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A WAVELET CHARACTERIZATION OF THE NORTH ATLANTIC OSCILLATION VARIATION AND ITS RELATIONSHIP TO THE NORTH ATLANTIC SEA SURFACE TEMPERATURE

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ABSTRACT

In this study, Multiresolution Fourier Transform (MFT) spectral analysis is employed to resolve the temporal structure of the variation of the North Atlantic Oscillation (NAO) in terms of various frequency components. The NAO index displays fluctuations on multiple timescales, resulting in an MFT spectrum characterized by the occurrences of distinct frequency bands at certain times in the record. These frequency bands are examined within the context of annual to interdecadal spectral components. The relative contribution by each of these spectral components toward the overall NAO variability varies with time.

Phase analysis of the spectrum demonstrates that, in addition to some apparent 'random' fluctuations, the phase of each of the spectral components on occasions exhibits relatively constant value over a period of time (from a few years to a decade). In addition, a significant coherent relationship between the NAO and the North Atlantic sea surface temperature (SST) is found at interannual and interdecadal timescales. Some evidence has also been found to suggest that the phase of the interdecadal component of the NAO is itself modulated by the North Atlantic SST at a timescale of about 60 years. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: North Atlantic Ocean; wavelet analysis; North Atlantic Oscillation; North Atlantic SST; interannual and interdecadal variability; Multiresolution Fourier Transform spectral analysis

1. INTRODUCTION

Teleconnection patterns of low frequency variability modes in the atmosphere have been identified and documented by a number of investigators, e.g. Wallace and Gutzler (1981) and Barnston and Livezey (1987). This paper focuses on one of these low frequency atmospheric circulation patterns, namely the North Atlantic Oscillation (NAO). The NAO teleconnection pattern is a dominant mode of atmospheric variability in the North Atlantic sector, accounting for more than 30% of the hemispheric variability in the surface pressure data (Cayan, 1992). Although the NAO pattern is most pronounced during the winter season, it is identifiable throughout the year. The NAO, as well as its 'sister' BWA (Baffin Island–West Atlantic), has been used to describe climatic variability in such parameters as temperature and precipitation over regions extending from eastern North America to western and central Europe (Walker and Bliss, 1932; van Loon and Rogers, 1978; Rogers and van Loon, 1979; Hurrell, 1995; Shabbar *et al.*, 1997). Applying complex empirical orthogonal function analysis to gridded sea level pressure fields obtained from observation and simulation runs from two GCMs (one from the Geophysical Fluid Dynamic Laboratory and another one from the National Center for Atmospheric Research), Barnett (1985) demonstrated that the NAO is a 'natural mode of spatial response (standing wave) of the global climate system', and is generated by the nonlinear internal dynamics of the atmospheric circulation alone.

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The NAO is characterized by variations on multiple timescales. For example, Hurrell and van Loon (1997) showed a power spectrum of the NAO index for the 130 winters from 1865 to 1994, revealing significant variance at quasibiennial periods, as well as enhanced power in the 6- to 10-year period band. They stated that the latter period band 'has become more pronounced over the latter half of this century.' Schneider and Schonwiese (1989) have also found significant spectral peaks at 1.7, 2.2 and 7.5 years in monthly NAO data from 1881 to 1984. Using the 1900–1983 winter NAO index, Rogers (1984), on the other hand, displayed prominent spectral peaks at around 20 years and 7.3–8.0 years. Cook *et al.* (1998), who used tree ring chronologies as proxy data to reconstruct the 1701–1980 winter NAO index, described concentrations of spectral power around periods of 24, 8 and 2 years, as well as identifying an interdecadal oscillation with a period of about 70 years. Because persistence or 'memory' of the atmosphere is measured in terms of weeks, these interannual to interdecadal variations in the NAO index have led many investigators to look towards the oceans (mainly the North Atlantic Ocean) for the cause.

The possibility that at least some aspects of the NAO could be predicted from Atlantic SST (sea surface temperature) conditions has motivated a number of climatologists to investigate the air–sea interaction over the North Atlantic Ocean. Bjerknes (1964), for example, described signals in SST records of the subtropical and subpolar Atlantic Ocean that varied on decadal timescales. More recently, Deser and Blackmon (1993) and Kushnir (1994), using more extensive data sets than those available to Bjerknes, provided additional evidence to support the earlier findings. Although causal relationship has not yet been firmly established, SST variability has been shown to be correlated with atmospheric anomalies on the same timescales (Bjerknes, 1964; Deser and Blackmon, 1993; Kushnir, 1994). In particular, Bjerknes and Kushnir suggested that on decadal and longer timescales, the variation in the NAO is forced by the SST variability.

Other than some recent work by investigators such as Schneider and Schonwiese (1989) and Hurrell and van Loon (1997), there has been very little work on the characterization of the temporal structure of frequency contributions to the modulation of the NAO. Such time-frequency localization analysis is essential because it not only leads to further understanding of the relative contribution of various processes thought to influence the NAO variability, but it can also help in identifying other oscillatory processes which might influence the NAO.

