Differences in the quasi-biennial oscillation and quasi-triennial oscillation characteristics of the solar, interplanetary, and terrestrial parameters

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[1] The 12-month running means (12 m) and the parameter (12–36 m) representing the quasi-biennial oscillation (QBO) and quasi-triennial oscillation (QTO) were examined and spectrally analyzed for several solar, interplanetary, and terrestrial parameters. Solar indices (including solar open magnetic flux in solar latitudes <45°) had a QBO in the form of double peaks separated by ~2–3 years during sunspot maximum years and smaller waves in other phases of the sunspot cycle. In the interplanetary space a similar structure was seen only in interplanetary total magnetic field B. Interplanetary N and V had long-term variations different from solar variations. For ground-level solar proton events as well as all solar proton events observed in satellites and for geomagnetic Dst and Ap, a partial relationship with V (solar wind) is indicated. Cosmic rays observed on Earth seem to have peaks matching with those of solar indices. In the terrestrial atmosphere, stratospheric wind has a predominant QBO similar to solar indices, but the sequence is more uniform than that of the QBO of solar indices. The El Niño-Southern Oscillation (ENSO) indices (T-D) and Pacific sea surface temperature have overall characteristics different from those of stratospheric winds or solar indices. Thus there seem to be probably at least four QBO-QTO regimes, namely those of (1) solar indices at low solar latitudes, (2) interplanetary parameters near Earth, (3) terrestrial low-latitude stratospheric zonal winds, and (4) terrestrial ENSO phenomena.

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1. Introduction

[2] The term quasi-biennial oscillation (QBO) was first introduced in connection with the stratospheric low-latitude zonal winds by *Reed et al.* [1961] and *Veryard and Ebdon* [1961], who noticed that the winds were in one direction (say, westerly) for several months, reversed their direction (to say, easterly) within a month or two, continued to remain in that direction for several months, and then reversed again abruptly after a few months. The reversal occurred after about a year so that the complete cycle was of roughly 2 years and was considered initially as biennial, until it was discovered later that the spacing was more than 2 years and less than 3 years; hence the term QBO (2–3 years) was introduced. Even today, some workers (mostly meteorologists) reserve this term for stratospheric low-latitude winds only. Here, we use it in its general sense, namely, a variation of 2–3 year periodicity, in any parameter.

[3] A QBO has been noticed in the series of several parameters, for example in solar activity indices, geomagnetic indices, stratospheric ozone and temperatures, ENSO (El Niño-Southern Oscillation) phenomena, etc. In this communication, the characteristics of all these are examined in detail and compared, and it is shown that even though all these can be broadly termed as QBOs, these are qualitatively different.

2. QBO of Solar Indices

[4] The most prominent periodicity in solar indices (sunspot number, 2800 MHz flux, etc.) is, of course, the ~11-year periodicity. However, many higher and lower periodicities have been reported, namely, a ~88 year cycle [*Gleissberg*, 1965], a 22-year Hale magnetic cycle [*Hale*, 1924], periodicities of a few months [*Kane*, 2003, and references therein]. In particular, a QBO has been reported in many solar indices and the solar magnetic field [*Obridko and Shelting*, 2001; *Kononovich and Shefov*, 2002; *Knaack and Stenflo*, 2004, and references therein].

[5] Figure 1a shows for solar cycles 21, 22, and 23 (partial), a plot of the 3-month, 12-month, and 36-month running means of sunspot numbers Rz. The 3-month running means show considerable month-to-month variations, mostly erratic. The 12-month running means are smoother, and

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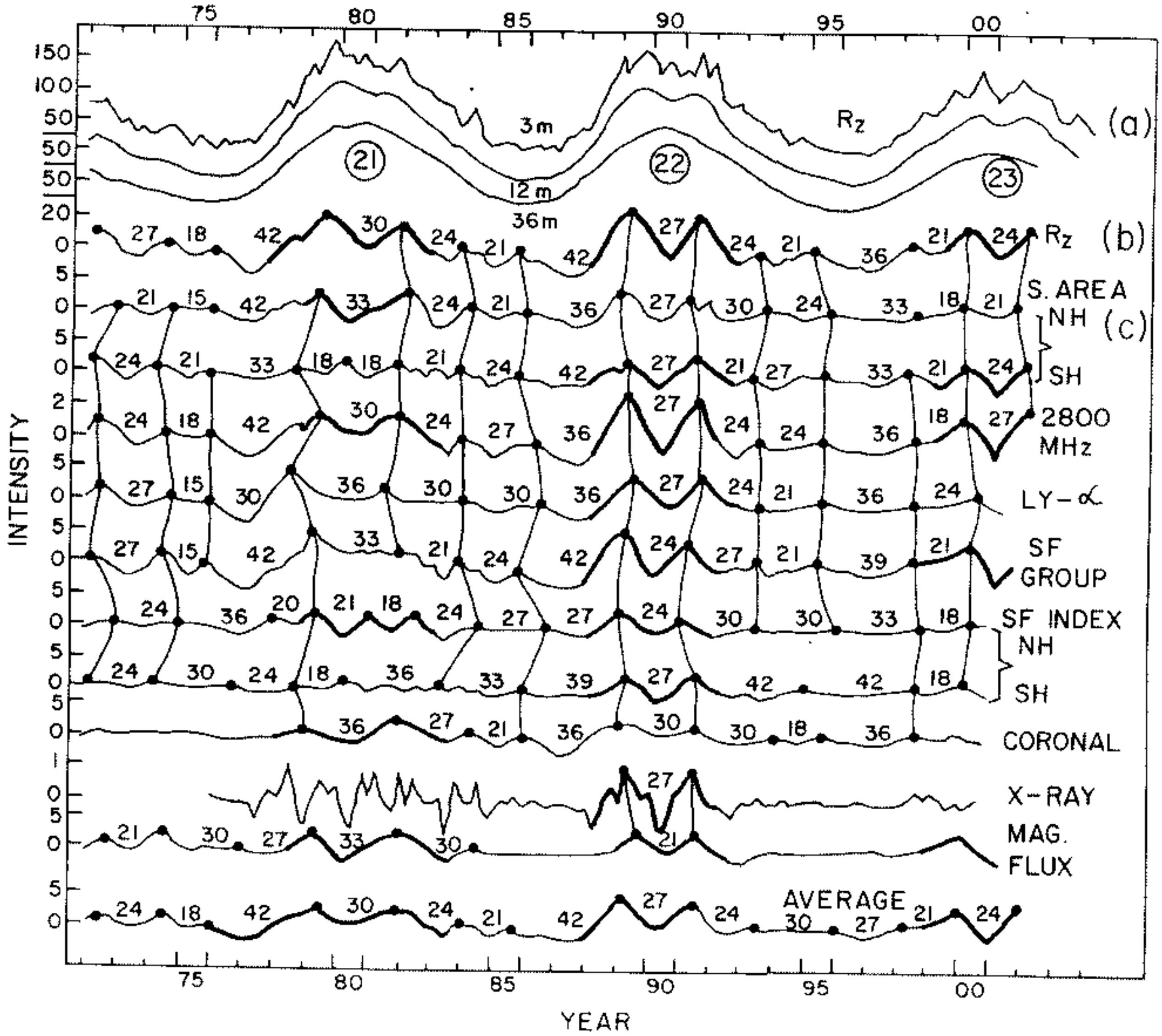

Figure 1. Plots of (a) 3 m, 12 m, 36 m running means of sunspot numbers Rz, (b) (12–36 m) of sunspot numbers Rz, (c) (12–36 m) of several other solar indices (units arbitrary). The bottom plot is for average of solar indices (excluding X rays). Thicker lines indicate double peaks near sunspot maxima.

