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The Role of the Solar Cycle in the Relationship Between the North Atlantic Oscillation and Northern Hemisphere Surface Temperatures

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ABSTRACT

The North Atlantic Oscillation (NAO) is one of the leading modes of climate variability in the Northern Hemisphere. It has been shown that it clearly relates to changes in meteorological variables, such as surface temperature, at hemispherical scales. However, recent studies have revealed that the NAO spatial pattern also depends upon solar forcing. Therefore, its effects on meteorological variables must vary depending upon this factor. Moreover, it could be that the Sun affects climate through variability patterns, a hypothesis that is the focus of this study. We find that the relationship between the NAO/AO and hemispheric temperature varies depending upon solar activity. The results show a positive significant correlation only when solar activity is high. Also, the results support the idea that solar activity influences tropospheric climate fluctuations in the Northern Hemisphere via the fluctuations of the stratospheric polar vortex.

Key words: solar activity, North Atlantic Oscillation, Arctic Oscillation, Northern Hemisphere, surface temperature

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1. Introduction

Although there are many indicators of solar influence on our climate (Hoyt and Schatten, 1997), the processes through which decadal and secular solar changes operate on climate remain unclear (Rind, 2002). Recently, it has been hypothesized that solar variations occurring on timescales of years can influence climate by affecting major modes of atmospheric variability. The principal candidate for being influenced in this way is the North Atlantic Oscillation (NAO), a seesaw of surface pressure between high latitudes and the subtropics in the eastern part of the North Atlantic (van Loon and Rogers, 1978). This because: (1) the interannual variability of the NAO can be forced by stratospheric perturbations that propagate downward to the troposphere (Baldwin and Dunkerton, 1999), taking into account that the stratosphere is sensitive to solar activity variations (Hood et al., 1993; Labitzke, 2001); (2) the NAO is recognized as the main mode of climate variability in the extratropical Northern Hemisphere, producing around 60% of the winter mean sea level pressure (SLP) variance in the region; (3) there is a statistical correlation between the increasing trend found in the second half of the 20th century in the winter NAO index and that in the winter Northern Hemisphere surface temperature (NHT), which could explain, at least partially, global heating (Hurrell, 1995).

Kodera (2002) showed that the spatial structure of the NAO varies significantly according to the phase of the solar cycle. During solar maximum phases, the NAO covers the Northern Hemisphere and extends into the stratosphere, which is similar to the Arctic Oscillation (AO) (Thompson and Wallace, 1998), except for the Pacific sector. By contrast, for minimum solar phases, the NAO is confined to the eastern Atlantic sector and to the troposphere. Ruzmaikin and Feynman (2002) found that the Northern Annular Mode (NAM) is influenced by solar changes. They concluded that in periods of deep, steady minimum solar activity, the NAM index is lower than during periods of deep, steady maximum solar activity. Gimeno et al. (2003) showed that, for solar maximum phases, the wintertime NAO and NHT are correlated positively, but during minimum phases the correlations are not

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significant or even negative (result assumed up to the time of writing).

The three studies above identify differences in the NAO extension, phase or relationship with the NHT according to the phase of the 11-year solar cycle. However, these results should be checked using other indicators of solar activity that are also closely related to NHT anomalies, such as the length of the solar cycle. Friss-Christensen and Lassen (1991) found a close association between these two variables: when the sunspot cycle is long (around 12 years), the Earth is colder than when it is short (around 10 years). This result is consistent with studies performed with other solar-like stars. Using 18 such stars, Baliunas and Soon (1995) found that shorter cycle lengths are associated with brighter chromospheric emissions.

Other interesting activity indices are the F10, coronal green line, and Lyman-α indices. The F10 index is the 10.7 cm radio flux (2800 MHz), and is widely used because its measure is more reliable than sunspot number, although its series is shorter. This flux has its origins in the higher layers of the chromosphere and lower layers of the Sun's corona, and changes gradually depending on the sunspot groups. The intensity levels consist of the sum of three sources: unperturbed solar surface, developing active regions, and short-life increases above diary level. This index was used by Kodera (2002) to divide temporal series into two groups depending on the solar activity. The coronal green line activity index measures the total energy emitted at a wavelength of 530.3 nm by the Sun's corona (the outermost layer of the Sun). It gives the radiant energy emitted by the entire visible corona within the Fe XIV spectral line, i.e. the emission from excited, ionised iron atoms. This index was studied by Rybansky et al. (1994). The Lyman-α index gives a measure of the activity also on the far side of the Sun. UV radiation from the Sun hits the surrounding interstellar hydrogen, which interacts with the solar wind and brightens in the Lyman-α spectral line. The more it brightens, the more active is the region of the Sun.

