GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 20, PAGES 2235-2238, OCTOBER 1, 1994

Statistical significance and pattern of extratropical QBO in column ozone

Hu Yang and Ka Kit Tung

Department of Applied Mathematics, University of Washington, Seattle, Washington

Abstract. Statistical tests are performed on 30 years (1957-1986) of Dobson station data. The triple-period (30, 20, and 8.6 months) extratropical QBO signal in ozone is found to be statistically significant. Earlier tests, based on 9 years of TOMS data, gave ambiguous results. We further suggest an objective method of extracting ozone QBO signal in the extratropics using a linear regression model.

Introduction

Despite many studies on the subject, the Quasi-Biennial Oscillation (QBO) in total ozone at extratropical latitudes remains an ill-defined phenomenon. In most studies, extratropical ozone QBO signal is extracted by a least-square-fit to the 30-mb or 50-mb Singapore wind or by a filter admitting a frequency band around the frequency of the equatorial QBO. An implicit assumption is made in these studies that the extratropical ozone QBO should have the frequency of equatorial QBO. On the other hand, evidence shows that the power spectra of extratropical ozone contain a major peak at 20-month, in addition to the equatorial QBO period [*Hilsenrath and Schlesinger,* 1981; *Tung and Yang,* 1993; 1994a,b]. Tung and Yang argued that the 20-month component in total ozone is an integral part of the extratropical ozone QBO phenomenon, and found in 13 years of TOMS data a characteristic triple period signature (at 30, 20 and 8.6 months) in the power spectra. They explained the presence of the 20-month and 8.6-month periods as arising from the difference and sum of the annual and the equatorial QBO frequencies, since $1/12 - 1/30 = 1/20$, and $1/12 + 1/30 \approx 1/8.6$. No statistical study was done because of the shortness of the TOMS data record. In this study, we perform tests of the statistical significance of the power spectra of extratropical ozone QBO using 30 years of ground Dobson station data. We further calculate the global pattern of ozone QBO using 13 years of TOMS data.

Statistical test

To establish the existence and spectral properties of the extratropical ozone QBO, we calculate the squared coherency between the deseasoned total ozone and winter-time Singapore wind. For total ozone, we use the 30 years of latitudinal band-averaged ozone data for the Northern Hemisphere, calculated from provisionally revised Dobson instrument records (by Bojkov) and published in the Report of the International Ozone Trends Panel 1988 [*WMO,* 1989]. The winter-time 30-mb Singapore wind (defined as Singapore wind in December, January, and February, zeros in other months) is chosen here to represent the effect of the phase of equatorial QBO wind on the winter-time transport in the extratropics. During winter months, planetary wave breaking in the extratropics is enhanced in the easterly phase of the equatorial QBO, as compared to the westerly phase [*Holton and Tan,* 1980; *Dunkerton and Baldwin,* 1991]. Irreversible mixing due to the enhanced planetary waves breaking leads to an E.-P. flux divergence anomaly, which in turn induces an anomaly in the mean diabatic meridional circulation. We believe that the anomaly circulation is responsible for creating an ozone QBO in the extratropics. Such an effect is mostly absent during summer, when there is no stratospheric waveguide for the extratropical planetary waves.

The result for the squared coherency is shown in Figure 1. At all four latitude bands, which covers latitudes from 30°N to 80°N, the spectral peaks near 30 months are statistically significant at 99% level. This is in contrast to the results obtained by Lait et al [1989], who calculated the coherency squared between 30-mb Singapore wind and 9 years of TOMS ozone data. Their results showed that the coherency squared is significant at 95% level between 60°N and 70°N, but is below the significant level between 20°N and 60°N. We believe the difference is due to the length of data record used: their 9 years of data versus our 30 years. At middle latitudes (30°N–52°N), the spectral peaks near 20 months and 8.6 months are also significant at 95% level in the 30 year record. At high latitudes (53°N–80°N), the 8.6-month peaks are still significant at 99% level, while the 20-month peaks seem to be slightly below significance level. Note, however, that station data records at high latitudes tend to be less continuous, and the way missing data are filled in may contaminate the spectrum.

