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Long-term variations in the characteristics of the equatorial stratospheric zonal winds

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सार – समतापमंडलीय भूमध्यरेखीय क्षेत्रीय पवनों में 1951 से लेकर वर्तमान समय तक विशेषकर उच्चतर स्तर पर प्रचुर रूप से दीर्घ अवधि परिवर्तन पाए गए है। कभी-कभी ये एकदिष्ट होते हैं लेकिन प्रायः इनसे सूर्य के धब्बों के चक्र (11 वर्ष में परिवर्तन) सहित बहु-आवधिक संरचनाओं का पता चलता है। समतापमंडलीय तापमान और भूविभव ऊँचाइंयों से भी बहु-आवधिक परिवर्तनों का पता चलता है। प्रायः इनकी लगभग 20 वर्ष की आकृति देखने में आती है।

ABSTRACT. Stratospheric equatorial zonal winds from 1951 onwards up to the present show considerable long-term variations, more so at higher levels. These are rarely monotonic and often show multi-periodic structures, including a sunspot cycle (11 year variations). Stratospheric temperatures and geopotential heights also show multi-periodic variations. A periodicity near 20 years is encountered often.

Key words – Stratosphere, Equatorial winds, Long term variation, QBO, Sunspot cycle.

1. Introduction

Zonal winds in the equatorial stratosphere show a predominant quasi-biennial oscillation (QBO), first observed by Reed *et al.* (1961), Veryard and Ebdon (1961) and Angell and Korshover (1962). Several updates followed, (for example, the one by Naujokat, 1986) which described the characteristics of the observed QBO at various altitudes. A theoretical explanation was proposed by Holton and Lindzen (1972). Takahashi and Boville (1992) simulated the QBO using a three dimensional mechanistic model of the stratosphere. Angell (1986) studied the variations in the periods and amplitudes of the QBO during 1951-85 and their relationship with volcanic eruptions (Agung, El Chichon) as also with El Nino phenomena and solar activity. He concluded that it is not possible to state with confidence whether the observed time variations of QBO period were due to variations in equatorial sea-surface temperature or changes in solar activity or alterations in stratospheric temperature and thermal wind associated with volcanic eruptions. For 30 hPa level, Naujokat (1986) mentioned for 1953-85, an average value of –6 m/s for mean zonal wind. In this note, we examine whether the mean zonal wind and its easterly and westerly components show any long-term variations from 1951 onwards.

2. Data

The zonal wind monthly values used are mostly from Pawson *et al.* (1993) (henceforth referred to as PW) and further data sent to us kindly by Dr. Barbara Naujokat. The zonal wind time series are compiled from data at three stations:

Station	*Location*	*Time period*
Canton Island	172°W 3°S	1953-67
Gan, Maldive Island	73°E 1°S	1967-75
Singapore	104°E 1°N	1974 onwards

for 70, 50, 30, 20 and 10 hPa, with values at 40 and 15 hPa interpolated in pressure scale heights.

3. Procedure of analysis

Fig. 1 illustrates the procedure of analysis we adopted. The top plot shows the monthly means of the 50 hPa level zonal wind. The numbers 2-20 indicate the QBO cycle numbers as defined in Dunkerton and Delisi (1985) (the first cycle observed at Balboa begins in 1952). The large fluctuations represent the QBO (Quasi-biennial oscillation) with 18 peaks in 42 years, yielding an average

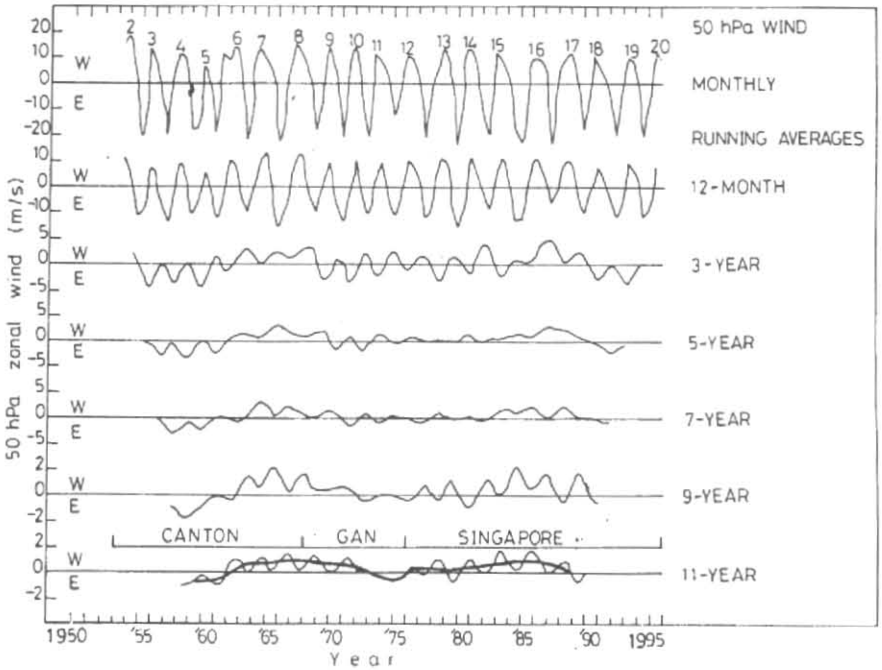


Fig. 1. Plot of monthly values of PW 50 hPa zonal wind (Pawson *et al.*, 1993) and their running averages over 12-months and 3, 5, 7, 9, 11 years (Westerly positive, Easterly negative)

peak spacing of ~2.33 years (28 months). The next plot shows the 12-month running averages, 2 values per year, centered 6 months apart. The seasonal effect is eliminated but the QBO persists. The next plot shows 6 values (3-year) running averages. The QBO still persists, with smaller amplitudes. Further plots are 10 value (5-year), 14 value (7-year), 18 value (9-year) and 22 value (11-year) running averages. The QBO is now almost eliminated, though a small amplitude QBO fluctuation persists. Further running averages over 4 successive (6-monthly) values show the smooth variation plotted as a thick line on the last (11-year mean) plot. A smooth variation of ~1 m/s is seen.

Could this be because of a mixture of data from three stations? We do not think so, for two reasons. Firstly, the data for the last 20 years (1975-95) are of Singapore alone and show fluctuations of ~1m/s, same as for earlier period for Canton and Gan. Secondly, several authors have mentioned that stratospheric zonal wind data from different low latitude locations show almost similar characteristics (Naujokat, 1986; Barnston and Livezey, 1989). Dunkerton (1990) compared the 50 hPa data plots for Singapore (1° N, 256° W *i.e.* 104° E), Balboa (9° N, 80° W) and Ascension (8° S, 14° W) and showed that good agreement exists between the three stations, though the amplitude of the QBO is somewhat larger at Singapore (nearer to equator). Also, the zero crossings of the Singapore plot of Dunkerton (1990) are almost the same (within a month or two) as those for the PW data plots shown in our Fig.1, even for period before 1975 when our data refers to canton and Gan. Maruyama (1991) reported a similar match. It may be noted, however, that Angell (1986, 1988) reported some differences between Balboa (9° N) and Ascension (8° S) which were related to the effect of volcanic eruption of Agung in 1963.

