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Trends in sunspots and North Atlantic sea level pressure

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[1] We analyze the periods 1878–1944 and 1944–2008. The quasi-stationary wave in the North Atlantic region was stronger and the baroclinity steeper in 1878–1944 than in 1944–2008. The North Atlantic Oscillation Index—as defined by the Climate Research Unit, University of East Anglia—was higher in the former period too. We illustrate these statements by maps of sea level pressure and air temperature at the surface. The long-term trends in the North Atlantic Oscillation Index are linked to the trend in sunspot number such that when, in the mean, the sunspot numbers were high (Gleissberg maxima) the trends in the two quantities were parallel; and when the mean sunspot numbers were low (Gleissberg minima) the trends in the North Atlantic Oscillation Index and sunspots were opposite. We find the connections between the trends statistically significant, and we infer that the level of solar activity played a role in the trends of the past two centuries in the North Atlantic region. However, we cannot as yet provide a mechanism linking the solar trends to those in the atmosphere and ocean, but as a step toward an explanation, the equator to pole temperature gradient is steeper in a Gleissberg minimum than in a maximum.

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1. Introduction

[2] *Van Loon et al.* [2007a] and *van Loon and Meehl* [2008, 2011] have shown a sea level pressure (SLP) response in the Pacific Ocean basin to maxima in decadal solar activity. Here, we shall be dealing with trends in the SLP of the North Atlantic and in the North Atlantic Oscillation (NAO). The period of interest is 1878 to 2008. Within this period, we compare two intervals 1878–1944 and 1944–2008, which had similar global temperature trends but at different levels of temperature.

[3] The NAO has been known for several centuries [see *Stephenson et al.*, 2003; *Wallace*, 2002; *van Loon and Rogers*, 1978, for historical references]. It was named in 1924 by Gilbert Walker [*Walker*, 1924]. The NAO affects the weather and climate over a vast region from the eastern United States to Europe and the Middle East [see, e.g., *van Loon and Rogers*, 1978; *Hurrell and van Loon*, 1997]. It does not have the persistence of the Southern Oscillation nor does it have a regular period or marked precursors; but a given phase may predominate for several decades [*van Loon and Rogers*, 1978, Figure 13]. The NAO has been described numerous times, and we mention here only one of the earlier studies: the one by *Defant* [1924] which with 25 years of observations gave a good quantitative picture of the Oscillation and its teleconnections.

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2. Anomalies of Sea Level Pressure and Surface Air Temperature

[4] The NAO Index we use was made by the Climate Research Unit (CRU) at the University of East Anglia [*Jones et al.*, 1997, 2003]. It consists of the SLP difference between Gibraltar and southwestern Iceland, and thus measures mainly conditions over the central and eastern Atlantic Ocean and Europe. Figure 1 shows a time series of northern winters in the index, with an eleven-year running mean applied to emphasize longer timescale *trends*. Despite the eleven-year smoother, the index time series exhibits variability at higher frequencies. It is evident that the index trend tended on average to be higher and always positive in the former than in the latter part of the period, and that a linear trend in the long term mean shows a gradual decline from the 1880s to the present.

[5] The following maps in Figures 2a and 2b, based on the Hadley2 data set [*Basnett and Parker*, 1997], contain the SLP anomalies in 1878–1944 and 1944–2008. Both anomaly maps show a positive NAO Index from Europe across to North America with positive SLP anomalies in the south and negative anomalies to the north. However, the gradients (geostrophic wind) are appreciably steeper in the former period, 1878–1944, than in the latter, 1944–2008. The mean westerly southwesterly wind was thus stronger in the former period; and it is evident from the distribution of SLP anomalies that the mean northeast trade winds also were stronger in 1878–1944. This is what could be expected from the index time series in Figure 1. Thus, the quasi-stationary wave in the

