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Key Points:
- We examined the signals of El Niño–Southern Oscillation events, geomagnetic activity, solar wind, and solar proton events on the winter daily North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices.
- The autoregressive models for the indices included trends of solar activity, the Quasi-Biennial Oscillation, and sudden stratospheric warming.
- A day-to-day signal of Kp, solar wind speed and dynamic pressure on the NAO/AO indices was found. For the AO, solar proton events had a negative effect.

Supporting Information:
Supporting Information may be found in the online version of this article.

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Statistical Associations Between Geomagnetic Activity, Solar Wind, Solar Proton Events, and Winter NAO and AO Indices

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Abstract Numerous studies have revealed evidence that winter climate in the Northern Hemisphere is related to the solar cycle and space weather. Most of the studies investigating the impact of space weather on the North Atlantic Oscillation and Arctic Oscillation indices (NAOIs and AOIs) analyzed monthly or seasonal data. In this work, we evaluated the responses of winter NAOI/AOI to space weather changes on the day-to-day timescale during 1950–2020 by using an autoregressive (AR) model with additional predictors, such as month, linear trend, trends of solar irradiance and Kp indices, the Quasi-Biennial Oscillation (QBO) and El Niño–Southern Oscillation, the presence of sudden stratospheric warming (SSW) and high stratospheric aerosol loading (HSAL), and space weather variables, reflecting the day-to-day effect. Winter daily NAOI (AOI) follows the AR model of the 4th (5th) order. We found a positive day-to-day effect of Kp, solar wind speed (SWS) > 300 km/s, Bz ≤ 3.15 nT, and solar wind dynamic pressure (P) with a lag of 2 days on the NAOI and the AOI. For the AOI, additionally, the period of 1 day before–2 days after the solar proton event onset had a negative effect, and the signal of Kp and SWS was observed only for the east QBO phase. For the NAOI, a stronger effect of P was found on the presence of a strongly positive QBO phase. A stronger signal of Kp and SWS was found during HSAL. The signal of SWS > 300 km/s on the NAOI/AOI was different in sign during the periods with and without SSW.

Plain Language Summary Numerous studies have revealed evidence that winter climate in the Northern Hemisphere is related to the solar cycle and space weather. Most of recent studies investigating the impact of space weather on North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices analyzed monthly or seasonal data. In this work, we evaluated the responses of winter daily AO and NAO indices to space weather changes during 1950–2020 by using the autoregressive model with additional predictors, such as month, linear trend, trends of solar irradiance and Kp indices, variables of the Quasi-Biennial Oscillation and the El Niño–Southern Oscillation, the presence of sudden stratospheric warming and the period of high stratospheric aerosol loading, and space weather variables, reflecting the day-to-day effect. Our study showed a day-to-day signal of Kp, solar wind speed, the Bz component of the interplanetary magnetic field, and solar wind dynamic pressure on the NAO and the AO indices. During the period of 1 day before–2 days after the solar proton event onset, lower AO indices were observed.

1. Introduction
The coupling of solar variability and processes in the middle and lower atmosphere is of major scientific interest—especially in connection with ongoing global warming. Numerous studies have revealed evidence that the 11-year solar cycle (SC) affects atmospheric wind and temperature (Crooks & Gray, 2005; Gray et al., 2010; Labitzke & van Loon, 1988; Seppälä et al., 2013). In addition, atmospheric processes are linked to space weather variables such as solar proton events, geomagnetic activity, and solar wind, especially at higher latitudes. An intensification of cyclonic activity correlates with energetic solar proton >90 MeV energy events (Veretenenko & Thejll, 2004), increased geomagnetic activity (Ivanov, 2007), and high-speed solar wind (HSSW) (Prikryl et al., 2016). There is statistical evidence indicating that northern winter and spring circulations are affected by geomagnetic activity levels (Seppälä et al., 2013) and solar wind dynamic pressure (Lu, Jarvis, & Hibbins, 2008; Lu et al., 2013). The solar wind magnetic sector structure affects the winter upper-tropospheric vortices (Tinsley et al., 1994; Wilcox et al., 1973).

The climate variability in the Atlantic sector and in Europe to a large extent relates to the North Atlantic Oscillation (NAO) (Visbeck et al., 2001). Phases with a positive NAO index refer to a stronger than usual subtropical high-pressure center over the Azores and a deeper than normal Icelandic low. This results in above-normal...
temperatures in northern Europe and eastern United States. Negative NAO phases occur during a weak subtropical high and a weak Icelandic low (Hurrell et al., 2003). Oscillations between high and low NAO phases produce large changes in the wind speed and direction over the Atlantic as well as the heat and moisture transport between the Atlantic and adjacent continents (Hurrell et al., 2003). During the winter season (December–February), the NAO accounts for more than one-third of the total variance in sea level pressure over the North Atlantic. In the so-called “positive phase,” higher-than-normal surface pressures south of 55°N combine with a broad region of anomalously low pressure throughout the Arctic to enhance the climatological meridional pressure gradient (Hurrell & Deser, 2009).

The Arctic Oscillation (AO; also called the Northern Annular Mode (NAM)) indices are defined as the first principal component of Northern Hemisphere (NH) sea level pressure anomalies poleward of 20°N and are characterized by pressure anomalies of one sign in the Arctic and with the opposite anomalies centered about the latitudes of 37–45°N (Thompson & Wallace, 1998). It modulates the circulation pattern over the middle and high latitudes, thereby regulating the frequency and intensity of significant weather events. In the negative phase of the AO, the polar low-pressure system over the Arctic is weaker. The opposite is true when the AO is positive: the polar circulation is stronger, which forces cold air and storms to remain farther north. During NH winter, the AO clearly dominates the NAO structure over the Atlantic sector (Hurrell & Deser, 2009). Fluctuations in the AO are also associated with pressure anomalies over the North Pacific of the same sign as those over the Atlantic. This feature gives the NAM an almost annular (or zonally -symmetric) structure that reflects a more hemispheric-scale meridional seesaw in SLP between polar and middle latitudes (Hurrell & Deser, 2009). As NAO and the closely related AO are the most prominent patterns of atmospheric circulation over NH high and middle latitudes, they are closely related to atmospheric chemistry in NH. It has been shown that these oscillations influence long-range transport of chemicals (Bacer et al., 2016; Duncan & Bey, 2004; Eckhardt et al., 2003) and control the rate at which chemicals are transported across the troposphere-stratosphere boundary (Cohen et al., 2007; Cuevas et al., 2013) as well as the chemical transformation processes, etc.

The stratospheric circulation is most variable during winter when the polar stratosphere remains mostly in darkness and cools radiatively. The resulting difference in air temperature between the pole and lower latitudes leads to the formation of a strong westerly zonal wind, the polar vortex. The stratospheric polar vortex (SPV) is a band of strong westerly winds that forms in the stratosphere between about 16 and 48 km above the North Pole. Due to high temperature gradient between the middle latitudes and the North pole, the SPV emerges each year. In autumn when there is no solar heating in polar regions, SPV starts to form, strengthens during winter, and breaks down in spring when sunlight returns to the polar regions (Waugh et al., 2017). The strength of the SPV is well correlated with the variations of planetary waves propagating from the troposphere to the stratosphere (Asikainen et al., 2020; Salby & Callaghan, 2002). In the positive phase of the AO, the polar vortex is strong and anomalously cold, and a ring of strong winds circulating around the North Pole acts to confine colder air across polar regions. By contrast, in the negative phase of the AO, the polar vortex is weak, and the polar jet stream slows and meanders so that the extensions of polar low-pressure lobes reach much farther to the south and block the normal circulation of the atmosphere. Therefore, the so called “blocking events” associated with cold waves in the Atlantic and in Europe and increased storminess in the mid-latitudes are formed during the negative AO phase. (Thompson & Wallace, 1998). When the SPV is stronger than normal, it tends to support a positive NAO, while a weaker than normal SPV is more likely to coincide with a negative NAO (Baldwin & Dunkerton, 2001).

Possible influences of the SC and space weather on the NAO and AO have been reported in literature. Numerous studies have suggested an impact of the 11-year SC on the winter NAO (Andrews et al., 2015; Gray et al., 2013; Ineson et al., 2011; Scaife et al., 2013). Analyses of the most recent decades suggest a synchronized NAO-like response pattern to the SC, whereas long-term climate data sets demonstrate that the 2–4-year delayed signal resembles the positive (negative) phase of the NAO following a solar maximum (minimum) (Andrews et al., 2015; Gray et al., 2013; Ma et al., 2018; Scaife et al., 2013). It has been shown that the mean value of the winter NAO index was significantly more positive during the declining phase than in other cycle phases of the 11-year SC (Maliniemi et al., 2014). Hodd et al. (2013) found that the NAO index progressed from a mainly negative phase prior to the solar maximum to a mainly positive phase at and following the solar maximum. Kodera (2002) showed that during the sunspot maximum, NAO had a hemispherical structure extending into the stratosphere, while during the sunspot minimum, it was confined to the eastern Atlantic sector and the troposphere. Additionally,
other studies have suggested that the strengthening of the NAO pattern was related to the solar maxima (Huth et al., 2006; Ineson et al., 2011; Sfîcă et al., 2015).

