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Spectral characteristics of the quasi-biennial oscillation of total Ozone

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सार— 50 hPa निम्न अक्षांश क्षेत्रीय वायु के 12 महीने के परिचालित माध्यों और अक्षांश क्षेत्रों अर्थात् एन. पी. (उत्तरी ध्रुवीय), एन. टी. (उत्तरी शीतोष्ण), टी. आर. ओ. (उष्णकटिबंधी), एस. टी. (दक्षिण शीतोष्ण) और एस. पी. (दक्षिण ध्रुवीय) के कुल ओज़ोन मानों का 18 वर्षों के दो क्रमिक कालखंडों नामतः-1958-1975 और 1976-1993 में अलग-अलग स्पेक्ट्रल विश्लेषण किया गया है। 1958-1975 के कालखंड में वायु वेग 2.45 वर्षों से अधिकतम था किन्तु 1.98 और 3.05 वर्षों में दो बार अपेक्षाकृत कम किन्तु उल्लेखनीय रूप से अधिकतम था। ओज़ोन केवल एन. पी., एन. टी. और एस. टी. क्षेत्रों में लगभग समान रूप से अधिकतम (2.37, 2.41, 2.48 वर्षों) था जबकि टी. आर. ओ. और एस. पी. क्षेत्रों में यह भिन्न भिन्न रूप में अधिकतम (2.27 और 2.12 वर्षों) था। 20-21 माह में सभी ओज़ोन श्रृंखलाएँ उल्लेखनीय रूप से अधिकतम थीं जो कि वायु श्रृंखला में स्पष्ट रूप से महत्वपूर्ण थी। ओज़ोन की चरम सीमा 3-5 वर्ष के बैंड में भी पाई गई हैं। 1976-1993 के कालखंड में पैटर्न भिन्न थे।2.51 वर्षों में वायु में केवल एक अधिकतम चरम सीमा थी। एन. पी., एन. टी. और एस. टी. क्षेत्रों में ओज़ोन लगभग समान रूप से अधिकतम (2.41, 2.45, 2.45 वर्षों) था जबकि टी. आर. ओ. और एस. पी. क्षेत्रों में चरम सीमा (2.32 और 2.29 वर्षों) भिन्न थी। 20-22 महीनों और 3-5 वर्ष के बैंड में सभी ओज़ोन श्रृंखलाएं विशिष्ट रूप से चरम बिन्दु पर थीं किन्तु ये वायु श्रृंखलाओं में विद्यमान नहीं थीं। 3-5 वर्ष के बैंड संभवतः एन्सो प्रभावों को इंगित करते हैं। वायु और ओज़ोन के मध्य व्यति सहसंबंध के विश्लेषण से पता चलता है कि टी. आर. ओ. के नियम पूर्वी वायु नियम के समान थे जबकि 4 और 6 ऋतुओ में एन. टी., एस. टी. और एन. टी., एन. पी. क्षेत्र चरणबद्ध विस्थापित थे।

ABSTRACT. The 12-month running means of the 50 hPa low latitude zonal wind and total ozone values for the latitude zones NP (North Polar), NT (North Temperate), TRO (Tropical), ST (South Temperate), SP (South Polar) were subjected to spectral analysis, separately for the two successive 18 year intervals, 1958-1975 and 1976-1993. In the interval 1958-1975, the wind had a prominent peak at 2.45 years and two smaller but significant peaks at 1.98 and 3.05 years. For ozone, only NP, NT and ST had roughly similar peaks (2.37, 2.41, 2.48 years), while TRO and SP had different peaks (2.27 and 2.12 years). All ozone series had significant peaks at 20-21 months, barely significant in the wind series. Ozone peaks were noticed in the 3-5 years band also. In the interval 1976-1993, the patterns were different. The wind had only one prominent peak at 2.51 years. For ozone, NP, NT, ST had roughly similar peaks (2.41, 2.45, 2.45 years) while TRO, SP had different peaks (2.32 and 2.29 years). All ozone series had significant peaks at 20-22 months and in the 3-5 year band; but these were absent in the wind series. The 3-5 year band probably indicates ENSO effects. A cross-correlation analysis between wind and ozone showed that TRO maxima coincided with westerly wind maxima, while NT, ST and NT, NP were phase shifted, by 4 and 6 seasons.

Key words—Total ozone, Quasi-biennial Oscillation, Spectra.

1. Introduction

It is known since long that the stratospheric low latitude wind has a quasi-biennial oscillation (QBO) which is reflected in total ozone (Funk and Garnham 1962). Angell and Korshover (1976) made a global analysis of total ozone, updated later by Angell and Korshover (1983). Hasebe (1983) used filtered data from Nimbus 4 backscattered ultraviolet (BUV) and ground-based observations and reported a poleward phase propagation in the northern and southern mid-latitudes. Zerofos *et al.* (1992) also reported a poleward phase propagation but at half the speed. Yang and Tung (1994) used a regression model to obtain the ozone QBO pattern from TOMS data and showed little evidence of a gradual phase propagation. In a later analysis, Yang and Tung (1995) gave more details of the ozone QBO signal. It is strongest in the middle and high latitudes and is present