double-humped structures near the solar maxima are seen. In the 36-month running means, only a strong 11-year cycle remains. To bring out the QBO, the 36-month running means are subtracted from the 12-month running means. The residues, henceforth termed as (12–36 m), are shown in Figure 1b. These show a series of peaks, with peak separations in a wide range (21–42 months). However, the prominent, large-amplitude peaks (marked by thick lines) are as double peaks near solar maximum, with peak separations of ~30 months in cycle 21, 27 months in cycle 22, and 24 months in cycle 23. Thus the QBO of Rz is not a uniformly regular occurrence. It is in the form of major double peaks near solar maxima and minor peaks in the descending, minimum and ascending phases of the solar cycle. In Figure 1c, similar plots of (12–36 m) are shown for several other solar indices (data from NOAA website), namely, sunspot area (northern (NH) and southern (SH) solar hemispheres), 2800 MHz radio emission, Lyman alpha, solar flare monthly group index SF, and its NH and SH parts, coronal green line intensity index, X ray background, and solar open magnetic flux for solar latitudes <45° [*Wang and Sheeley*, 2002]. All these show strong double peaks near solar maxima and comparatively small peaks on either side. An intercorrelation analysis between the (12–36 m) of all these solar indices showed positive correlations of 0.60 or more, except for correlations between NH and SH values of sunspot areas and solar flare indices, where correlations were poor (less than +0.40) and also with background X rays, where overwhelming effects of individual events seem to be still lurking. Hence an average was calculated for all indices except X rays and the average is plotted at the bottom of Figure 1. As expected, the major features are the double

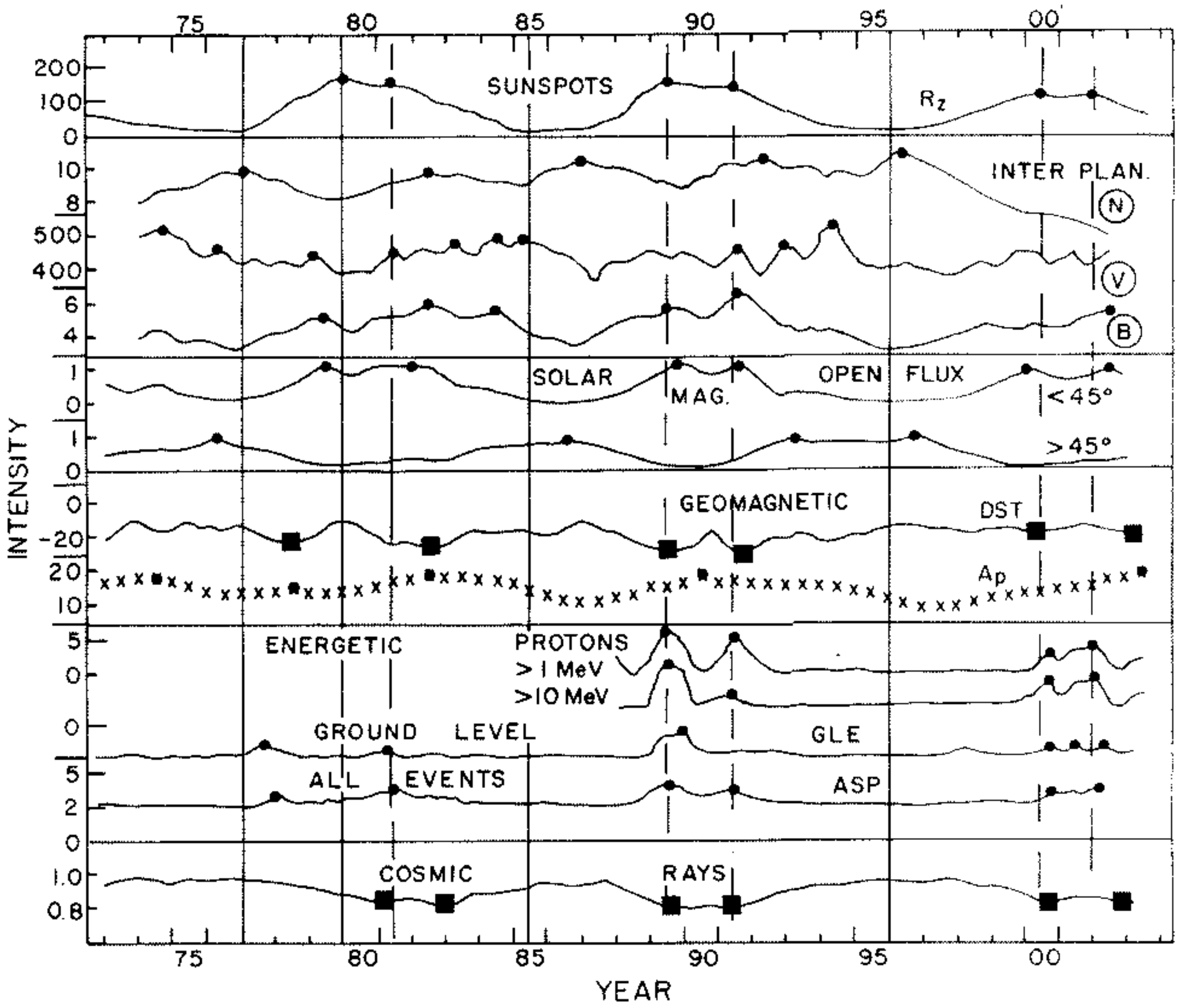

Figure 2. Plots of the 12-month running means of sunspot number Rz; interplanetary parameters (number density (N), solar wind velocity (V), total magnetic field (B)); solar magnetic open fluxes (<45° and >45° solar latitudes); geomagnetic indices: Dst and Ap; solar energetic proton fluxes (energies exceeding 1 and 10 MeV); cosmic ray flux (average of neutron monitor intensities at Calgary, Kiel, Moscow, Climax) (units arbitrary). The maxima are marked by dots. Minima for Dst and cosmic rays are marked by full squares. Vertical lines mark sunspot minimum years.

peaks at solar maxima 1979–1981, 1989–1991, and 1999–2001, with smaller oscillations in between.

3. QBO of Interplanetary Parameters

[6] Figure 2 shows a plot of the 12-month running means of sunspot number; interplanetary parameters (number density (N), solar wind velocity (V), total magnetic field (B)); solar magnetic open fluxes (<45° and >45° solar latitudes); geomagnetic indices: Dst and Ap; solar energetic proton fluxes (energies exceeding 1 and 10 MeV) [*Bazilevskaya et al.*, 2001]; cosmic ray flux (average of neutron monitor intensities at Calgary, Kiel, Moscow, Climax). The maxima are marked by dots. The long-term variations are not similar for all these parameters. In particular, the double peaks near sunspot number Rz maxima are matched by solar open magnetic flux for solar latitudes <45° (but not for solar latitudes >45°), by proton fluxes, by cosmic ray decreases (marked by full squares), partly by interplanetary total magnetic field B, partly by geomagnetic Dst decreases (shown by full squares), and not at all by interplanetary N and V. Intercorrelations were calculated for a series of ~100 or more data points. Different correlation levels had different 2σ errors (95% confidence levels) as 0.20 ± 0.18, 0.40 ± 0.16, 0.60 ± 0.12, 0.80 ± 0.06. For the 12-month running means (12 m), the following was noted:

[7] 1. Sunspots had highly significant positive correlations with interplanetary magnetic field B ($+0.77 \pm 0.06$), solar open magnetic field for latitudes <45° (+0.91), all solar proton (ASP) events (+0.84), and good negative correlation with cosmic rays (−0.85), as expected.

[8] 2. Solar open magnetic fields for latitudes <45° and >45° were highly negatively intercorrelated (−0.82), indicating radically different evolutions of solar magnetic fields

