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ORIGINAL PAPER

Winter North Atlantic Oscillation impact on European precipitation and drought under climate change

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Abstract

The North Atlantic Oscillation (NAO) is responsible for the climatic variability in the Northern Hemisphere, in particular, in Europe and is related to extreme events, such as droughts. The purpose of this paper is to study the correlation between precipitation and winter (December–January–February–March (DJFM)) NAO both for the historical period (1951–2000) and two future periods (2001–2050 and 2051–2100). NAO is calculated for these three periods by using sea level pressure, while precipitation data from seven climate models following the representative concentration pathway (RCP) 8.5 are also used in this study. An increasing trend in years with positive DJFM NAO values in the future is defined by this data, along with higher average DJFM NAO values. The correlation between precipitation and DJFM NAO is high, especially in the Northern (high positive) and Southern Europe (high negative). Therefore, higher precipitation in Northern Europe and lower precipitation in Southern Europe are expected in the future. Cross-spectral analysis between precipitation and DJFM NAO time series in three different locations in Europe revealed the best coherence in a dominant cycle between 3 and 4 years. Finally, the maximum drought period in terms of consecutive months with drought is examined in these three locations. The results can be used for strategic planning in a sustainable water resources management plan, since there is a link between drought events and NAO.

1 Introduction

NAO is defined as an index that measures the difference in sea level pressure between Ponta Delgada in the Azores and the Icelandic station of Stykkisholmur. Alternatively, the difference in pressure between Gibraltar or Lisbon and Iceland has been used. While it is possible to calculate the NAO index for both summer and winter values, the climate variability is most strongly governed by the variability in atmospheric circulation during the winter; hence, winter NAO is far more relevant (Folland et al. 2009).

The North Atlantic Oscillation (NAO) has been long recognized as one of the main major pattern of atmospheric variability and surface climate in the North Hemisphere (Hurrell 1995; Walker 1924; Walker and Bliss 1932). It is related to the western winds in the subpolar North Atlantic and its fluctuation governs changes in the frequency of extreme daily events in Europe. Northern Europe positive NAO conditions greatly reduce the incidence of extreme low temperatures but increase the risk of heavy rainfall and severe storms (Smith et al. 2014; Scaife et al. 2008). NAO has been showed to drive multidecadal climate variability in the Northern Hemisphere, including ice loss in the Arctic and tropical storm activity in the Atlantic (Delworth et al. 2016).

Droughts are extreme events that can have a large impact on the environment and the society, both locally and globally (Tsanis et al. 2011). Drought is often identified by the Standardized Precipitation Index (SPI), which can be calculated for different time periods (e.g., 3, 6, 12 months), using the corresponding precipitation data (Vrochidou et al. 2013; Vrochidou and Tsanis 2012). In many areas, significant connections exist between large-scale climate patterns, such as NAO and regional hydrologic extremes like droughts. This is because variations of sea surface temperature and sea level pressure are significantly associated with interannual and interdecadal variations in regional and global precipitation (Hu and Feng 2001). A relationship between precipitation and NAO (Trigo et al. 2004; Mariotti and Arkin 2007), as well as between SPI and NAO (Li et al. 2015; Bonaccorso et al. 2015), has been established in the past. For Crete, in Fig. 1, the variability of SPI12 (in meteorological station, Lagolio) and

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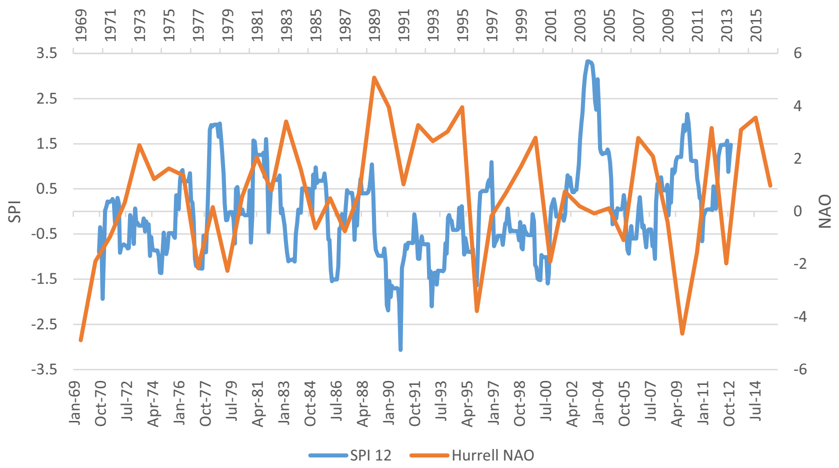

