THE QUASI-BIENNIAL OSCILLATION IN ATMOSPHERIC OZONE

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Introduction

Since the discovery of a near two year oscillation in the zonal wind of the tropical stratosphere two decades ago, the properties of this variation have been thoroughly described (Wallace, 1973; Coy, 1979) and theoretically modeled (Holton and Lindzen, 1972; Plumb, 1977). A quasi-biennial oscillation (QBO) has been noted in a number of atmospheric variables and in portions of the atmosphere far removed from the tropical stratosphere. Included in these investigations have been extratropical zonal winds (Angell and Korshover, 1962, 1964, 1970; Shah and Godson, 1967; Belmont et al, 1974) temperature in the stratosphere, (Angell and Korshover, 1978a; Reed, 1965; Nastrom and Belmont, 1975), atmospheric ozone (Funk and Garnham, 1962; Ramanathan, 1963; Rangarajan, 1963; Angell and Korshover, 1964, 1975, 1976, 1978b; Shah, 1967; Oltmans, 1972; Wilcox et al, 1977) and tropospheric temperatures (Landsberg et al, 1962).

The nature and cause of a QBO outside of the tropical stratosphere have remained elusive despite considerable interest in the phenomena as noted above. The purpose of this paper is to more clearly delineate the extent and character of the QBO in atmospheric ozone and in particular to see where and how it is related to the tropical stratosphere zonal wind oscillation.

The Data

Since the main features of the wind variation at equatorial latitudes have been extensively verified, the winds at a single station and pressure level were chosen as representative for purposes of comparison with ozone behavior. The 50 millibar wind at Balboa, located at 9° N and 80° W, was used. These data were compared with those from a station in the Pacific (Ponape) at about the same latitude to verify that there were no important longitudinal differences, particularly in the timing of the oscillation. Parts of the analysis described later between the Balboa winds and various components of the ozone field were repeated using the winds from the Pacific region with no difference in the results.

Use was made of ozone data in several forms. The record of total ozone amounts from ground based observations is the longest set of observed ozone data. During the period from January 1958 to December 1978 there were 16 stations with nearly complete monthly data. But, for the fifteen year period from January 1964 to December 1978 there are an additional 28 locations with such nearly complete records. Because of this greater spatial coverage beginning in January 1964, the period January 1964 to December 1978 was chosen as most representative of global ozone behavior while still of sufficient length to study the QBO. The total ozone data were also considered in the form of global monthly mean maps from which the data were extracted at grid determine the timing between winds and ozone, the lag of the maximum correlation was used as well as the phase of the cross-spectrum to aid in interpretation of the results. This information was portrayed by plotting both the lag at which the largest positive correlation and largest negative correlation occur. This brings out differences in the length of the period since the difference in the lag between maximum positive and negative correlation corresponds to one-half the period of the variation. To assess changes in the ozone QBO with altitude, four stratospheric levels were chosen as representative of the region of interest. The ozonesonde levels considered were 100, 50, 30 and 10 mb corresponding to the Umkehr layers 125-62.5 mb, 62.5-31.2 mb, 31.2-15.6 mb and 15.6-7.8 mb. There are no vertical profiles from tropical or south polar latitudes that cover a sufficient period of time for statistical analysis of a QBO. The vertical profile information was also subjected to a lagged correlation analysis with the Balboa 50 mb winds to determine the phase relationship of the QBO with altitude.

The Results

A spectrum analysis of the Balboa 50 mb zonal wind reveals a "clean", prominent peak at the QBO period. A similar analysis of individual total ozone stations shows some stations with relatively prominent peaks at this period while others show no significant response. It is also possible to have significant spectral peaks at the QBO period in two different parameters and in different regions of the atmosphere without the existence of a significant relationship between them (Trenberth, 1980). Since a major objective of this paper is to define the relationship between tropical stratosphere zonal winds and atmospheric ozone, a cross-spectral analysis was used to determine whether these atmospheric parameters are related. A cross-spectrum between Balboa winds and ozone may produce a very significant coherence (figure 1a) as with the ozone station at Mauna Loa (20°N) or no significant relationship at the QBO period (figure 1b) as at Arosa (47°N). The variation of the strength of the relationship between the Balboa winds and globally analyzed ozone as a function of latitude is shown in figure 2. There is a striking lack of hemispheric symmetry in the squared coherences between wind and globally analyzed ozone during the period 1964-1978. There is indication of a very significant relationship in the N.H. polar and tropical regions and a near significant coherence in the S.H. mid latitudes. There are relative minima in the N.H. mid-latitudes, S.H. tropics and Antarctica. In the south polar region the data are insufficient to place much confidence in the result.

