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# LOWER STRATOSPHERIC OZONE'S INFLUENCE ON THE NAO CLIMATIC MODE

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**Abstract**

In the historical and contemporary climate records there is a plenty of evidence that climate system responds to the homogeneous external forcings with a regional specificity. A statistical analysis of the North Atlantic Oscillation (NAO) time series – an internal climatic mode, currently believed to be the main driver of the regional climate variability of the North Atlantic region – and the spatial-temporal evolution of the lower stratospheric ozone, reveals the leading role of $O_3$ in their coherent centennial variability.

We show that observed coherence is due to the ozone's influence on the surface temperature and pressure, which determine the alternating multidecadal changes of NAO phase. In addition, a mechanism of ozone influence on the regional climate variability is briefly discussed.

**Key words:** lower stratospheric ozone, driver of NAO multidecadal variations, galactic cosmic rays

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**Introduction.** The historical and contemporary climatic records are full of evidence that climate system evolves non-uniformly with time. Rather, it responds with a regional specificity to the uniformly distributed external forcings like solar variability, astronomical factors and greenhouse gas concentration – the most abundant among which is carbon dioxide ($CO_2$). The Intergovernmental Panel on Climate Change [1], as well as many of the on-line teaching platforms,

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attribute these irregularities to the existence of internal climatic modes, which modify regionally the effect of the global warming. The North Atlantic Oscillation (NAO) is one such mode, which has an important influence not only on the north Atlantic basin, but also on the adjacent continents. The NAO is associated with changes in weather (on inter-annual time scales) and climate conditions – on longer time scales. The NAO manifests itself as coherent variability in the main quasi-stationary Atlantic centres of action, i.e. the Icelandic centre of low atmospheric pressure and Azores centre of high pressure. It affects the direction of the main atmospheric storm-tracks, and correspondingly the transport of heat and moisture over Europe, as well as the heat content and salinity of the ocean, the formation of high latitude deep-water, sea ice cover, etc. [2].

The drawback of such an interpretation of the regional climate response is easily seen in the fact that we still do not know the factors driving the internal climatic modes. This paper is an attempt to throw some more light on the factors determining the inter-decadal variability of NAO, offering not only the statistical evidence for its relation to the centennial evolution of the lower stratospheric ozone, but also a mechanism describing its influence on the surface temperature and pressure, and their alternating changes over the North Atlantic.

**Data and methods used.** The data for the ozone mixing ratio at 70 hPa, for the period 1900–2010, have been taken from the ERA 20 century reanalysis (ERA20C). The data of NAO index – defined as the difference between the pressures over Azores and Iceland – are from the Climatic Research Unit, University of East Anglia (`https://crudata.uea.ac.uk/cru/data/nao/`). For the statistical analysis we have used a NAO record for winter months (Dec, Jan, Feb, Mar). The time series *mean* has been extracted from each seasonal NAO value and the difference has been divided by the *mean* (of the entire data record), i.e. (NAO(yr) – mean NAO)/mean NAO. Ozone and NAO time series are smoothed by the moving average procedure over 11 points window. The non-stationary $O_3$ anomalies are calculated as deviations from their continuously changing decadal mean.

To estimate the degree of relation between lower stratospheric ozone and NAO, we have used a lagged correlation analysis to identify any possible delay in the response of the dependent variable. Correlation maps of the interconnected parameters were plotted only from statistically significant values at $2\sigma$ level (i.e. 95%). Two hypotheses were examined: 1) the independent variable is NAO, which determines the spatial time variations of $O_3$ in the lower stratosphere; 2) the independent variable is $O_3$, which alters the different phases of NAO mode.

**Results.** The time evolution of the winter NAO index since 1900, presented in Fig. 1, shows the existence of three periods with alternating positive and negative NAO phases. It is easily seen that between 1900 and 1929 the NAO was in a positive phase; within the period 1930–1982 – in negative one, and during the following 1983–1998 period it was again in its positive phase.