Fig. 1 SPI12 calculated in Lagolio station, Crete, and Hurrell station based NAO

the NAO (published by Hurrell and National Center for Atmospheric Research Staff 2016) is presented.

In a large number of drought events, the NAO signal is approximately the inverse of the SPI signal (for example the 1972–1976 and the 1988–1994 drought events). Therefore, it would be beneficial for the prediction of the annual precipitation and the magnitude of drought events to examine the behavior of the NAO index under climate change.

Moreover, southern locations (Lisbon and Gibraltar) have the advantage of yielding a stronger winter in December–January–February–March (DJFM) signal (Jones et al. 1997, Smith et al. 2014) due to the prolonged winter compared to the Azores region. However, for the rest of the seasons, the correlation between precipitation and NAO is significantly reduced, due to reduced rainfall events.

The importance of NAO in climate prediction has been highlighted even more over the last two decades. Numerous studies have used NAO to correlate climate and weather parameters to the difference in pressure in North Atlantic. In various studies (Smith et al. 2014; Munoz-Diaz and Rodrigo 2004; Trigo et al. 2002), the correlation between precipitation and NAO was performed, while the impact of NAO to hydrology has also been studied (Hurrell 1995; Vergni et al. 2016; Kahya 2011; Svensson et al. 2015). As reported in previous studies (Hurrell and Van Loon 1997; Krichak and Alpert 2005), there was a generalized negative correlation of NAO with precipitation in Southern Europe and a positive correlation in Northern Europe. An extensive historical review of the calculation methodologies of NAO was performed by Wanner et al. (2001).

The purpose of this study is to examine the relation between the winter NAO and precipitation using data from seven climate models following the + 8.5 W/m^2 representative concentration pathway (RCP), for two projected periods (2001–2050, 2051–2100). In the first part, a spatial distribution of the correlation between NAO and precipitation and its effects is performed throughout Europe. Preliminary results are presented in an EGU 2017 abstract by Tsanis and Tapoglou (2017). In the second part, an analysis is performed on specific locations. The purpose of this analysis is to compare the periods (years/cycle) of the NAO and the precipitation time series and examine when these two parameters coincide.

2 Spatial distribution analysis

In this part, the correlation between the DJFM NAO and precipitation is studied, both for the historical period (1951–2000) and the projected periods, 2001–2050 and 2051–2100, by using the results of climate models. The purpose of this study is to identify the correlation between precipitation variability and NAO variation in Europe. A set of seven climate models, from the EURO-CORDEX dataset was used in this process, all of which correspond to RCP 8.5 climate scenario.

2.1 Precipitation data

The data used both for mean sea level pressure and precipitation was the ones following the GCM/RCM combination models presented in Table 1.

Table 1 Climate models used in this study

GCM	RCP 8.5
IPSL-CM5A-MR	IPSL-INERIS-WRF331F
CNRM-CM5	CNRM-ALADIN53
MPI-ESM-LR-r2	CSC-REMO2009
MPI-ESM-LR	CLMcom-CCLM4-8-17
EC-EARTH	DMI-HIRHAM5
CNRM-CM5	SMHI-RCA4
ICHEC-EC-EARTH	SMHI-RCA4

The increase in precipitation between the three study periods is higher in the Northern part of Europe, while there is only a small decrease in precipitation in Southern Europe and the Mediterranean. For the mean values of the seven climate models, the variation in annual DJFM precipitation for the periods 2001–2050 and 2051–2100 compared to the historical period 1953–2000 are presented in Fig. 2.