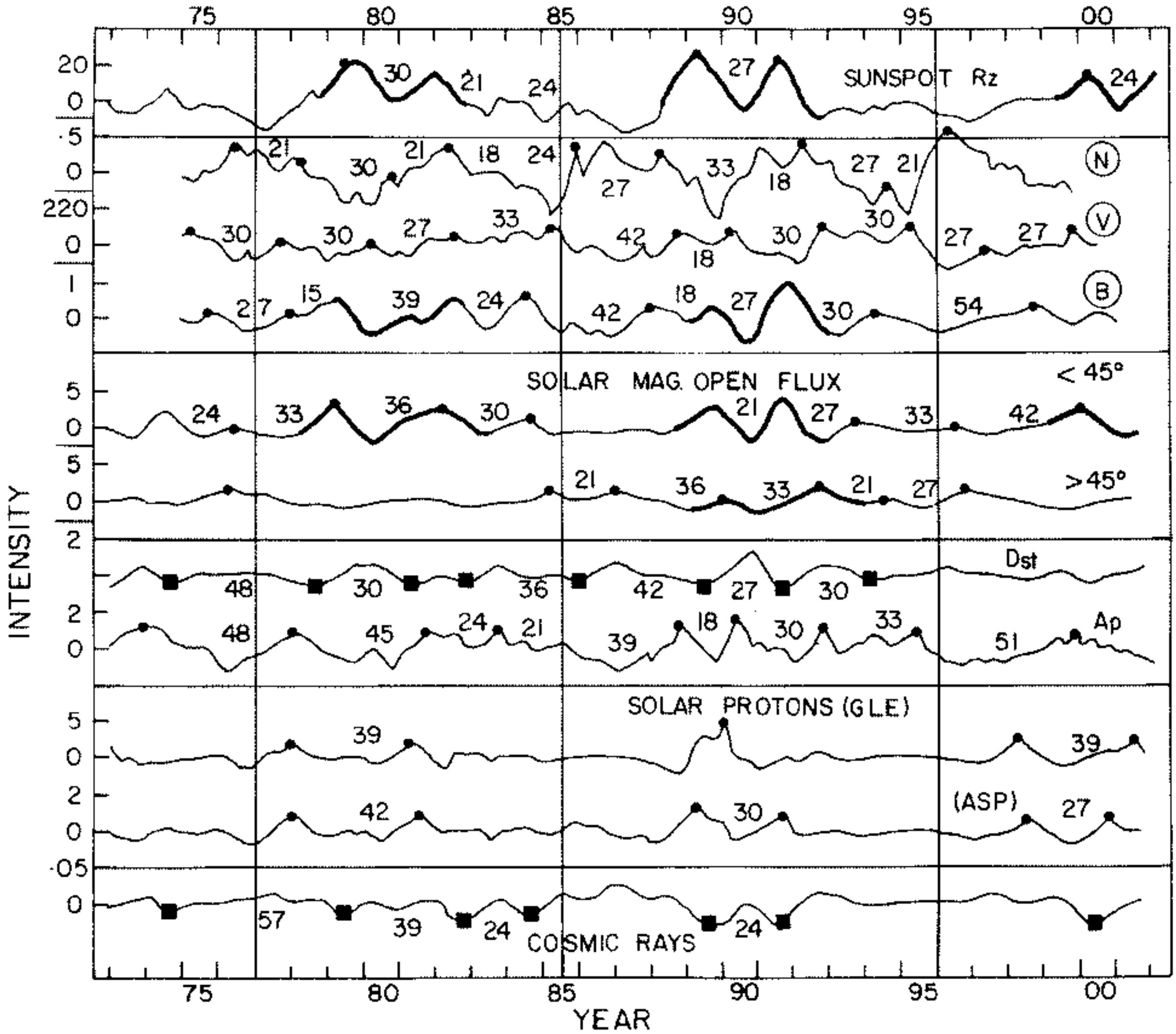

Figure 3. Plots of the parameter (12–36 m) for sunspot number Rz; interplanetary parameters (number density (N), solar wind velocity (V), total magnetic field (B)); solar magnetic open fluxes (<45° and >45° solar latitudes); geomagnetic indices: Dst and Ap; solar energetic proton fluxes (energies exceeding 1 and 10 MeV); cosmic ray flux (average of neutron monitor intensities at Calgary, Kiel, Moscow, Climax) (units arbitrary). The maxima are marked by dots. Minima for Dst and cosmic rays are marked by full squares. Vertical lines mark sunspot minimum years. Thicker lines indicate double peaks near sunspot maxima.

at low and high solar latitudes during the sunspot cycle. Hence sunspots also had a high negative correlation (antiparallelism) with open flux >45° (−0.88).

[9] 3. Whereas interplanetary B variation had some resemblance with sunspots, interplanetary N and V had variations very unlike those of sunspots and B and very unlike each other. They were not even anticorrelated (correlations were very low, <0.40). N variation had some resemblance with high-latitude solar open magnetic field (+0.61 ± 0.12).

[10] 4. Interplanetary V had a good correlation with geomagnetic Ap (+0.70), in agreement with the linear relationship reported long ago between solar wind velocity and Kp [*Snyder et al.*, 1963], but V was not well correlated with Dst. The Dst had a good correlation (−0.69) with interplanetary B, probably because of the Bz component, which is large negative during geomagnetic storms. Thus Dst was related to Bz while Ap was related to V, and Ap had only a low negative correlation (−0.39 ± 0.16) with Dst because V and B were poorly correlated (+0.15).

[11] 5. Ground-level energetic proton events (GLE) were well correlated (+0.73) with all solar proton events (ASP) observed by satellites and moderately correlated with sunspots (+0.53).

[12] Figure 3 shows the parameter (12–36 m) for all these indices. The double peaks near sunspot maxima are now seen prominently (marked by thick lines) only in sunspot numbers, solar open magnetic flux (<45° latitude), and partly in interplanetary B, energetic protons, and cosmic rays, indicating that the solar emission characteristics are

not transmitted fully to interplanetary parameters and still less to geomagnetic indices. Intercorrelations showed the following:

[13] 1. Sunspots Rz had good positive correlation only with solar magnetic flux in low latitudes (<45°, +0.66). Correlation with solar magnetic flux in high latitudes (>45°) was also high (−0.67) but negative, indicating that the open magnetic fluxes in <45° and >45° have QBO variations opposite to each other. If these extend into interplanetary space, the effects could be different at different locations in the heliosphere.

[14] 2. Sunspots and cosmic rays had a moderate negative correlation (−0.59). Correlations of sunspots with all other parameters were low.

[15] 3. Interplanetary N had low correlations with all parameters except interplanetary V for which the correlation was negative (−0.60).

[16] 4. Interplanetary V was well correlated (+0.72) with geomagnetic Ap.

[17] 5. Interplanetary B was well correlated with geomagnetic Dst (−0.69, probably due to the relationship with the Bz component) and also with solar open magnetic flux (<45° latitude), indicating that this flux spreads into interplanetary space around the Earth.

[18] 6. Since N, V, B, Dst, and Ap all show QBOs with amplitudes almost constant all through 1971–2000, these should not be related to QBOs of solar indices, which are strong during sunspot maxima and weak during and near sunspot minima.

[19] 7. For geomagnetic indices, QBO of Ap seem to be related to QBO of interplanetary V, and QBO of Dst seem to be related to QBO of interplanetary B. Since QBOs of interplanetary V and B were unrelated (+0.05), these two should be considered as separate, unrelated entities. QBO of B was moderately related (+0.44) to QBO of sunspots and well related (+0.66) to QBO of solar open magnetic flux (<45° latitude).

[20] The long-term variations of interplanetary parameters and geomagnetic indices have been studied earlier. *Feynman* [1982] noticed that whereas the solar wind drives the geomagnetic activity, the 11-year sunspot cycle was very different from the 11-year cycle of solar wind. The latter could be decomposed into an "R" component (due to sporadic or short-lived solar events) with the phase and amplitude of the sunspot cycle and, an "I" component (due to long-lived solar features as coronal holes), almost 180° out of phase with the "R" component. *Gorney* [1990, and references therein] mentioned a major peak occurring during the declining phase of the sunspot cycle and a secondary minor peak occurring near the sunspot maximum. *Kane* [1997] analyzed data of aa indices for 1868–1994 and reported QBOs and quasi-triennial oscillations (QTOs) almost absent near sunspot minima and present mostly as 2 or 3 peaks, one near or before the sunspot maximum and the others (one or two) in the declining phase of the sunspot cycle. However, a considerable variation from one cycle to another was indicated. From Figures 2 and 3, one can see that the QBO patterns of N, V and Ap are very different from each other in cycles 21, 22, and 23, and phase relationships with sunspot maxima are also highly variable. *Gnevyshev* [1967] pointed out a double-peak distribution in the intensity of some coronal processes and *Gonzalez and Gonzalez* [1987] reported 1.5 and 3.7-year periodicities in interplanetary magnetic field (IMF) polarity, but these features do not seem to be reflected as such in N or V. Some other complicating factors seem to be involved in producing the QBOs of N and V, which are qualitatively different from the QBOs of solar indices.

