Multiannual variability of the North Atlantic pressure and temperature, imposed by the lower stratospheric ozone

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ABSTRACT

Analyses of the Northern Hemisphere’s sea level pressure, air surface temperature and lower stratospheric ozone, during the period 1900-2019, reveal an existing coherence in their temporal variability. The coherence is heterogeneously distributed over the globe, and the patterns of ozone impact on the pressure and temperature are different. More specifically, the strongest ozone influence on the sea level pressure is found in the main “centres of action” – i.e. the Aleutian low and the region of NAO formation. The ozone influence is localised mainly in the latitudinal belt 40-75°N, where the ozone mixing ratio at 70 hPa is reduced during the most of the 20-th century (compared to the first decade of the 21-st century). This peculiarity of ozone spatial distribution we attribute to the energetic particles trapped in the Earth’s radiation belts, activating themselves ion-molecular reactions of ozone production in the region of Regener-Pfotzer ionisation maximum. Consequently, the spatial-temporal variations of the lower atmospheric ionisation could be a good explanation for irregularly distributed ozone and its regionally specified impact on the climatic variables.

SIGNIFICANCE STATEMENT

We tried to understand the regional character of the Northern Hemisphere’s winter weather conditions. The latter is usually attributed to the North Atlantic Oscillation (NAO), but we actually do not know the factors impacting the NAO variability itself. We found that at multiannual time scales the surface pressure is only weakly related to the temperature variations, while its correlation with the ozone at 70 hPa is unexpectedly strong – especially in the active regions of the weather phenomena formation. The ozone variability, itself, we attribute to the variable intensity of energetic particles precipitating in the lower atmosphere – where they activate ion-molecular reactions producing ozone. This finding opens new horizons for understanding the regionality of atmospheric variation at different time scales.

1. Introduction

The Northern Hemisphere winter conditions are significantly influenced by the North Atlantic Oscillation (NAO), defined as the sea-level pressure gradient between the Icelandic minimum and the Azores maximum (Hurrell et al., 2003). The synchronous variations of the subtropical and subarctic atmospheric pressure is noticed long ago (Walker, 1925), manifesting itself as a simultaneous strengthening of the sub-polar low pressure and the subtropical high pressure (the positive NAO phase), or synchronous weakening of the

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pressure in both centres of action (the *negative* phase of NAO). This seesaw in the North Atlantic pressure variability is accompanied by corresponding changes in the winter storm-track over the North Atlantic and Europe. For example, the global thermally driven *subtropical jet* (i.e. a local maximum of the wind speed) – typical for the *negative* NAO phase – is bifurcated during the *positive* phase of NAO (Woolings et al., 2010, their Fig.1). The appearance of the additional mid-latitude jet (propagating from the North America toward the Scandinavian peninsula) is supposedly due to the interaction of the synoptic scales departures from the mean flow’s strength and position (known as “transient baroclinic eddies”, Thompson et al., 2002), and the mean flow itself.

Supposing that the bifurcation of the subtropical jet (during the positive NAO phase) is forced by the eddies–mean flow interactions, we have to elucidate the factor(s) responsible for the variability of the amplitude of circulation eddies (anomalies). At synoptic time scale, the intensification or weakening of eddies is usually related to the strength of the thermally driven subtropical jet. For example, the stronger jet – with its vertical wind shear and meridional gradient of potential vorticity (limiting itself the eddy movement in meridional direction) – organises the baroclinic eddies, ensuring their vertical propagation. The latter, in turn, reinforces the jet. Oppositely, the weaker jet allows self-organisation of eddies in baroclinically unstable flow (poleward of the subtropical jet) – even in the absence of thermal forcing (Thompson et al., 2002). However, the drivers(s) affecting the subtropical jet’s strength are still unclear.

Despite the short life cycle of NAO atmospheric mode, it possesses distinct decadal variations (e.g. Pozo-Vázquez et al. 2001; Raible et al. 2001, 2004; Athanasiadis et al., 2020; Christiansen et al., 2022). Moreover, the proxy reconstructions of NAO reveal existence of well pronounced trends, during the last few centuries (Appenzeller et al. 1998). On the other hand, the absence of atmospheric memory from one winter season to the next one, suggests that the long-term variability of NAO reflects either the greater heat capacity of the ocean (and respectively its long memory), or it is a projection of some external influences on the climatic system.