2.2 DJFM NAO calculation

In order to calculate the DJFM NAO, the results of the seven climate models, using mean sea level pressure in Lisbon and SW Iceland, were used. Since the winter (DJFM), NAO is examined in this study; only the data considering the months December–January–February–March are used for the NAO calculation. The first step in the calculation of NAO is the normalization of the pressure values in each location separately, by subtracting from each value the mean of the time series and dividing with the standard deviation (Eq. 1).

$$\mathrm{Pr}_{\mathrm{norm}} = \frac{\mathrm{Pr} - \overline{\mathrm{Pr}}}{\sigma_{\mathrm{Pr}}} \qquad (1)$$

where $\mathrm{Pr}_{\mathrm{norm}}$ the normalized pressure, Pr the pressure, $\overline{\mathrm{Pr}}$ the mean pressure of the timeseries, and σ_{Pr} the standard deviation of the pressure timeseries.

The period for which the normalization parameters (mean and standard deviation) were calculated was the historical period (1950–2000). The parameters calculated are then applied to the two projected period time series (2001–2050 and 2051–2100). In this way, the NAO for the projected periods is calculated in relation to the historical one. The seven models studied have similar mean sea level pressure (MSLP) values in the separate locations. The MSLP between the models in SW Iceland is 99,547 ± 436 Pa while for Lisbon is 101,606 ± 190 Pa for the historical period. These values do not change significantly for the two projection periods.

NAO is calculated by subtracting the normalized pressure in Lisbon ($\mathrm{Pr}_{\mathrm{norm,\ Lisbon}}$) from the normalized pressure in SW Iceland ($\mathrm{Pr}_{\mathrm{norm,\ SW\ Iceland}}$), according to Eq. (2).

$$\mathrm{NAO} = \mathrm{Pr}_{\mathrm{norm},\mathit{Lisbon}} - \mathrm{Pr}_{\mathrm{norm,SW}\ \mathit{Iceland}} \qquad (2)$$

The mean and the 95 and 5% percentile of the calculated NAO using the seven climate models are presented in Fig. 3. The average standard deviation between the different NAO calculated varied from 0.5–0.8 and it is similar for all study periods.

The calculated by each climate model DJFM NAO and the published by Hurrell and National Center for Atmospheric Research Staff (2016) were compared next. The average RMSE between these values was 0.8, while the correlation between the seven calculated DJFM NAO and Hurrell NAO varied from 0.3–0.7. These differences can be attributed to three main factors. First and foremost, the calculated NAO in the present study DJFM NAO uses climate model data that vary significantly, while Hurrell NAO use data measured at