4. QBO of Terrestrial Parameters

[21] On the Earth, two phenomena have received considerable attention in recent decades. One is the phenomenon of ENSO (El Niño-Southern Oscillation) where the waters in Pacific have sudden warmings (El Niño near the Peru-Ecuador coast, occurring with a frequency of 2–7 years) accompanied by reduced values of the Tahiti minus Darwin atmospheric pressure difference (T-D). Another is the oscillation in the low-latitude stratospheric zonal wind, identified as a QBO. Figure 4a shows a plot of the 12-month running means of (T-D). The negative values are painted black and represent well-documented El Niño events (years marked, from *Quinn et al.* [1987] and updates). The events are spaced in a wide range of 2–7 years, and a QBO is not very obvious (average spacing is ~4 years, more like a QTO). Figure 4b shows a plot of (12–36 m) for sunspots, where a QBO is prominent only as double peaks near sunspot maxima (vertical lines mark sunspot minima). Figure 4c shows a plot of the 12-month running means of the 30-mb level low-latitude zonal wind [*Naujokat*, 1986; B. Naujokat, private communication, 2004]. A remarkably uniform sequence of QBO is seen, though the spacing in successive peaks is not constant (varies in a range of 24–33 months). The succeeding plots Figure 4d are for 12-month running means (actually, only two value running means over successive winter and summer values) of mesospheric and stratospheric temperatures at northern hemisphere middle latitudes, for altitudes 108, 97, 92, 87, 80, 70, 60, 50, 40, 30 km [*Semenov et al.*, 2002], and 16–25 km [*Angell*, 2003]. As can be seen, at 108, 97, and 92 km, there are some double peaks but these are not matching with sunspot double peaks, contrary to the claim of *Kononovich and Shefov* [2002]. At 87 and 82 km, the QBOs are weak, and the main feature is a long-term cooling since ~1975 to ~1986. At lower altitudes, the QBO is more prominent, but the peaks do not match with each other.

[22] Intercorrelations indicated the following:

[23] 1. Many correlations were low (<0.40) indicating, in general, poor relationships.

[24] 2. Sunspots had a moderate but negative (−0.43 ± 0.16) correlation with temperature at 108 km, mainly because some double peaks occurred in the temperature series at solar minima (vertical lines). This is certainly not what *Kononovich and Shefov* [2002] envisaged.

[25] 3. The ENSO index (T-D) had moderate positive correlations with temperatures at 87 km (+0.46) and 80 km (+0.51) altitudes, but low correlations for temperatures at all other altitudes.

[26] 4. The 30 mb wind had a good correlation (+0.61 ± 0.12) only with stratospheric temperatures in the 16–25 km altitude range (100–30 mb).

[27] 5. Temperatures at 108, 97, 92 km were poorly correlated with each other, but 108 km had moderately negative correlations with 87 and 80 km temperatures.

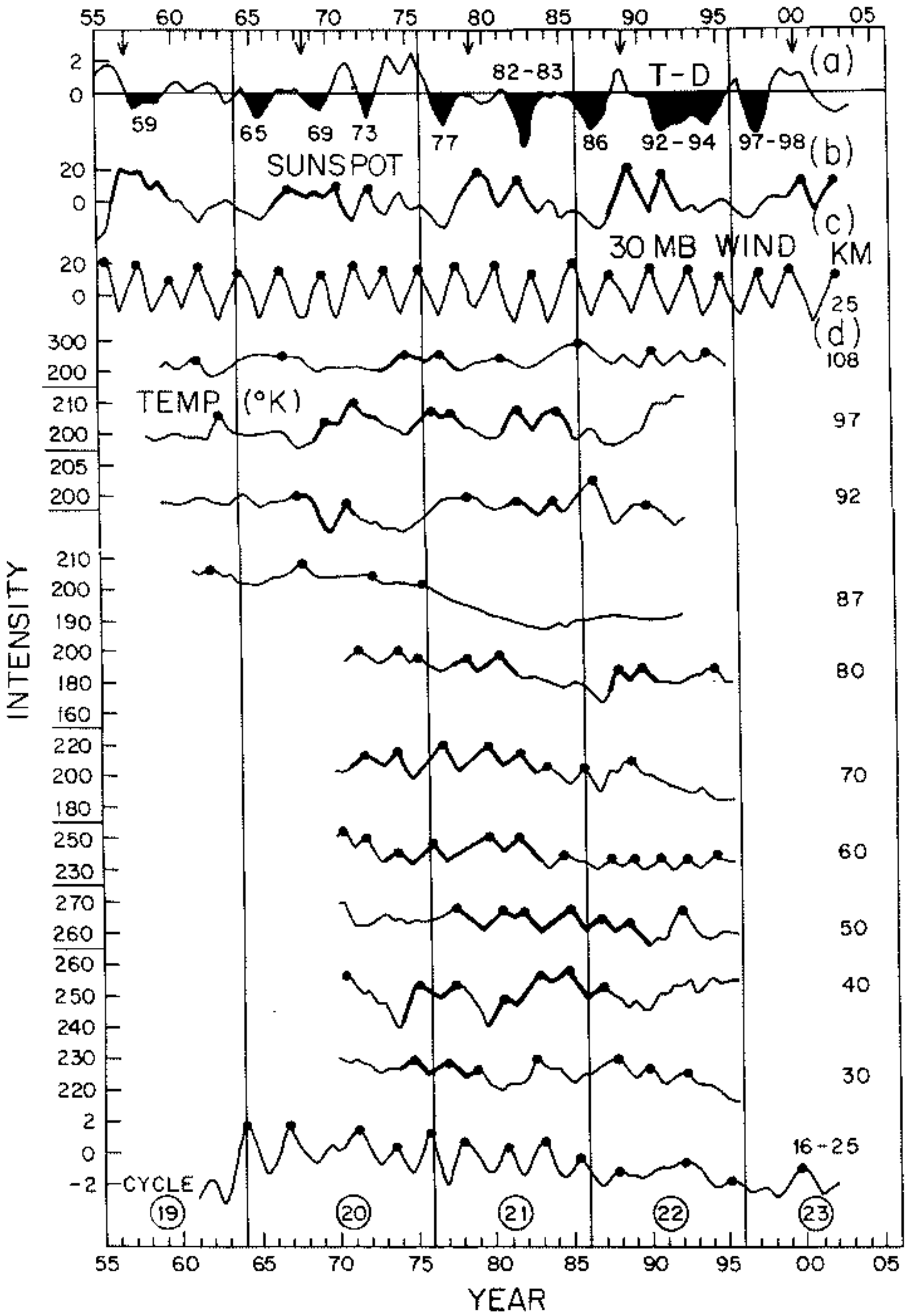

Figure 4. Plots of (a) 12-month running means of ENSO index (T-D) (negative values painted black representing El Niño events), (b) (12 36 m) for sunspots, (c) 12-month running means of the 30-mb level low-latitude zonal wind, (d) 12-month running means of mesospheric and stratospheric temperatures at northern hemisphere middle latitudes, for altitudes, 108, 97, 92, 87, 80, 70, 60, 50, 40, 30 km, and 16–25 km (units mostly arbitrary). The maxima are marked by dots. Vertical lines mark sunspot minimum years. Arrows indicate sunspot maxima. Thicker lines indicate double peaks.

However, a visual inspection indicated erratic behaviors, with QBOs only as isolated double peaks, phase shifted with respect to each other.

[28] 6. Temperatures at altitudes below 87 km seemed to have striking QBO oscillations with moderate or good (~+0.60) intercorrelations, indicating a partly common origin.

