

Latitude dependence of the quasi-biennial oscillation and quasi-triennial oscillation characteristics of total ozone measured by TOMS

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Abstract. The 12-month moving averages of total ozone mapping spectrometer (TOMS) total ozone data for 14 years (1979–1992) were examined for quasi-biennial oscillation (QBO) and quasi-triennial oscillation (QTO) and compared with stratospheric low-latitude zonal wind and equatorial eastern Pacific sea surface temperature (SST). The equatorial ozone had a strong QBO with a period of ~ 30 months, and its maxima tallied with westerly wind maxima. At other latitudes the ozone maxima spacings were often different from 30 months, more so in the northern hemisphere. A spectral analysis showed that both hemispheres had one peak at ~ 20 months and another peak at ~ 30 months, only up to $\sim 50^\circ$ latitude. At higher latitudes these peaks shifted to ~ 23 and ~ 36 months. For 0° – 50° the ~ 30 -month periodicity in the northern hemisphere showed abrupt phase changes, while the southern latitudes showed a roughly gradual phase shift. The northern hemisphere had an additional periodicity at ~ 4 years, roughly matching the SST. Analysis of the same data without 12-month averaging showed the above characteristics more clearly and revealed additional peaks at ~ 0.7 years (8–9 months) and ~ 1.30 years (16–17 months). All of these peaks showed shifts (mostly increases) at higher latitudes.

1. Introduction

A quasi-biennial oscillation (QBO) in the equatorial stratospheric zonal winds was discovered by *Reed et al.* [1961] and *Veryard and Ebdon* [1961]. Soon, it was also discovered in the total column ozone near the equator by *Funk and Garnham* [1962] and at middle and high latitudes by *Angell and Korshover* [1962]. *Hasebe* [1980, 1983], *Tolson* [1981], *Hilsenrath and Schlesinger* [1981], and *Oltmans and London* [1982] studied the latitudinal structure of the ozone QBO using Dobson and Nimbus 4 backscattered ultraviolet (BUV) data and reported hemispheric asymmetry, implying that the ozone at the equator was strongly connected with the ozone in the northern subtropics but not with the ozone in the southern subtropics. Using 9 years (1979–1987) of total ozone measurements from the total ozone mapping spectrometer (TOMS) on Nimbus 7, *Bowman* [1989] reexamined these results and stated that the equatorial QBO in ozone was much more symmetric than was reported earlier and was generally out of phase with ozone in the subtropics. Also, the extratropical QBO ozone anomalies were confined to the winter and spring seasons and conceptually, were like a ~ 27 -month QBO period modulated by the 12-month seasonal cycle, resulting in the sum and difference components of ~ 8.3 and 21 months, besides the QBO period. *Shiotani* [1992] used TOMS data from 1979 to 1989 and reported annual, quasi-biennial, and ~ 4 -year periodicities for equatorial total ozone. Earlier, *Hasebe* [1980] had noticed a

4-year periodicity from ground-based network ozone data of 15 years, which was confirmed later by *Hasebe* [1983], using Nimbus 4 BUV data also. *Hasebe* [1983] reported a poleward phase propagation of the QBO in the northern and southern mid-latitudes and an equatorward phase propagation at northern high latitudes. *Zerefos et al.* [1992] also reported a poleward phase propagation. However, the QBO pattern obtained using a linear regression model by *Yang and Tung* [1994] from TOMS data showed little evidence of a gradual phase propagation. *Yang and Tung* [1995] reexamined the TOMS, BUV, and Dobson data and reported that first, the QBO signal was strongest in the middle and high latitudes and was present mainly in the winter–spring season. Second, the extratropical ozone QBO signal was out of phase with the equatorial ozone signal, the latter being in phase with the equatorial stratospheric zonal wind QBO signal. Third, there was no gradual phase propagation. Instead, there were three distinct regions, namely tropical, midlatitudinal, and polar regions, in each of which the ozone QBO signal had a fairly constant phase, and large phase shifts occurred in the in-between transition regions. Many other details were mentioned.

In most of these analyses, monthly values are used, and the QBO characteristics show considerable seasonal dependence (strong in winter–spring etc.). However, QBO characteristics could also have a season-independent component. In this paper we propose to isolate this component by calculating 12-month moving averages, which would eliminate (or at least reduce considerably) the seasonal effects, and to compare the characteristics at different latitudes, using TOMS data for 14 years (1979–1992). Also, an update of the earlier TOMS analyses by *Bowman* [1989] and *Shiotani* [1992] is given.

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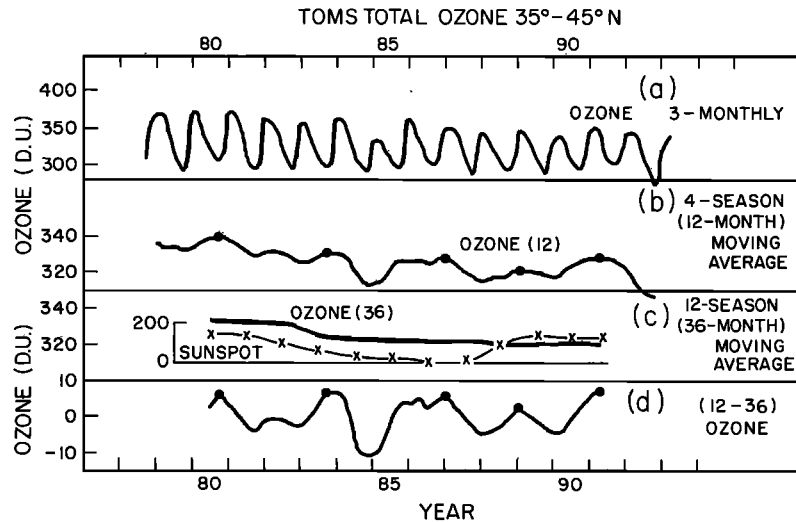


Figure 1. A sample plot of total ozone mapping spectrometer (TOMS) total ozone at 35°–45°N including (a) 3-monthly averages, (b) 4-season (12-month) moving averages (the dots indicate maxima), (c) 12-season (36-month) moving averages (the crosses represent sunspot numbers), and (d) Parameter (12–36) representing the difference between 4 season and 12 season averages (Figure 1b minus Figure 1c).

2. Data

The data used are the TOMS ozone data (*Bowman and Krueger* [1985], *Herman et al.* [1991], upgraded version 7.0), averaged over 5° latitude belts, from which data for the 45°W longitude are selected for analysis. Figure 1 shows a sample plot and illustrates the processing procedure. Figure 1a shows the 3-month averages of TOMS ozone data for the 35°–45°N latitude belt. Even though only 4 points/yr are plotted, a strong seasonal variation is seen, which masks other effects. Figure 1b shows the 4-season (12-month) moving averages, designated as ozone (12), where the maxima marked by dots indicate possible QBO. However, there is also a downward trend, including a solar cycle effect. This can be estimated by evaluating further 12-season (36-month) moving averages, designated as ozone (36), as shown in Figure 1c. The crosses show the sunspot numbers, which seem to show a downward trend parallel to the ozone changes during 1980–1987. However, for later periods, the ozone level does not rise parallel to the sunspots, indicating the superposed ozone depletion known to have occurred in recent years. For our purpose of isolating the QBO the nature of the trend (solar cycle effect, depletion, etc.) is not important, and the QBO is isolated by subtracting Figure 1c from Figure 1b. The residuals designated as ozone (12–36) are shown in Figure 1d. It is interesting to note that the maxima indicated by dots are in the same position in Figures 1b and 1d, and the peak spacings are not altered.

3. QBO and QTO Characteristics by Visual Inspection of Plots

Figure 2 shows a plot of the 4-season (12-month) moving averages. The bottom plot is for the 30 mbar stratospheric wind at Singapore [*Pawson et al.*, 1993]. *Bowman* [1989] used data only for 1979–1987, which contained ~3–4 QBO cycles. Here, during 1979–1992, five QBO cycles are included, and the peak spacings are 27, 30, 30, 36, and 30 months (all are multiples of 3 as our basic unit is a 3-month average). The second plot from the bottom shows the 4-season moving averages of

TOMS ozone in the 5°N–5°S belt (near the equator) and shows peaks almost exactly in the same positions as those for the 30 mbar wind, indicating an excellent match between these two. The other plots from the bottom upward are for increasing latitude belts 5°–15°, 15°–25°, 25°–35°, etc., solid curves representing northern latitudes and crosses representing southern latitudes. The following may be noted:

1. The dots on the solid curves represent the northern latitude maxima, and the spacing in months is indicated by the numbers. As can be seen, the spacings vary in a wide range, and many are much larger than the wind QBO spacing of 30 months. Some of the spacings look like quasi-triennial oscillation (QTO).

2. The spacings for similar northern and southern latitudes are not similar. For example, for 35°–45°N the spacings were 36, 39, 24, and 27 months, while for 35°–45°S the spacings (circled numbers) were 27, 27, 33, 30, and 27 months. The procedure of selecting peaks is somewhat subjective. In the 35°–45°N plot, a peak in the beginning of 1986 rather than at the end could make the spacings 36, 33, 30, and 27 months somewhat similar to the spacings for 35°–45°S. However, some major differences remain. In general, spacings near 30 months are seen more often in the southern latitudes than in the northern latitudes. Thus there are considerable hemispheric differences. (These results are only crudely valid. Precise spectral analysis is presented in section 5.)