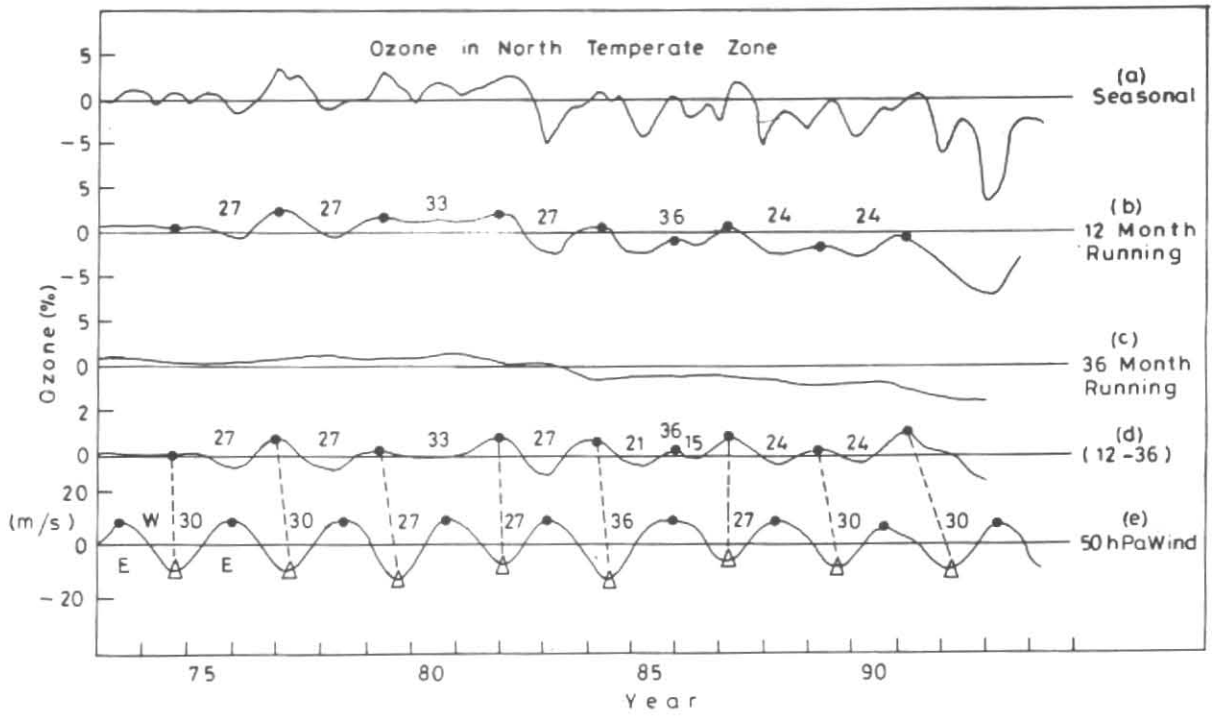

Fig.1. Plot of the total ozone values in the NT (North Temperate) zone, (a) 3-monthly means, for seasons DJF, MAM, JJA, SON, (b) 4 season (12-month) running means, (c) 12 season (36-month) running means, (d) (12-36) *i.e.*, difference between 4 season (12-month) and 12 season (36-month) running means. (e) Plot of the 12-month running means of the 50 hPa low latitude (Singapore) zonal wind. (westerly, positive; easterly, negative). The numbers indicate spacings in months, between successive peaks

mainly in the winter-spring season in both hemispheres, with no gradual phase propagation from the subtropical to the high-latitude region.

Before comparing and QBO and ozone QBO phases, it is necessary to check whether the spectral characteristics of the two are similar. In this communication, we present a detailed spectral analysis of the wind data and the ozone data from ground-based observations, compiled and supplied to us by Dr. Angell.

2. Data

The ozone data are in the form of per cent deviations of seasonal total ozone (*i.e.* deseasoned averages) for the four seasons DJF, MAM, JJA, SON, for broad regions North Polar (about 8 stations), North Temperate (North America, Europe, Asia and Soviet Union, about 65 stations), Tropical (about 8 stations), South Temperate (about 7 stations), South Polar (3 or more stations). Fig.1 shows a sample plot for the North Temperate region for 1973 onwards. The top plot (a) for the 4 seasonal values per year indicates fluctuations of only about 5% during a year (the values are deseasoned), a steady background up to about 1982, and a decrease thereafter. When the data are smoothed by obtaining 12 month (4 season) running means, the values are as shown in Fig.1(b). Some peaks are seen, with spacings in the range 27-39 months, *i.e.*, a QBO, but not very regular. Fig.1(c) shows running means over 12 seasonal values. It depicts a smooth variation, devoid of QBO but representing higher periodicities, including the solar cycle and, of course, the long-term trend which is a steady level up to about 1981 and a gradual decrease thereafter (hockey-stick model). If these 12 season (36 month) means are subtracted from the 4 season (12 month) means, the residues, termed as (12-36) hereafter, are shown in Fig.1(d). The long-term trend and high periodicities have been eliminated and QBO has been isolated in a simple way. The spacings between the peaks in Fig.1(d) are exactly the same as in Fig.1(b), indicating that this procedure does not distort the QBO pattern. Fig.1(e) shows the 4 season (12 month) running means of the 50 hPa low latitude (mostly Singapore, see Pawson *et al.*, 1993) winds (westerly positive, easterly negative). Here, the peak spacing is in a narrower range (27-36 months). The ozone maxima [dots on the plot of Fig.1. (d) seem to be roughly coincident with the easterly wind maxima (triangles on the plot of Fig.1.(e)].

