

STUDY OF THE NORTH ATLANTIC OSCILLATION
INFLUENCE ON THE CLIMATE OF EUROPE
AND BALKAN PENINSULA

Tsvetelina Velichkova[✉], Natalya Kilifarska, Antonia Mokreva

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Abstract

Numerous climate studies have shown that the North Atlantic Oscillation (NAO) has a significant influence on weather conditions in Europe. Regarding the impact of the NAO on the climatic variables over the Balkans, there is a divergence of opinions among contemporary publications. The contradictory results can be attributed to several factors that make the climate of the region complex and multifaceted.

This research focuses on the analysis of surface pressure and wind variability at 850 hPa, as a function of the sign and value of the NAO index, in a dense network of data provided by ERA 5, for the period 1940–2023. Using an artificial neural network, we show that: (i) the high sensitivity of northwestern Europe and the Mediterranean to NAO values is confirmed by our analysis; (ii) the impact of moderately negative NAO values is small in the Balkan region; (iii) the NAO values below the 2σ level have a significant impact on the Balkan Peninsula, due to the activation of Mediterranean cyclones.

Key words: North Atlantic Oscillation, sea level pressure, horizontal winds, climate variability

Introduction. Atmospheric circulation is of significant importance to variations of temperature and precipitation in Europe, particularly in winter [1,2]. Atmospheric dynamics' variability is highly related to the North Atlantic Oscillation (NAO), which offers a framework for understanding the dynamics of atmospheric

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conditions in this region. According to the principal component analysis-based definition, the NAO is the leading empirical orthogonal function describing the pressure anomalies over the Atlantic sector (20° – 80° N, 90° W– 40° E). According to the station-based definition, the NAO mode reflects the pressure difference between the subtropical Azores and the subpolar region around Iceland.

The NAO index, which ranges from positive to negative, is the measure of the intensity of the NAO phases. Higher than usual pressure over the Azores or abnormally low pressure over Iceland (corresponding to positive values of the NAO index) amplifies the meridional circulation (from the tropical higher to the polar lower pressure), which gradually turns eastwards due to the action of the Coriolis force. This northward shift of the transport of the wetter Atlantic air masses makes winters over England and Scandinavia milder and snowier. At the same time, winters in the Mediterranean region are drier and colder than usual.

Conversely, the weakening of high pressure over the Azores and low pressure over Iceland corresponds to the negative phase of the NAO, making winters in northern Europe drier and colder, while in southern Europe and the Mediterranean are milder and wetter.

The NAO's impact on the temperatures over Europe is a subject of extensive research [1, 3]. BAKER et al. [4] have indicated a possible correlation between spring sea surface temperature anomalies and the summer NAO. DROUARD et al. [5] discovered that the positive phase of the mode and a wave-7 pattern contributed collectively to the anomalous increase in temperature in the north-western European region. LI et al. [6] have examined the connection between a European blocking event and consecutive North Atlantic Oscillation positive events, particularly in the context of two intense heatwaves that occurred in July and early August of 2018. Their analyses indicate that the combined effect of blocking events and positive NAO index could increase the frequency, persistence, magnitude, and extent of heat waves over Europe.

The results of observational studies have shown that the NAO has a significant impact on winter precipitation. HURRELL [1] has found that the correlations were positive in the northern region and negative in southern Europe. Other researchers have also reported a notable positive correlation in north-western Europe, while a negative correlation has been identified over South Europe [7]. KANG et al. [8] have analyzed the effect of NAO on the precipitation in Europe and North Africa by using a nonlinear vector autoregressive model augmented with an exogenous variable. Their study has shown that monthly rainfall has either increased or stayed the same in northern and western Europe, and stayed the same or decreased in the south.

