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Solar Wind Variations Related to Fluctuations of the North Atlantic Oscillation

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[1] A study on a possible solar wind interaction with the North Atlantic Oscillation (NAO) is performed. Results are presented suggesting a relationship between the NAO index and the electric field strength *E* of the solar wind. A possible scenario for the suggested interaction is that an electromagnetic disturbance is generated by the solar wind in the global electric circuit of the ionosphere. This disturbance is then dynamically propagating downward through the atmosphere and subsequently influencing the large-scale pressure system in the North Atlantic region. A relationship is also evident on longer time-scales when using the group sunspot number as a proxy for the solar wind. *INDEX TERMS:* 2164 Interplanetary Physics: Solar wind plasma; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2409 Ionosphere: Current systems (2708); 1610 Global Change: Atmosphere (0315, 0325)

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 natural causes of climate change in relation to the expected global warming due to man's activities. Assuming that the Sun is partly responsible for the observed climate changes, there are at least three plausible mechanisms [*Reid*, 2000]: a) influence through a variable solar irradiance; b) solar wind interaction through a magnetosphere/atmosphere coupling; and c) indirect influence through an interplanetary magnetic field modulation of cosmic rays.

[3] *Eddy* [1976] presented the first clear evidence of a link between solar variability and changes in the Earth's climate when pointing out the coincidence between the Maunder Minimum (1645 to 1715) and the so-called Little Ice Age period in northern Europe. Examples of more recent results are the connection between solar variability and high-latitude stratospheric temperatures and geopotential heights [*Labitzke and van Loon*, 1988], and the connection between the solar cycle length and the temperature of the northern hemisphere [*Friis-Christensen and Lassen*, 1991]. A different relationship between solar activity and variations of the Earth's climate was suggested by *Svensmark and Friis-Christensen* [1997]. Based on a mechanism first explored by *Dickinson* [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_s of the interplanetary magnetic field. B_s 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 B_sV. A widely used measure of the overall geomagnetic activity is the planetary magnetospheric *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

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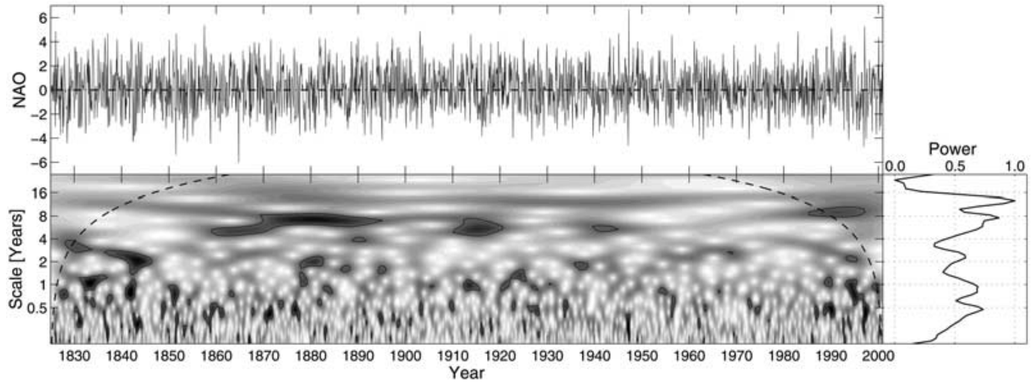

Figure 1. Wavelet analysis of the NAO index. Monthly NAO indices between 1825–2000 are given in the upper panel. The lower panel shows the corresponding wavelet power spectra for temporal scales ranging from 2 months up to 20 years. Dashed lines indicate the zone of influence whereas the solid lines show the 95% confidence level. As given by the normalized power density plot in the lower right panel, the most distinguishing peaks are the result of biannual, annual, and decadal fluctuations.

averages of solar wind parameters and sunspot numbers are probably well correlated [*Cliver et al.*, 1998; *Rigozo 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

[7] 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.

[8] 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

[9] 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.

[10] 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

[11] *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.