4. Running averages

Let us examine now whether the variation shown in Fig. 1 for 50 hPa level is seen at other levels also. Fig. 2(a) upper part shows the plots of 5 year running averages and the lower part shows plots of 11-year running averages, for 10, 15, 20, 30, 40, 50 and 70hPa. For levels 40hPa and above, the 5 year running averages are negative, indicating larger strength of the easterlies. For 50 hPa, easterlies and westerlies have roughly similar strengths while for 70 hPa, westerlies dominate. However, at all levels, the averages have considerable time variations, not similar to each other. The 11-year averages show larger variations of an oscillatory nature for higher levels (10, 15, 20, 30 hPa), a striking up trend for 40 hPa, a small oscillation for 50 hPa

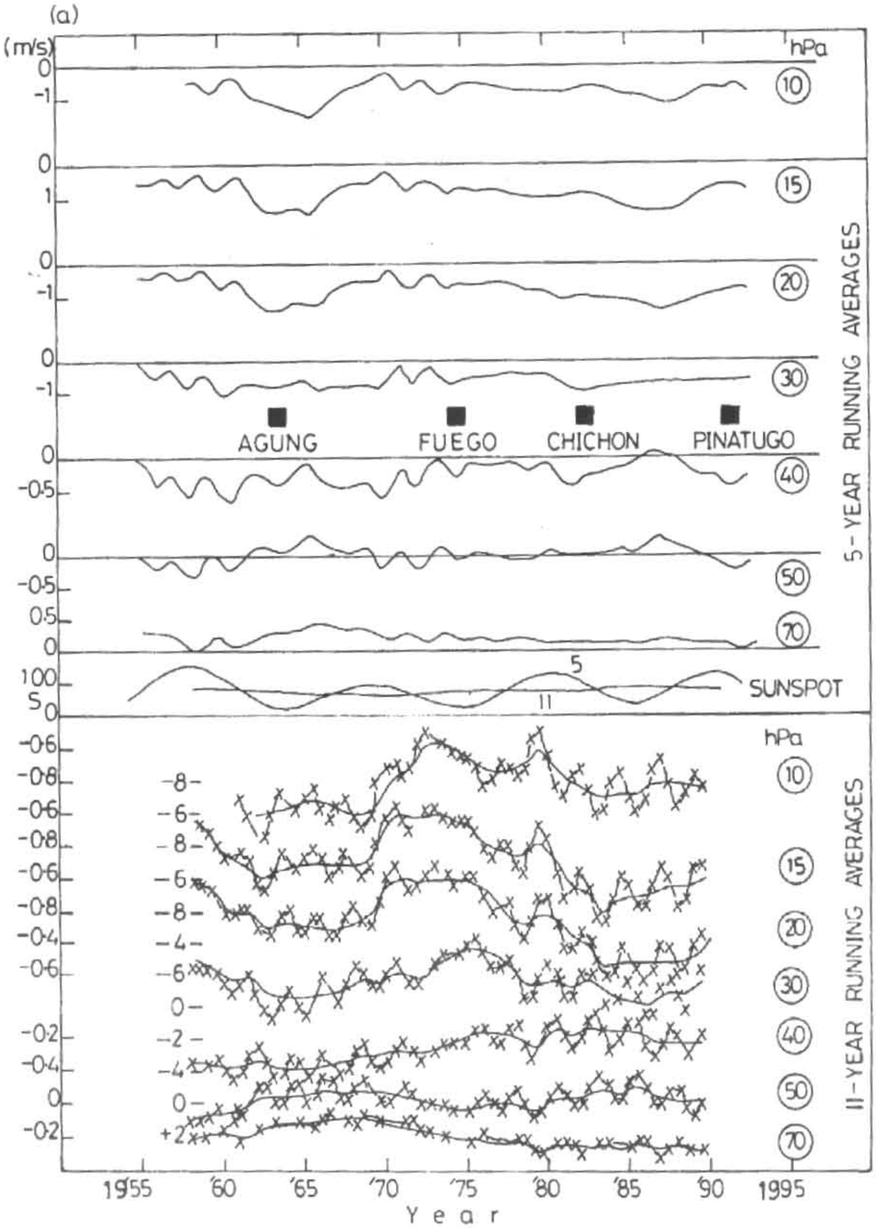


Fig. 2(a). Upper part, 5-year running averages; Lower part, 11-year running averages, for 10, 15, 20, 30, 40, 50, 70 hPa zonal wind. Full squares indicate occurrences of volcanic eruptions Agung (1963), Fuego (1974), Chichon (1982) and Pinatubo (1991). Plots in the middle show 5-year (full line) and 11-year (thick line) averages of sunspot number

and mainly a dowtrend for 70 hPa. The full squares mark the presence of volcanic eruptions Agung (1963), Fuego (1974), Chichon (1982) and Pinatubo (1991). No specific relationships with these are discernible, either because none exist or because the effects may have been obliterated due to averaging over 5 years. Recently, Dr. Angell kindly sent us zonal wind data for Ascension, Balboa and Singapore for 10, 30, 50 hPa. Fig. 2(b) shows the plots of 5-year and 11- year running averages for these three locations (ASC, BAL, SING) as also for the PW data. For each level, the four plots are remarkably similar, indicating that these variations are genuine and, the magnitudes are larger at higher levels.

Recently, Fraedrich *et al.* (1993) calculated the EOFs (Empirical orthogonal functions) of the time development of the spatial structure of zonal wind using the PW data. We read out the amplitudes of EOFs 1 and 2 of their Fig. 6

