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QBO Signal found at the Extratropical Surface through Northern Annular Modes

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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 in the extratropical stratosphere and tracing the signal, using the annular modes as a filter, down through the atmosphere to the surface. Then the statistical significance of the surface signal is established.

Introduction

The equatorial quasi-biennial oscillation (QBO), a quasi-periodic descent of alternating easterlies and westerlies in zonal winds, is a well known phenomenon [*Reed et al.*, 1961]. Since its discovery, numerous observational and modeling 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 such as column ozone concentrations, angular momentum and wave forcing [*Holton and Tan*, 1980 and 1982; *Randel and Cobb*, 1994; *Tung and Yang*, 1994a; *Baldwin and Tung*, 1994; *Yang and Tung*, 1994 and 1995]. *Hsu and Yung* [1999] also found evidence of the equatorial QBO signal in tropospheric chemicals, such as methane, which are photochemically affected by the stratospheric ozone overhead. Nevertheless, tropospheric meteorological connections to the QBO have not been convincingly demonstrated.

Landsberg [1962] and *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* [1975] attempted to isolate aspects of the QBO in the sea level pressure using composite analysis. He found little evidence of a connection. *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* [1975 and 1980] 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; *Ogallo et al.*, 1988; *Nicholson and Kim*, 1997].

Most recently, *Baldwin et. al.* [2001] extended the composite analysis of *Holton and Tan* [1980] who showed the difference between 1000-hPa geopotential for the two phases of the QBO. Although a difference pattern was found through this analysis no statistical tests were performed in either of the two studies.

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 (NAM) to show that the QBO signal can be traced from the upper stratosphere down to the extratropical surface. The NAM are empirically determined as the spatial structure at each level which explains the most variance and they are used as a filter to improve the signal to noise ratio at each height. We use Baldwin and Dunkerton's time series [*Baldwin and Dunkerton*, submitted 2001] 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 and Paolino* [1980] and *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

The QBO winds were provided by Barbara Naujokat [*Naujokat*, 1986]. 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 set were taken from three locations; Canton Island, the Maledives and Singapore.

In the extratropics, three main data sets are used; 40 years of geopotential height anomalies [*Baldwin and Dunkerton*, submitted 2001], 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 and Dunkerton* [submitted 2001] 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

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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 coefficients of this EOF quantify the resemblance of the geopotential height at a given time to the spatial structure of the EOF. By analyzing the variations in just the coefficients of the first EOF, we are able to suppress some of the small scale fluctuations in the atmospheric system and 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* [1998], which is also called the Arctic Oscillation or the AO. This means that Baldwin and Dunkerton's coefficients at the surface correspond to the values over the last 40 years in both of the longer data sets. Trenberth published a 100-year time series [*Trenberth and Paolino*, 1980] of sea level pressure (SLP) anomalies which Thompson and Wallace projected onto the surface EOF [*Thompson and Wallace*, 2000]. This data set consists of monthly SLP coefficients from January, 1899 to May, 2000. Jones produced an even longer time series [*Jones*, 1994]. The data used here consists of his surface air temperature (SAT) anomalies projected onto Thompson and Wallace's AO pattern [*Thompson and Wallace*, 2000]. 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 spec-

