QBO Signal found at the Extratropical Surface through Northern Annular Modes

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Short title: ANNULAR MODE CONNECTION TO THE QBO

Abstract. A QBO (quasi-biennial oscillation) signal is found in 150-year, Northern Hemisphere, surface air temperatures which have been projected onto an annular mode at the surface. The signal is tied to the equatorial QBO by demonstrating coherence of the annular mode in the extratropical stratosphere with the QBO and tracing the signal, using the annular modes as a filter, down through the atmosphere to the surface. Then the statistical significance of the signal is established.

Introduction

The equatorial quasi-biennial oscillation (QBO) in zonal winds is a well known phenomenon [*Veryand and Ebdon,* 1961; *Reed et. al.,* 1961; *Reed and Rogers,* 1962; *Reed,* 1965; *Wallace,* 1973; *Coy,* 1979]. It is the quasi-periodic descent of easterly winds over westerly winds above the equator. Since its discovery, much effort has been spent searching for a connection to extratropical events. Numerous observational [*Tucker and Hopwood,* 1968; *Angell and Kroshover,* 1970; *Belmont et. al.,* 1974; *Hasebe,* 1983; *Lait et. al.,* 1989; *Bowman,* 1989; *Hamilton,* 1989; *Gray and Dunkerton,* 1990] and theoretical [*Tung and Yang,* 1994b; *Randel and Cobb,* 1994; *Kinnersley and Tung,* 1999] studies have attempted to confirm the existence of the QBO's influence in the extratropics. Due to this effort, the QBO signal has been found in stratospheric extratropical variables like column ozone concentrations, angular momentum and wave forcing [*Holton and Tan,* 1982; *Oltmans and London,* 1982; *Randel and Cobb,* 1994; *Tung and Yang,* 1994a; *Yang and Tung,* 1994; *Baldwin and Tung,* 1994; *Yang and Tung,* 1995]. Hsu and Yung [*Hsu and Yung,* 1999] also found evidence of the QBO signal in tropospheric chemicals, such as methane, which are directly affected photochemically by the stratospheric ozone overhead. Nevertheless, tropospheric dynamical signals of the QBO have not been convincingly demonstrated, despite wide spread reports.

Landsberg [*Landsberg,* 1962] and Lamb [*Lamb,* 1972] have compiled reviews of phenomena in the atmosphere as well as other geophysical realms which exhibit two year periodicities. Some of their examples date back thousands of years. In the more recent past, attempts have been made to link these periodic events to the equatorial QBO. For instance, Ebdon [*Ebdon,* 1975] attempted to isolate aspects of the QBO in the sea level pressure using composite analysis. He found little evidence of a connection. Brier [*Brier,* 1968] found that the QBO explained 2% of the monthly variance in Northern Hemisphere sea level zonal wind. This is hardly evidence enough to confirm the influence of the QBO in the extratropics. Trenberth [*Trenberth,* 1975; *Trenberth,* 1980b] found a pronounced QBO signal in Southern Hemisphere surface pressure differences and 500 mb zonal winds using EOF (empirical orthogonal function) analysis. Although he found the QBO's relationship with the biennial oscillations to be "remarkably coherent", he notes that there is not a long enough data record to be conclusive.

Some biennial signals which were originally attributed to the QBO have since been found to be better correlated with other phenomena. A prime example of this is the African rainfall time series which was originally thought to be associated with the QBO and has since been shown to be coherent with ENSO (El Nino Southern Oscillation) [*Ropelewski and Halpert,* 1987; *Ropelewski and Halpert,* 1996; *Ogallo,* 1988; *Ogallo et. al.,* 1988; *Beltrando,* 1990; *Hastenrath,* 1990; *Nicholson and Kim,* 1997; *Mutai,* 2000].

It remains to be shown then that extratropical dynamical variables at the surface have a signal which is statistically significant and related to the equatorial QBO. One of the main difficulties is that surface winds, pressure and temperature are especially noisy compared to their stratospheric values.

In this study, we use multiple data sets filtered by the northern annular modes to show that the QBO signal can be traced from the upper stratosphere down to the extratropical surface. Annular modes are used to improve the signal to noise ratio at each height. We use Baldwin's time series [*Baldwin and Dunkerton,* 1999] at 17 levels to trace the signal from the stratosphere, where the effects of the QBO have already been established, down to the surface level. To verify this signal we use coherency to test the relationship between the QBO and the NAM index. At the surface, longer time series from Trenberth [*Trenberth and Paolino,* 1980] and Jones [*Jones,* 1994] allow a more thorough analysis of the signal. This surface data is projected onto the northern annular mode (NAM) index so that it corresponds to an extension of the shorter 17-level data. From these longer time series we can show that the QBO signal is statistically significant at the surface.