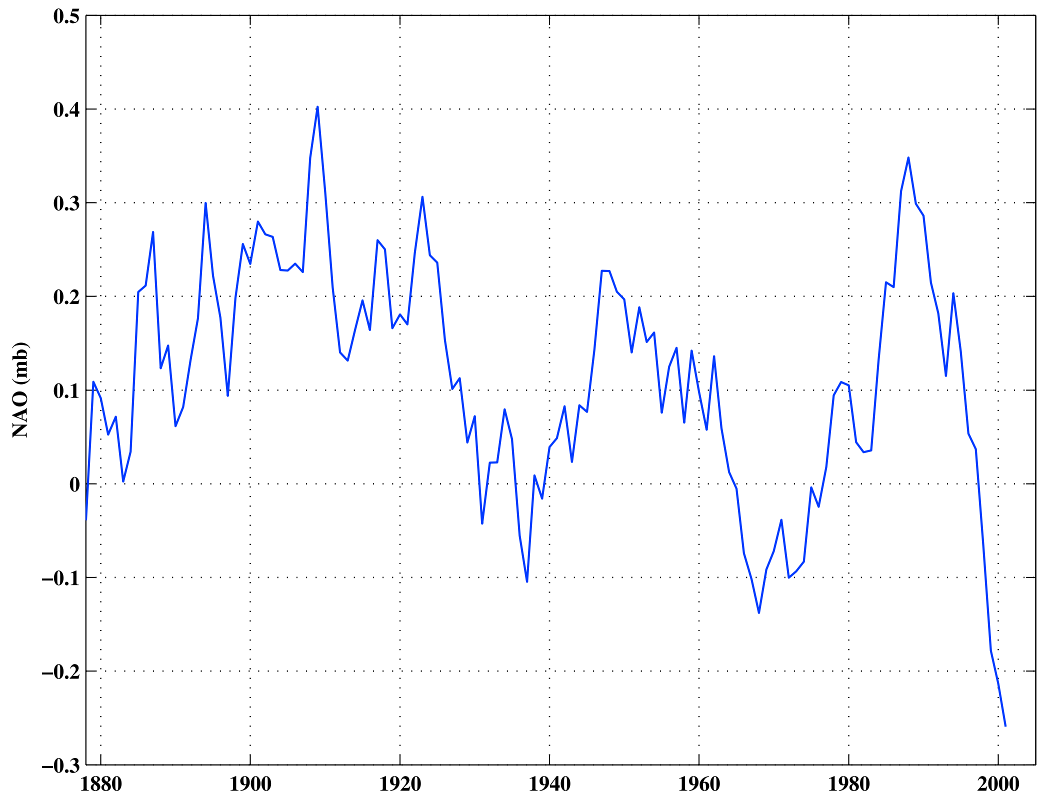


Figure 1. Time series of the December–February average of the NAO Index (Gibraltar-Iceland) from CRU for 1821–2006. The seasonal time series have been further smoothed by a 135-month (approximately 11-year) running mean.

North Atlantic region was stronger in 1878–1944 than in 1944–2008, and the baroclinity in the troposphere was stronger too, as expressed in the steeper SLP gradients.

[6] The sea surface temperature (SST) anomalies in Figure 3 fit well with the pressure (wind) anomalies in Figure 2. Figures 3a and 3b show the opposite anomaly pattern; especially in the trade-wind regions. The intensity of the pattern is, however, greater in the first period in agreement with the steeper SLP gradients in the same period (Figures 2a and 2b). There are no tropospheric temperature anomalies for the first period, but one can deduce from the anomaly patterns in Figures 2 and 3, that the quasi-stationary waves in the North Atlantic domain and the baroclinity (south-north temperature difference) were stronger in 1878–1944 than in 1944–2008.

3. A Solar Connection?

[7] Figure 4 shows the eleven-year running means of the NAO Index and of the sunspot numbers for December–February averages (Figure 4a) and June–August averages (Figure 4b); the smoothed values are similar in both extreme seasons. The sunspot series data are obtained from the NOAA websites through the Solar Influence Data Analysis Center (SIDC) of the Royal Observatory of Belgium. The time series runs through two Gleissberg maxima, 1830s till 1870s and 1940s till about 2000, and one Gleissberg minimum from the 1880s till the 1930s. In each of the two smoothed Gleissberg maxima there are two peaks, whereas the Gleissberg minimum is lowest in the first decade of the 20th century.

[8] The smoothed NAO Index (Figures 4a and 4b) also has two peaks, coinciding with the peaks of the Gleissberg maxima but has a maximum in the Gleissberg minimum; in other words, the trend in the NAO Index is positively correlated with the trend in the sunspot numbers in the Gleissberg maxima, but negatively correlated with the sunspots in the Gleissberg minimum.