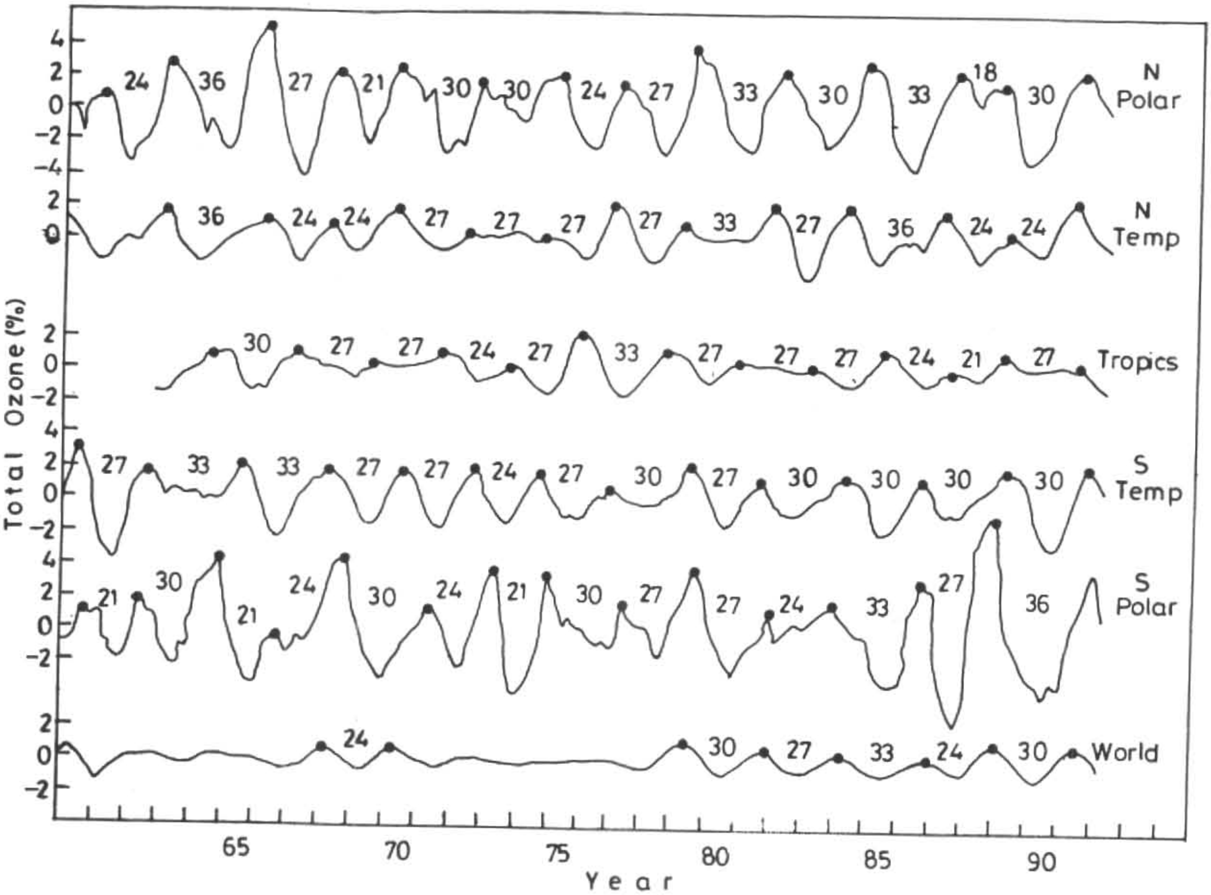

Fig.2. The (12-36) values of total ozone in North Polar, North Temperate, Tropical, South Temperate, South Polar regions and the global average (World). The numbers indicate spacings in months, between successive peaks

Fig.2 shows the (12-36) ozone values for all the five (North Polar, North Temperate, Tropical, South Temperate, South Polar) regions as also for the global average (World). The numbers indicating the spacings in months (only in multiples of 3, as 3 months is the minimum unit used) are in the range of 21-36 months and the peaks are not in the same months for all the region, possibly indicating phase propagation. The plot at the bottom shows global average (World), with a very intermittent QBO.

3. Spectrum analysis

To decipher the periodicities involved, a power spectrum analysis was conducted, by using MESA (Maximum Entropy Spectral Analysis, Burg, 1967; Ulrych and Bishop, 1975), which detects periodicities much more accurately than the conventional BT (Blackman and Tukey, 1958) method. Similar to the parameter lag m in BT, MESA has a parameter called LPEF (Length of the Prediction Error Filter), which can be chosen. With low LPEF, only low periodicities are resolved. Larger LPEF resolve larger periodicities, even those approaching the data length, but the errors are larger and, low periodicities are resolved. Larger LPEF resolve larger periodicities, even, those approaching the data length, but the errors are larger and,low periodicities show peak-splitting. An LPEF of ~50% of the data length is generally adequate and was used in the present analysis.