During NH winter and spring, mean values of NAO indices are correlated with geomagnetic activity (Bochniček & Hejda, 2005; Bucha & Bucha, 1998; Maliniemi et al., 2016; Palamara & Bryant, 2004; Thejll et al., 2003), solar wind speed (SWS) (Zhou et al., 2014), and solar wind dynamic pressure (Lu, Jarvis, & Hibbins, 2008; Lu et al., 2013). The value of the 12-month moving average of NAO indices positively correlated with the corresponding values of Kp indices and the electric field strength of the solar wind (Boberg & Lundstedt, 2002). Lu, Jarvis, and Hibbins (2008) have shown that there was a statistical relationship between monthly values of solar wind dynamic pressure and the NAM, which is close to the NAO. High-speed solar wind is the reason of energetic electron precipitations (EERs) (Asikainen & Ruopsa, 2016). EEP strengthens the SPV and has been found to correlate with the monthly NAOI and AOI (Bauergaertner et al., 2011; Maliniemi et al., 2014, 2016; Salminen et al., 2019). The indices of the NAO and the AO showed correlations on the day-to-day timescale with the SWS, and minima in the indices were found on days of SWS minima during years of high stratospheric aerosol loading (HSAL) (Zhou et al., 2014). The physical mechanism of this day-to-day effect may be explained by the effect of the relativistic electron precipitation (REP) on the flow of the downward current density (J) which affects the distribution of electric charge in the clouds (Tinsley, 2012). A high loading of volcanic aerosols results in a lower rate of ion concentration, a lower conductivity, and a higher column resistance in stratospheric ultrafine layer (near 40 km altitude) at high latitudes (Tinsley & Zhou, 2006). The resistance of this column is constantly decreased by ionizing radiation due to REP (positively correlated with SWS) which produces Bremsstrahlung X rays that can dominate the ion pair production in the stratosphere (Frahm et al., 1997; Tinsley & Zhou, 2006; Zhou et al., 2014), and a decrease in REP showed a stronger decrease in J during periods of a higher stratospheric column resistance (Tinsley & Zhou, 2006).

Correlations linking the atmospheric variations to solar-geomagnetic activity showed changes in this relationship at different time scales. The analysis of time series of the NAO index and the aa index of the period from December to March during 1869–2009 showed a non-linear association between the NAO index and the aa index (Y. Li et al., 2011). Correlations between atmospheric changes and solar or geomagnetic activity indices are often strongly dependent on the phase of the Quasi-Biennial Oscillation (QBO) (Maliniemi et al., 2016; Palamara & Bryant, 2004). The analysis of the monthly data shows that geomagnetic activity correlated positively with NAM for the entire 20th century during easterly QBO (Maliniemi et al., 2016; Palamara & Bryant, 2004) while early and late winter NAM responded to geomagnetic activity very differently (Maliniemi et al., 2016). The QBO is one of the most remarkable phenomena in the Earth's atmosphere. It results from the interaction of vertically propagating waves with the horizontal background flow. The QBO dominates the variability of the equatorial stratosphere (~16–50 km) and is easily seen as downward propagating easterly and westerly wind regimes, with a variable period averaging approximately 28 months (Baldwin et al., 2001; Coy et al., 2016). At a given altitude, the winds might start as westerlies, but over time they weaken and eventually reverse, becoming strong easterlies. The amplitude of the easterly phase is about twice as strong as that of the westerly phase. QBO (zonal-mean equatorial zonal wind) between 30 hPa and 50 hPa usually is used in the studies analyzing the impact of QBO on northern winter circulation (Baldwin et al., 2001; Maliniemi et al., 2016). The geomagnetic forcing of atmospheric circulation in the NH in January could be modulated by the QBO (Palamara & Bryant, 2004; Seppälä et al., 2013). The effect of the EEP (proxy to Ap indices) on the SPV was stronger during the east QBO phase with a lag of 6 months (Salminen et al., 2019). This effect may be explained by the larger ozone mass mixing ratio in the lower polar stratosphere during the east QBO phase than during the west QBO phase with the difference maximizing when the QBO is lagged by 6 months (Salminen et al., 2019).

Other phenomena such as stratospheric sudden warming (SSW) and volcanic eruptions have been shown to affect the atmospheric pattern (Asikainen et al., 2020; Baldwin & Dunkerton, 2001; Tinsley et al., 1994). SSW is characterized by a very rapid increase (by about 40 K in a week) in the stratospheric polar cap temperature at about 10-hPa level (Kuroda, 2008). Enhanced planetary wave convergence and meridional circulation may lead to the breaking of the polar vortex, resulting in an SSW (Asikainen et al., 2020). Recent advanced studies on the troposphere-stratosphere coupling have revealed that SSW significantly influences the tropospheric climate (Asikainen et al., 2020; Baldwin & Dunkerton, 2001; Kuroda, 2008; Limpasuvan et al., 2004). It was demonstrated that the effect of SSW propagated down to the surface and lasted more than 2 months after the onset of SSW and that the surface pressure signal shifted more toward a negative pattern of the AO (Thompson & Wallace, 1998).
occurrence of SSW was more frequent in the east QBO winters and the effect of the QBO phase on the occurrence of SSW was stronger during the period of low GMA or when the El Niño–Southern Oscillation (ENSO) was in the cold phase (Salminen et al., 2020). According to the results of Asikainen et al. (2020), the enhancement of SPV and other dynamic responses in the atmosphere related to an increase in Ap indices (a proxy to EEP amount) was seen only during winters when SSW occurred, and the changes due to Ap were observed before the onset of SSW.

ENSO is an ocean-atmosphere coupled system with an irregular periodic fluctuation of sea surface temperatures, wind, and pressure over the equatorial Pacific Ocean. ENSO plays a key role in global inter-annual variations in weather and climate (Trenberth & Caron, 2000). ENSO affects the strength and variability of the SPV and SSW events, and these, in turn, may contribute to NAO variability (Domeisen et al., 2019; Huang et al., 1998; Maliniemi et al., 2018). A non-linear association was found between warm ENSO events and the NAO (Bell et al., 2009; Huang et al., 1998). The analysis of the data of the coherent and incoherent periods between the NAO and the warm ENSO phase showed that most of the incoherent years fell in the minimum phase of the SC (Huang et al., 1998). It was determined that SC modulated the ENSO effect on the Pacific/North American pattern (D. Li & Xiao, 2018). It is possible that Solar-geomagnetic variations influenced the link between the ENSO and the NAO and AO.

The associations between NAO and AO indices and space weather variables were mostly analyzed by using their monthly or seasonal values. In recent years, the multiple linear regression was used to analyze the relationship of winter sea level pressure (at the same time, the NAO and AO pattern) with the Nino3.4 index, stratospheric aerosol optical depth, QBO, and solar and geomagnetic activity only by using monthly data (Gray et al., 2013; Roy et al., 2016; Maliniemi et al., 2018, 2019). However, the monthly or annual data cannot fully capture the consequences of the short-term effect of space weather events on the NAOI and AOI variations within any months and seasons.

In this work, we evaluated the responses of NH winter (December-February) AO and NAO indices (AOI and NAOI) to some space weather changes on the day-to-day timescale during the period of 1950–2020 by using an autoregressive (AR) model with additional predictors. The daily-level analyses could be more accurate and instructive in clarifying the effects of such space weather events as HISSW or solar proton events (SPEs), and such an analysis also accounts for potential short-term impacts related to the global electric circuit (GEC). At first, we created an AR model for the daily NAOI and AOI and analyzed the statistical associations between residuals obtained by fitting these models and the ENSO and the QBO. Secondly, we created AR models with additional predictors for the NAOI and AOI by including the month, the linear trend, the trends of solar activity and the geomagnetic activity evaluated as the 2-year mean values of, respectively, solar flux and Kp indices, solar wind variables, SPEs, the variables of the ENSO and QBO, the presence of SSW, and the volcanic eruption level. The analyses were performed separately for different winter months. Apart from this, we analyzed the statistical associations between monthly space weather variables and the autocorrelations and parameters of the AR models for the NAO and AO indices created for different winters and months.