[9] Figure 5a is the cross-wavelet power spectrum for monthly average time series of sunspots and the NAO Index; again, from SIDC and CRU, respectively. The longer-timescale relationships evident in Figures 4a and 4b are reproduced in comparisons using these monthly mean data (not shown). The cross-wavelet power spectrum reveals timescales (periods) and times when the NAO Index and the sunspot time series have power in common. The significant regions of power in time versus period space in Figure 5a are outlined in black. These regions are significant at the 95% level with respect to a population of 1000 red noise spectra from a Monte Carlo simulation of lag-1 auto-regressive (AR-1) processes with coefficients taken from AR-1 fits to the sunspot and NAO Index time series. Methods and formulae for the significance tests are provided by *Torrence and Compo* [1998] and *Grinsted et al.* [2004].

[10] The cross-wavelet power spectrum in Figure 5a shows significant common power for periods centered on 11 years in the years 1840–1887, 1920–1965, and 1976–1995. These times roughly correspond to the times in Figure 4 when the 11-year running mean winter (Figure 4a) and summer (Figure 4b) curves for the NAO Index and sunspot numbers coincide.

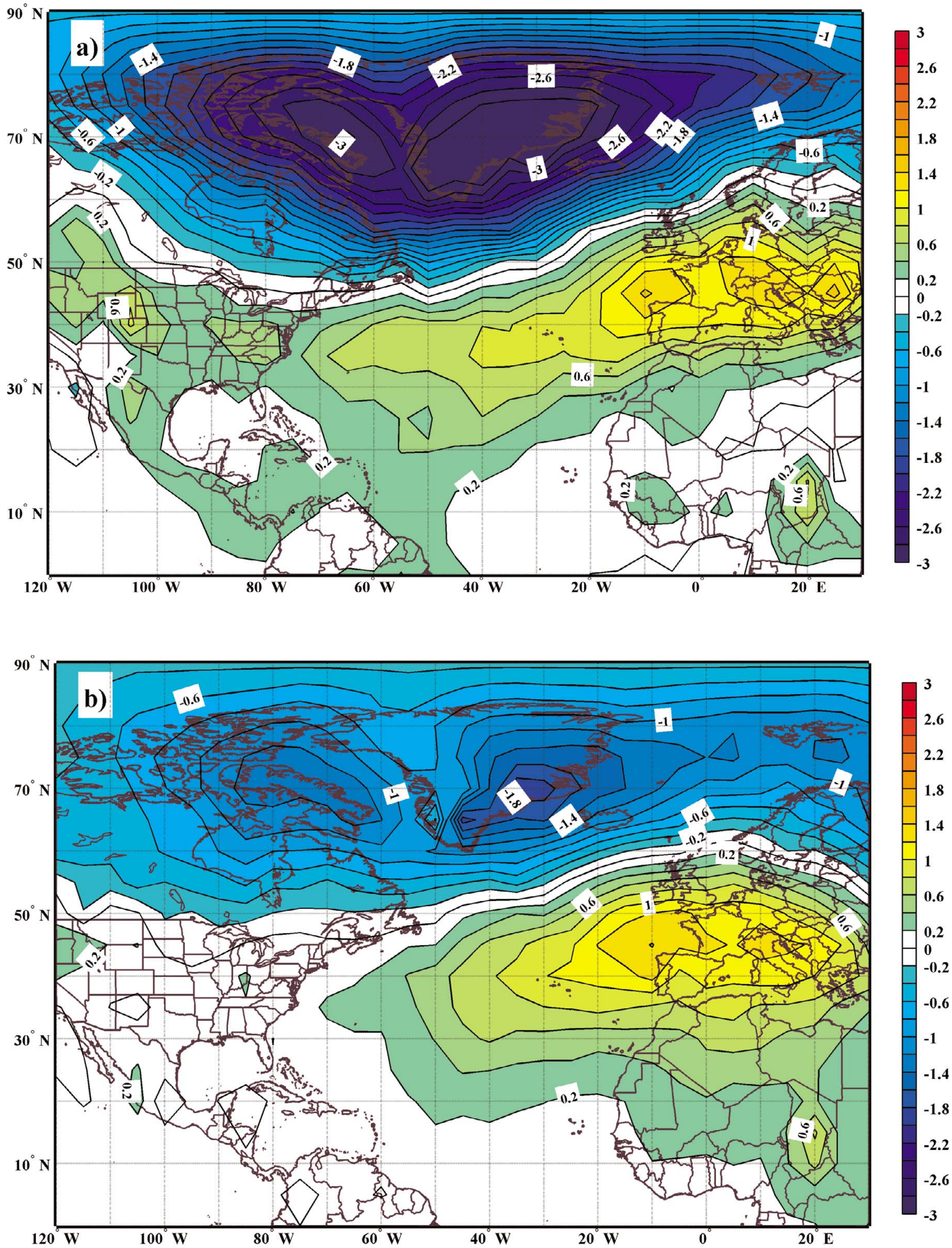


Figure 2. (a) December–February (seasonal) average SLP anomalies for the period 1878–1944 from the Hadley2 data set. Anomalies are computed with respect to a climatology spanning 1950–1979. (b) Seasonal SLP anomalies as in Figure 2a but for the period 1944–2008.

