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Extra-tropical QBO Signals in Angular Momentum and Wave Forcing

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Abstract. Although the period of the equatorial stratospheric quasi-biennial oscillation (QBO) is approximately 30 months, quasi-biennial modulation of the extratropical annual cycle may be expected to produce additional spectral peaks at approximately 8.6 and 20 months in the extratropics. Using Northern Hemisphere data for 1964-78 and global data for 1978-93 it is shown that these spectral peaks are robust in both angular momentum and Eliassen-Palm flux divergence. This spectral signature represents a circulation anomaly in both hemispheres, and implies a dynamical origin to the previously observed similar spectral peaks in column ozone in the extratropics.

Introduction

The quasi-biennial oscillation (QBO) of the equatorial stratosphere is known to have an effect on extratropical dynamical variables as well as trace chemical species [*Holton and Tan,* 1980; *Holton and Tan,* 1982; *Garcia and Solomon,* 1987; *Lait et al.,* 1989; *Dunkerton and Baldwin,* 1991; *Randel and Cobb,* 1994]. Typically, these effects are seen as variations synchronized to the QBO's period, which is variable with a long-term average of about 28 months (30 months for the last 15 years). *Gray and Dunkerton,* [1990] first noted the possibility that an annually varying circulation transporting an equatorial QBO tracer anomaly would form new harmonics with frequencies equal to the sum or difference of any pair of initial frequencies and suggested a low frequency (5 - 7 year) modulation of the tracer QBO signal in the extratropics. Recently *Tung and Yang,* [1994a,b] suggested that a QBO signal modulated by an annual cycle should produce an anomaly spectrum containing *shorter* periods, at 20 months and 8.6 months. More importantly, they argued that such extra tropical QBO anomalies should exist in the transporting circulation itself (and therefore should exist in the wave Eliassen-Palm flux divergence) through a dynamical mechanism (*Holton and Tan,* [1982]). This theory states that the dynamical QBO should act to modulate the annual cycle (or vice versa) in the extratropics in the following way. Consider a 30-month harmonic, $Q(t)$, that acts to modulate an annually periodic function, $F(t)$, consisting of an annual mean and a sinusoid with an annual period. Then, since $\frac{1}{12}+\frac{1}{30}\doteq\frac{1}{8.6}$ and $\frac{1}{12}-\frac{1}{30}\doteq\frac{1}{20}$, we have

$$F(t)\cdot Q(t)=[A+B\sin(\frac{2\pi t}{12months})]\sin(\frac{2\pi t}{30months})=$$
$$A\sin(\frac{2\pi t}{30months})+\frac{B}{2}\cos(\frac{2\pi t}{20months})-\frac{B}{2}\cos(\frac{2\pi t}{8.6months}).$$

The result is a three-peak spectrum (30, 20, and 8.6 months) for the product. It should be noted that the shape of the spectrum does not depend critically on the sinusoidal nature of $Q(t)$ and $F(t)$. *Tung and Yang,* [1994a] showed that a similar spectrum results from actual QBO data that are nonzero only during the winter months. (This can be viewed as a product of $Q(t)$ (for QBO), and $F(t)$, which is an on-off function with 12-month period.) The 3-peak spectrum may be expected to be the signature of a QBO circulation anomaly in the extratropics. They showed that such a spectral signature appears in extratropical column ozone data.

Since the 3-peak spectrum is predicted theoretically and observed in column ozone data, it is a logical next step to enquire if such a spectrum may be seen in dynamical variables, in particular angular momentum and wave driving (as measured by the Eliassen-Palm flux divergence [*Edmon et al.,* 1980]). The purpose of this paper is to explore the extent to which such a spectral signature may be seen in observational data in both hemispheres.

Data Set and Processing

The data consist of daily National Meteorological Center (NMC) 12Z heights and temperatures. For the period 1/1/64—9/23/78 these data are available north of 18°N at the levels 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 10 hPa. For the period 9/24/78—5/8/93 the grid has global coverage and the levels 5, 2, and 1 hPa are included.