[29] Figure 5 shows a plot of the 12-month running means of (Figure 5a) 30 mb wind, (Figure 5b) two ENSO indices, namely (T-D) and the sea surface temperatures (SST) in the Nino 1 + 2 region near Peru-Ecuador coast (black portions mark EL Niño events), (Figure 5c) Total Ozone Mapping Spectrometer (TOMS) total ozone in low latitudes, (Figure 5d) tropospheric and low stratospheric

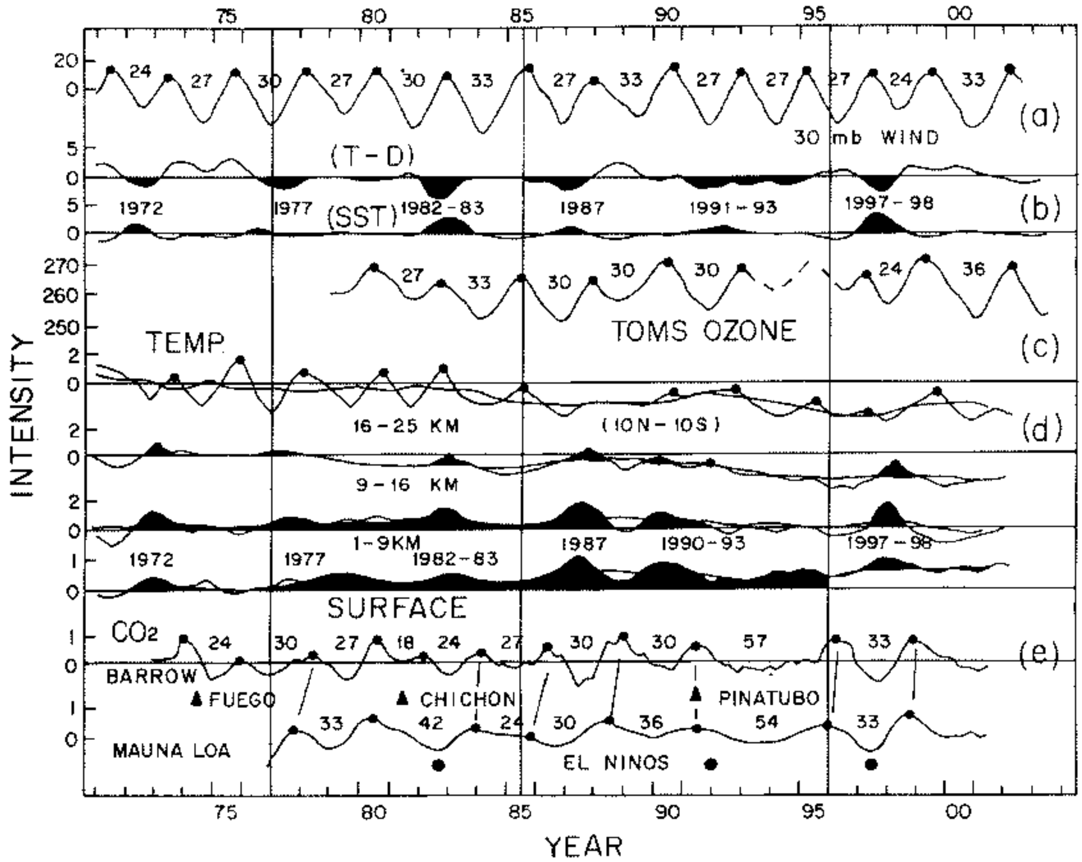

Figure 5. Plots of the 12-month running means of (a) 30 mb wind, (b) two ENSO indices, namely (T-D) and the sea surface temperatures (SST) in the Nino 1 + 2 region near Peru-Ecuador coast (black portions mark EL Niño events), (c) Total Ozone Mapping Spectrometer (TOMS) total ozone in low latitudes (dashes show missing data, (d) Tropospheric and low stratospheric temperatures in low latitudes (10°N 10°S) (e) Carbon dioxide concentrations at Barrow (70°N) and Mauna Loa (20°N). Vertical lines mark sunspot minimum years. Full triangles represent volcanic eruptions.

temperatures in low latitudes (10°N–10°S) [*Angell*, 2003], (Figure 5e) carbon dioxide concentrations at Barrow (70°N) and Mauna Loa (20°N) (NOAA/CMDL website). Intercorrelations indicated the following:

[30] 1. The low-latitude 30 mb wind was highly correlated (+0.77 ± 0.06) with low-latitude TOMS ozone and moderately correlated (+0.51) with low-latitude lower-stratosphere (16–25 km, 100–30 mb) temperatures. Thus in this region, there was almost a perfect harmony between winds, ozone, and temperatures. There was no relationship with tropospheric temperatures at lower altitudes.

[31] 2. The index (T-D) was negatively correlated (−0.69) with Pacific SST, as expected (El Niño events). The correlation was not very high because in different events, the two indices do not change fully alike (e.g., in 1991–1994, SST variations were very modest but T-D variations were large). (T-D) seemed to be negatively correlated with middle tropospheric (850–300 mb) and surface temperatures (−0.55 and −0.37), while SST was positively correlated, indicating El Niño influences in the lower and middle troposphere.

[32] 3. Temperatures in adjacent layers (100–30, 300–100, 850–300, surface) had moderate positive intercorrelations, probably because higher layers have lesser ENSO effects and larger wind effects. However, surface temperatures seemed to have negative correlation (0.62) with stratospheric temperatures, probably indicating the well-known tropospheric warming associated with stratospheric cooling.

[33] 4. The CO_2 variations at Barrow and Mauna Loa were not fully alike (+0.55 only) but both were unrelated to 30 mb wind (0.20 or less) and moderately related to (T-D) (~+0.50) and SST (~−0.50), indicating some ENSO influence. However, there could be complications due to volcano effects (Fuego in 1974, Chichon in 1981, Pinatubo in 1991, marked in Figure 5 by full triangles near CO_2 plots).

5. Spectral Analysis

[34] A spectral analysis gives the average characteristic of a time series, and for series where the characteristics are not stationary (e.g., strong QBO in some part and none in the other), the average value may not be very meaningful. Nevertheless, comparison of average characteristics for simultaneous intervals may reveal broad differences in characteristics, if there are any. To obtain quantitative estimates of the spectral characteristics of the interannual variability, all the series were subjected to spectral analysis by maximum entropy method (MEM) [*Burg*, 1967; *Ulrych*

and Bishop, 1975], which locates peaks much more accurately than the conventional BT [*Blackman and Tukey*, 1958] method. However, the amplitude (power) estimates in MEM are not very reliable. Hence MEM was used only for detecting all the possible peaks T_k (k = 1 to n), using length of the prediction error filter (LPEF) as 30% and 40% of the data length. These T_k were then used in the expression:

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

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 estimate A_o (a_k, b_k), and their standard errors (by a least-square fit). From these, amplitudes r_k and their standard error σ_k (common for all r_k in this methodology, which assumes white noise) were calculated. Any r_k exceeding $2\sigma_k$ is significant at a 95% (a priori) confidence level.

[35] Figure 6 shows the spectra (amplitudes, versus periodicities T detected by MEM) for the series of the parameter (12–36 m) of solar indices plotted in Figure 1 for 1971–2001. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level. Since running mean is not bandpass limited, it allows leakage of many high-frequency components with periods shorter than the length of the filter. Thus periodicities less than 12 months may appear spuriously. These are ignored here, as the main purpose is to study the QBO. Also, use of the 36-month running mean may introduce some spurious peaks. To check this, a spectral analysis was carried out for (12–48 m) and (12–60 m), i.e., with filters of 48-month and 60-month running means. These showed spectra similar to those of (12–36 m), indicating that the leakage problems were negligible second-order effects. Most of the solar indices in Figure 1 showed strong double peaks near solar maxima and small peaks before and after solar maxima (including solar minima). Here, their spectra show prominent peaks near 2.5 (QBO), 3.3 (QTO), 5.4 years, but the most prominent peak is near 9.5 years, indicating that the double peak structure repeats with a roughly solar cycle frequency. Also, whereas the sunspot areas in the northern (NH) and southern (SH) hemispheres have similar spectra (peaks near 2.5, 3.2, 5.0, 9.5 years), the solar flare (SF) indices for NH and SH have differences (NH has 3.5 years while SH has 2.9 years).

[36] *Kononovich and Shefov* [2002, and references therein] used MEM and found a lot of unstable frequencies in the range of periods 3 to 0.7 years and a lot of noise in the solar variations, while the method of principle components showed, as a main feature, two prominent maxima near sunspot maxima, with nearly equal amplitudes but different widths in different cycles 12–17. When they represented QBO by Airy functions, they found that for all cycles, these were a superposition of a triad of consecutive, nearly equal extinction wave trains appearing regularly with 10–11 years interval. The wave period was found to be about 38 months at epoch of sunspot maxima, linearly diminishing to 21 months toward the cycle end. For cycles 21, 22, and 23, we found different widths for the double peaks (~30, 27, and 24 months, respectively).