[12] 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 Kp index, and the dynamic pressure P of the solar wind for the period 1973 to 2000. General features of both E and Kp are

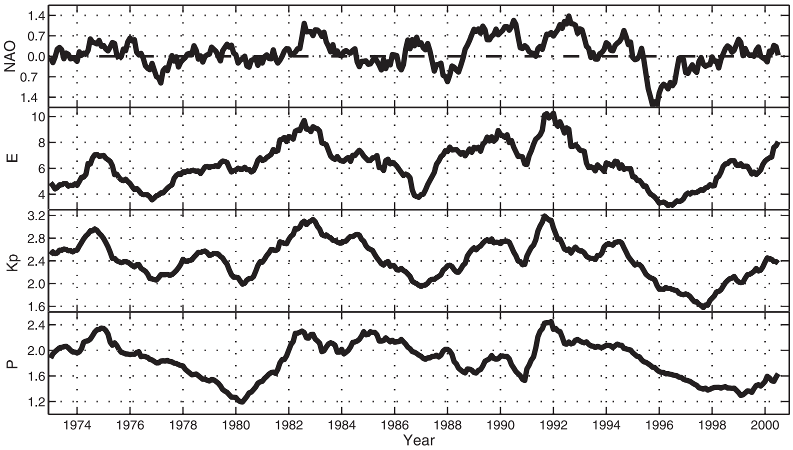

Figure 2. Time series of twelve month moving averages of the NAO index compared to variations in the solar wind and the geomagnetic activity. E is the electric field strength B_sV of the solar wind in units of 10^{-4} Vm^{-1} and P is the solar wind pressure nV^2 in units of $10^6\mathrm{m}^{-1}\mathrm{s}^{-2}$. The time series cover the period 1973 to 2000, a 28 year sequence including solar cycle minima in May 1976, August 1986, and October 1996.

significantly reflected in the evolution of the NAO index. 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.

[13] 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.

[14] 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].

[15] 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

[16] *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

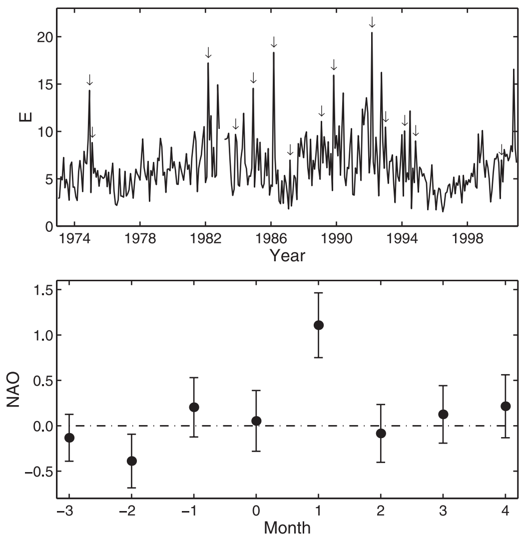

Figure 3. The NAO response to solar wind variation. Monthly averages of E for the period 1973 to 2000 are presented in the upper panel. 14 arrows indicate winter months with an distinct ($>3.5 \times 10^{-4}$ Vm^{-1}) increase in E compared to the previous month. The lower panel shows the average NAO response to these 14 increases. The superposed sequences begin three months before and end four months after the electric field increase. The bars represent the standard error of the mean. E is in units of 10^{-4} Vm^{-1}.

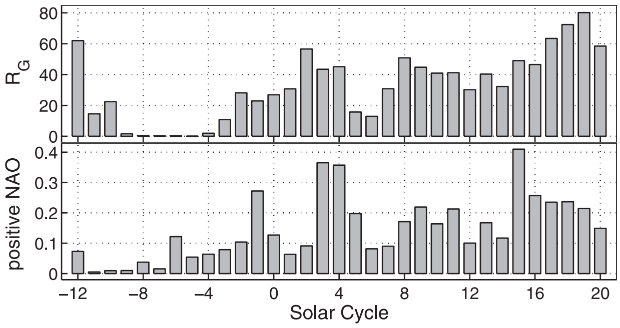

Figure 4. Group sunspot numbers (top panel) and positive NAO indices (lower panel), averaged for 33 solar cycles between 1610 and 1976. Solar activity trends like the Gleissberg cycle seem to be present in the NAO data.

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.

[17] 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 Minima (cycles −10 to −4), the Dalton Minima (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

[18] 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 different amounts to the NAO. Which of the different proposed mechanisms that are truly interacting with the NAO have not yet been fully determined.

[19] Solar wind characteristics affect the terrestrial environment through geomagnetic activity. The tentative results presented here hint that the electric field of the solar wind is in some way affecting the NAO. The aim of this study is not to answer the question on how the solar wind could influence the NAO. Instead, the study is an attempt to investigate whether solar wind characteristics are able to influence large-scale pressure systems on Earth. These first results suggest that there is a physical relationship. A more detailed study has to be performed before any certain conclusions can be drawn. Further knowledge of the possible connection between solar wind variations and the NAO index might improve the accuracy of NAO predictions.

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