation of ATP indices with extreme precipitation is an intriguing topic for the atmospheric sciences community. As the light of discussions, the air that gained moisture on the North Atlantic caused severe rainfall on the western shores of Europe due to the influence of dominant westerly flows in the mid-latitudes. Therefore, the 90th threshold values of precipitation along the coastline of Western Europe from Portugal to Norway are relatively high and in the range of 20 mm or more. Besides, Southern Europe and the Mediterranean Basin have a moderate threshold value of 13-15 mm, whereas Eastern European countries have low thresholds.

Along with these, various MLR coefficients are derived for the ATPs and frequencies of rainy days with the precipitation amount more than 90th percentile value, more than 10 mm and less than 1 mm, respectively. When the ATP coefficients were analyzed for the number of days exceeding the threshold values of 90%, extreme precipitation has occurred in the northern sections of the 50°N latitude while the NAOi and MOi are in positive phase; the NCPi is in the negative phase. This result verifies the positive correlation between NAOi and MOi based on Spearman-Pearson correlation methods. Even though, there is no significant correlation between any other indices of ATPs and NCPi, the positive phase of NCPi brings severe extreme rainfall to the western Atlantic

coast of Norway. Except for northern side of the 55°N latitude and the North Atlantic region, eastern Europe and southern Spain experience a lower number of days with extreme precipitation during the NAOi positive phase. In addition, in the positive phase of the MOi, the west of the Mediterranean basin (Spain, Italy, southeastern France, etc.) has a considerable amount of rainy days under 1 mm and it has a severe dry winter period. In the positive phase of the NCPi, Central-Western European countries have severe arid days, nevertheless; as moving towards Scandinavia, NCPi has a sharp opposite effect. For NAOi and MOi in the positive phases, the northern part of the United Kingdom (Scotland), and the western region of Scandinavia such as Norway have inclined to exceed 10 mm/day precipitation. These indices also create different impacts over Turkey and the Western Mediterranean countries. In the negative phase of NCPi, the Alpines have values exceeding 10mm.

Acknowledgment

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