Global ozone QBO pattern from TOMS data

We have shown that the extratropical ozone QBO is significantly correlated with winter-time Singapore wind at periods of about 27–30 months, 20–21 months and 8–9 months. (The equatorial QBO period has var-

Paper number 94GL02120
0094-8534/94/94GL-02120$03.00

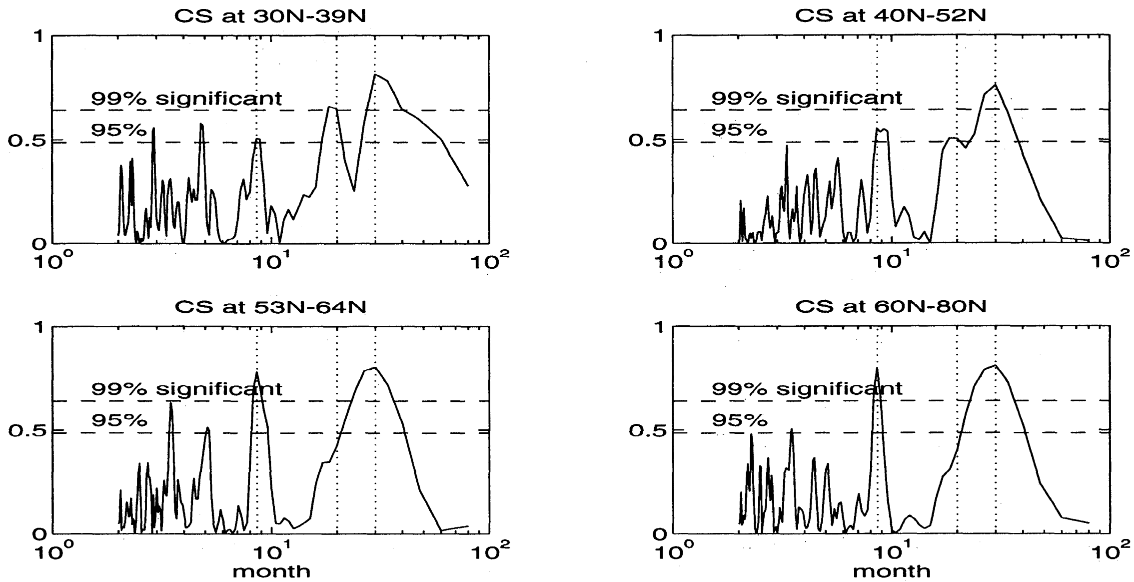


Figure 1. Coherency-squared between the deseasoned total ozone based on 30 years of Dobson station data and winter-time Singapore wind at various latitude bands. The horizontal dashed lines mark the statistical significant level at 99% and 95%. The vertical dotted lines mark the periods of 8.6 months, 20 months and 30 months, respectively.

ied from 27 months to 30 months from the first two decades to the last. This also affects the sum and the difference with the annual frequency.) As explained in Tung and Yang [1994a,b], such a 3-peak spectrum of extratropical ozone QBO results from an anomaly in the dynamical transport. An extension of the equatorial QBO phenomenon, which is characterized by a spectrum of a single major peak at about 27 to 30 months, depending on the period of the data record, is by itself not an adequate representation of the extratropical ozone QBO phenomenon, which is characterized by a 3-peak spectrum. Instead, the extratropical ozone QBO should be represented by the equatorial QBO *multiplied by a seasonally varying function*, which can be determined empirically.