2. Data

Due to the fact that the NAO is more intense during winter, most studies refer exclusively to wintertime. In the study reported herein, we used several wintertime means, computed as December–January–February (DJF), December–January–February–March (DJFM), and November–December–January–February–March (NDJFM); and spring means computed as March–April–May (MAM). The NAO index used here was that calculated by Jones et al. (1997), as the normalized difference of SLP between Ponta Delgada (Azores) and Reykjavik (Iceland). Anomalies of Northern Hemisphere surface temperature (combined land surface and sea surface temperature) data were those compiled by Jones (1994). The AO index (Thompson and Wallace, 2000) for the DJF period was also used. Because we were looking for solar influence, the interannual period was determined by the availability of the solar indices.

For a measure of the solar activity, data from http://www.ngdc.noaa.gov/stp/SOLAR/getdata.html were used. For the length of the solar cycle, measured from sunspot numbers, the period of study is 1856–1995. Thirteen cycles were included, divided into three groups according to their length: 10, 11 and 12 years (rounding to the nearest integer); 1867 and 1954 were removed from the record because a change between two different sized cycles occurs in the middle of winter.

F10 index measurements have been made at local noon by the National Research Council of Canada since 1947, and are expressed in solar flux units (1 s.f.u.=10^{-22} W m^{-2} Hz^{-1}). The coronal green line index (FeXIV 530.3 nm) used is computed from photometric patrol observations made at eight ground-based stations. Lomnicky Peak in the Slovak Republic serves as the reference station for calculating the index. Its units are 10^{16} W sr^{-1}. The Lyman-α index (from Mg II index) comes from the extracted database from SOLAR2000 (Tobiska et al., 2000); version v1.23a. SOLAR2000 is an empirical solar irradiance specification tool for accurately characterizing Arctic Oscillation solar irradiance variability across the solar spectrum. This dataset is particularly useful because of the long time series of the Lyman-α index, measured in photon flux (photons m^{-2} s^{-1}). SOLAR2000 also provides values of the total solar irradiance at all wavelengths that reach the top of the Earth's atmosphere (S, in W m^{-2}). The common available period for these series (F10 index, coronal green line index, Lyman-α index, and SOLAR2000) is 1948–2002, which includes five 11-year solar cycles. This was the utilized period. Wintertime means (December, January, and February) were used in this case, in order to compare the results

Table 1. Periods corresponding to 10-, 11-, and 12-year solar cycles.

10-year cycles	11-year cycles	12-year cycles
1914–1923	1856–1866	1868–1878
1924–1933	1879–1889	1890–1901
1934–1943	1955–1964	1902–1913
1945–1953		1965–1976
1977–1986		
1987–1995		

Table 2. Sample sizes (N), means (first number of each column) and standard deviation (second number of each column) for the NHT and NAO, calculated for different periods of solar cycles shown in Table 1.

	10-year cycles		11-year cycles		12-year cycles	
N (years)	59		32		47	
	Means	Standard deviation	Means	Standard deviation	Means	Standard deviation
SUN SPOTS	64.65	46.45	58.89	50.67	45.97	35.68
NHT (DJF)	−0.02	0.32	−0.22	0.33	−0.29	0.30
NHT (DJFM)	−0.04	0.30	−0.24	0.30	−0.30	0.26
NHT (NDEFM)	−0.04	0.28	−0.27	0.28	−0.30	0.25
NHT (MAM)	−0.03	0.24	−0.22	0.20	−0.26	0.24
NAO (DJF)	0.67	1.25	0.54	1.35	0.62	1.17
NAO (DJFM)	0.55	1.08	0.36	1.14	0.49	1.06
NAO (NDJFM)	0.46	0.92	0.25	1.11	0.34	0.93
NAO (MAM)	0.03	0.92	−0.06	0.70	0.07	0.94

Table 3. Correlations between the NHT and NAO. The first number in each column corresponds to 10-year cycles, the second to 11-year cycles, and the third to 12-year cycles. Numbers in bold are significant at a 95% confidence level.

