

## NORTH ATLANTIC OSCILLATION AND VARIATIONS OF GEOMAGNETIC FIELD

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### Abstract

The North Atlantic Oscillation is one of the most influential climatic modes in the Northern Hemisphere. However, the mechanism(s) standing behind its wide spectra of variations is still unknown despite its numerous investigations. This paper presents evidence for a synchronization between secular variations of geomagnetic field intensity and NAO long-term variability. Analysis of the connectivity between geomagnetic secular variations and the sea-level pressure – point by point, in a grid with resolution 10 [deg] in latitude and longitude – reveals that the strength of their relation is unevenly distributed over the Northern Hemisphere. Based on the machine learning analysis over the period 1900–2019, we found that there are two centres of significant geomagnetic-pressure relations – the weaker of them is placed slightly north of Iceland, and the stronger one is in a close proximity to Azores islands. The suggested mechanism for geomagnetic influence on the near surface climatic conditions includes the geomagnetic modulation of energetic particles precipitating in Earth's atmosphere, and their impact on the lower stratospheric ozone. The analysis of ozone–pressure relation shows, in addition, reasonable similarities with the spatial patterns of geomagnetic-pressure relations.

**Key words:** North Atlantic Oscillation, sea-level pressure, geomagnetic field, lower stratospheric ozone

**Introduction.** The North Atlantic Oscillation (NAO) describes the pressure variations between subtropical Azores islands and sub-polar Icelandic region. The

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higher than usual pressure over the Azores or abnormally low pressure over Iceland (positive NAO) favours the intense meridional circulation, which is gradually turned east, due to the Coriolis force action. The poleward shift of the mid-latitude westerly winds, and their intensification, brings the wetter air masses from the Atlantic over northern Europe, making the winters milder and snowy. At the same time the winters in the Mediterranean region are drier and cooler. The weakening of Azores high and Icelandic low pressure corresponds to the negative phase of NAO – making the winters in northern Europe drier and colder, while southern Europe and Mediterranean are milder and wetter.

The examination of pressure fluctuations over Azores and Icelandic regions reveals that they are fairly well synchronous. Figure 1a presents the smoothed winter pressure variations in Ponta Delgada (Azores) and Reykjavík (Iceland) during the period 1900–2022. Such a synchronisation motivates some authors to suggest that NAO mode fluctuates between its *positive* and *negative* phases. The fluctuations are irregular and could be observed on annual basis, as well as at longer time scales – decades, centuries, etc.

The reasons for NAO variability have been sought in (i) the amount of ice deposited in the Barents and Kara seas [<sup>1,2</sup>], in (ii) quasi-periodic 11-year solar magnetic cycle [<sup>3,4</sup>], in (iii) explosive volcanic eruptions – tossing a great amount of sulphur dioxide (SO<sub>2</sub>) in the atmosphere [<sup>5</sup>], etc. The mechanism of influence of all these factors on the NAO phase relies on the assumption of changes in atmospheric zonal circulations initiated by the mentioned factors [<sup>6</sup>].

The variations in the low stratospheric ozone – projected down to the surface (through an imposed variability on the near tropopause temperature and humidity [<sup>7</sup>]) – are able to change the near surface temperature and pressure. Thus the ozone-NAO covariance, reported by [<sup>8</sup>] could trigger the phase transition between positive and negative phases of NAO. In this case the question is: Who is the driver of the lower stratospheric ozone's variations?

Previous investigations discover that the ozone in the lower stratosphere is strongly influenced by galactic cosmic rays, and more precisely by the low energy electrons in the secondary ionisation layer created by them in the lower stratosphere, known as Regener–Pfotzer maximum [<sup>9</sup>]. The spatial distribution of the latter is controlled by the heterogeneous structure of geomagnetic field intensity, which focuses or defocuses energetic particles in certain regions over the globe [<sup>10</sup>]. This motivates us to explore the possibility for existence of statistical relations between geomagnetic secular variations, NAO index, and sea-level pressure.

**Data and methods.** For the description of North Atlantic Oscillation mode (NAO) we have used the NAO index, provided by the Climatic research unit within the University of East Anglia <https://crudata.uea.ac.uk/cru/data/nao/>. We have used a record of seasonal NAO values – calculated as mean of monthly NAO values for the period November–April. Then the seasonal time record has been

standardised through extraction of records mean and normalisation on the record's standard deviation.