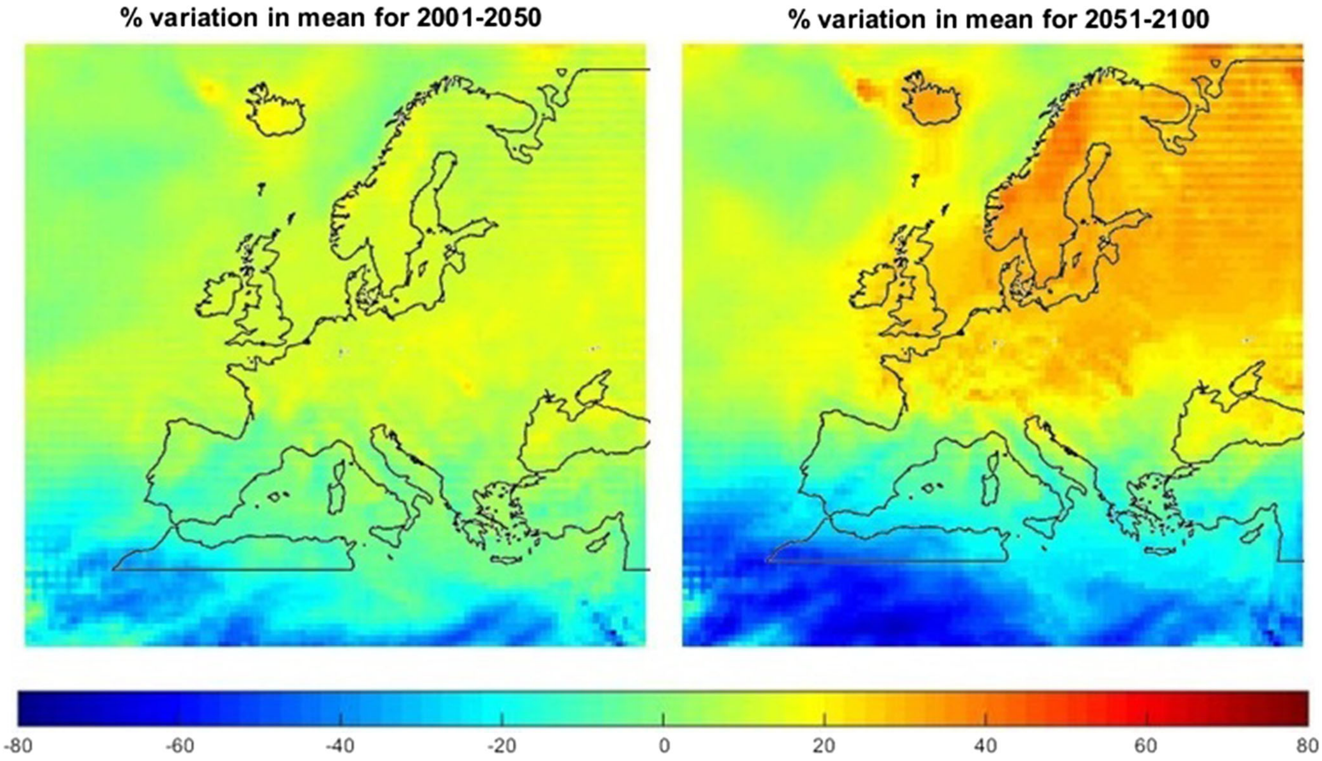

Fig. 2 Mean percentage variation of DJFM precipitation in Europe for 2001–2050 and 2051–2100 compare to 1953–2000

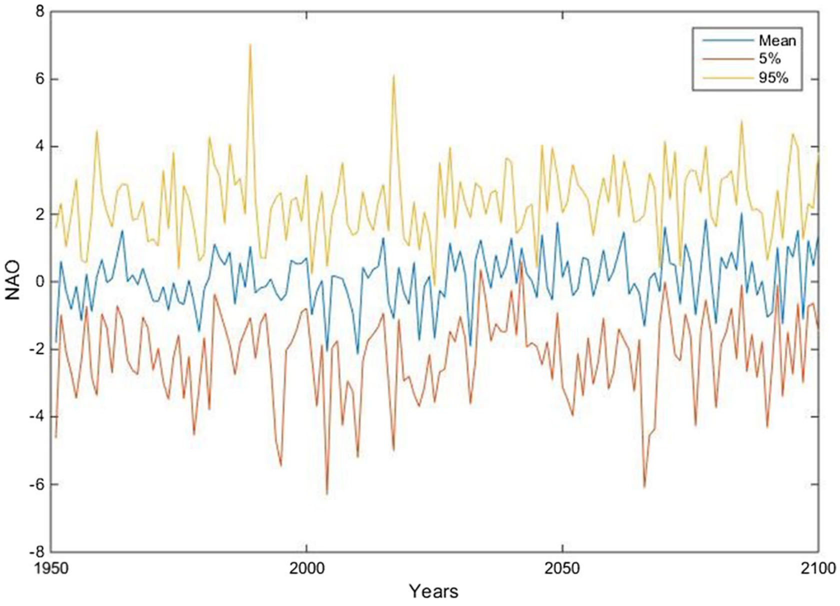

Fig. 3 Mean and the 95 and 5% percentile of the NAO calculated using seven climate models

the specific locations. The locations of the data that represent are different; NAO values calculated by Hurrell and National Center for Atmospheric Research Staff correspond to the difference between stations in Lisbon and Reykjavik; however, when using climate model data, the accuracy is averaged over the grid size. Finally, the normalization period is also different. Since the NAO values calculated by historical data and by climate model data are different, the climate model data used is also used for the historical period.