	NHT (DJF)			NHT (DJFM)			NHT (NDJFM)			NHT (MAM)		
	10 yr	11 yr	12 yr	10 yr	11 yr	12 yr	10 yr	11 yr	12 yr	10 yr	11 yr	12 yr
NAO (DJF)	0.20	0.14	**0.32**	0.21	0.17	0.23	0.18	0.05	0.17	0.06	−0.19	**-0.37**
NAO (DJFM)	0.24	0.19	0.27	**0.29**	0.24	0.21	0.23	0.09	0.15	0.13	−0.16	**-0.40**
NAO (NDJFM)	0.21	0.22	0.25	0.25	0.25	0.20	0.20	0.14	0.16	0.15	−0.06	**-0.44**
NAO (MAM)	**0.37**	0.08	0.01	**0.36**	0.12	−0.05	**0.32**	0.17	−0.07	0.22	0.34	0.02

with those of Gimeno et al. (2003). For dividing the series depending on solar activity, values equal to or above the median, for each solar index, were considered as high activity years, and the rest as low activity years.

NHT data were obtained from http://www.cru.uea.ac.uk/cru/data/temperature/. A normalized index of the northern stratospheric temperature averaged over the polar cap (70°–90°N) was computed from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis temperature data at 50 hPa.

3. Results

Years corresponding to solar cycle lengths of 10, 11 and 12 years are displayed in Table 1. Although the sample size is different for each group (59, 32 and 47 years, respectively) there were no significant differences among NAO index means (Table 2), being more important for the NHT [as expected based on Friss-Christensen and Lassen (1991)], since the NHT falls as the length of the period increases. The discrepancy between the behaviour of the NAO and NHT suggests a different relationship between them, according to the length of the solar cycle.

Table 3 shows correlations between the NAO and NHT for wintertime and spring, those in bold being significant at a 95% level. There are significant and strong negative correlations between wintertime NAO and springtime NHT for the longest cycles (12 years). These results are in clear agreement with those of Gimeno et al. (2003), as longer periods correspond to lower solar activities. In the study reported herein, using sunspot numbers, it was found that correlations between wintertime NAO and spring NHT were negative and significant for minimum phases. This is a remarkable result, both for its predictive potential and because it supports the idea that solar activity can influence the NHT through changes in major atmospheric circulation modes. However, Gimeno et al. (2003) also found positive significant correlations between wintertime NAO and NHT for high solar activity that do not appear when the length of the cycle is used. This is not surprising, since solar cycle length represents the whole cycle, and not only the extremes, as in Gimeno et al. (2003). Changes in atmospheric circulation due to the NAO has immediate effects on temperature fields due to changes in advection of temperature, and delayed effects when other factors, such as the SST or snow cover, are considered.

Table 3 also shows positive significant correlations between wintertime NHT and springtime NAO for the shortest cycles (10 years).

For the F10, coronal green line, Lyman-α, and total irradiance (S) indices, the methodology is very similar