This study is focused on the geomagnetic variability associated with the source of the geomagnetic field in the Earth's core. One type of the variations of internal geomagnetic field is the secular variations of the total geomagnetic field intensity (SV), generated at the core-mantle boundary. They have been derived from the International Geomagnetic Reference field model (IGRF-13), calculated for each 5-year interval. This means that at annual basis the SV are a step-like function, which has been smoothed by 5-point moving average procedure.

The sea level pressure and the ozone mixing ratio at 70 hPa are taken from two models of ECMWF – i.e. ERA 20 century (covering the period 1900–2010), and ERA Interim (applicable since 1979 up to 2019) <https://apps.ecmwf.int/datasets/>. Both reanalyses have been merged at the year 2000. The merging procedure includes an equalisation of decadal means of both reanalyses, for the period 2001–2010. This procedure ensures a smooth transition between both reanalyses, avoiding the step-like changes between their means. Monthly records of all atmospheric variables have been derived in a grid with 10 deg step in latitude and longitude. The winter seasonal data have been calculated from corresponding monthly values during the period December–March for each year. The variability of atmospheric variables is much stronger (compared to geomagnetic SV) and requires more substantial smoothing to reveal their long-term variations. So the atmospheric data have been smoothed by 11-year moving window.

The statistical relations between geomagnetic field and atmospheric variables have been estimated by the use of classical cross-correlation method as well as by two non-parametric techniques of the *machine learning* analysis – i.e. support vector machine (SVM) and artificial neural networks (ANN). The non-parametric models generally make no assumptions regarding the relationship of  $\mathbf{X}$  and  $\mathbf{Y}$ . In other words they assume that the true underlying function governing the relationship between  $\mathbf{X}$  and  $\mathbf{Y}$  is not known a priori, hence the term black box. Instead, they attempt to discover a mathematical function (which often does not have a closed form) that can approximate the representation of  $\mathbf{X}$  and  $\mathbf{Y}$  sufficiently well.

The SVM belongs to the subsection of the supervised machine learning (i.e. controlled self-learning) and includes initial “training” of the program – by default on 2/3 of the entire data record. On the rest of the data (not involved in the training process), it is checked to what extent the already trained program is able to describe the dynamics of changes in the real data. The SVM can be used to solve two problems: (a) classification of objects with different characteristics and (b) regression, i.e. finding the functional dependence of the variable  $\mathbf{Y}$  on a group of independent variables  $\mathbf{X}$ . Like any regression problem, the functional dependence of the dependent variable on the independent ones is described by the

following function:

$$(1) \quad \mathbf{Y}(X_i) = f(X_i) + \text{noise}.$$

The task is then to find a functional form  $f(X_i)$  that can correctly predict new cases not used in the training procedure.

SVM uses a group of mathematical functions called kernels. The role of the kernels is to transform the input data into a required form. Different SVM algorithms use different types of kernel functions  $\varphi$ , such as: linear, nonlinear, polynomial, radial basis function (a real function whose values depend only on the distance to some fixed point), and sigmoid (a mathematical function whose graph resembles the shape of the letter S). In our analysis, we used an algorithm based on the Gaussian radial basis function described by the formula:

$$(2) \quad \varphi(X_i) = \exp(-\gamma|X_i - X_j|^2),$$

where the positive constant  $\gamma$  is often expressed as  $\gamma = 1/(2\sigma^2)$  ( $\sigma$  is the standard deviation of the data record). It is the most commonly used type of kernel function when we do not have a priori knowledge, since its values are bounded over the entire range of the real x-axis of this function. The learning process involves successive optimization of the error (i.e., the deviation of the model from the real input data) described by the equations

$$(3) \quad \mathbf{w}^\top \varphi(X_i) + b - Y_i \leq \varepsilon + \vartheta_i^*$$

$$(4) \quad y_i - \mathbf{w}^\top \varphi(X_i) - b \leq \varepsilon + \vartheta_i; \quad \vartheta_i, \vartheta_i^* \geq 0 \quad \text{for } i = 1, 2, \dots, N,$$

where  $\mathbf{w}$  is the vector of coefficients,  $b$  is a constant,  $\vartheta_i, \vartheta_i^*$  are input control parameters. The index  $i$  denotes the number of training data and  $X_i$  are the independent variables.