2. Methods

2.1. Data

The values of daily NAO and AO indices (NAOI and AOI) were obtained from the National Oceanic and Atmospheric Administration (NOAA) database ftp://ftp.cpc.ncep.noaa.gov/cwlinks/ since 1950. We used the daily Kp and Ap index as a measure of GMA, solar radio flux at 10.7 cm (F10.7) which is an excellent indicator of solar activity and is more relevant than the sunspot number as it reproduces most of the variability of the UV band (Tapping, 2013), daily mean values of solar wind plasma parameters (proton density (Np, proton/cm^3), SWS (km/s), solar wind dynamic pressure (P, nPa)), solar proton >10 MeV flux (pfu = protons/(cm^2-day-sr)), and values of the B_x, B_y, and B_z components of the interplanetary magnetic field (IMF) presented in GSM coordinates. These data were downloaded from NASA/GSFC’s OMNI data set through https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/omni_01_av.dat (accessed on 4 March 2021). Data on Kp and F10.7 were used for the period since 1950, data on other solar wind parameters—since 1964, and data on solar proton flux—since 1967. Solar proton events (solar proton >10 MeV energy flux over 10 pfu) and geomagnetic storms (GS) (Ap ≥ 30 nT) were used as space weather events. The monthly data of the F10.7 (Kp) were used to determine the level of
solar activity (GMA), and the level was determined as high if monthly F10.7 (Kp) was > the median of monthly F10.7 (Kp) during the winter period. Monthly QBO data—zonal-mean equatorial zonal wind velocity (EZWV) at 30 hPa pressure level—were downloaded from the Climate Data Center through http://www.daculawather.com/4_qbo_index.php for 1950–1959 and from Climate Explorer database through https://climexp.knmi.nl/data/inqbo.dat for the period since 1960. Niño3.4 indices were taken from the Climate Explorer database (https://climexp.knmi.nl/data/erssst_nino3.4a.dat). We defined the periods of HSAL as such: December 1963–February 1966, December 1982–February 1984, and December 1991–February 1995 following the volcanic eruptions of the Mt. Agung, El Chicon, and Pinatubo, respectively. The data on SSW were obtained from (Butler et al., 2015) for 1958–2013, from (Siddiqui et al., 2015) for 1950–1957, and from (Shi et al., 2020) for 2018–2019. For 2014–2016 (Manney & Lawrence, 2016), we included a major SSW that occurred in March 2016, while a minor SSW that occurred in January 2015 was not included.

### 2.2. Statistical Analysis

As the daily values of the NAOI and AOI are highly autocorrelated, we used a pth-order AR model (AR(p)) (Cryer & Chan, 2008) for the analysis of the winter NAOI and AOI time series:

\[
Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + e_t
\]

(1)

where \(Y_t, Y_{t-1}, Y_{t-2}, \ldots, \) and \(Y_{t-p}\) are the NAOIs (or AOIs) on the \(t\) day and on the \(p\)th previous days, respectively, \(\phi_i\) are parameters of the model, and \(e_t\) is white noise.

First, we determined the order of the AR model for winter NAOI and AOI. To choose the order \(p\) of the AR(p) model, the Ljung-Box (L-B) test (Cryer & Chan, 2008) was used. The L-B test is applied to the residuals of a time series after fitting an autoregression-moving average model to the data. The test examines \(m\) autocorrelations of the residuals. If the L-B statistic is non-significant, then models’ error is random. We chose the minimal order of such AR whose p-value of the L-B test was >0.05. The coefficients of the AR model were estimated by both the fast maximum likelihood (ML) algorithm (McLeod & Zhang, 2008) (the data of November-March were used) and the least squares (LS) method (the December-February data were used).

Second, we analyzed the associations of the residuals of the time series of the AR model with the Niño3.4 indices, EZWV, SSW, and space weather variables. As space weather variables, we used the trends of the long-term variation of solar and geomagnetic activity evaluated as the 2-year mean value of the daily solar flux and Kp indices (respectively, the F10.7trend and the Kp trend) and the daily values of Kp, solar wind variables, and the presence of SPE. We used space weather variables reflecting a short-term signal with a lag of 0, 1, and 2 days. As before solar flares and coronary mass ejection, disturbances in the solar magnetic field occur and solar radiation increases, it is possible that changes in the solar magnetic field affect atmospheric circulation. Therefore, we assessed the effect of 1–2 days before the onset of the SPE on the residuals of the time series of the AR model.

The associations between the residuals and the continuous environmental variable were assessed by calculating correlations, by analyzing the graphical presentations of the mean values of the residuals, or by using the regression tree (Breiman et al., 1984). This algorithm begins allocating the data into the first two non-overlapping partitions, or branches, using every possible binary split on every field. The algorithm selects the split that minimizes the sum of the squared deviations from the mean in the two separate partitions. This splitting rule is then applied to each of the new branches. Correlations were assessed by using Spearman’s correlation coefficients. For samples of non-correlated measurements, to compare the mean values, \(t\)-test for two groups and ANOVA for more than two groups were used. As a non-linear association between the ENSO and the NAO/AO pattern was observed (Huang et al., 1998), we included the cubic trend of the Niño3.4 index, binary variables of El Niño (Niño3.4 index > mean + SD), La Niña (Niño3.4 index < mean – SD), and a strong El Niño event (Niño3.4 Index >mean + 2*SD) as explanatory variables in the model for the residuals of the NAOI and AOI. Statistically significant variables from them were used as the Niño3.4 variables in further models.

Third, we analyzed the associations between the winter (December–February) daily NAOI and AOI and daily space weather variables during January 1950–February 2020 by using the AR model with additional predictors such as the month (a categorical variable, the reference category being February), the linear trend, the years of HSAL, SSW (equal to 1 on 1–5 days before the onset of SSW until the end of February and 0 otherwise), the
variables reflecting the effect of the QBO and the ENSO, variables of the F10.7trend and the Kptrend, and the space weather variables:

\[
Y_t = \beta_0 + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} + \cdots + \varphi_p Y_{t-p} + \beta_1 (\text{month} = \text{December}) + \beta_2 (\text{month} = \text{January}) + \beta_3 (\text{variable of F10.7 trend}) + \beta_4 (\text{variable of Kp trend}) + \beta_5 \text{SSW} + \beta_6 \text{HSAL} + \beta_7 (\text{variables of ENSO}) + \beta_8 (\text{variables of EZWV}) + \beta_9 \text{var}
\]

where \(Y_t, Y_{t-1}, \ldots\) are the NAOI/AOI indices, \(\varphi\) and \(\beta\) are regression coefficients, and \(\text{var}\)—is space weather variables giving day-to-day signal.

Apart from this, we improved this model by including the statistically significant interactions of the F10.7trend, Kptrend, Kp, and other space weather variables with ENSO events, SSW, and the QBO phase as additional predictors in the AR model. The coefficients of the models were assessed by using the Least Square method. To assess the impact of space weather variables, we presented the standardized beta coefficients with their standard error (SE) and the p-value of beta. The beta values were calculated per increase of 1 SD for continuous space weather variables. In addition, the analysis was performed in different winter months, on days with a high or low sulfur aerosol loading, and during the east and the west QBO phases (eQBO and wQBO, respectively). To confirm the statistical association between space weather variables and the NAO and AO indices, we performed a set of superposed epoch analysis for the response of the NAO index and the AO index with the key days of the onset of GS defined by the Ap index (Ap \(\geq 30\)), the period of Kp \(> 3\) that took place at least for 3 consecutive days, and SPE. As the daily values of the NAOI/AOI are highly correlated on the key day, to detect a statistically significant signal of GS or SPE, we used the paired \(t\)-test to compare the mean of the differences between the daily indices at neighboring lags with 0.

We assessed the effect of the ENSO, the QBO phase, SSW, the sulfur aerosol loading level, the SC phase, Solar-geomagnetic activity, SWS, P, and SPE on the variations of parameters in the AR model for the daily NAOI and AOI. As the monthly mean values of the NAOI and AOI were varied, we fitted a mean-centered AR model (Cryer & Chan, 2008):

\[
(Y_t - \mu) = \varphi_1 (Y_{t-1} - \mu) + \cdots + \varphi_p (Y_{t-p} - \mu) + \epsilon_t
\]

for indices in each winter and each month. Apart from this, we assessed autocorrelations and partial correlations up to the 4th order for separate winters and months. The parameter \(\mu\) did not differ much from the mean value of \(Y_t\). Following that, we analyzed the associations of these monthly or winter correlations and AR parameters with the environmental variables.

3. Results

3.1. The AR Model for the NAO and AO Indices

Figures 1a and 1b show time series of winter daily NAOI and AOI and time series smooth out with a 61 days running mean. In the daily time series, a random fluctuations are seen. The autocorrelation and partial correlation functions of these time series show AR process of higher order.

The fitting of the AR model for the daily NAOI and AOI showed that the winter NAOI followed the AR(4) model, and the daily AOI followed the AR(5) model. During winter, the changes in the NAOI (AOI) during 1–4 (1–5) previous days may explain about 93% (95%) of the variance in the NAOI (AOI) on the current day (Table S1).