Previous studies have employed an analysis technique in which a Fourier decomposition is applied to a moving window of certain time length from the beginning to the end of a time series. This has resulted in a loss of resolution in the frequency–time spectrum, especially with respect to the precise identification of periods of contribution to the spectrum by the various spectral components. In this study, Multiresolution Fourier Transform (MFT) spectral analysis method is employed, which combines the windowed Fourier Transform and the wavelet transform into a single transform (Wilson *et al.*, 1992), to obtain a more resolved characterization of the temporal structure of the amplitude and phase modulations of the annual cycle of the NAO, as well as those of the interannual cycles. In addition, the frequency–time relationship between the NAO and the North Atlantic SST is described, and the modulation of the NAO by the SST on a decadal to interdecadal timescales is demonstrated. What the authors hope to show, and what other related studies have not, is that there is a coherent relationship between the NAO, in terms of amplitude and phase, and the North Atlantic SST at interdecadal spectral components, especially at a 60-year cycle. Evidence will be presented that this relationship is not continuous throughout the study record, but appears to be 'sporadic'.

2. MULTIRESOLUTION SPECTRAL ANALYSIS

In this section some relevant aspects of the multiresolution spectral and cross-spectral analysis used in this study are briefly reviewed. The method combines the windowed Fourier Transform and the wavelet transform into a single transform which has some specific advantages for studying geophysical signals. Further details regarding this technique can be found in Wilson *et al.* (1992), Stockwell *et al.* (1996) and Huang *et al.* (1997). A useful introduction to the application of wavelet analysis to meteorological data is given by Torrence and Compo (1998). For detailed discussions of the wavelet analysis of time series, the reader is encouraged to refer to these published articles, as well as to references therein. Therefore, only a very brief description is provide herein.

2.1. Multiresolution Fourier transform

For a continuous one dimensional time series $x(t)$ its continuous multiresolution Fourier transform at time τ, frequency f, and scale σ is defined by:

$$F_{\mathrm{m}}(f, \tau, \sigma) = \int_{-\infty}^{+\infty} x(t) g(t-\tau, \sigma) e^{-i2\pi ft} \, \mathrm{d}t \tag{1}$$

where $g(t, \sigma)$ is an appropriate window function. The dilation, or scaling, parameter σ increases the 'width' of the window function for lower frequencies, while decreasing for higher frequencies; it is controlled by selecting a specific functional dependence of σ with frequency f. Following Stockwell *et al.* (1996), the Gaussian window is used as the window function, and $\sigma = 1/f$ is chosen (Huang *et al.*, 1997).

In essence, this transform takes a one-dimensional function of time into a two-dimensional function of time and frequency. For a given scale parameter σ as a function of f, $F_{\mathrm{m}}(f, \tau, \sigma)$ is written as $F_{\mathrm{m}}(f, \tau)$ which is a complex function with amplitude and phase defined by:

$$A(f, \tau) = |F_{\mathrm{m}}(f, \tau)| \tag{2}$$

and

$$\Phi(f, \tau) = \tan^{-1} \frac{\mathrm{Im}(F_{\mathrm{m}}(f, \tau))}{\mathrm{Re}(F_{\mathrm{m}}(f, \tau))}, \tag{3}$$

respectively. From the amplitude and phase given above, a sinusoid function is obtained,

$$C(f, \tau) = A(f, \tau) \cos[2\pi ft + \Phi(f, \tau)] \tag{4}$$

which provides a combined depiction of amplitude and phase at a given frequency. The function $C(f, \tau)$, evaluated at a particular frequency f is called the 'component.'

2.2. Multiresolution spectra and cross-spectra

Following a direct analogy with Fourier power spectra, multiresolution spectral density can be defined as:

$$S_{\mathrm{m}}(f, \tau) = F_{\mathrm{m}}(f, \tau) F^{*}_{\mathrm{m}}(f, \tau) = |F_{\mathrm{m}}(f, \tau)|^2 \tag{5}$$

where ( )* indicates the complex conjugate of ( ). The multiresolution cross-spectral density for two signals $x_1(t)$ and $x_2(t)$ are given by:

$$S_{\mathrm{m}12}(f, \tau) = S_{\mathrm{m}1}(f, \tau) S^{*}_{\mathrm{m}2}(f, \tau). \tag{6}$$

The amplitude and phase difference of cross-spectra are thus given by:

$$A_{12}(f, \tau) = |S_{\mathrm{m}12}(f, \tau)| \tag{7}$$

and

$$\Phi_{12}(f, \tau) = \tan^{-1} \frac{Q_{12}(f, \tau)}{P_{12}(f, \tau)}, \tag{8}$$

respectively. Here, $P_{12}(f, \tau)$ and $Q_{12}(f, \tau)$ are the real and imaginary parts, respectively, of the cross spectrum. $S_{\mathrm{m}1}(f, \tau)$ and $S_{\mathrm{m}2}(f, \tau)$ are the multiresolution Fourier transform for $x_1(t)$ and $x_2(t)$, respectively.

Essentially, all the fundamental results of the theory of multiresolution spectral analysis are the generalizations of results from the conventional theory of Fourier spectral analysis, in the sense that the latter is the average of the former for which the time series is purely stationary. The statistical significance test procedure used in this study was developed by Torrence and Compo (1998). The procedure is based on comparing theoretical wavelet spectra for white and red noise with Monte Carlo results. These spectra are then used to establish a null hypothesis significance test.

3. DATA

In this study, a 126-year time series of the NAO and the North Atlantic SST indices from January 1865 through December 1991 was used. The first NAO index was defined by Walker and Bliss (1932) and subsequently modified by Rogers (1984), who constructed an NAO index starting from 1894, using sea level pressure anomalies from Ponta Delgados, Azores and Akuyreyri, Iceland. Hurrell (1995) selected Lisbon, Portugal and Stykkisholmur, Iceland in order to extend the record back another 30 years; this is the index used in the present study. Because an NAO index based on station pressure is affected by small-scale transient meteorological phenomena not related to the NAO, the index is smoothed using a low-pass filter with five weights (1, 4, 6, 4, 1) to remove fluctuations with periods less than 3 months. This smoothed NAO index is shown in Figure 1(a).