The data were subjected to quality control to remove any erroneous grids. All missing data were linearly interpolated in time. Horizontal wind components were

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then calculated using the linear balance method [*Robinson et al.*, 1986; *Hitchman et al.*, 1987; *Randel*, 1987]. Daily values of the Eliassen-Palm flux [*Edmon et al.*, 1980] and its divergence were then calculated.

All data were then deseasoned by subtracting the daily climatological values (which were first smoothed using a 31-day running mean). Although the data are deseasoned, some power remains at the 12-month period because the variance of the anomaly may have seasonal preferences. Spatial empirical orthogonal functions (EOFs) were calculated using band-pass filtered data retaining periods from six to 60 months. Power spectra were calculated using a Hanning window fast Fourier transform routine. For consistency with the EOF calculations, the spectra were also calculated using the six to 60-month filtered data.

Results

In the Northern Hemisphere, interannual stratospheric variability of the zonal wind or angular momentum is dominated by a north-south dipole structure centered at about 40°N. This structure is clearly seen in the leading spatial EOF of zonal wind [*Nigam*, 1990; *Dunkerton and Baldwin*, 1992] as well as correlations with the QBO [*Dunkerton and Baldwin*, 1991; *Baldwin and O'Sullivan*, 1994]. To examine the power spectrum of angular momentum (which is proportional to $u\cos\theta$ times another $\cos\theta$ from spherical geometry) in the stratosphere, two methods were employed. One method is to examine the angular momentum within a latitude-height "box" representing *either* the northern or southern part of the dipole. [See *Dunkerton and Baldwin*, 1991 for details of the calculations.] For example, an angular momentum time series or a time series of the net EP flux out of such a box could be calculated for the region 18-38°N and 10-1 hPa. An alternate method is to obtain the time series of the principal component corresponding to one of the leading spatial EOFs (which are calculated for a similar box, but using all latitudes – typically 18° to the pole). As shown below, this method works well if *one* of the leading EOFs contains the variations of interest. The EOF method has the advantage that no arbitrary partitioning into north and south regions is needed.

Angular Momentum

Principal component time series were calculated for the leading modes of variability of 1978-93 angular momentum for the region 10-1 hPa and 18-90°N. The first EOF of angular momentum is shown as Figure 1. It is displayed by correlating its principal component time series with the time series of angular momentum at each grid point. (The same diagram could be obtained by correlating with zonal-mean wind.) The dipole structure is centered near 40°N. Both parts of the dipole structure are maximized near 10 hPa simply by the choice of the angular momentum box with a lower boundary at 10 hPa.

The power spectrum of the principal component of

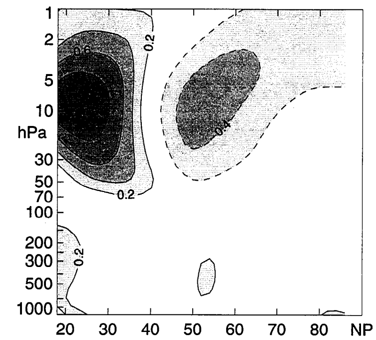

Figure 1. The first spatial EOF of Northern Hemisphere angular momentum, for the period 1978-93. The pattern represents the correlation coefficient between principal component time series for the first EOF (calculated within a box between 10 and 1 hPa and 18-90°N) and angular momentum data. The data have been band-pass filtered to retain variations in the 6-60 month range. This mode accounts for 16.2% of the spatially-averaged variance.

the first EOF is shown as Figure 2. The spectrum is dominated by peaks near 30, 20, and 8-9 months. The 8-9 month peak shows a broad, double-peak structure (but note the nonlinear period-scale used). Using the alternate method of averaging the angular momentum over the latitude band 18-38°N results in nearly identical spectral peaks (not shown), while using the northern half of the dipole (42-66°N) results in weaker peaks near 20 and 30 months, but a much stronger single peak in the 8-9 month band (not shown).