A neural network can be regarded as a non-linear mathematical function which 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  $\mathbf{X}$  to  $\mathbf{Y}$  is determined by the internal structure of the neural network (i.e., the topology and the choice of activation functions), and by the values of a set of parameters called weights ( $w_1, w_2, \dots, w_t$ ). The process of determining these parameters' values is often called learning or training.

The neural network mapping is then written in the form

$$\mathbf{Y} = \mathbf{Y}(\mathbf{X}; \mathbf{w}),$$

which denotes that  $\mathbf{Y}$  is a function of  $\mathbf{X}$ , being itself parameterized by  $\mathbf{w}$  [11]. We have used two of the most popular neural network architectures – i.e. multilayer perceptron (MLP) and the radial basis function (RBF).

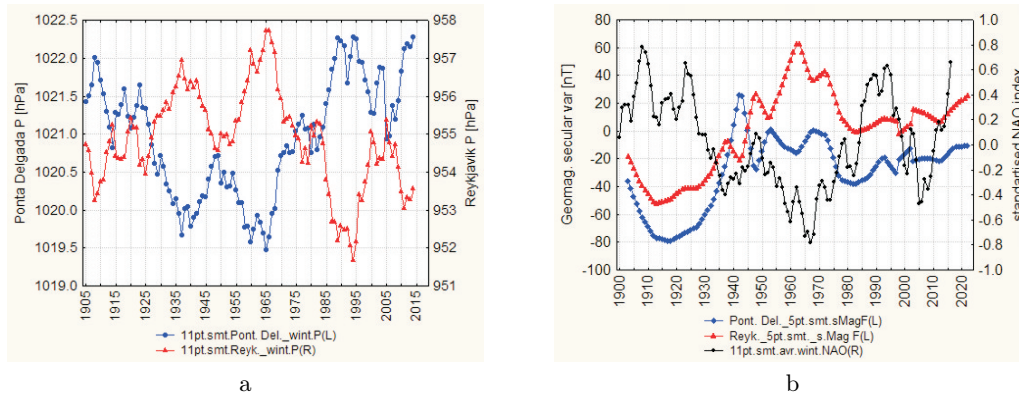


Fig. 1. Time series of winter sea-level pressure (P) at the two centres of action of NAO – Ponta Delgada – blue curve, and Reykjavík – red curve (left panel), and geomagnetic field's secular variations (annual values) – right panel. The black line presents temporal variation of winter NAO index, within the period 1900–2022. Pressure data and NAO index are smoothed by 11 year moving window, while geomagnetic variations – by 5 point window. Data source: European Centre for Middle range Weather Forecast <https://apps.ecmwf.int/datasets/> and University of East Anglia <https://crudata.uea.ac.uk/cru/data/nao/>

The most suitable model (among the bulk of possibilities, 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 training and testing subsamples, and (ii) minimisation of model's error of both samples.

**Geomagnetic–NAO relations.** Synchronicity in changes of the sea level pressure over Azores and Iceland islands is known since 1770, when the Danish priest and missionary Hans Egede Saabye has noticed it. Later on, in the 1920s, the British climatologist Sir Gilbert Walker called it the North Atlantic Oscillation. The Azores and Icelandic regions have been named by some authors “centres of action” of NAO climatic mode.

The interaction of geomagnetic field with all Earth's shells – i.e., the atmosphere, the biosphere, Earth's crust, mantle and core – motivates some scientists to suggest an existing relation between geomagnetic field variability and changes in climatic variables [12–14]. Examination of geomagnetic secular variations in Ponta Delgada and Reykjavík reveals that they are very similar (see Fig. 1b), unlike the temporal variations of sea-level pressure at both stations (Fig. 1a). On the other hand, the comparison of geomagnetic field and the long-term NAO variations with time, show well pronounced covariance in antiphase (see Fig. 1b). This is a hint that if geomagnetic field has some influence on NAO mode, it certainly is not a direct impact.