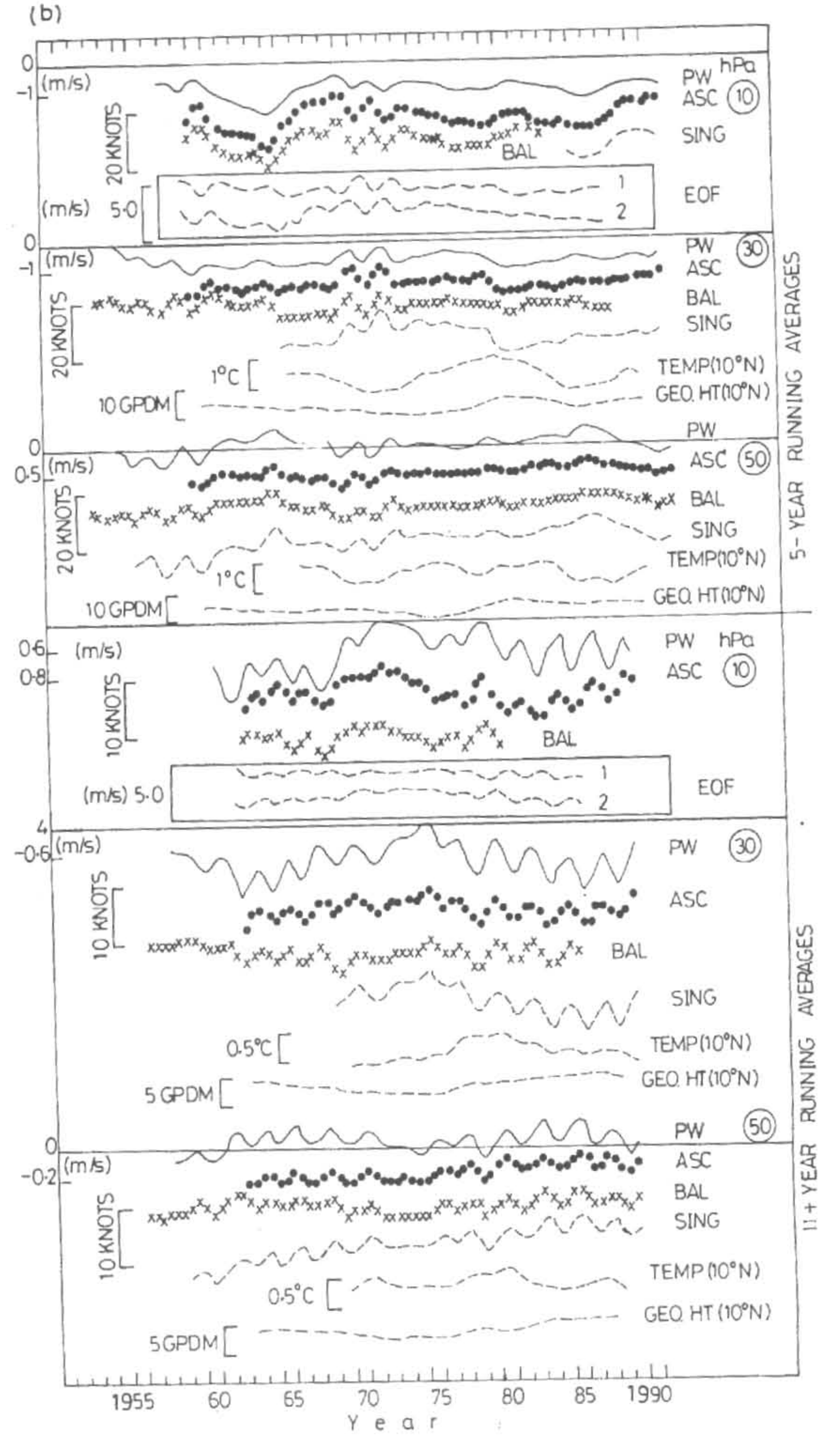


Fig. 2(b). Upper part, 5-year running averages; Lower part, 11-year running averages of zonal wind for PW d[illegible] and for individual locations Ascension (ASC), Balboa (BAL) and Singapore ([illegible]ING) for 10, 30, 50 hPa. In the 10 hPa panels, the amplitudes of EOF analysis (1 and 2) (Fraedrich *et al.*, 1993) are shown. In the 30, 50 hPa panels the corresponding level temperatures and geopotential heights (PW data) are shown

TABLE 1

Correlation coefficients and Regression coefficents between zonal wind series (y) and time only ($y = a_o + at$), Sunspots only ($y = a_o + bS$) and both simultaneously ($y = a_o + at + bS$)

5-year running averages	Simple regression $y = a_o + at$		Simple regression $y = a_o + bS$		Bivariate regression $y = a_o + at + bS$		
	Corre. Coeff.	a(m/s/10 years)	Corre. Coeff.	b(m/s/100 sunspot)	Multiple Corr. Coeff.	a(m/s/10 years)	b(m/s/100 sunspot)
70 hPa	-.40	-.35** ± .09	-.28	-.71** ± .28	+.49	-.36 ± .09	-.75** ± .26
50 hPa	+.25	+.33* ± .15	-.52	-1.96** ± .38	+.57	+.30* ± .13	-1.93** ± .37
40 hPa	+.46	+.73** ± .17	-.33	-1.53** ± .52	+.56	+.72* ± .16	-1.45** ± .46
30 hPa	-.12	-.21 ± .21	+.08	+.40 ± .60	+.14	-.20* ± .20	+.38 ± .60
20 hPa	-.49	-1.53** ± .32	+.37	+3.34** ± 1.00	+.60	-1.49** ± .30	+3.18** ± .86
15 hPa	-.35	-1.14** ± .35	+.45	+4.19** ± .99	+.56	-1.09** ± .32	+4.07** ± .93
10 hPa	+.05	+.14 ± 37	+.34	+2.87** ± .99	+.34	-0.01 ± .36	+2.88* ±1.00
11-year running averages							
70 hPa	-.67	-.50** ± .07	-.68	-4.45** ± .62	+.86	-.40** ± .05	-3.61** ± .45
50 hPa	+.23	+.18 ± .10	-.16	-1.08 ± .88	+.31	+.22* ± .10	-1.54 ± .88
40 hPa	+.72	+.83**± .10	+.25	+2.52* ± 1.27	+.73	+.81** ± .11	+.83 ± .93
30 hPa	-.05	-.07 ± .17	+.21	+2.34 ± 1.44	+.20	-.01 ± .17	-2.33 ± 1.49
20 hPa	-.52	-1.15** ± .24	-.48	-9.37** ± 2.21	+.65	-.95** ± .23	-7.40** ± 2.02
15 hPa	-.44	-.89** ± .24	-.49	-8.80** ± 2.01	+.59	-.70** ± .22	-7.40** ± 1.93
10 hPa	+.30	+.60* ± .26	-.18	-2.91 ± 2.19	+.52	+1.18** ± .28	-8.42** ± 2.32

*indicates significance at 2° level and ** at higher levels

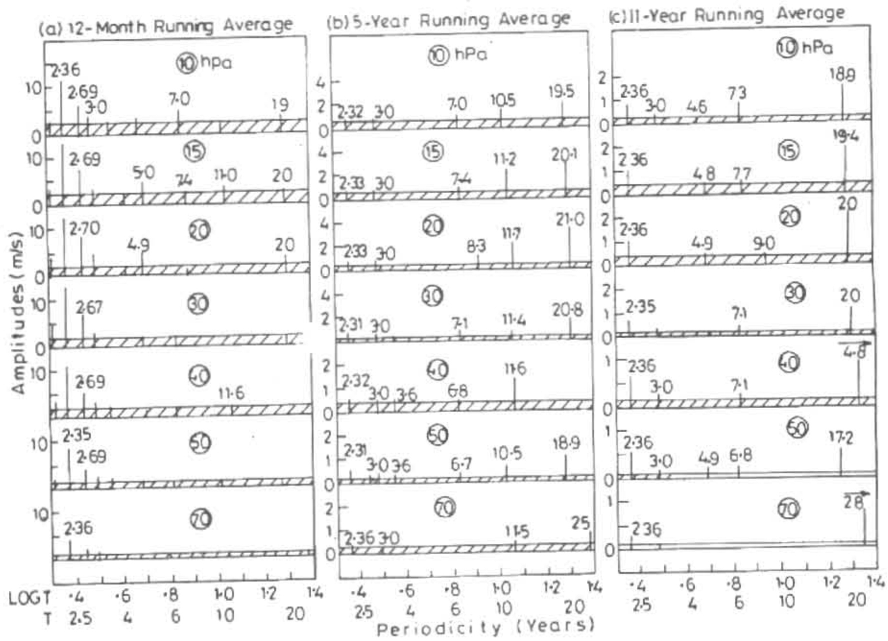
and, in our Fig. 2(b), the 5-year and 11-year averages of EOF 1 and 2 are plotted in the panels referring to 10 hPa. There are considerable variations in EOF 1 and 2 amplitudes.