Some authors are tempted to explain the long-term NAO variability as an aggregated effect of the short-term stochastic variability of tropospheric circulation (e.g., Stephenson et al, 2000; Feldstein, 2000). The other types of explanations relate the long-term NAO variability to: (i) the other components of climatic system like the ocean, the cryosphere and
the other atmospheric modes (e.g. Grötzner et al., 1998; Cassou, 2008; Ineson & Scaife, 2009; Cagnazzo & Manzini, 2009; Petoukhov and Semenov, 2010; Warner, 2018; Årthun et al., 2021), or (ii) factors external to the climate system – e.g. anthropogenic and volcanic forcing (Wallace and Thompson, 2002; Shindell, et al., 2003; Fischer et al., 2007), and solar variability (Kodera, 2002; Ruzmaikin & Feynman, 2002, Kirov & Georgieva, 2002; Georgieva et al., 2007; Gray, et al., 2016).

Among the external forcing, the increased concentration of greenhouse gases is the most frequently analysed. However, the anthropogenic explanation of the NAO positive trend – observed during the second half of 20-th century – becomes very unlikely after the phase transitions of NAO latter on (see Figure 1). Moreover, according to Christiansen et al., (2022) the modelling skill of historical ensembles including well mixed greenhouse gases or anthropogenic aerosols is not significantly different from zero. The effect of the other candidate – the volcanic forcing – is quite short lasting. For example, the effect of gasses, ash and water vapour – tossed by the volcanic eruption in the atmosphere – becomes negligible after 2-3 years (Shindell, et al., 2003).

Fig. 1. Centennial evolution of NAO index, derived by the University of East Anglia https://crudata.uea.ac.uk/cru/data/nao/index.htm (Jones et al., 1997), compared with CO2 density.

Regarding the other external forcing – i.e. the solar activity – there is a large disagreement in scientific community. This controversy is rooted in the non-stationary
temporal synchronization of NAO and solar variability – being stronger in periods of increased solar activity (e.g. Maruyama et al., 2018; Drews et al., 2022). Moreover, the correlation between NAO and sunspot numbers changes alternatively its sign, with a periodicity of approximately 50 years (Gruzdev and Bezverkhnii, 2020). This situation motivates Thiéblemont et al., (2015) to conclude that 11-year solar cycle simply synchronises the internally inherent quasi-decadal NAO variability.

Some authors interpret the NAO variability as a remnant of breaking synoptic waves (during their interaction with the three-dimensional winter flow) – evolving in NAO like anomalies (Franzke et al., 2004). The wave breaking critically depends on the strength of the mean flow (Thompson et al., 2002), and accordingly on the sea surface temperature gradients. Consequently, one might expect that the spatial-temporal evolution of the near surface temperature and pressure should be synchronised – at least to some extent. Analysis of instantaneous correlation map of the air temperature at 2m above the surface and the sea level pressure reveals, however, that this is not the case (see Figure 2).

Fig. 2 Instantaneous cross-correlation map of air surface temperature and sea level pressure (unfiltered winter values), calculated for the period 1900-2019. Correlation coefficients higher than 0.195 are statistically significant, according to the two-sided Student t-test.

Figure 2 shows clearly that the pressure–temperature temporal synchronisation varies over the globe not only by strength, but also by sign. Note that the in-phase covariance of temperature and pressure is found over the North Atlantic Ocean, as well as in a latitudinal belt – roughly corresponding to the subtropical atmospheric jet. Over the rest of the world, the temperature and pressure covariate in antiphase. This means that at longer time scales the troposphere could not be treated as an ideal gas and the diabatic heating has an important impact on the atmospheric thermodynamics (refer to Eq. 1). This could be an explanation for
the problems of the contemporary climatic models to reproduce adequately the NAO long-term variability (Simpson et al., 2018; Blackport and Fyfe, 2022; Christinsen et al., 2022).