3. A striking feature is the ozone depression during 1985 (marked hatched in Figure 2) which seems to have occurred at all southern latitudes exceeding 15° but not in the northern latitudes, as was also seen in a similar depression during 1987 at high southern latitudes. Ozone is reported to have a relationship with the well-known phenomenon of Southern Oscillation, a representative of which is the equatorial eastern Pacific sea surface temperature (SST). Positive temperature anomalies are associated with occurrences of El Niño, which are warm water episodes on the Peru-Ecuador coast. The top plot in Figure 2 shows the 12-month moving averages of the equatorial eastern Pacific SST. The warm water events of

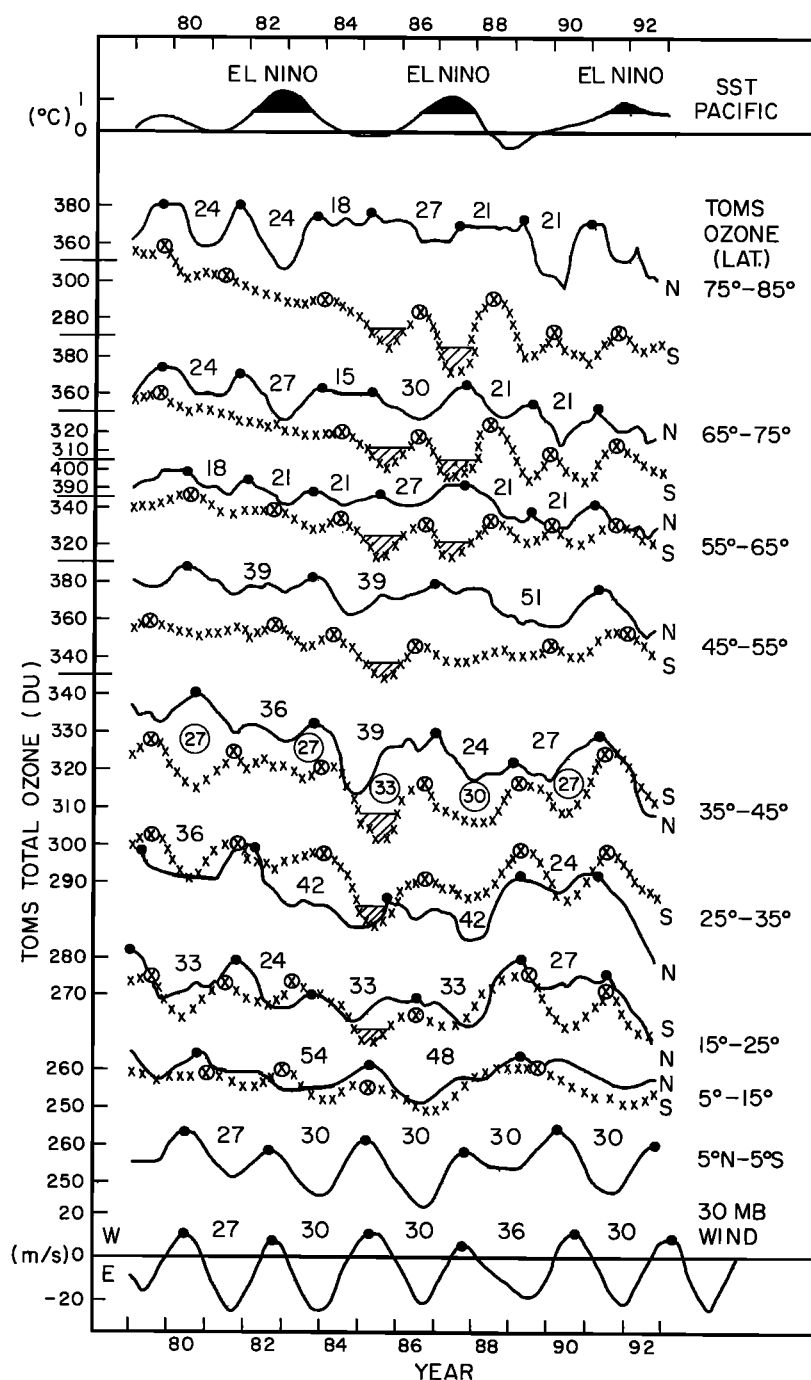


Figure 2. Plots of 4-season (12-month) moving averages. From top, equatorial eastern Pacific sea surface temperature (SST), TOMS total ozone in different latitude belts, and 30 mbar equatorial zonal wind (westerly positive, easterly negative). Dots and circled crosses indicate maxima in the plots of the northern (solid curves) and the southern (crosses) latitude ozone. Numbers indicate spacings (in months) between successive maxima.

1982–1983, 1986–1987, and 1991–1992 are indicated in black, and only the 1987 event seems to have some association with ozone changes in the southern high latitudes. *Bojkov* [1987] has discussed some of these associations.

The hemispheric differences are by no means limited to the QBO and QTO characteristics. Figure 3 shows the long-term changes represented by the 12-season (36-month) moving averages for various latitude belts, solid curves representing the northern latitudes and crosses representing the southern latitudes. First, the ozone values at high latitudes are considerably

larger (by ~50 Dobson units (DU) or more) in the northern latitudes. Second, the variability is very different in the northern and southern latitudes. For latitudes exceeding 45° the northern latitudes have a small decline (~2%) from 1980 to 1986 and a slightly larger decline (~3%) from 1986 to 1990. In the southern high latitudes, there is a large decline (~5%) from 1980 to 1986 (evolution of the Antarctic ozone hole) and almost a steady level or slight increase thereafter. In lower latitudes the situation seems to have reversed. The northern latitudes have a steady decline from 1980 to 1986, while the

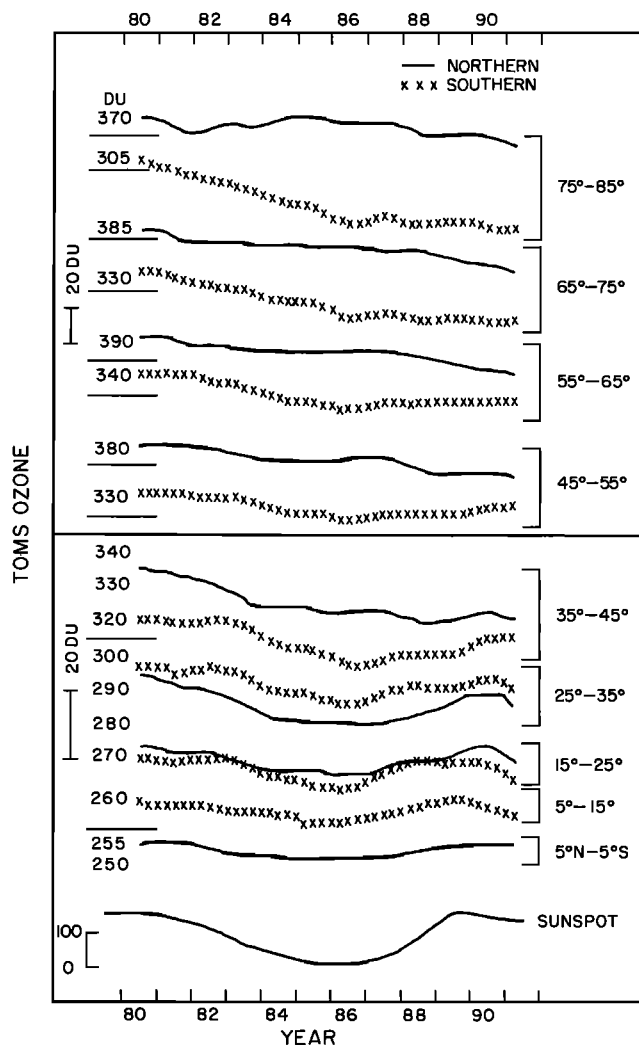


Figure 3. Plots of 12-season (36-month) moving averages of TOMS total ozone in northern (solid curves) and southern (crosses) latitude belts. The bottom plot is for sunspot numbers.

southern latitudes seem to have a steady level in 1980–1982, followed by a decline thereafter up until 1986. From 1986 onward, there is a steady level or rising tendency. (In years after 1992, there is probably a global decline, not discussed in this paper.) The bottom plot in Figure 3 shows the sunspot numbers. The ozone decline from 1980 to 1986 is parallel to the sunspot numbers, but from 1986 onward, ozone did not increase much with the sunspot numbers, indicating that there is a long-term ozone depletion superposed.

Possible reasons for these discrepancies can be various. The equatorial QBO may percolate to higher latitudes with or without phase shifts, but other effects may be superposed and may alter the positions of the maxima. Alternatively, the peak spacings at higher latitudes may be due to altogether different periodicities. A cross-correlation and spectrum analysis could give more precise information.