One way of determining such a function is to use a statistical linear regression model of the form

$$\text{Ozone} = \alpha\cdot\text{Trend} + \beta\cdot\text{Solar} + \gamma\cdot\text{QBO} + \cdots + \text{Residual},$$

where the Trend, Solar and QBO components are represented by a linear (or "hockey stick") function, F10.7-cm solar flux and 30-mb (or 50-mb) Singapore wind, respectively. It has been argued [*WMO,* 1989] that since ozone variations are seasonally dependent, the coeffi-

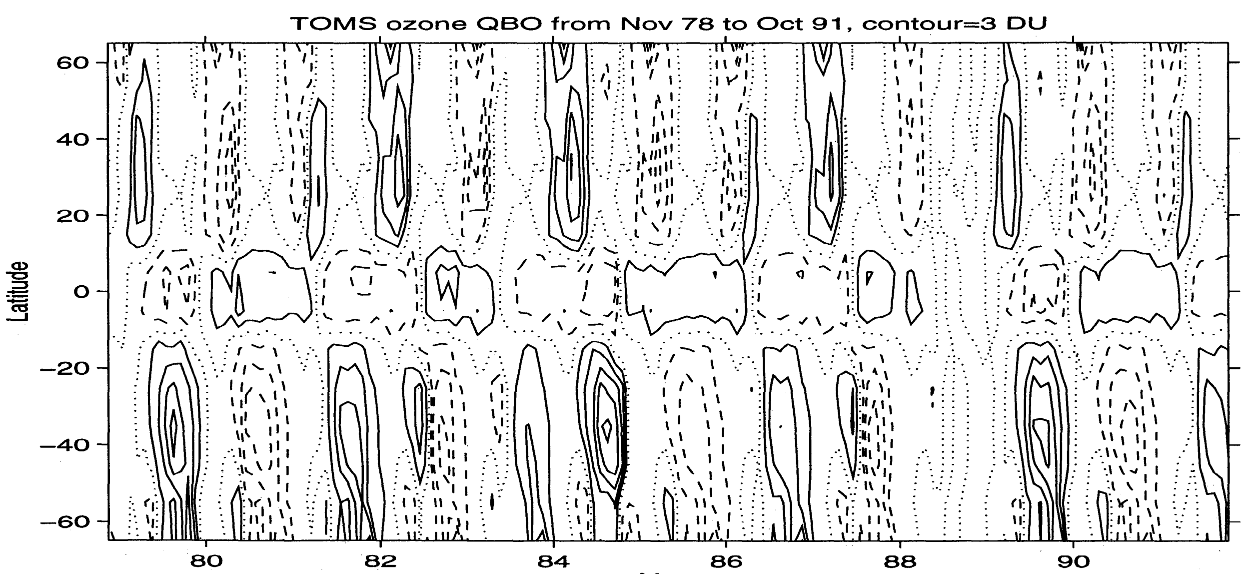
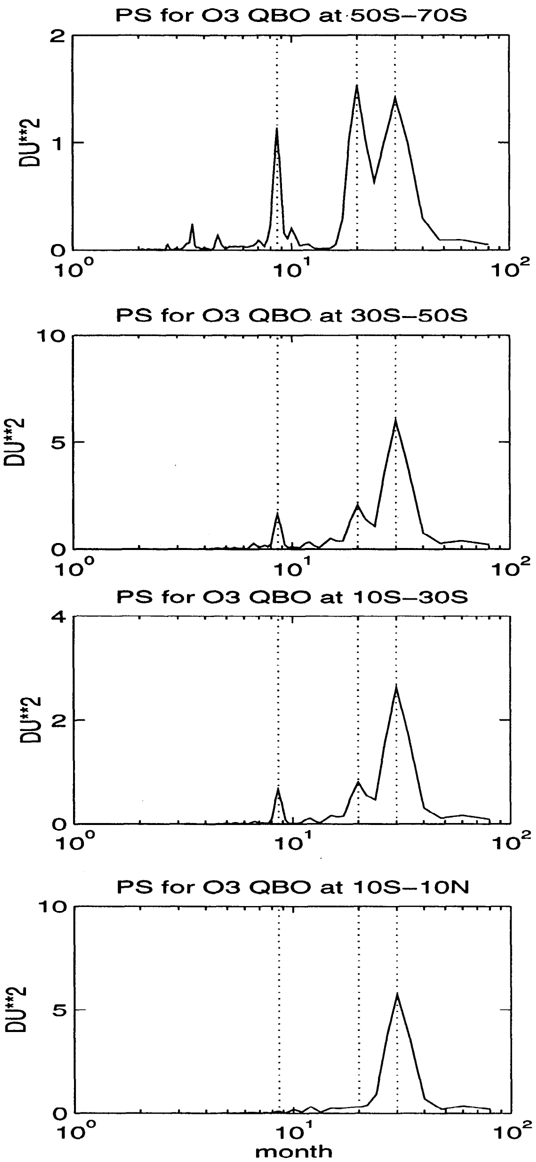


Figure 2. Global pattern of ozone QBO obtained from the first 13 years of TOMS data. Contour levels are 0 (dotted), ±3DU, ±6DU, $\cdots$, with solid (dashed) lines for positive (negative) contours.