The North Atlantic SST index time series, shown in Figure 1(b), is based on the monthly SST anomaly averaged over the North Atlantic in an area enclosed by 30–60°N by 60°W–0°. The data were derived from optimal smoother product prepared by Kaplan *et al.* (1998), which originally came from the MOHSST5 data set (Parker *et al.*, 1994) of the GOSTA product (Bottomley *et al.*, 1990).

4. PERIOD–TIME LOCALIZATION OF THE NAO

Plate 1 displays a multiresolution spectrum of the time series of the NAO index in the period–time domain. The most noticeable feature in the figure is that the NAO index shows time-dependent variability with contributions from distinct frequency bands at certain times. For the convenience of the present discussion, the spectrum was divided into three period bands: (i) annual cycle component (ANC) (1–2 years); (ii) interannual cycle component (IAN) (2–10 years); and (iii) decadal/interdecadal cycle component (DEC) (> 10 years). Using the statistical significance test procedure developed by Torrence and

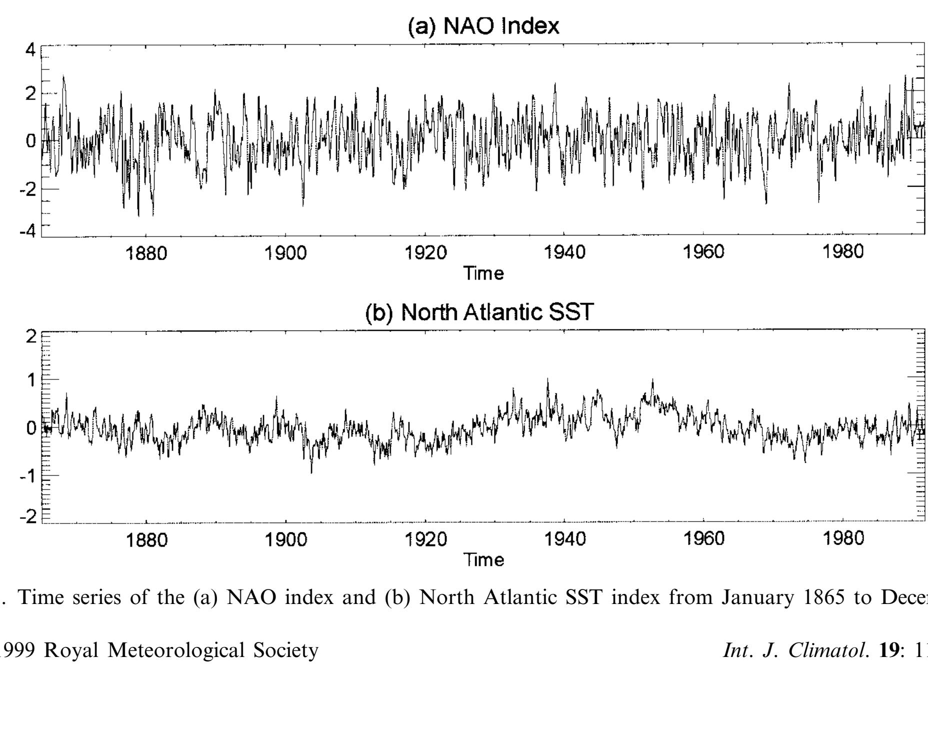

Figure 1. Time series of the (a) NAO index and (b) North Atlantic SST index from January 1865 to December 1991

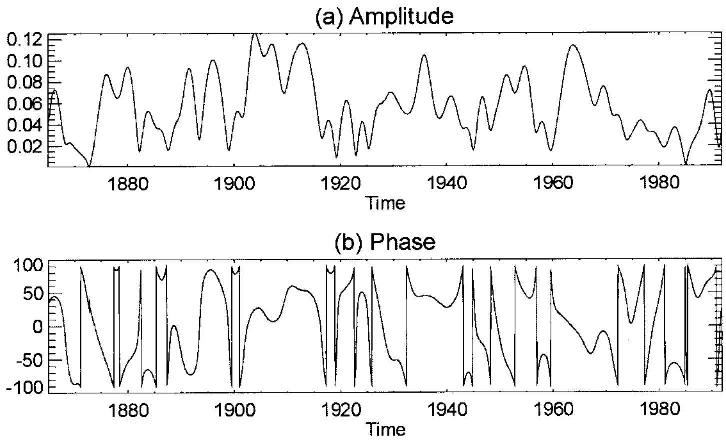

Figure 2. Time series of the (a) amplitude and (b) phase of the annual component term of the multiresolution Fourier transform of the NAO index

Compo (1998), the thick contour lines in Plate 1 which encompass regions of statistically significant 95% confidence level for red noise were calculated. The degree of significant contribution by the ANC component toward the overall modulation of the NAO appears to be as a result of an overestimation of the statistical significance of higher frequency contribution by the significance test. The resolving power of the MFT becomes weaker in the low frequency regime, resulting in a column feature observed in the DEC spectral component.

An inspection of Plate 1 demonstrates that the modulation of the NAO is strongly influenced by the presence of the IAN component prior to 1900, with an exception around 1880 when most of the spectral terms ranging from ANC to DEC appear to have contributed to the overall NAO variation. The IAN contribution is relatively weak from around 1890 to 1910. From around 1910 to about 1925, there is a gradual shift in the contribution from higher periodic terms of the IAN component to the DEC component, although just prior to 1920, there is evidence of simultaneous contribution by periodicities ranging continuously from about 4 years to decades.