On the other hand, the climate sensitivity to the near tropopause ozone variations has been established long ago, and by many authors (e.g. Manabe and Wetherald, 1967; Ramanathan et al., 1976; de Forster and Shine, 1997; Stuber et al., 2001; Kilifarska, 2012; Kilifarska et al., 2020). Numerical experiments (Stuber et al., 2001; Kilifarska et al., 2018) confirm that models’ climate is indeed sensitive to the near tropopause ozone variation. However, the climate models fail to reproduce the real spatial-temporal variation of the lower stratospheric ozone, due to the non-recognition of the second source of ozone at these levels (Kilifarska, 2013). The recent models are based on the assumption that the lower stratospheric ozone density is controlled solely by the stratospheric circulation.

The ozone production in the lower stratosphere is activated by the low energy electrons in the Regener-Pfotzer ionization maximum (Kilifarska, 2013). The heterogeneous spatial distribution of the latter is projected on the lower stratospheric ozone density (Kilifarska et al., 2020). Combined with the strong ozone influence on the near surface climate, energetic particles in the Regener-Pfotzer maximum could be a reasonable explanation of the regional specificity of climate variations.

The present study is focused on the analyses of coupling between the Northern Hemisphere air surface temperature and sea level pressure, particularly over the North Atlantic Ocean – the region of formation of NAO atmospheric mode. The role of the lower stratospheric ozone variability and its relation to the spatial-temporal synchronicity of atmospheric pressure and temperature is also studied. We have found that the lower stratospheric ozone influences the sea level pressure mainly in a latitudinal belt characterised by a centennially lower ozone mixing ratio at 70 hPa. The strongest winter ozone impact coincides with the two active circulation centres in the Northern Hemisphere – i.e. the Aleutian low and region of NAO formation.

2. Data and Methods

a. Data

Monthly mean data of air temperature at 2m above the surface, ozone mixing ratio at 70 hPa and sea-level pressure are taken from the merged re-analyses ERA 20 century (https://apps.ecmwf.int/datasets/data/era20cm-edmm/levtype=sfc/) and ERA Interim.
covering the period 1900-2019. Both reanalyses were merged at the year 2000. The merging procedure includes an equalization of the decadal means of both records, taken over the period 2001–2010 – smoothing in such a way the transition between the two reanalyses, and avoiding possible step-like changes between their means. Monthly records of all atmospheric variables have been derived in a grid with 5 deg step in latitude and longitude. The wider winter seasonal means (covering the period November-April) has been used in our analysis. Our attention was focused on the multiannual variability of atmospheric variables, so the fluctuations shorter than 5 years have been suppressed by applying 5-point moving average procedure.

Long record of galactic cosmic rays’ data (since 1700 up to 1951) is provided by the World Data Centre for Paleoclimatology, Boulder, Colorado, and the NOAA Paleoclimatology Program. After 1951, the record was extended by calibrated data from the Moscow neutron monitor. The 11-year solar cycle, existing in the data, has been suppressed by 11-year running average procedure.

b. Statistical methods

Due to the non-linear temporal evolution of climatic variables, we have applied the artificial neural network (ANN) technique – for detection of potential relations between analysed variables. The 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. \( X(X_1, X_2, X_3, \ldots, X_N) \) and \( Y(Y_1, Y_2, Y_3, \ldots, Y_M) \). The precise form of the function, which maps \( X \) to \( Y \) 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 \( (w_1, w_2, \ldots, w_t) \). The process of determining these parameters’ values is often called learning or training. So, the neural network mapping could be written in the form:

\[
Y = Y(X; w)
\]

which denotes that \( Y \) is a function of \( X \), being itself parameterized by \( w \) (Bishop, 1994). We have used two of the most popular neural network architectures – i.e. multilayer perceptron (MLP) and the radial basis function (RBF). The most suitable model (among the bulk of possibilities, provided by the ANN) is chosen through optimisation between the following criteria: (i) maximisation of model’s performance (i.e. regression

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coefficients) derived for each of training and testing subsamples, and (ii) minimisation of model’s error of both samples.

We have used also the lagged cross-correlation analysis to study the coherence in temporal variability of galactic cosmic rays’ intensity and ozone mixing ratio, as well as the covariance between near surface pressure and temperature. This classical approach has been chosen, because it provides an assessment of the time delay of responding variable to the applied forcing. The cross-correlation coefficient is calculated by shifting the independent variable m steps back in time, which determines the negative sign of the responding variable’s time lag.