Data Sets and Processing

A number of data sets were used for this study. The QBO winds used were provided by both Barbara Naujokat [*Naujokat,* 1986] and NCEP [*Kalnay,* 1996]. The Naujokat data set is 7 levels (70, 50, 40, 30, 20, 15, 10 mb) of detrended daily zonal winds from 1953 to 1997. Measurements for this data were taken from three locations; Canton Island, the Maledives and Singapore. The NCEP QBO was calculated, for all months between January, 1958 and May, 2000, from updated NCEP reanalysis of zonally averaged 30 mb winds at the equator.

In the extratropics, three main data sets are used; 40 years of geopotential height anomalies [*Baldwin and Dunkerton,* 1999], 100 years of sea level pressure anomalies [*Trenberth and Paolino,* 1980] and 150 years of surface air temperature anomalies [*Jones,* 1994]. The 40-year annular mode data from Baldwin [*Baldwin and Dunkerton,* 1999] starts in January, 1958 and continues to January, 1998. The geopotential height anomalies north of 20 degrees were 90-day low-pass filtered from November through April and the first EOF (empirical orthogonal function) was calculated at 17 different levels between 1000 and 10 mb. The first EOF picks out the spatial map which describes the most variance. The coefficient of this EOF describes the magnitude with which the geopotential height at a given time resembles the spatial structure of the EOF. By analyzing the fluctuations of just the first coefficient, we are able to suppress some of the extraneous noise in the atmospheric system. This allows us to better resolve the QBO signal. It is important to note that the surface EOF is exactly the same as the one calculated by Thompson and Wallace [*Thompson and Wallace,* 1998]. This means that Baldwin's coefficients at the surface correspond to the values over the last 40 years in both Trenberth's and Jones' data sets.

Trenberth published a 100-year time series [*Trenberth and Paolino,* 1980] of sea level pressure (SLP) anomalies which he projected onto Thompson's surface EOF. This data set consists of monthly SLP coefficients from January, 1899 to May, 2000.

Jones produced an even longer time series [*Jones,* 1994]. His data consists of surface air temperature (SAT) anomalies, which he projected onto Thompson's AO coefficients. The monthly mean values for January, February and March (JFM) start in 1851 and end in 1997.

Analysis of this data consists mainly of comparing the power spectra of the annular mode filtered time series to one another, to the QBO's spectrum and to a generated red noise spectrum. The comparison is made by calculating coherence and confidence intervals. Coherence is found using a Hanning window, fast Fourier transform routine. Confidence for the coherence is found by using the null hypothesis of zero coherence. Confidence intervals for the power spectra are found using F-statistics to compare the spectra to a red noise spectrum, or a first order Markov process. Gilman et al. [*Gilman et. al.* 1963] provide a good way to calculate the shape of experimental red noise spectra and their method is used to produce the appropriate null hypotheses for the observed power spectra. The 95% confidence level is determined for the 27 month peak and multiple realizations are used to improve the confidence.

Results

The QBO winds are quasi-periodic, varying between periods of 24 to 36 months. Over the last 40 years the period averages to about 27 months[1]. Following this QBO signal in the power spectra of Baldwin's 17-level data, we can trace its influence down to the extratropical surface using the first EOFs as a filter (see figure 1). Figure 1 shows that every level of the northern annular mode data, from 10 mb to 1000 mb, has a peak figure 1

[1] Since most of the data is analyzed using only winter months this corresponds to either a 9 month period for a 4 month year, or a 6.75 month period for the SAT data which is only available for January through March. For convenience, 27 months is used to refer to this period throughout the rest of the paper.

at the same frequency as the equatorial QBO (seen in the first frame). The dotted vertical line represents this 27-month signal. Coherency analysis on year round daily values shows that the QBO and the NAM are coherent at this 27-month period for each level where the QBO winds are defined, between 70 mb and 20 mb. Figure 2 shows the squared coherence at the 20 mb level and the 70 mb level. However, coherence between the surface annular mode and the QBO winds is not statistically significant for this type of direct analysis. Only by using a monthly average and considering just the winter months, when the geopotential heights exhibit the most variance, are we able to see a significant 27-month peak in the coherence spectrum between the surface NAM index and the 70 mb QBO winds (see figure 3). This result is especially interesting because the 27-month signal in the 40-year NAM index is not statistically significant. Since the QBO has such a strong signal, it is possible that the coherence analysis just picked out a 27-month period in a noisy time series. In order to show that the surface signal is significant we need to look at the longer time series provided by Trenberth and Jones (see figure 4 and figure 5).

