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On correlations between the North Atlantic Oscillation, geopotential heights, and geomagnetic activity

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[1] We investigate correlations between geomagnetic activity indices, the North Atlantic Oscillation (NAO), and stratospheric geopotential heights. It is shown that the correlation between the geomagnetic index *Ap* and the NAO index is high and significant since about 1970, that it is significant during winter only, that it was not significant before about 1970, and that the correlations are dominated by quasi-decadal scales of variability. Analysis of the spatial pattern of correlations, restricted to the Northern Hemisphere and wintertime, shows that significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000. However, for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere. This might indicate that a solar forcing, primarily acting in the stratosphere, is propagating its influence downward in the later period but not in the earlier. *INDEX TERMS:* 1650 Global Change: Solar variability; 1620 Climate dynamics (3309); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Thejll, P., B. Christiansen, and H. Gleisner, On correlations between the North Atlantic Oscillation, geopotential heights, and geomagnetic activity, *Geophys. Res. Lett.*, *30*(6), 1347, doi:10.1029/2002GL016598, 2003.

1. Introduction

[2] Apparent relations between solar activity, or parameters closely related to solar activity, and climate data have often been reported [*Herman and Goldberg*, 1978; *Pittock*, 1983; *Hoyt and Schatten*, 1997; *van Loon and Labitzke*, 2000, and references therein]. At the same time, it is well known that a substantial part of the Northern Hemisphere (NH) climate variability is associated with the North Atlantic Oscillation (NAO) [*Hurrell et al.*, 2001; *Jones et al.*, 1997]. Particularly wintertime climate in the Atlantic sector appears to be governed by this meridional oscillation of atmospheric mass. Pressure, temperature, and precipitation patterns correlate to the NAO - climate factors for which apparent connections to solar activity have been reported in scientific literature.

[3] A few studies have now reported apparent relations between the NAO itself and solar-activity related parameters. *Bucha and Bucha* [1998] studied the relationship between geomagnetic activity and NH surface temperatures and pressures, including two indices describing the state of the NAO. *Kodera* [2002] showed that the spatial structure of the NAO differs significantly according to the phase of the solar cycle, while *Boberg and Lundstedt* [2002] showed that a highly significant correlation exists between an NAO index and solar-wind parameters since 1973. In this paper we will examine and extend - going back in time, separating into seasons, and going up into the stratosphere - previous studies in order to give a fuller understanding of the detected correlations. We also discuss the findings in relation to known variations of the dynamical coupling between the stratosphere and the troposphere. The analysis is restricted to the NH.

[4] Correlation results must be interpreted on the background of stringently derived significance levels. Especially the overestimation of the number of degrees of freedom often leads to erroneous conclusions. Throughout this paper we determine significance of results by use of 'Monte Carlo' (MC) simulations of the statistical procedures on surrogate data [e.g., *Theiler and Prichard*, 1996], and subsequently inspect the distribution of the correlations in the surrogate data. The surrogate data are generated by scrambling the harmonic phases of a series. Such surrogate data ensure that the MC procedure can perform the Null-hypothesis test on suitable material; data series that are physically unrelated to the target series but which have the necessary similarity in statistical terms, e.g. the auto-correlation, and therefore have as many independent points as the original series. The use of the 'scrambled phases method' constitutes a very conservative approach. Throughout this study, we report the percentages of trials that achieved a similar or lower correlation, thus enabling estimates of how likely the result is to be a non-random occurrence.

2. The Temporal View: *Ap* Versus NAO

[5] Recently, *Boberg and Lundstedt* [2002] investigated the correlations between geomagnetic activity and solar-wind parameters on the one hand and the NAO index on the other hand. They showed that annually smoothed series of the geomagnetic index *Kp* and the NAO correlate highly and significantly since 1973. We investigate this further by splitting the series into seasons and by going further back in time. In doing this, we have used the geomagnetic index *Ap* which is directly derived from *Kp* but that, unlike *Kp*, is a linear measure and thus more appropriate when smoothing is applied. We have further used the geomagnetic index *aa* to extend the temporal coverage back to 1868. Seasonal averages of *Ap* and *aa* are practically interchangeable - in the period of overlap, 1932 to 2000, they have a correlation of 0.96. The NAO is mainly a winter phenomenon but it is also an important index in summer although its influence is more regional and isolated to the troposphere whereas the NAO/AO reaches into the stratosphere in winter. In this study we have used the *Jones et al.* [1997] NAO index.