MESA has a drawback *viz*., the power estimates are not reliable (Kane and Trivedi, 1982). Hence, MESA was used only to identify the possible periodicities T_k, which were then used in the expression :

$$f(t) = A_0 + \sum_{k=1}^{n} [a_k \operatorname{Sin}(2\pi t/T_k) + b_k \operatorname{Cos}(2\pi t/T_k)] + E \qquad (1)$$

$$= A_0 + \sum_{k=1}^{n} r_k \operatorname{Sin}(2\pi t/T_k + \theta_k) + E$$

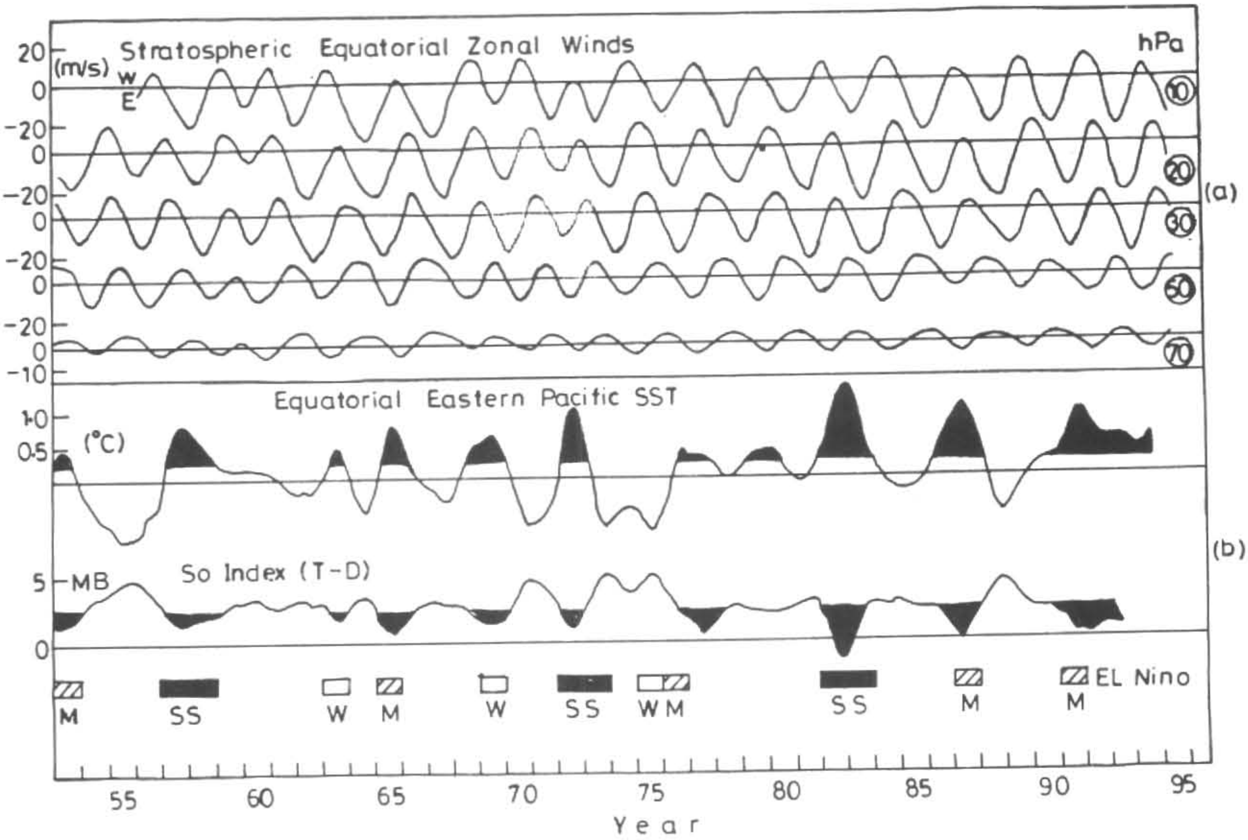

Fig.3. Plots of the 12-month running means of (a) Stratospheric low latitude zonal winds at 10,20, 30, 50, 70 hPa and (b) equatorial eastern Pacific sea-surface temperature SST, the Southern Oscillation Index represented by Tahiti minus Darwin mean sea-level atmospheric pressure difference (T-D) and, El Ninos (rectangles, full, strong; hatched, moderate; blank, weak)

where $f(t)$ is the observed series and E the error factor. A Multiple Regression Analysis [(MRA). Bevington 1969] was then carried out to obtain the best estimates of A_o, (a_k, b_k) and their standard errors, by a least-square fit. From these, r_k and their standard error σ (common for all r_k in this methodology) can be calculated and any r_k exceeding $2\ \sigma$ would be significant at a 95% (a priori) confidence level.

From daily radiosonde observations, Pawson *et al.* (1993, and further private communication to us) obtained and reported monthly mean zonal winds at 70,50,30,20, 10 hPa, with values at 40 and 15 hPa interpolated linearly in pressure scale heights, for 1953-1995. The plots of the 12-month running means (Fig.3) look very similar to each other except that the amplitude is largest near 20 hPa, decreases only slightly between 20 and 50 hPa and decreases considerably below 50 hPa. Also, the maxima occur later at lower altitudes, by about 10 months from 10 to 50 hPa. Fig.4 shows the spectral characteristics, *i.e.*., the amplitudes of the periodicities, some of which are far above the 2σ level (marked hatched) and thus highly significant. The most prominent periodicity is 2.34-2.37 years (~28 months) while the next prominent peak (about half size) is at 2.67-2.70 years (~32 months) and there are other smaller peaks near 2.10, 3.00, 3.65, 4.8, 7.0 and 19 years. However, though this wind QBO was first identified by Reed *et al.* (1961) and Veryard and Ebdon (1961) as a '26-month oscillation', its period had increased to 27.7 months by 1986 (Naujokat, 1986) and is reported to be currently 28.1 months (Pawson *et al.*, 1993), (No explanation for this long-term change has been given so far in the literature, nor is any offered here). Thus the spectra shown in Fig.4 could be an average of a varying characteristic. Since the ozone data are from 1958 to 1993, the data were divided into two portions 1958-1975 and 1976-1993, each of 18 years. Since wind characteristics are similar at all levels, only 50 hPa data are used for comparison with ozone data for the five regions. Fig.5 shows the spectra, for (a) 1958-1975 and (b) 1976-1993. The following may be noted :