For the same period, PW (pages 292, 293) have given the 10°N temperature and geopotential height plots for 30, 50, 100 hPa. In Fig. 2(b) we show the .. ear and 11-year running averages of the temperature and geopotential height (at 10°N) in the 30 and 50 hPa panels. These two parameters also show considerable time variations.

5. Linear trends and sunspot cycle relationship

Are these fluctuations related to sunspot cycle? The middle part of Fig. 2(a) shows a plot of 5 -year (thin line) and 11-year (thick line) running averages of the sunspot numbers. We carried out a correlation analysis between these plots and (a) time (to determine linear trends) and (b) sunspot number. Table 1 shows the results. The simple regression with time shows generally low correlations (less than 0.5). But the linear trends represented by the coefficient a (expressed as m/s/10 years) are often significant at a 2σ level (marked as *) or even better (marked as **) and are up trends in some cases and dowtrends in others. For simple regression with sunspots also, the correlations are generally small. But the regression coefficients represented by b (expressed as m/s/100 sunspots) are often significant at a 2σ or better level and are positive in some cases and negative in others. When a bivariate analysis is carried out, the correlations improve but rarely exceed 0.6. However, linear trends are significant at all levels except 30 hPa and are positive (overall uptrend) for 50, 40, 10 hPa and negative for 70, 20, 15 hPa for the 11-year averages. Overall, the rather low correlations are unsatisfactory, indicating that just linear trends and/or solar cycle relationships do not explain fully the observed variations.

For 30 and 50 hPa, we had temperature and geopotential height data as plotted in Fig. 2(b). We



Figs. 3(a-c). MESA results (Amplitudes) of the various periodicities located in MESA for (a) 12-month running averages, (b) 5-year running averages and (c) 11-year running averages of zonal wind at 10, 15, 20, 30, 40, 50, 70 hPa. Note that the abscissa scale is logarithm of periodicity T. The hatched portion marks de 2σ limit

correlated these with the wind data at the same l. 'els. The correlations were as follows:

	Temperature	*Geopotential height*
30 hPa wind (5 year averages)	−.14 ± .13	−.66 ± .08
30 hPa wind (11 year averages)	−.01 ± .13	−.67 ± .08
50 hPa wind (5 year averages)	−.03 ± .13	+.13 ± .13
50 hPa wind (11 year averages)	−.05 ± .13	+.39 ± .11

Thus, only 30 hPa winds and geopotential heights have some negative relationship.

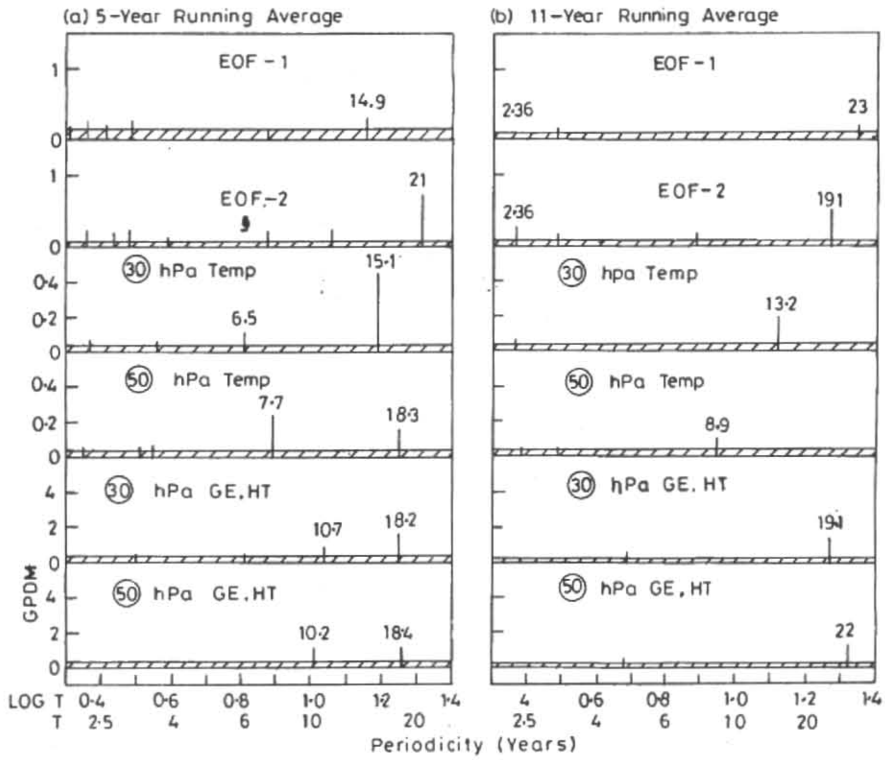
6. Power spectrum analysis

A different approach would be to do a Power Spectrum Analysis, for which we used MESA (Maximum Entropy Spectrum Analysis, Burg 1967; U' ch and Bishop, 1975). MESA detects periodicities much more accurately than the conventional method BT (Blackman and Tukey, 1958). In BT, only certain frequencies (k/2m) can be studied where k = 1, 2, ... , m and m = lag, and the recommended lag is ~25% or less of the data length. Thus, in a 100 point data series, only periods of 50 or less can be studied in BT. In MESA, there is no such restriction and periodicities even near the data length can be studied. However, the amplitude estimates in MESA are not very accurate (Kane and Trivedi, 1982). Hence, we used MESA only for locating possible peaks T_k (k = 1 to n) and then, these T_k were used in the expression:

$$f(t)=A_o+\sum_{k=1}^{n}\left[a_k\sin\left(2\pi t/T_k\right)+b_k\cos\left(2\pi t/T_k\right)\right]+E$$

$$=A_o+\sum_{k=1}^{n}\left[r_k\sin\left(2\pi t/T_k+\phi_k\right)\right]+E \qquad (1)$$