The NAO mode can be considered the result of joined fluctuations of the intensity and direction of the Atlantic storm tracks and the eddy-driven jet [9]. SERREZE et al. [10] have demonstrated the existence of considerable dissimilarity in cyclone activity between winters with different sign of NAO indices. It has

been observed that the intensity of cyclone activity over the North Atlantic is amplified during periods in which the NAO index is positive. In addition, a poleward shift of cyclones has been noticed [11]. This general pattern is confirmed in [12]. ROGERS [13] has observed a north-eastward position of the primary North Atlantic cyclone path while the atmospheric mode is in its positive phase. This direction coincided with the North American east coast, with the cyclone reaching its maximum intensity slightly south of the climatological Icelandic low. In the negative phase, the orientation is indicative of a predominant eastern-western alignment, with a centre positioned approximately at 45°N of latitude.

A number of studies have been conducted to determine the correlation between wind and the North Atlantic Oscillation across Europe. The findings of PRYOR et al. [14] revealed substantial increases in wind speed during the mid- to late 20th century. This period is characterised by the predominant positive NAO. DICKSON et al. [15] observed shifts in wind conditions during the transition from the highly negative phase in the 1960s to the highly positive phase in the beginning of the 1990s. IVERSEN and BURNINGHAM [16] have employed a wind rose analysis and ascertained that south-western winds exhibited a positive correlation with the winter NAO index, while north-easterly winds demonstrated a negative correlation. These findings are in line with the assumption that the positive NAO phase is associated with an enhancement of wind frequencies from the southwest and a decrease from the northeast (see [17]).

Conversely, conclusions regarding the influence of the NAO on climatic variances over the Balkans are contradictory. Furthermore, considering the spatial irregularity of pressure systems, we were curious as to the extent to which sea-level pressure over the European continent, particularly the Eastern Mediterranean and the Balkans, could be attributed to NAO variability. It is reasonable to expect the effects of the NAO to fade with increasing distance from the Atlantic region. However, we expected to identify a threshold of NAO values indicative of the activation of Mediterranean cyclones, which frequently affect the Balkans. If successful, this could pave the way for future synoptic prediction.

Data. The wind and pressure data in this study are obtained from ERA-5 for the period 1940–2023 (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download>). The mean monthly values of sea level pressure and two horizontal wind components (U, V) at 850 hPa are used in this analysis. We have focused on the region with coordinates 30°N–70°N latitude and –30°W–60°E longitude in order to estimate the strength of the NAO influence on the surface pressure and winds variability with space and with the NAO phase.

In order to reduce the within-group variability, the atmospheric pressure and wind data have been divided into two subsamples corresponding to the phase of the NAO – positive or negative. These composite records were then analyzed for their temporal synchronization with the corresponding NAO subsamples. The

analysis focuses on the cold season, covering the months between November and April. The present study investigates also the deviations of the surface pressure and winds at 850 hPa from the dynamically varying mean, which was calculated for each 10-year period from 1940 to 2023. Such an approach has been motivated by the non-stationarity of the climatic data records.

For the purposes of this analysis, the NAO index, provided by the Climatic Research Unit at the University of East Anglia (<https://crudata.uea.ac.uk/cru/data/nao/>), was utilized. Due to the fact that the NAO influence on climatic variables is stronger during the cold season, the record used for further analysis consists of the corresponding monthly values for the period November – April, taken in each year.

Methods. We have used the artificial neural network (ANN) regression technique to detect the possible non-linear relations between lower stratospheric ozone and sea level pressure. The ANN, with its ability to detect non predefined relations such as nonlinear effects and/or interactions, is more flexible than any other method using a fixed function for statistical modelling. In addition, ANN does not require explicit distributional assumptions (such as normality). We have used ANN belonging to the class of a *supervised* machine learning, which includes a phase of initial “training”. By default, the training is performed on 2/3 of the entire data record. The rest of the data (not involved in the training process), are used for a validation of the created model.

Generally speaking, the neural network transforms a set of input variables into a set of output ones, performing in such a way mappings between two sets of variables, i.e. $\mathbf{X} = (X_1, X_2, X_3, \dots, X_N)$ and $\mathbf{Y} = (Y_1, Y_2, Y_3, \dots, Y_M)$. The precise form of the function, which maps $\mathbf{X}$ on $\mathbf{Y}$ is determined by the internal structure of the neural network (i.e. number of neurons and hidden layers, activation functions, etc.), and by the values of parameters called *weights* $\mathbf{w} = (w_1, w_2, \dots, w_t)$. The process of determining these parameters’ values is often called learning or training. The neural network mapping is then written as:

$$(1) \quad \mathbf{Y} = f(\mathbf{X}; \mathbf{w})$$

which denotes that $\mathbf{Y}$ is a function of $\mathbf{X}$, being itself parameterized by $\mathbf{w}$ [18].