(1) In Fig.5(a) for the 18 years 1958-1975, the 50 hPa wind has a strong peak at 2.45 years (29 months) and two smaller peaks at 1.98 years and 3.05 years, all significant at

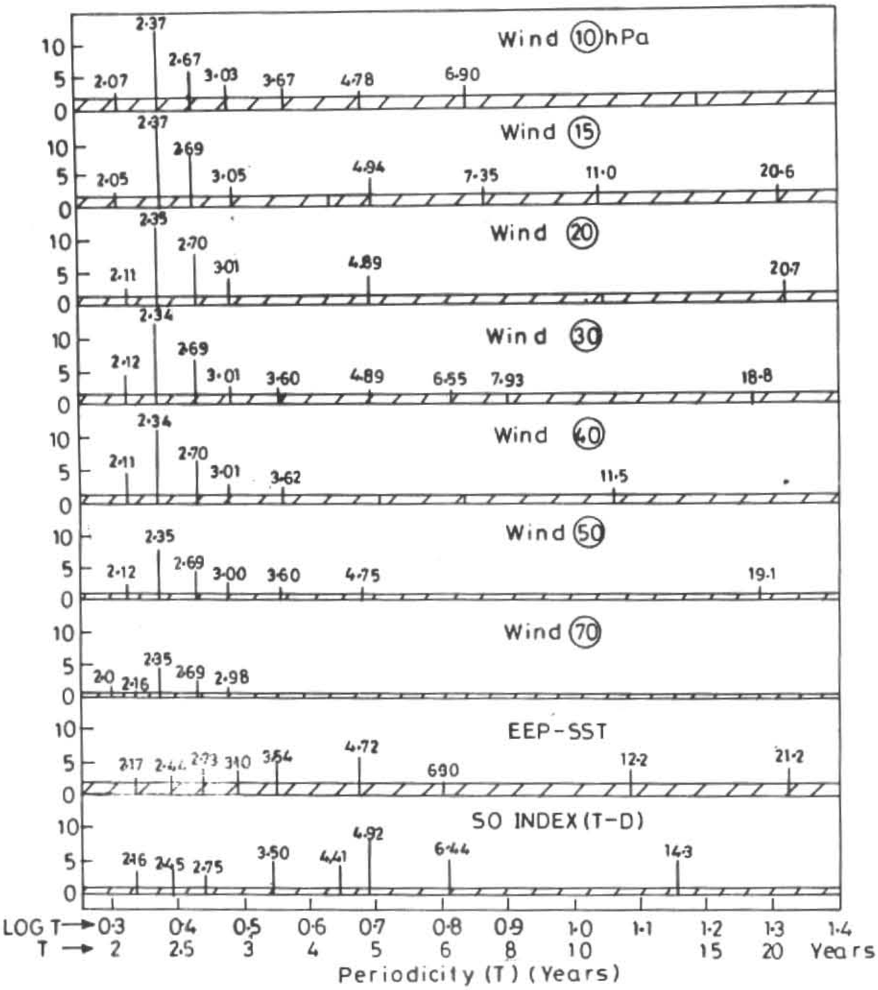

Fig.4. Amplitudes of the periodicities (numbers indicate years) obtained by MESA of the time series for 1953-1995 for stratospheric winds at 10, 15, 20, 30, 40, 50, 70 hPa, and equatorial eastern pacific SST and Southern Oscillation Index (T- D). Note that the abscissa scale is logarithm of periodicity T

a 4σ or better level. In ozone, NP, NT and ST have significant peaks at 2.37, 2.41 and 2.48 years, not exactly at 2.45 years of the wind, but very near. However, TRO and SP have strong peaks at 2.27 and 2.12 years, different from the 2.45 year wind peak. (In this periodicity region, MESA is very accurate, with accuracy of 0.05). All ozone plots show peaks at 20-21 months, some highly significant; but this peak is barely significant in 50 hPa wind. Yang and Tung (1994) have attributed the 20 month peak to an aliasing (difference and sum) of the annual (12 month) and QBO (30 month) periods, the other aliased period being 8 months, not seen here as we have used 12-month running averages.

(2) In Fig.5(b) for the 18 years 1976-1993, the 50 hPa wind has only one very strong peak at 2.51 years (30 months), NP, NT, ST have peaks at 2.41, 2.45, 2.45 years, very near to 2.51 years of the wind. But TRO and SP have peaks at 2.32 and 2.29 years, different from the 2.51 year wind peak. On the other hand, all ozone plots have significant peaks at 20-22 months. Besides, NP and SP have a strong peak near 2.90 years, NT at 3.16 years and TRO at 3.36 years. Also, all ozone plots have peaks in the 4-5 year range.