For the mean time series in Fig. 3, the statistical characteristics are presented in Table 2.

The results in Table 2 indicate that during the second and third period the number of years with positive NAO will increase. Moreover, in contrast to the historical period, the number of positive NAO years will be more than the negative ones. More specifically, in 1950–2000, 56% of the years had negative NAO. This percentage drops to 42 and 34% for 2001–2050 and 2051–2100, respectively. The average value of positive and negative NAO demonstrates an interesting pattern. While in 2001–2050, the number of negative NAO years is smaller than the period 1951–2000; the average value is lower, demonstrating that the negative values in 2001–2050 are stronger than the ones in 1951–2000. This pattern is not followed by the average positive NAO values, which constantly grow stronger.

The correlation between the DJFM NAO and the precipitation throughout Europe was studied next. Amongst the seven climate models studied, the correlation between precipitation and NAO varied slightly. Figure 4 shows the correlation between the DJFM NAO and the precipitation for the EC-EARTH/DMI-HIRHAM5 climate model, for the three study periods. One model is selected for the representation of the results since the mean of the seven models cannot depict correctly the correlation due to conflicting results in some grid cells.

The correlation between DJFM NAO and precipitation varied from − 0.8 to 0.9. In Northern Europe, the correlation between precipitation and DJFM NAO is positive, while in Southern Europe and mainly in the Mediterranean Sea the correlation is negative. In Central Europe, there is no significant correlation between the NAO and the DJFM precipitation. Moreover, while the correlation is similar between 1951–2000 and 2001–2050, it reduces significantly during 2051–2100, especially in the North-Eastern Europe.

In Northern Europe, where the correlation between NAO and precipitation is positive, the average DJFM precipitation

Table 2 Positive and negative NAO distribution for the three study periods

	Years with positive NAO	Percentage of positive NAO values	Years with negative NAO	Percentage of negative NAO values	Average values when NAO is positive	Average values when NAO is negative
1951–2000	22	44	28	56	0.553	− 0.49
2001–2050	29	58	21	42	0.56	− 0.81
2051–2100	33	66	17	34	0.76	− 0.66