In this analysis we have used two of the most popular neural network architectures, i.e. *multilayer perceptron* (MLP) and the *radial basis function* (RBF). MLPs are general-purpose, flexible, nonlinear models that can approximate virtually any function to any desired degree of accuracy, in the case of enough hidden neurons and enough data. MLPs can be used when the knowledge about the form of the relationship between the independent and dependent variables is quite uncertain.

The other type of activation functions – the radial basis function (RBF) – is particularly useful for solving **nonlinear problems** by approximating complex relationships in the data, including pattern recognition. Unlike traditional feed-

forward neural networks, RBF networks are focused on *local regions* of the input space, which are close to neuron centres in the hidden layers.

The most suitable model (among the bulk of outputs, provided by the artificial neural network) is chosen through optimisation between the following criteria: (i) maximisation of model's performance (i.e. regression coefficients) derived for each of the training and testing subsamples, and (ii) minimisation of model's error of both samples.

Results. Figures 1 and 2 present the surface pressure deviations from the dynamically varying mean during the period 1940–2023 in dependence of the strength and phase of NAO index. Both figures show in addition the vector fields of the horizontal wind. Besides the size of the vectors (illustrating wind direction

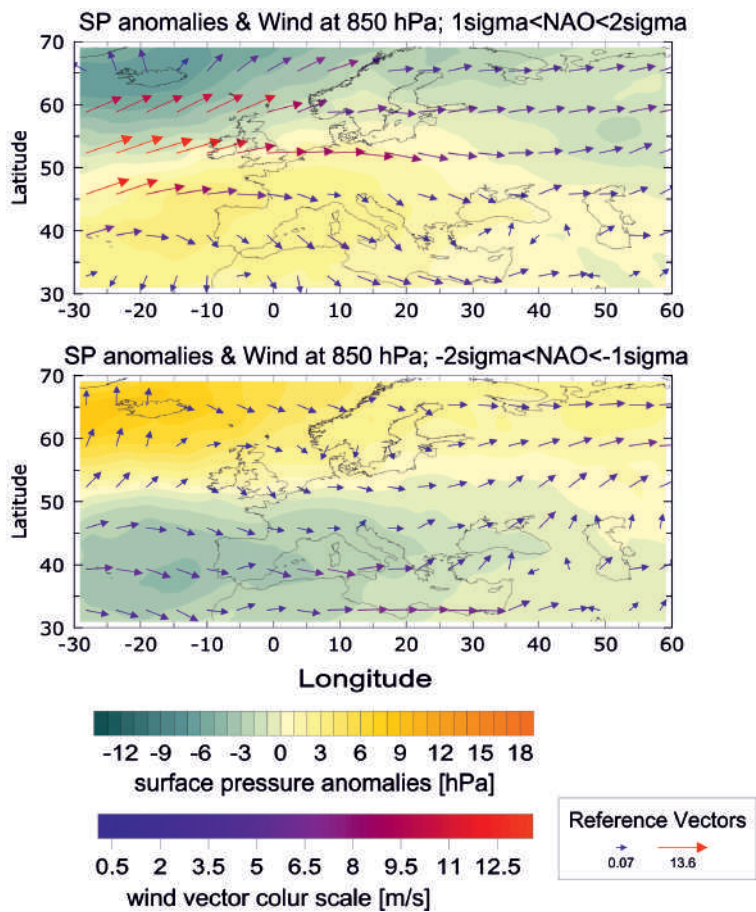


Fig. 1. Spatial distribution of the sea level pressure anomalies and horizontal wind vectors at 850 hPa, corresponding to moderate NAO values between $\pm 1\sigma$ and $\pm 2\sigma$. Wind direction is indicated by vector orientation, while the wind speed is shown by colour (from blue for weak winds to red for strong winds). Note that the spatial distribution of positive and negative pressure anomalies are opposite during different NAO phases