4.1. Annual cycle component (ANC)

In the ANC component, the multiresolution spectrum visibly discloses fluctuations in both the amplitude and frequency of the annual cycle. To examine the amplitude modulation of the annual cycle component of the NAO, Figure 2(a) was plotted, which gives an indication of the annual cycle component strongly modulated at the IAN and DEC timescales. A very noticeable feature, for example, in the amplitude time series is the relatively large broad peak from around 1900 to 1915. Several broad, but relatively less intense peaks follow at the DEC timescale. The peak in the early 1960s is interesting in that it takes about 20 years to decay to almost zero by around 1985.

The temporal variation in phase for the annual cycle of the NAO is shown in Figure 2(b). Within the length of the record under investigation, there are two time periods during which the phase remains relatively constant. The first one occurs from around 1900 to 1915, and the second one extends from the early 1930s to the early 1940s. Following Barnett (1985), this indicates a particular climatic regime in which the sense of annual component contribution to the overall NAO variation remains the same in each of the time periods. The interdecadal aspect of this is also apparent. There is also evidence, for example around 1920, of rapid, random fluctuations in phase from -90 to $+90°$, and vice versa, indicating sudden changes in the phase contribution by the annual component toward the variation in the positive/negative phasing of the NAO. There is a third feature, which displays a gradual, systematic change in the phase, from positive to negative. This feature can be observed from around 1925 to the early 1930s, from around 1945 to the early 1950s (there are 2 cycles in this period), and from 1960 to 1970. The

1960–1970 period appears to be associated with a decadal fluctuation of the annual cycle. In the early 1970s, the phase of the annual component 'jumps' from -90 to $+90°$, and with the exception of a short period from around 1980 to 1985, the phase remains dominantly positive to the end of the record.

4.2. Interannual cycle component (IAN)

In the period–time spectrum in Plate 1, a noticeable contribution by the IAN component before 1900 is observed. Contributions from the longer periods of the IAN component during the 1910s are observed shifting to the shorter periods of the component for much of the remaining portion of the record, with the 2- to 4-year periodic terms quite evident from around 1925. A short, but statistically significant contribution from the 2- to 4-year periodic terms is also noticeable in the early 1960s. Therefore, much of the IAN contribution to the NAO variation from 1925 to 1970 appears to come from fluctuations with periods of 2–4 years. In contrast to the findings of Hurrell and van Loon (1997), this result is more consistent with the result of Schneider and Schonwiese (1989), who, using the autocovariance spectral analysis of the monthly NAO index from 1881 to 1984, reported an enhanced presence of fluctuations in the NAO with timescales of 2–3 years in the latter half of the record. Visible contributions from various terms in the IAN component can also be observed during the following time windows: the late 1930s–1945, 1950–1955 and 1965–1970.

It was found by Huang *et al.* (1998) that the NAO displays marked coherence with ENSO events at oscillations of 2–4 years and 5–6 years. Angell and Korshover (1984) had also reported evidence of a connection between ENSO and the sea level pressure field associated with the Icelandic low and Azores high. It is of interest, therefore, to examine these period bands more closely. Amplitude and phase of the 2- to 4-year period band are shown in Figure 3(a) and (b), respectively, while those of the 5- to 6-year period band are shown in Figure 4(a) and (b), respectively.

The interannual to interdecadal variations in the amplitude of the 2- to 4-year period band are quite evident in Figure 3(a). Prior to 1910, this period band is influenced by a quasiregular interannual fluctuations at timescales of 5–7 years. After 1910 however, it is strongly characterized by interdecadal fluctuations. Beginning around 1970, contribution to the NAO variation from the 2- to 4-year period band becomes relatively small.

The relatively large peak in the amplitude of the 5- to 6-year period band in Figure 4(a) around 1915 is associated with the significant MFT spectral area of the NAO shown in Plate 1. After this peak, the amplitude of the quasidecadal fluctuation in the 5- to 6-year period band is relatively constant. From around 1970, however, the fluctuation becomes shorter. In addition, it is interesting to note that the occurrences of larger amplitudes in Figure 3(a) and Figure 4(a) are generally associated with times of relatively constant phase.

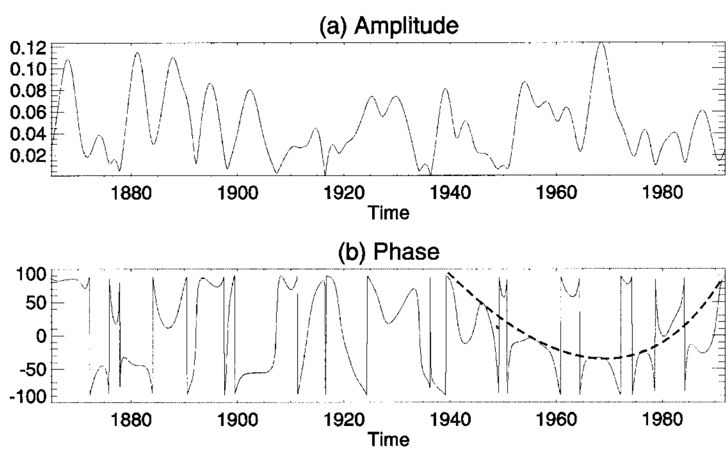

Figure 3. Same as Figure 2, except for the 2- to 4-year interannual component term. Note the very interesting feature in the temporal evolution of the phase marked by the dashed line

