Interhemispheric Asymmetry and Annual Synchronization of the Ozone Quasi-biennial Oscillation

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ABSTRACT

The quasi-biennial oscillation (QBO) in total column ozone has been examined at several tropical stations. The ozone QBO at Mauna Loa (19.5°N) was found to have a remarkable annual synchronization. Both positive and negative extremes in the deseasonalized ozone time series almost always occur between December and March. The annual cycle-QBO phase locking is much more pronounced in this ozone record than it is for the familiar QBO in the prevailing tropical stratospheric winds. This result is taken as evidence that the dynamical QBO acts to modulate a strong seasonal ozone transport from midlatitudes to the tropics. If this transport is connected with quasi-stationary planetary waves, then this interpretation offers an obvious explanation for the interhemispheric asymmetry in the ozone QBO that has been noted in many earlier studies.

1. Introduction

The familiar quasi-biennial oscillation (QBO) of tropical stratospheric temperatures and zonal winds is known to be accompanied by a corresponding oscillation in total column ozone (Ramanathan 1963; Angell and Korshover 1973; Oltmans and London 1982; Hasebe 1983). The ozone QBO in the tropics and subtropics has a clear phase relation with the wind QBO: normally total ozone is a maximum (minimum) about the time of maximum prevailing westerlies (easterlies) at the 50 mb level. The ozone QBO is roughly in phase at all latitudes from about 15°S to 25°N. Poleward of 25°N there is still some quasi-biennial variability in total ozone, but its connection with the tropical QBO may not be quite as clear (e.g., section 3 of Angell and Korshover 1973). It appears that on average the middle and high latitude ozone QBO is 180° out of phase with the tropical variation (Oltmans and London 1982).

The basic explanation for the ozone QBO was advanced by Reed (1964a). He noted that the time of maximum westerly shear at a particular level corresponds to the warmest phase of the temperature QBO on the equator. This should therefore be the time of maximum diabatic cooling near the equator. This diabatic cooling will induce sinking of air parcels through isentropic surfaces (which at low latitudes are nearly horizontal). This descent of the air in the middle stratosphere produces an increase in total column ozone (since at high levels the ozone is replaced by chemical production on rather short timescales). Thus, the maximum total ozone might be expected when the atmospheric column had been displaced farthest downward into the middle stratosphere. This should occur after the descent of the westerly shear zone (i.e. at the time of maximum westerlies in the middle stratosphere). The limited satellite and Umkehr observations available confirm that the ozone QBO is most pronounced in the lower stratosphere (say, below 20 mb; Oltmans and London 1982).

Ling and London (1986) represented these ideas in a fairly sophisticated numerical model of the vertical distribution of equatorial ozone. This model incorporated a realistic photochemistry as well as vertical advection by the diabatic circulation (calculated using a prescribed temperature QBO). Ling and London found that they could account for the observed features of the ozone QBO near the equator when they employed reasonable parameters to treat the radiative transfer and photochemical processes in their model.

While the basic mechanism responsible for the ozone QBO near the equator appears to be well understood, there remain some puzzling features of the ozone observations. The ozone QBO appears to have a significant interhemispheric asymmetry, being stronger on the northern side of the equator than on the southern side. Oltmans and London (1982) found this asymmetry in both global analyses based on monthly mean surface Dobson measurements and total ozone data derived from the results of the backscattered ultraviolet (BUV) experiment on the Nimbus-4 satellite (see Fig. 6 of Oltmans and London 1982).

The interhemispheric asymmetry of the ozone QBO is in striking contrast to the remarkable symmetry of the zonal wind QBO (e.g. Reed 1964b). The wind QBO

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within about 20° of the equator appears to be symmetric between the hemispheres to within a few percent. It is thought that the QBO in zonal mean temperature is very close to that which would be in thermal wind balance with the zonal wind QBO (Reed and Rogers 1962). Thus one would anticipate a temperature QBO that is also very symmetric between hemispheres (the temperature observations themselves are consistent with this supposition; e.g. Reed 1964b). If the radiative effects of the same small temperature perturbation are similar on either side of the equator, then one would suppose that the QBO diabatic circulation would have interhemispheric symmetry as well. Thus it is difficult to account for the large asymmetry seen in the total ozone QBO by appealing only to Reed's mechanism.