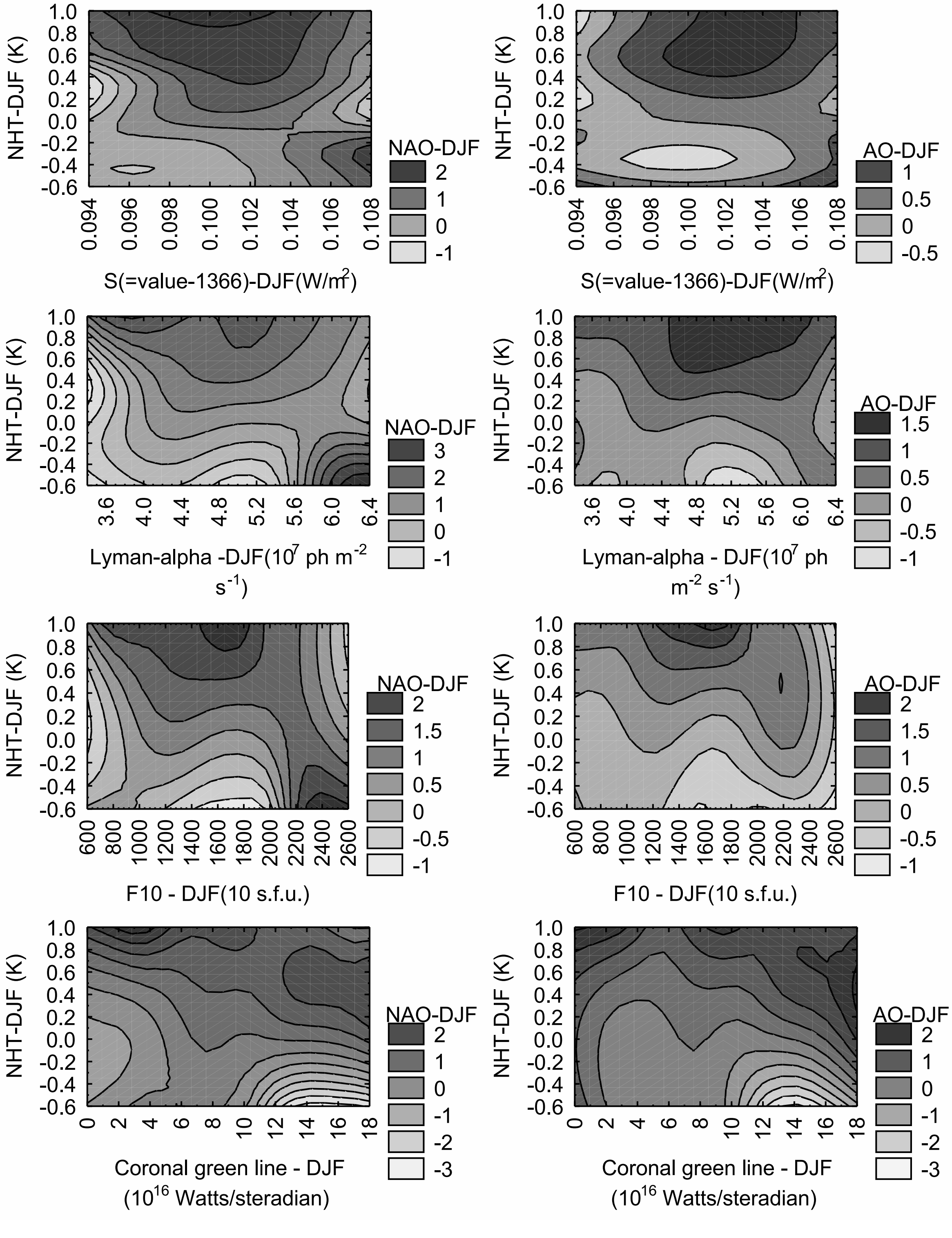

Fig. 1. Contour plot using wintertime (December, January, and February) anomalies of: NAO and NHT (first column), AO and NHT (second column), and wintertime values of total solar irradiance (anomalies with respect to 1366, necessary for the computation, first row), Lyman-α index (second row), 10.7 cm solar radio flux (third row), coronal green line index (last row)(NAO/AO=Distance Weighted Least Squares).

Table 4. Correlation between wintertime (December, January, and February) means of NAO/AO and NHT/T50 anomalies for the series divided by solar activity depending on F10, coronal green line, Lyman-α, and S indices. Values in bold are significant at a 95% confidence level: (a) NAO vs NHT; (b) AO vs NHT; (c) NAO vs T50; and (d) AO vs T50.

		F10	Coronal green line	Lyman-α	S
(a)	High activity	**0.42**	0.33	**0.42**	**0.42**
	Low activity	0.22	0.24	0.21	0.21
(b)	High activity	**0.42**	**0.42**	**0.48**	**0.48**
	Low activity	0.19	0.16	0.13	0.13
(c)	High activity	−0.37	**−0.46**	**−0.39**	**−0.39**
	Low activity	0.10	0.14	0.10	0.10
(d)	High activity	**−0.50**	**−0.59**	**−0.49**	**−0.49**
	Low activity	−0.26	−0.23	−0.29	−0.29