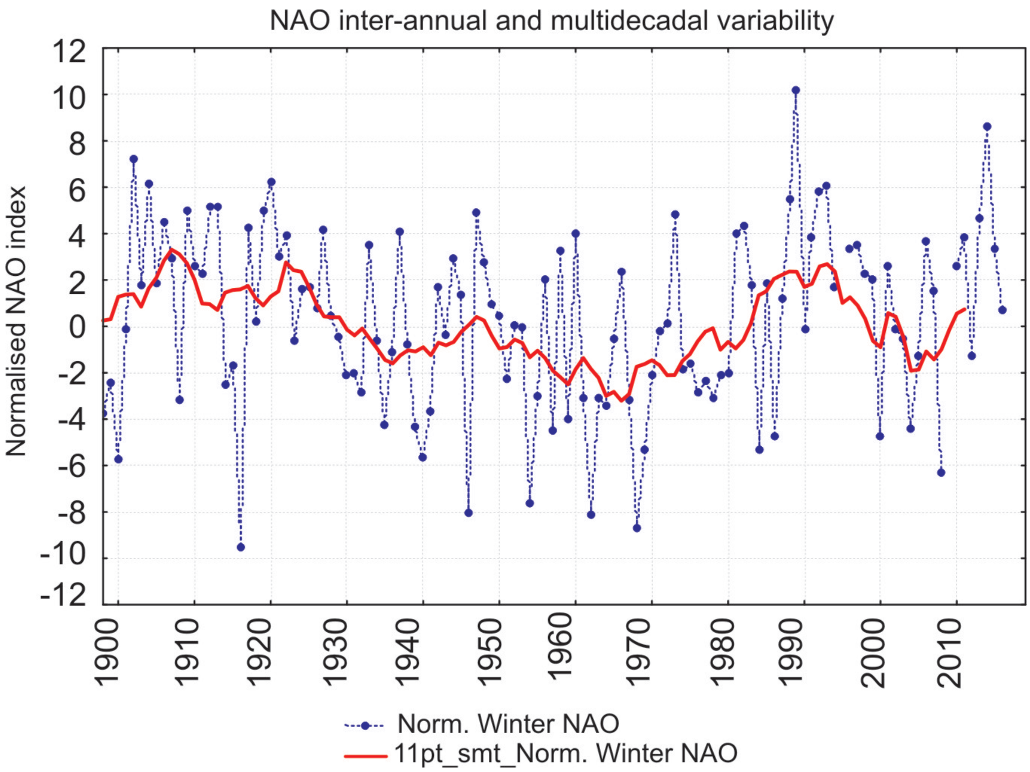


Fig. 1. Time series of normalised winter NAO index (i.e. the difference between surface pressure in Azores and Iceland); dashed line with dots illustrates the inter-annual variability, while the thick red curve represents the smoothed by 11 point moving average NAO index