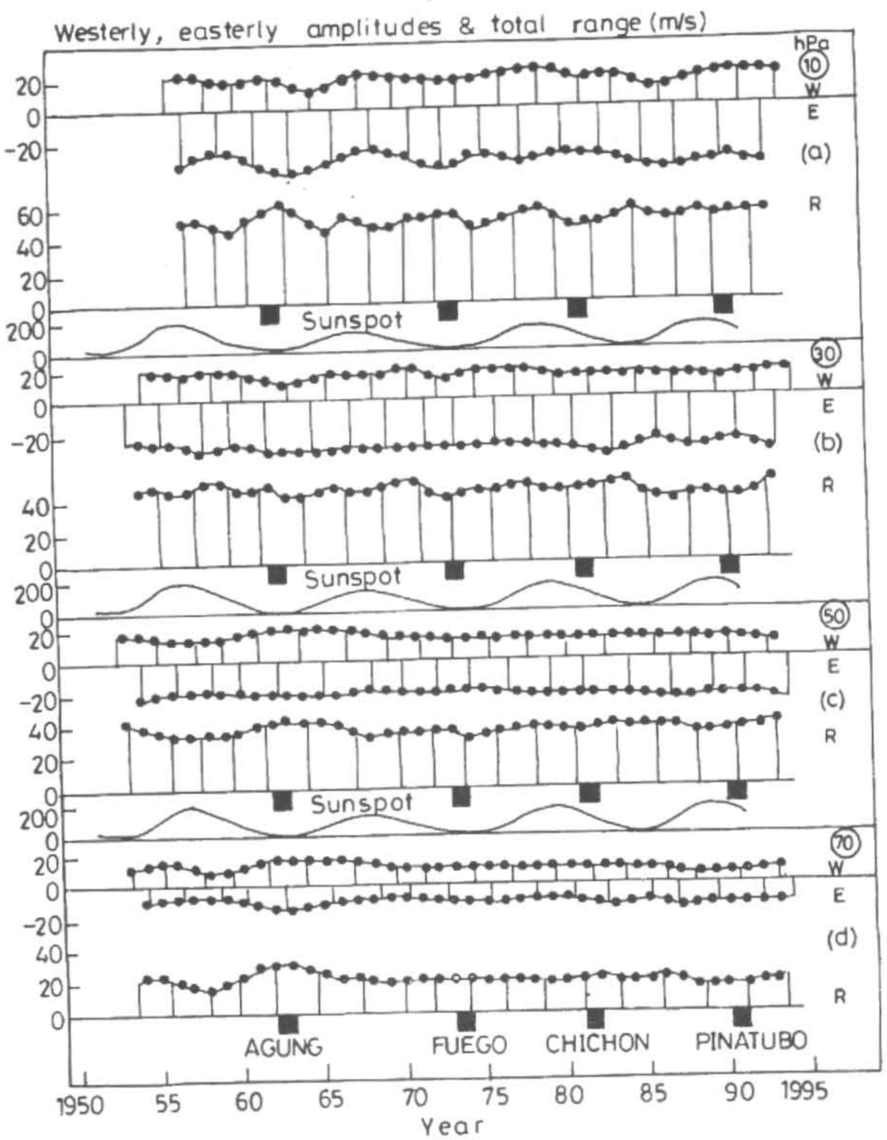
Where $f(t)$ is the observed time series and E is the error factor. A Multiple Regression Analysis (Bevington, 1969) was then conducted to get the best estimates (by a least square fit) of A_o, (a_k, b_k), and their standard errors. From these r_k and their standard error σ_k (same for all r_k in this methodology) can be calculated and r_k exceeding $2\sigma_k$ can be considered as significant at a 95% a priori confidence level. In MESA, there is a parameter LPEF (Length of the Prediction Error Factor) somewhat equivalent to lag m in BT. We used LPEF = 50% of the data length.



Figs. 4(a&b). MESA results for EOF 1 and 2 for temperature and geopotential height at 30 and 50 hPa for (a) 5-year running averages and (b) 11-year running averages

Fig. 3 shows a plot of the amplitudes of periodicities at various levels. Fig. 3(a) refers to analysis of the 12-monthly means series (2 values per year). As expected, all levels show QBO, the most prominent wave being at $T = 2.36$ years (~28 months) and a subsidiary one at $T = 2.69$ years (~32 months). Thus, the QBO region has a doublet structure. There are also 2 smaller periodicities *viz.* $T = 2.10$ ant $T = 3.00$ in the same region. Since MESA is very accurate in this region, this fine structure is genuine. The $T = 2.36$ years periodicity has amplitudes of 12.0, 13.0, 12.9, 12.9, 10.7, 8.6 and 4.4 m/s at 10, 15, 20, 30, 40, 50, 70 hPa respectively while $T = 2.69$ has amplitudes 6.7, 7.8, 8.0, 6.7, 5.8, 4.6 and 2.1 m/s. PW have mentioned that the QBO spacing was ~26 months in the sixties but increased to ~28 months in recent years. To check changes in the doublets, the 20 hPa data were divided into two equal parts. The 1953-74 and 1975-95 parts showed $T = \sim 2.35$ year with amplitudes 10.9 and 18.9 respectively while $T = \sim 2.7$ years showed amplitudes 8.4 and 2.7. Thus, the amplitudes and relative proportions of these two components seem to change considerably with time. There are, of course, other periodicities of smaller amplitudes near $T = 5.0$, 7.0, 11.0 and 20 years. In MESA, amplitudes of any periodicity are generally not affected by the presence of other periodicities. However, since QBO amplitudes are overwhelmingly large, some effect on amplitudes of other periodicities could have occurred. To bring out the larger periodicities better, MESA was applied to the 5-year running averages. Fig. 3(b) shows the results. The QBO has been almost eliminated and periodicities near $T = 7$, 11 and 20 years appear prominently. Thus, a solar cycle (11-year) association seems to be present at all levels and the reason for the low correlations in Table 1 should be the presence of other periodicities (notably $T = 7$ and 20 years).

Fig. 3(c) shows results of MESA of the 11-year averages. As expected, the 11-year peaks have disappeared. The small peaks near T = 5 and 7 years are probably side lobes of no consequence. Curiously, a small QBO reappears at all levels. The main peaks in Fig. 3(c) are near T = 17-21 years. This was obvious from Fig. 2(a) lower part where waves of large periodicity are seen at 10, 15, 20, 30 and 50 hPa. For 40hPa, there are no waves [Fig. 2(a)] but there is a long-term upward trend, which shows up in MESA as a very large periodicity (T=48 years). Similarly, for 70 hPa, the rise from 1958 to 1967 and the fall thereafter in Fig. 2 (a) (bottom), shows up in MESA [Fig. 3(c)] as a large periodicity of $T = 28$ years. The effect