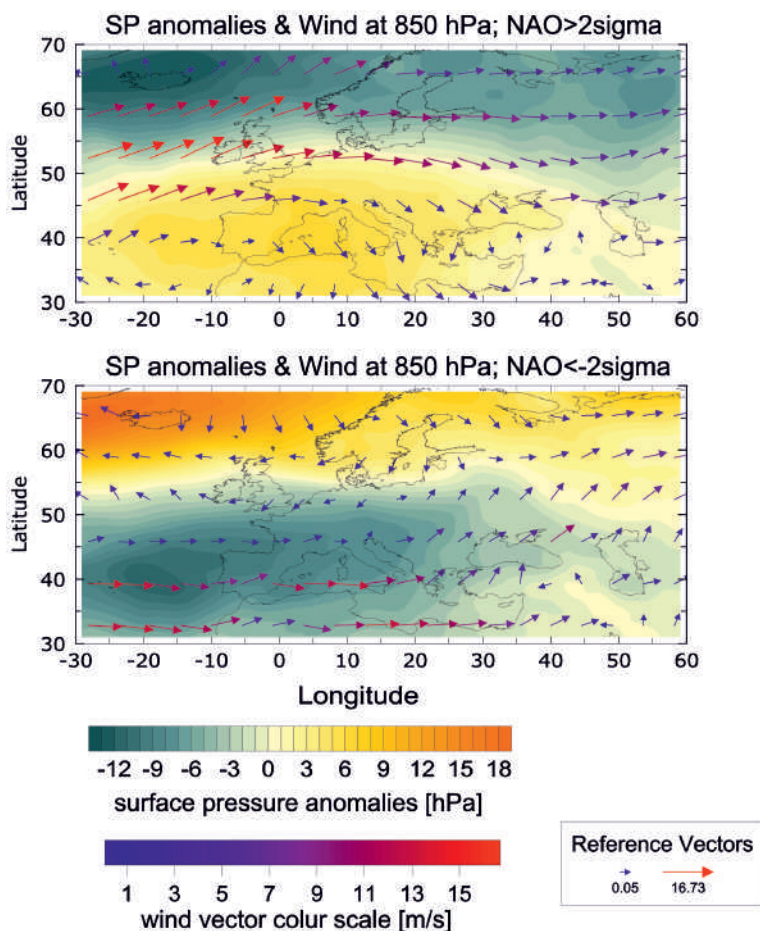


Fig. 2. Spatial distribution of the sea level pressure anomalies and horizontal wind vectors at 850 hPa, corresponding to strong NAO values (exceeding $\pm 2\sigma$). Note the stronger latitudinal gradient of pressure anomalies and intensification of circulation over Northern Europe or Mediterranean, depending on the NAO phase

and speed), the different wind strength is represented by the colour scale varying between blue (light wind) and red (strong wind).

The spatial distribution of anomalous pressure and horizontal winds corresponding to NAO variations in the range ± 1 – ± 2 standard deviations (σ) is presented in Fig. 1. On the other hand, Fig. 2 illustrates the distribution of these anomalies in cases where NAO values exceed ± 2 standard deviations. Comparison of the two figures shows that, in general, the configuration of the ground pressure anomalies is maintained. Positive NAO values are characterized by positive pressure anomalies at latitudes below 50° – 55° N and negative at higher latitudes. Negative NAO values are in turn accompanied by negative anomalies at low latitudes and positive anomalies at high latitudes. However, the latitudinal gradient

of pressure anomalies is much stronger for NAO anomalies exceeding $\pm 2\sigma$ deviations from its long term record's mean.

The North Atlantic Oscillation undoubtedly influences the climatic characteristics of northern Europe and the Mediterranean. However, what is its influence on the Balkans, and Bulgaria in particular, is still a matter of debate. Some authors find no or weak connection [19], others find a significant relation of surface pressure, circulation and precipitation with the NAO [20].

The maps of anomalous pressure and winds show that as the NAO becomes more positive (Fig. 1, 2), the north-eastward transport – from the Atlantic to the Nordic countries and northern Europe – intensifies. On the other hand, with a strengthening of the negative NAO values, the Atlantic transport over the Mediterranean and northern Africa is enhanced.