The coherences calculated from individual station total ozone data and Balboa winds (as shown in the examples of figures 1a and 1b) and plotted in a manner similar to figure 2 are in good agreement with the data of figure 2 but show somewhat higher coherences at mid-latitudes of the S.H. Analysis of the satellite total ozone data for the period 1970-76, also shows a somewhat stronger relationship at mid-latitudes of the S.H. They confirm the maximum in the N.H. tropics and the relative minima in the coherences at N.H. mid-latitudes and S.H. tropics. At high latitudes the satellite data set has a number of missing months of data and the calculated coherences are less reliable estimates of the actual relationship.

In addition to knowing the strength of the relationship between tropical stratosphere zonal winds and ozone (as measured by the coherences) it is of interest to know the timing of the relationship. The lag of the largest positive and negative correlations between the winds and globally analyzed total ozone are plotted as a function of latitude for the period 1964-78 in figure 3. The lag for the negative correlations are plotted as X's and represent the number of months the maximum easterly wind at 50 mb at Balboa occurs before the maximum in total ozone in the particular latitude belt. The circles, representing the lag of maximum positive correlation, indicate the number of months that the Balboa westerly wind maximum occurs ahead of the total ozone maximum. Also plotted as dashed lines are the phase of the cross-spectrum at a period of 25 months and the phase plus or minus 12.5 months. The phase of the cross-spectrum is consistent with the maximum cross-correlations and most closely fits the lag of the largest negative correlations.

At equatorial latitudes winds and ozone are essentially in phase (lag of largest positive correlation near 0 or 27 months). In the N.H. the phase shifts at middle and high latitudes so that a generally out-of-phase relationship prevails (lag of largest negative correlation near 0). In the S.H. there is a phase change in tropical latitudes toward a more nearly out-of-phase relationship. The phase shifts in each hemisphere correspond to the regions of low coherence noted earlier. Consideration of correlations between tropical winds and individual station total ozone and satellite data confirm the description of figure 3 with phase shifts in the S.H. tropics and N.H. mid-latitudes. Also to be noted is the variation with latitude of the length of the period of the QBO with the longer period in the equatorial and north polar regions. The middle and high latitude response of ozone appears to occur several months later in the N.H. There is also an apparent tendency for the response of ozone to the tropical winds to occur earlier at the higher latitudes.

Although ozone vertical profile information is severely limited as noted earlier, several tentative conclusions about the QBO response of ozone with altitude can be made. At subtropical and middle latitudes of the N.H. there appears to be little or no phase shift with altitude in the region between 15 and 30 km. In the S.H. this constant phase with altitude also prevails at mid-latitudes in the layer from 15-25 km with possibly a slight shift at higher altitudes of 1 or 2 months. At polar latitudes of the N.H. there appears to be a tendency for the response to occur a few months earlier at the lowest and highest levels studied although this may not be significant considering the large uncertainties in the data. At the present time there is insufficient equatorial data to test the relationship between winds and ozone as a function of altitude.

Discussion

The lack of symmetry about the equator in the relationship between tropical stratosphere winds and ozone is in contrast to the wind oscillation itself where there appears to be a good deal of symmetry in the amplitude and timing of the QBO within 20° of latitude on each side of the equator (Reed, 1965; Wallace, 1973). This assymetry may indicate the mechanism by which the wind field interacts with the ozone field in the stratosphere. As suggested by Dütsch and Ling (1973) the intensification of the downward leg of the stratospheric extension of the Hadley call accompanying the easterly phase of the biennial oscillation in the 25-30 km layer could result in increased poleward transport and hence a buildup of ozone at tropical and subtropical latitudes. Since the well developed Hadley cell of the S.H. winter is shifted northward into the N.H. (Palmén and Newton, 1969) and the wintertime N.H. Hadley cell is not similarly shifted into the S.H., the poleward transport of ozone to higher latitudes is centered north of the equator. Ozone would then be transported poleward by the quasi-horizontal eddies in conjunction with the annual poleward transport of ozone (Wilcox et al, 1977). The minima in the strength of the relationship between tropical stratosphere winds and ozone (figure 2) near 35°N and 15°S seems to be in the area where the eddy transports interact with the enhanced ozone reservoir. It is not clear why these should be areas of diminished response.