[37] Figure 7 shows the spectra for the parameter (12–36 m) for interplanetary parameters, etc. (as in Figure 3), for 1975–2001. The spectra of QBO and other periodicities are almost similar for sunspots and interplanetary N (peaks near 2.0, 2.5, 5.0, 9.8 years), but sunspots have a QTO peak near 3.2 years which is missing in N. For interplanetary V, there is an extra peak at 4.0, while for interplanetary B, the sunspot peak at ~5.2 is shifted to 4.6 years. The solar open magnetic flux (<45°) has spectra very similar to sunspots, but for open flux (>45°) the sunspot peak at 3.2 years is missing. Thus the 3.2-year peak seems to be confined to low solar latitudes. Geomagnetic Dst and Ap have slightly different peaks (5.1 and 5.4 years, respectively), and both have a peak near 3.5 years, different from the sunspot peak 3.2 years. Ground-level energetic particle events (GLE) and all solar proton events (ASP) have peaks at ~2.8 and 3.9 years, different from the sunspot peaks 3.2, 5.2 years, though the ~3.9 years is similar to 4.0 years of V. Cosmic rays (CR) have peaks almost similar to sunspots. Thus for all these parameters, some peaks are similar to sunspots but some others are significantly different. In the QBO region, sunspots, N, V, B, open fluxes (<45° and >45° both), and Ap have a peak in the 2.4–2.6 year range, but others have significantly different peaks, at 2.2, 2.3, or 2.7, 2.9, 3.0 years. Thus only a partial connection with sunspots is indicated. The unrelated peaks may have evolved in interplanetary space or may be related to solar phenomena like coronal holes, etc., which evolve differently from sunspots.

[38] Figure 8 shows for 1970–1992 the spectra for sunspots (12–36 m), and for (12 m) of the ENSO index Tahiti minus Darwin pressure difference (T-D) and low-latitude 30 mb zonal winds, and midlatitude temperatures at 108, 97, 92, 87, 80, 70, 60, 50, 40, 30, 16–25 km altitudes (plots of Figure 4). The 30 mb wind has just one prominent QBO peak at 2.4 years. Interestingly, sunspots and (T-D) also have a similar QBO peak, but it is small, and a larger peak is at ~5.0 years (there is a small peak near 3.3 years). The resemblance between the spectra of sunspots and (T-D) is remarkable and it is tempting to claim an association between the two, but sunspots have a strong peak at ~10 years, which is missing in (T-D). The ~5-year peak in (T-D) is mainly because the El Niños seem to have occurred with a spacing of 4–6 years. *Nuzhdina* [2002] claims from a correlation and spectral analysis, a reasonable connection between solar activity, geomagnetic variations, and the cyclic dynamics of ENSO phenomena. Earlier, *Diamantides* [1998] considered the 11-year solar cycle as modulating the long-term dynamics of the Southern Oscillation during 100 years (1890–1990). However, no physical mechanism of such a connection is offered. A relationship between ENSO and 30 mb wind was discussed by *Angell* [1992], particularly for the El Niño of 1991–1992, but for the recent El Niño of 1997–1998 no relationship is seen [*Kane*, 2004]. The traditional view that ENSO is an internal cycle of positive and negative feedback within the coupled ocean-atmosphere climatic system in the tropical Pacific [*Graham and White*, 1988, and references therein] probably still holds, and a physical connection with seismic events in the Pacific bottom is also hinted [e.g., *Walker*, 1995].

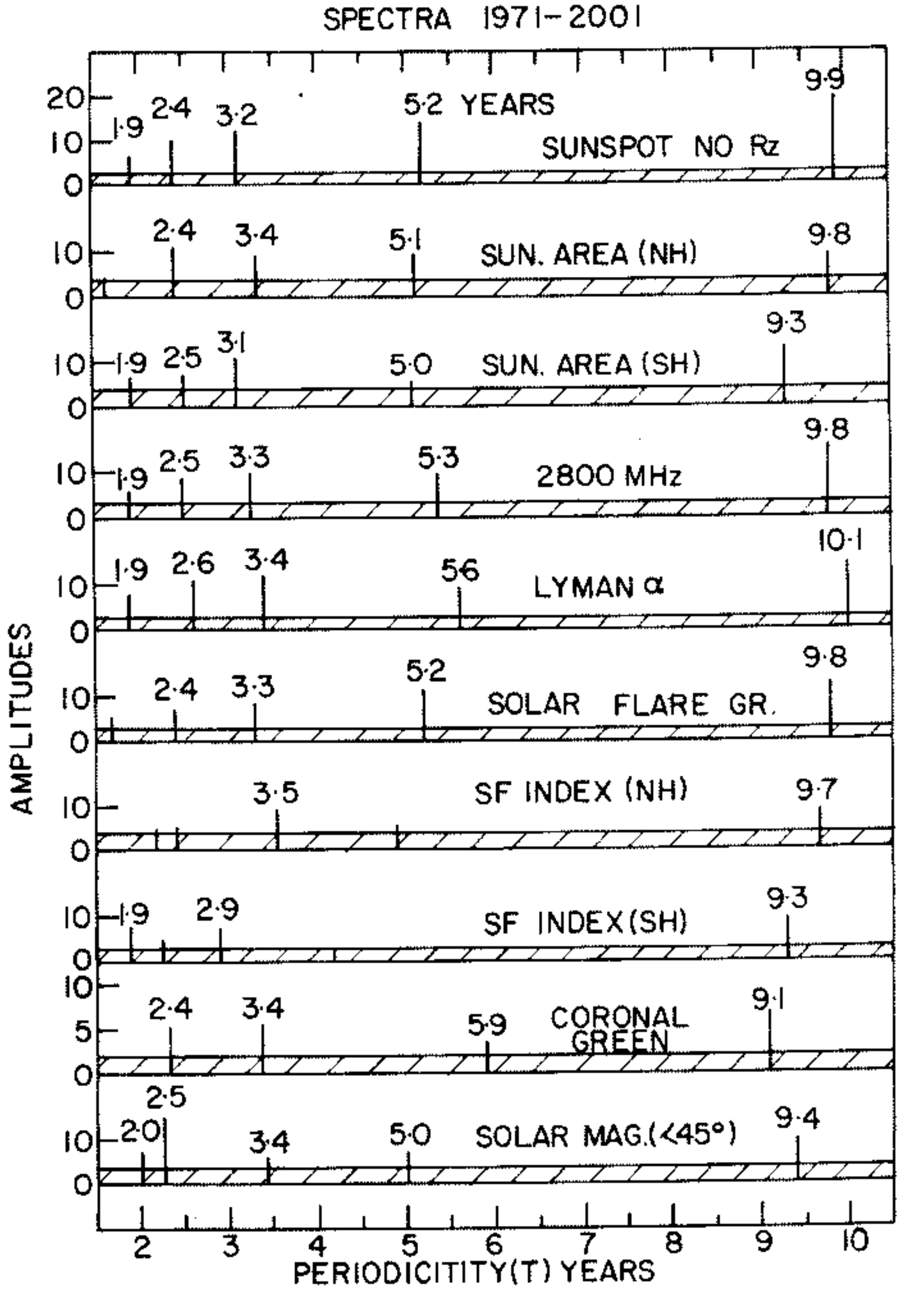

Figure 6. Spectra (amplitudes *versus* periodicities T in years, detected by maximum entropy method (MEM)) for the series (1971–2001) of the parameter (12–36 m) of various solar indices. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level.

[39] For temperatures, Figure 8 shows for 108 km only a significant periodicity of 5.1 years (same as for sunspots) and an insignificant QBO periodicity of 2.3 years. At 97 and 92 km, there are barely significant QBO periodicities at 2.6–2.7 years (different from the 2.4 years of sunspots). Thus the QBO connection of these temperatures with sunspot activity mentioned by *Kononovich and Shefov* [2002] seems to be uncertain. At 87 and 80 km, there are no significant periodicities. At 70, 50, 16–25 km, there is a QBO periodicity at 2.4 years which matches with sunspots, but it matches with 30 mb wind and (T-D) also. Hence solar connection is doubtful. Incidentally, the QBO of the 30 mb wind has been theoretically explained by *Lindzen and Holton* [1968] and *Holton and Lindzen* [1972] in terms of absorption in the stratosphere of vertically propagating equatorial Kelvin and Rossby-gravity waves generated in the troposphere. No connection with solar activity is envisaged, except that recently, *Salby and Callaghan* [2000] have suggested that some properties of the wind QBO may vary slightly on the 11-year solar cycle timescale (solar modulation of terrestrial stratospheric wind QBO) and *Soukharev and Hood* [2001] present additional statistical evidence for