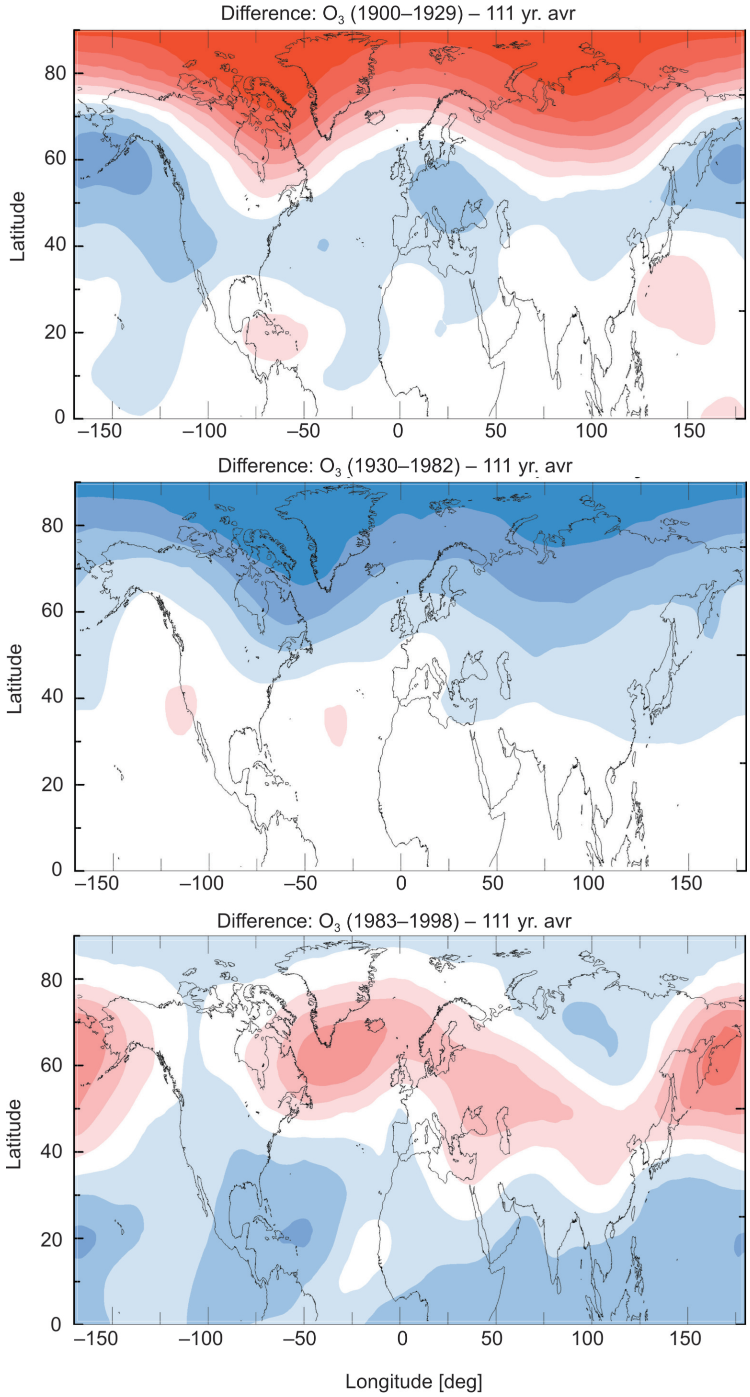


Fig. 2. Spatial distribution of the winter $O_3$ deviations from its non-stationary means at 70 hPa, shown for three periods of different NAO phases: positive during the first period, negative during the second and positive again during the third period