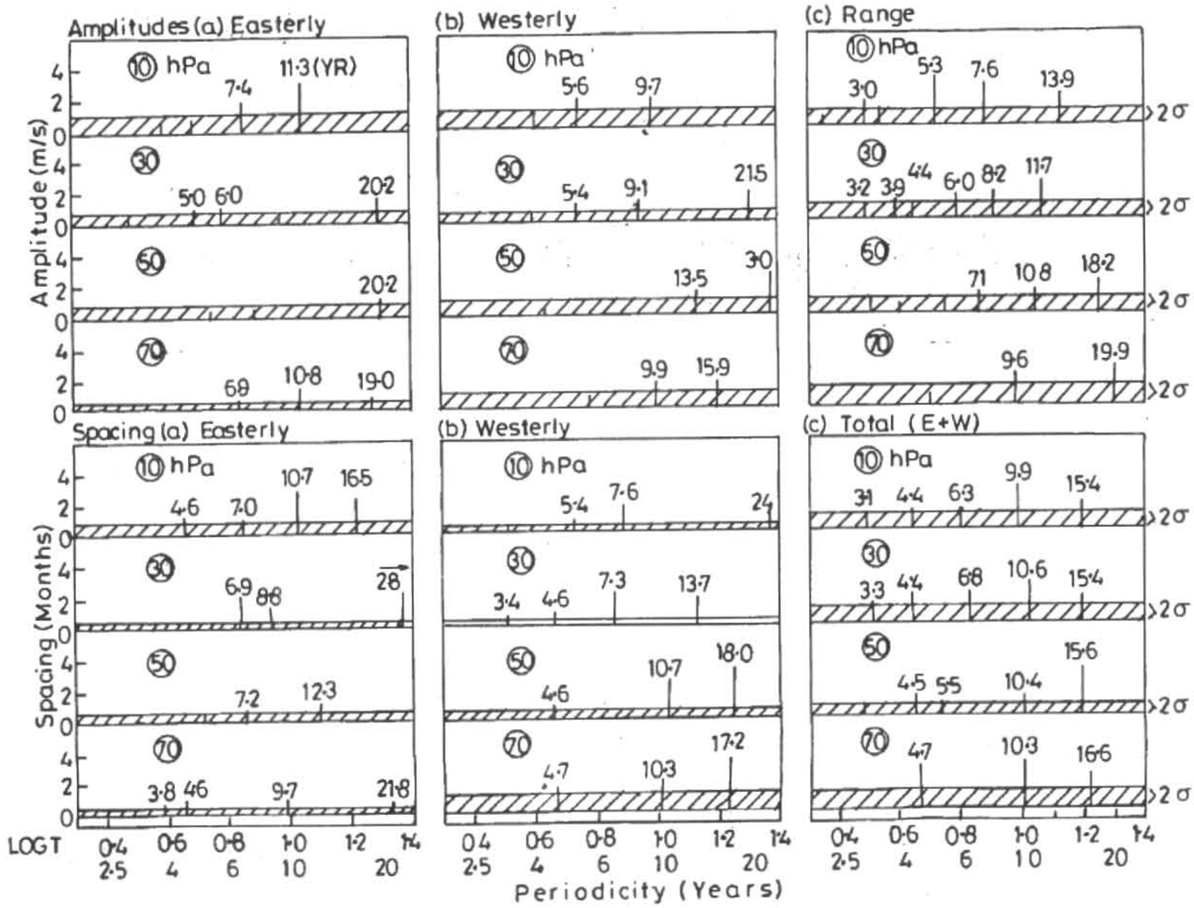
Figs. 5 (a-d). Maximum velocities of the westerly (positive) and easterly (negative) zonal wind modes and the total range for (a) 10 hPa, (b) 30 hPa, (c) 50 hPa, (d) 70 hPa. Full squares indicate volcanic eruptions. Smooth, thick lines show annual sunspot numbers

of trends on MESA has been studied in detail in Kane and Trivedi (1986), where it is shown that large trends have virtually no effect on smaller periodicities; but larger periodicities can be greatly distorted and even simple linear trends may appear as large periodicities comparable to the data length. In the present case, Fig. 2(a) and Fig. 3(c) indicate that oscillations of ~20 years seem to have occurred in the mean zonal wind, with ranges up to 0.5 m/s.

Fig. 4 shows the MESA results for EOF 1 and 2 temperature and geopotential heights. Many significant periodicities are seen.

7. Analysis of the easterly and westerly modes

The mean zonal wind we have studied so far is a mean of two heterogeneous quantities *viz.* the vectorial sum of easterly and westerly regimes following each other.



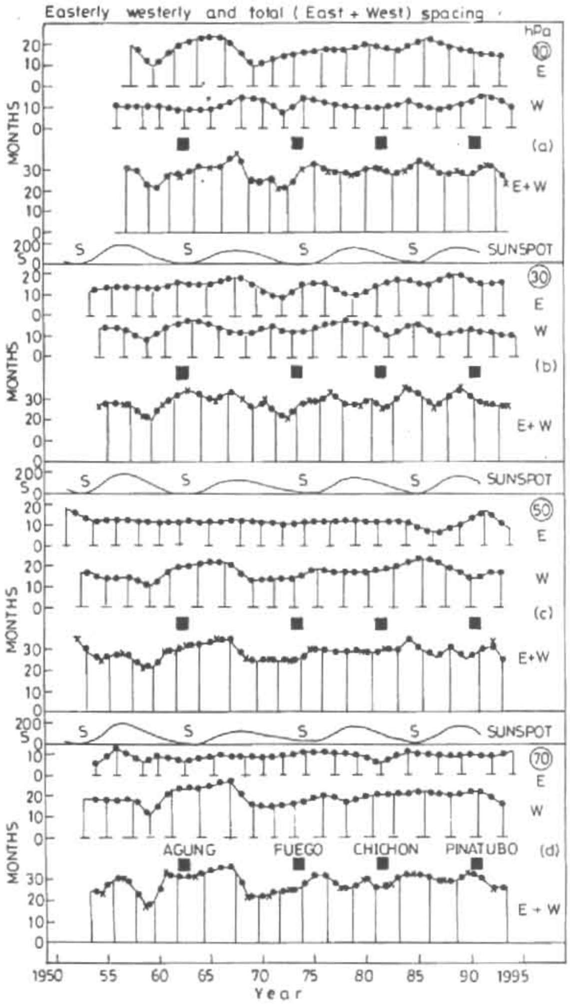
Figs. 6(a-c). MESA results for amplitudes (upper half) and spacings (lower half) for (a) easterly, (b) westerly and (c) total (east + west) for 10, 30, 50, 70 hPa

Thus, changes in the mean wind would be caused by changes in the easterly or westerly wind modes or both. In Fig. 1, two main characteristics of each mode are: the spacing and the amplitudes. We now examine the long-term changes in each of these and other parameters.

(*i*) *Amplitude variations*

Fig. 5 shows a plot of the maxima of the velocities of the westerly and easterly modes for 10, 30, 50, 70 hPa. Fig. 5(a) refers to 10 hPa. Angell (1986) gave similar plots for earlier periods. The present ones are updates of the same. In the top plot, the vertical lines show the amplitudes, above zero line for westerly and below zero line for easterly. The horizontal separation between successive vertical lines is, of course, not uniform. But, the tips of the successive vertical lines are joined by straight lines, separately for the westerly and easterly amplitudes and the values at uniform (yearly) separations are marked by full circles. For 10 hPa, the westerly amplitudes show depressions near 1965 and 1987 in an otherwise steady level. On the other hand, the easterlies show oscillatory structure throughout. The Range *R viz.* easterly maximum to westerly maximum (followed by *vice-versa*) is also shown and shows an oscillatory structure. The full squares show the occurrence of volcanic eruptions and do not seem to be related to the wind variations. A plot of the sunspot number is also shown. A direct correlation analysis between wind and sunspot showed very low correlations, indicating no relationship or interference by other factors. Hence, we carried out a Power Spectrum Analysis of all these series in Fig. 5(a) as also in Figs. 5(b - d) which refer to 30, 50, 70 hPa.