[11] Figure 5b is a scale average time series (SATS), similar to the scale-averaged wavelet power examples of *Torrence and Compo* [1998], obtained by averaging the cross-wavelet power in the period band between 10 and 12 years in Figure 5a. The horizontal dashed line is the 95% significance level for the SATS, obtained as described by *Torrence and Compo* [1998]. The significant times in this time series are similar but not identical to significant times in

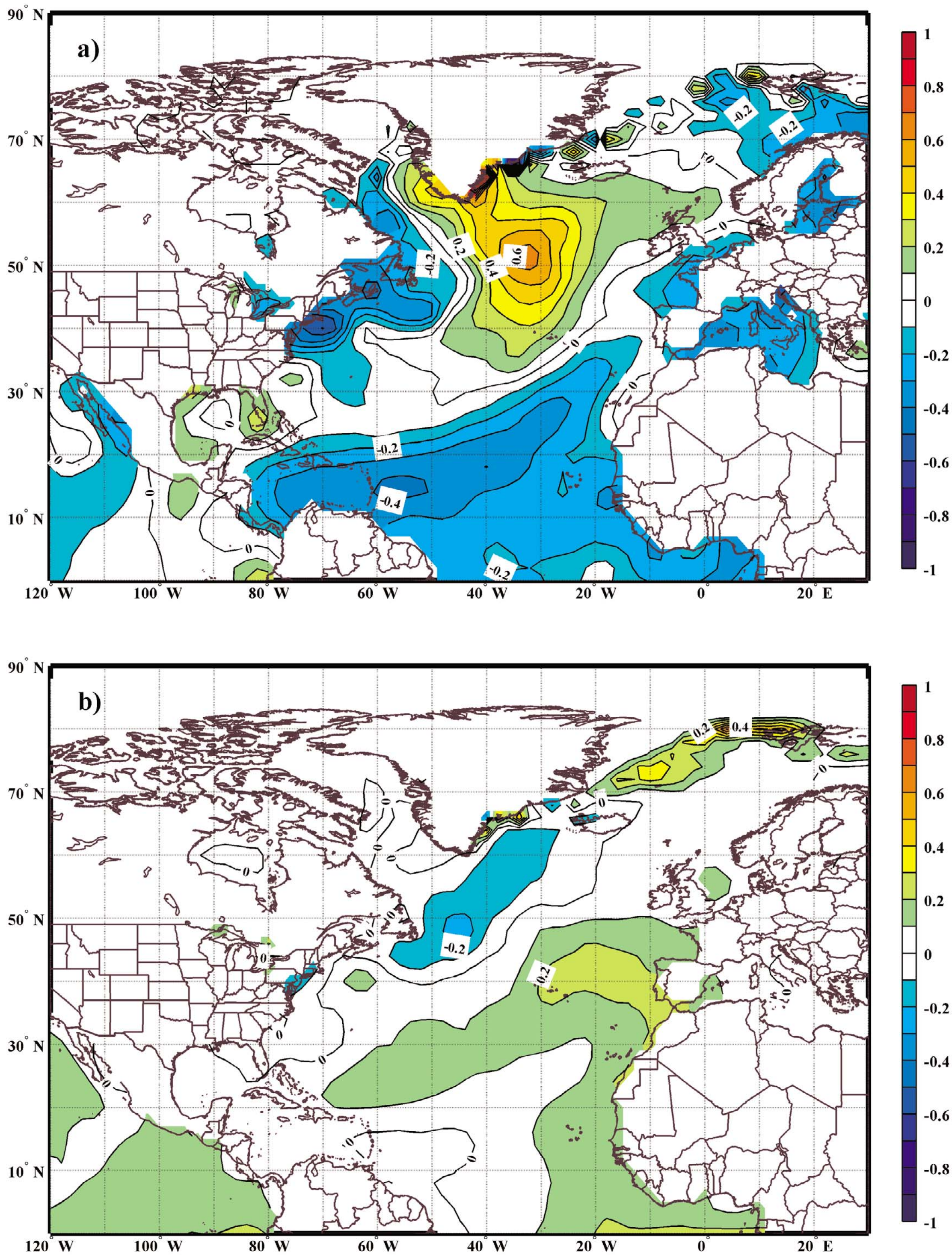
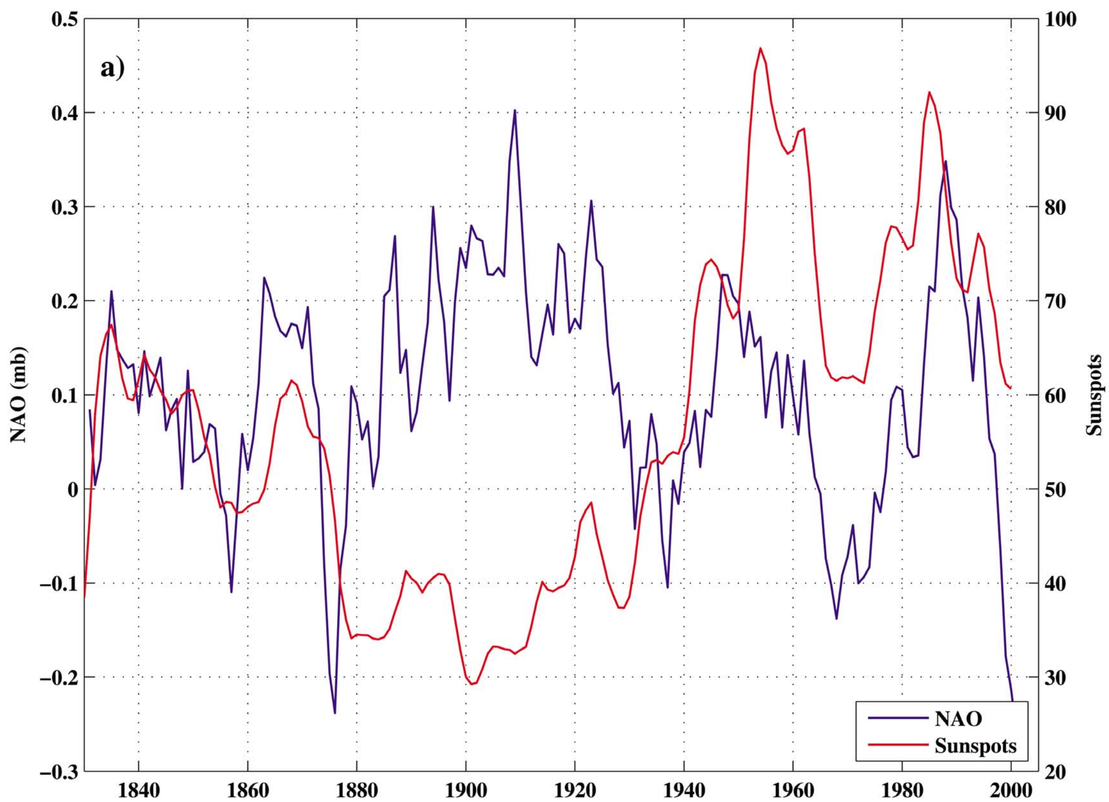


Figure 3. (a) December–February (seasonal) average sea surface temperature (SST) anomalies for the period 1878–1944 from the NOAA Extended Sea Surface Temperature data set. SST anomalies are computed relative to a climatology from the period 1950–1979. (b) Seasonal SST anomalies as in Figure 3a but for the period 1944–2008.

Figure 5a (i.e., because the red-noise bases are different). Significant cross-wavelet power in the SATS in Figure 5b include the years: 1838–1872, spanning the first Gleissberg maximum in our record; 1878–1895, during the beginning of the Gleissberg minimum; 1914–1933 during the end of the same Gleissberg minimum; 1933–1959, during the beginning of the second, stronger Gleissberg maximum; and 1980 till the present, covering the end of the current Gleissberg maximum.