4. Cross-Correlation Analysis

The wind values in the bottom plot of Figure 2 were correlated with the 12-month moving averages of ozone shown in

Figure 2 and also with their corresponding parameters (12–36) shown in Figure 1d. Correlations were larger for the parameter (12–36), mainly because the long-term ozone changes (which may be unrelated to wind) are eliminated in this parameter. Figure 4 shows the correlation plots for northern latitudes on the left side and southern latitudes on the right side. The lags and leads examined are from -9 to $+9$ seasons, almost one QBO cycle (30 months, 10 trimesters) on either side, and refer to the parameter with respect to wind. Positive lag means that the parameter showed maxima later than the wind maxima, and negative lag means that the parameter attained maxima earlier than the wind. The following may be noted:

1. Ozone at 5°N – 5°S (top plot) is highly correlated (correlations >0.7) with wind, at almost zero lag. In the next belt, 5° – 15° in both hemispheres, the correlations reduce to ~ 0.3 – 0.5 , but the lag is still almost zero. It may be noted, however, that *Yang and Tung* [1995] reported a nodal line for column ozone near 10° – 12° of latitude in both the hemispheres, across which there is a 180° phase change. Our latitude range is too broad to detect such a fine structure.

2. For higher latitudes the correlations are larger (~ 0.5), but the phase shifts considerably, from 0 to -4 seasons. The transition seems to be sharp, near 15° in both the hemispheres, and in agreement with the findings of *Bowman* [1989] and *Yang and Tung* [1995], though they reported seasonal differences, which are eliminated in our analysis.

3. In the northern latitudes, there seems to be another phase shift between the 45° – 55° belt and the 55° – 65° belt, from -4 seasons to $+2$ seasons, which is maintained in the 65° – 75° belt. *Yang and Tung* [1995] have mentioned such a possibility,

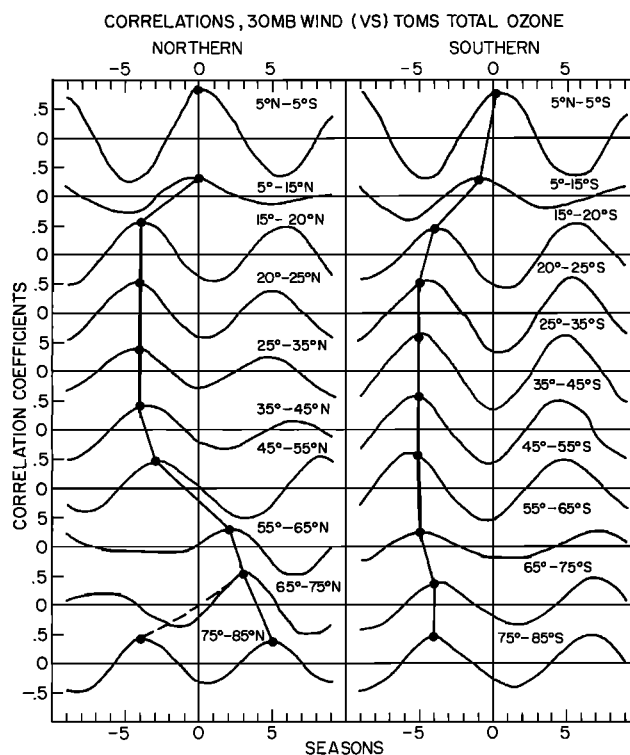


Figure 4. Cross correlations between 30 mbar wind and the parameter (12–36) of TOMS total ozone at different latitudes, northern on the left side and southern on the right side. Correlation maxima (dots) are joined by connecting lines to indicate phase shifts.

but in the north polar region (75°–85°) the phase reverts back to –4 seasons. In the southern hemisphere the phases at all latitudes above 15° seem to remain at –4 to –6 seasons.

Figure 5 shows a similar analysis for correlations between equatorial eastern Pacific SST and the TOMS ozone data, using the parameter (12–36), for northern latitudes on the left side and southern latitudes on the right side. The top plot (common to both sides) is for the equatorial region ($\pm 5^\circ$) and shows low correlations (~ 0.3), indicating either that the relationship between equatorial ozone and SST is poor or that it is overwhelmed by the relationship of equatorial ozone with stratospheric wind. The next plots are for the latitude belt 5°–15°. Here the correlations are higher (~ 0.5), either because the relationship of ozone with SST has improved or because the wind effect is weaker, as was indicated by the low correlations for this latitude belt in Figure 4. Also, for higher latitudes the correlations are higher (~ 0.5) (again for the same reason) but for the northern latitudes only. Regarding the phase the equatorial ozone has a minimum (marked by triangles) near the SST maximum (zero line), and there is a gradual phase shift in the northern latitudes, from +3 seasons at the equator to –2 seasons at 35°. At 35°–45°, there seems to be a transition; correlations are low, and for higher latitudes the phase has shifted considerably. If ozone maxima (marked by circles) are considered, there seems to be a gradual phase propagation, from +9 seasons at the equator to approximately –8 seasons at the poles. In the southern hemisphere the phases are almost constant, with ozone minima within 2 seasons of the zero line, and ozone maxima occurring 4 seasons later. However, the correlations in southern latitudes are generally low (~ 0.3), indicating a poor relationship between ozone and SST. Let us now examine the spectral characteristics of all these parameters.

5. Spectrum Analysis

To decipher the periodicities involved, a power spectrum analysis was conducted by using maximum entropy spectral analysis (MESA) [Burg, 1967; Ulrych and Bishop, 1975], which detects periodicities much more accurately than the conventional [Blackman and Tukey, 1958] (hereinafter referred to as BT) method. Similar to the parameter lag m in BT, MESA has a parameter called the length of the prediction error filter (LPEF), 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 show peak splitting. An LPEF of $\sim 50\%$ of the data length is generally adequate and was used in the present analysis.

MESA has a drawback, namely, 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

$$\begin{aligned} f(t) &= A_0 + \sum_{k=1}^n [a_k \sin(2\pi t/T_k) + b_k \cos(2\pi t/T_k)] + E \\ &= A_0 + \sum_{k=1}^n r_k \sin(2\pi t/T_k + \phi_k) + E \end{aligned} \quad (1)$$

where $f(t)$ is the observed series and E is the error factor. A multiple regression analysis (MRA) [Bevington, 1969] was then carried out to obtain the best estimates of A_0 , (a_k , b_k), and

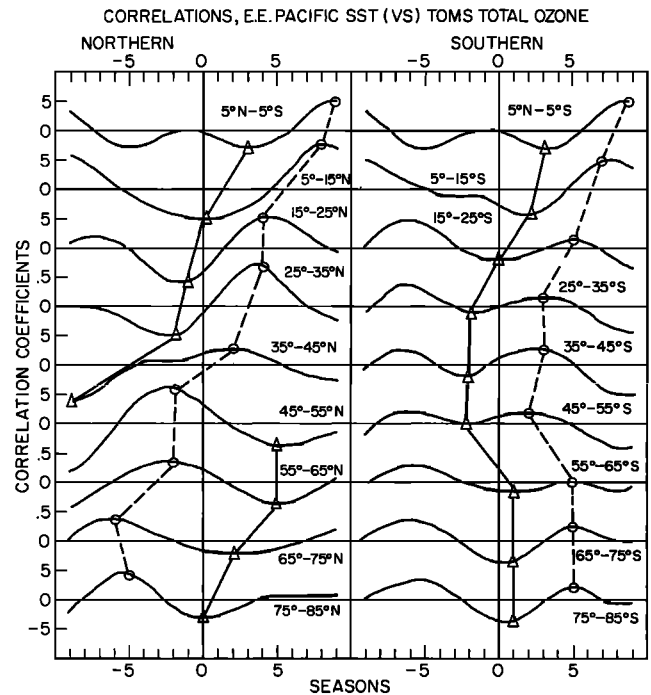


Figure 5. Cross correlations between equatorial eastern Pacific SST and the parameter (12–36) of TOMS total ozone at different latitudes, northern on the left side and southern on the right side. Correlation maxima (circles) and minima (triangles) are joined by connecting lines to indicate phase shifts.

their standard errors by a least squares 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 2σ would be significant at a 95% (a priori) confidence level.

Some aspects of this methodology need to be emphasized here. First, MESA peak detection is very, very accurate. For example, the present data are seasonal values (four values per year) for ~ 13 years (i.e., 52 data points). In the conventional BT method, with a generally recommended lag m of 25% of the data length (in this case, $m = 13$), only certain frequencies $k/2m$ can be investigated (i.e., $1/26$, $2/26$, \dots , and $13/26$, where the folding frequency is 0.5). In terms of periodicities these are 26, 13, \dots , 2.36, 2.16, and 2.00. Thus, if the periodicity was 2.25, it would be missed. In MESA, there is no such restriction. Any frequency (of course, less than the folding frequency 0.5) can be investigated, and the steps are a matter of choice. Thus, between 2.0 and 3.0, ~ 70 steps were investigated, and the periodicities could have an accuracy of 0.01. This was earlier checked by feeding artificial samples [see Kane, 1977, 1979]. MESA resolves peaks even slightly better than the criterion mentioned by Ulrych and Bishop [1975], namely, two frequencies, f_1 and f_2 , can be resolved if the data length exceeds $1/(f_1 - f_2)$. Since the amplitudes are finally estimated by MRA (MESA is used only for locating periodicities T), the main restriction comes from MRA. Here the standard error of all periodicities is equal. However, if two periodicities are too close, the method gives larger standard errors for both those periodicities. In general, a separation of 0.10 (e.g., 2.50 and 2.60) is enough for resolution.