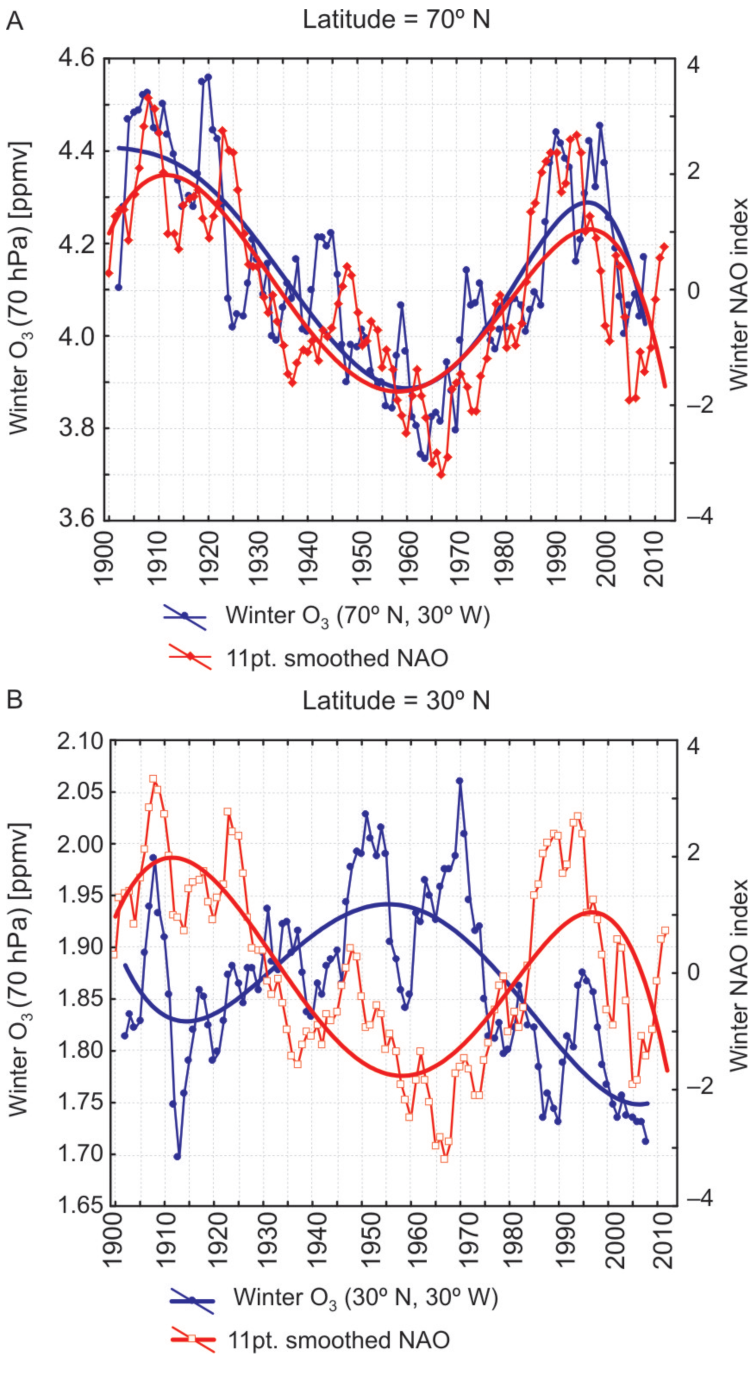


Fig. 3. Smoothed (by 11 points moving average) time series of winter NAO (red curves with diamonds or squares) and ozone mixing ratio at 70 hPa (blue dotted curves) are compared for Iceland (A) and Azores (B). The polynomial fits to each time series (thicker red and blue curves) are shown to guide the eyes