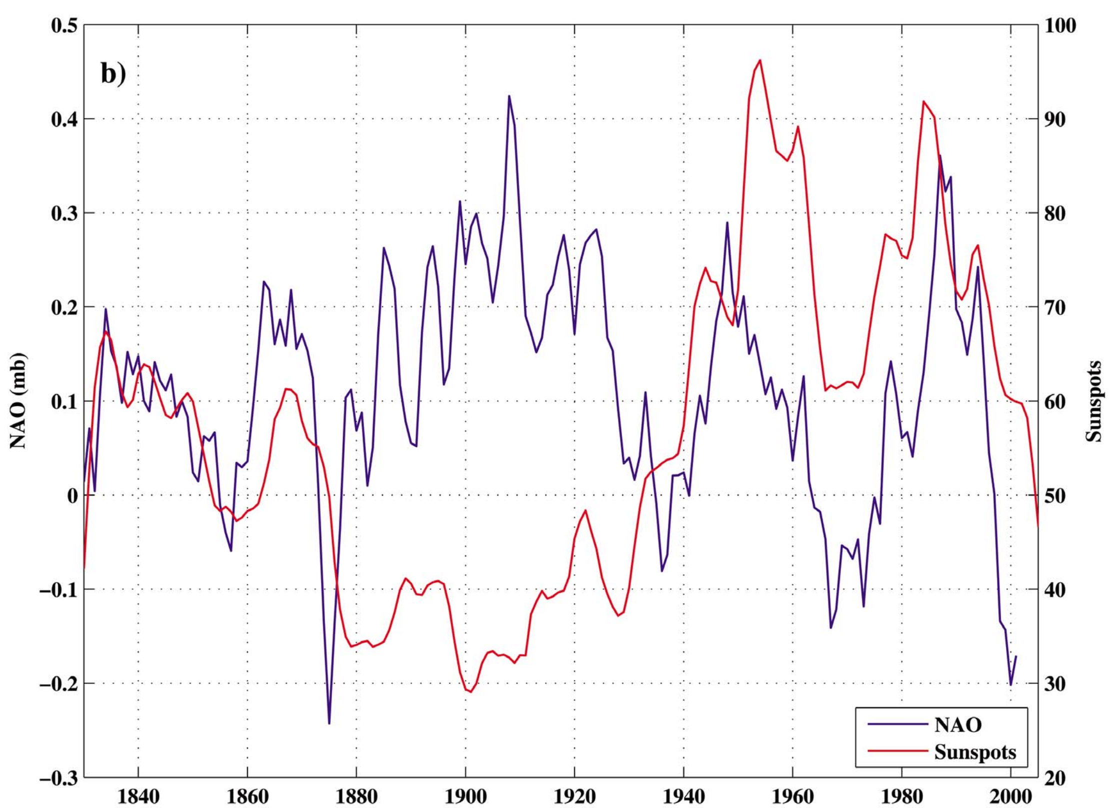


Figure 4. (a) 135-month (approximately 11-year) running means of the December–February averages for sunspot numbers (red) from SIDC and the NAO Index (blue) from CRU spanning the years 1821–2006. (b) Same as Figure 4a but for June–August averages.