MESA does not need any filtering and can reveal all peaks even if these are in a wide range. Figure 6 shows the spectra (i.e., amplitudes of the various periodicities detected by

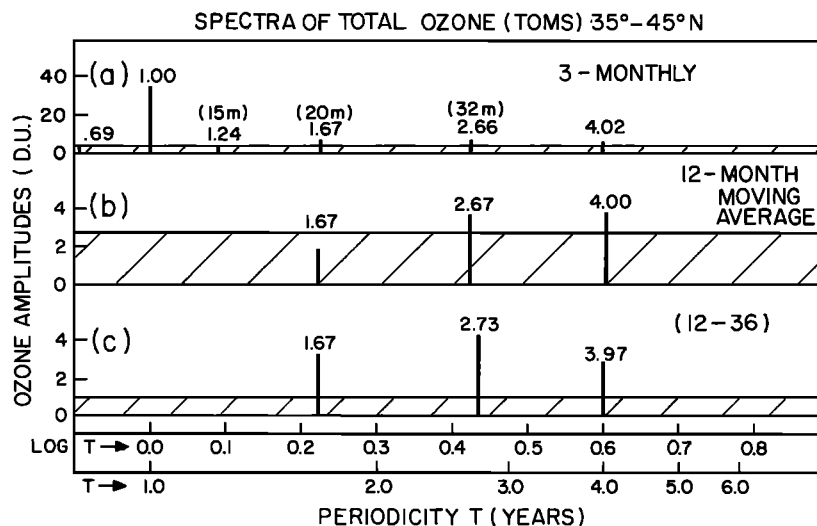


Figure 6. Amplitudes of the various periodicities in the 35°–45°N TOMS total ozone series detected by MESA for (a) 3-month averages, (b) 4-season (12-month) moving averages, and (c) the parameter (12–36). Numbers indicate periodicities in years (those in parenthesis indicate in months).

MESA) for the TOMS (35°–45°N) ozone plot shown earlier in Figure 1. Figure 6a shows spectra for the 3-month averages, and, as expected, the strongest periodicity is the annual wave ($T = 1.00$ year). The hatched portion shows the 2σ limit. From the sum and difference periods of 8.3 and 21 months mentioned by Bowman [1989] and Tung and Yang [1994a, b] the period 0.69 years (~ 8 months) is hardly significant, probably because we have used 3-month averages. However, small but significant peaks are seen at 1.24 years (15 m), 1.67 years (20 m), 2.66 years (32 m, QBO), and 4.02 years. In Figure 6b for 12-month moving averages the 1.67 year peak becomes insignificant, but 2.67 and 4.00 year peaks stand out significantly. In spectra for parameter (12–36) in Figure 6c the same peaks appear. In addition, the 1.67 year peak also becomes significant. Thus the parameter (12–36) is a very good representative of QBO, in all aspects. Hence, for further spectral analysis, only the parameter (12–36) is used.

Figure 7 shows the spectra for all parameters, for northern latitudes on the left side and southern latitudes on the right side. The top plots (common to both sides) are for the 30 mbar wind and show one strong peak at 2.57 years (31 m) and a much smaller peak at 5.0 years. The next plots, also common to both sides, are for the equatorial ozone (5°N–5°S) and show one prominent peak at 2.52 years and a smaller peak at 4.00 years. The good correlation (>0.7) between the equatorial wind and ozone is mainly due to the similarity of the 2.57 and 2.52 year peaks and the correlation is not perfect (nearing 1.00), mainly because the other small periodicities of 5.0 and 4.0 years are not similar. In the succeeding plots both the northern and southern latitudes show a small peak near 1.7 years (20–21 m) and a larger peak near 2.4–2.6 years. MESA is very accurate in this region, and experiments with artificial samples [Kane, 1977, 1979] show that peaks can be distinguished easily, if differing by 0.05 or more. Hence 2.42 is different from 2.58 and certainly different from 2.73. In general, the amplitudes increase from low latitudes to middle latitudes, but the amplitude in the equatorial region is also large. The periodicity near 1.70 years is small and insignificant in the equatorial region, appearing only at exequatorial latitudes in both the hemispheres, and has been emphasized by

Tung and Yang [1994a] as a distinguishing factor of the extratropical ozone. However, our spectra show another equally (or probably more) substantial periodicity near 3.7–4.0 years in the northern latitudes, which is almost absent in the southern latitudes. This is an additional reason why the plots for the southern latitudes in Figure 2 have peak spacings nearer to 30 months, while spacings in the plots for the northern latitudes are often wide off the mark. In our view this is the most important hemispheric difference. Yang and Tung [1994] refer to a three-peak spectrum of extratropical ozone QBO, but the peaks are near 30, 20, and 8 months and there is no reference to a peak near 4.0 years. However, Hasebe [1980, 1983] did report a 4-year oscillation and named it FYO. Shiotani [1992] examined the TOMS equatorial ozone data and found a variation associated with the El Niño–Southern Oscillation (ENSO) cycle (~ 4 years).

Yang and Tung [1995] mention that the QBO signal is strongest in the middle and high latitudes. Since we have the amplitudes for specific periodicities, it would be interesting to check their latitude dependence. Figure 8a shows the latitude distribution of the amplitudes. As mentioned earlier, MESA is very accurate in the QBO and QTO region if the data series have more than 50 points, as in the present case (14 years, 56 trimester points). In Figure 7, all the periodicities are not exactly alike. For example, the ~ 20 -month period has a range of 1.64–1.90 years (20–23 m), and the ~ 30 -month period has a range of 2.29–2.73 years (27–33 m). These may or may not be the same periods. Assuming that they are, Figure 8a shows the latitude dependence. Larger amplitudes are at larger latitudes, except for the 30-month period, which shows a large amplitude at the equator also. Some periods that are very different from the respective group are marked with rectangles, and comparing their amplitudes with the rest may or may not be justified. For the ~ 4 -year group, there are no observations in the southern latitudes.

Regarding phase shifts with latitude, Angell and Korshover [1962] reported a meridional propagation of the QBO at the phase speed of 0.2 m/s from 10° to 47°N and much slower or no propagation farther north. Hasebe [1980] found a phase reversal between these latitudes. Later, Hasebe [1983] and recently

Zerefos *et al.* [1992] reported poleward phase propagation from the northern and southern midlatitudes. Yang and Tung [1995] reexamined ground-based and satellite data in detail and concluded that there were three distinct regions, namely, tropical, midlatitudinal, and polar, in each of which the phase was fairly constant, and large phase shifts occurred only in the transition regions. In our Figure 4 this behavior is roughly confirmed for the general QBO pattern. It would be interesting to see whether a similar pattern is obtained for the individual periodicities near 1.70 years (~ 21 m), 2.50 years (~ 30 m), and 3.80 years seen in Figure 7, though the periodicities do not tally exactly. Figure 8b shows the results. For the period near 1.7 years, there is no data point at the equator, but the phases are very different in the northern and southern latitudes. Tung and Yang [1994a, p. 2706, 1994b] have made a detailed study of this (20 m) periodicity and mention that "it is almost antisymmetric between the two hemispheres, suggestive of a circulation component that has a global pattern from one hemisphere to another." Some antisymmetry is seen in our Figure 8b, top plot.

For the period near 2.50 years (30 m) (Figure 8b, middle plot) the phases shift considerably (3 rad, half a cycle) from the equator to $\sim 40^\circ$ latitude. In the northern hemisphere the shift is rapid from 0° – 20° and slower or uncertain thereafter. In the southern hemisphere the shift is almost gradual. The nodal line at 10° – 12° latitude, across which there is a reported 180° phase change [Yang and Tung, 1995], is included here but crudely because of the wide latitude belts (10° width). Above 40° the southern latitude phases remain constant up to the polar region, but in the northern latitudes the phase changes are indicative of distinct regions as indicated by Yang and Tung [1995]. Also, the ~ 30 -m period changes considerably, to 2.38 years (29 m) at 50° , 3.01 years (36 m) at 60° , and 3.34 years (40 m) at 70° . In the northern polar region (75° – 85°), there are two periods, 2.27 years (27 m) and 3.69 years, very different from the QBO and QTO at lower latitudes. For this polar region, Yang and Tung [1995] mention possible complications due to the presence or absence of midwinter sudden warmings, but such an effect is not expected in 12-month moving averages. In any case, some complications probably due to local (polar) circulation patterns are indicated.