The correlation coefficients of geomagnetic variations at Ponta Delgada and Reykjavík with NAO index (statistically significant at 95% level) are shown in

T a b l e 1

Correlation coefficients of geomagnetic secular variations in Ponta Delgada and Reykjavík

| Correlation: | Pont.Delg. | Time lag [yrs] | Reykjavík | Time lag [yrs] |
|--------------|------------|----------------|-----------|----------------|
| SV magF&NAO  | 0.61       | −46            | 0.5       | −30            |

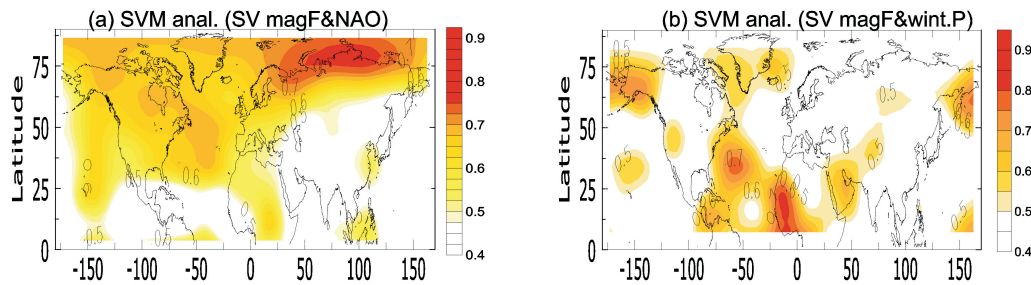


Fig. 2. Correlation coefficients of geomagnetic secular variations regressed on NAO index (a) and sea-level pressure (b), during the period 1900–2019, by using the support vector machine analysis. The contours of correlation beneath 0.5 are omitted

Table 1. They imply that the geomagnetic–NAO coupling is stronger over the Azores centre of action. This result suggests that geomagnetic influence on NAO index is not homogeneously distributed over the globe.

An estimation of the spatial distribution of geomagnetic–NAO temporal covariance is shown in Fig. 2(a). The map is constructed from the correlation coefficients between measured and predicted values of NAO, calculated by the support vector machine analysis with geomagnetic secular variations as independent variable. A glance on the figure confirms that the geomagnetic–NAO coupling is stronger in the central Atlantic (near the Azores Islands). It reveals also that the strongest relation between geomagnetic secular variations and the long-term variations of NAO index is detected in northern Siberia (between Kara and Laptev seas). Meanwhile, one of the hypotheses trying to explain the long-term NAO variability assumes that it could be related to the amount of ice in Kara and Barents seas. This analysis shows, however, that the suggested relation might be in the opposite direction – i.e. variations of NAO perhaps alter the amount of ice in the arctic seas.

**Coupling between geomagnetic secular variations and sea level pressure.** By its definition, the NAO index is an integral characteristic of the pressure variability over the North Atlantic Ocean. So, a more precise idea about the relation between geomagnetic variations and sea level pressure could be derived by a direct comparison of their temporal evolution in each node of our grid. For this purpose the seasonal data of winter sea-level pressure have been regressed on the annual values of geomagnetic secular variations, using the Support Vector Ma-

chine analysis. The correlation map of measured and predicted values of pressure, calculated in each grid point by SVM analysis with geomagnetic secular variations as independent variable, is presented in Fig. 2(b). It illustrates the spatial distribution of geomagnetic impact on the sea-level pressure variations, during the examined time interval 1900–2019.

The comparison of both panels in Fig. 2 shows that the strong geomagnetic–pressure coupling is detected in much smaller regions than the geomagnetic–NAO relation. Indeed, two of the regions with strong geomagnetic–pressure connectivity are found near both centres of action of NAO mode – i.e. the Azores and Iceland islands. Moreover, two additional centres of strong geomagnetic–pressure coupling have been detected in West Africa, Kamchatka–Alaska region and Arabian Peninsula.

The geomagnetic field, however, is not able to influence the non-magnetic media. Consequently, the well pronounced covariance with sea level pressure requires a mechanism of supposed geomagnetic influence. Indeed, this is the weak point of all previous studies, reporting an evidence of geomagnetic–climate relations – i.e. the missing mechanism of influence. However, the combination of knowledge gained from different branches of Earth sciences, helps the recent discovery of a chain of relations between geomagnetic field and atmospheric variables [10,15]. The brief description of the mechanism is given in the following section.