[6] Figure 1 shows annual averages of *Ap* and NAO from 1932 to 2000. These two parameters show a certain degree

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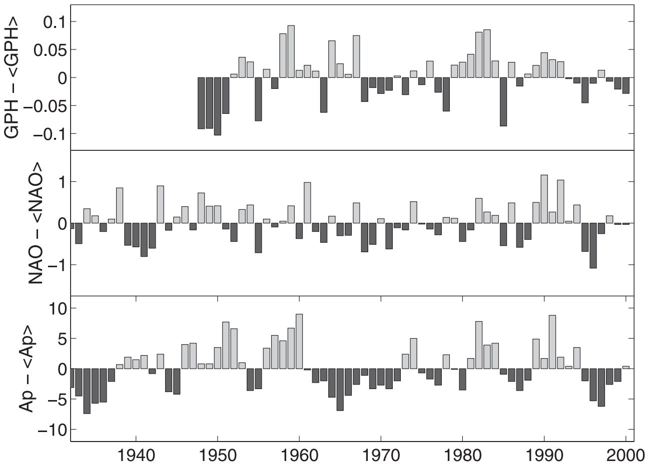

Figure 1. Annual means of the geomagnetic index *Ap*, the NAO index, and the GPH at 20 hPa at 50°N, 140°W.

of correlation since around 1970, but appears uncorrelated before that. This impression is confirmed by the results in Table 1. For the period 1973 to 2000, annual averages of *Ap* and NAO have a highly significant correlation of 0.62, while there is a lack of correlation for the time period from 1932 to 1972. Table 1 also shows the results of correlating seasonal averages. Apparently, high and significant correlations are only found for winters after around 1970.

[7] In Figure 2 we show how the correlation between *aa* and NAO evolve over a century, from 1886 to 1985. The data have been split into seasons, and correlations are computed within a 31-year sliding window. As before, we find that the correlations are high and significant only during the winter season, and that the correlations were lower and not significant before about 1970. Figure 2 shows the 99% significance level for winter only, as the other seasons never reach this level. Note that the significance level itself varies over time, which is an effect of non-stationarity.

[8] The high winter-time correlation is mainly due to quasi-decadal variability. A cross-coherency analysis reveals that the winter series for *Ap* and NAO (1973–2000) have a significant coherency-squared for time-scales from 7 to 10 years.

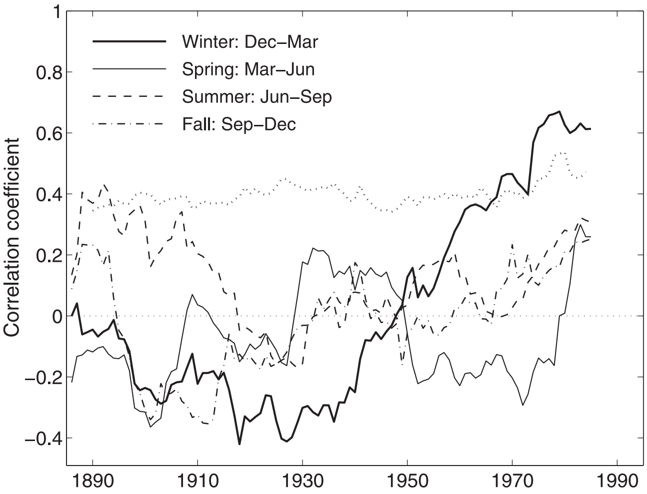

Figure 2. Correlations between seasonal means of NAO and the geomagnetic index *aa* for sliding 31-year intervals. The dotted curve shows the 99% significance level for winter-time data, a conservative choice according to 'Thomson's rule' [*Thomson*, 1990].