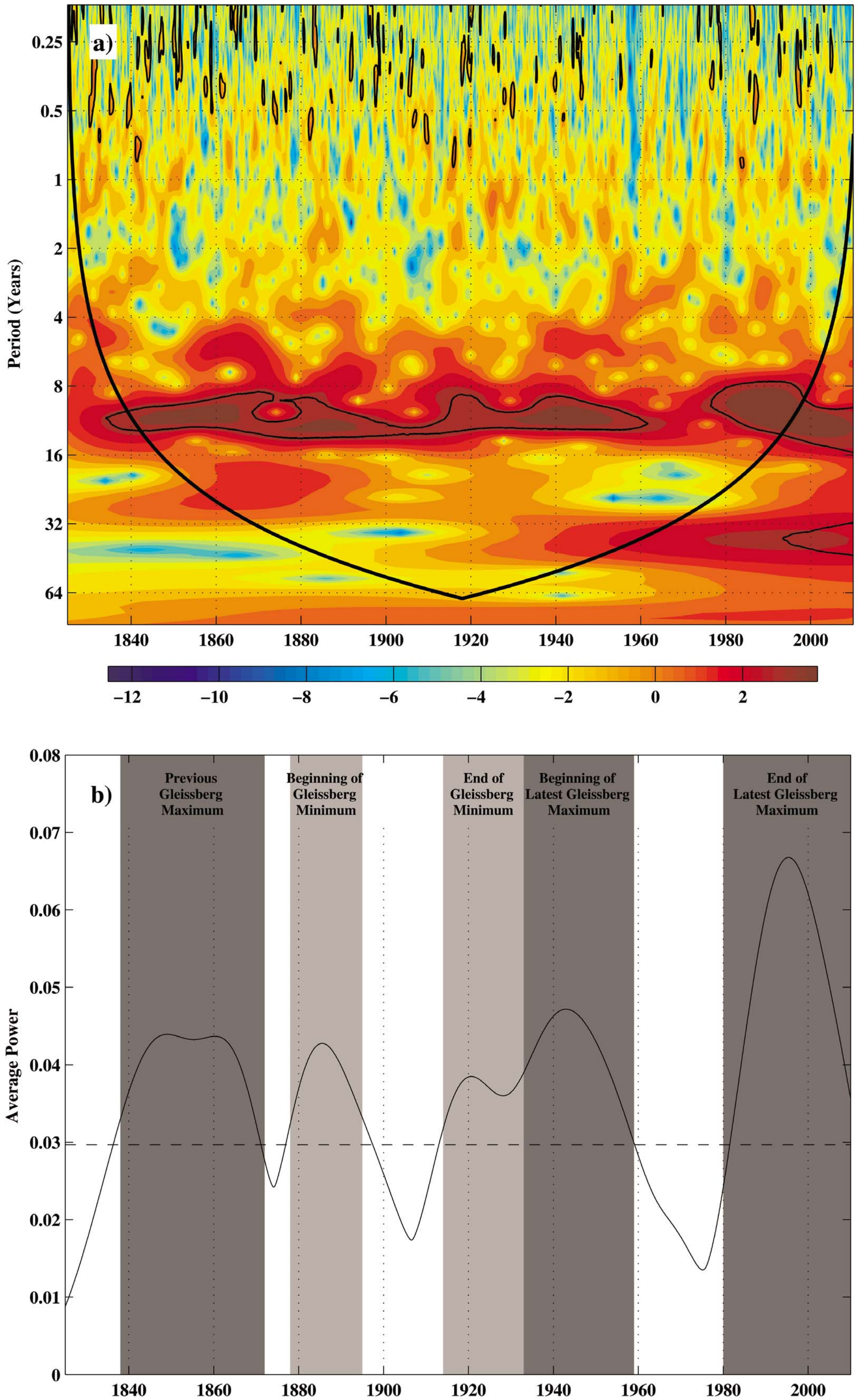

a)
Period (Years)
0.25
0.5
1
2
4
8
16
32
64
1840
1860
1880
1900
1920
1940
1960
1980
2000
−12
−10
−8
−6
−4
−2
0
2
b)
Average Power
Previous Gleissberg Maximum
Beginning of Gleissberg Minimum
End of Gleissberg Minimum
Beginning of Latest Gleissberg Maximum
End of Latest Gleissberg Maximum
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Figure 5

[12] Cross-wavelet coherence and phase (not shown here) were also examined for the monthly average NAO index and sunspot time series. Coherent episodes in the 8 to 16 year period band were limited to even shorter time spans; 1845–1855 with NAO index leading sunspots and 1975–1990 with NAO index and sunspots roughly in phase. There was no significant cross-wavelet coherence for the time span during the Gleissberg minimum (1878–1933), where time series in Figures 4a and 4b appear to be out of phase. Interestingly, the cross-wavelet coherence is significant and strong, and the NAO index and sunspot time series are in phase, at 32-year periods for the years 1880–1950 encompassing the Gleissberg minimum in the data record. This coherence and phase at 32-year periods remains unexplained for now.

4. Discussion

[13] It is well known that the North Atlantic mean SST rose from the second half of the 19th century to the present in two steps [e.g., *Rayner et al.*, 2006; *Reynolds et al.*, 2007], from about 1878 to 1944 and from 1944 into the 21st century. It is commonly assumed that the second rise was owing principally to increasing greenhouse gases in the atmosphere. However, at the same time solar activity—judged by the number of sunspots—rose from a long period of lower activity (weaker 11-year oscillations during a Gleissberg minimum) to one of higher activity (Gleissberg maximum), and it would be unwise to ignore or disparage this fact.