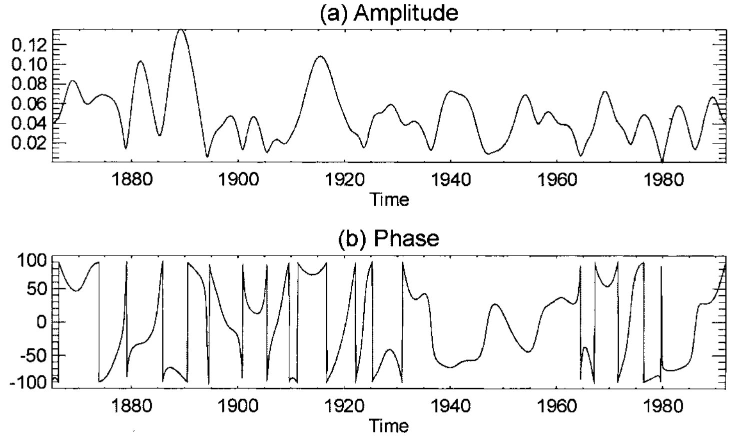

Figure 4. Same as Figure 2, except for the 5- to 6-year interannual component term

The temporal evolution of the phase of the 2- to 4-year period mode of the NAO variation is demonstrated in Figure 3(b). In a qualitative examination, it is again noticed, as with the ANC component, the existence of time periods of relatively constant phase, indicating 'locking' of the 2- to 4-year mode in a particular phase. This is quite evident during the 1925–1935 period, in the first half of the 1940s, and during most of the 1950s. One very notable behaviour in the temporal structure of the phase occurs from around 1950 to the end of the record, and is indicated in the figure by the dashed line. Physical significance, if any, of this feature relative to the NAO phase variation is now under investigation.

Both the 2- to 4-year period band in Figure 3(b) and the 5- to 6-year period band in Figure 4(b) display time periods during which the phase gradually changes, with timescales of 2–6 years. Furthermore, an interdecadal variation in the phase of the 5- to 6-year period band is noted, with a gradual rise in the phase from about -60 to about $+40°$ from around 1940 to the early 1960s, with an interruption in this systematic rise near 1950. Except for a sharp spike in 1980 and a sudden rise near 1985, another gradual, albeit shorter, change in the phase of the 5- to 6-year period band occurs from $-90°$ around 1975 to $+90°$ in 1991, the end of the record.

4.3. Decadal/interdecadal cycle component (DEC)

Apart from its role in driving large amplitude interannual fluctuations in the atmospheric circulation over the Atlantic sector, the NAO index has shown evidence of variability also at DEC timescales. Hurrell and van Loon (1997) have shown contributions of decadal periodicities to the amplitude of the NAO index since the late 19th century. As can be observed in Plate 1, the strongest contribution by the DEC component occurs during the following periods: 1875–1880; 1920–1925 and late 1980s to the end of record. It is interesting to note that from around 1940 to the early 1970s, contribution from the decadal components is almost absent.

The period since the early 1970s has seen the most prolonged positive phase of the NAO, with highest values of the index recorded during the late 1980s and the early 1990s. The DEC variability of the NAO index is also quite evident in the time series of the nonnormalized DEC (>10 years) period component (Figure 5), derived from MFT. It can be observed from the figure that from the early 1970s, there has been a rise in the amplitude of the DEC component of the NAO variation, in agreement with the results of Hurrell and van Loon (1997), who noted that the 6- to 10-year period band 'has become more pronounced over the latter half of this century.' This rise in the DEC component is correlated with a similar rise in the NAO index noted by Hurrell (1995). During this time interval, the NAO is largely responsible for the unusually warm and wet winters observed across much of Europe (Hurrell, 1995).

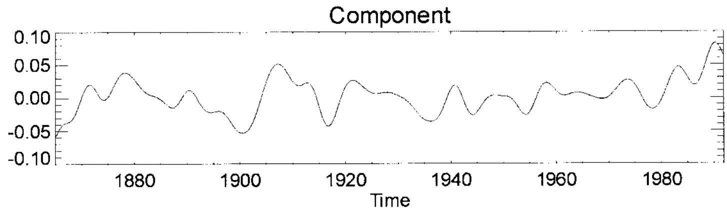

Figure 5. Time series of the decadal/interdecadal component term of the multiresolution Fourier transfrom of the NAO index

On a more general basis, various decadal changes in the atmospheric circulation and lower tropospheric temperature over the North Atlantic and adjacent land areas appear to be strongly linked to the behaviour of the NAO (Hurrell and van Loon, 1997; Shabbar *et al.*, 1997). Because the characteristic timescale over which atmospheric circulation anomalies develop is on the order of days to weeks, previous studies (such as Kushnir (1994) and references listed therein) have presented various evidences which point to the possibility that the DEC variability of the NAO is caused by the changes in the North Atlantic SST. Additional new findings will now be provided, which are consistent with this view from a different perspective.

5. RELATIONSHIP BETWEEN THE NAO AND THE NORTH ATLANTIC SST

Plate 2 shows a multiresolution spectrum of the time series of the North Atlantic SST index from January 1865 to December 1991 in the period–time domain. In contrast to the spectrum of the NAO index in Plate 1, it can be immediately observed that much of the power seems to reside in the long-term DEC timescales. Notable contribution by the DEC components to the North Atlantic SST variability appears to take place during periods 1880–1885, 1900–1925, 1930–1960, and 1970 to the mid-1980s. Not all of them however are *statistically significant* at the 95% confidence level. There is also evidence of sporadic concentration of power in the ANC timescale, indicating a contribution to the overall North Atlantic SST anomaly by the annual cycle component during such time periods as the 1870s, 1930s, and the latter part of the 1980s.