3. The Spatial View: *Ap* Versus GPH

[9] By correlating the sea level pressure (SLP henceforth) and the Geopotential Height (GPH) with the *Ap* index and comparing to the same correlations using the NAO index we can map the extent and character of the correlation observed above. We use NCEP reanalysis GPHs [*Kalnay et al.*, 1996]. Figure 3 shows the correlation coefficient at sea level and at 20 hPa in the stratosphere, as well as shaded significantly correlated areas, for two periods: 1949–1972 and 1973–2000.

Table 1. Seasonal Correlation Results for NAO vs. *Ap*

Season	R 1973 to 2000	R 1932 to 1972
All year	**0.62 (98.9)**	0.06 (28.0)
Spring (MAMJ)	0.21 (75.9)	0.04 (16.3)
Summer (JJAS)	0.27 (80.8)	0.06 (33.9)
Fall (SOND)	0.23 (83.9)	0.01 (4.9)
Winter (DJFM)	**0.56 (99.5)**	0.04 (17.1)

R is the Pearson correlation coefficient between series with one binned data point per year for the indicated season. Significance levels (in parenthesis) give the percentage of Monte Carlo trials performed on surrogate series that achieved smaller or the same correlation. The numbers in bold face are those we consider highly significant and unlikely to be due to chance.

[10] In both periods the correlation between NAO and SLP has strong and significant maxima over Spain and Iceland as expected from the definition of the NAO. We, like *Boberg and Lundstedt* [2002], use the *Jones et al.* [1997] NAO index based on the Gibraltar - Iceland pressure difference, rather than the Azores - Iceland difference. We see that weaker positive correlations are found in an annulus surrounding the negative correlations over the polar region resembling the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998]. At 20 hPa the pattern of correlations is in both periods dominated by a dipole with a negative center over the East of the Eurasian continent and a positive center over North America in the later period and northern Europe in the earlier period. Only centers are statistically significant.

[11] The pattern of correlations between *Ap* and SLP strongly resembles that between NAO and SLP in the later period, only with the main center dislocated from Spain to the middle of the North Atlantic. Some similarity should be expected as the *Ap* index and the NAO index have a correlation of 0.6 in this period, but the global extent of the similarity of the correlation patterns suggests that the NAO index is a sufficient choice when one wants to study the connections between the solar activity and the tropospheric variability. In the earlier period (where the *Ap* index and the NAO have a correlation of only 0.3) the correlations between *Ap* and SLP are much weaker and nowhere significant. In both periods the correlations between *Ap* and stratospheric GPH resemble those between NAO and SLP both regarding strength and patterns.

[12] We conclude that the NAO has a deep vertical extent, as observed by *Thompson and Wallace* [1998], in