Figure 2

figure 3

figure 4

figure 5

Figure 4 shows the power spectrum of Trenberth's 100-year SLP data. The peak of interest surpasses the 95% confidence level but the height of the peak is sensitive to the sample size and sample overlap. For this realization of the data, a sample size of 18 years with an overlap of 4 years was used. The power spectra of the samples was then averaged. At 27.5 months, which is within the QBO frequency range, there is a statistically significant peak.

In order to instill more confidence in this result, it is helpful to look at an even longer time series. Figure 5 shows the power spectrum of Jones' 150-year SAT time series. This spectrum has a robust average peak centered at the 27-month period. It is insensitive to sample size and overlap. As an example the figure shown is an average of two 80-year samples. This is a typical power spectrum and the 27 month peak is obviously significant.

Conclusions

Previous studies have shown that the QBO has an influence on the extratropical stratosphere. Unfortunately, a lack of data has made it difficult to verify the significance of the signal in the troposphere, where the signals are typically more noisy. However, using the short (40-year) NAM time series as an indicator we can trace the 27 month signal from the upper levels down to the surface, where longer time series are available. The short filtered time series are found to be coherent with the QBO and the longer time series are used to verify the significance of the surface signal. 150 years of data is needed to be certain that there is a significant signal at the QBO frequency. From our analysis, we conclude that the equatorial QBO signal is transmitted to extratropical latitudes not only in the upper atmosphere but also at the surface. Unfortunately, the method of transmission cannot be determined by this type of analysis and it instead leaves us with some intriguing questions about the mechanisms involved in transmitting this signal.

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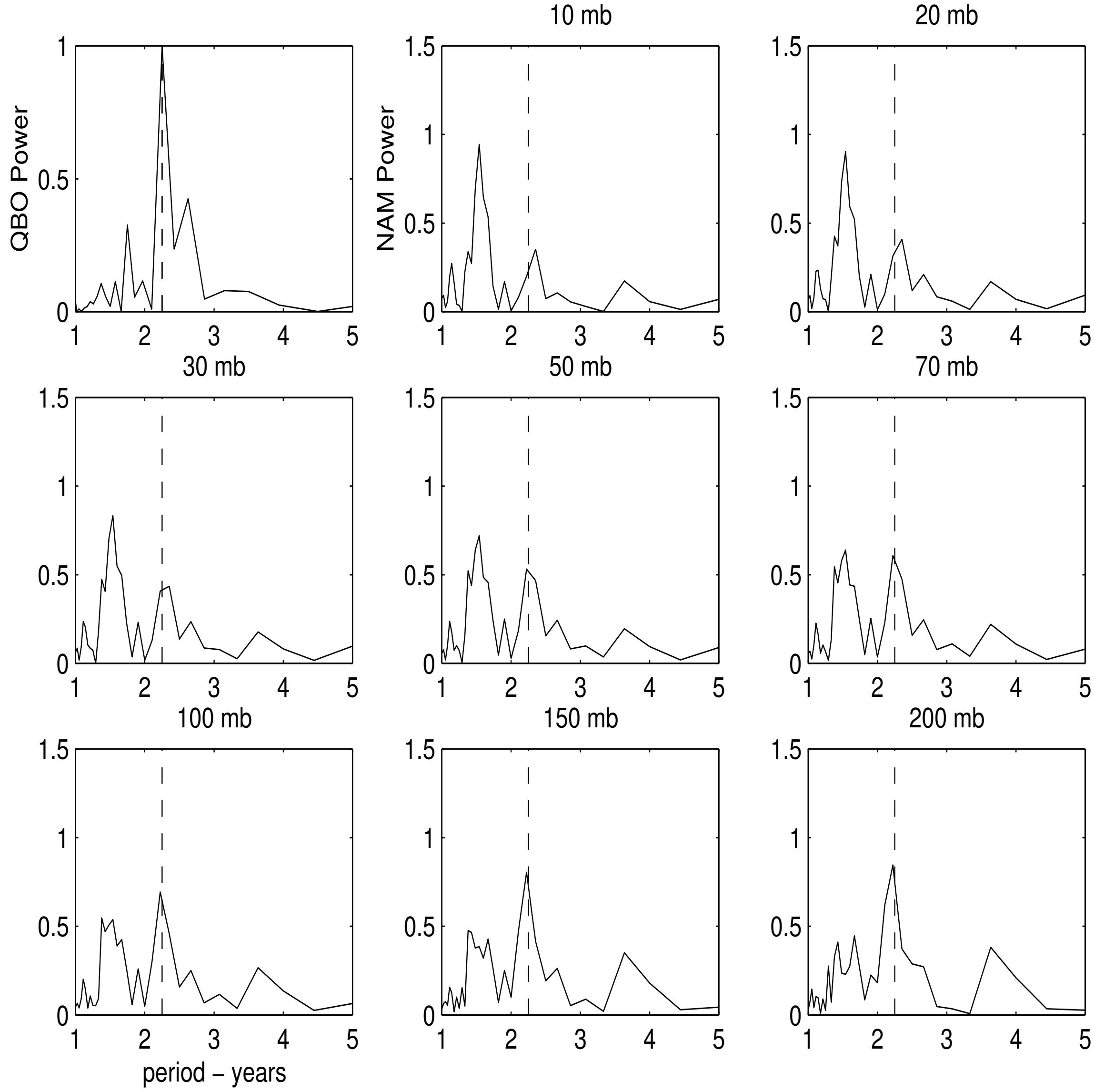
Figure 1. Power spectrum of the QBO at 30 mb and of Baldwin's NAM at 17 levels from 10 mb down to 1000 mb. The dotted vertical line indicates the frequency associated with a 27 month period, characteristic of the QBO. The spectra is calculated using only winter months (December, January, February and March).