EOFs from 1964-93 (10-hPa data only; no data above 10 hPa were available prior to 1978) angular momentum data (not shown) indicate that no single mode describes well the variations in the three spectral bands. Although results for the southern part of the dipole showed a strong spectral peak at 20-30 months, there was little evidence for the 8-9 month peak. However, in the northern part, 42-66°N, strong separate peaks near 20 and 30 months and a modest peak at about 8.2 months may be seen in the angular momentum data (Figure 3).

In the Southern Hemisphere the first EOF of angular momentum, calculated using the region 10-1 hPa

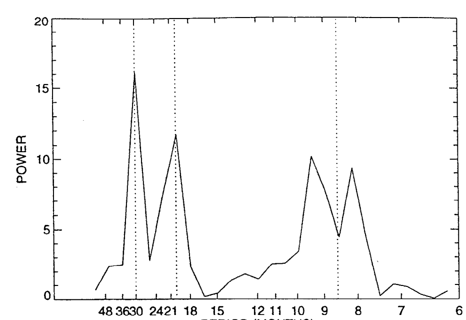

Figure 2. Power spectrum of the principal component of the first EOF of Northern Hemisphere angular momentum (as used in Figure 1). The power spectrum was calculated using a Hanning window fast Fourier transform routine. The dotted lines represent the QBO (30 months), and periods expected from interaction with the annual cycle (20 and 8.6 months).

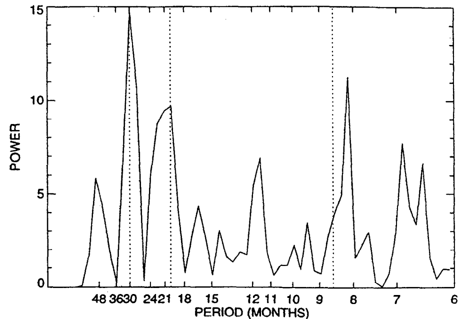

Figure 3. Power spectrum of the angular momentum time series calculated for 42-66°N at 10 hPa for the years 1964-93.

and 18-90°S (Figure 4), is characterized by variations in one stratospheric region equatorward of 58°S. The corresponding spectrum (Figure 5) has a broad spectral peak covering 20-30 months while the other dominant peak is centered on 8-9 months. Separate peaks at 20 and 30 months are not resolved.

Wave Forcing

The above calculations were repeated, replacing angular momentum by the net Eliassen-Palm flux out of the latitude-height boxes. This time series is equivalent to the average EP flux divergence over the box. Previous results [*Dunkerton and Baldwin,* 1991] indicate a fairly close relationship between wave driving (as measured by the EP flux divergence) and the acceleration of the zonal wind. ~~Figure 6 illustrates the~~ first EOF of the EP flux divergence, which is remarkably similar to the first EOF of angular momentum, but with a more spatially compact structure and a dipole centered about 5° farther north. The corresponding spectrum (Figure 7) shows a strong peak in the 8-9 month range and a broad peak covering the 20-30 month band. The peaks near 20 and 30 months, which could be seen in angular momentum, are not individually resolved.

In the Southern Hemisphere no single EOF described well the spectral peaks of the net EP flux, but the average over the equatorward part of the dipole (18-58°S) did resolve the peaks. As with the Northern Hemisphere, the Southern Hemisphere EP flux data exhibit spectral peaks at 8-9 and 20-30 months (Figure 8). This result, showing very similar spectra for both hemispheres, in both angular momentum and net EP flux, is a strong indicator that the 3-peak signature of the QBO is genuine.

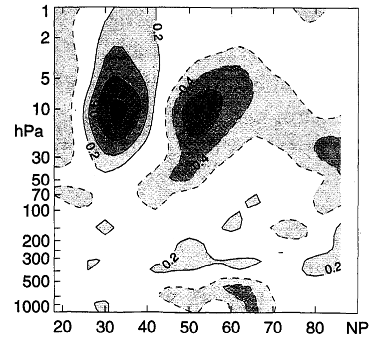

Figure 6. The first spatial EOF of Northern Hemisphere net Eliassen-Palm flux divergence. This mode accounts for 21.4% of the spatially-averaged variance.