One potential cause of the interhemispheric asymmetry is the action of large scale planetary waves in transporting ozone parallel to isentropic surfaces. If the QBO somehow modulated the planetary wave activity this could lead to significant differences in the ozone QBO between the hemispheres, since planetary waves are much stronger in the Northern Hemisphere than in the Southern Hemisphere. Since stratospheric planetary waves are also very strongly modulated by season, one might anticipate some connection between the annual cycle and the ozone QBO. The present paper uses observational data in an attempt to investigate this issue.

Section 2 provides a discussion of the implications of the observed meridional structure of the ozone QBO and suggests how the QBO/annual cycle coupling ought to be reflected in ozone data. The data employed to verify this suggestion are then briefly described in section 3. The data analysis discussed in section 4 will then document a close connection between the annual cycle and the ozone QBO. Conclusions are summarized in section 5.

2. General discussion

The transport of ozone in the stratosphere can be conveniently regarded as a combination of (i) diabatically-induced cross-isentropic (CI) air motion, and (ii) the movement of air along isentropic (AI) surfaces. In a simplified model of the zonal mean stratospheric composition advanced by Holton (1986) the CI transport is envisaged as directly depending only on the zonal-mean diabatic heating, while the AI transport is assumed to include downgradient mixing. In fact, neither of these assumptions can be rigorously justified. Mahlman (1985) showed that the CI transport of a vertically-stratified tracer in midlatitudes can be significantly underestimated when only the zonal-mean diabatic circulation is considered (i.e. when correlations of the eddy components of diabatic motion and tracer concentration are ignored). However, Mahlman also found that the effects of the deviations from zonal symmetry play a less important role in determining the CI transport in the tropics (Mahlman, private communication). In principle, the zonally-averaged AI transport need not produce downgradient mixing. However, the observed slopes of constant mixing ratio surfaces for tracers such as ozone and N_2O can only be understood if the AI transport acts on average to produce downgradient meridional mixing (i.e. it must act to flatten the slopes of the isopleths, see Mahlman 1985; Holton 1986).

In the present discussion it will be assumed that Holton's model provides a valid conceptual view of stratospheric ozone transport. Thus it is supposed that a knowledge of the QBO modulation of temperature allows one to determine the effect of CI transport on the ozone QBO. As discussed above, at the equator one expects the CI transport to cause a maximum in total column ozone coincident with the maximum westerlies in the lower stratosphere. The phase of the temperature QBO changes abruptly by about 180° near 15° latitude (e.g., Reed 1964b). Thus, the effects of CI circulation on the ozone QBO should also reverse poleward of 15°. This must be reconciled with the observation that the ozone QBO is basically in phase between the equator and at least 25°N latitude (Oltmans and London 1982).

In a recent study, Gray and Pyle (1988) forced a QBO in a zonally-averaged dynamical–photochemical model and obtained a QBO in column ozone with an in-phase region that has a slightly wider meridional extent than would be anticipated on the simple basis discussed above. This seems to be due largely to the effects of the cross-equatorial meridional flow in advecting equatorial ozone anomalies poleward. However, their model results still show an equatorially centered ozone QBO at low latitudes, which has a very weak amplitude by 20° latitude. This contrasts with the observations which suggest that the amplitude of the ozone QBO may actually be almost as strong at 20°N as at the equator (e.g., Oltmans and London 1982; Hasebe 1983).

It thus appears likely that the effects of AI mixing may have to be invoked to explain the observed ozone QBO, at least poleward of about 15°. Figure 1 shows an idealized climatology of zonal mean ozone mixing ratio for winter in the Northern Hemisphere. Below about 25 km these ozone isopleths slope downward and poleward with slopes considerably steeper than the isentropes. Thus motions that simply mix air along the isentropes should increase the total ozone at low latitudes and reduce it at higher latitudes (see the heavy arrow in Fig. 1).