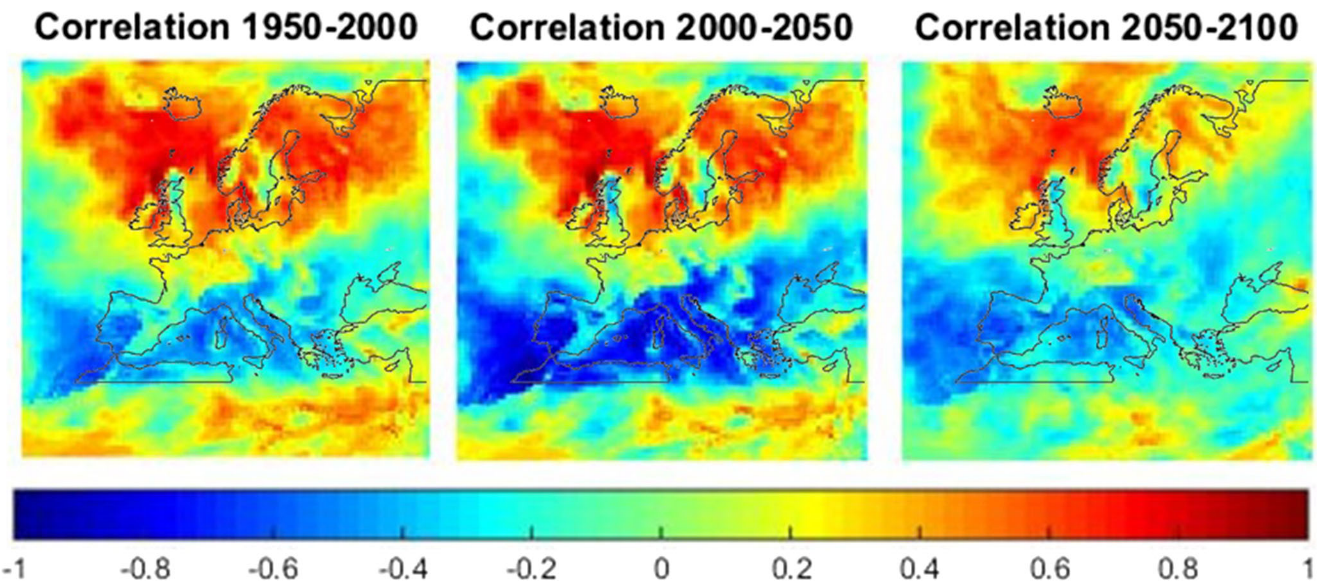

Fig. 4 Correlation between NAO and DJFM precipitation for the EC-EARTH/DMI-HIRHAM5 model

tends to increase throughout the years as a result of the increase of the NAO values (Table 2). In Southern Europe where the correlation between NAO and precipitation is negative, the precipitation decreases gradually. Similar results are derived for the remaining six climate models.

3 Precipitation-NAO analysis in three locations

Three locations where chosen to examine the connection between NAO and precipitation; the first one in Crete, Greece, the second near Madrid, Spain, and the third one near Oslo, Norway. The trend of precipitation in Spain is negative, in Norway positive, and in Greece is slightly negative.

3.1 The fast Fourier transform

By using the fast Fourier transformation (FFT), the time series of precipitation can convert to frequency space and can reveal their dominant periods of variation. Figure 5 shows the results of the precipitation in frequency space in years per cycle of the pattern of the precipitation for the three study periods and for the three locations. The results in Fig. 5 represent the mean of the seven models.

The FFT analysis for Spain indicates that the period of precipitation does not change significantly for the first two study periods, while for the third one, the dominant period moves to 3.3 years. In the case of Norway, the most significant period appears at about 4 years for the first and third study periods, while in the second study period (2001–2050), it appears to have much less power, with the most dominant period appearing in about 2.5 years. For Greece, the most significant period appears in about 3.5 years, with the exception of the third period where the largest peak appears at 2.1 years. The second largest period which is comparable to the one on the first two periods has moved to period of 4 years.

The same FFT analysis was performed to the mean NAO time series, constructed from the results of the seven climate models. The FFT analysis results are presented in Fig. 6.

The period with the maximum power appears at around 3.5 years per cycle for the first and the third study periods, while this peak moves to 3.1 years for the second study period. The FFT analysis for the NAO is in accordance with the one in Norway, where the correlation between NAO and precipitation is also high, while for Greece, the results are similar, especially for the second and third study period. On the contrary, in Spain, the FFT analysis has similar results only for the third study period. Cross-spectrum analysis between NAO and precipitation time series revealed correlation between 0.4–0.8 and best coherence between 3 and 4 years period for all locations and time periods. Higher correlation appeared for Norway and Greece, while Spain has a lower one.

3.2 Drought analysis

The SPI drought index is calculated in a monthly time step requiring data of at least 20–30 years. The calculation procedure follows the methodology developed by McKee et al. (1995) which consists of two main steps. First, the monthly data are fitted to a gamma distribution and then they are normalized, so that the mean value of the new time series is zero over a specified time period. In this work, when calculating the standardized indices, the gamma distribution is fitted to the data corresponding to the period (1951–2100) in order to compare the current conditions with the expected ones in future