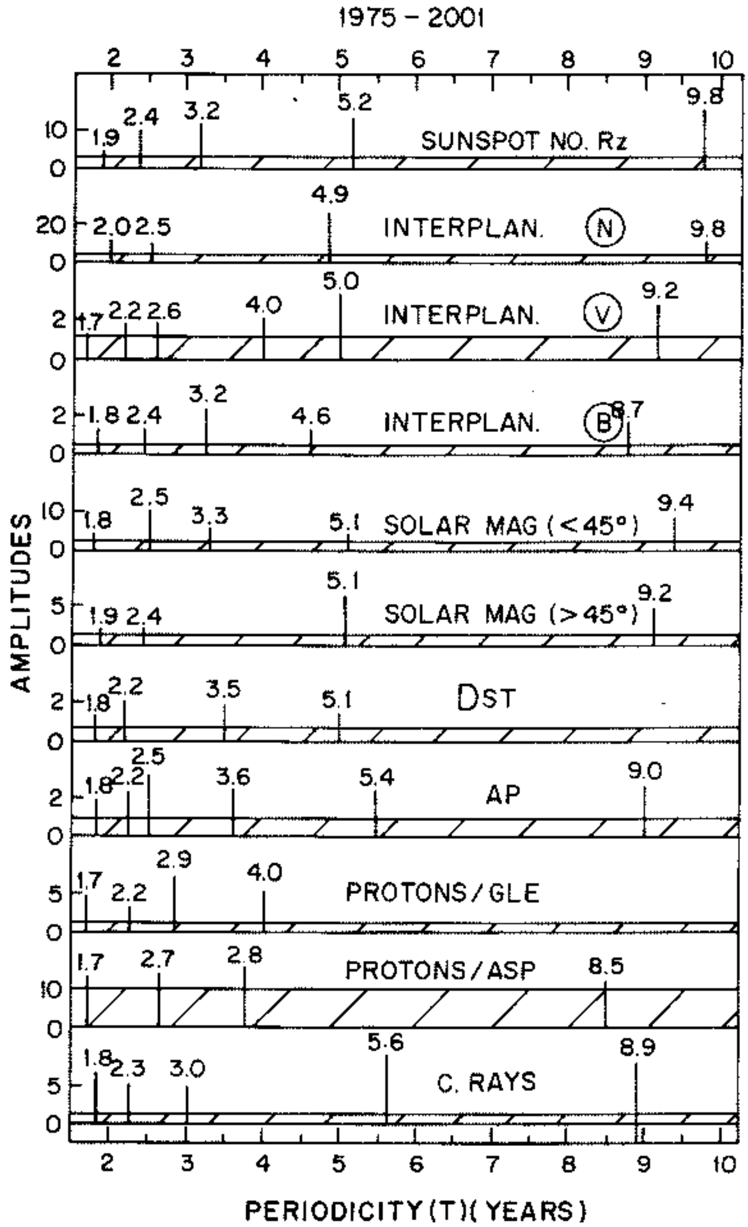

Figure 7. Spectra (amplitudes versus periodicities T in years, detected by MEM) for the series (1975–2001) of the parameter (12–36 m) of various solar, interplanetary, and geomagnetic indices. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level.

the modulation of the QBO near the stratopause by the radiative and photochemical effects of solar ultraviolet variations (the durations of the westerlies and easterlies of the equatorial zonal winds show subtle differences between solar maximum and minimum conditions).

[40] Figure 9 shows for 1971–2001 (plots of Figure 4), the spectra for (12 m) of the 30 mb wind and the ENSO indices Tahiti minus Darwin pressure difference (T-D) and Pacific sea surface temperature anomalies (SST), TOMS low-latitude ozone, zonal low-latitude temperatures at 16–25, 9–16, 1–9 km and surface, and (12–36 m) of CO_2 concentrations at Barrow (70°N) and Mauna Loa (20°N). As before, 30 mb wind has one prominent QBO peak at 2.4 years. The ENSO indices (T-D) and SST also have small QBOs near 2.5 years but have larger peaks at ~3.7 (QTO) and 5.1 years. TOMS ozone has 2.4 (QBO) and 4.7 year peaks, very similar to 30 mb wind, indicating very good parallelism. Temperatures at surface and 850–300 mb have 2.6 (QBO) and 3.7 (QTO) years, similar to (T-D) and SST, indicating ENSO influence, but the 5.1 year ENSO peak is missing in these temperatures. The 300–100 mb temperature has an insignificant QBO and has prominent peaks at 3.8 (QTO) and 4.6 years, somewhat similar to the 3.6–3.8 and 5.1–5.2 years of ENSO. The temperature at 100–30 mb (16–25 km), as well as the CO_2 concentrations at Barrow and Mauna Loa have 2.5 (QBO) and

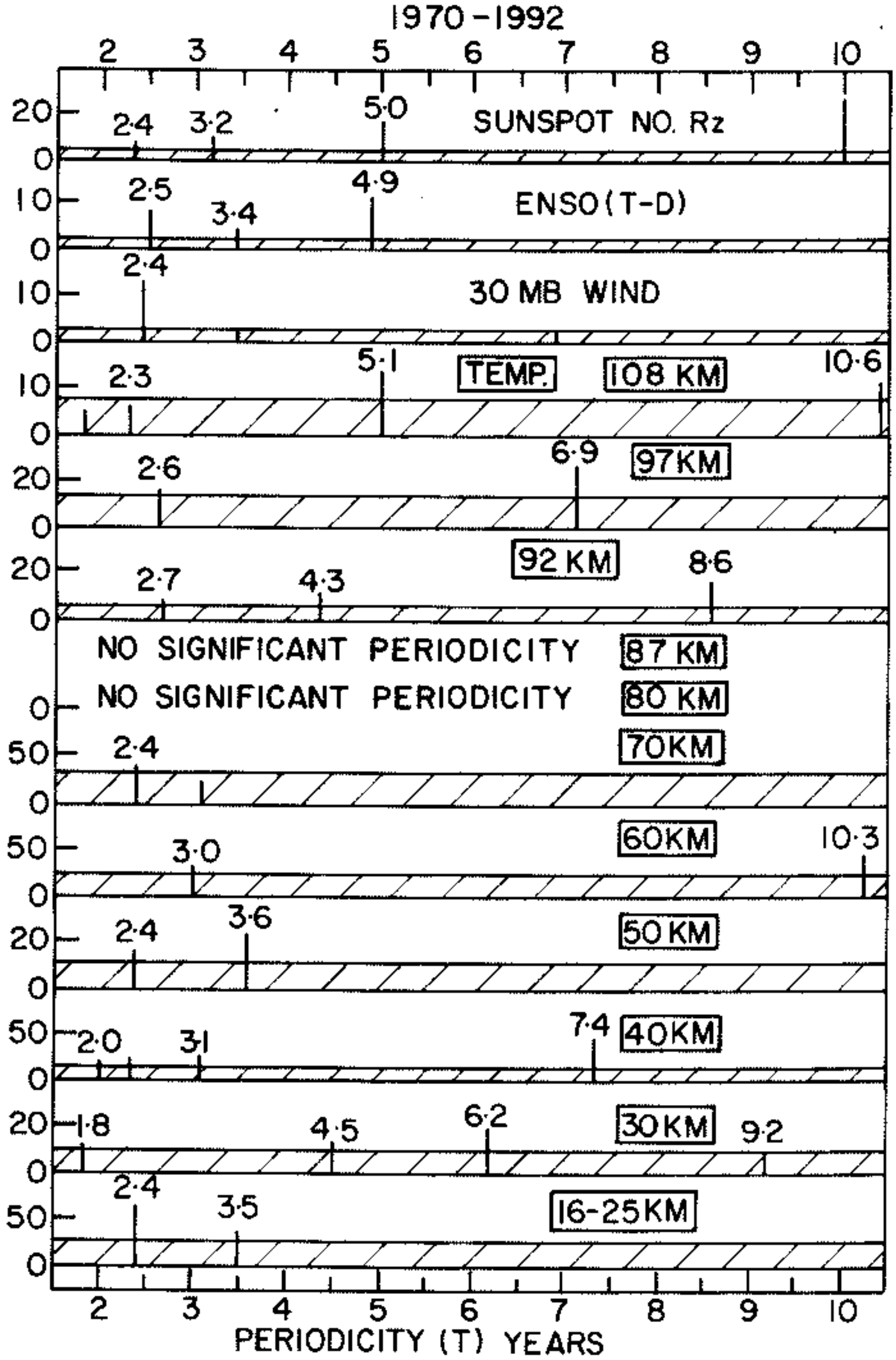

Figure 8. Spectra (amplitudes versus periodicities T in years, detected by MEM) for the series (1970–1992) of the parameter (12–36 m) of sunspots and 12 m of various terrestrial parameters. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level.