Figure 2. Coherence between (a) the 15 mb QBO winds and the 20 mb NAM index and (b) the 70 mb QBO winds and the 70 mb NAM index. The dashed horizontal line indicates the 95% confidence level. Coherence is found using daily data throughout the year for both the QBO winds and the NAM index.

Figure 3. Coherence between the 70 mb QBO winds and the 1000 mb NAM index. The dashed horizontal line indicates the 95% confidence level. Coherence is found using monthly averaged winter (DJFM) values for both the QBO winds and the NAM index.

Figure 4. Power spectrum of Trenberth's 100 year sea level pressure (SLP) time series. The monthly index values from 1899 to 1957 are based on data described in Trenberth and Paolino (1980). Only the winter months (DJFM) are used for this calculation. The dashed line indicates the 95% confidence interval and the bold line is the appropriate red noise power spectra. The dotted line demarks the 27.5 month period.

Figure 5. Power spectrum of Jones' surface air temperature (SAT) data. The monthly index is based on winter months (JFM) from 1851 to 1997. The dashed line indicates the 95% confidence interval and the bold line is the appropriate red noise power spectrum. The vertical dotted line represents the 27 month period.



10 mb
20 mb
30 mb
50 mb
70 mb
100 mb
150 mb
200 mb
QBO Power
NAM Power
period – years