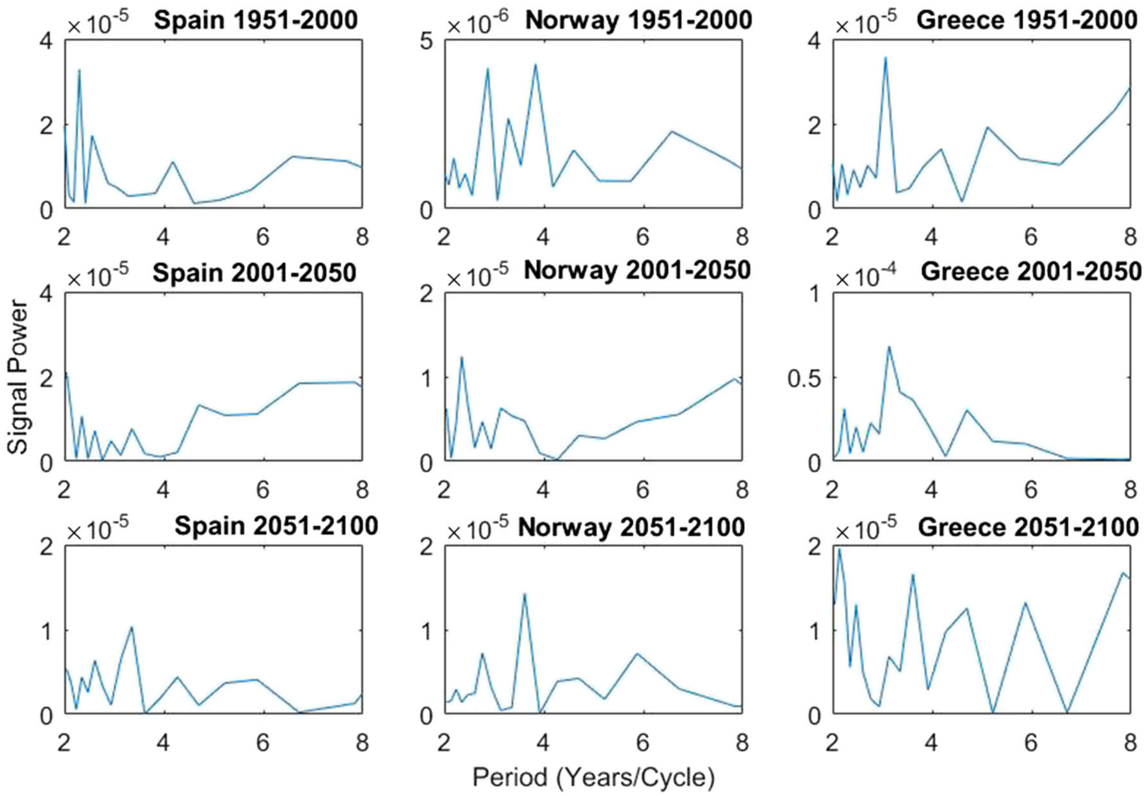

Fig. 5 FFT analysis on mean DJFM precipitation data in three locations for the mean values of the seven climate models

drought events. The index can be calculated for various time scales, representing different drought impacts to the system. In smaller time scales (3–12 months), the indices are used to describe short-term drought events that have a severe impact on the agricultural sector. In larger time scales (12–24 months), these indices are used in water management and climate study. The objective of this study is to examine the variation of extreme events with middle- and long-term duration under climate change; the 12-month time scale is used.

In the same locations (Norway, Spain, and Greece), the SPI 12 is calculated and the number of months with values < − 1 and < − 2 are presented in Table 3.

As the number of years with positive NAO increases, the number of months with drought (SPI < − 1) decreases in Norway and increases in Spain, while there is a slight variation in Greece. Moreover, the number of months with extreme drought conditions (SPI < − 2) follows a similar general trend, leading to increased number of months with extreme drought in Spain and decreased in Norway. While there is no direct link between the NAO variation and the SPI drought index,