The time series of residuals calculated by estimating AR parameters by ML and LS methods were highly correlated: \(r = 0.998\) (0.986) for the NAOI (AOI) model. A statistically significant positive linear trend was observed in the residuals of the AR(4) for the NAOI and the AOI. Time series of residuals in the NAOI (AOI) model were positively associated with the F10.7trend (F10.7trend>170). No statistically significant correlations between long-term variation in Kp and time series of residuals were found. However, the results of the regression tree algorithm showed that the mean values of the residuals in the NAOI model were significantly higher during periods of greater long-term GMA (Kptrend>1.3). The time series of the residuals positively correlated with EZWV, daily Kp and SWS with a lag of 0, 1, and 2 days, and with P with a lag of 1 and 2 days. A positive association between Kp the day before and residuals in the NAOI/AOI model (Figures 2a and 2c) and mean values
of the NAOI/AOI (Figures 2e and 2g) were found. Moreover, stronger positive associations between the mean values of the NAOI/AOI were detected. The same tendency was seen for associations with SWS on the same day (Figures 2b, 2d, 2f and 2h) and with P 2 days before (Figures 3a–3d). A possible stronger association between Kp and the residuals was seen during the east QBO phase (Figures 2i and 2k) compared to that during the west QBO phase. A possible different signal of SWS lower than 300 km/s was seen on days of SSW and on days without SSW (Figures 2j and 2l). The interaction term between the categories of the ENSO (neutral, La Niña, moderate El Niño, and strong El Niño), and the Kp/SWS categories in two-way ANOVA for the residuals of the NAOI was statistically significant. A statistically significant associations between SWS and the residuals for the NAOI (AOI) were found only during moderate El Niño events (neutral ENSO and moderate El Niño).

The regression tree algorithm showed a positive effect of SWS >500 km/s with a lag of 2 days on the residuals in the NAOI model, and a positive effect of SWS >450 km/s on the same day on the AOI residuals. The mean values of the residuals in the models for the NAOI/AOI were statistically significantly lower on days of B > 3.15 nT. During the period of 1 day before–2 days after the onset of SPE, the mean values of residuals in the AOI model were significantly lower as compared to other days. Therefore, in the analysis, we assessed the effect of this period named as SPE1.

The analysis of the mean values of the residuals of the NAOI and AOI model during different mean equatorial zonal wind levels did not show any non-linear associations. However, for the EZWV, the cut-off of 6.34 m/s was detected by using the regression tree algorithm. In the multivariate models, we used the following QBO variables: EZWV or 1*(EZWV > 6.34).

3.2. Statistical Associations of the Residuals of the AR Model of the NAO and AO Indices With the ENSO

The results of the one-way ANOVA and the t-test showed a statistically significantly higher mean value of the residuals of the winter AOI during La Niña events. A significantly higher mean value of the residuals of the NAOI during La Niña events was found in February. A higher mean value of the residuals of the NAOI was detected during strong El Niño events compared to those during the days of moderate El Niño events (mean + 1*SD < Niño3.4 ≤ mean + 2*SD) (Figures 4a and 4b), and the differences were more pronounced during higher levels of solar and geomagnetic activity. The results of the two-way ANOVA with the categorical predictors of ENSO events and the month showed a statistically significant effect of the ENSO events on the residuals of the NAOI and AOI and for the AOI, and a significant interaction between the month and ENSO events was found.
In the AR(4) model for the NAOI and in the AR(5) model for the AOI with additional predictors such as the month, the linear trend, the F10.7trend, the SSW, the HSAL, (EZVW > 6.34), and (Kptrend > 1.3), the positive effect of La Niña was significant (Table 1).

3.3. The Effects of Space Weather Variables on the NAOI and AOI

We analyzed the associations between the winter daily NAOI and AOI $Y_t$ (4) and (5), respectively) and daily space weather variables by using the following AR model with additional predictors:
Figure 3. The mean values with ±standard error during different intervals of P 2 days before: for the residuals of the (a)/(b) NAOI/AOI and for the (c)/(d) NAOI/AOI.

\[ Y_i = \beta_0 + \varphi_1 Y_{i-1} + \varphi_2 Y_{i-2} + \cdots + \varphi_4 Y_{i-4} + \beta_{11}(\text{month} = \text{December}) + \beta_{12}(\text{month} = \text{January}) + \beta_3 \text{years} + \beta_4 F10.7 \text{trend} + \beta_5 K\text{trend} > 1.3 + \beta_6 \text{SSW} + \beta_7 \text{HSAL} \] (4)

and

\[ Y_i = \beta_0 + \varphi_1 Y_{i-1} + \varphi_2 Y_{i-2} + \cdots + \varphi_5 Y_{i-5} + \beta_{11}(\text{month} = \text{December}) + \beta_{12}(\text{month} = \text{January}) + \beta_3 \text{years} + \beta_4 (F10.7 \text{trend} > 170) + \beta_5 K\text{trend} > 1.3 + \beta_6 \text{SSW} + \beta_7 \text{HSAL} \] (5)

Figure 4. The mean values of the residuals in the autoregressive (AR) model for (a) the NAOI and the (b) AOI and the parameters (c) \( \mu \) and (d) \( \phi_2 \) in monthly AR models with 95% CI during La Niña, moderate El Niño (El Niño*), and strong El Niño (El Niño+) events.
Table 1
The Effect of Environmental Variables During 1950–2020 in the Autoregressive (AR) (4) Model for the NAOI and in the AR (5) Model for the AOI

| Variable | NAO index | | AO index | |
|----------|-----------|------------------|-----------|------------------|------------------|------------------|------------------|------------------|------------------|
|          | $\beta$ (SE) | $p$ | $\beta$ (SE) | $p$ | $\beta$ (SE) | $p$ | $\beta$ (SE) | $p$ | $\beta$ (SE) | $p$ |
| Additional predictors in AR model* | | | | | | | | | | |
| SSW | $-0.019 (0.006)$ | 0.002 | $-0.059 (0.013)$ | <0.001 | | | | | | |
| F10.7trend | 0.007 (0.003) | 0.022 | | | | | | | | |
| F10.trend > 170 | | | | | | | | | | |
| Kp t | $0.077 (0.018)$ | <0.001 | $0.154 (0.036)$ | <0.001 | | | | | | |
| (EZWV > 6.34) | $0.018 (0.007)$ | 0.007 | $0.020 (0.014)$ | 0.153 | | | | | | |
| La Niña | 0.019 (0.008) | 0.015 | 0.052 (0.016) | 0.001 | | | | | | |
| The short-term effect of space weather variables (for SW parameters since 1964) c | | | | | | | | | | |
| Kp lag 0 | 0.004 (0.003) | 0.131 | $0.014 (0.006)$ | 0.013 | | | | | | |
| Kp lag 1 | 0.008 (0.003) | 0.005 | $0.014 (0.006)$ | 0.013 | | | | | | |
| Kp lag 2 | 0.006 (0.003) | 0.038 | $0.006 (0.006)$ | 0.381 | | | | | | |
| GS lag 0–2 | 0.025 (0.008) | 0.001 | | | | | | | | |
| SWS lag 0 | | | | | | | | | | |
| (SWS > 300 lag 0) with SSW | $-0.041 (0.031)$ | 0.192 | $-0.122 (0.064)$ | 0.058 | | | | | | |
| (SWS > 300 lag 0) without SSW | $0.059 (0.022)$ | 0.006 | $0.132 (0.042)$ | 0.002 | | | | | | |
| SWS > 500 lag 2 | 0.017 (0.008) | 0.038 | | | | | | | | |
| $B_y > 3.15$ lag 0 | $-0.019 (0.009)$ | 0.045 | $-0.048 (0.019)$ | 0.013 | | | | | | |
| P lag 2 | 0.008 (0.003) | 0.014 | $0.015 (0.007)$ | 0.027 | | | | | | |
| (P lag 2)* (EZWV > 6.34) | 0.013 (0.004) | 0.001 | | | | | | | | |
| SPE1 | | | | | | | | | | |
| The short-term effect of space weather variables during the east QBO phase c | | | | | | | | | | |
| Kp lag 1 | 0.009 (0.003) | 0.018 | $0.021 (0.008)$ | 0.006 | | | | | | |
| SWS lag 0 | | | | | | | | | | |
| (SWS > 300 lag 0) without SSW | 0.072 (0.033) | 0.028 | | | | | | | | |
| P lag 2 | 0.007 (0.004) | 0.106 | $0.015 (0.010)$ | 0.105 | | | | | | |
| SPE1 | $-0.098 (0.051)$ | 0.052 | | | | | | | | |
| The short-term effect of space weather variables during moderate El Niño c | | | | | | | | | | |
| Kp lag 2 | 0.021 (0.009) | 0.018 | $0.040 (0.017)$ | 0.018 | | | | | | |
| SWS lag 0 | 0.024 (0.010) | 0.023 | $0.032 (0.020)$ | 0.115 | | | | | | |
| SWS > 300 lag 0 | 0.098 (0.043) | 0.022 | $0.122 (0.080)$ | 0.127 | | | | | | |
| P lag 2 | 0.015 (0.010) | 0.115 | $0.043 (0.018)$ | 0.012 | | | | | | |
| The short-term effect of space weather variables during strong El Niño c | | | | | | | | | | |
| Kp lag 1 | $-0.007 (0.018)$ | 0.714 | $-0.061 (0.029)$ | 0.036 | | | | | | |
| SWS > 300 lag 0 | 0.269 (0.076) | <0.001 | $0.132 (0.117)$ | 0.258 | | | | | | |
| SPE1 | $-0.369 (0.119)$ | 0.002 | | | | | | | | |
| The effect of several space weather variables | | | | | | | | | | |
| (1) Kp lag 1 | 0.009 (0.003) | 0.008 | | | | | | | | |
| Kp lag 0 | | | | | | | | | | |
| (SWS > 300 lag 0) without SSW | 0.044 (0.022) | 0.041 | $0.103 (0.047)$ | 0.027 | | | | | | |
| (SWS > 300 lag 0) with SSW | | | | | | | | | | |
| $B_y > 3.15$ lag 0 | | | | | | | | | | |

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where φ and β are regression coefficients and var is a variable of Kp, GS, SWS, P, or SPE. The estimates of β3−β5 and β7−β9 are presented in Table 2. β3 and β9 are coefficient slopes per 1 SD (44 for F10.7trend, 1.1 for Kp, 101 for SWS, and 1.4 for P) for continuous variables.