The generally uniform phase of the relationship between tropical winds and ozone in the 20-30 km layer at subtropical and middle latitudes (not shown here) also suggest that the QBO in ozone is not driven directly by vertical motions in the zonal wind QBO itself, but through the intermediate action of horizontal eddy transport. It appears that only in a relatively narrow equatorial band is there the possibility of direct influence of the vertical motions of the wind QBO on the ozone distribution. Unfortunately sufficient tropical ozone data at specific levels in the atmosphere do not exist to verify this conclusion by determining any phase shift with altitude in the ozone QBO.

Conclusion

An examination of the relationship between tropical stratosphere zonal wind and ozone indicate a variable response with latitude with the N.H. tropics and polar regions and S.H. mid-latitudes showing the strongest response with relatively weaker response at N.H. mid-latitudes and the S.H. tropics. In tropical regions the west winds and ozone maxima are in phase while at higher latitudes a more nearly out-of-phase relationship prevails. At subtropical and middle latitudes the QBO in ozone does not appear to change phase with altitude. These features are suggestive of an interaction between the tropical zonal winds and poleward transport by horizontal eddies in conjunction with the annual poleward transport of ozone.

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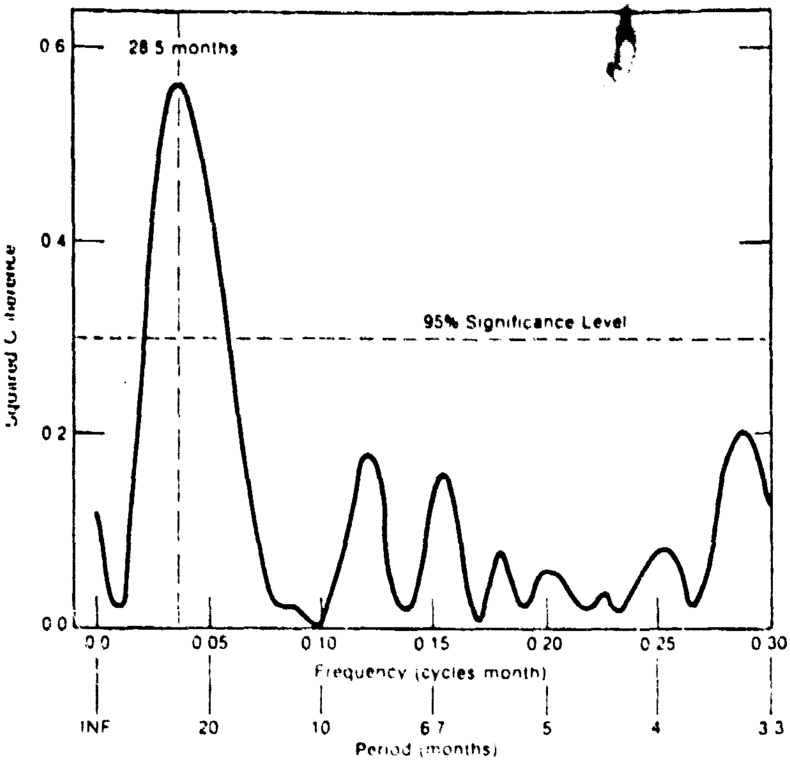

Figure 1a Smoothed squared coherence of the cross-spectral estimate between Balboa 50mb zonal wind and Mauna Loa total ozone for the period Jan 58 - Dec 78