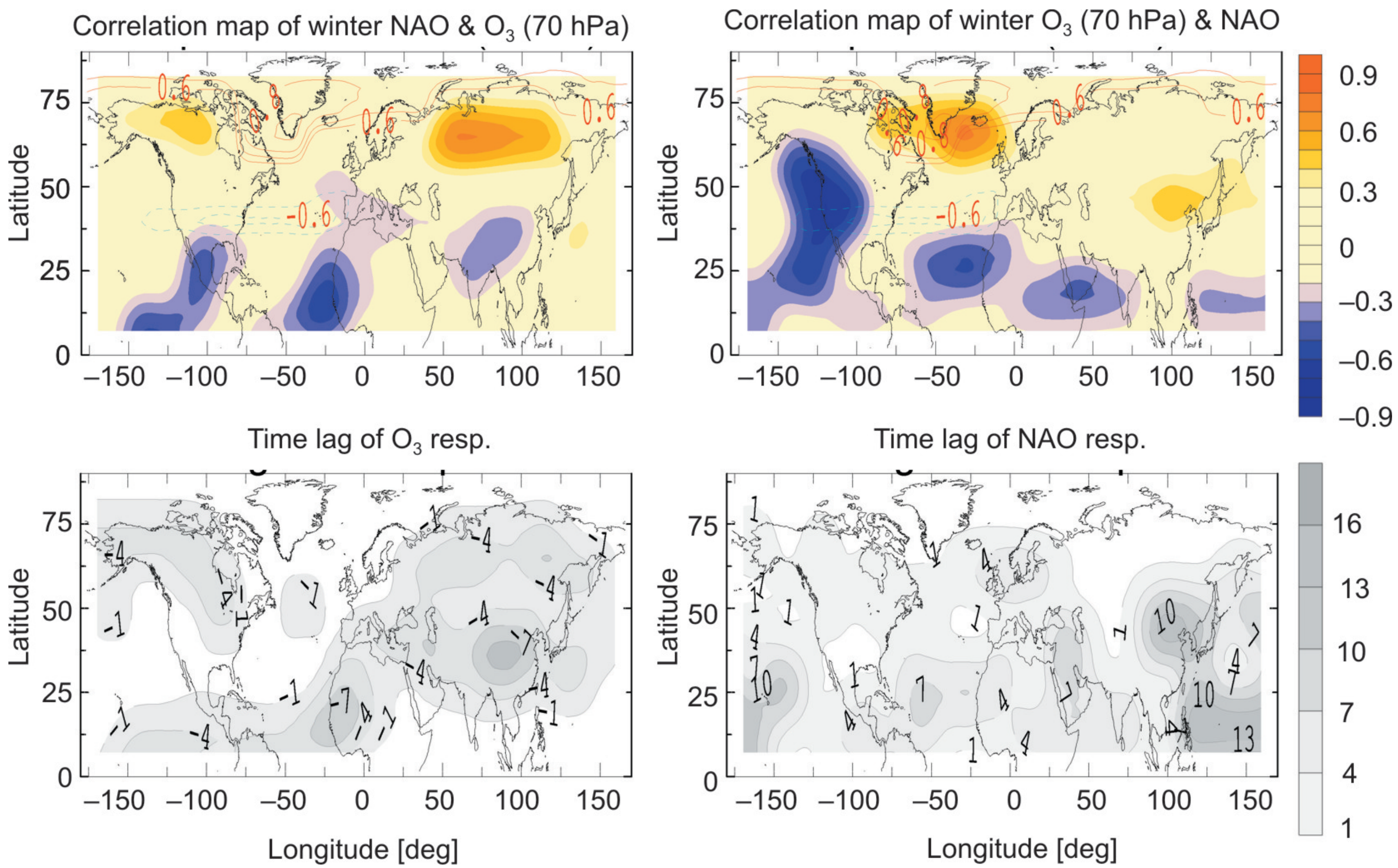


Fig. 4. Correlation maps of the winter ozone mixing ratio at 70 hPa and NAO index, calculated for the period 1900–2010. In the *left* panel the leading factor is NAO index, while in the *right* one the independent variable is ozone at 70 hPa. The instantaneous NAO-ozone correlation is depicted by red contours (positive) and dashed contours (negative correlation). The lagged correlations are denoted by coloured shading – blue for negative, orange – for positive ones

On the other hand, many authors report for the enhanced climate sensitivity to the near tropopause $O_3$ density [3–6]. For this reason we decided to investigate whether similar variations exist in the lower stratospheric $O_3$ density. Figure 2 presents the spatial distribution of $O_3$ mixing ratio at 70 hPa for each of the examined periods. It is easily noticed that during the first third of the 20th century there is a rise of the polar $O_3$ density accompanied by its reduction at extratropical latitudes. In the middle of the century the situation is reversed – the density of polar $O_3$ is reduced, while that at mid-latitudes it remains unchanged or weakly increased. The last third of the century shows a transition from second back to the first period again.

This coherent alternation of the NAO index and the spatial patterns of the lower stratospheric ozone anomalies, during the 20th century, imply the existence of a relation between both variables. The comparison between their time records in two points with coordinates: 70°N, 30°W (the approximate latitude and longitude of Iceland), and 30°N, 30°W (the approximate coordinates of Azores islands) is shown in Fig. 3. The coherence in the temporal variations of NAO and the lower stratospheric $O_3$ – over the two centres of action of NAO mode – is easily noticeable. This covariance is in phase over Iceland and in anti-phase over the Azores.

We have performed a quantitative estimation of the relation between NAO and $O_3$ density by the use of a lagged cross-correlation analysis. Two hypotheses have been examined: (i) the multidecadal variations of NAO drive the corresponding changes in $O_3$ spatial distribution, and (ii) the centennial variations of the lower stratospheric $O_3$ density influence the surface temperature and pressure, which in turn transposes onto different phases of NAO index. The lagged correlation coefficients – describing the "NAO influence on the ozone" – have been weighted through the value of the autocorrelation function of NAO index corresponding to a given time lag [7]. This procedure reduces the impact of the heavily lagged cross-correlation coefficients. The physical reasoning for such a weighting is based on the fact that the climate memory for the changes of NAO mode is relatively short, i.e. at the 10th year after the initial forcing the system does not remember it. Furthermore, from the statistically significant (at $2\sigma$ level) correlation coefficients, calculated in each point of our grid, we have drawn the correlations maps shown in Fig. 4. The lagged correlations are depicted by coloured shading – *blue* for antiphase correlations, *orange* – for in-phase ones.

The left panel in Fig. 4 illustrates the strength of the correlation between NAO and ozone, where the NAO index is an independent variable. The right panel shows the opposite case in which the forcing (independent) variable is the $O_3$ density. The covariances, where the source of influence (i.e. ozone or NAO) is inseparable are drawn by contours in both panels. It is easily noticeable that over the North Atlantic region the NAO influence on the lower stratospheric $O_3$ is undetectable (see Fig. 4, left panel). Conversely, the ozone impact on the main centres of action of NAO mode (i.e. the south Greenland – Iceland and Azores – African's western shores) is easily noticed. The northern centre of $O_3$ influence fairly well overlaps the region of an instantaneous high latitude ozone – NAO correlation (Fig. 4, right panel). The ozone's influence on NAO mode is even stronger over the Pacific shores of North America and its influence is well traceable over the tropical region. On the other hand, NAO correlation with the tropical ozone is less pronounced, with an $O_3$ response delayed by 4–10 years (left bottom panel of Fig. 4). Unlike the mechanism for ozone influence on the surface temperature [15,16] we do not know any mechanism for delayed impact of NAO on the lower stratospheric $O_3$. This implies that the more active partner in the NAO-ozone coupling is played by the lower stratospheric $O_3$.