In the AR models with additional predictors for the indices, a statistically significant impact was detected for SSW, a higher long-term GMA, and La Niña events. The NAOI were positively associated with the F107trend and the presence of EZWV >6.34 m/s. The indices were positively associated with the day-to-day fluctuation of Kp, a lower than 3.15 nT By, and P; moreover, the effect of Kp was stronger on the previous day for the NAOI and on the same and the previous day, for the AOI. The effect of P was stronger 2 days before (Table 1). For the NAOI, a signal during GS and 1–2 days after them was detected and a stronger effect of P on the presence of a strongly positive QBO phase was found. The AOI were positively associated with SWS and negatively associated with SPE1 (Table 2). The signal of a SWS>300 km/s was associated with higher NAO/AO indices during the period without SSW. No significant effect of solar proton density or other components of the IMF on winter NAOI or AOI was found.

The effect of Kp for indices was stronger during the east QBO phase. For the AOI, the effect of Kp and SWS was statistically significant only during the east QBO phase while during the west QBO phase, the p-values of beta coefficients of Kp and SWS were over 0.6. During the period of moderate El Niño, the effect of Kp was found with a lag of 2 days for both AOI and NAOI, the effect of P with a lag of 2 days was significant only for AOI, whereas the effect of SPE was not detected (Table 1). The signal of SWS>300 km/s on the NAOI was statistically significant only during El Niño events and during this period, it was not dependent on SSW. The effect of Kp was not observed on the NAOI during strong El Niño; while a negative effect of Kp on the AOI during strong El Niño was found (Table 1). In the model with two space weather variables (Kp and SWS or P), only Kp was significant.

In the model with several space weather variables, both the variables P and Kp or (SSW > 300 km/s without SSW) and Kp were significant for the NAOI. For the AOI, Kp, SWS, a higher By, and SPE1 had a significant impact. If P was included in the model, then continuous Kp was non-significant: only categorical variables of Kp and P were statistically significant for the AOI (Table 1).

Further, we tried to elucidate whether there were any differences between the effects of space weather variables on the NAOI and AOI during the periods of HSAL and those without HSAL. During the periods without strong El Niño, signals of Kp and GS (Ap ≥ 30) on the same day were statistically significant on the NAOI only during the period of HSAL (Table 3). Besides, for the NAOI, a statistically significant interaction term of HSAL with the SWS on the same day (β (SE) = 0.021 (0.009), p = 0.026) was found. For the AOI, a statistically significant signal

| Table 1 Continued |
|-------------------|
| Variable | NAO index | AO index |
| Variabele (2) (P lag 2)*(EZWV > 6.34) | $0.009 (0.003)$ | $0.002$ |
| Kp lag 1 | $0.008 (0.003)$ | $0.019$ |
| (3) Kp lag 0 | $0.022 (0.008)$ | $0.003$ |
| (SWS > 300 lag 0) with SSW | $-0.155 (0.066)$ | $0.018$ |
| $B_y > 3.15$ lag 0 | $-0.054 (0.020)$ | $0.007$ |
| SPE1 | $-0.109 (0.040)$ | $0.006$ |
| (4) Kp lag 0 > 15 | $0.040 (0.016)$ | $0.013$ |
| P lag 2 > 3.1 | $0.038 (0.018)$ | $0.035$ |
| (SWS > 300 lag 0) with SSW | $-0.168 (0.069)$ | $0.014$ |
| SPE1 | $-0.105 (0.040)$ | $0.009$ |

$\beta$—coefficient slopes per 1 SD increase in continuous variables. In the model additionally included the month, the linear trend, and HSAL. In the model with the month, the linear trend, HSAL, SSW, the variable of the F10.7trend, (Kptrend > 1.3), (EZWV > 6.34) if this variable was not included in the interaction term, and the La Niña event.

Note. *denotes the sign of the interaction or combined term.
of SWS was detected only during the period of HSAL, and higher absolute values of beta for P and SPE1 during HSAL were observed. During the east QBO phase, a day-to-day effect of Kp and GS on the AOI was stronger during the periods of HSAL (Table 2).

A different signal of space weather variables (excluding B,) on the teleconnections was found during different months. The signal of Kp, SWS, and P on the NAOI was stronger in late winter, especially in January (Table 3). A stronger signal of the SPE1 on the AOI was observed in early winter, and a significant effect of Kp, SWS, and P on the AOI as additional predictors was observed in December (Table 3). In late winter, the signal of Kp, SWS, and P on the AOI was statistically significant only during the east QBO phase (Table 3).

### 3.4. The Superposed Epoch Analyses

The results of the superposed epoch analyses confirmed the observed signal of space weather variables on the daily NAOI/AOI. We found a significant mean increase in the NAOI on the 2nd (the 3rd day) after the onset of GS as compared to 1–3 days (1–4 days) before the onset of GS (Figures 5a and 5b). A statistically significant increase in the NAOI on the day of the onset of the period of Kp > 3 for ≥3 consecutive days and 1–3 days after them as compared to the 1st-5th days before the onset of a period of a Kp > 3 (Figures 5c and 5d) was found. During the period without La Niña, an increase in the AOI on the day after of the onset of the period of Kp > 3 as compared to the 3rd and the 4th days before the key day was observed (Figures 5e and 5f). A decrease in the AOI was observed from the onset of the SPE (Figure 5g). On the days of the SPE onset and 1–3 days after, a decrease in the AOI was significant as compared to that registered 2–5 days before the SPE (Figure 5h).
3.5. The AR Models for the NAO and AO Indices During Different Winters and Months

We fitted mean-centered AR(3) models for the NAOI and AOI in each winter (December-February) and mean-centered AR(2) models for indices in each month. The order of the AR model was chosen to be lower because winter and monthly time series were shorter. In more than 95% of winters or months, the residuals in the chosen AR models could be considered as non-correlated.

The study showed that some parameters of the AR models fitted during different months were not equal for different ENSO events. For the NAOI (AOI), the parameter $\mu$, little different from the mean value of the NAOI/AOI (Cryer & Chan, 2008), was higher during strong El Niño (La Niña) events as compared to the neutral ENSO (Figure 2c). During strong El Niño events, the parameter $\phi_2$ was lower in comparison with the neutral ENSO and the moderate ENSO for the NAOI (Figure 4d). During the months with predominant SSW events, a lower $\phi_2$ for the AOI was detected. A downward trend in the strength of the 1–3rd order of autocorrelations for the NAOI and a rise in $\mu$ for both monthly indices was observed. During months with EZWV > 6.34 m/s, lower autocorrelations of 1–3rd order and a higher $\mu$ for monthly models for both indices was found. During the descending SC phases, higher autocorrelations for the NAOI were observed. The monthly Kp, P, and SWS (the Ftrend) positively correlated with $\mu$ in the model for both indices (for the NAOI). If SPE occurred in the first half of the month or in last half of the previous

| Variable | December | January | February |
|----------|----------|---------|----------|
| NAO index | | | |
| Kp lag 1 | 0.003 (0.006) | 0.12 (0.004) | 0.009 | 0.008 (0.003) | 0.029 |
| (SWS > 300 lag 0) | 0.054 (0.036) | 0.133 | | 0.057 (0.033) | 0.085 | 0.066 (0.060) | 0.270 |
| SWS > 500 lag 2 | 0.001 (0.020) | 0.981 | | 0.034 (0.013) | 0.008 | 0.014 (0.010) | 0.168 |
| (P lag 2)*(EZWV > 6.34) | 0.011 (0.008) | 0.139 | | 0.017 (0.007) | 0.007 | 0.011 (0.006) | 0.019 |
| AO index | | | |
| Kp lag 0 | 0.021 (0.010) | 0.030 | | 0.011 (0.010) | 0.266 | 0.010 (0.010) | 0.320 |
| Kp lag 1 | 0.020 (0.010) | 0.047 | | 0.008 (0.010) | 0.432 | 0.014 (0.010) | 0.136 |
| SWS lag 0 | 0.024 (0.012) | 0.039 | | 0.004 (0.011) | 0.688 | 0.015 (0.012) | 0.225 |
| (SWS > 300 lag 0) | 0.120 (0.058) | 0.039 | | 0.116 (0.075) | 0.121 | 0.232 (0.165) | 0.159 |
| P lag 2 | 0.027 (0.013) | 0.029 | | −0.006 (0.011) | 0.613 | 0.031 (0.013) | 0.014 |
| SPE1 | −0.106 (0.059) | 0.074 | | −0.108 (0.062) | 0.081 | −0.083 (0.062) | 0.184 |