For the 3.8-year periodicity the pattern is seen only in the northern hemisphere, and the phase shift with latitude seems to be gradual, from 1.5 to 5 rad from 0° to 50° latitude and from 5 back to 1 rad from 50° to the south polar region. This is in contrast to the observations of Hasebe [1983], who reported that the FYO was almost symmetric to the equator (we do not see it in the southern hemisphere). A spectral analysis of the equatorial eastern Pacific SST anomalies [Angell, 1981, also private communication, 1981–1997] showed a very prominent peak at 4.2 years (shown in our Figure 7, bottom plot), not exactly the same as the ~ 3.8 -year peaks in the ozone plots, and the phase was the same as the phase of ozone at $\sim 30^\circ$ N. Thus midlatitude ozone maxima are associated with SST maxima. In contrast, the equatorial ozone is approximately half a cycle out of phase, and hence equatorial ozone minima would be associated with SST maxima. These results for the equatorial region are in general agreement with the dynamical responses discussed by Hasebe [1993].

However, as shown in Figure 2 (top plot) for equatorial eastern Pacific SST representing the El Niño–Southern Oscillation (ENSO) phenomenon, these events are not cyclic and occur abruptly, lasting for a year or so, and do not seem to have a one-to-one relationship with ozone at any latitude. As shown

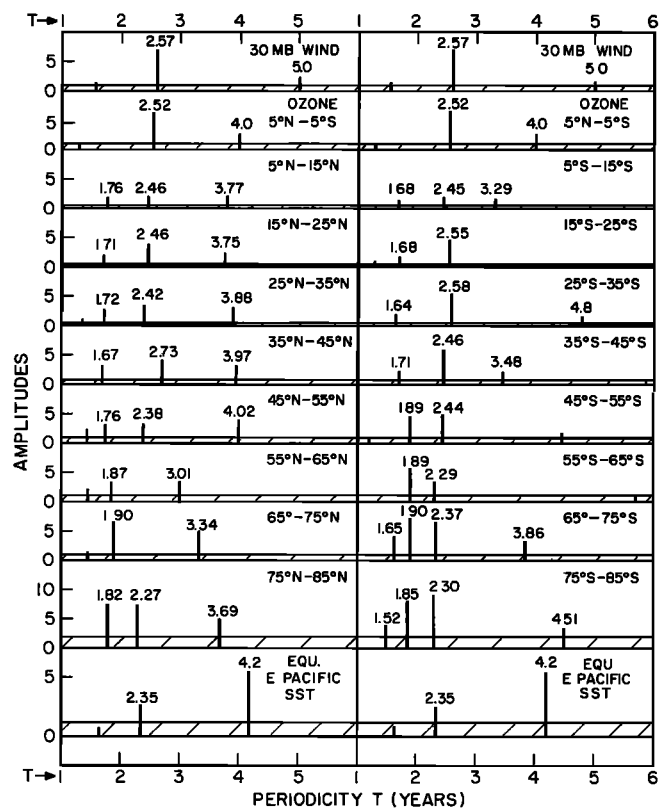


Figure 7. Amplitudes of the various periodicities detected by maximum entropy spectral analysis (MESA) in the 12-month moving averages of 30 mbar wind (top plot), equatorial eastern Pacific sea surface temperature (SST) (bottom plot), and the parameter (12–36) for the TOMS total ozone at different latitudes, for northern on the left side and southern on the right side. The numbers represent periodicities T in years. The hatched portions indicate the 2σ limits.

by Bojkov [1987] in his detailed study of the 1983 and 1985 ozone distribution anomalies, there are two major complicating factors, namely, the QBO and volcanic eruptions, and the QBO “sets the stage” for major ozone deficiencies, while circulation changes due to the ENSO events and volcanic eruptions serve to augment the effect. Zerefos *et al.* [1992] examined the ENSO effects in ozone and found an inphase relationship between Southern Oscillation Index (SOI) (represented by Tahiti minus Darwin atmospheric pressure) and tropical total ozone but an insignificant relationship with high-latitude ozone unless the ENSO event was very strong (e.g., 1982–1983), in which case, low-ozone values at middle and polar latitudes followed the ENSO event within a few months. Krzyscin [1994] considers these approaches incomplete and states that not only the phase of the QBO but the phase of the solar activity (high or low) and the time of the ENSO appearance (cold or warm season) need to be considered simultaneously.

6. Possible Distortions Due to the Use of 12-Month Moving Averages

In the analysis so far, 12-month moving averages have been used, mainly to reduce the effect of the annual wave. Could this procedure have affected some characteristics of the QBO waves? Many workers have such an apprehension, probably based on the warnings of some specialists [e.g., Mitchell *et al.*,

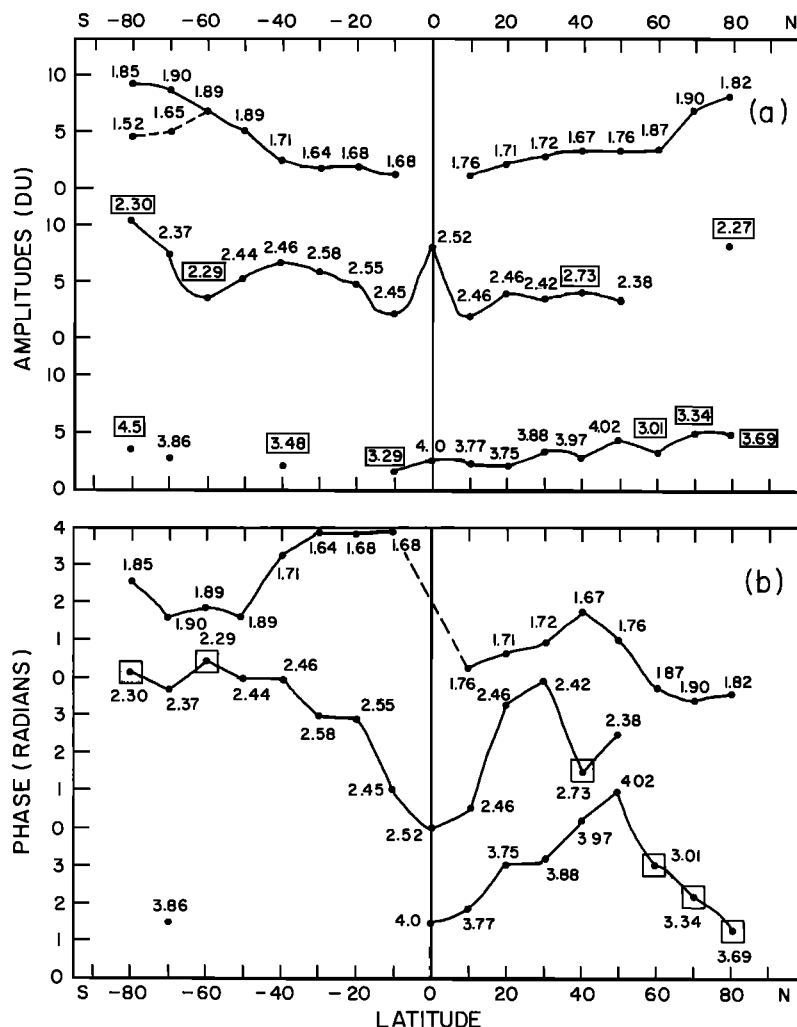


Figure 8. Latitude dependence of (a) the amplitudes and (b) the phases of the periodicities detected by MESA in the TOMS total ozone series. The numbers indicate the periodicities involved, the numbers in rectangles indicating periodicities off the mark in that group and hence unreliable. In Figures 8a and 8b the top plot is for the periodicity ~ 1.70 years (20 m), the middle plot is for the periodicity ~ 2.50 years (30 m), and the bottom plot is for the periodicity ~ 4 years.

1966] that the moving average procedure introduces some sidelobes. Mathematically, a 12-month moving average eliminates the 12-month wave (and its harmonics at 6, 4, and 3 months, etc.) completely but also reduces the amplitudes of higher periodicities, for example, that of a 2-year wave to $\sim 65\%$ and that of a 3-year wave to $\sim 85\%$, and has almost no effect on higher periodicities [see Kane, 1996]. In Figure 6 it was shown that in the spectra of original (3-monthly) values the annual wave predominated, dwarfing all other periodicities. However, in the spectra of 12-monthly moving averages the annual wave disappears and other periodicities stand out, though with reduced amplitudes. To check the effect on other characteristics (e.g., phases), the whole analysis was repeated, using 3-monthly original values (not 12-month moving averages). Also, values were used for smaller latitude intervals, namely, 5° latitude belts, instead of the 10° belts used so far. The results of a spectrum analysis are shown in Figure 9, for northern hemisphere on the left side and southern hemisphere on the right side. In the top panels the dots indicate the strong peak at 2.57 years and the weak peaks at ~ 2.0 and 5.0 years, observed in 30 mbar wind (these peaks are slightly different

from those of Figure 7, as 3-monthly values were used instead of the 12-monthly moving averages used in Figure 7). The triangles indicate the weak peak at 2.35 years and the strong peak at 4.2 years in equatorial eastern Pacific SST. For the peaks in ozone a comparison of Figure 9 with Figure 7 indicates the following:

1. At almost all latitudes the strongest peak in Figure 9 is the annual wave (1.00 years). MESA indicated this as 3.99 seasons, which is 1.00 years, correct to the second decimal place. This indicates the accuracy with which MESA detects peaks. Hence all other peaks indicated should be accurate to at least 0.02. In contrast to Figure 7 the annual wave has now a very large amplitude, reaching values up to 90 DU in the northern polar region. If the ordinate scale is chosen as to accommodate such magnitudes, all other peaks would be dwarfed into insignificance. Hence the ordinate scale in all panels is restricted to within 0–20 DU, and the amplitude of the annual wave is marked with one arrow for amplitudes between 15 and 30 DU, two arrows for 30–60 DU, and three arrows for amplitudes >60 DU. In MRA the amplitude of the strongest peak also dictates the standard error, which is com-

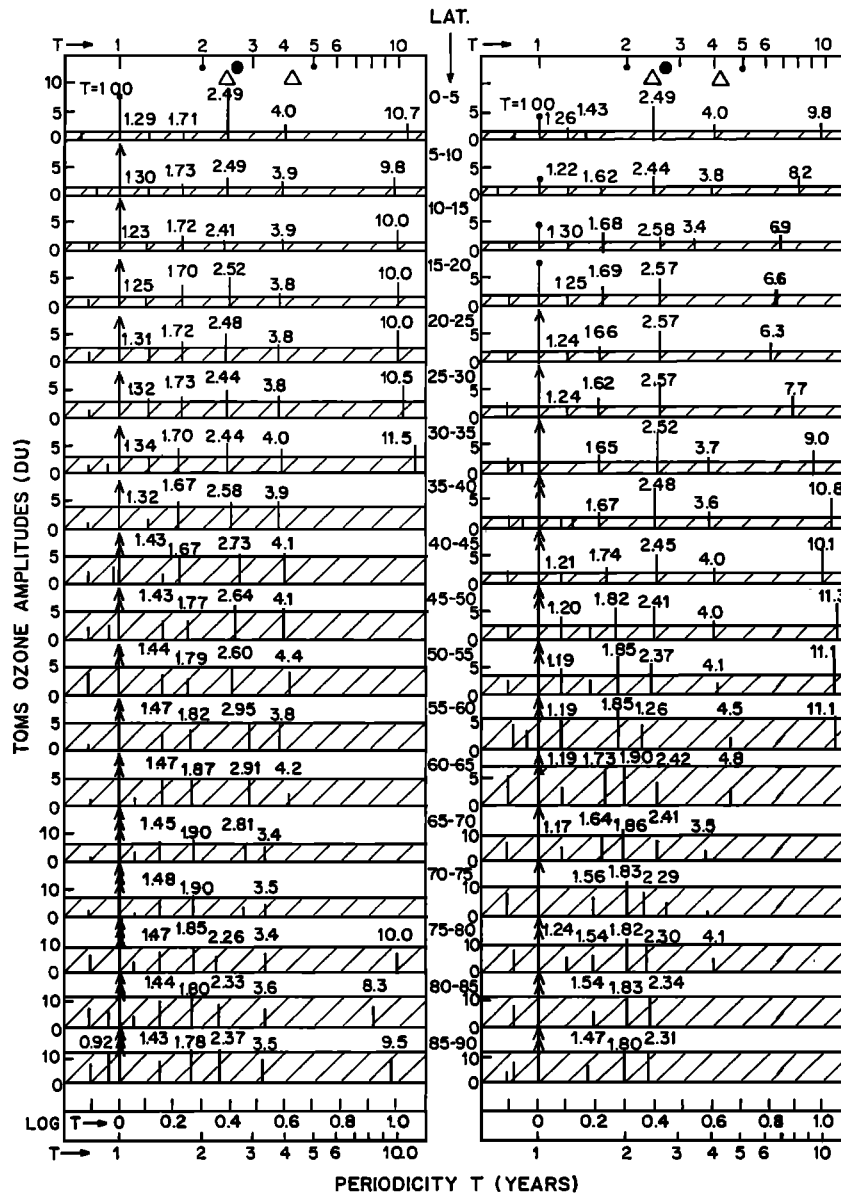


Figure 9. Amplitudes of the various periodicities detected by MESA of the original values (four seasonal values per year) of TOMS ozone at different latitudes, northern on the left side and southern on the right side. The numbers represent periodicities T in years. The hatched portions indicate the 2σ limits. In the top panel, dots indicate the periodicities 2.00, 2.54, and 5.2 years observed in 30 mbar equatorial zonal wind, and triangles indicate 2.35 and 4.2 years observed in equatorial eastern Pacific SST. For the annual wave (1.00 years) the amplitude is out of scale, and one arrow indicates amplitude 15–30 DU, two arrows indicate 30–60 DU, and three arrows indicate >60 DU.

mon to all other periodicities. In the present case the amplitude of the annual wave was a few Dobson units at low latitudes, and the standard error was ~ 1 DU. So, whereas the annual wave was very significant, other periodicities having amplitudes of a few Dobson units were also significant at or above a 2σ level, indicated by the hatched marking. At higher latitudes the annual wave has a larger amplitude, and the standard error is also larger (~ 2 – 3 DU). So, whereas the annual wave is still highly significant, the other periodicities of a few Dobson units amplitudes start losing their significance. At very high latitudes the annual wave in northern latitudes has an amplitude of $\sim 90 \pm 5$ DU and is highly significant. However, other periodicities of amplitudes up to even 10 DU are no

more significant (or barely significant) at a 2σ level. Thus studying other periodicities in the presence of a strong annual wave is not desirable. Figure 7 clearly shows the advantage of using 12-monthly moving averages for this purpose.

2. In both hemispheres, there is a peak at ~ 0.7 years (8–9 months), often inside the hatched marking, and hence not significant at a 2σ level. However, it is consistently there at middle and high latitudes and is probably the 8.3-month QBO-annual wave modulation peak mentioned by *Bowman* [1989]. So, in spite of its apparently low statistical significance, this peak seems to be genuine. This peak was absent in Figure 7 because the procedure of 12-month averaging destroys such a peak.

3. There is a peak at 1.23–1.30 years (15–16 months) which is apparently not significant (or barely significant) but appears persistently at low latitudes, more so in the northern hemisphere. At higher latitudes it seems to shift to ~ 1.45 years (17–18 months) in the northern hemisphere and to ~ 1.50 – 1.60 years (18–19 months) in the southern hemisphere. These peaks at 15–19 months do not seem to be mentioned in the literature. However, another much more persistent peak is near 1.70 years (20–21 months) and is probably the 21-month QBO-annual wave modulation peak mentioned by *Bowman* [1989]. However, these peaks are present at equatorial and low latitudes also. So, the modulation is not necessarily only in middle and high latitudes. Incidentally, these peaks were absent in Figure 7 as they are destroyed by the 12-month moving average procedure.

4. There is a QBO peak at all latitudes, strong at the equator also, with a periodicity of 2.49 years, similar but not quite equal to the strong 2.54-year periodicity of the 30 mbar wind. One could ignore the difference but for the fact that the ozone periodicity is not the same at all latitudes. Also, there is the added complication that 30 mbar wind has another, smaller peak at ~ 2.00 years and ENSO (represented by equatorial eastern Pacific SST) also has a peak near 2.35 years. These ozone peaks have amplitudes of ~ 5 DU and at higher latitudes where the standard error is a few DU these peaks become insignificant. Similar peaks were seen in Figure 7 also and were significant. So, the 12-monthly averages demonstrate these peaks in a better way.

5. There is a peak near 4 years, more persistent in the northern hemisphere low and middle latitudes. At higher latitudes it shifts to ~ 3.5 years. The amplitudes are significant at low latitudes but become insignificant at higher latitudes. Figure 7 also showed these characteristics.

Thus the 12-month moving averages show these peaks in a better way.

The latitude dependence of the amplitudes and the phases of some of these periodicities are shown in Figures 10a and 10b. Figure 10a shows the amplitudes. The 0.7- and 1.30-year periodicities are insignificant or barely significant at all latitudes and are not considered. Amplitudes of the annual wave (1.00 years) are a few DU near the equator, increasing monotonically to ~ 90 DU near the northern polar region but only to ~ 50 DU near the southern polar region. Amplitudes of the ~ 1.70 year (20 month) periodicity are ~ 1 DU near the equator and rise almost monotonically to ~ 10 DU near the polar regions, where the periodicities also change (increase) considerably to ~ 1.85 years (22 months). Amplitudes of the ~ 2.50 -year (30-month) periodicity are ~ 7 DU near the equator but fall rapidly to ~ 2 DU near 15° – 20° latitude and increase thereafter to ~ 6 – 8 DU, with latitudes up to $\sim 50^{\circ}$ in the northern hemisphere and 40° in the southern hemisphere. Amplitudes fall thereafter to ~ 4 DU up to $\sim 70^{\circ}$ and rise thereafter to ~ 10 DU. In the northern hemisphere the periodicity changes considerably, increasing to ~ 2.85 years (34 months) at latitudes 55° – 65° and decreasing to ~ 2.30 years (28 months) at higher latitudes. In the southern hemisphere also the periodicity changes to ~ 2.30 years (28 months) in the polar region. Amplitudes of the ~ 4 -year periodicity, seen more consistently in the northern hemisphere, are ~ 2 – 3 DU near the equator, rise to ~ 6 DU near 55° , and have a sharp drop to ~ 2 DU thereafter, followed by a rise to ~ 8 DU near the poles, where the periodicity also decreases considerably to ~ 3.5 years. In the southern hemisphere this periodicity is almost absent in $\sim 10^{\circ}$ –

30° latitude and thereafter has an almost constant amplitude of 2–3 DU, with uncertain behavior in the polar region. These striking changes in the periodicities at higher latitudes, seen earlier in Figure 7 also, seem to be features not detected before.