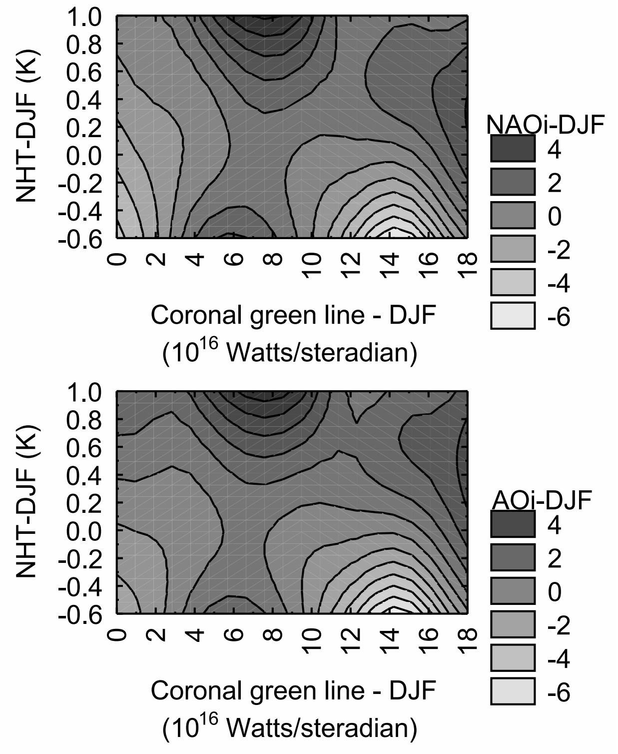

Fig. 2. Contour plot using wintertime (December, January, and February) anomalies of: NAOi and NHT (above) or AOi and NHT (below) and wintertime values of the coronal green line index (NAOi/AOi=Distance Weighted Least Squares).

to that in Gimeno et al. (2003). Figure 1 (first column) shows contour plots of each index (S: first row; Lyman-α: second row; F10: third row; coronal green line: fourth row) with NHT and NAO, using distance weighted least squares. To perform this fit, we needed to divide Lyman-α values by 10^{11} (because their values were too large compared to NAO and NHT values) and subtract 1366 from S, since S is almost constant and the variations were of a low order. These graphs allow us to visualize the relationship between the magnitudes of the three variables at a glance.

For the F10, Lyman-α, and S indices, Fig. 1 shows a strong positive correlation between the NAO and NHT for high solar activity (lower values of NHT for negative NAO, and higher values of NHT for positive NAO). This relationship seems to be inverted at the highest values, but this may be due to boundary errors. The situation is slightly different for the coronal green line, which shows a positive relationship between the NAO and NHT for higher values; also for the highest. These results generally agree with Gimeno et al. (2003), although our figures are slightly different for the extreme values.

To check this relationship between the NAO and NHT for high activity, the series were divided into two groups: one for high activity and the other for low activity, where "high activity" corresponds to the years with a solar index value above the median. These years are almost the same for the F10, Lyman-α, and S indices; only the coronal green line shows some differences. Table 4a shows the correlation index between the NAO and NHT for high and low activity series. For the whole series, this correlation index is 0.34, and is significant at the 95% level. For the F10, Lyman-α, and S series, the correlation is higher and also significant for high activity (0.42), whereas it is lower and nonsignificant for low activity. The case of the coronal green line is somewhat different, with the correlation for high activity being nonsignificant (0.33), although still higher than that for low activity.

Following Kodera (2002), solar maximum phases are associated with a NAO pattern very similar to that of the AO. Therefore, we repeated the contour plots (Fig. 1, second column) and these last correlations (Table 4b) using the AO index. The results in Fig. 1 are very similar to those found with the NAO index. The correlations in Table 4b confirm that the relationship between the AO and NHT occurs only during high activity winters, even for the coronal green line in this case.