Figure 1a

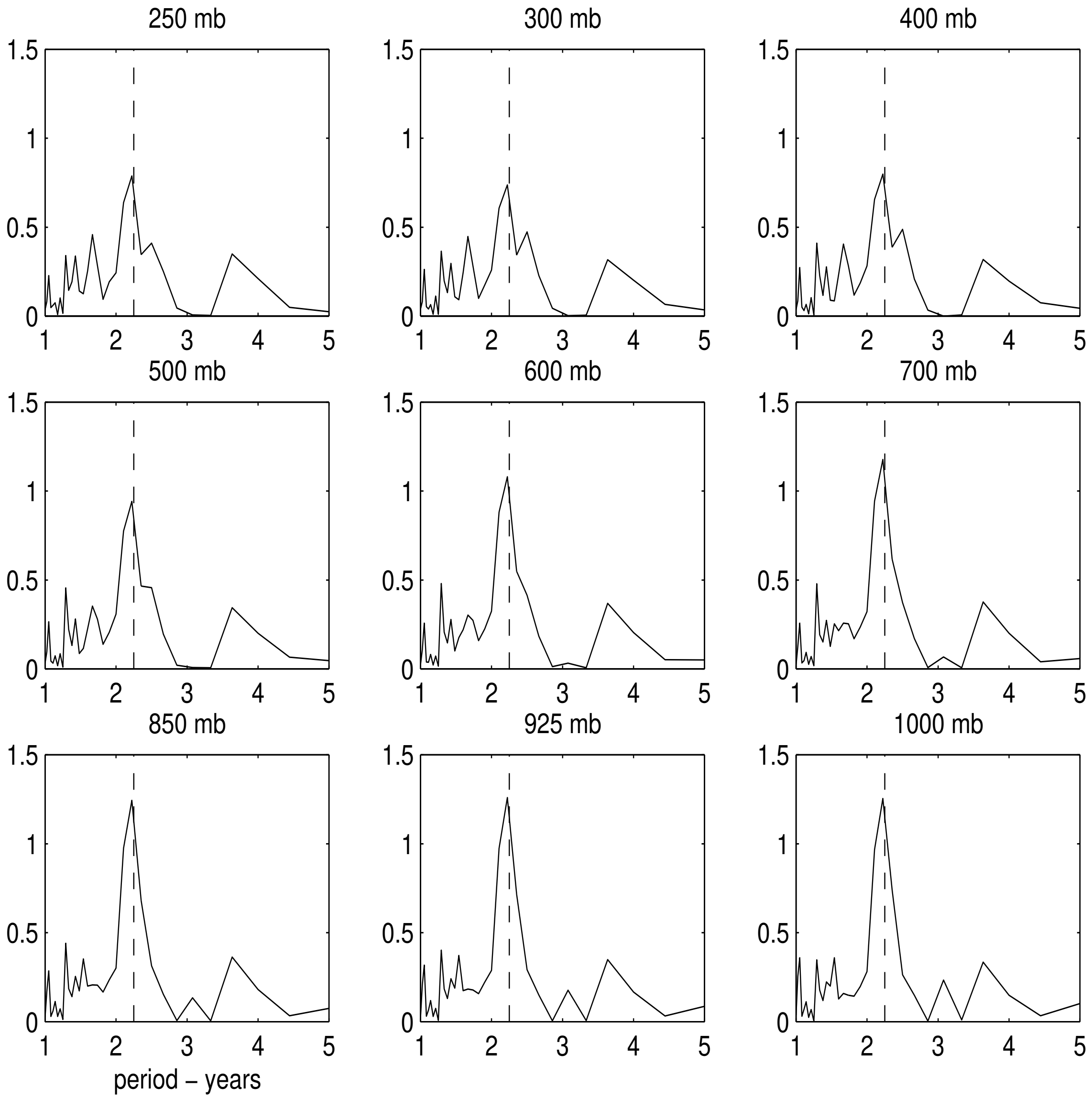

250 mb
300 mb
400 mb
500 mb
600 mb
700 mb
850 mb
925 mb
1000 mb
1.5
1
0.5
0
1
2
3
4
5
period – years