The significant peaks of the ozone plots in the 3-5 year region are almost absent or insignificant in the 50 hPa wind and look similar to peaks in the well-known terrestrial phenomenon ENSO, manifested in the Southern Oscillation Index (Tahiti minus Darwin mean sea-level atmospheric pressure difference T-D) and in the equatorial eastern Pacific sea surface temperature SST. The bottom part of Fig.3 shows the plots of the 12-month running means of the ENSO parameters. The maxima of SST and the minima of (T-D) are painted black and are very well associated with El Nino events shown by rectangles. The spectra of SST and (T-D) are shown at the bottom of Fig.4. There is some evidence

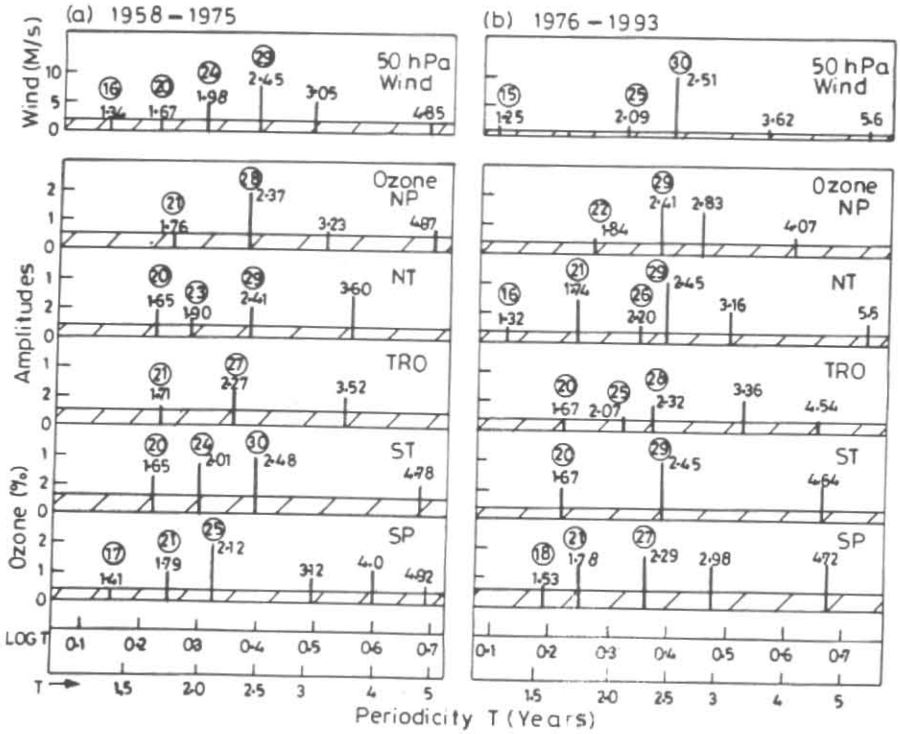

Fig.5. Amplitudes of the periodicities (numbers indicate years, circled numbers indicate months) obtained by MESA for the series for the 50 hPa wind and total ozone at the five regions NP, NT, TRO, ST, SP, for (a) 1958-1975, (b) 1976-1993

here that ozone is affected by ENSO parameters also. Though we have used only the 50 hPa level for comparison while other levels also could affect ozone, the discrepancies cannot be attributed to the winds at other levels, as winds at all levels have exactly the same QBO period.

In the present analysis, simple low-pass and high-pass filters (12-month and 36-month running means) are used. Some workers have expressed misgivings about their use. MESA does not need any filtering and all possible periodicities are revealed in a wide range, though large periodicities (comparable with the data length) can show errors if there is a large long-term trend (Kane and Trivedi, 1986). Fig.6 shows the spectra of the NT ozone series for 1976-1993. In (a) for 3-monthly means (DJF, MAM, JJA, SON), major peaks are seen at 12, 16, 21, 29 months and minor peaks at 8, 10, 14 months, 2.9 years and 5.9 years. (The peaks at 12 months or lower are not very large, because the values are deseasoned). The triple-period (30, 20, and 8.6 months) mentioned by Yang and Tung (1994) is observed. In (b) for the 12- month running means, peaks below 1.73 years (21 months) are suppressed, but others remain almost intact and a small peak at 2.21 years appears. In (c) where the 36-month running means are subtracted from the 12-month running means, the spectra are almost the same as for (b). Thus, by and large, the procedure of running averages does not seem to cause any major distortions. Stolarski *et al.* (1992) also came to the same conclusion.

4. Phase changes with latitude

Unless the periods of the QBO are exactly alike, the phases cannot be compared precisely. For example, if two periods are 2.40 and 2.50 years and the waves start with common maxima, in 30 years, these would have completed 12.5 and 12 cycles and would be in opposite phases. However, in Fig.1, the ozone maxima in (d) did show some coincidence with the 50 hPa wind easterly maxima in (e). Thus, some average lag or lead may exist. To check the same, a cross-correlation analysis was performed between the 4 season (12 monthly) running means of the 50 hPa wind *versus* the corresponding ozone values for the five regions (NP, NT, TRO, ST, SP) separately for the two intervals 1958-1975 and 1976-1993. Fig.7 shows the plots for shifts - 12 to +12 seasons. No assumption is made regarding the frequency of the QBO. As can be seen in Fig.7(a) for 1958-1975, for tropical ozone (TRO), the ozone maxima almost coincide with the 50 hPa wind westerly maxima. For NT and NP, the lag is about 4 and 6 seasons, indicating phase shifts. The maximum correlation coefficient for the tropics (TRO) is 0.75 ± 0.05 and is about the same for NP, NT, ST