*In the AR model, the additionally included predictors were those defined in Table 2 excluding the month. *Without SSW; wQBO - the west QBO phase; eQBO - the east QBO phase; $\beta$—coefficient slopes per 1 SD increase in continuous variables.
month, then the modulus of the mean values of $\phi_1$ and $\phi_2$ in the model for the AOI was higher. During the period of the descending SC, higher autocorrelations of the 1st - the 4th order of the NAOI and a higher $\mu$ for monthly models for both indices were found. The correlations between the corresponding characteristics in the wintertime series and space weather variables were similar, but the significance was lower due to a smaller sample size. The effects of several space weather variables on the autocorrelations and parameters of the AR models in monthly time series are presented in Table 4. If monthly values of Kp were included in the model for $\mu$ and $\phi_2$, the effect of SWS, EZWV,
and P was non-significant. During months with predominant SSW, the effect of Kp on the \( \mu \) was weaker (Table 4). During months with strong El Niño, the parameter \( \phi_2 \) was more negative.

### 4. Discussion

In our study, we found day-to-day effects of geomagnetic activity, SWS, \( B_z \), P, and SPE on the NAO and AO indices. These effects were determined adjusting for the effects of indices on 1–5 previous days, the linear trend, the long-term effect of solar irradiance and a higher GMA, SSW, a high level of aerosol loading, the presence of a higher EZWV, and ENSO. The novelty of our study lies in the use of 4th-5th order AR models with additional predictors and the detection of statistically significant effects of La Niña, the presence of a higher EZWV for the NAOI, and the detection of statistically significant signals of Kp, SWS, \( B_z \), P, and SPE in the day-to-day models. The effect of space weather variables on NAOI and AOI was QBO phase-dependent, a different effect of Kp and SWS was determined during moderate and strong El Niño, and distinct effects of SWS > 300 km/s were observed during the periods of SSW and those without SSW. Apart from this, for the first time, we assessed the associations of autocorrelations and parameters of the AR models in the monthly time series and space weather variables.

#### 4.1. The Long-Term Effect of Solar-Geomagnetic Activity on the Day-To-Day Variation of Winter NAOI/AOI

Geomagnetic activity and solar UV radiation had a long-term effect on both NAO and AO indices. According to the applied multivariate models, higher NAOI and AOI were observed during periods of higher solar UV radiation and higher geomagnetic activity. This is in line with the results obtained by other authors (Bochníček & Hejda, 2005). The mechanism that explains the long-term effect of solar UV radiation and geomagnetic activity on winter NAOI or AOI may be associated with their impact on the SPV (Gray et al., 2010; Maliniemi et al., 2014; Seppälä et al., 2009, 2013; Thompson & Wallace, 1998; Veretenenko & Ogurtsov, 2013).

### Table 4

*The Effect of Space Weather Variables on Autocorrelations and on Parameters in Autoregressive Models Created for the NAOI and AOI During Different Months*

| Variable | NAO index | AO index | NAO index | AO index |
|----------|-----------|----------|-----------|----------|
|          | \( \beta \) (SE) | \( p \) | \( \beta \) (SE) | \( p \) | \( \beta \) (SE) | \( p \) | \( \beta \) (SE) | \( p \) |
| Decade   | 0.011(0.002) | <0.001 | 0.021(0.005) | <0.001 | 0.001(0.001) | 0.080 |
| Kp       | 0.037(0.006) | <0.001 | 0.072(0.015) | <0.001 |
| Kp*SSW   | −0.010(0.004) | 0.003 | −0.034(0.009) | <0.001 |
| El Niño* | −0.180(0.101) | 0.075 | 0.588(0.225) | 0.009 |
| SSW      | −0.044(0.020) | 0.028 | −0.102(0.042) | 0.014 | −0.101(0.042) | 0.016 |
| El Niño +| −0.087(0.039) | 0.028 |
| SPE      | −0.073(0.024) | 0.002 |

*El Niño—moderate El Niño; El Niño + – strong El Niño; SC↓—solar cycle descending phase. \(^{b}\)EZWV—EZWV > 6.34 m/s; \( \beta \)—coefficient slopes per 10 increase for Kp variables, and per 1 increase for P.

*Note.* *denotes the sign of the interaction or combined term.*
High-speed solar wind, Interplanetary coronal mass ejections, SPEs, Stream Interaction Regions, and GS that peak in the solar maxima and the descending phase are the main sources of energetic particles—protons, electrons, and heavier ions (Richardson & Cane, 2010; Sinnhuber et al., 2012). Energetic particle precipitation (EPP) is the major source of nitrogen oxides (NOx) and hydrogen oxides (HOx) in the polar middle and upper atmosphere (Meraner & Schmidt, 2018; Sinnhuber et al., 2012). Both chemical components catalytically deplete stratospheric ozone. Since HOx is short-lived in the stratosphere, the HOx-induced ozone depletion lasts only a few days, and a more expressed impact on ozone could be seen only above 45 km (Verronen et al., 2006). Therefore, stratospheric ozone destruction mainly is attributed to NOx. As during polar winters there is little or no sunlight around, NOx produced via EPPs by downward vertical transport due to strong polar vortex can lead to the appearance of significant amounts of NOx in the upper stratosphere (Randall et al., 2006) and subsequently can have a significant effect on the stratospheric ozone content, since NOx destroys odd oxygen through catalytic reactions (Baumgaertner et al., 2011; Grenfell et al., 2006; Meraner & Schmidt, 2018; Meredith et al., 2011; Mironova et al., 2015; Smith-Johnsen et al., 2017; Verronen et al., 2011). Moreover, NOx could persist longer than for 2 months after its generation (Randall et al., 2001).

It has been shown that EEP causes significant ozone loss by 5%–20% in the mesosphere and stratosphere during wintertime (Andersson et al., 2018). In the polar/night stratosphere, it was detected the changes in atmospheric chemistry due to EEP at a weekly timescale. Over high latitudes (>75°N) in winter, a decrease in total ozone at 30–35 km altitude was observed after EEP events during one week period (Karagodin et al., 2018) and a lower mixing ozone concentration at 30–45 km altitude was observed some days after HSSW accompanied by an increased Ap over 70°N latitudes (Lee et al., 2018).

A reduction of stratospheric ozone at 150-1 hPa was observed at >70°N latitudes in winter with a higher GMA levels (Baumgaertner et al., 2011). Ozone is the main factor controlling thermal structure of the stratosphere, as it absorbs solar UV radiation and also infrared radiation from the Earth. Ozone loss during winter leads to radiative warming above the stratosphere and cooling in the lower polar stratosphere (Asikainen et al., 2020; Baumgaertner et al., 2011). The enhancements in the mesospheric temperature by up to 12 K and a decrease in stratospheric temperature by about 10 K was observed 3 days after the onset of major GS occurred on 07.11.2004 and this signal has persisted for about 10 days (Hocke, 2017). An increased GMA (and in this way and EEP) strengthens the planetary waves in the stratosphere which transfer EEP induced effects poleward, downward, and into the troposphere (Seppälä et al., 2013). Therefore, stratospheric ozone loss due to EEP are expected to enhance in the SPV, contributed the changes in the NAOI/AOI (Asikainen et al., 2020; Baldwin & Dunkerton, 2001; Meraner & Schmidt, 2018; Seppälä et al., 2013). During winter, a large circulation anomalies in the lower stratosphere are related to substantial shift in the AO/NAO. The effect of anomalies in the pressure variation at middle stratosphere reaches the tropopause in 10–20 days (Baldwin & Dunkerton, 2001). The 1-month response time of a distinct increase in electric field of SW on the NAO was reported by (Boberg and Lundstedt, 2002). Therefore, the proposed mechanism which links the particle precipitation to the circulation changes in the stratosphere is mostly related to ozone loss, indirectly caused by particles precipitating into the high latitude atmosphere within the wintertime SPV (Maliniemi et al., 2016). Moreover, changes in ozone layer are closely related to radiative forcing and therefore indirect effect on the NAO/AO could be seen.

We found a positive effect of a stronger west QBO (EZWV > 6.34 m/s) on the NAOI. The QBO affects the strength of SPV, the meridional circulation in the tropical stratosphere, and subtropical jets (Gray et al., 2018). A relationship between the QBO and the northern SPV is often referred as the Holton-Tan effect (Holton & Tan, 1980), that is, a phenomenon in which the strength of the winter SPV is influenced by the QBO. During the west (east) QBO phase, the SPV is stronger (weaker) (Baldwin & Dunkerton, 2001). However, the analysis of the QBO in terms of a single-level EZWV may not reflect the vertical structure of the QBO (Andrews et al., 2019; Gray et al., 2018). To represent the QBO, the principal component analysis of the EZWV at several pressure levels (Gray et al., 2018) or the EZWV at 30 hPa and 15 hPa (Andrews et al., 2019) was used. It is probable that a higher EZWV at 30 hPa represents positive westerly winds at other pressure levels.