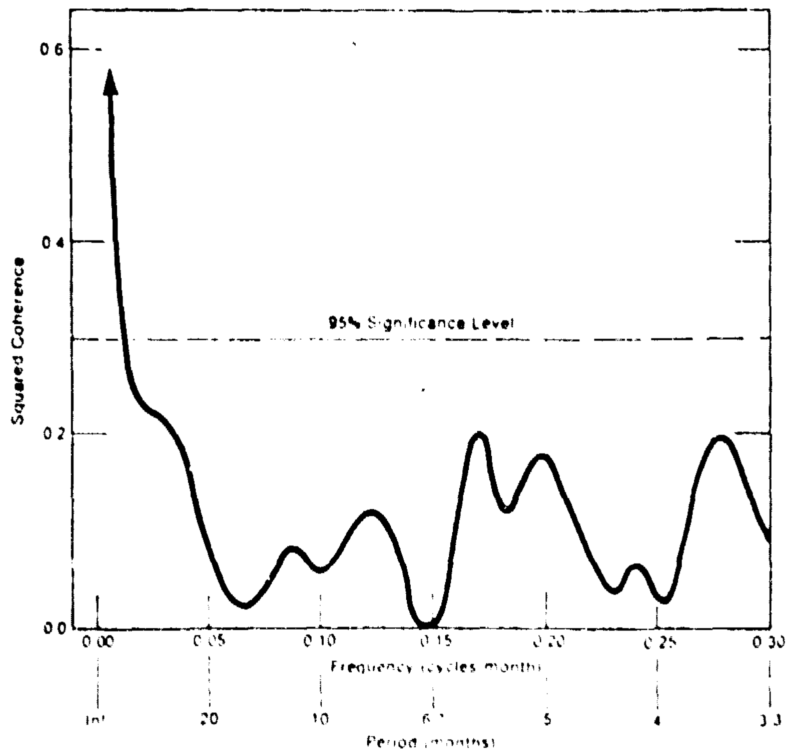

Figure 1b Smoothed squared coherence of the cross-spectral estimate prewhitened detrended Balboa 50mb zonal wind and Arosa total ozone for the period Jan 58 - Dec 78

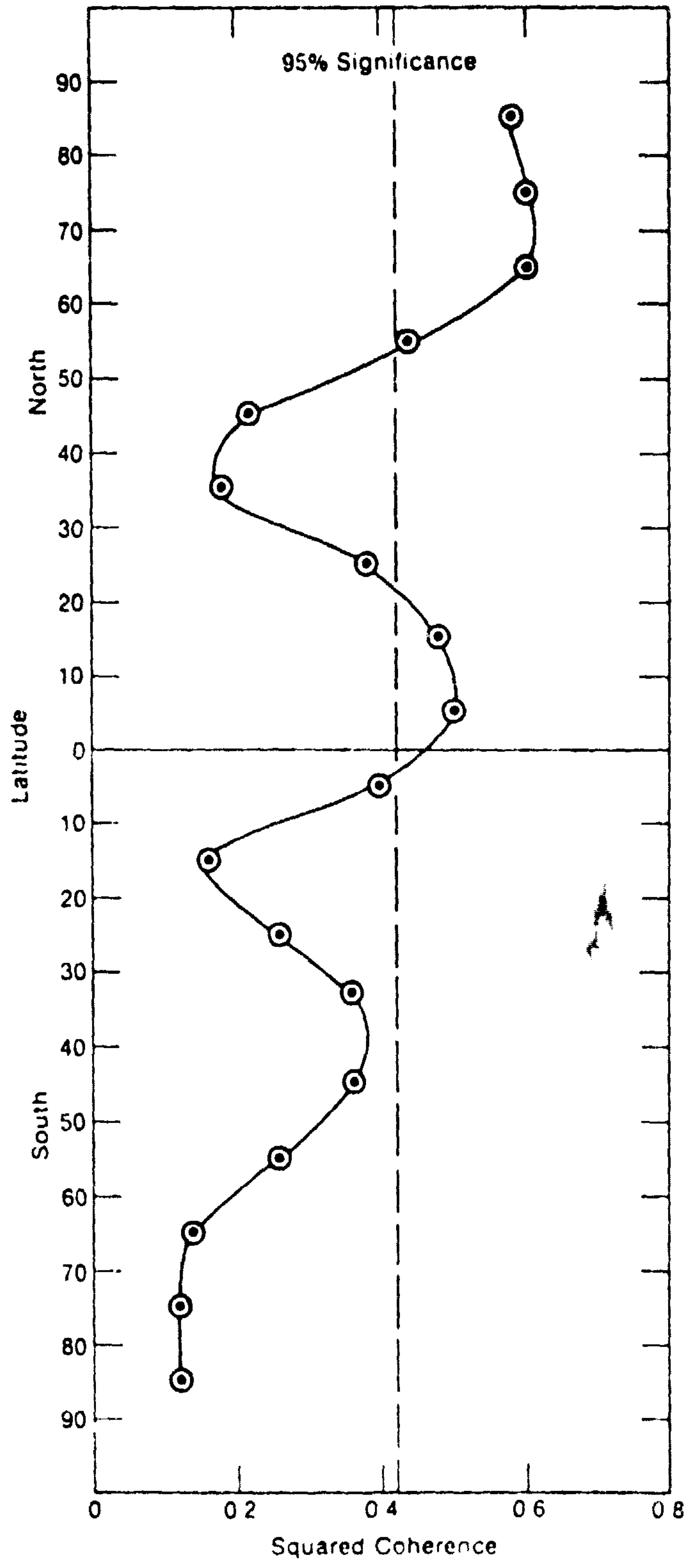

Figure 2. Squared coherence between prewhitened, detrended Balboa 50mb zonal winds and global grid point total ozone data for the period 1964 - 78