Fig. 6 (upper half) shows the MESA results of the yearly series of (a) easterly, (b) westerly amplitudes and (c) the Range for the four selected levels 10, 30, 50, 70 hPa. In the easterly amplitudes, periodicities 5-7 years,



Figs. 7(a-d). Easterly (E) and Westerly (W) mode spacings and their sum (E + W) for (a) 10 hPa, (b) 30 hPa, (c) 50 hPa and (d) 70 hPa. Volcanic eruptions (full squares) and sunspot cycles (thick smooth lines) are shown

~11 years and ~20 years are significant above the 2σ level marked hatched. In the westerlies, about 5 years, 9 years and some higher periodicities are significant and the periodicity 30 year in 50 hPa westerly amplitude could be due to a long-term downtrend. In the Range (*R*), many periodicities are significant, throwing into doubt their meaningfulness. The sunspot cycle (~11 years) is seen sometimes and is certainly not the major periodicity in any series.

(ii) Spacing variations

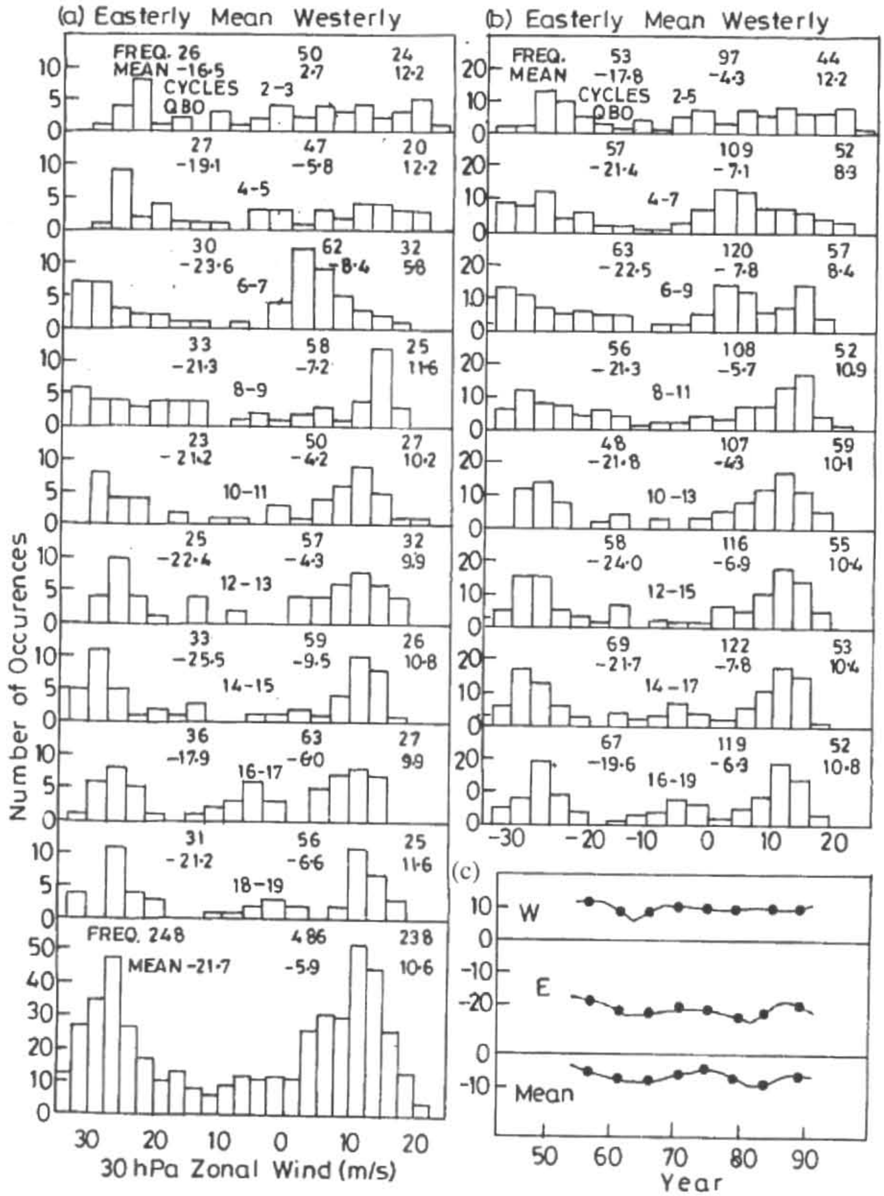
Fig. 7 shows a plot of the easterly and westerly spacing and the total spacing (E+W). Considerable fluctuations are seen from year to year. Correlations with sunspot numbers were low and no specific relationship with volcanic eruptions (black squares) is discernible. Results of a Power Spectrum Analysis are shown in the lower half of Fig. 6. There are many significant periodicities (above the 2σ level marked hatched), mostly around 4-5, 6-7, 9-10 and ~15 years. Thus, there is an indication of a sunspot cycle (~11 years); but many other periodicities are equally important. The origin of these needs further exploration.

(iii) Variations in the bimodal distribution

As mentioned by Naujokat (1986), the frequency distribution of the zonal wind component is bimodal with two clearly separated peaks. For the 30 hPa level, the two peaks for the mean distribution for 1953-85 were symmetrical with respect to the mean of –6 m/s. Recently, PW (page 282) have presented updated distributions for 10, 30 and 50 hPa. We examined the 30 hPa original monthly value distributions averaged over 2 successive QBO cycles (~4.5 years). Fig. 8(a) shows the distributions for QBO cycles 2-3, 4-5, 6-7, 8-9, 10-11, 12-13, 14-15, 16-17 and 18-19. As can be seen, the patterns change considerably from one epoch to the next and are often very different from the average two peaked structure for the whole period shown at the bottom of Fig. 7(a). To improve the statistics, two successive plots in Fig. 8(a) were averaged to give averages for 4 QBO cycles (~9 years) with an overlap of ~4 years. These are shown in Fig. 8(b) for QBO cycles 2-5, 4-7, 6-9, 8-11, 9-13,12-15, 14-17 and 16-19. Again, considerable variations in patterns are seen and a X^2-test showed some of these significantly different (at a 95% level) from the average pattern showed at the bottom of Fig. 8(a). In Fig. 8(a), the numbers indicate the total frequencies and the average values for easterlies, westerlies and their mean. For example, in the average curve at the bottom, 248 easterlies had a mean value of –21.7 (m/s), 238 westerlies had a mean value of +10.6 (m/s) and the general mean of 486 values was –5.9 (m/s). These mean values changed considerably with time, as shown in Fig. 8(c), more so for easterlies than for westerlies.