Plate 3 shows the amplitude of a multiresolution cross-spectrum between the time series of the NAO index (NAOI) and of the North Atlantic SST index (NASSTI). The contribution to the relationship between the NAOI and the NASSTI by the ANC period band is evident during 1875–1880, 1900–1910, 1930–1940, and the latter part of the 1980s. A strong connection on the DEC period band is evident

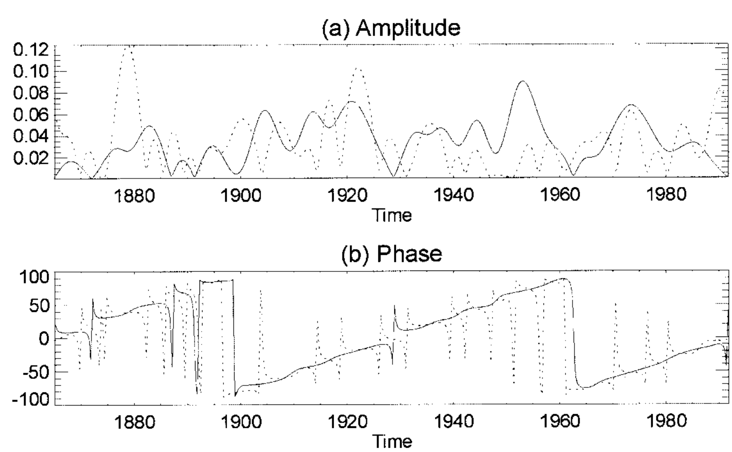

Figure 6. Same as Figure 2, except for the decadal/interdecadal (> 10 years) period component term of the NAO index (dashed line) and the North Atlantic SST (solid line)

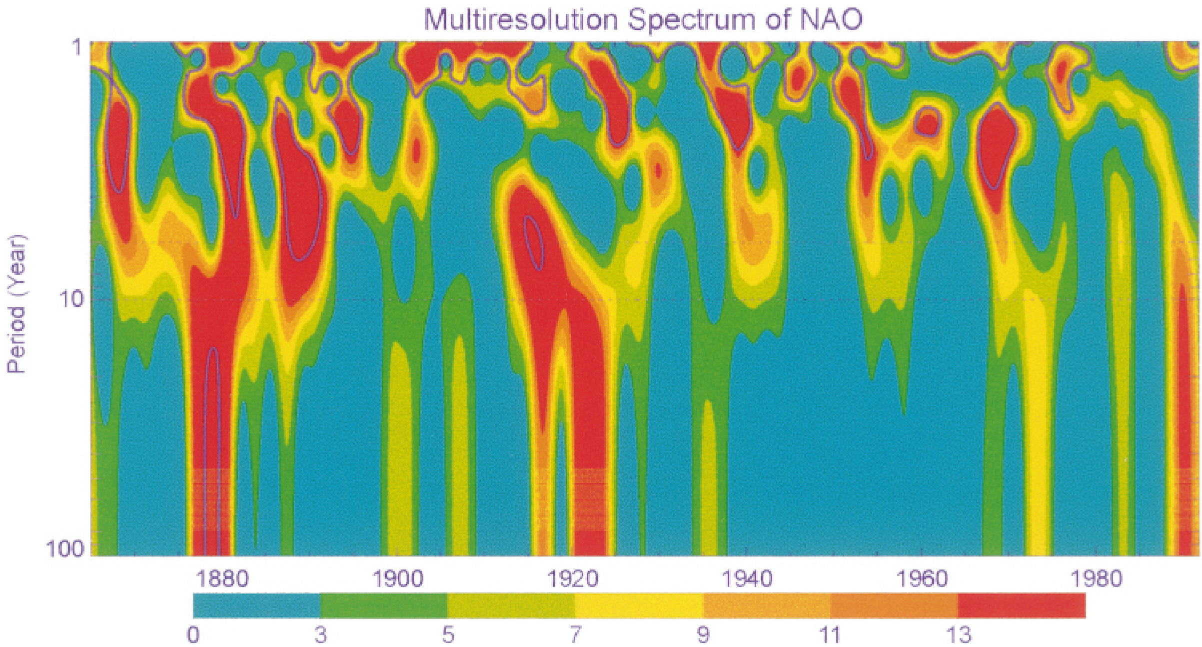

Plate 1. Multiresolution spectrum of the NAO index time series. The solid black lines indicate the 95% confidence level for red noise. Two, 6- and 10-year periods are identified by the horizontal dashed lines