Many different mechanisms might contribute to the isentropic mixing needed to explain the ozone QBO, e.g. the dissipation or nonlinear breaking of equatorial waves. However, the prominent equatorial waves in the lower stratosphere are rather well confined to within about ±15° of the equator (e.g., Wallace 1973), and

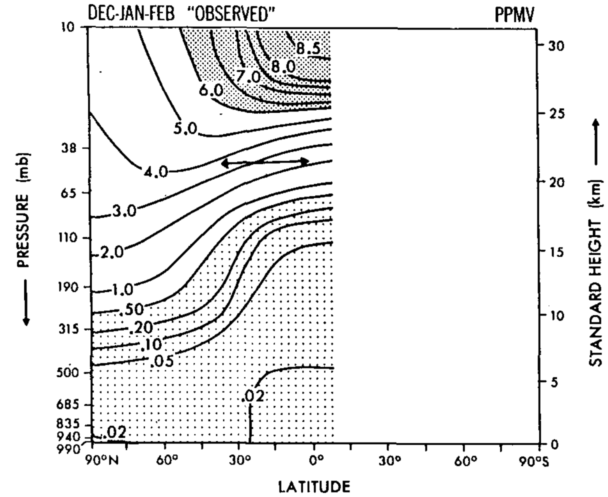

FIG. 1. Climatology of zonal mean ozone mixing ratio for Northern Hemisphere winter. Contours are labelled in parts per million by volume. The heavy arrow is a schematic representation of an isentropic surface. Adapted from Mahlman et al. (1980).

thus any mixing they induce would also be largely restricted to this latitude range. A more attractive candidate for explaining the ozone QBO poleward of 15° is mixing associated with the dissipation or breaking of planetary waves originating in the midlatitude region. When these planetary waves dissipate they might be expected to produce meridional AI mixing. It is quite conceivable that the strength and/or meridional extent of such mixing could be modulated by the QBO in the mean winds, thus allowing the AI transport to contribute to the ozone QBO.

If meridional AI mixing is to explain the observed phase of the QBO in the 15°–25° latitude belt, then ozone transport from higher latitudes ought to coincide with mean westerlies in the lower stratosphere. If this transport extends to even lower latitudes, then it could act to reinforce the effects of the CI transport near the equator. The assumption of a QBO-modulated transport to low latitudes from the region poleward of 25° also offers an obvious explanation for the ozone QBO at higher latitudes (which generally appears to be 180° out of phase with the oscillation in the 0°–25° band).

Unfortunately, it is not clear a priori from dynamical considerations how the modulation of wave transports by the QBO should actually operate. In January during the easterly QBO phase the zero wind line in the 70–20 mb region is typically around 20°–30°N (e.g., §10 of Newell et al. 1974). By contrast, in the westerly phase there may be no zero wind surface at these heights anywhere on the winter side of the equator. Thus one could argue that stationary planetary waves should penetrate into low latitudes much more readily during the westerly phase and hence cause more tropical mixing (as the waves either break or are gradually dissipated). On the other hand, if one imagines that the wave-induced mixing should be strongly concentrated in the vicinity of the zero wind surface then it may actually be in the easterly phase that significant mixing in the 20°–30° latitude belt takes place. As noted above, the empirical evidence favors the first interpretation: i.e. that mixing is enhanced during the westerly QBO phase. This view of the role of AI transport is schematically illustrated in Fig. 2.

Without more detailed theoretical modelling studies, the details of how planetary waves might affect the ozone transport will likely remain obscure. However, given the observed annual cycle of wave activity, it is virtually certain that any such transport will be strongest in winter and will be insignificant in summer. This has implications for the ozone QBO. One might imagine that near the equator the ozone QBO is generated largely by CI transport in the manner envisaged by Reed (1964a). This should result in an ozone oscillation phase-locked in a simple manner with the dynamical QBO. The importance of the planetary wave contribution presumably grows with increasing latitude until (poleward of 15°) the AI transport must account for the entire ozone QBO. The strong annual modulation of planetary wave strength will preclude a simple phase-locking with the wind QBO. In particular, strong