Although the applied software provides an estimation of statistical significance of correlation coefficients, we cannot rely on the standard Student’s t-test, because our smoothed time series are serially correlated. This is due to the fact that standard test of significance could inflate the calculated Z-values, providing false positives. For this reason, we have used the methodology suggested by Afyouni et al., (2019), based on the recalculation of the correlation coefficients’ variance, taking into account not only the autocorrelation coefficients of both time series, but also their cross-correlation. Other available approaches, providing a solution of the problem of serially correlated records, are based on re-calculation of effective degree of freedom, and the assumption that analysed time series do not correlate. This requirement is not met by our time series, because they covariate in time. Moreover, our main purpose is to estimate the strength and reliability of their cross-correlation.

3. Results

a. Temperature-pressure covariance in the Northern Hemisphere

The first law of thermodynamics postulates the conservation of atmospheric energy, i.e.:

\[ c_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dP}{dt} = Q \]  \( (1) \)

where T is the temperature in Kelvin degrees, P is the atmospheric pressure, \( c_p \) – the specific heat of air at a constant pressure and Q is the net heating rate per unit mass. At first approximation, the atmosphere could be assumed adiabatic for fast processes without exchange of heat with the environment. This means that relation between near surface

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temperature and pressure follows the ideal gas law – a molecular form of which is given by Eq.2:

\[ PV = N k_B T \]

(2)

where \( V \) is the volume taken up by the gas, \( N \) is the number of molecules in the gas, and \( k_B \) is Boltzmann's constant. According to Eq. (2), the temporal variations of the near surface temperature and pressure should be synchronised – at least at short time scales. At longer time scales, however, the impact of diabatic heating (\( Q \)) should be of great importance. So, the examination of the pressure-temperature correlation of climatic time series could provide a first impression about the validity of the ideal gas approximation at longer time scales.

The map of simultaneous correlation between near surface temperature and pressure illustrates, that a strong temperature-pressure coupling is found only in limited regions of the Northern Hemisphere (see Figure 2). Having in mind that causality is of greatest importance for detection and attribution analyses, we have performed a two way lagged correlation – changing consequently the leading factor (temperature or pressure). The derived correlation maps are shown in Figure 3. The top left panel of Figure 3 illustrates the temperature impact on the sea level pressure, while the right one – the pressure effect on the air surface temperature. The lower panes present the time lags of the response to the applied forcing – i.e. that of the sea level pressure (left) and the near surface air temperature (right).

There are several findings, following from Figure 3, which should be noted: (i) the long-term pressure–temperature coupling is dominantly in antiphase (oppositely to the expected from the ideal gas law); (ii) at higher latitudes, the pressure impact on the air temperature is stronger and covers wider regions in the Northern Hemisphere (although temperature response is delayed by 7-13 years); (iii) at tropical latitudes the temperature influence on the sea-level pressure is slightly better pronounced, and pressure response is delayed by 4-7 years; (iv) over the North Atlantic region the lagged pressure-temperature correlation is very poor.

Comparison of Figure 2 and 3 shows that pressure-temperature variations over the North Atlantic region evolve more or less independently in time. This is well illustrated in the Figure 4, presenting the evolution of both variables at two main centres of NAO mode – i.e. Ponta Delgada (Azores) and Reykjavik (Iceland). The short-time fluctuations (i.e. shorter than 5 years) are dumped by smoothing the raw data with 5 point moving window.
Conclusively, the long-term synchronization between subtropical and subarctic pressure variability (determining NAO climatic mode) could not be attributed to corresponding changes of the air surface temperature. This implies that the long-term evolution of both variables is determined either by different factors, or at least by different influential mechanisms of the same forcing.

Fig. 3 Lagged correlation between air temperature at 2m above the surface (T2m) and the sea level pressure (SP), calculated for the period 1900-2019. Top left panel illustrates the T2m impact on the pressure, while the top right – the pressure influence on the temperature. Bottom left panel presents the time delay of SP response to the temperature forcing, while the bottom right – the time lag of T2m response to the pressure forcing.

b. Statistical evidence for lower stratospheric ozone influence on the near surface pressure

Prediction of the North Atlantic pressure evolution is not trivial, because recently it becomes clear that positive trend in global temperature is not simply projected on the sea
level pressure. So, the expectations for positive and increasing NAO pattern during 21-st century (Hurrell et al., 2003) remained elusive. On the other hand, the recent discovery of NAO sensitivity to the lower stratospheric ozone variations (Velichkova & Kilifarska, 2019) gives us a motivation for further analysis of the statistical relation between sea level pressure and ozone near the tropopause.