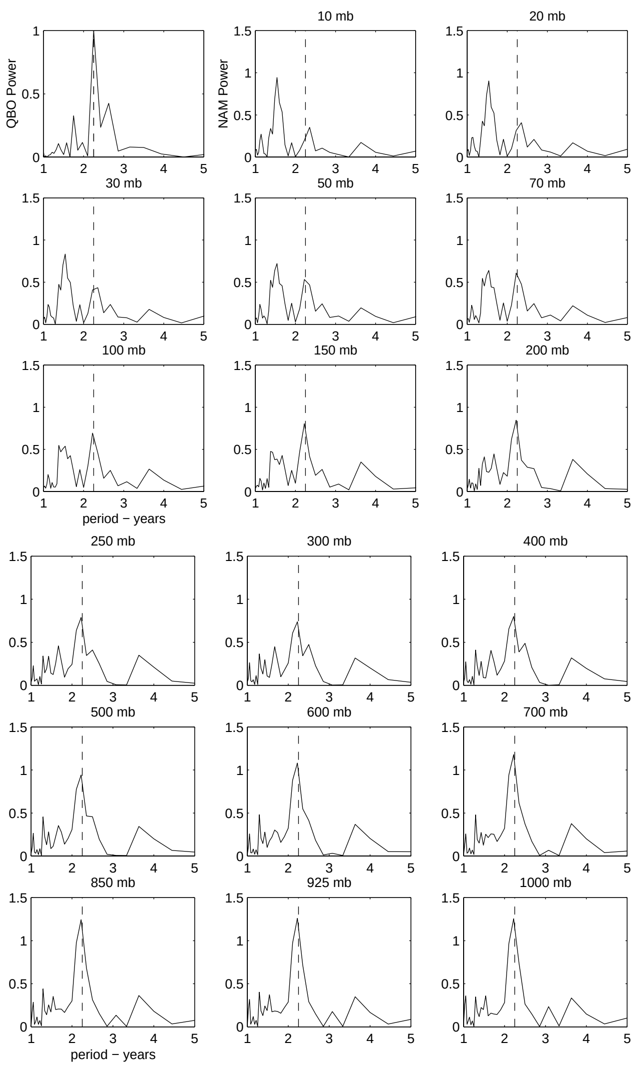

Figure 1. Power spectrum of the QBO at 30 mb is shown in the first frame and Baldwin's NAM at 17 levels from 10 mb down to 1000 mb are shown in the subsequent frames. The dotted vertical line indicates the frequency associated with a 27 month period, characteristic of the QBO. The spectra is calculated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

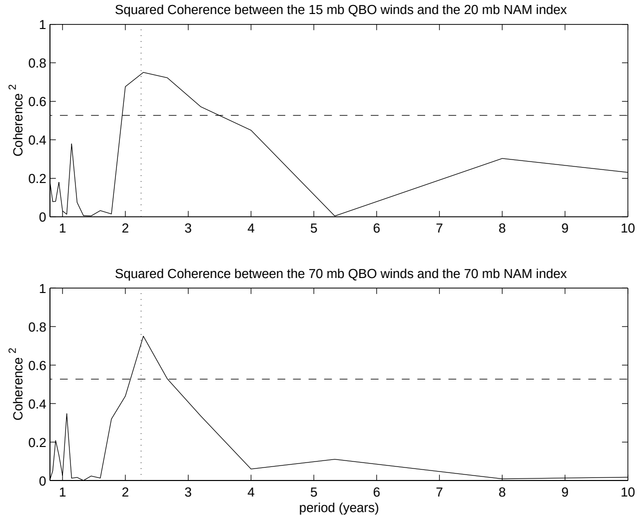

Figure 2. Coherence between (a) the 15 mb QBO winds and the 20 mb NAM index and (b) the 70 mb QBO winds and the 70 mb NAM index. The dashed horizontal line indicates the 95% confidence level. Coherence is found using daily data throughout the year for both the QBO winds and the NAM index.

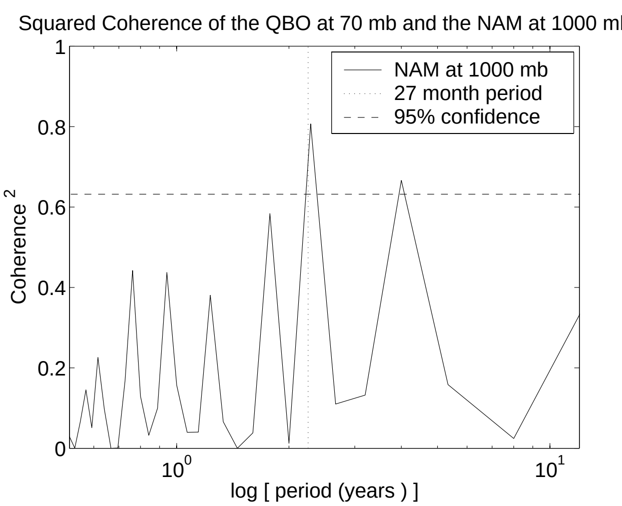

Figure 3. Coherence between the 70 mb QBO winds and the 1000 mb NAM index. The dashed horizontal line indicates the 95% confidence level. Coherence is found using monthly averaged winter (DJFM) values for both the QBO winds and the NAM index.