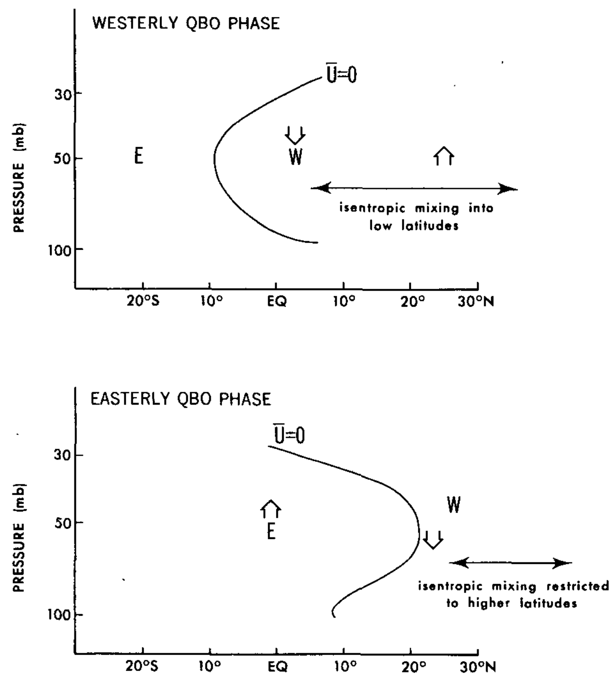

FIG. 2. Schematic diagram showing how the cross-isentropic and along-isentropic (AI) transports may be contributing to the ozone QBO. The top (bottom) panel shows conditions during a boreal winter during the westerly (easterly) phase of the QBO. The wide arrows represent the effects of the QBO-modulated component of the diabatic circulation. The thin arrows are meant to represent the extent of significant AI mixing. In the proposed scheme the AI transport of ozone-rich air from midlatitudes acts to reinforce the maximum in low latitude ozone seen in the westerly phase of the QBO.

increases in ozone in the 15°–25°N latitude band ought to occur only in boreal *winters* when there are westerly mean winds. Thus the ozone QBO maxima might be observed only in winter (or perhaps near the end of winter). When the time series of the total ozone values are deseasonalized in the usual way (i.e. by subtracting the long-term means for each month of the year), this will result in a preference for the minima to also occur in winter. Thus the ozone QBO poleward of 15°, while having *on average* a particular phase with respect to the dynamical QBO, should actually look rather different than the low latitude wind QBO (which is not so strongly coupled to the annual cycle). This anticipated relation between the annual cycle and the QBO will be documented in section 4 below.

The planetary wave-induced AI transport would be expected to be much stronger in the Northern Hemisphere than in the Southern Hemisphere. This provides an obvious explanation for the interhemispheric asymmetry of the ozone QBO. It also suggests that in the Southern Hemisphere the synchronization with the annual cycle may be such that the ozone extremes should tend to occur in austral winter.

3. Data

Studies of long-period variations in ozone amounts are necessarily hampered by data limitations. Satellite observations provide global coverage for relatively brief periods. In order to investigate the nature of annual cycle-QBO coupling it is desirable to have very long records which are available only from surface Dobson stations. The number of such stations equatorward of 25° with reasonably long records is very small. Table 1 gives the positions and record lengths for those Dobson stations judged to be useful for the present study. The actual data employed were the monthly mean total ozone values reported in the publication "Monthly Ozone Data for the World" issued by the Canadian Atmospheric Environment Service in Toronto.

In addition to the ozone values monthly mean values of the 50 mb zonal wind at Singapore (1.3°N, 103.9°E) and Truk (7.6°N, 151.9°E) were employed to characterize the dynamical QBO. These were supplied by the Data Support Section at the National Center for Atmospheric Research in Boulder, Colorado.

TABLE 1. The locations of the Dobson stations where data was employed for this study.

Station	Latitude	Longitude	Period of useful record
Mauna Loa	19.5°N	155.6°W	1965–86
Kodaikanal	10.2°N	77.5°E	1960–82
Huancayo	12.1°S	75.3°W	1964–85
Darwin	12.5°S	130.8°E	1966–74
Samoa	14.3°S	170.6°W	1976–85

4. Analysis

Each ozone record was deseasonalized by subtracting the long term means for each month of the year. Figure 3 shows a five-month running mean of the resulting anomaly time series for Mauna Loa (the unsmoothed time series is rather noisy). The ozone values appear to display a long-term downward trend, although this may well result from drifts in the instrument calibration (e.g., Komhyr and Grass 1972). Of more interest is the well developed QBO seen in the data, with peak-to-peak amplitude of roughly 20 Dobson units (d.u.).