Figure 10b shows the phase changes. For the annual wave (1.00 years), there is an asymmetric change due to reverse seasons in the two hemispheres. For the 1.70-year periodicity the phase changes are similar to those in Figure 7, indicating the hemispheric antisymmetry referred to by *Tung and Yang* [1994a, b]. For the 2.50-year QBO in the northern hemisphere the phase changes rapidly by ~ 3 rad (180°) from 0° to 15° , remains steady up to $\sim 30^{\circ}$, reverts back to the equatorial phase for $\sim 30^{\circ}$ – 50° latitude, and changes again to the 30° phase thereafter. The pattern is similar to that mentioned by *Yang and Tung* [1995], except that instead of three distinct regions, namely, tropical, midlatitudinal, and polar, mentioned by them, there seem to be four distinct regions, equatorial, low latitudinal, midlatitudinal, and polar. In contrast, in the southern hemisphere the phase change seems to be gradual, ~ 5 rad from 0° to $\sim 60^{\circ}$ and a steady phase thereafter. The patterns are certainly different in the two hemispheres. Earlier, Figure 8 gave similar indications. For the 4-year periodicity in the northern hemisphere the phase changes gradually by $\sim 180^{\circ}$ from 0° to $\sim 50^{\circ}$ and is very erratic thereafter. In the southern hemisphere this periodicity is missing for 15° – 30° latitude, but there is a sharp phase change from 0° to 15° latitude and the phase is constant up to $\sim 70^{\circ}$, and erratic thereafter. Some inkling of this was seen in Figure 8 also.

7. Conclusions and Discussion

The 3-monthly TOMS ozone values were subjected to 4-season (12-month) moving averages, designated as ozone (12). These values were subjected to further 12-season (36-month) moving averages, designated as ozone (36). When these 36-month averages were subtracted from the 12-month averages, the residuals designated as ozone (12–36) gave a good representation of the QBO and QTO (quasi-biennial and quasi-triennial oscillations) of ozone. The characteristics of these were studied and compared with those of stratospheric winds and ENSO phenomena. A similar analysis was done by using the original 3-monthly TOMS values also. The results may be summarized as follows:

1. The plots of the 12-month averages of the 30 mbar equatorial zonal wind (westerly positive, easterly negative) matched well with those of the low-latitude (5°N – 5°S) ozone, with peak spacings of ~ 30 months. At other latitudes the peak spacings were very irregular, differing widely from the average of ~ 30 months, more so in the northern hemisphere. For the same latitude belt, peaks in the northern and southern latitudes did not tally. The long-term variability of ozone was also very different at different latitudes and different for similar northern and southern latitudes.

2. A cross-correlation analysis of the 30 mbar equatorial zonal wind (westerly positive, easterly negative) with the ozone in the various latitude belts showed that the maximum correlation was high (>0.7) at almost zero lag for the equatorial ozone (westerly wind maxima coinciding with ozone maxima), low (~ 0.3) but almost with no lag for the 5° – 15° latitude belt in both hemispheres (this belt includes the nodal line at 10° – 12° across which there is reported a 180° phase change, see *Yang and Tung* [1995]), and medium (~ 0.5) with a large phase shift

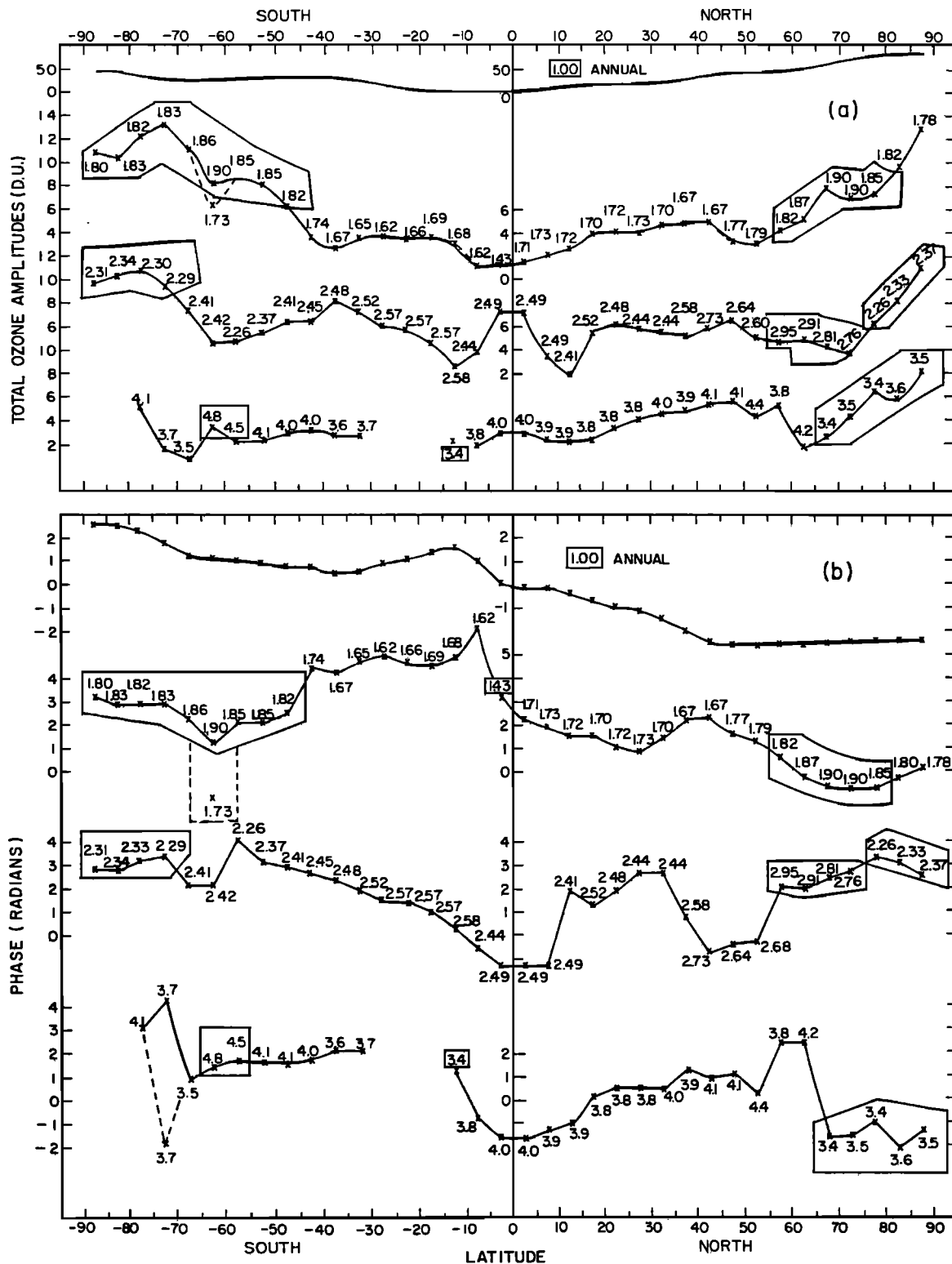


Figure 10. Plot of (a) amplitudes in Dobson units and (b) phases in radians, of the various periodicities (indicated by numbers) versus latitude. Periodicities that are slightly different from the group are marked.

(approximately -4 seasons) for a wide latitude range 15° – 45° in both hemispheres. For higher latitudes in the southern hemisphere the phase remained constant up to the polar region, but for higher northern latitudes the phase shifted from -4 seasons to $+4$ seasons from 45° to 85° latitude, indicating

complicating factors in the northern high latitudes. Thus there was considerable hemispheric difference.

3. A cross-correlation analysis of the equatorial eastern Pacific sea surface temperature with ozone showed low correlation in the equatorial region and higher correlations at non-

equatorial latitudes. There was considerable hemispheric difference.

4. The 30 mbar wind and the equatorial ozone had one strong peak at ~ 2.50 years (30 m) and another small peak at 5.0 years in wind and 4.0 years in ozone. At other latitudes, ozone had a small but significant peak near 1.70 years (20 m) in both the hemispheres and a peak near 2.4–2.6 years in both the hemispheres up to $\sim 55^\circ$ latitude. At higher latitudes this peak disappeared in the northern latitudes, and peaks near 3 years appeared, while in the southern latitudes this peak shifted to ~ 2.35 years. There were peaks near 4 years in the northern hemisphere but rarely in the southern hemisphere.