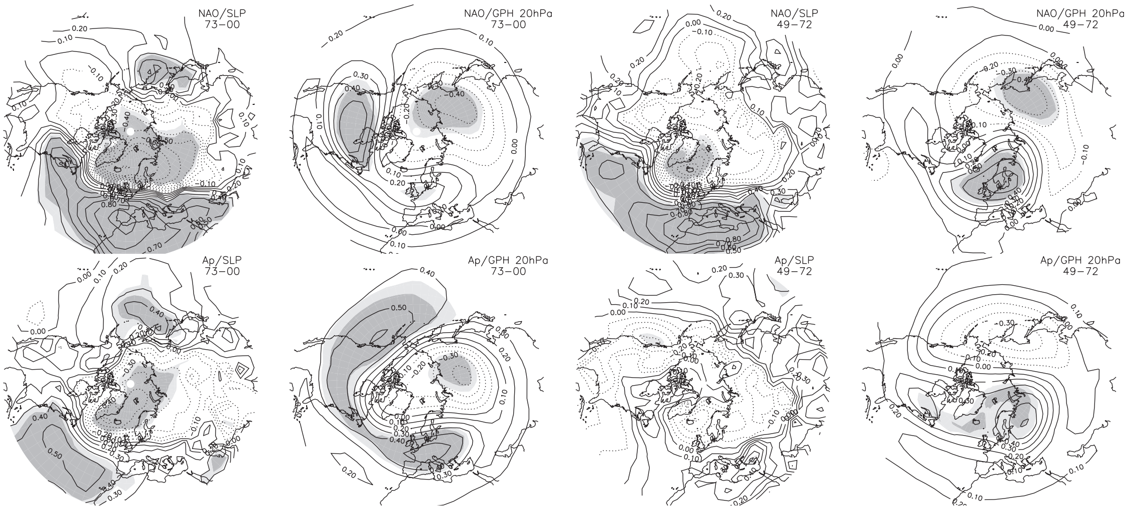

Figure 3. Correlation of NAO (upper panels) or *Ap* (lower panels) with sea level pressure (leftmost and third columns of panels) during NH winter, and with the 20 hPa GPH from 1973 to 2000 (second column), and from 1949 to 1972 (rightmost column). Solid contours indicate levels of positive correlation, dotted contours negative correlation. Shaded areas are significant locally at the 95% level. Heavily shaded are significant at 99%, locally.

both periods although its imprint in the stratosphere is different in the two periods. In the period 1949–1972 the *Ap* has no significant correlations at the surface while some significanct correlations are found in the stratosphere. In the 1973–2000 period significant correlations are found for *Ap* in both the stratosphere and at the surface.

[13] Figure 1 shows the data series at 20 hPa for GPH and *Ap*, over the Gulf of Alaska, where the correlation is strong. We see that the correlation appears to be caused by multi-annual or quasi-decadal scale variability, and that this match is missing before about 1970. This is consistent with the cross-coherency analysis.

4. Results

[14] In our analysis, restricted to the northern hemisphere, we have found that, 1) we can verify the reported correlation between smoothed geomagnetic indices and the NAO index, and that it is highly significant in the period 1973–2000, 2) we find that only the winter season series are significantly correlated. The presence of a correlation during winters only is consistent with the notion that the solar-climate link works through the stratopshere. 3) Extending the analysis back to 1886 shows that the correlation found is unique to the period after about 1970, 4) cross-coherency analysis of annual winter series for *Ap* and NAO reveals that the correlation is driven by variability on time-scales of 7–10 years, 5) in the later period, 1973–2000, significant correlations between *Ap* and SLP and between *Ap* and stratospheric GPH are found for the northern hemisphere winters. However, in the earlier period, 1949–1972, no significant correlations are found at the surface while some significant correlations are found in the stratosphere, 6) the NAO index stands out, as it describes in detail the correlations between *Ap* and SLP and between *Ap* and stratospheric GPH in the later period. It therefore does not seem likely that the correlations between winter climate in the Northern Hemisphere and *Ap* can be improved upon by choosing another index of the large scale circulation.

5. Discussion

[15] We have studied the correlation between the NAO index, surface pressure in the Northern Hemisphere, and the stratospheric geopotential height on the one hand and solar activity on the other. We have used geomagnetic indices as proxies for solar activity as they constitute widely used, homogeneous time series extending back in time for well over a century. As geomagnetic activity is fundamentally generated by the solar wind, we can regard the results presented here as being representative also for correlations with the solar wind [*Boberg and Lundstedt*, 2002]. Our study has focused on the NAO which is predominantly a winter phenomenon. Other investigators have used other solar activity proxies and considered other seasons. Notably, *van Loon and Labitzke* [2000] have demonstrated that the summer stratosphere correlates strongest with the 10.7 cm solar radio flux - *f*10.7. A_p and *f*10.7 are not strongly correlated however - during winters the correlation is 0.23–0.43 (depending on smoothing) and not statistically significant, and the results from the investigations by e.g. van Loon and Labitzke are not directly comparable to the present work which employs A_p.