8. Conclusions

(*i*) The mean value of the zonal wind showed considerable changes with time. The changes were rarely monotonically upward or downward and were mostly oscillatory and different at different altitudes. Spectral analysis showed significant periodicities in a large range and often included a sunspot cycle (~11 years).



Figs. 8(a-c). Bimodal distributions of zonal wind at 30 hPa level (a) averaged over two successive QBO cycles 2-3, 4-5, ... , 18-19 and the average plot for all cycles, (b) averaged over four successive QBO cycles with an overlap of two cycles, 2-5, 4-7, ..., 16-19, (c) Plots of the westerly, easterly and mean winds

(*ii*) The amplitudes and spacing of the easterly and westerly modes also showed periodic structures, often including the sunspot cycle.

(*iii*) The bimodal distributions changed considerably from one QBO cycle to next, specially the easterly mode.

The reasons for all these changes need further exploration. The longer periodicities may be indicative of climatic changes. A periodicity near 20 years seems similar to a solar magnetic cycle (22 years), though a connection between the two seems difficult to explain.

Regarding the origin of the wind QBO, the Holton and Lindzen (1972) model was based on two modes, an eastward propagating Kelvin wave and a westward propagating Rossby-gravity wave and was able to produce an oscillation similar to the observed one. However, Lindzen and Tsay (1975) soon recognized that an additional equatorial easterly gravity wave mode was required to account for the observed easterly acceleration of the QBO. Recently, Dunkerton (1997) showed that if a suitable spectrum of mesoscale gravity wave is added to the observed Kelvin and Rossby-gravity waves, the combined zonal forcing can produce a realistic QBO. Alexander and Holton (1997) presented a model study of zonal forcing in the equatorial stratosphere by convectively induced gravity waves. Gęller *et ql.* (1997) made one-dimensional calculations for the evolution of the stratospheric QBO for time-varying equatorial Kelvin and mixed Rossby-gravity waves. Some of the features of QBO detected in the present study may have origin in tropospheric perturbations.

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References

Alexander, M. J. and Holton, J. R., 1997, "A model study of zonal forcing in the equatorial stratosphere by convectively induced gravity waves", *J. Atmos. Sci.*, **54**,3, 408-419.

Angell, J. K., 1986, "On the variation in period and amplitude of the Quasi-biennial oscillation in the equatorial stratosphere, 1951-85", *Mon. Wea. Rev.*, **114**, 2272-2278.

Angell, J. K., 1988, "Variations and trends in tropospheric and stratospheric global temperatures 1958-87", *J. Climate*, **1**, 1296-1313.

Angell, J. K. and Korshover, J., 1962, "The biennial wind and temperature oscillation of the equatorial stratosphere and their possible extension to higher latitudes", *Mon. Wea. Rev.*, **90**,127-132.

Barnston, A. G. and Livezey, R. E., 1989, "A closer look at the effect of the 11-year solar cycle and the Quasi-biennial oscillation on the Northern hemisphere 700 hPa height and extratropical North American surface temperature", *J. Climate*, **2**, 1295-1313.

Bevington, P. R., 1969, "Data reduction and error analysis for the physical sciences", McGraw-Hill Book Co., New York, 164-176.

Blackman, R. B. and Tukey, J. W., 1958, "The measurements of power spectra", Dover, New York, p190.

Burg, J. P., 1967, "Maximum Entropy Spectral Analysis. Paper presented at the 37th meeting", Society of Exploration Geophysics, Oklahoma City, October.

Dunkerton, T. J., 1990, "Annual variation of deseasonalized mean flow acceleration in the equatorial lower stratosphere", *J. Meteor. Soc. Japan*, **68**, 499-508.

Dunkerton, T. J., 1997, "The role of gravity waves in the Quasi-biennial oscillation", *J. Geophys. Res.*, **102**(D22), 26053-26076.

Dunkerton, T. J. and Delise, D. P., 1985, "Climatology of the equatorial lower stratosphere", *J. Atmos. Sci.*, **42**, 376-396.

Fraedrich, K., Pawson, S. and Wang, R., 1993, "An EOF analysis of the vertical-time delay structure of the Quasi-biennial oscillation", *J. Atmos. Sci.*, **50**, 3357-3365.

Geller, M. A., Shan, W., Zhang, M. and Tan, W. W., 1997, "Calculation of the stratospheric Quasi-biennial Oscillation for time-varying wave forcing", *J. Atmos. Sci.*, **54**, 7, 883-894.

Holton, J. R. and Lindzen, R. S., 1972, "An updated theory for the quasi-biennial cycle of the tropical stratosphere", *J. Atmos. Sci.*, **29**, 1076-1080.

Kane, R. P. and Trivedi, N. B., 1982, "Comparison of Maximum Entropy Spectral Analysis (MESA) and Least-Squares Linear Prediction (LSLP) methods for some artificial samples", *Geophysics*, **47**, 1731-1736.

Kane, R. P. and Trivedi, N. B., 1986, "Effects of linear trend and mean value on maximum entropy spectral analysis", *Proc. Ind. Acad. Sci. (Earth Planet. Sci.)*, **95**, 201-208.

Lindzen, R. S. and Tsay, C. Y., 1975, "Wave structure of the tropical stratosphere over the Marshall Islands area during 01 April –01 July, 1958", *J. Atmos. Sci.*, **32**, 2008-2021.

Maruyama, T., 1991, "Annual and QBO-synchronized variations of lower-stratospheric equatorial wave activity over Singapore during 1961-89", *J. Meteor. Soc. Japan*, **69**, 219-231.

Naujokat, B., 1986, "An update of the observed Quasi-biennial oscillation of the stratospheric winds over the tropics", *J. Atmos. Sci.*, **43**, 1873-1877.

Pawson, S., Labitzke, K., Lenschow, R., Naujokat, B., Rajewski, B., Wiesber, N. and Wohlfart, R. N., 1993, "Climatology of the Northern Hemisphere Stratosphere derived from Berlin Analyses. Part 1: Monthly Menas", Meteorologische Abhandlungen des Instituts fur Meteorologie der Freien Universitat Berlin, Neue Folge Serie A Monographien Band 7/Heft 3.

Reed, R. J., Campbell, W. J., Rasmusson, L. A. and Rogers, D. J., 1961, "Evidence of a downward propagating annual wind reversal in the equatorial estratosphere", *J. Geophys. Res.*, **66**, 813-818.

Takahashi, M. and Boville, B. A., 1992, "A three-dimensional simulation of the equatorial Quasi-biennial oscillation", *J. Atmos. Sci.*, **49**, 1020-1035.

Ulrych, T. J. and Bishop, T. N., 1975, "Maximum Entropy Spectral Analysis and auto-regressive decomposition", *Rev. Geophys. Space Phys.*, **13**, 183-200.

Veryard, R. G. and Ebdon, R. A., 1961, "Fluctuations in tropical stratospheric winds", *Meteor. Mag.*, **90**, 125-143.