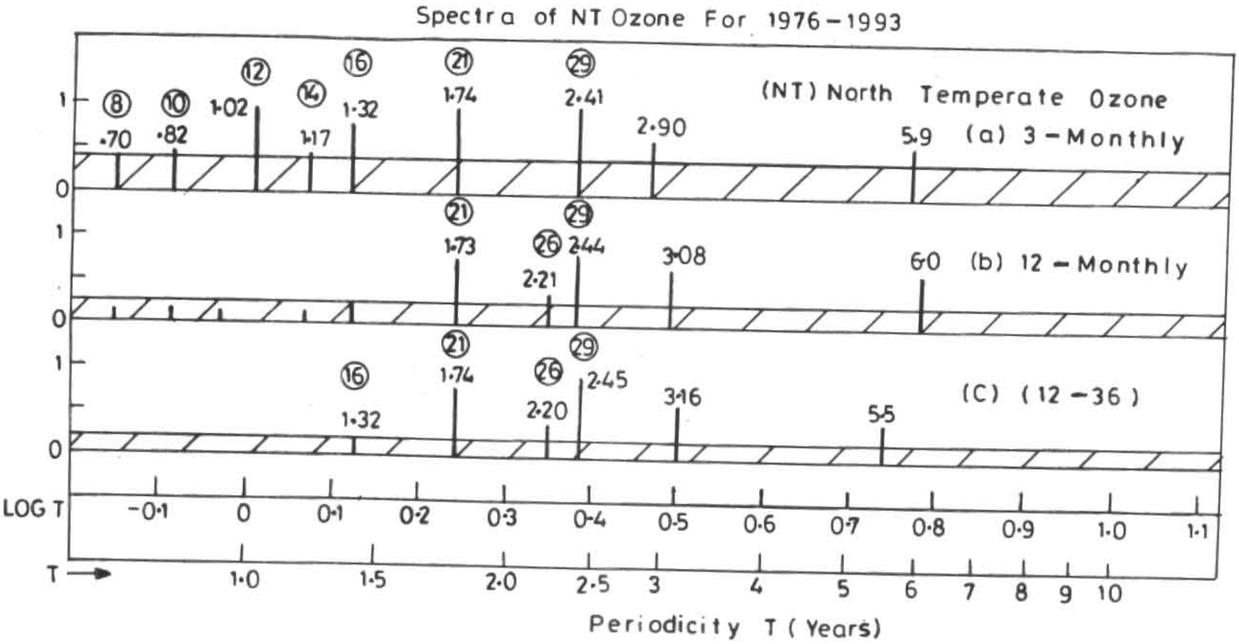

Fig.6. Amplitudes of the periodicities obtained by MESA for the total ozone series of the NT (North Temperate) region, for 1976- 1993, (a) 3-monthly means, (b)-12-month running means, (c) (12- 36) values

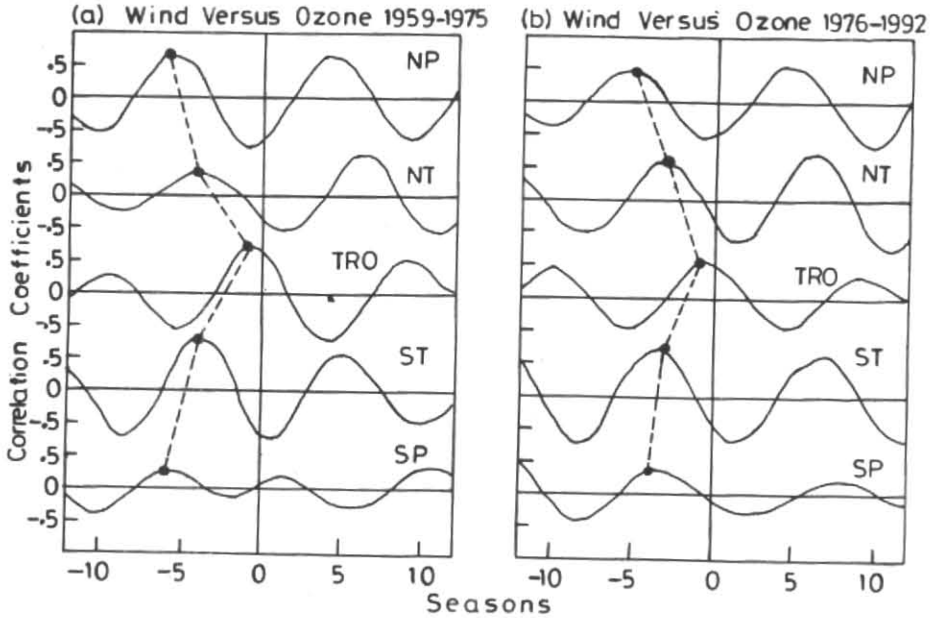

Fig.7. Cross-correlation between the 12-month running means of the 50 hPa wind versus, the (12-36) values of ozone in the regions NP, NT, TRO, ST, SP for (a) 1959-1975, (b) 1976-1992. The dots indicate the maximum correlations, connected by dashed lines to illustrate the phase shifts

but is low (0.25 ± 0.11) for SP. But the phase shift is seen in the southern hemisphere (TRO, ST, SP) also, by roughly the same amount. In Fig.7(b) for 1976-1993, similar characteristics are seen, but the phase shifts for NP and SP are smaller.

