Solar Wind Variations Related to Fluctuations of the North Atlantic Oscillation

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1. Introduction

[2] Heat radiation from the Sun is believed to be the primary factor for the Earth’s climate condition. This phenomenon is not sufficient to explain the observed global temperature fluctuations on Earth during the last century. Several attempts have been made over the last decade to clarify if variations in the solar activity could, to some extent, be responsible for these climate fluctuations. The aim of this research is to make us better understand the extent, be responsible for these climate fluctuations. The natural causes of climate change in relation to the expected long-time effects of solar activity on the Earth’s climate was suggested by [1980]. A different relationship between solar activity and variations of the Earth’s climate was suggested by [1975]. Based on a mechanism first explored by [1975], they presented a coupling between the interplanetary magnetic field modulated rate of cosmic ray infall and the global cloud cover.

[4] Solar wind structures like coronal mass ejections, solar energetic proton events, high-speed streams, and slow solar wind regions interact with the Earth’s magnetosphere causing geomagnetic activity [Richardson et al., 2000]. The solar wind also modulates the current flow in the global electric circuit, evidently causing changes in tropospheric temperature and wind dynamics [Lundstedt, 1984; Tinsley, 2000]. These results motivate a study on a possible connection between solar wind variations and fluctuations of large-scale pressure systems on Earth like the NAO. We begin the study by describing the data used followed by the results and a short conclusion.

2. Data

2.1. Data of Solar Origin

[5] Some of the most geoeffective solar wind parameters are the flow speed \( V \), the proton density \( n \), and the southward component \( B_z \) of the interplanetary magnetic field. \( B_z \) is equal to \(-B_z\) when \( B_z < 0 \) and equal to 0 when \( B_z \geq 0 \), where \( B_z \) is the interplanetary magnetic field component parallel to the Earth’s magnetic dipole. By using these three parameters one can construct proxies for the dynamical pressure \( P \) and the electric field strength \( E \) of the solar wind. The pressure \( P \) exerted on the Earth’s magnetosphere is best represented by \( nV^2 \) whereas the electric field \( E \) can be described by \( ByV \). A widely used measure of the overall geomagnetic activity is the planetary geomagnetic \( Kp \) index [Mayaud, 1980]. The \( Kp \) index is evaluated using the amplitude of the variation of the horizontal magnetic components \( X \) and \( Y \) at the Earth’s surface at geomagnetic latitudes between 48° and 63°. We use monthly averages of \( E \), \( P \) and \( Kp \) for the period 1973–2000 to investigate the possibility of a solar wind interaction with the Earth’s atmosphere and the NAO.

[6] Homogeneous observations of solar activity over many solar cycles are essential when investigating the Sun’s long-time effects of solar activity on the Earth’s climate. One of the most suitable solar activity parameter used for this purpose is the group sunspot number \( R_G \) [Hoyt and Schatten, 1992]. Compared to the more common Wolf sunspot number \( R_Z \), it is more self-consistent, less noisy, and also based on many more observations. Solar cycle
averages of solar wind parameters and sunspot numbers are probably well correlated [Cliver et al., 1998; Rigoglioso et al., 2001]. We use solar cycle averages of $R_G$ from 1610 to 1976, as a proxy for the solar wind, to study any possible long-term effects of solar activity on the NAO.

2.2. The North Atlantic Oscillation Index

A substantial portion of the climate variability in the Atlantic sector is associated with the North Atlantic Oscillation [Visbeck et al., 2001; Marshall et al., 2001]. With variations occurring on a wide range of time scales, the NAO is a hemispheric meridional oscillation in atmospheric mass between the Arctic and the subtropical Atlantic [Hurrell et al., 2001]. The dimensionless NAO index, which expresses the temporal behavior of this oscillation, is defined as the normalized sea-level pressure difference between Stykkisholmur, Iceland (65°N, 23°W) and Ponta Delgadas, Azores (38°N, 26°W). Phases with positive NAO index refers to a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low. Due to the increased pressure difference, more and stronger winter storms cross the Atlantic Ocean in a northeast direction. This results in above-normal temperatures in northern Europe, the eastern United States, and parts of Scandinavia. Negative phases occur during a weak subtropical high and a weak Icelandic low. As a result of the reduced pressure gradient, fewer and weaker winter storms cross the Atlantic Ocean in a more eastward direction. This condition brings moist air into the Mediterranean and cold air to northern Europe.

We chose to use the NAO index as our climate indicator due to the availability of long data records and sequences with high temporal resolution. Measured NAO indices are available from 1864, whereas reconstructed indices go back to 1500 [Luterbacher et al., 2001]. Two different NAO index sets are used in the analysis: 1) monthly values from 1825 to 2000; and 2) solar cycle averages from 1610 to 1976.

3. Results

3.1. NAO variability

Climate variability of the North Atlantic region is primarily caused by the NAO [Hurrell, 1995]. Substantial contribution to this variability comes from 2–5 year oscillations as well as decadal fluctuations [Stephenson et al., 2000]. Determining the underlying mechanisms of the NAO variability is still an area of speculation [Marshall et al., 2001]. Some of the proposed mechanisms are: 1) eddy-mean flow interactions internal to the atmosphere; 2) stratospheric/tropospheric planetary wave interactions; 3) remote forcing from the tropics; and 4) thermal coupling with the ocean mixed layer. The proposed mechanisms would operate on a wide range of time scales.