### 4.2. The Short-Term Effect of Geomagnetic Activity, SWS, P, and SPE on the Day-To-Day Variation of Winter NAOI/AOI

We found the day-to-day response of the NAOI and AOI to space weather variables such as Kp, P, Bz, SWS, and SPE after excluding the impact of the long-term variation in both solar UV radiation and geomagnetic activity. According
to the multivariate models, during NH winter, the NAOI and the AOI positively correlated on the day-to-day timescale with geomagnetic activity, a higher SWS, and solar wind dynamic pressure (P), and these effects were stronger on the NAOI in late winter. These statistical associations correspond well with the results obtained by other authors (Bochníček & Hejda, 2005). According to our results, SWS > 300 km/s was associated with a higher NAOI/AOI during the period without SSW adjusting for the effect of Kp. However, SWS > 300 km/s occurring during SSW as well as $B_\parallel > 3.15$ nT were negatively associated with the NAOI/AOI in the multivariate model.

This day-to-day effect of Kp and solar wind variations may be explained by their effect on the flow of the downward current density ($J_z$) in the GEC, affecting meteorology via changes in cloud microphysics (Tinsley, 2008, 2012; Tinsley et al., 2021) because Kp, SWS, and P were positively associated with the energetic particle flux and a higher $B_\parallel$ related to the changes in the ionospheric potential (Harrison & Usoskin, 2010). Previously, it was shown that Kp positively correlated with the auroral electron flux (Hardy et al., 1987). Besides, EEPs were related to a higher SWS and Np (Asikainen & Ruopsa, 2016; Gao et al., 2015), GS (Longden et al., 2008; Meredith et al., 2011), and Stream Interaction Regions (Yuan et al., 2015). The SWS determines the energetic electron flux precipitating from the radiation belts at subauroral latitudes (Tinsley, 2008; Zhou et al., 2014). The analysis of the associations between SW parameters and EEP events showed a positive correlation between the energetic electron flux and SWS, whereas SWS minima were related to minima in EEP precipitating from the radiation belts (Lee et al., 2018; Tinsley et al., 1994; Wilcox et al., 1973; Zhou et al., 2014). According to the results of Asikainen and Ruopsa (2016), SWS is the most important property affecting EEP, and that may explain the short-term impact of SWS on the NAOI and AOI. EEPs affect $J_z$ by modulating the conductivity between 20 and 60 km of altitude (Nicoll & Harrison, 2014; Tinsley, 2000) and produce x-ray bremsstrahlung, which can penetrate down to 20–30 km and produce ion-pairs (Frahm et al., 1997; Mironova et al., 2015; Tinsley, 2008). This X-ray emissivity was associated linearly with the product of solar wind density and SWS (Cravens, 2000; Whittaker et al., 2016), which highly correlated with P on the day-to-day time scale in our study ($r = 0.881$). Our results showed a positive association between P and the NAO/AO indices. This may be explained by the strong correlation between P and X-ray emission intensity due to bremsstrahlung regarding to solar wind. EEP and the changes in the ionospheric potential due to changes in $B_\parallel$ affect the ionosphere-earth current density in the GEC (Harrison & Usoskin, 2010; Rycroft et al., 2012; Tinsley, 2000).

The physical mechanisms of tropospheric responses to EEP and changes in $B_\parallel$ are believed to operate via the action of $J_z$ on clouds, affecting the cloud microphysics. $J_z$ responds to changes in ionospheric potential or in column resistance in less than 10 min, and as $J_z$ flows through clouds, it takes only a few hours for the microphysics to respond to $J_z$ changes (Lam & Tinsley, 2016). Increases in $J_z$ increase the amount of net space charge on droplets, air ions, and aerosol particles, which is generated as $J_z$ flows through gradients of conductivity. In the cloud processes, there is a continual conversion from thermal energy to potential energy to latent heat release, and very small energy inputs can divert the energy flow. The space charges can affect the scavenging of nuclei in the clouds by changing the rates of the collision with droplets of ice-forming nuclei and condensation nuclei (Tinsley & Leddon, 2013). This results in an increased concentration of small cloud condensation nuclei (CCN) and a decreased concentration of large CCN (Tinsley, 2012). Changes in CCN size and concentration affects cloud microphysics—that is, the indirect aerosol effect, cloud cover, precipitation, and latent heat (Lam & Tinsley, 2016). When clouds form in air with elevated concentrations of CCN, they contain higher concentrations of smaller cloud droplets; the resulting reduction in the size of the droplets slows their coalescence into raindrops and delays the onset of rain. This allows more water to be carried above the freezing level, and thus increases the release of latent heat of freezing and the vigor of the updrafts in the storms. (Andreae & Rosenfeld, 2008; Rosenfeld et al., 2008; Tinsley, 2012) Winter storms at high latitudes in the NH are often found at locations such as the Icelandic Low region (Tinsley, 2012). These changes in weather occurred due to changes in CCN concentration, and this may be explain the day-to-day signal of Kp, SWS, P, and $B_\parallel$ on the NAOI/AOI. Additionally, changes produced in CNN size and concentrations leading to altered properties of clouds could have more prolonged, that is, long-term effects on atmospheric circulation. Changes in cloud cover, height, lifetime, albedo and infrared opacity affect regional radiative balance (could cause both, radiative warming and radiative cooling) and thereby contributing a substantial forcing to regional atmospheric dynamics and circulation (IPCC, 2013).

The results of the study demonstrated that the atmospheric dynamical response to the EEP depended on the presence of volcanic aerosol in the stratosphere (Tinsley, 2012; Zhou et al., 2014). For a few years after injections of SO$_2$ into the stratosphere by major explosive volcanic eruptions, at high latitudes, the column resistance in the
stratospheric ultrafine layer (near 40 km altitude) was found to be higher compared to that observed during years of low volcanic activity (Tinsley & Zhou, 2006). We found a stronger effect of Kp, GS, and SWS on the NAOI/ AOI during the years of HSAL, which, in turn, confirms the atmospheric coupling with these space weather variables via the GEC. We found differences in the sign of the signal of low SWS (≤300 km/s) during the period with and without SSW. Days of SWS ≤ 300 km/s were related to a reduction in the flux of EEP. Mínima in the SWS and deep minima in the EEP flux were associated with changes in the IMF direction that occur as the heliospheric current sheets that form the boundaries of solar wind magnetic sector, pass over the Earth (Tinsley et al., 1994; Zhou et al., 2014). This signal of the SWS may be explained by different states of stratospheric and mesospheric resistance and the ionospheric potential during the period with and without SSW. At high magnetic latitudes, the ionospheric potential correlated strongly with the solar wind sector structure and determined the flow of the current density (Jz) to the Earth’s surface that passes through clouds and modifies space charge in them (Tinsley et al., 2021). SSW was related to numerous ionospheric parameters, such as the total electron content, peak electron density, and electric field, especially at equatorial and low latitudes (Chau et al., 2012), and the effect of the SSW on ionospheric dynamics in high- and middle-latitude regions has been discovered (Mošná et al., 2021; Yasyukevich et al., 2017). Besides, an EEP-related enhancement of the SPV was observed during the SSW and before its onset (Asikainen et al., 2020). During months with SSW, an increase in EEP was linked to the stronger changes in adiabatic heating in the stratosphere at middle-high latitudes (Asikainen et al., 2020). It is possible that the changes in the adiabatic heating/cooling affect the processes in the cloud microphysics due to Jz.

We found that the period of 1 day before—2 days after the onset of the SPE was associated with a statistically significantly lower AOI. The analysis of the effects of the SPE on cyclone activity showed that SPS with energy >90 MeV were accompanied by a temperature increase at 200–100 mb levels at high-latitude NH stations during the cold period and the deepening of cyclone over south-eastern Greenland due to the advection of cold (Veretenenko & Thejll, 2008). These SPEs were related to an increase in the vorticity index and were positively correlated with cyclonic activity at the 300 hPa level at 50°–60°N and a decrease in vorticity index at 37°–55°N (Veretenenko & Thejll, 2008). These conditions indicated lower indices of AO, which is in line with our results. SSPEs can induce ionization, dissociation, and excitation in the mesosphere and the stratosphere (Jackman et al., 2009), and therefore SPEs are associated with an increase in Jz currents in NH, and especially in SH polar regions (Tinsley, 2012). Depending on the energy of protons, SPEs ionize the atmosphere down to 20 km—mostly over the polar region (Jackman et al., 2009; Seppälä et al., 2006). Apart from this, Veretenenko (2021) has found that ionization changes are associated with powerful SPEs and may influence the state of the SPV on the day-to-day time scale. The Jz variation due to SPE depended on the extent of the increase in stratospheric resistivity due to enhanced H2SO4 aerosol levels following major volcanic eruptions (Tinsley et al., 1994; Zhou et al., 2014). Our results also showed a stronger SPE signal on the AOI during years of HSAL, confirming the effect of SPE on Jz. The effect of SPE on planetary waves during the westerly QBO phase was also established in our study.