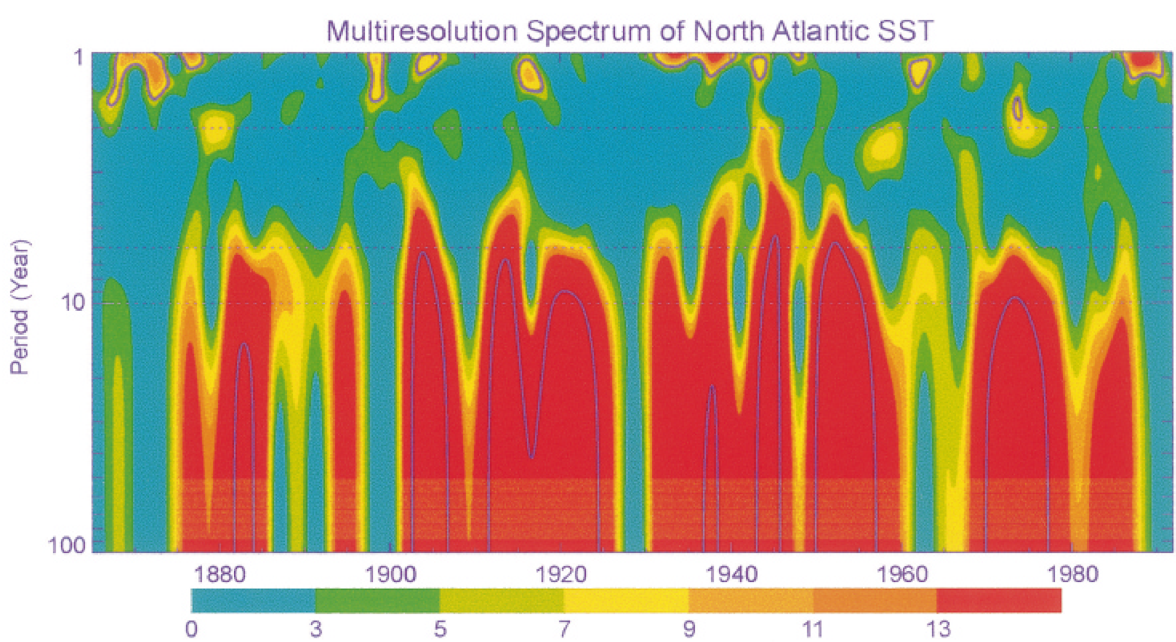

Plate 2. Same as Plate 1, except for the North Atlantic SST

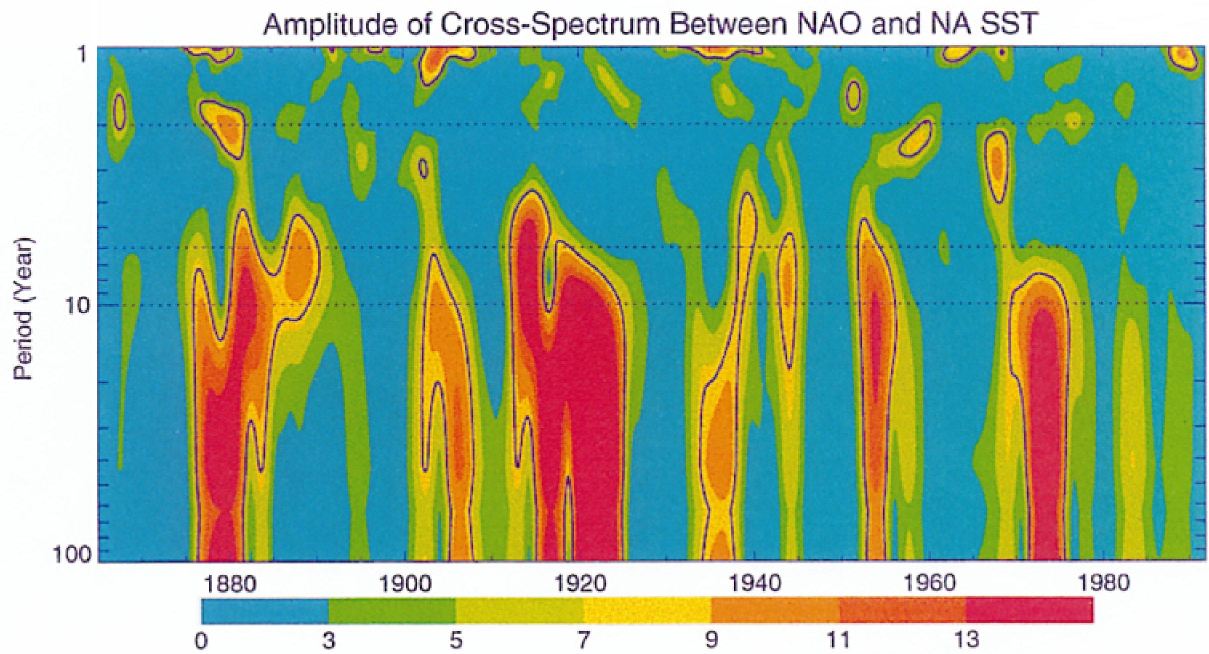

Plate 3. Same as Plate 1, except for the cross-coherence between the NAO index and the North Atlantic SST index

during periods centered around 1880, 1920, and 1955; a similar connection can be observed from around 1970 to 1975. Is there any systematic pattern in this which can be characterized with some degree of generality? To seek some partial answer to this question, the amplitude and phase of the DEC component of the NAOI are compared with those of the NASSTI. Figure 6 shows the comparison.

In Figure 6(a), the DEC amplitudes of the NAOI and the NASSTI are compared. It can be observed that the time series are complex and modulated. On short timescales, a clear relationship between the indices is not easily discernible. However, there is visual evidence indicating that, on a long timescale (20–30 years), the amplitude trend of the NASSTI is correlated with the amplitude trend of the NAOI. For example, from around 1900 to 1920, a gradual rise is observed in the amplitude of the NASSTI corresponding to a similar rise in the amplitude of the NAOI. Another example is observed in the period from around 1960 to 1980. There are also times, on shorter timescales, when they are negatively correlated. The amplitude of the NASSTI, for example, displays a downward trend from around 1972, while that of the NAOI has gone up from around 1980.