The upper right panel in Fig. 4 clearly shows the existence of two centres of ozone's influence on the surface temperature and pressure. The centre of the maximal positive correlation is placed near the southern edge of Greenland, while that of the negative one – between the Azores and the Eastern Pacific. This means that ozone enhancement over Greenland or its depletion over the Azores is accompanied by a positive NAO index. Alternatively the simultaneous rise of $O_3$ at polar and its reduction at mid-latitudes – as found during the second third of 20th century (refer to Fig. 2) – forces the NAO mode toward its negative phase. In other words, each of the ozone's centres of action could affect the NAO phase, as well as their simultaneous forcing alter the NAO variability.

**Discussions and conclusions.** Statistical evidence for the lower stratospheric ozone control on the phase of the climatic NAO mode raises at least two more questions: 1) Which are the factors affecting the temporal and spatial variations of the lower stratospheric $O_3$, and 2) What is the mechanism of $O_3$ influence on the surface temperature?

In regard to the first question, the widely spread opinion (i.e. that the Brewer–Dobson circulation is the main factor determining the lower stratospheric $O_3$ density) is not able to explain not only the spatial heterogeneity of $O_3$ distribution, but also the severe reduction of polar ozone during the middle of 20th century (see the middle panel of Fig. 2). Moreover, some numerical experiments have shown that only 30% of the ozone's variability at extratropical and high latitude could be attributed to the transport from the tropical upper stratosphere, where $O_3$ is produced photochemically [8]. More recent investigations [9] have revealed that galactic cosmic rays (GCR), freely accessing the lower stratosphere [10–12], could activate the production of ozone under certain conditions (i.e. the dry atmosphere and increased concentration of lower energetic electrons). According to these studies the impact of GCR on the lower stratospheric $O_3$ is heterogeneously distributed over the globe – effect related itself to the geomagnetic focusing of GCR in specific regions over the Earth [13,14].

Regarding the second question, i.e. the mechanism of $O_3$ influence on the surface temperature, our previous studies show that it should be related to ozone's influence on the tropopause temperature, which controls the upper troposphere static stability, and the possibility for a vertical upwelling of the moister, middle tropospheric air masses [15,16]. For example, the reduction of the lower stratospheric ozone density cools the tropopause, making the upper troposphere conditionally unstable [17]. As a result the wetter middle tropospheric air masses are easily uplifted in the upper troposphere, increasing in such a way the greenhouse warming of the given region. Here it is worth to remind that the greatest impact in the greenhouse effect has the upper tropospheric water vapour providing more than 90% of the effect of the whole water content in the troposphere [18]. Consequently, the *depletion* of the near tropopause $O_3$ is accompanied by a surface *warming*, while the ozone's excess – with a cooling of the planetary surface [19].

In the context of the current results, suggesting lower stratospheric ozone's influence on the climatic NAO mode, it should be stressed that according to our hypothesis, and the positive correlation between $O_3$ and NAO (refer to Fig. 4, right panel), the raise of ozone density over Greenland and Iceland should be followed by a surface cooling and pressure decrease (in accordance with the ideal gas law: $\mathbf{p} = \rho \cdot \mathbf{R} \cdot \mathbf{T}$, where $\mathbf{p}$ is the pressure, $\rho$ is the density of the air mass, $\mathbf{R} = 8.3144598$ J·mol$^{-1}$·K$^{-1}$ is the atmospheric gas constant, and $\mathbf{T}$ is the temperature). Consequently, the $O_3$ abundance over its centre of action above Greenland and Iceland is followed by a reduced surface pressure, which according to JONES's et al. [20] definition of NAO, corresponds to a positive NAO phase. Conversely, the depletion of polar $O_3$ density stimulates regional surface warming and pressure raise, followed respectively by a negative NAO phase – a situation observed in the middle of the 20th century (refer to Fig. 1 and 2).

Similarly, the $O_3$ depletion above the Azores is accompanied by a surface warming and pressure raise, which corresponds to the positive NAO phase. Conversely, the ozone's enhancement in the extra-tropics will cool the surface, preparing in such a way the appearance of the negative NAO phase.

In conclusion, the statistical evidence for the lower stratospheric $O_3$ impact on the climatic NAO mode is complementary to the previous investigations and illustrates that the regional variability of North Atlantic climate – attributed currently to the internal climatic mode NAO – is actually driven by the temporal-spatial variations of the lower stratospheric ozone. The ozone's centennial variability we attribute to the unevenly distributed impact of galactic cosmic rays, influencing the amount of ozone density in the lower stratosphere [16,21].

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