Recently, Li and Wang (2003a, b) suggested that the NAO and AO indices should be defined as follows: the difference in the normalized monthly zonal-mean sea level pressure between 35°N and 65°N for the whole hemisphere [Arctic Oscillation index (AOi)] or for the sector from 80°W to 30°E [North Atlantic Oscillation index (NAOi)]. Contour plots and correlations were also performed for these indices, leading to similar conclusions. Figure 2 shows the contour plot using the coronal green line as an example. The correlations computed using this solar index to divide the NAOi, AOi and NHT depending on the solar activity are significant for high solar activity in this case (0.47 for NAOi vs. NHT, and 0.55 for AOi vs. NHT)

Kodera (2002) also found that, for maximum solar phases, the NAO structure extends into the stratosphere. In this link between stratosphere and troposphere could be the origin of the connection between solar activity and tropospheric weather through climate variability modes. Thus, the variations in solar activity would change the stratospheric conditions influencing the stratospheric polar vortex and, therefore, the stratospheric part of the NAO/AO mode. These changes could then propagate into the troposphere.

To check the solar influence in the stratospheric vortex related to NAO/AO, we repeated the contour plots (Fig. 3) and correlations (Tables 4c and d) using the northern stratospheric temperature averaged over the polar cap (T50) as a stratospheric index, instead of the NHT. The contour plots in Fig. 1b show a clear relationship between the polar stratospheric temperature and the NAO/AO for high solar activity. This relationship is not so clear, and perhaps even absent, for low solar activity. Thus, for high solar activity, a drop in the polar cap temperature in the stratosphere (speeding up of the polar stratospheric vortex) is associated with a higher NAO/AO index (which is defined in the lower troposphere) and vice-versa. These results are confirmed by the correlations in Tables 4c and d.

These results point to the fact that the stratospheric vortex is the link through which the solar activity influences tropospheric fluctuations. The signal is robust and physically consistent with the polar vortex characteristics when the stratospheric temperature averaged over the polar cap (70°–90°N) is correlated with the AO index, in high solar activity data. The magnitude of correlations between the AO and temperature at 50 hPa, obtained for the high solar activity, diminishes for tropospheric temperatures, which shows the propagation of the solar-related signal from stratosphere to troposphere.

Kodera and Kuroda (2005) found a possible mechanism of solar modulation of the spatial structure of the NAO. Their results show that when solar activity is high, the leading mode of the interannual variations of the zonal-mean zonal wind in the upper stratosphere–stratopause region has a meridional dipole structure. This dipole-type anomaly extends into the troposphere by accompanying changes in the meridional propagation of planetary waves. Change in the meridional propagation of waves in the lower stratosphere and troposphere induces meridional circulation and produces a seesaw pattern in the surface pressure between the polar and surrounding region, resulting in the NAO extending across the Northern Hemisphere. This hemispheric extent is the reason that the NAO is well correlated with the NHT only for high, and not for low, solar activity when the NAO is restricted to the Atlantic sector. In this case, the circulation associated with the pressure gradient affects the temperature only around the Atlantic and Europe (which is not even one half of the hemisphere), where the more intense winds related to a higher NAO index lead to a warmer winter. Therefore, it has a poor relationship with temperature in regions distant from this sector.

4. Concluding remarks

In conclusion, our results show a dependence on solar cycle length in the relationship between the NAO and the NHT. There are negative significant correlations for 12-year cycles, with the NAO leading the NHT, and significant positive correlations for 10-year cycles, with the NHT leading the NAO, both results having predictive potential. The former result supports that of Gimeno et al. (2003), and although the mechanism responsible for these negative correlations during the lower active cycles remains unclear, it could be related to the coupling with snowcover (Bojariu and Gimeno, 2003) and changes in the albedo, as well as in wave propagation. On the other hand, the positive correlations during the most active solar cycles could be explained by the stratospheric connection (Kodera and Kuroda, 2005)

The results obtained from the 10.7 cm solar radio flux, the coronal green line, the Lyman-a index and the total irradiance are very similar to those of Gimeno et al. (2003), which suggests that, for high solar activity, there is a strong relationship between the NAO/AO and the NHT that does not appear for low solar activity. This result is a consequence of the different spatial extent of the NAO according to the solar cycle: confined to the Atlantic sector during low solar activity, but hemispheric during high solar activity (Kodera, 2002).