The phase relationship between the DEC component of the NAOI and that of the NASSTI in Figure 6(b) appears to be much more systematic. From around 1900, a gradual change in the phase of the DEC component of the NASSTI from -90 to $+90°$ is observed, until 1960, at which time the cycle seems to repeat itself. For the NAOI, in addition to a quasiregular fluctuation on interannual timescales, a very gradual rise in the phase component is observed, which appears to track the gradual phase change in the NASSTI. Therefore, evidence of a very long-term phase modulation in the pattern of the DEC component of the NAOI by the NASSTI on the order of about 60 years is observed. Prior to 1900, this long-term modulation seems to be absent. In addition, a clear indication of the occurrence of near-zero amplitude in Figure 6(a) is observed whenever there is a sudden change in phase. This is consistent with what happens, for example, when the NAO goes through a transition from one phase to another.

Oscillations with periods of around 60 years have been noted by some recent studies. In their spectral analysis of the 1701–1980 winter NAO index reconstructed from climatically sensitive tree-ring chronologies from North America and Europe, Cook *et al.* (1998) found, aside from the 'usual' periods of 2.1 and 3 years, an additional significant spectral peak at a period of 70 years. Schlesinger and Ramankutty (1994) had also found the 65–70-year oscillation in their singular spectrum analysis of the global and regional surface temperature time series, particularly in the North Atlantic and North America sectors. The authors would like to suggest that the 60-year phase oscillation in the DEC component of the NAOI and the NASSTI found in this study is related to the one discussed in the studies quoted above. Furthermore, it has been demonstrated that this oscillatory relationship between the NAOI and the NASSTI appears to be absent prior to 1900. This result is not only in agreement with, but clarifies the finding by Cook *et al.* (1998) who reported that the 70-year peak 'totally disappeared' when they analyzed the reconstructed NAO index prior to 1874, and prompting them to state that it is 'a transient or chance phenomenon . . . and, therefore, should not be regarded as a long-term feature of the North Atlantic climate system' (Cook *et al.*, 1998).

Schlesinger and Ramankutty (1994) attributed the probable cause of the 60–70-year oscillation to an internal oscillation of the atmosphere–ocean system. This hypothesis is supported by a numerical experiment conducted by Delworth *et al.* (1993) in which the investigators performed long simulations using a coupled atmosphere–ocean general circulation model, and found fluctuations in SST and the thermohaline circulation in the North Atlantic with an average timescale of 40–60 years. There have been some other studies which, with a focus on the North Pacific, have attempted to explain inter-decadal oscillations in terms of processes, with different timescales, connecting the tropics and extra-tropics. Gu and Philander (1997), for example, stated that 'it is in principle possible for links between the extratropics and the tropics—rapid and poleward in the atmosphere, slow and equatorward in the ocean—to cause continual interdecadal climate fluctuations.' However, as far as it is known, there is no evidence in the open literature of this mechanism operating in the Atlantic sector.

6. CONCLUSIONS

The NAO is characterized by variations on multiple timescales. MFT spectral analysis method was used to identify and describe the temporal contributions of various frequency regimes to the overall variability of the NAO. The MFT analysis of these components has produced results whose main points are summarized below:

(i) Relative contributions of the three components to the total variance of the NAO is not constant in time. Instead, each component itself is strongly modulated on various timescales ranging from interannual to interdecadal. This creates a rather complicated MFT spectrum of the NAO, which is characterized by a combined effect of frequency and amplitude modulations involving bifurcation and merging of the dominant frequencies with time.
(ii) Temporal variation in phase for the ANC, IAN, and DEC components show that at times the phase remains constant for periods of time ranging from about a few to 10 years. During any of these constant phase periods, the 'sense' or state of contribution of a component to the total NAO modulation remains the same. Each component also displays random fluctuations in phase from -90 to $+90°$, and vice versa. The phase of each component is also characterized by gradual, systematic changes, indicating quasiperiodic fluctuations of the component.
(iii) Multiresolution cross-spectral analysis indicates a strong coherent relationship between the NAO and the North Atlantic SST at ANC and DEC timescales.
(iv) On the DEC timescale, the phase of the NAO index and of the North Atlantic SST index show almost exactly the same gradual rise from $-90°$ in 1900 to $+90°$ in 1960. This suggests modulation in the DEC component of the NAO by the North Atlantic SST at a timescale of about 60 years.

In addition to these findings, there are many intriguing relationships presented in this study for which further research is needed to find physical explanations. For example:

(i) Since around 1970, the NAO index for winter shows a trend with increasing positive values (Hurrell 1995). In the present study, it is found that the decadal/interdecadal period component terms in the MFT analysis of the NAO index (which includes all seasons) display a similar trend beginning around 1980. But this does not appear to be related to changes in the North Atlantic SST, as demonstrated by the cross-coherence MFT spectrum between the NAO index and the SST index. What is causing the secular trend in the NAO index for the last 20 years?
(ii) Comparing the phase of the NAO index and the North Atlantic SST index, it is found that the decadal/interdecadal component of the NAO appears to be modulated by the North Atlantic SST with a timescale of about 60 years. If this is 'real' (and this cannot be certain because evidence of this is only observed for 1 cycle) what is the origin of this cycle? Is this in any way related to the interdecadal oscillation with a period of about 70 years which Cook *et al.* (1998) found? A corollary to this is: Why is this relationship absent prior to 1900?
(iii) Why is the contribution from the decadal/interdecadal component term toward the overall NAO variation relatively absent during the period from around 1940 to the early 1970s?
(iv) From around 1940 to the early 1960s, the phase of the 5- to 6-year period band changes from about -60 to $+40°$. No other part of the record shows this feature. What is the cause of this gradual fluctuation on a decadal timescale for the 5- to 6-year period band?

The authors hope to pursue these and other questions in the future for a greater elucidation of the nature of the NAO variability.

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