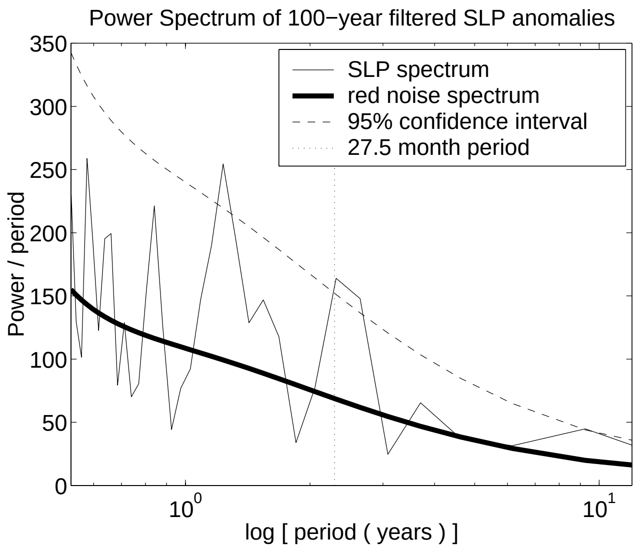

Figure 4. Power spectrum of Trenberth and Paolino's 100 year sea level pressure (SLP) time series. Only the winter months (DJFM) are used for this calculation. The dashed line indicates the 95% confidence interval and the bold line is the appropriate red noise power spectra. The dotted line demarks the 27.5 month period.

tra are found using F-statistics to compare the spectra to a red noise spectrum, or a first order Markov process. *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 in the spectra.

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. Following this QBO signal in the power spectra of Baldwin's 17-level winter 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 NAM data, from 10 mb to 1000 mb, has a peak at the same frequency as the equatorial QBO (seen in the first frame). The dotted vertical line represents this 27-month signal [1]. 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 at 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 (using year round daily data). 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). Note that the 27-month signal in the 40-year surface NAM index is not statistically significant by itself. 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 on its own we need to look at the longer time series provided by Trenberth and Paolino (see figure 4) and Jones (see figure 5).

Figure 4 shows the power spectrum of Trenberth and Paolino's 100-year filtered 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 is used. The power spectra of the samples are 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 filtered 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. The narrow peak at 27 months is a consequence of minimal averaging over this long data record and is obviously significant.

Conclusions

Previous studies have shown that the QBO has an influence on the extratropical stratosphere, but the tropospheric influence has not been convincingly established. Using the short (40-year) NAM time series as an indicator we 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 equatorial QBO and the longer time series are used to verify the significance of the surface signal. One hundred years of extratropical sea level pressure data are averaged to produce a significant peak at the 27 month period, but the results are sensitive

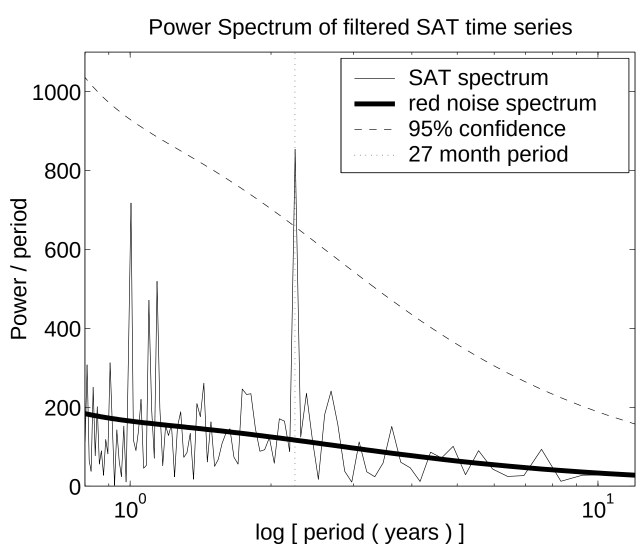

Figure 5. Power spectrum of Jones' surface air temperature (SAT) data. The monthly index is based on winter months (JFM) from 1851 to 1997. The dashed line indicates the 95% confidence interval and the bold line is the appropriate red noise power spectrum. The vertical dotted line represents the 27 month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

[1]Since only winter data are used, the three-peak spectrum [*Tung and Yang*, 1994b], which represents the effect of intereaction between the QBO and the annual cycle, is not expected.

to sample size and overlap. However, 150 years of surface air temperature data is long enough to provide a definitive, robust peak 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 to the surface. The method of transmission cannot be determined by this type of analysis. It is, however, consistent with the theory that the QBO modulates the wave guide for vertically propagating planetary waves. This influences the intensity of the polar vortex in the winter extratropical stratosphere which in turn affects the tropospheric planetary waves in the extratropics which are sensitive to the upper boundary condition [*Baldwin et al.*, 2001; *Thompson et al.*, submitted 2001].

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