Figure 1b

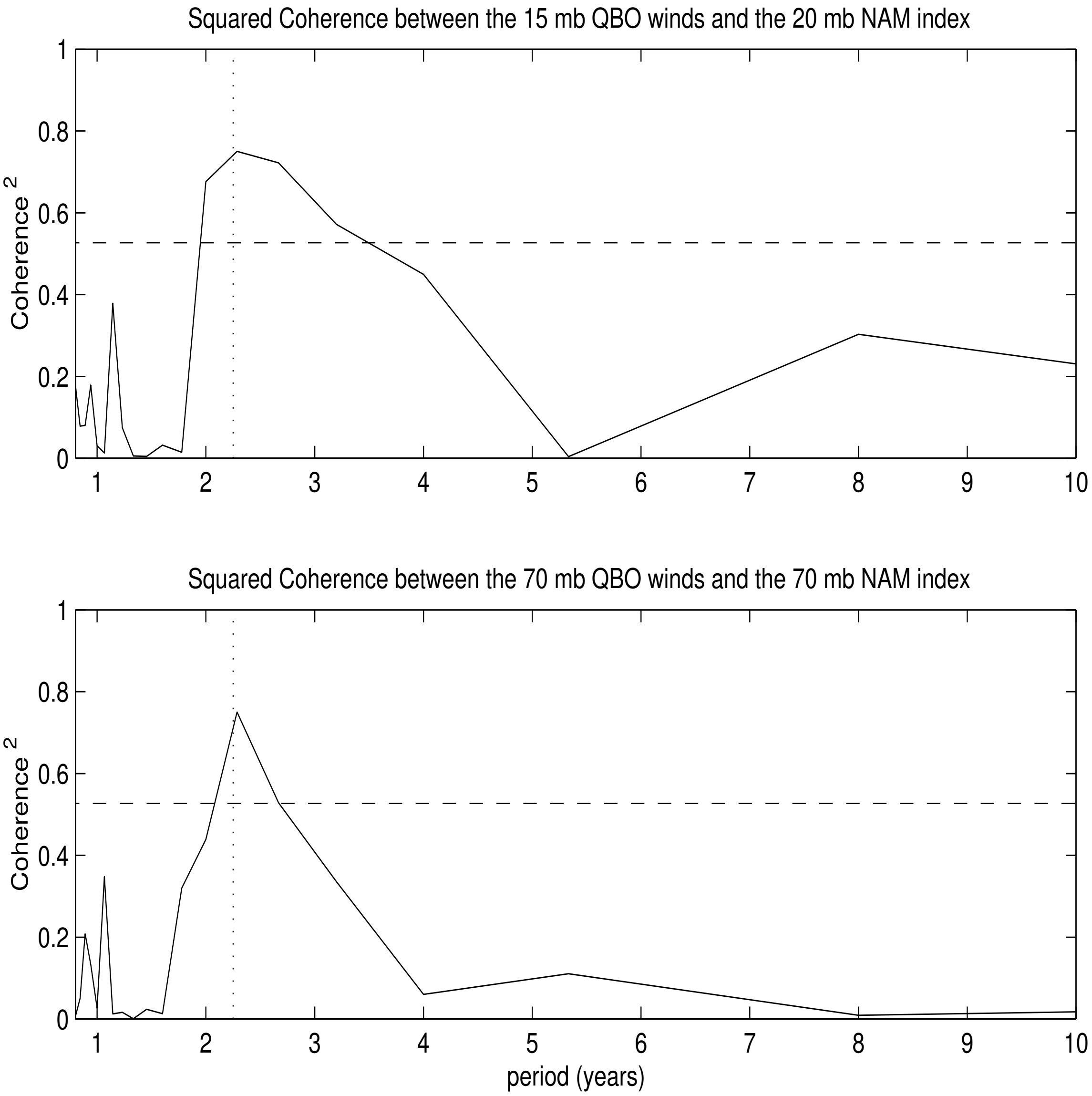

Squared Coherence between the 15 mb QBO winds and the 20 mb NAM index
Coherence 2
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5
6
7
8
9
10
Squared Coherence between the 70 mb QBO winds and the 70 mb NAM index
Coherence 2
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5
6
7
8
9
10
period (years)