The quantification of the relationship between the NAO and the surface pressure variations has been the subject of neural network analysis. The essence of the method lies in modelling the variation in surface pressure with time as a function of NAO variability. The analysis was conducted at each grid point with a resolution of one degree in latitude and longitude, and then the correlation coefficient between the model and measured pressure values was calculated for the period 1940–2023. The results of the analysis are presented in the form of correlation.

The correlation map illustrating the relationship of pressure with positive NAO values shows a relatively low degree of connectivity between them (i.e. less than 0.5) – over the Atlantic, England and all northern Europe (Fig. 3). Pressure over the eastern Mediterranean and Black Sea region, Asia Minor and the Middle East is also practically unrelated to positive values of the North Atlantic Oscillation. On the other hand, the variations of the surface pressure are fairly well synchronized with the positive NAO values over Iceland and the central Mediterranean (Fig. 3).

The relationship of surface pressure with negative NAO values is shown in Fig. 4. It can be seen that the centres of moderate and strong connectivity – visible in Fig. 3 – have moved over Western Europe (from its former position over the central Mediterranean), and southeast of Iceland (Fig. 4), respectively, with the one over Spain being dominant. In addition, over Central and Eastern Europe, the Black Sea and the Caspian regions, there is a band in which the surface pressure is substantially synchronized with the negative values of the North Atlantic Oscillation.

Analysis of the vector fields corresponding to positive and negative NAO values shows that, regardless of the sign of the NAO, the main west-to-east transport occurs through areas where the surface pressure is not, or is weakly, controlled by the North Atlantic Oscillation (red arrows). Figure 3 shows that in case of positive NAO values, the Balkans are weakly influenced by the west-eastern transport passing much further north. This is mainly due to the Alps and Carpathians, which strongly modify the direction and strength of the wind in the southernmost

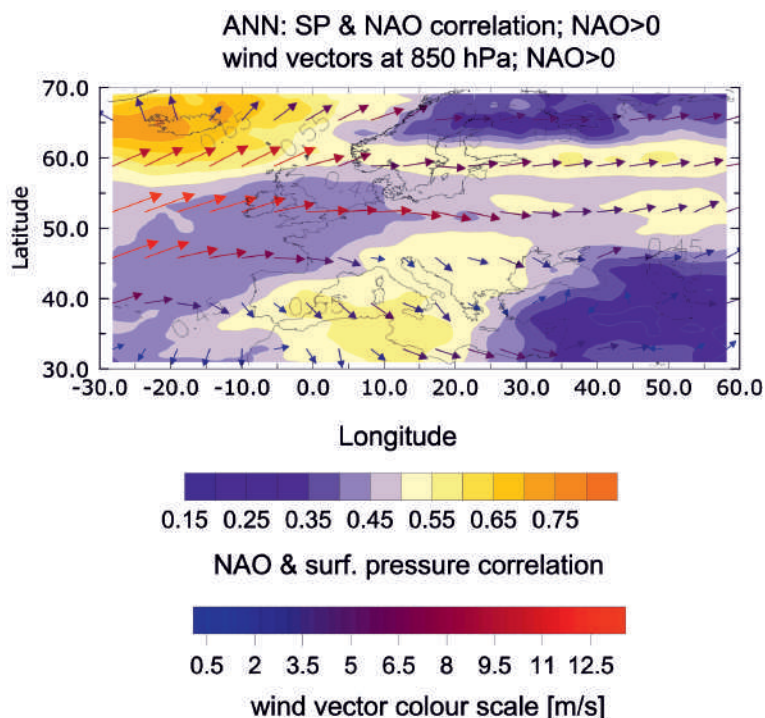


Fig. 3. Correlation map between modelled and observed sea level pressure values during positive NAO phases (1940–2023). Regions with correlation coefficients above 0.5 indicate strong synchronization between NAO and local pressure variability. The highest in-phase synchronicity is found only over Iceland and the central Mediterranean. Coloured arrows indicate the mean wind direction at 850 hPa corresponding to the positive NAO phase

part of the trajectory of the Atlantic moist air masses transported eastward. In cases of negative NAO values, the main transport from the Atlantic takes place over the Mediterranean. This influence reaches Greece and often affects Bulgaria in the form of Mediterranean cyclones.