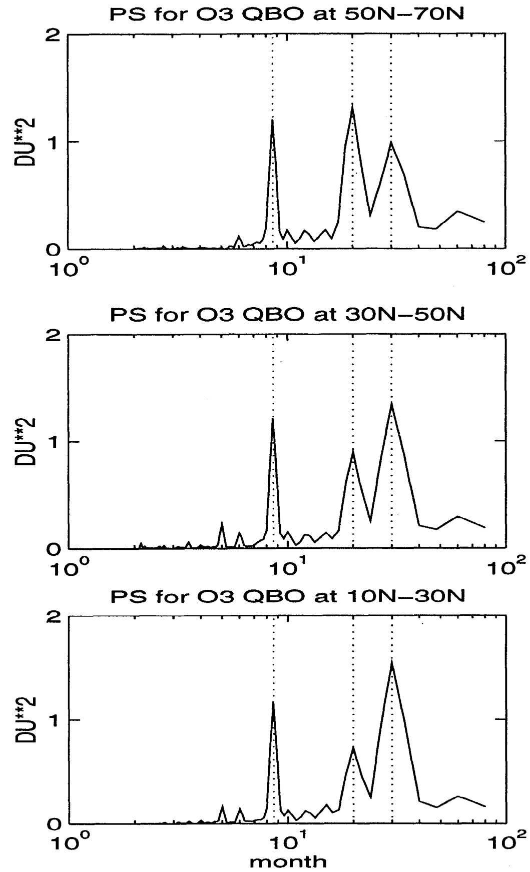


Figure 3. Coherency-squared between the deseasoned total ozone based on 30 years of Dobson station data and winter-time Singapore wind at various latitude bands. The horizontal dashed lines mark the statistical significant level at 99% and 95%. The vertical dotted lines mark the periods of 8.6 months, 20 months and 30 months, respectively.

cient for linear trend α should be seasonally varying. Some authors (e.g. Stolarski et al [1991] and Randel and Cobb [1994]) extended this to other coefficients β, γ, etc, while other authors continued to adopt constant values. A seasonally varying γ determined by the linear regression model is the correct approach from what we have found.

Thirteen years of TOMS data is used to fit a linear regression model of the above form. The "coefficients" are allowed to vary from month to month. Since the 30-mb Singapore wind U is not symmetric (easterly wind lasts longer and has higher amplitude than westerly wind for the TOMS data period), "QBO" in the model is represented by $U - \text{mean}(U)$. In addition, a lag (or lead) is allowed between the wind and ozone for each latitude and is determined by minimizing the residual in the model. Because the equatorial QBO wind is vertically coherent in the 10–50 mb layer with a downward phase propagation of about 1 km per month, the choice of a particular level or layer where the wind is used as the index is not crucial as long as a lag (or lead) is allowed (see *Tung and Yang,* 1994a). The resulting quantity, γ·QBO, which we define as the "ozone QBO", is shown in Figure 2, and the corresponding spectra of γ·QBO at various latitude bands are shown in Figure 3.