A wavelet analysis of the NAO index is presented in Figure 1 to demonstrate its temporal variability. Monthly values from 1825 to 2000 are plotted in the upper panel and a wavelet power spectra, using procedures described by Torrence and Campo [1998], is presented in the lower panel. The power spectra covers NAO variations with periods between 2 months and 20 years. As shown by the power plot in the lower right panel, a large fraction of the wavelet signal is the result of decadal oscillations. Peaking at a scale of about 12 years, these fluctuations have a period approximately the length of the solar sunspot cycle. Another large fraction of the wavelet signal is found at scales below one year. As will be presented in the next section, some of these NAO fluctuations show a close relationship to the solar wind variation.

3.2. Solar Wind Parameters and NAO

Mansurov et al. [1974] presented a coupling between the strength of the interplanetary magnetic field and sea level pressure fluctuations at Mould Bay, Canada (76°N, 119°W). A consistent effect was found by Page [1989] who analyzed the sea level pressure at Thule, Greenland (76°N, 69°W). These results support the proposal by Tinsley [2000] describing how the solar wind can modulate the currents in the global electric circuit in the ionosphere and how this modulation can cause changes in tropospheric dynamics. Furthermore, the results motivate a study on the possibility of a solar wind interaction with the Earth’s atmosphere and the subsequent influence on the NAO.

Figure 2 present time series of twelve month moving averages of the NAO index, the electric field strength $E$ of the solar wind, the planetary magnetospheric $K_p$ index, and the dynamic pressure $P$ of the solar wind for the period 1973 to 2000. General features of both $E$ and $K_p$ are
An obvious exception to this similarity is the positive NAO phase during the second half of 1986. The linear correlation between $E$ and NAO is 0.62. Assuming a normal distribution, this correlation is significant at the 99% level. The linear correlation between $Kp$ and NAO is 0.57 at a 98% significance level. By comparing the top and bottom panel of Figure 2, it is seen that the geoeffective solar wind pressure $P$ does not show a close similarity to the NAO index variation. The correlation coefficient for $P$ is 0.29.

The results presented in Figure 2 suggest that the solar wind is, in some way, contributing to the temporal evolution of the NAO. The low correlation between $P$ and the NAO index suggests that the influence, where the internal pressure of the Earth’s atmosphere is affected, is not initiated by external pressure changes. Instead a more reasonable scenario, as suggested by the relatively high correlation between $E$ and the NAO index, begins with an electromagnetic disturbance induced by the solar wind in the global electric circuit of the ionosphere.

But how can this electrical input affect the lower atmosphere? Baldwin and Dunkerton [2001] found evidence of stratospheric mean-flow variations inducing circulations that penetrate the lower troposphere. This downward propagation takes between 15 and 50 days and is most pronounced during winter months (November through March). Monthly averages of $E$ are given in the upper panel of Figure 3, where the most pronounced increases in $E$ during winter months are indicated by arrows. The lower panel of Figure 3 gives the average NAO response to the 14 indicated $E$ increases positioned on month 0. A distinct NAO peak is evident on the month following the $E$ increase. This one month response time suggests that the downward propagation of the proposed solar wind induced electromagnetic disturbance is a dynamic process. Furthermore, the NAO response to the $E$ increase is only found during winter months suggesting a propagation scenario similar to the one proposed by Baldwin and Dunkerton [2001].

Moreover, when shifting the twelve month moving average of $E$ (see Figure 2) forward by three months, the linear correlation between $E$ and the NAO increases from 0.62 to 0.67. A similar effect is found for the $Kp$ index where the correlation increases from 0.57 to 0.60. This three month time lag could be the overall result of a solar wind connection to the lower troposphere during winter months only.

3.3. Group Sunspot Number and NAO

Eddy [1976] was the first to present a clear coupling between variations in solar activity and changes in the Earth’s climate. He pointed out the connection between the prolonged Maunder Minimum and the cold climate in northern Europe during the second part of the 17th century. Cliver et al. [1998] showed that during this period the solar}
wind was slower and the southward component of the solar wind much smoother compared to present values. This result together with the fact that the NAO has a substantial impact on the climate in northern Europe motivates a study on a possible relationship between long-term solar wind variations and NAO fluctuations.

Figure 4 gives group sunspot numbers in the upper panel and the NAO index for positive phases in the lower panel. Both data sets are averaged for solar cycles between 1610 and 1976. Gross solar activity features, like the Gleissberg cycle [Gleissberg, 1958] with the Maunder Minimum (cycles 10 to 4), the Dalton Minimum (cycles 6 and 7), and the minima around cycle 14, are evident in the NAO data. The linear correlation between the two data sets is 0.56.

4. Conclusion

The NAO is a major contributor to the climate in the North Atlantic. It extends from the arctic region down to the tropics and can be measured high up in the stratosphere. Several phenomena have been proposed as mechanisms contributing to the temporal fluctuation of the NAO. The suggested phenomena would operate on different time scales (days to years to decades) as well as contribute in some way affecting the NAO. Richardson, I. G., E. W. Cliver, and H. V. Cane, Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind, J. Geophys. Res., 105, 18,203–18,213, 2000.


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