Conclusions. The spatial patterns of pressure and horizontal wind anomalies support the general understanding that the winter circulation over Europe is closely related to the variability of the pressure gradient between Ponta Delgada and Reykjavik (according to the UEA data set).

In addition, the quantitative analysis of the relation between the sea level pressure and the NAO (by using the method of artificial neural networks) shows that the synchronization in their temporal variability is not evenly distributed in space.

Thus, during the positive phase of the NAO, the correlation between the modelled (as a function of the NAO) and the measured pressure records is greater than 0.5 in only two regions – Iceland and the central Mediterranean (see Fig. 3). The negative NAO phase, on the other hand, is characterized by a larger region

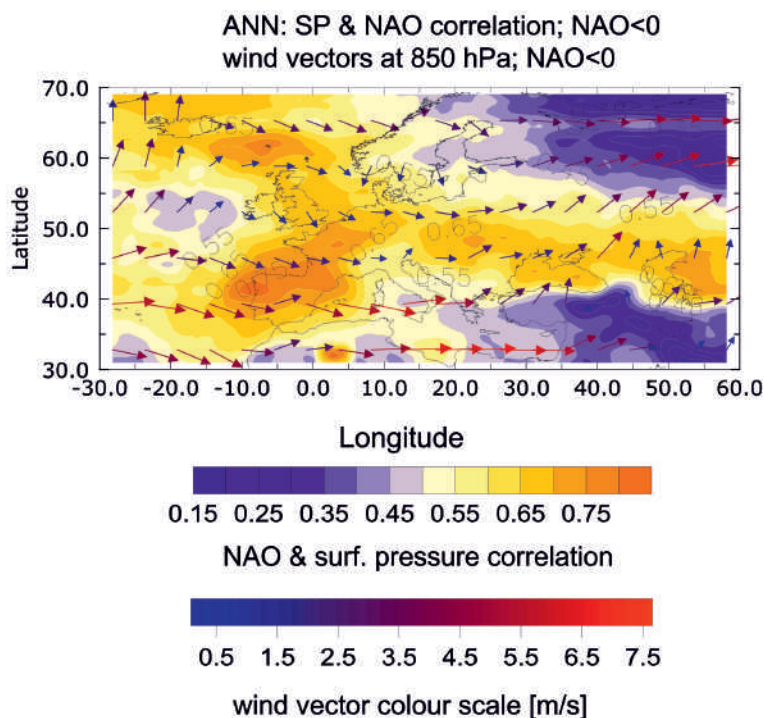


Fig. 4. Correlation map between modelled and observed sea level pressure values during negative NAO phases (1940–2023), with overlaid wind vectors at 850 hPa. Note the broader region of strong in-phase synchronization (correlation > 0.5) between NAO and sea level pressure. The dominant wind transport is shifted southward, enhancing Mediterranean cyclone activity that affects Southeastern Europe

of close synchronization between NAO and sea level pressure with a correlation coefficient much higher than 0.5 (see Fig. 4). The region of strong synchronicity has the shape of a bow (from Portugal and Western Europe to the island of Iceland). It stretches across Europe like an arrow reaching the Caspian Sea.

On the other hand, weakly negative NAO values (i.e. between -1σ and -2σ) do not or only weakly influence the pressure field over the Balkans. For NAO values lower than -2σ , the Balkan Peninsula enters the NAO influence zone, manifested by the activation of Mediterranean cyclones.

In conclusion, monitoring the temporal variability of the NAO index could be a useful indicator for medium-range forecasting of intense precipitation and storm events during the cold season.

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*Climate, Atmosphere and Water Research Institute, Bulgarian Academy of Sciences,
66 Tsarigradsko Shosse Blvd, 1784 Sofia, Bulgaria*
e-mails: tsvetelinavelichkova@abv.bg, natalyakilifarska@gmail.com,
antmokreva@gmail.com