Fig. 4 Time series of sea level pressure and air temperature measured in Ponta Delgada (a) and Reykjavik (b), smoothed by 5 point moving window

Prior studies reveal that ozone density at 70 hPa is significantly influenced by the energetic particles in the lower atmospheric ionisation layer, known as the Regener-Pfotzer maximum (Kilifarska et al., 2022). Beyond the auroral oval, the Regener-Pfotzer maximum is determined by the secondary ionisation and the products of nuclear decay, resulting from the interaction of primary cosmic rays with the atmospheric atoms and molecules. At lower latitudes, however, the Regener-Pfotzer maximum is filled mainly by energetic particles trapped in the Earth’s radiation belts. In regions with weaker geomagnetic field or with higher azimuthal magnetic gradient, these particles are lost in the atmosphere, where they contribute to the ionisation in the Regener-Pfotzer maximum. At middle latitudes, this low atmospheric ionisation layer is placed above the tropopause, where the atmospheric humidity is severely reduced – due to the freeze drying process near the tropopause (the tropospheric cold point). Thus, the availability of low energy electrons in a dry lower stratosphere activates the process of ozone production at these levels (Kilifarska, 2013). Consequently, the heterogeneously distributed humidity, and low atmospheric ionisation, over the globe is the main reason for irregular production of ozone in the lower stratosphere. This is the physically based explanation of the hemispherical asymmetry and longitudinal variations of the lower stratospheric ozone.
stratospheric ozone density (Kilifarska, 2017), reported from many authors (Hood & Zaff, 1996; Pan et al., 1997; Stablova, 2001; Peters et al., 2008).

Examination of the ozone and pressure time series (with supressed sub-decadal periodicities) reveals that the synchronised anti-phase pressure variations in Azores and Iceland is accompanied by corresponding opposite changes of ozone in the lower stratosphere (see Figure 5). Interestingly, the strongest decrease of pressure in Ponta Delgada corresponds to the highest values of ozone at 70 hPa, during the examined period. Oppositely, the highest pressure values in Reykjavik correspond to the lowest ozone density during the period 1925-1975. Calculated cross-correlation coefficients, presented in Table 1, confirm the good synchronicity of these variables in both cases – with suppressed variations shorter than 5 years, and shorter than 11 years.

![Figure 5](image-url)

Fig. 5 Time series of ozone at 70 hPa (black or blue curve) and sea level pressure (red one), smoothed by 11 point moving window, shown for Ponta Delgada (a) and Reykjavik (b). Note that in both sites, the ozone abundance is accompanied by reduction of the sea level pressure.

<table>
<thead>
<tr>
<th>Site</th>
<th>5pt.smt. O₃&amp;SP</th>
<th>11pt.smt. O₃&amp;SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reykjavik</td>
<td>-0.57</td>
<td>-0.78</td>
</tr>
<tr>
<td>Ponta Delgada</td>
<td>-0.55</td>
<td>-0.73</td>
</tr>
</tbody>
</table>

**Table 1.** Simultaneous cross-correlation coefficients of ozone at 70 hPa and sea level pressure, calculated for the period 1900-2019, at Reykjavik (Iceland) and Ponta Delgada (Azores). The middle column shows the coherence in temporal variability of time series smoothed by 5 point moving window. The correlation coefficients in the right column are derived for the time series with supressed sub-decadal variations of analysed variables. All correlations are statistically significant at confidence level α=0.05.
Having in mind the non-linear character of climatic time records, and deficiencies of linear statistics, furthermore we have applied the artificial neural network technique (regression problem). The spatial distribution of the ozone-pressure temporal synchronisation has been estimated by mapping ozone temporal variations on the atmospheric pressure, applying the neural network in each node of our grid with resolution 5 deg. in latitude and longitude. The map presented in Fig. 6 shows the correlation coefficients between observed and modelled values of the sea-level pressure, as a function of the lower stratospheric ozone. The figure shows that the strongest ozone impact on the sea level pressure is found over the main “centres of action” of atmospheric circulation – i.e. the Aleutian low pressure system, and the North Atlantic region between Azores and Iceland islands (see Fig. 6). This finding reveals that the near surface pressure could be affected distantly by the variations in the lower stratospheric ozone density. The mechanisms for ozone influence on the sea level pressure are discussed in the following subsection.