At the tropical region, ozone QBO has an amplitude of about 6 Dobson Units (DU) and a period of about 30 months. At middle latitudes of Northern Hemisphere, ozone QBO has an amplitude of about 12–14 DU, with a clear 3-peak spectrum, as expected. Note that due to the presence of the 20- and 8.6-month components, the ozone QBO at middle latitudes has a more complicated phase relationship with that at the equator. The stronger extratropical QBO anomalies, which are synchronised to the winter-spring season, are narrower (shorter in duration) than the equatorial anomalies and have an opposite phase. The anomalies at other seasons are close to zero. When such anomalies of the duration of a season are projected onto 30-month oscillations, as is the case when a narrow-band filter centered arround the equatorial QBO frequencies is used [*Hasebe,* 1983, 1984; *Lait et al,* 1989], a mostly out of phase broad pattern emerges with the appearance of some phase propagation. The ozone QBO has an amplitude of about 14–16 DU in the middle and high latitudes in Southern Hemisphere, implying a east-minus-west phase difference of about 30 DU.

Conclusion

The extratropical ozone QBO has a 3-peak spectrum, with major peaks at periods of about 27–30 months, 20–21 months and 8–9 months. Using 30 years of ground station data, we have shown that the spectral signature appears to be statistically significant. Methods of extracting extratropical ozone QBO based on a narrowband filter that admits only the frequency of the equatorial QBO may significantly underestimate the QBO signal. Linear regression models can be used to objectively extract the ozone QBO provided that the empirical coefficient is allowed to vary seasonally. The resulting QBO has a larger amplitude and a more complicated phase relationship than those obtained by a filter. It has also the characteristic 3-peak spectrum, which is a manifestation of the effect of equatorial QBO wind modulating the Brewer-Dobson circulation.

Acknowledgments. The research is supported by NASA, under Grants NAGW-1605 and NAG-1-1404. We thank Dr. R. D. McPeters for providing us with the version 6 TOMS data used in this report.

References

Dunkerton, T. J., and M. P. Baldwin: Quasi-biennial modulation of planetary-wave fluxes in the northern hemispheric winter. *J. Atmos. Sci., 48*, 1043–1061, 1991.

Hasebe, F.: Interannual variations of global ozone revealed from NIMBUS 4 BUV and ground based observations. *J. Geophys. Res., 88*, 6819–6834, 1983.

Hasebe, F.: The global structure of the total ozone fluctuations observed on the time scales of two to several years, in *Dynamics of the Middle Atmosphere*, edited by J. R. Holton and T. Matsuno, pp 445–464, Terra Sci. Pub., Tokyo, Japan, 1984.

Hilsenrath, E., and B. M. Schlesinger: Total ozone seasonal and interannual variations derived from the 7 year Nimbus 4 data. *J. Geophys. Res., 86,* 12087–12096, 1981.

Holton, J. R., and H. C. Tan: The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *J. Atmos. Sci., 37*, 2200–2208, 1980.

Lait, L. R., M. R. Schoeberl, and P. A. Newman: Quasi-biennial modulation of the Antarctic ozone depletion. *J. Geophys. Res., 94*, 11559–11571, 1989.

Randel, W. J. and J. B. Cobb: Coherent variations of monthly mean total ozone and lower stratospheric temperature, *J. Geophys. Res. 99*, 5433-5447, 1994.

Stolarski, R. S., P. Bloomfield, and R. D. McPeters: Total ozone trends deduced from Nimbus 7 TOMS data, *Geophys. Res. Lett., 18*, 1015-1018, 1991.

Tung, K. K., and H. Yang: On global quasi-biennial oscillation in column ozone, in *Coupling Processes in Middle and Lower Atmospheres*, edited by E. V. Thrane, T. A. Blix and D. C. Fritts, Kluwer Academic Pub., The Netherlands, pp 1-24, 1993.

Tung, K. K., and H. Yang: Global QBO in circulation and ozone, Part I: Reexamination of observational evidence, *J. Atmos. Sci.*, in press, 1994a.

Tung, K. K., and H. Yang: Global QBO in circulation and ozone, Part II: A simple mechanistic model, *J. Atmos. Sci.*, in press, 1994b.

WMO: *Report of the International Ozone Trends Panel 1988*, World Meteorological Organization Global Ozone Research and Monitoring Project–Report No. 18, 1989.

H. Yang and K. K. Tung, Department of Applied Mathematics, FS-20, University of Washington, Seattle, WA 98195.

(received June 22, 1994; accepted August 5, 1994.)