Another remarkable aspect of the QBO in Fig. 3 is the extent to which both the maxima and minima tend to occur in boreal winter. This can be seen explicitly in Fig. 4, which is a histogram showing the calendar month when the clear extremes in Fig. 3 occur. All of the extreme negative anomalies and all but one of the positive extremes occurred between December and March. In fact the "QBO" in Fig. 3 may be better thought of as a succession of two-year cycles punctuated by occassional three-year cycles (i.e., January to January of 1966–69, 1975–78, and 1980–83). This is just the kind of behavior predicted by the arguments given in section 2.

There is no guarantee that the Mauna Loa results are representative of the zonal mean. However, the satellite-derived total ozone climatology of Prabhakara et al. (1976) reveals that (at least in the long term mean) the ozone distribution at 20°N is fairly close to being zonally symmetric. A comparison of the Mauna Loa station data with a time series of 20°N satellite-derived zonal mean ozone mixing ratio is discussed at the end of this section.

It remains to demonstrate that the coupling with the annual cycle is actually stronger for the Mauna Loa ozone QBO than for the tropical wind QBO itself. Figure 5 shows five month running means of the deseasonalized time series of zonal wind at Singapore (1.2°N), and Fig. 6 is a histogram similar to Fig. 4 but for the Singapore winds. There is some indication of coupling with the annual cycle (most extremes occur between September and February), but it is not as striking as for the Mauna Loa ozone. For example, if one looks at the easterly extremes in Fig. 5, one finds they seem to occur near boreal winter for the first part of the record (i.e., February 1966, January 1969, November 1970, November 1972), but then start wandering throughout the year (i.e., March 1975, August 1977, January 1980, June 1982, September 1984). A similarly complicated picture emerges if one uses the month nearest the zero crossings in Fig. 5 to characterize the phase of the QBO (many crossings early in the record occur in April–June, but later there are two in January and one each in December, March and September).

In conclusion, there does seem to be some kind of connection of the QBO and annual cycle in the Sin-

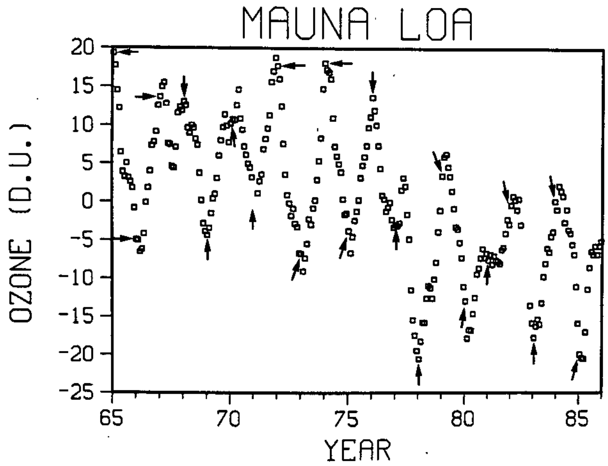

FIG. 3. Time series of anomalies in monthly mean total ozone values measured at Mauna Loa (19.5°N, 155.6°W). The anomaly is defined as the monthly value minus the long term mean for the appropriate month of the year. The ordinate is labeled in Dobson units. The results plotted are smoothed with a five-month running mean. The arrows point to the value for each January.

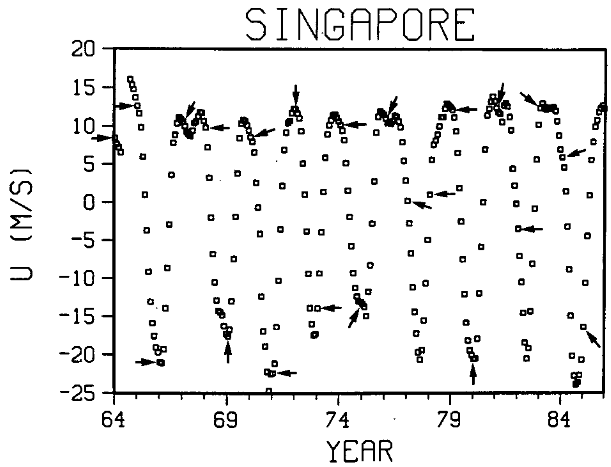

FIG. 5. Time series of monthly mean zonal 50 mb wind at Singapore (1.3°N, 103.9°E) deseasonalized and smoothed as in Fig. 3.

gapore winds, but (in contrast to the Mauna Loa ozone record) it is not so strong that one could reasonably regard the oscillation in Fig. 5 simply as a series of two and three year cycles. An examination of the zonal wind time series at Truk (not shown) led to the same conclusion.