We found a stronger signal of Kp and SWS on the AOI during the east QBO phase. It is probable that the effects of equatorial zonal winds are related to a different atmospheric electrical state. During easterly QBO, an enhanced particle precipitation makes the SPV strong enough to resist the effect of planetary waves, and in westerly QBO, when the effect of planetary waves on the SPV is small, the enhancement of the SPV due to particle precipitation would have a smaller relative effect (Maliniemi et al., 2016). A stronger signal of space weather variables during eQBO was also shown by other authors. A higher mean monthly winter AO during the days of HSSW during eQBO was also found for the period of 1995–2003 (Georgieva et al., 2007). Moreover, during eQBO, a stronger coupling between SWS and winter surface sea temperature was detected (Zhou et al., 2016).

4.3. The Signal of ENSO Events on the NAO and AO Indices

According to the AR model with additional predictors, we found a statistically significant signal of the period of La Niña for the NAOI/AOI. This effect of La Niña signals on the NAOI and the AOI may be explained by their effect on the SPV (Van Loon & Labitzke, 1987). El Niño and La Niña events affect the upward-propagating planetary-scale Rosby waves: additional heating in the equatorial area during these events causes an amplification of the jet streams in the troposphere and affects the propagation of the planetary waves in the stratosphere by warming the winter North Pole (Calvo et al., 2008; Ermakova et al., 2019). Cold ENSO events (La Niña) were associated with a strong SPV and a weak Aleutian high in the stratosphere (Baldwin & O’Sullivan, 1995; Van Loon & Labitzke, 1987). Therefore, an increase in the mean daily NAOI and AOI during La Niña events may be explained by the effect of a stronger SPV.
We found a stronger signal of SWS on the NAOI/AOI during El Niño and the signals of Kp and SPE were distinct during moderate and strong El Niño. These different effects may be explained by the difference in the atmospheric electricity and atmospheric circulations during different ENSO events. An ENSO signal was found in global lighting activity and GEC. During the warm ENSO phase (El Niño), a higher lighting activity generally was observed in the NH (Chronis et al., 2008). Additionally, a strengthening in diurnal variation of the GEC (Harrison et al., 2011) and an increase in the ionospheric potential (Slyunyaev et al., 2021) were also observed during El Niño events. Thus, the stronger signal of a higher SWS may be explained by the effect on more disturbed GEC during El Niño.

The stratification of El Niño events according to amplitude showed that the response to moderate El Niño events resembled the negative phase of the NAO/AO while the response to strong El Niño events tended to resemble the positive NAO/O (Toniazzo & Scaife, 2006). The observed European response to El Niño consists of a superposition between both tropospheric and stratospheric influences. For the strongest El Niño events, tropospheric forcing dominates the European response (Bell et al., 2009). It is probable that in the absence of the stratospheric influence on the NAOI and AOI, the signal of Kp was non-significant (negative) for the NAOI (AOI). The SPEs and the strongest effect of SPE on the AOI were detected.

We have detected a highly non-linear yet robust response to ENSO that changed sign over the eastern North Atlantic as the amplitude of the El Niño anomaly increased. The results from a series of experiments with a general circulation model indicate that the response to strong ENSO events is reproducible given the sea-surface temperature anomalies in the tropical Pacific. During El Niño events, an increase in wave-1 eddies and a reduction in wave-2 eddies occurred; an increase in wave-1 overwhelmed the decrease in wave-2, thus causing weaker SPV (Ermakova et al., 2019; Garfinkel & Hartmann, 2008) and an intensification of the high-pressure center in the stratosphere and the low-pressure center in the troposphere located over the Aleutian region (Calvo et al., 2008; Van Loon & Labitzke, 1987). In about two-thirds of the El Niño events, the predominantly negative NAO and AO were observed.

To verify the suggested mechanism of the day-to-day tropospheric responses to space weather changes, more measurements of atmospheric electricity would be needed. We did not include the cosmic rays intensity (CRI) in the models because these highly correlated with GMA. However, the analysis of the effect of signal of Kp (SWS or P) on the NAOI/AOI could be carried out on different CRI and HSAL levels and during ENSO and SSW events and the east/west QBO phases. This requires an even longer observation period. The analysis of space weather signal for stratospheric mean zonal wind speed, temperature, heat flux, and the amplitudes of the planetary waves may be help to confirm the proposed mechanism. The problems for testing the mechanism for global electrical effects on clouds and atmospheric dynamics have been widely discussed by Lam and Tinsley (2016).

4.4. The AR Models for the Day-To-Day Variation on Winter NAOI/AOI

The variation in the NAOI and AOI was dependent on the Rosby wave (long wavelength atmospheric oscillations) system (Woolings et al., 2008). The daily NAOI and AOI were highly correlated, and it is probable that the dynamics of the NAOI/AOI may be described by the AR model (1) or (3). We detected that the dynamics of the NAOI (AOI) followed the AR(4) (AR(5)) model, and the change in the daily indices on days 1–5 might explain about 93% of the variation in the indices on those days. The Rosby wave breaking is a potential mechanism linking the tropospheric and stratospheric circulation (Kunz et al., 2009; Lu et al., 2013) and the major driving mechanism of the tropospheric NAO/AO (Feldstein & Franzke, 2006; Lu et al., 2013). Therefore, it is possible that special predictors disturbed the circulation described by the AR models.

According to the mean-centered AR models created for the NAOI/AOI during different months, the effect of Kp on the NAOI and AOI on the monthly scale was lower during the months with predominant SSW. During the periods without SSW, there were statistically more suitable conditions for EEP due to a higher GMA descending into the lower atmosphere (Lu, Clilverd, et al., 2008). Apart from this, the SSW and strong El Niño might have affected the parameters of the monthly AR model, and stronger (weaker) autocorrelations during the descending SC phase (a stronger west QBO phase) were detected. It is probable that these factors affected the dynamics of day-to-day NAOI and AOI described by the AR model.
5. Conclusions

We found that the winter NAOI (AOI) followed the AR(4) (AR(5)) model, and the change in the NAOI (AOI) on 1–4 (1–5) days after might explain about 93% (95%) of the variance in the NAOI (AOI) on the next day. In the AR models with additional predictors, a higher long-term variation in solar UV radiation and geomagnetic activity, La Niña events, and, for the NAOI, the presence of EZWV >6.34 m/s were statistically significant. The NAOI/AOI were positively associated with the short-term fluctuation of Kp, a lower than 3.15 nT Bz, and P with a lag of 2 days; moreover, the effect of Kp was stronger on the previous day for the NAOI and on the same and the previous day for the AOI. The AOI was positively associated with SWS and negatively associated with SPE. The signal of a higher SWS than 300 km/s during the period without SSW was associated with a higher NAOI/AOI. For the AOI, the effect of Kp and SWS was statistically significant only during the east QBO phase.

The signal of SWS >300 km/s on the NAOI was statistically significant only during El Niño events, and SSW had no significant impact during these periods. During strong El Niño, Kp had no effect on the NAOI, while for the AOI, a statistically significant negative effect of Kp was found. In the model with a few space weather variables, both the variable of P and Kp or (SWS >300 km/s without SSW) and Kp were significant for the NAOI. Meanwhile, Kp, SWS, a higher Bz, and SPE had a significant impact on the AOI.

During the years of a higher stratospheric aerosol loading (December 1963–February 1966, December 1982–February 1984, and December 1991–February 1995), a stronger impact of the short-term variation in Kp and SWS (Kp, SWS, P, and SPE) on the NAOI (AOI) was detected. The signal of Kp, SWS, and P on the NAOI was stronger in late winter, especially in January, and a stronger signal of the SPE on the AOI was observed in early winter. The associations between the NAOI and space weather variables were not identical during the east and the west QBO phases. A stronger short-term signal of Kp and P on the NAOI and a stronger impact of Kp and SPE on the AOI were characteristic for the eQBO.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Datasets related to this article are publicly available and can be found at: The daily North Atlantic Oscillation and Arctic Oscillation indices: https://ftp.cpc.ncep.noaa.gov/cwlinks/; Space weather data: https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/omni_01_av.dat; The QBO data: https://www.daculaweather.com/4_qbo_index.php for 1950–1959 and for https://climexp.knmi.nl/data/inqbo.dat since 1960. The Niño3.4 data: https://climexp.knmi.nl/data/iersst_nino3.4a.dat; The coefficients of the autoresressive (AR) models and the predicted values and residuals in the AR models are presented in Tables S1 and S2; these data will be deposited in institutional repository (https://www.vdu.lt/cris/home).

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