Figure 2

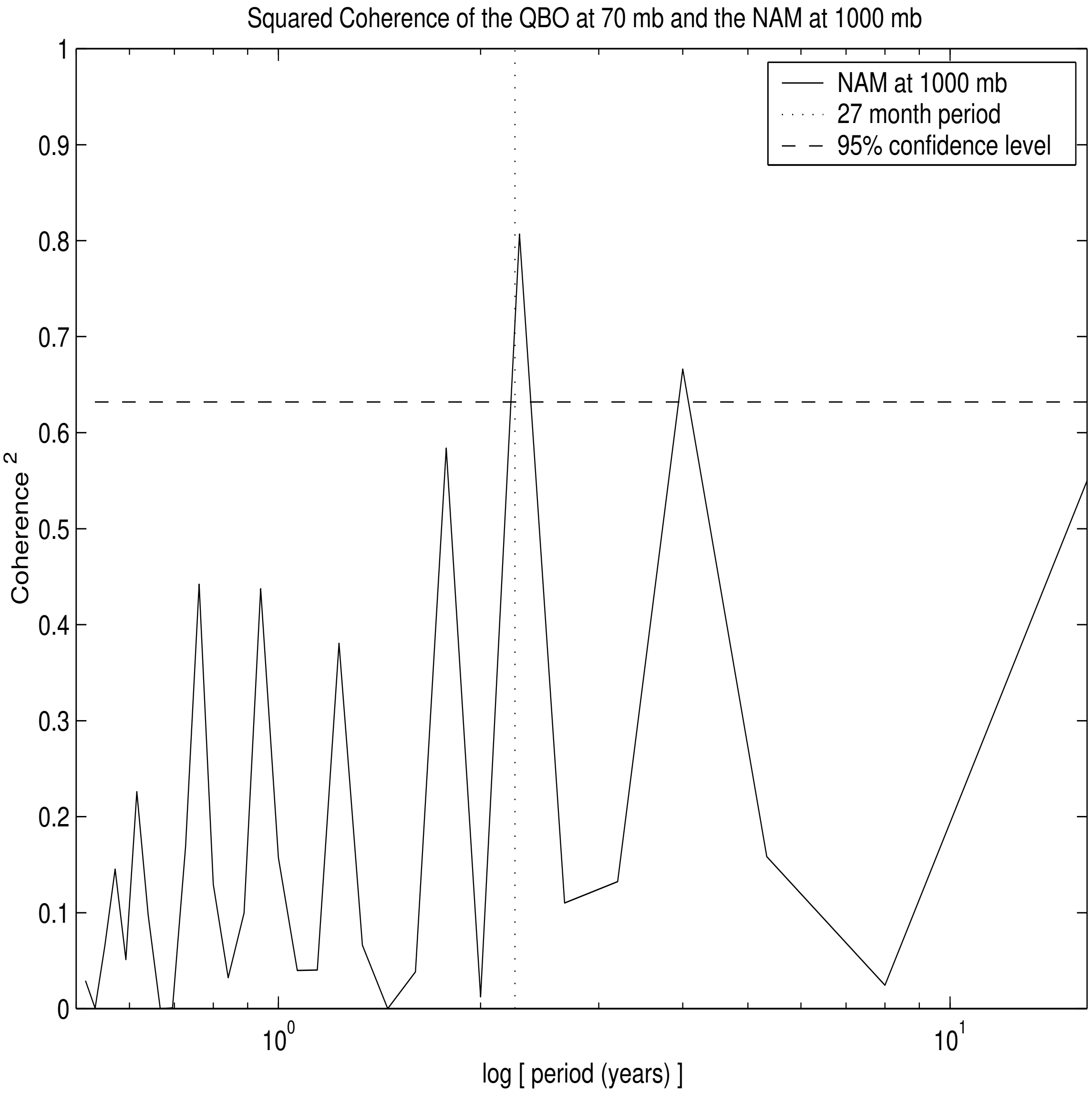

Squared Coherence of the QBO at 70 mb and the NAM at 1000 mb
NAM at 1000 mb
27 month period
95% confidence level
Coherence 2
log [period (years)]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^0
10^1