[16] How can we explain the results 1–6? We see three possible explanations that might be put forward.

[17] 1. *The influence from the Sun on the atmosphere increased through time and reached a strong enough level in the 1970's that the correlations we study become statistically significant*. Solar activity has indeed varied through time - the sunspot number shows an increase from the Maunder Minimum with centennial scale variability. At the moment the variability in the solar cycles is moderate, compared to the high reached in cycle 19 (late 1950's). However, sunspots merely represent the active agent, whatever it is. One proposal, by *Lockwood et al.* [1999],

is that a study of geomagnetic activity and its relationship, during the time of spacecraft observations, to the variations in the strength of the interplanetary magnetic field (IMF) shows an increase through the 20'th century. The strength of the IMF regulates the flux of galactic cosmic rays (GCR) to Earth and it has been suggested [*Dickinson*, 1975; *Svensmark and Friis-Christensen*, 1997] that GCRs play a role in cloud formation. Modulating the clouds could have considerable impacts on climate. Solar irradiance has also increased, according to reconstructions of solar irradiance before the spacecraft observations of solar irradiance started [*Hoyt and Schatten*, 1993; *Fligge and Solanki*, 2000, *Lean*, 2000]. The *Lean* [2000] irradiance reconstruction shows a flattening since about 1950. If the irradiance has been constant since then, and if irradiance is the only mechanism whereby the Sun influences climate, then the steadily rising correlation in our Figure 2, for winter time, since about 1920 is apparently difficult to reconcile with these assumptions. This explanation thus depends on knowing just which mechanisms (or combination thereof) actually drives the climate.

[18] 2. *The state of the atmosphere changed in the 1970's so that it became sensitive to solar influence then, but was not so before*. Since we use a 31-year sliding window technique to represent the changes in correlation, we note that the winter curve in Figure 2, is merely consistent with a switch (sudden or gradual) sometime in the interval 1950–1970 in the correlation between NAO and *aa* from a state of low correlation to one higher. It is, however, known [e.g., *Thompson et al.*, 2000] that the atmosphere became more zonally dominated with a tendency for a stronger stratospheric vortex after around 1970. *Lindzen and Giannitsis* [2002] have suggested that the troposphere underwent an abrupt change in the 1970's. And *Perlwitz and Graf* [2001] have pointed out that the weak and strong vortex situations differ substantially in the dynamical coupling between the stratosphere and troposphere. In a weak vortex situation the troposphere will influence the stratosphere but not vice versa, while the coupling in a strong vortex situation goes both ways. We do find significant correlations between *Ap* and stratospheric GPH in both periods while the correlations between *Ap* and SLP are significant only in the later period. One could speculate that the direct physical influence related to the *Ap* index is mainly in the stratosphere and that this is communicated downward in the later period but not earlier due to the differences in the strength of the vortex. This mechanism is consistent with our observation that the correlation between *Ap* and NAO is significant only in winters.

[19] 3. *All we see is just a chance occurrence, and there is no real physical link*. Critics of analyzes based on statistical arguments can always make the valid comment that results are due to chance occurrences and are not due to real physical relationships. We have taken steps to realistically evaluate the probability that the results are due to chance - namely, by using MC simulations of the statistical procedures applied to suitable surrogate data. The surrogate data were expressly chosen so as to mimic the appropriate statistical properties of the data used. For instance, we model the different seasonal properties of the series, and thus the significance levels take the higher variability in e.g. winters into account.

[20] Having thus taken appropriate steps to reduce the risk that we have found a chance occurrence, we fall back on the first two possibilities - that the correlation is real. We cannot discern which of the two are right - increased influence or increased sensitivity - or if perhaps a mix of the two would be possible, without further studies.

[21] **Acknowledgments.** We have used data from the Climatic Research Unit at University of East Anglia. NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, at http://www.cdc.noaa.gov/. This work was supported by the Danish Climate Centre, and by an ESA Research Fellowship. We thank two anonymous reviewers for useful comments.

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