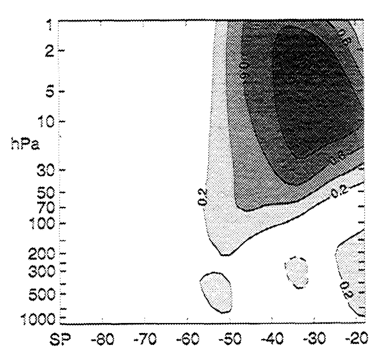

Figure 4. As in Figure 1, except Southern Hemisphere. This mode accounts for 18.7% of the spatially-averaged variance.

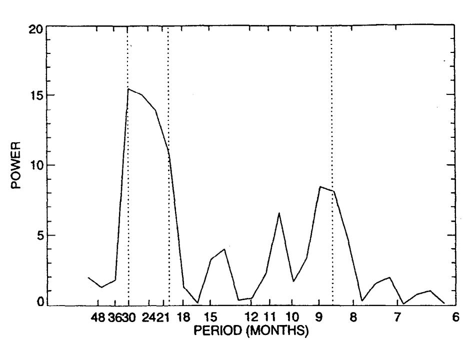

Figure 5. As in Figure 2, except Southern Hemisphere.

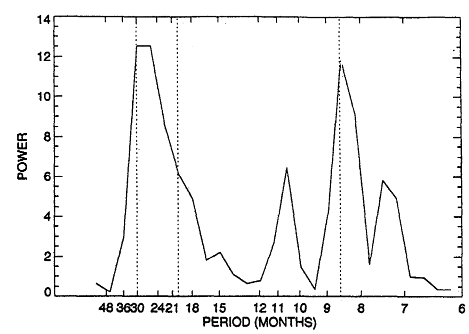

Figure 7. Power spectrum of the principal component of the first EOF of Northern Hemisphere net Eliassen-Palm flux divergence.

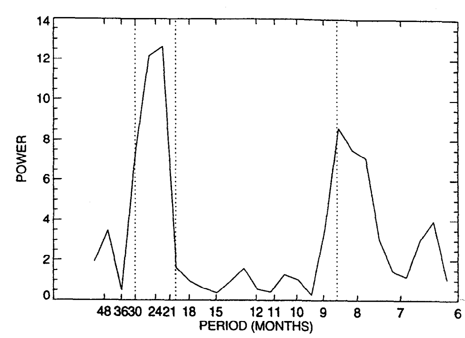

Figure 8. As in Figure 7, except Southern Hemisphere for the latitudes 18-58°S.

Discussion

By examining time series representing stratospheric angular momentum and EP flux divergence, a spectral signature with 3 peaks (30, 20 and 8-9 months) emerges. This signature is anticipated by the quasi-biennial modulation of an extratropical annual cycle and has been seen independently in column ozone data.

By looking at three independent data sets (NH, 1978-93; SH, 1978-93; NH, 1964-78) the spectral peaks are found to be robust, although neighboring peaks are in some cases smeared together. A statistical treatment of the significance of these peaks is the subject of a separate paper, but the strong similarity between the spectral signatures of both angular momentum and EP flux in both hemispheres provides strong evidence in favor of the reality of the 3-peak signature of the QBO in the extratropics. Yang and Tung (1994) recently established the statistical significance of the three-peak spectrum for column ozone.

The 20 and 30-month peaks are separately resolved in the angular momentum time series in both the 1978-93 series and in the 30-year series. The two-peaks are smeared into a broad peak in the EP-flux divergence data. Arguably, the angular momentum data would be the highest quality data. In the case of EP flux data, the many differentiations and use of fluxes make the time series somewhat noisy. Also, the spectral resolution in a 15-year data set is barely sufficient to resolve separate peaks.

These observations support the hypothesis that the QBO is responsible for anomalies in the transport circulation in both hemispheres which result in variability on the same time scales in ozone.

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