The only other long Dobson record in the tropics of the Northern Hemisphere is from Kodaikanal (10.2°N). Unfortunately, the data at this station (not shown) appear to be very much contaminated by spurious trends and discontinuities, which complicate any interpretation. No very clear connection between the QBO and annual cycle can be seen in this record. The results do clearly demonstrate that the total ozone QBO has a smaller amplitude at Kodaikanal than at Mauna Loa (perhaps 10–15 d.u. peak-to-peak). This meridional gradient in the amplitude is consistent with the earlier results of Oltmans and London (1982).

In the Southern Hemisphere tropics the only very long record is from Huancayo (12.1°S). Unfortunately, these data (not shown) also suffer from apparently spurious discontinuities and trends. However, a weak QBO (less than 10 d.u. peak-to-peak) can still be discerned. The asymmetry in amplitude between Kodaikanal and Huancayo (at similar latitudes but in different hemispheres) suggests that the AI transports significantly influence the ozone QBO even at Kodaikanal.

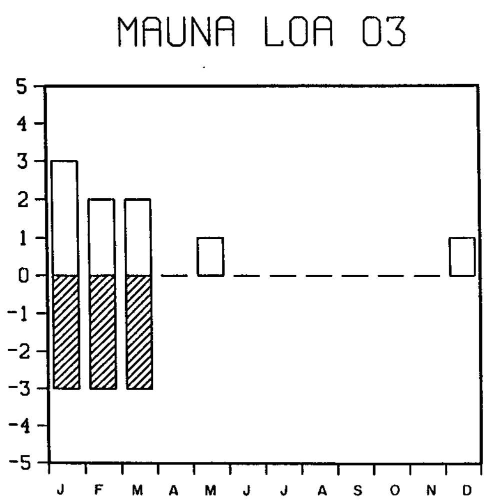

FIG. 4. Unshaded histogram gives the number of occasions when a clear maximum in the time series of Fig. 3 occurred in each month of the year. The shaded bars give the same information for the clear minima in Fig. 3.

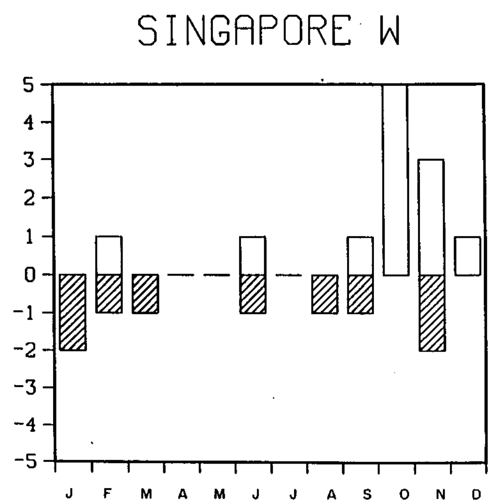

FIG. 6. As in Fig. 4 but for the Singapore wind time series.

As far as one can tell (given the small signal and serious data problems) the timing of the maxima and minima in the Huancayo series is very different from that seen at Mauna Loa. In particular, there is no tendency for the extrema to occur preferentially in December–March. This is confirmed by inspection of the shorter, but higher-quality ozone records at Darwin (12.5°S; Fig. 7) and Samoa (14.3°S; Fig. 8). At these stations there appears to be an overall tendency for the extrema to occur in the middle of the year (i.e. around austral winter), although the phase-locking with the annual cycle is much less evident than it is at Mauna Loa (and the clear identification of extrema is less straightforward). The phase relation between QBO at Darwin/Samoa and that at Mauna Loa is also rather variable. Much of the time Darwin/Samoa seems to lead Mauna Loa by about six months, while at other times Mauna Loa leads by about the same amount. It is also striking that at all those times when the clear extrema at Darwin/Samoa *do* occur in boreal winter (i.e. January 1969, January 1974, January 1979, February 1984 and February 1985) the Darwin/Samoa QBO is almost exactly one year *out of phase* with that at Mauna Loa. Thus at any particular time the Mauna Loa and Darwin/Samoa ozone QBOs are virtually never in phase. This fact suggests that the mechanisms generating the ozone QBO in the two hemispheres have considerable independence. It also emphasizes the complexity of the structure of the ozone QBO relative to that of the wind QBO.