A relationship between the stratospheric polar vortex and NAO/AO indices (defined at the lower troposphere) is found only for high solar activity. This

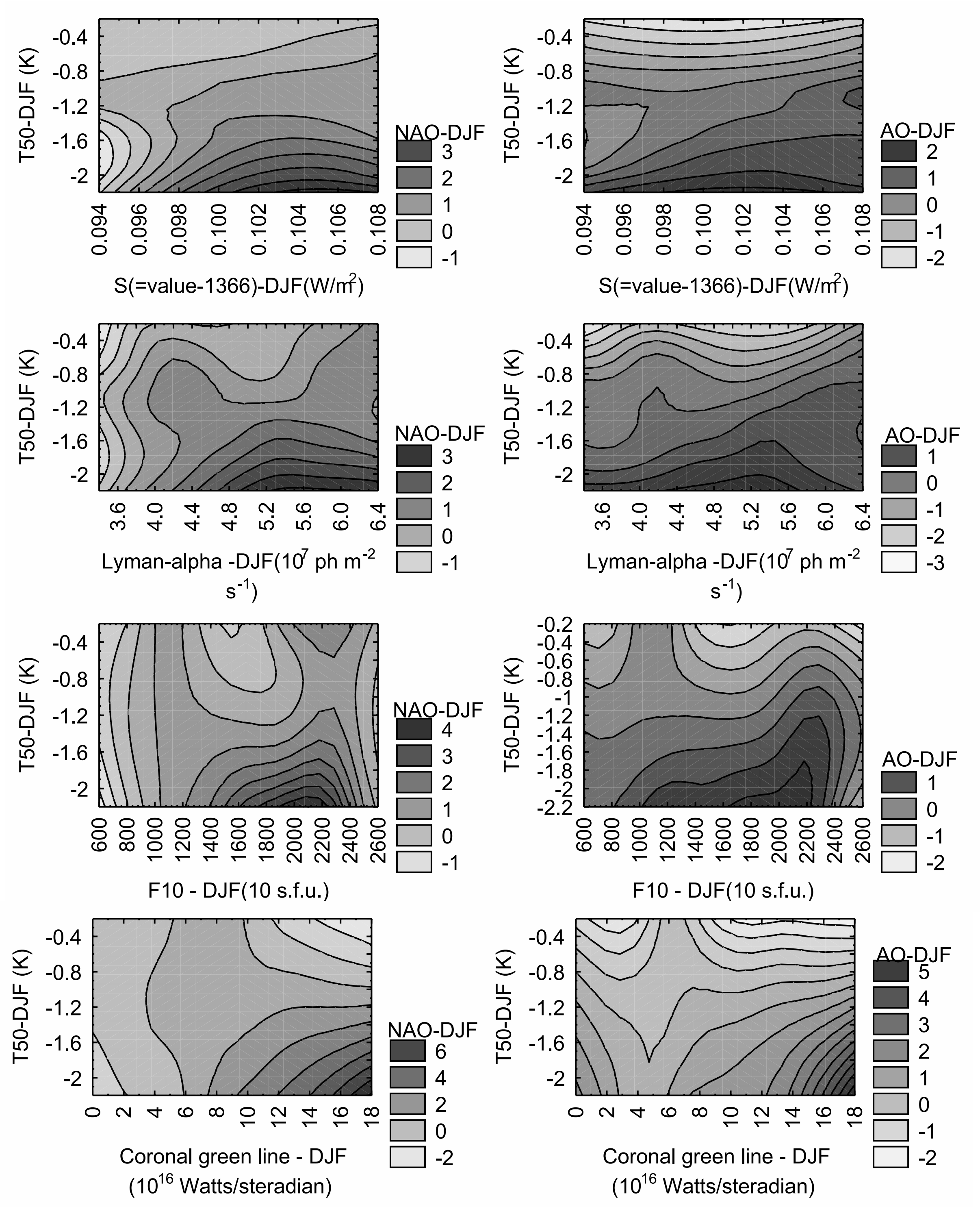

Fig. 3. As Fig. 1, but using T50 instead of NHT.

fact means that changes in the stratosphere affect the troposphere only during winters of high solar activity, which supports the hypothesis of Kodera and Kuroda (2005), who suggest that the solar influence is due to the downward extension of zonal-mean zonal wind anomalies produced in the stratosphere being strong during high solar activity and weak during low solar activity . Thus, solar activity seems to influence the Northern Hemisphere tropospheric climate fluctuations via the fluctuations of the stratospheric polar vortex.

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