![Fig. 6 Spatial distribution of the lower stratospheric ozone impact on the sea-level pressure, estimated by the neural network technique, during the period 1900-2019.](image)

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Fig. 7 Spatial distribution of the air temperature response to variations in the lower stratospheric ozone, during the period 1900-2019, as determined by artificial neural network technique.

Meanwhile we have examined the spatial-temporal covariance between ozone at 70 hPa and the air surface temperature (T2m). The neural network technique has been applied again in each node of our grid, comparing the similarities in temporal evolution of ozone and temperature. The result presented in Fig. 7 illustrates the spatial distribution of correlation between observed and modelled temperature values, with ozone used as independent variable. The glance on the correlation map reveals that the strongest ozone-temperature coupling is detected at tropical regions of the Indo-Pacific Ocean and Indonesia. Comparison of Figs. 6 and 7 shows that the strongest ozone impact, on the sea level pressure, does not match the ozone influence on the air temperature.

This result indicates that there are different mechanisms for the lower stratospheric ozone influence on the near surface pressure and temperature. More details about these mechanisms could be found in the next subsection.

c. Mechanisms of lower stratospheric ozone influence on the near surface temperature and pressure

The atmospheric ozone is a strong radiatively active gas, adsorbing in several spectral bands of electromagnetic radiation (Forster & Shine, 1997). Consequently, changes in the lower stratospheric ozone density impact the local stratospheric temperature, and as a result – the pressure at the certain levels (due to the changes in the diffusion velocity of atmospheric molecules). These pressure changes are detected also by barometers on the sea-level, because the atmospheric pressure is an integral characteristic of the weight of the whole atmospheric column above the sea surface. Consequently, the changes in the lower stratospheric ozone cold have a direct impact on the sea-level pressure through changing temperature and diffusivity at the levels of ozone changes.

On the other hand, the Eq. 2 illustrates that the near surface atmospheric pressure depends also on the near surface temperature. The latter, in turn, depends on many factors, one of which is the greenhouse warming. It is well known that the strongest greenhouse gas is the atmospheric water vapour. However, despite the greatest amount of water vapour in the lower troposphere its impact in the greenhouse effect is only 10% (Inamdar et al., 2004). The rest 90% of the greenhouse effect belongs to the upper tropospheric water vapour, regardless of
its tiny concentration (Sinha & Harries, 1995; Spencer & Braswell, 1997). Consequently, the understanding of the near surface temperature variability goes through understanding of factor(s) and mechanism(s) controlling the spatial-temporal variability of the upper tropospheric water vapour.

As mentioned above, the changes in the lower stratospheric ozone density affect the near tropopause temperature, and consequently – the upper tropospheric static stability (North & Eruhimova, 2009; Young, 2003). Thus the abundance of ozone warms the tropopause, making the upper troposphere more stable, followed by its gradual drying – due to the suppressed upward propagation of moisture from the lower atmospheric layers. The greenhouse power of the depleted water vapour is significantly weakened and the near surface temperature cooled. Oppositely, the reduced amount of the lower stratospheric ozone cools the tropopause, making the upper troposphere more unstable. Consequently, more water vapour is lifted up in the upper troposphere, and the greenhouse warming of the Earth’s surface becomes stronger. In adiabatic systems the pressure follows temperature changes and consequently this is an indirect mechanism for ozone influence on the near surface pressure – i.e. through modulation of the temperature field. A schematic illustration of lower stratospheric ozone influence on the near surface temperature and pressure is shown in Fig. 8.