[14] The periods in Figure 2, 1878–1944 and 1944–2008, each cover six solar decadal oscillations, the former period characterized by the Gleissberg minimum and the latter one by the latest Gleissberg maximum. In the same period the amount of greenhouse gases in the atmosphere increased. It is therefore possible that both the increased solar activity and the growth in greenhouse gases worked in the same sense to cause the SLP and temperature changes in Figures 2 and 3.

[15] When one looks further back in the curves of Figure 4 there is more evidence to support a solar influence. This part of the curve spans another Gleissberg maximum, which is smaller and of shorter duration than the recent one. The association between the trends of the NAO Index and the sunspot numbers is, however, the same as in the later Gleissberg maximum, although it is generally agreed that the greenhouse gases then were not as prominent a constituent of the atmosphere as in the past several decades.

[16] So, it is also possible that independent of greenhouse gas concentrations, increased solar activity can partly mask or obscure the signal of the NAO, while conversely, when the solar activity is low, the NAO signal is more evident. This is consistent with the different amplitudes of the NAO signals in Figures 2 and 3.

[17] We can, as yet, offer no mechanism to explain how a solar influence might have worked, but only point to the different levels of solar activity in Gleissberg maxima and minima. It should also be noted that Figures 4 and 5 indicate that the effect is the same in all seasons. We also stress that apparently the effect of trends in the sun is different from that in the peaks of the sun's decadal oscillation [e.g., *van Loon et al.*, 2007a].

[18] Finally, a note on the amplitude of surface-air trends of temperature: Since 70% of the earth's surface is covered by oceans, one should probably consider the air temperature over the sea and the SST when looking for representative global trends. Temperature changes at the surface over the continents and over ice in winter are not very representative owing to the strong surface inversions which add out-of-proportion to positive global trends when destroyed by advection, wind, and cloud cover. Conversely, land and ice-based temperature trends also accentuate negative trends when the inversions build [*van Loon et al.*, 2007b, Figures 5–9].

5. Conclusions

[19] In the period 1878–1944, when both the amount of greenhouse gases in the atmosphere and the solar activity were lower, the quasi-stationary wave in the Atlantic Ocean in northern winter was stronger and the baroclinity steeper than in the period after 1944. In the North Atlantic Ocean this could be observed in a comparison of the trend in the North Atlantic Oscillation Index (SLP at Gibraltar minus SLP in Iceland) with the trend in sunspots. The trend in the Index was inversely associated with the trend in the sunspots. At long-term low solar activity (Gleissberg minimum) the NAO Index was stronger and its trend was the opposite of that of the sun. But in long-term higher solar activity (Gleissberg maxima) the mean NAO Index was lower and its trend followed that in the sun's activity.

[20] The cross-wavelet power spectrum (Figure 5a) for monthly average NAO Index and sunspot time series exhibits statistically significant power in common for the two time series for 11-year periods over time intervals 1840–1887, 1920–1965 and 1975–2000. The former earliest and latest time intervals overlap intervals during Gleissberg maxima when 11-year running means of seasonal time series for NAO Index and sunspots exhibited similar trends (Figures 4a and 4b). The middle time interval for which significant cross-wavelet power exists does not compare well with the 11-year running mean seasonal time series. The middle interval spans the end of a Gleissberg minimum and the early parts of the most recent Gleissberg maximum.

[21] In sum, it is unwise to underestimate the influence of the sun on circulation changes and temperature trends. But it is not necessarily so that what happened during the past two Gleissberg maxima and one minimum is representative of all times, given both the high variability of the sun and of the earth's climate system. *In the present sample* the solar

Figure 5. (a) Cross wavelet power spectrum for monthly time series of sunspot numbers and the NAO Index, 1825–2010. Contours outlined in bold black are statistically significant at the 95% level based on Monte Carlo simulations of a red-noise process. A bold black line marks the cone of influence, inside of which (i.e., for longer periods and at the beginning and end of the time series) edge effects influence the cross-wavelet power. (b) Scale average time series for the cross-wavelet power in the period band between 10 and 12 years in Figure 5a. Statistically significant peaks (see dashed line) within this band occurred between 1838 and 1872 (Gleissberg max), 1878–1895 (begin Gleissberg min), 1914–1933 (end Gleissberg min), 1933–1959 (begin Gleissberg max) and 1980-present (end Gleissberg max, note that significant power after 1990 lies within the cone of influence where power can be corrupted by edge effects).

activity in the second Gleissberg maximum was stronger and lasted longer and the minimum lasted longer than in the earlier observed Gleissberg oscillations since 1750 (e.g., SIDC).

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