Ling and London (1986) presented seven years (April 1970–May 1977) of zonally averaged ozone mixing ratios for the 22–27 km level determined from satellite BUV observations. Their Figure 1 gives the deseasonalized time series of this mixing ratio for 10° latitude intervals. The phase of their 20°N results compare well with that of the total ozone series at Mauna Loa shown in the present paper. In particular maxima in the 20°N satellite data are apparent in February 1972, February 1974 and February 1976; minima appear in February 1971, February 1973 and December 1974. This synchronization with the annual cycle is much less evident in the satellite results at the equator. The satellite observations show only a weak QBO at 10°S and 20°S, but one in which extrema are often observed in the middle of the year (i.e. at 20°S a maximum occurs in September 1973, and a minimum in August 1975). All of this is consistent with the picture of the QBO deduced from the single station data discussed earlier.

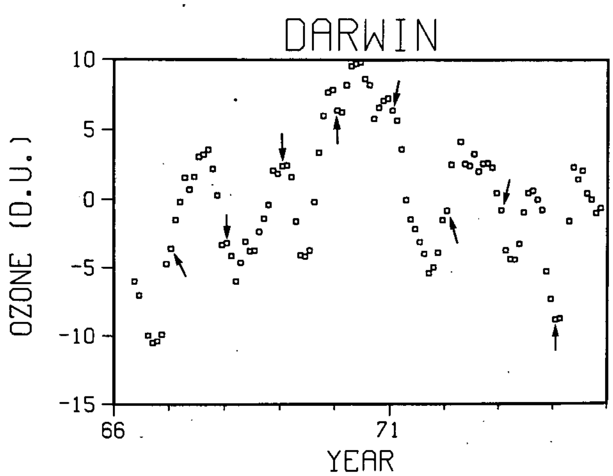

FIG. 7. As in Fig. 3, but for ozone observations at Darwin (12.5°S, 130.8°E).

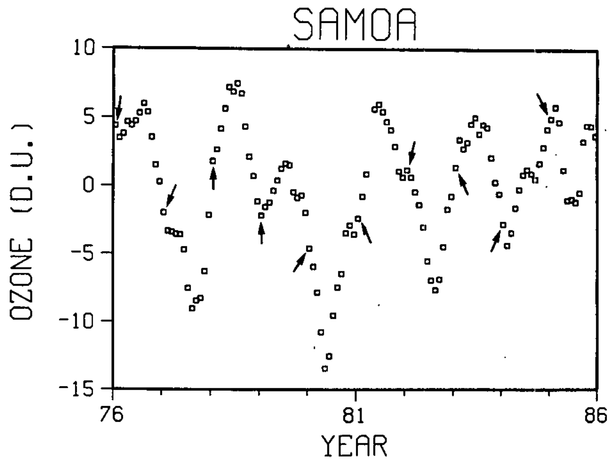

FIG. 8. As in Fig. 3, but for ozone observations at Samoa (14.2°S, 170.6°E).

5. Conclusion

The Mauna Loa (19.5°N) total ozone time series (as well as the satellite observations for 20°N) can be explained if the wind QBO acts as a "gatekeeper" allowing strong penetration of waves into the tropics (and associated AI mixing) only during the westerly phase. In particular, the strong annual synchronization of the Mauna Loa time series is consistent with this view. The results for the total ozone series at Darwin (12.5°S) and Samoa (14.3°S) are less regularly related to the annual cycle, but the general tendency is for an annual synchronization consistent with a significant planetary wave-induced mixing.

The data analysis presented here has been very simple, but it does suggest some wide-ranging conclusions. In particular it seems difficult to avoid the implication that the most efficient AI mixing across the 25°N latitude circle occurs when there are westerlies throughout the tropical middle stratosphere (rather than when there is a zero wind line in the vicinity of 20°N). Given the difference in ozone QBO amplitude between 10°N and 10°S, it seems likely that the AI mixing plays a role in generating the ozone QBO at least as far south as 10°N.

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