**Mechanism of geomagnetic influence on climate.** Climate sensitivity to the variations of ozone and water vapour near the tropopause was noticed long ago [16,17]. However, the mechanism of such sensitivity remains, unknown for a long time. On the other hand, the covariance between lowermost stratospheric ozone and tropopause temperature is well documented. Consequently, the spatial and temporal variations of the lower stratospheric ozone are able to affect the temperature near the tropopause. The latter, however, impacts the static stability of the upper troposphere and atmospheric humidity. In addition, models’ experiments [18] and satellite measurements [19] show that 90% of the greenhouse warming of our planet is provided by the water vapour in the upper troposphere. Thus, the ozone variations near the tropopause are projected down to the Earth’s surface, through modulation of near tropopause temperature and humidity [7].

For example, in periods (or in regions) with a reduced lower stratospheric ozone density, the tropopause becomes cooler, which destabilises the upper troposphere [20]. As a result the water vapour from the middle troposphere is easily uplifted in the upper troposphere. The increased humidity beneath the tropopause strengthens the greenhouse effect, raising in such a way the near surface temperature. Conversely, the enhancement of ozone density in the lower stratosphere is accompanied by a surface cooling.

As a test of this hypothesis we have investigated the spatial distribution of the relation between ozone at 70 hPa and the sea level pressure. The ability of the lower stratospheric ozone to explain the temporal variations of the sea-level

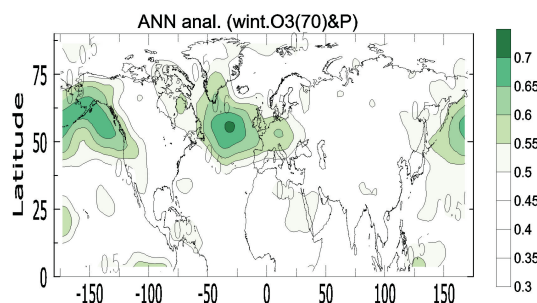


Fig. 3. Correlation map of the impact of ozone at 70 hPa on the sea level pressure, determined for the period 1900–2019, by the use of artificial neural network techniques. The correlations beneath 0.5 are ignored

pressure has been estimated by the use of the artificial Neural Network (ANN) technique – solving the regression problem. The technique is applied in each point of our grid with resolution 10 deg in latitude and longitude. The spatial distribution of correlation between measured and modelled values of pressure – by using the ANN with ozone as independent variable – is presented in Fig. 3. The figure shows that the strongest impact of the lower stratospheric ozone on the sea level pressure is found over the Atlantic and Pacific Oceans, at temperate latitudes. The comparison with Fig. 2b reveals that the strongest geomagnetic–pressure relation, over the Alaska and Aleutian islands, coincides very well with the strong ozone–pressure relations (Fig. 3). The second centre of the lower stratospheric ozone influence on the sea level pressure is situated in the North Atlantic, just between both centres of NAO action (Azores and Iceland).

The analysis of GCR influence on the lower stratospheric ozone density reveals that the regions of strongest ozone–pressure relations coincide with the strongest cosmic ray influence on the lower stratospheric ozone ([<sup>15</sup>], their Fig. 6.13). All these results suggest that geomagnetic–climate link of relations, proposed in [<sup>15</sup>] is well traceable during the examined period 1900–2019.

**Conclusions.** This paper offers a comparison among 120 year records of geomagnetic secular variations, NAO index, sea level pressure, and ozone at 70 hPa. The analyses of the spatial distribution of the regression coefficients between pressure and geomagnetic secular variations show the existence of temporal covariance between them at certain regions of the planet. We have tested the hypothesis that geomagnetic imprint on the sea level pressure is transmitted by a chain of relations including: (i) geomagnetic modulation of the galactic cosmic rays, and created by them secondary ionisation in the Regener–Pfotzer maximum, (ii) activation of the lower stratospheric ozone production by ion–molecular reactions just above the tropopause, (iii) projection of ozone variations on the temperature and humidity in the upper troposphere, (iv) imprint of ozone–water vapour vari-

ations over the sea-level pressure, through modulation of the greenhouse effect.

Analysis of the relation between ozone and sea level pressure confirms our hypothesis that the regions of strongest ozone-pressure relations are actually projections of the geomagnetic influence on GCR and their consecutive effect on the ozone density in the lower stratosphere.

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