3.4–3.6 (QTO) years similar to ENSO, but the 5.1-year peak of ENSO is missing. Thus only TOMS ozone peaks match with 30 mb wind peaks, while all other parameters seem to be associated with ENSO in the QBO and QTO ranges.

6. Conclusions

[41] The 12-month running means (12 m) and the parameter (12–36 m) representing the QBO (quasi-biennial oscillation) were examined and spectrally analyzed for several solar, interplanetary, and terrestrial parameters.

[42] 1. Solar indices (including solar open magnetic flux in solar latitudes <45°) had a QBO in the form of double peaks separated by ~2–3 years during sunspot maximum years and smaller waves in other years. Spectra showed peaks at ~2.5, 3.3, 5.1, 9.8 years, but solar open magnetic flux in solar latitudes >45° did not have the 3.3-year peak, indicating that solar evolution at high solar latitudes (coro-

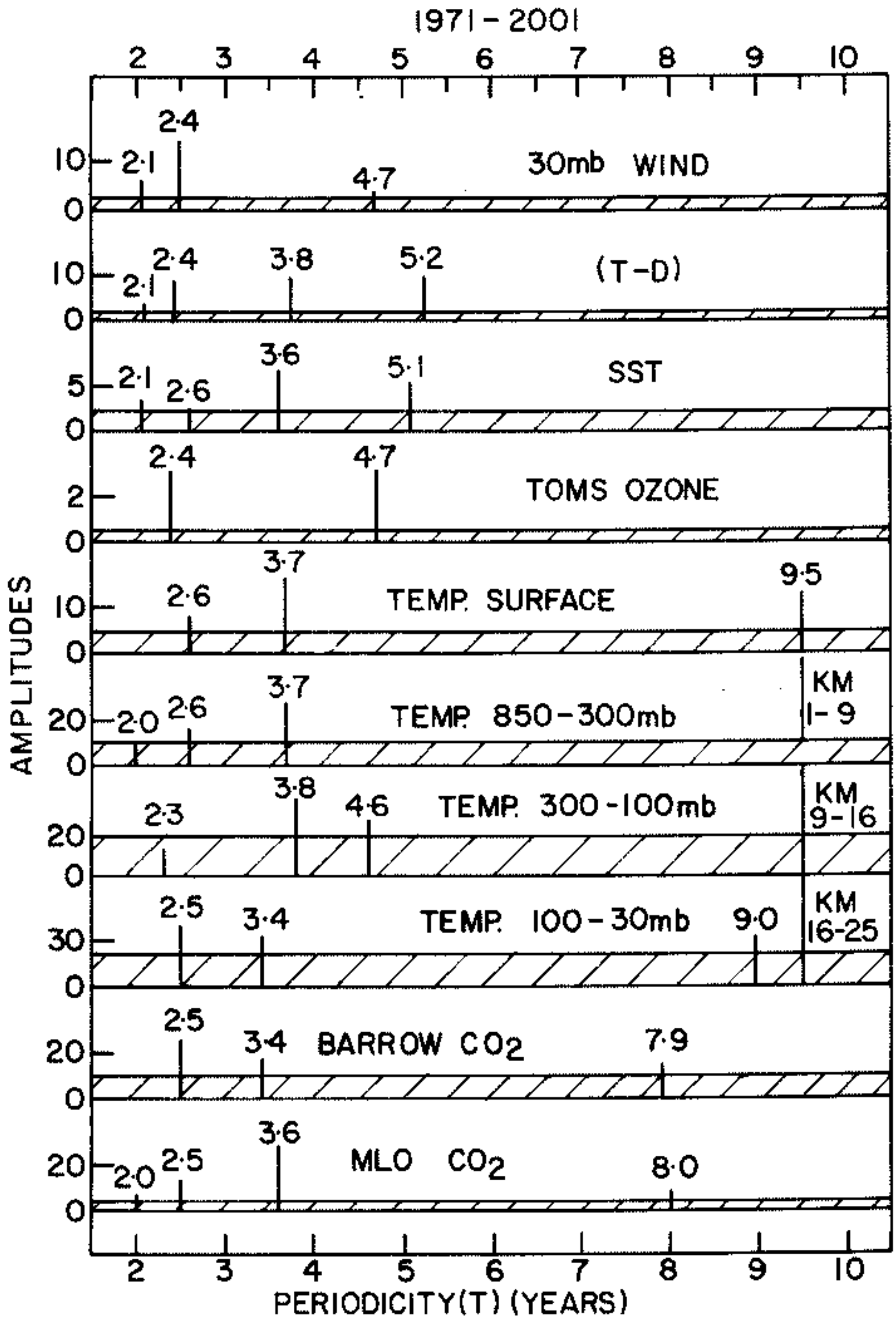

Figure 9. Spectra (amplitudes versus periodicities T in years, detected by MEM) for the series (1971–2001) of the parameters 12 m and (12–36 m) of various terrestrial parameters. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level.

nal holes, etc.) may be very different from evolution at low solar latitudes.

[43] 2. In the interplanetary space near Earth, a similar structure was seen only in interplanetary total magnetic field B. Interplanetary N and V had long-term variations different from solar variations and did not have the solar 3.3-year peak. V had an additional peak at 4.0 years. It seems that the QBO, QTO of V is not directly related to those of low-latitude solar indices. Ground-level solar proton events as well as all solar proton events observed in satellites had QBO peaks near 2.7–2.9 years and QTO peaks at 3.8–4.0 years, different from the 2.4–2.6 years of solar indices and V, and different from the 3.2 and 5.1 years of solar indices, but similar to 4.0 years of V. Thus, a partial relationship with V (solar wind) is indicated. In short, QBOs and QTOs in interplanetary space are not exactly similar to those of low-latitude solar indices.

[44] 2. Geomagnetic Dst and Ap had peaks in QBO region and ~5.2 years like solar indices and V but had peaks near 3.5 years, different from the 3.3 years of solar indices or

4.0 years of V, indicating only a partial connection, or some sort of distortion. Cosmic rays observed on Earth seem to have peaks matching with those of solar indices.

[45] 3. In the terrestrial atmosphere, stratospheric wind has a predominant QBO at 2.4 years (same as of solar indices) but the sequence is more uniform than that of the QBO of solar indices (prominent near sunspot maxima, weak elsewhere). The two QBOs (wind and solar indices) seem to be independent entities. The ENSO indices (T-D) and Pacific SST have a small QBO at 2.4–2.6 years (almost the same as of solar indices) but a much larger QTO at 3.6–3.8 years, in between the solar QTO of 3.2 years, the Dst and Ap QTO at 3.5–3.6 years, or the V-QTO at 4.0 years. The ENSO indices also have a 5.1 year peak similar to solar indices interplanetary N, V. However, ENSO seems to be mainly an ocean-atmospheric phenomenon, with overall characteristics different from those of stratospheric winds or solar indices.

[46] 4. The OBO of stratospheric ozone is similar to that of stratospheric wind. The temperatures at mesospheric altitudes have barely significant QBOs, dissimilar to QBOs of solar indices. Relationship, if any, could be with stratospheric wind or ENSO. At lower altitudes, stratospheric temperatures are related with stratospheric wind as there is a thermal wind balance [*Andrews*, 1987; *Andrews et al.*, 1987], but a connection seems to be with ENSO also, particularly in the troposphere.

[47] 5. Thus there seem to be four QBO-QTO regimes, namely those of (1) solar indices at low solar latitudes, (2) interplanetary parameters, (3) terrestrial low-latitude stratospheric zonal winds, and (4) terrestrial ENSO phenomena.

[48] Overall, the troposphere is under considerable influence of ENSO, stratosphere under the influence of stratospheric low-latitude wind, and upper layers with some effects like ENSO, and some like wind. Since QBO is present prominently in wind, but also in a minor way in ENSO, it is difficult to choose between QBO effects of wind and ENSO, but rough indications are as above. Solar indices also have a QBO, but it is strong near solar maximum and weak near solar minimum. However, the stratospheric QBO characteristics may be modified by the 11-year solar periodicity [*Salby and Callaghan*, 2000; *Soukharev and Hood*, 2001].

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