Fig. 8 Block-scheme of the various mechanisms of lower stratospheric ozone influence on the near surface temperature and pressure.
d. Factors influencing the spatial-temporal variability of the lower stratospheric ozone

In the lower stratosphere, a direct photochemical production of ozone (i.e. $O_2 + O + M \rightarrow O_3 + M$) is impossible, because the solar UV radiation reaching to the lower stratosphere, cannot dissociate any more the molecular oxygen. This extends the lifetime of the lower stratospheric ozone up to 3-4 years (Brasseur and Solomon, 2005), suggesting that the spatial distribution of the lower stratospheric ozone is controlled mainly by the stratospheric Brewer-Dobson circulation. However, recent multi-modelling experiments show that the amount of extra-tropical ozone is determined mainly by the local production, and that the impact of the tropical ozone, transported by the Brewer–Dobson circulation, is no more than 30% (Grewe, 2006). This result immediately raises the question: what is the source of ozone production at these latitudes and altitudes?

An answer could be found in Kilifarska (2013), presenting an evidence for the existence of a new ozone source in the lower stratosphere. This conclusion was completely unexpected, because to that moment the energetic particles have been considered only as destroyers of atmospheric ozone (e.g. Jackman et al., 1980; Rohen et al., 2005). The author reveals that the energy of the secondary electrons in the Regener-Pfotzer maximum is enough to produce the short lived tetraoxygen ion $O_4^+$, which products of dissociation determine the autocatalytic cycle of ozone production (Kilifarska, 2013).

The validity of this concept could be check-up by analysis of spatial-temporal coherence of energetic particles flux entering Earth’s atmosphere, and ozone density. Attempting to resolve the problem of causality, the lagged correlation analysis has been applied, which determines the time delay of the linear ozone response to particles’ forcing. The lagged correlation coefficients have been calculated in each node of our grid (with a resolution of 5 deg. in latitude and longitude). The coherence in ozone-particles’ evolution has been examined comparing the long-term variability of galactic cosmic rays (GCR) reaching the planetary surface (with 11-year solar cycle suppressed) and ozone mixing ratio at 70 hPa (with periodicities shorter than 5 years eliminated). Results are shown in Fig. 9, illustrating the spatial heterogeneity of GCR impact on the ozone. Note the particles’-ozone correlation varies not only in strength, but also in sign. These peculiarities should be attributed to the geomagnetic lensing of trapped energetic particles (in the lowest part of their trajectories) by heterogeneous geomagnetic field (Kilifarska et al., 2022).
Fig. 9 (top) Lagged correlation map of galactic cosmic rays and ozone mixing ratio at 70 hPa, calculated for the period 1900-2019. Values greater than 0.37 are statistically significant at $\alpha=0.05$ level (coloured shading); (bottom) Time delay of ozone response to GCR forcing in years.

Comparison of Figures 6 and 9 reveals that the strongest direct ozone impact on the sea level pressure corresponds to the regions with a negative GCR–ozone correlation. Moreover, the evolution of winter ozone at 70 hPa indicates that ozone mixing ratio over latitudinal belt 45°-75° N has been significantly lower during 20-th century, compared to the first decade of 21-st one (see Fig. 10). This could be a reasonable explanation for the positive NAO trend detected in the second half of 20-th century.
Fig. 10 Ozone temporal evolution at 70 hPa, during 20-th century, presented as a difference between corresponding decadal mean and the first decade of the 21-st century mean.

4. Discussion

The results presented in this study give a new perspective on the question: Why the Aleutian low and the region of the NAO formation act as centres determining the circulation variability in the Northern Hemisphere?

We found that besides the equator to pole temperature gradient, the circulation pattern could be affected also by pressure variations, imposed from the lower stratospheric ozone – especially in latitudinal belt 45°-75°N (refer to Figs. 6 and 9). Usually, the appearance of circulation anomalies is thought to be a stochastic process, related to the atmospheric/flow instability. This instability, however, could have its real physical forcing, i.e. the pressure fluctuations, induced by the variations of the lower stratospheric ozone density. Being a radiatively active gas, ozone abundance or depletion affects directly the sea level pressure, through local changes of the lower stratospheric temperature and respectively pressure. Figure 6 shows that the winter ozone’s impact on the sea-level pressure is strongest in the
regions of Bering Sea and Aleutian Islands, as well as in the North Atlantic – among Azores and Iceland islands – i.e. just over the main “centres of action”.