Figure 3

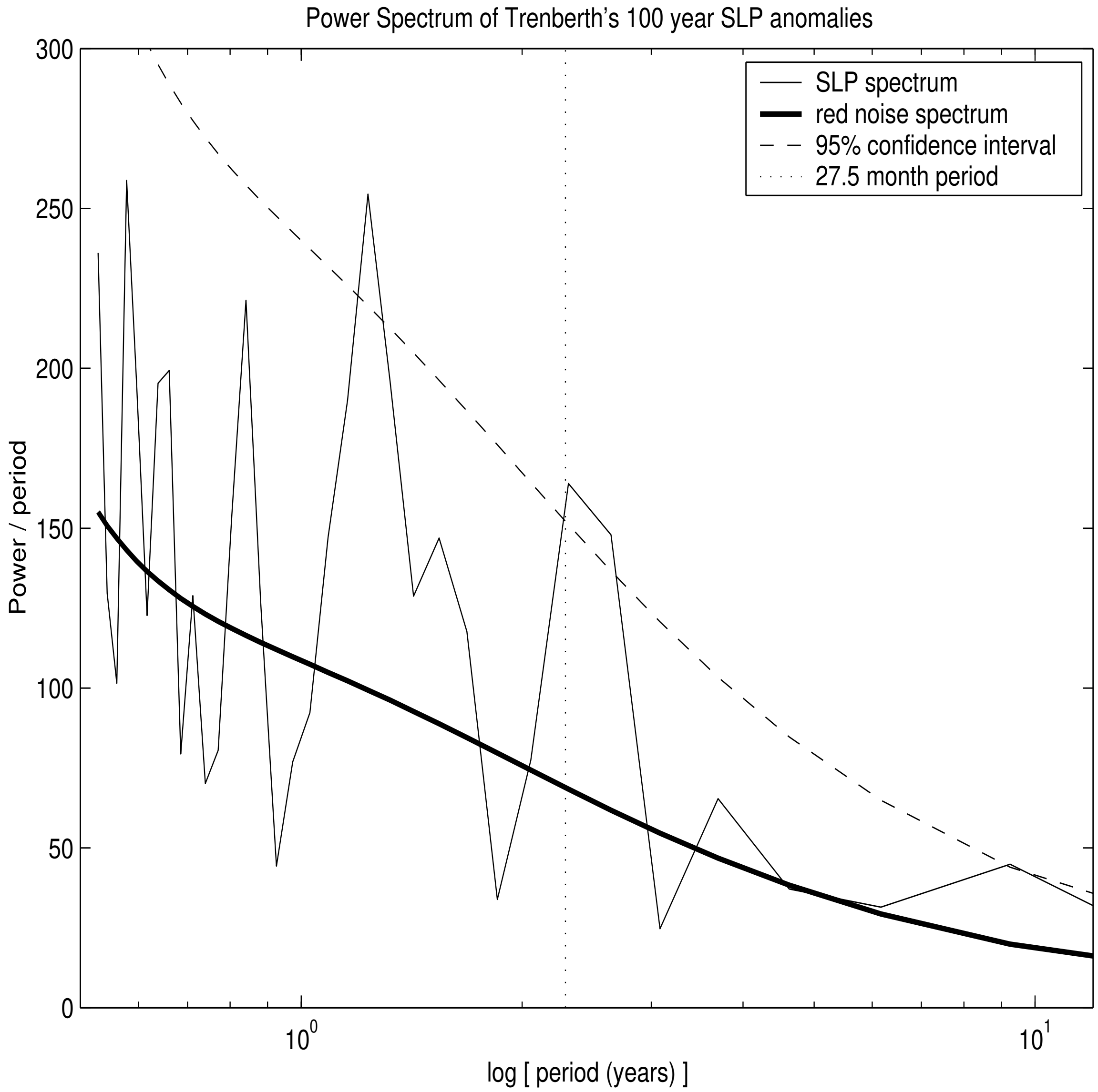
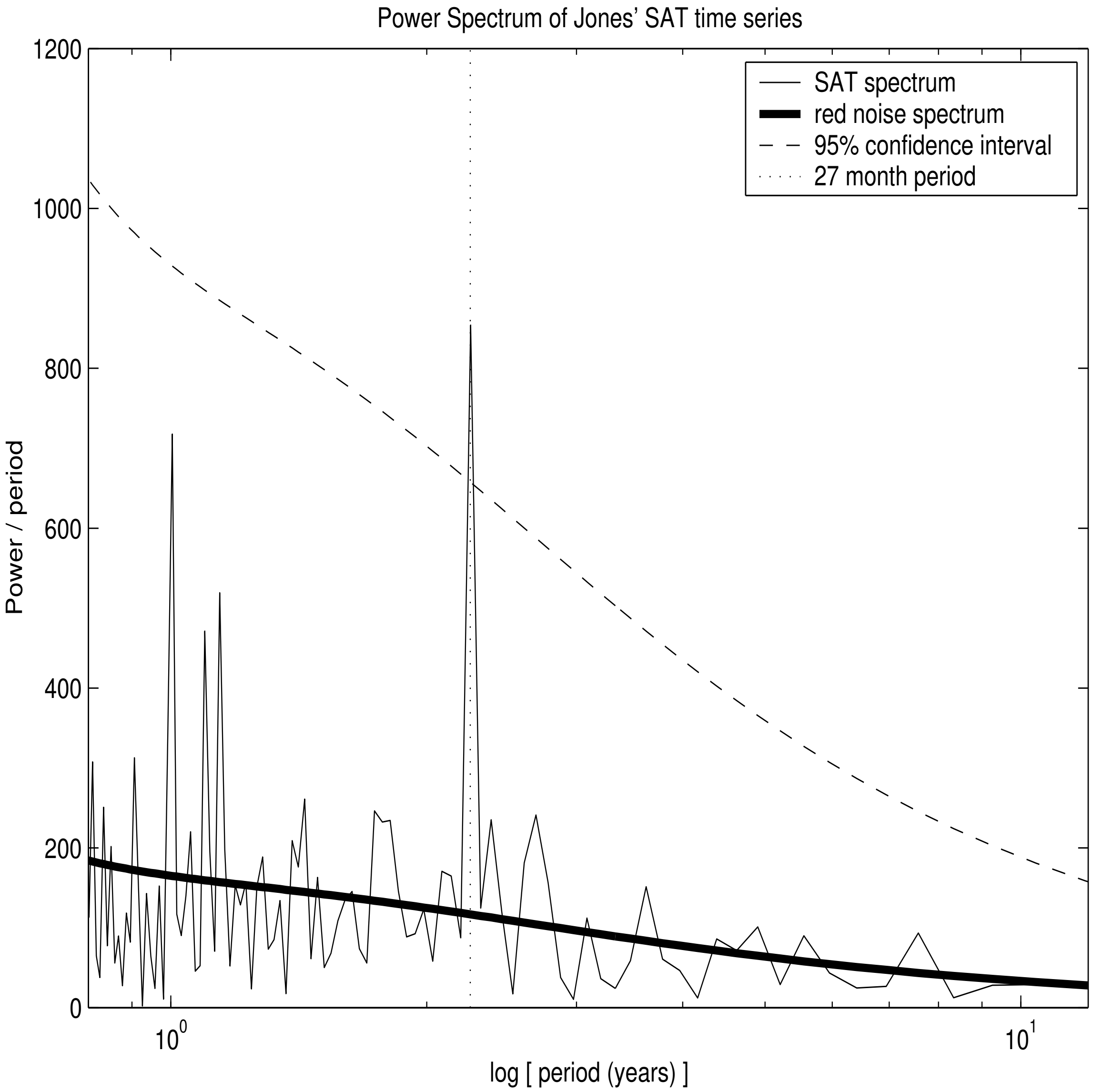

Power Spectrum of Trenberth's 100 year SLP anomalies
SLP spectrum
red noise spectrum
95% confidence interval
27.5 month period
Power / period
log [period (years)]
300
250
200
150
100
50
0
10^0
10^1

Figure 4



Power Spectrum of Jones' SAT time series
SAT spectrum
red noise spectrum
95% confidence interval
27 month period
Power / period
log [period (years)]
0
200
400
600
800
1000
1200
10^0
10^1

Figure 5