5. The amplitudes of the various peaks showed a gradual increase with latitude, except that at the equator the 30-m peak was as strong as those at the polar latitudes. The 20-m peak had opposite phases in the northern and southern latitudes. The 30-m peaks showed an almost gradual phase shift from 0° – 40° latitude, but with some indication of an abrupt change from 0° to 20° , particularly in the northern hemisphere. At higher latitudes the phase remained constant in the southern hemisphere but was erratic in the northern hemisphere, where the periods also changed. The 4-year peak seen mostly in the northern latitudes had a phase change from 1 to 5 rad from 0° – 50° latitude and from 5 back to 1 rad from 50° to the north polar region.

6. The results of an analysis of the original values (not the 12-month moving averages) were very similar to those of the analysis of the 12-month moving averages. In the northern hemisphere the phase of the 2.50-year (30 month) peak changed abruptly (roughly similar to *Yang and Tung* [1995]). In the southern hemisphere, there was an almost gradual phase change.

7. The analysis of original values also revealed persistent peaks at 0.7 years (8–9 months), which are probably the ~ 8 -month QBO-annual wave modulation peaks mentioned by *Bowman* [1989]. Persistent peaks were also observed at ~ 1.30 years (16 months) in low latitudes, which shifted to ~ 1.45 years (17–18 months) at higher latitudes. The other peaks also showed latitudinal shifts.

The characteristics of equatorial stratospheric zonal wind are well established. The wind oscillates between westerly and easterly directions with a period varying from 22 to 34 months. A time-height cross section [*Naujokat*, 1986] shows the progressive descent of the easterly and westerly winds and an asymmetry between their descending phases. The zonal wind is confined to $\sim \pm 15^\circ$ of the equator and is not strongly linked to the seasonal cycle [*Wallace*, 1973]. According to the theory of *Lindzen and Holton* [1968] and *Holton and Lindzen* [1972] the alternately descending westerlies and easterlies are driven by absorption in the stratosphere of vertically propagating equatorial Kelvin and Rossby gravity waves generated in the troposphere. The wave driving of the zonal flow produces a secondary mean meridional circulation (MMC), with descending motion along the equator during periods of westerly shear and ascending motion during easterly shear [*Plumb and Bell*, 1982]. The descending motion brings ozone-rich air from the higher stratosphere and increases the total ozone, which depicts a QBO similar to that of the wind. Thus the occurrence of QBO in equatorial ozone as well as temperature is well explained. However, the mechanisms for a QBO in the extratropical region seem to be controversial. Several mechanisms have been proposed. First, the equatorial QBO circulation could extend to higher latitudes. This is not favored because of its restriction

to $\pm 15^\circ$ of the equator, though *Plumb and Bell* [1982] produced a model in which the QBO circulation could extend up to 30° . Second, the seasonally varying mean meridional circulation (global MMC) may transport equatorial QBO ozone anomalies into the subtropics [*Holton*, 1989]. Here the extratropical QBO would have the same characteristics as the equatorial QBO. Third, there could be a combination of the two mechanisms mentioned above. The equatorial QBO would have a subtropical branch (out of phase with the equatorial branch), which could be carried to higher latitudes by the climatological mean and eddy circulations [*Gray and Pyle*, 1989; *Chipperfield and Gray*, 1992; *Gray and Ruth*, 1993]. A different type of theory [*Holton and Tan*, 1980] suggests that the equatorial zonal wind QBO could change the background flow and affect the vertical and meridional propagation of planetary-scale waves. *Hamilton* [1989] suggested that a connection between ozone at the equator and the subtropics could be due to stronger quasi-horizontal mixing of ozone in the lower stratosphere by planetary-scale waves during the westerly phase of the equatorial QBO. From his study of TOMS (1979–1987) data, *Bowman* [1989] had concluded that the abrupt phase shifts in ozone anomalies at $\sim 10^\circ$ latitude preclude the possibility that extratropical QBO was the result of quasi-horizontal transport of equatorial ozone anomalies to higher latitudes. Instead, the ozone anomalies resembled a seasonally modulated standing oscillation, possibly due to a quasi-biennial wave forcing of the planetary-scale MMC and the associated vertical advection of ozone. Recently, *Tung and Yang* [1994a, b] emphasized that the extratropical ozone QBO had only 20–30% of the equatorial 30-month QBO and a considerable portion was in the 20-month period, which could be thought of as the modulation of the seasonal anomaly (12-month period) by the 30-month period and hence needed the presence of an extratropical QBO anomaly in the transporting circulation. They proposed a simple mechanistic model based on the hypothesis that the extratropical QBO was caused by an anomalous seasonal circulation induced by an anomalous Eliassen–Palm (E–P) flux divergence, which may be caused in turn by the relative poleward and downward shift of the region of irreversible mixing (breaking) of the extratropical planetary waves during the easterly phase of the equatorial QBO as compared to its westerly phase. A higher tendency for the planetary waves to break in the easterly phase has been reported [e.g., *O’Sullivan and Salby*, 1990]. This model involves the indirect effect of the equatorial QBO in modulating the seasonal cycle of the extratropical circulation anomaly and hence results in the two periods 20 and 30 months in high-latitude ozone, with the maximum amplitude of the anomaly occurring during winter in the northern hemisphere and during late winter and early spring in the southern hemisphere. In the present paper, evidence is presented to show that the 16-month, 20-month, 30-month, and 4-year periods change their periodicities with latitude, some to higher periods, some to lower periods, in both the hemispheres. This is an abnormal feature and needs further investigation. Regarding the phase the 30-month equatorial component seems to extend up to $\sim 50^\circ$ latitude in both the hemispheres, with an almost gradual phase shift in the southern hemisphere but with four abrupt changes in the northern hemisphere. Part of it should be due to a combined effect of the equatorial QBO and its subtropical branch. The 4-year period seems to be seen more in the northern latitudes. For the equatorial region the ENSO effect is rather weak, overwhelmed by the wind effect. Nevertheless, *Shiotani* [1992] used equatorial ozone data at different

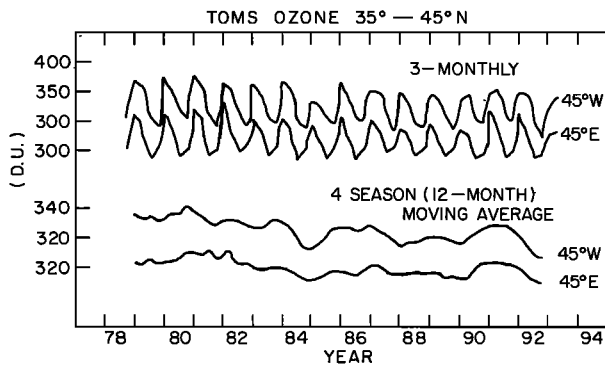


Figure 11. TOMS total ozone at 35°–45°N for two longitudes, 45°W and 45°E. Top plot is for 3-monthly values, and bottom plot is for 12-month moving average.

longitudes and isolated an east-west seesaw variation with a node around the dateline and a timescale of ~ 4 years. Hasebe [1993] derived mechanistic relationships describing the equatorial total ozone fluctuations in association with SST variations in terms of the advection effect and the tropopause effect (earlier termed as diabatic and adiabatic effects by Tung and Yang [1988]) and attributed the seesaw pattern of Shiotani [1992] to the tropopause effect. However, interaction between tropical and extratropical latitudes was not investigated. 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 solar backscattered ultraviolet (SBUV) on Nimbus 7. They reported that the wind QBO extended up to 2 mbar and that the ozone QBO was strong at all levels from 5 mbar 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. The shifting of periodicities remains a mystery. The QBO and QTO at middle and high latitudes may not be completely due to association with stratospheric equatorial zonal wind. ENSO also has a biennial component and a ~ 4 -year component [Rasmusson *et al.*, 1990]. Some tropospheric phenomena have QBOs, but these are dissimilar to the stratospheric wind QBO [Trenberth, 1980]. Meehl [1993] identified a biennial signal in the coupled ocean-atmosphere system and proposed mechanisms to explain the same. Yasunari [1989] presented evidence of a possible link of the QBOs between the stratosphere, troposphere, and sea surface temperature in the tropics. Reid [1994] and Kane and Buriti [1997] have shown that the tropospheric and stratospheric temperatures have QBOs not necessarily related to stratospheric winds and may have relations with ENSO also. Geller and Zhang [1991] illustrate a mechanism by which sea surface temperature variations can modulate tropical wave activity and a modulation in Kelvin and Rossby gravity waves will tend to force a stratospheric zonal flow oscillation with the same period as the oceanic QBO (~ 2.35 years). Geller [1993] and Reid and Gage [1993] discuss the troposphere-stratosphere-middle atmosphere coupling and the role of El Niño and the wind QBO. Thus some of the extratropical ozone periodicities may be related to tropospheric phenomena and/or their interaction with stratospheric winds. This needs further exploration.

In this paper, the TOMS data used were for 45°W longitude. For the equatorial region we tested one more longitude, and the 12-monthly plots were similar to those for 45°W. Also, our results tally with those of other workers [Yand and Tung, 1995]. For other latitudes, Figure 11 shows a plot for 35°–45°N, for longitudes 45°W and 45°E. Both the 3-monthly values as well as the 12-monthly moving averages are similar. Presently, a rigorous detailed analysis is in progress for checking whether the characteristics have any longitude dependence.

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