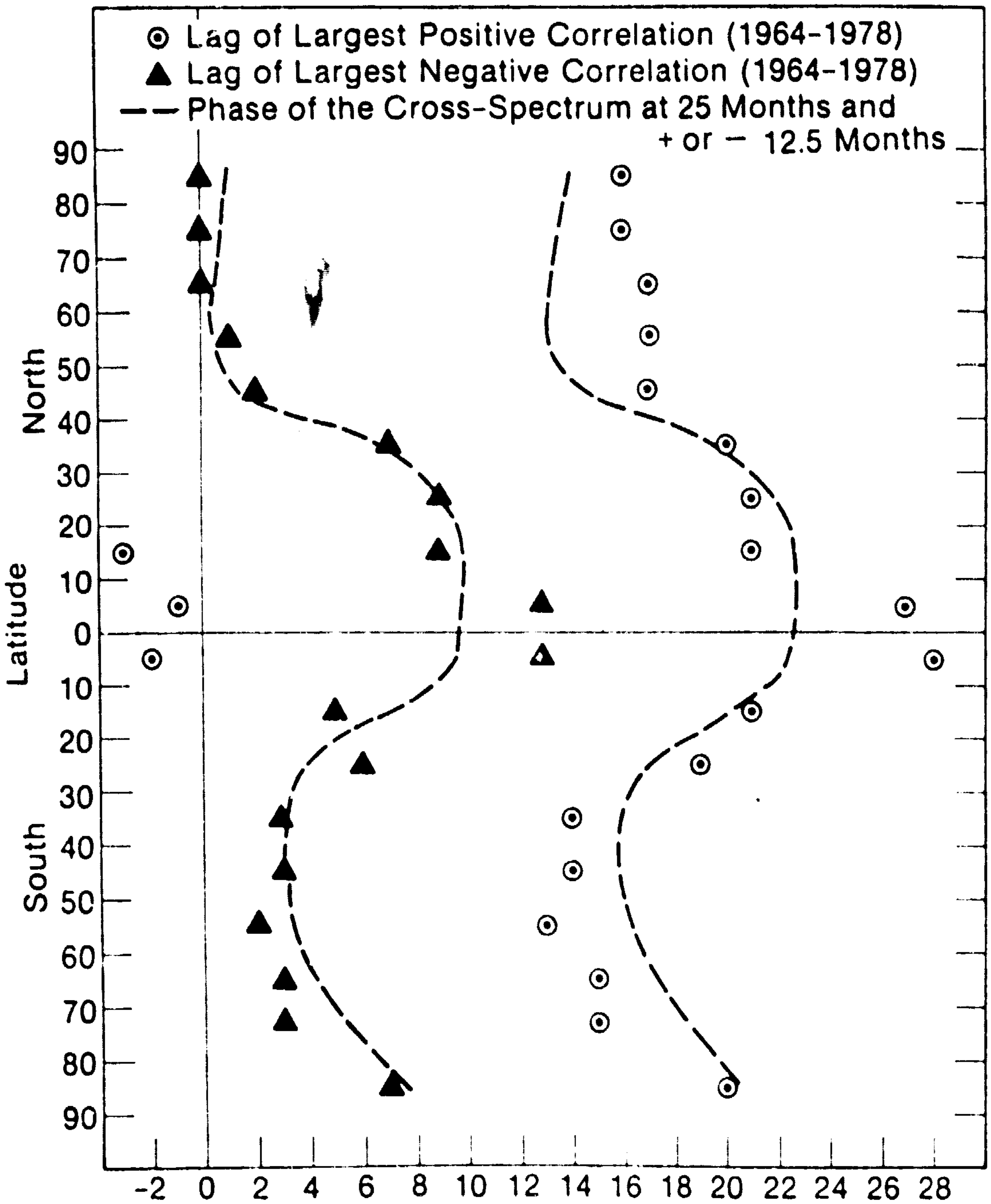

Figure 3: Lag between 50mb zonal wind and grid point total ozone (for positive lag winds lead ozone).