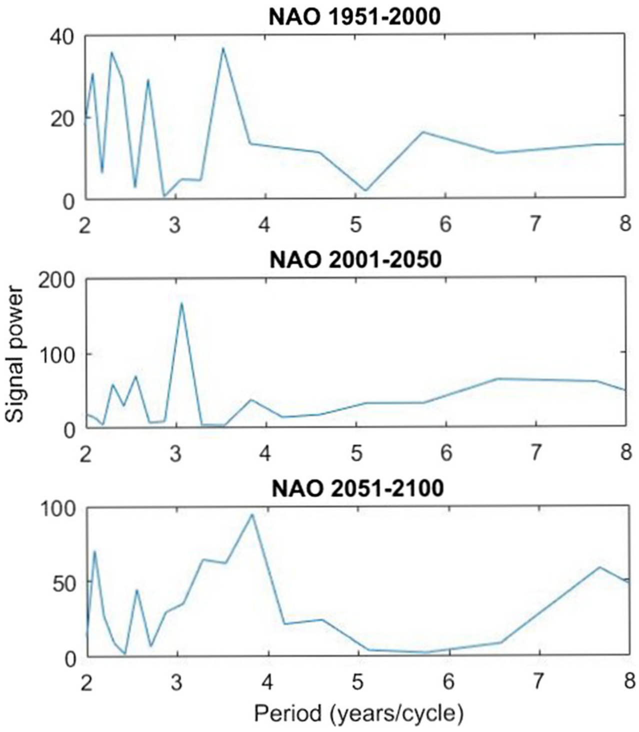

Fig. 6 FFT analysis of the mean NAO for the three study periods

Table 3 Number of months with SPI < − 1 and < − 2

	SPI < − 1			SPI < − 2		
	Norway	Spain	Greece	Norway	Spain	Greece
1951–2000	149	47	105	32	1	21
2001–2050	57	94	82	0	6	6
2051–2100	76	149	94	7	36	17

Table 4 Maximum number of consecutive months with SPI < -1 and < -2

	SPI < -1			SPI < -2		
	Norway	Spain	Greece	Norway	Spain	Greece
1951–2000	18	12	14	10	1	8
2001–2050	7	23	20	0	6	5
2051–2100	10	28	13	3	24	4

the above data indicate that there is a correlation between these two variables.

The maximum number of consecutive months with drought (SPI < -1) and extreme drought (SPI < -2) is also examined (Table 4).

The pattern is similar with the one described in Table 2. There is an increase in the maximum drought period in Spain; in Norway, there is a decrease, while in Greece, the number of consecutive months with SPI < -1 is approximately the same between 1950 and 2000 and 2051–2100. For extreme droughts (SPI < -2), the maximum number of consecutive months decreases in Greece and Norway, while in Spain, it increases drastically.

4 Conclusions

In this paper, the winter NAO was calculated using the precipitation and sea level pressure data from an ensemble of seven climate models following the RCP 8.5 scenario in order to study the correlation between the NAO and the precipitation in Europe. Next, the mean, 95 and 5% of the seven models, was determined and the mean NAO time series characteristics, such as the number of years with positive NAO, are calculated. For the mean NAO time series and for the second and third period, the number of years with positive NAO will increase. More specifically, in 1950–2000, 56% of the years had negative NAO. This percentage drops to 42 and 34% for 2001–2050 and 2051–2100.

For all time periods and all climate models studied, the correlation followed the same pattern, where in Northern Europe, there was a high positive correlation and in the Southern Europe, the correlation was negative. However, during the last study period (2051–2100), the correlation dropped from high positive to positive in the North-East Europe.

In the last part of this study, a FFT analysis was performed in three distinct locations, in Spain, Norway, and Greece. In this case, the mean precipitation and the mean NAO time series were used. When comparing the FFT signal between these locations and the corresponding NAO signal, there was an overlap in the period of the climate pattern in most cases. More specifically for Norway, where the correlation between NAO and precipitation is high, the precipitation and the NAO had the signal power in the same period. In Greece, these two signals were in fair accordance, but in Spain, where the correlation between NAO and precipitation is lower, the signals are similar only for the third study period.

There are also indications that the NAO is linked to the drought events in the three locations. As the number of years with positive NAO increase, there is a decrease in drought events and maximum period in Norway and an increase in Spain. In Greece, there is no significant negative or positive trend in the drought events and periods.

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