In the tropics, the relationship between stratospheric zonal winds and ozone is simple and correlations are high with almost zero phase shift. In extratropical latitudes, complications arise. Using TOMS data at finer latitude intervals, Yang and Tung (1995) reported that there was a nodal line at 10° - 12° across which the ozone QBO had a 180° phase change, probably due to a subtropical branch of the equatorial QBO. According to Tung and Yang (1994ab), the extratropical ozone QBO had only 20-30% of the equatorial 30-month QBO and a considerable portion was in the 20-month period, a modulation of the seasonal (12-month) and the 30 month period. Also, effects due to atmospheric temperature changes may be important. In the tropics, the stratospheric temperatures and ozone are in phase; but extratropical temperatures are out of phase and, in addition, the lower troposhere may have a considerable influence of ENSO phenomenon (Kane and Buriti, 1997), some of which may percolate to the extratropical stratospheric ozone. Thus, there are good reasons why extratropical ozone QBO may be different from the equatorial ozone QBO.

5. Conclusions

Spectral analysis was carried out for the 12-monthly running means of 50 hPa low latitude zonal wind and residuals of total ozone obtained as 12-monthly minus 36-monthly running means, for five latitude zones North Polar (NP), North Temperate (NT), Tropical (TRO), South Temperate (ST), South Polar (SP), for the two successive 18 year intervals 1958-1975 and 1976-1993. The following was noted :

(*i*) For 1958-1975, the 50 hPa and wind had a major peak at 2.45 years (29 months) and two smaller but significant peaks at 1.98 and 3.05 years. Only NP, NT, ST had similar major peaks. TRO had a peak at 2.27 years and SP at 2.12 years. All ozone series had significant peaks at 20-21 months, while wind had a barely significant peak at 20 months. Wind as well as ozone had peaks in the 3-4 year region also.

(*ii*) For 1976-1993, wind had only one strong peak at 2.51 years (30 months). NP, NT, ST had similar peaks; but TRO had a peak at 2.32 years and SP at 2.29 years. All ozone series had 20-22 month peaks while these were absent in the wind series. Ozone series had significant peaks in the 3-5 year region; but these were absent or insignificant in the wind series, indicating some other origin, probably ENSO effects.

It would thus seem that the spectral characteristics of both the stratospheric low latitude zonal wind and the stratospheric ozone change with time. In addition, extratropical ozone has a complicated structure, with modulation with annual cycle and probably interaction with ENSO effects.

6. Discussion

Hasebe (1983) had pointed out the existence of a quasi 4-year variation in total ozone in the tropics and Shiotani (1992) used TOMS Nimbus 7 data to show the existence of a zonally averaged variation in tropical ozone that is correlated with the Southern Oscillation. Gray *et al.* (1992) have hypothesized a mechanism by which stratospheric QBO influences ENSO variability while Geller and Zhang (1991) illustrate a mechanism by which SST variations can modulate tropical wave activity and finally, the SST-QBO would tend to force a stratospheric zonal flow oscillation with the same period as the oceanic QBO. Geller (1993) discusses the importance of tropospherically forced waves in determining the climatological state of the middle atmosphere. Recently, Geller *et al.* (1997) have calculated the stratospheric QBO for time-varying wave forcing.

A cross-correlation analysis indicated that in the tropics, ozone (TRO) maxima coincided with westerly wind maxima, while NT and NP showed phase shifts, larger for NP than for NT. No assumption was made regarding the frequency of the QBO. Similar behaviour was noticed for ST, SP also. With only three data points (TRO, NT, NP), it is not possible to say whether the phase shift with latitude is gradual. Yang and Tung (1995) feel that there is no compelling reason to conclude the presence of a gradual poleward phase propagation. Though the results of Zerefos *et al.* (1992) for the least square fits to the phases of the 27-month component look like a trend, Yang and Tung (1995) consider this a misinterpretation, as in each of the three regions *viz.* equatorial, midlatitude, polar, the 30-month component has a fairly constant phase, and phase changes (shifts) occur only at the boundaries between these regions.

Yang and Tung (1994) mentioned a triple period (30, 20, 8.6 months) extratropical signal in ozone. We find that the 20 month signal is present at tropical latitudes also. The same is true for the 8 month signal, though this is weak in the 3-month averages we have used. Yang and Tung mention that the QBO signal is strongest in the middle and high latitudes. Our results are in general agreement with their results, but polar QBO amplitudes are larger than the midlatitude amplitudes. Recently, Hollandsworth *et al.* (1995) investigated the structures of the QBO in zonal wind, temperature and layer ozone using National Meteorological Center (NMC) global geopotential height data and global ozone data from the SBUV on Nimbus 7. They reported that the wind QBO extended up to 2 hPa and the ozone QBO was strong at all levels from 5 hPa down into the lower stratosphere. The latitudinal structure of the ozone QBO varied significantly from layer to layer; but the lower and middle stratospheric QBO patterns were similar to the total ozone signal, discussed by us in this paper.

Acknowledgements

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