One reasonable question (related to the establishment of causality chain) is about the factor(s) determining the spatial-temporal variability of the lower stratospheric ozone. Our previous investigations uncover that it could be attributed to the variations of the Earth’s radiation belts, feeding the lower atmospheric ionisation in the Regener-Pfotzer maximum (Kilifarska et al., 2020; 2022). The amount of particles trapped in the Van Allen radiation belts is modulated by the solar variability and galactic cosmic ray fluxes, reaching the Earth’s magnetosphere (refer to a schematic diagram in Fig. 11).

Fig. 11 Schematic diagram of solar and geomagnetic modulation of cosmic rays (reaching Earth’s atmosphere), and their role for ozone production in the lower stratosphere, which in turn results in regional specificity of climate variations.

The latitudinal belt with reduced lower stratospheric ozone (within the most of the 20-th century) is under the influence of energetic particles trapped in the Van Allen radiation belts (see Figs. 9 and 10). The latter are fed primarily by galactic cosmic rays, the intensity of
which gradually decreases – up to the end of 20-st century (a modulation effect of the more active Sun, Rouillard & Lockwood, 2007). In agreement with the concept of the secondary source of ozone in the lower stratosphere (Kilifarska et al., 2013), the ozone mixing ratio at 70 hPa is significantly lower than its values during the first decade of 21-st century. The enhanced ozone density in the latter period is reasonably attributed to the severely reduced solar activity during the 24-th solar cycle, and corresponding raise of galactic cosmic ray flux.

The coupling between lower stratospheric ozone and atmospheric pressure and temperature could be traced at different time scales. This article shows evidence for their covariance at multidecadal time scales. A recent study illustrates, however, that such a coupling is well visible at daily and weekly time scales (Kilifarska & Pequini, 2023). These authors show that short lasting reduction of cosmic rays’ intensity is followed by well detectable depletion of near tropopause ozone density. The ozone response is regionally specified because of geomagnetic spatial irregularities, modulating the access of energetic particles into the lower atmosphere. This finding suggests that the stochastic nature of atmospheric circulation could be attributed – at least to some extent – to the spatial-temporal variability of the near tropopause ozone, due to its influence on the near surface pressure and temperature.

5. Conclusions

This paper shows statistical evidence for synchronisation of the long-term variations of winter ozone at 70 hPa, sea level pressure and near surface air temperature in the Northern Hemisphere. The different patterns of ozone influence on the pressure and temperature is an indication for different mechanisms of ozone effect. For example, the ozone impact on the sea level pressure could be direct (through local changes of the lower stratospheric temperature and pressure) or indirect – through changes of the near surface temperature, which in turn affects the pressure – in accordance with the energy conservation law.

The mechanism of distant lower stratospheric ozone effect on the near surface temperature consists of: (i) influence on the near tropopause temperature, (ii) alteration of the upper tropospheric static stability, followed by moistening or drying of the upper troposphere (Kilifarska et al., 2020); (iii) strengthening or weakening of the water vapour impact in the
atmospheric greenhouse effect (remind that the upper tropospheric water vapour ensures 90% of the impact of the whole atmospheric water vapour, Inamdar et al., 2004).

The regions of the strongest ozone influence on the winter sea level pressure correspond to the atmospheric “centres of action” – i.e. the Aleutian low and the region of formation of North Atlantic Oscillation (NAO). These regions coincide also with the strongest impact of energetic particles trapped in the Earth’s radiation belts on the lower stratospheric ozone density. This conjunction we interpret as a confirmation of our mechanism for energetic particles’ influence on the regional specificity of climate variability.

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Data Availability Statement.

Access to ERA-Interim data are deactivated since 1 June 2023, but ECNWF provides an updated reanalysis ERA 5 (https://registry.opendata.aws/ecmwf-era5), where atmospheric ozone, pressure and temperature could be retrieved from (registration is required). Data for cosmic rays flux, measured at the ground surface, are freely available at https://www.nmdb.eu/nest/ and http://cr0.izmiran.ru/common/links.htm. Graphs of NAO with CO₂, and ozone with sea level pressure and temperature, are created by the use of the STATISTICA commercial software (StatSoft's license). All maps are created by the use of the SURFER program, license held by the Golden Software. Schematic diagrams are created by MS Word program.

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