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Antarctic ozone recovery

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सार - मानव के मशीनी कार्यकलापों से वायुमंडल में रिसते हुए सी.एफ.सी. यौगिकों के विनाशकारी प्रभावों के कारण एंटार्कटिक ओज़ोन परत (एंटार्कटिक ओज़ोन छिद्र) में वर्ष 1976 से तथा वर्ष 1985 से और अधिक उल्लेखनीय रूप से ह्रास हुआ है। दक्षिणी ध्रुव डॉबसन ओज़ोन (मासिक माध्य केवल वर्ष 1999 की समाप्ति तक ही) के बारह महीनों के निरंतर माध्यों का स्पैक्ट्रल विश्लेषण किया गया जिससे 20-30 डी.यू. के कुल रेंज सहित क्यू.बी.ओ (अर्द्धवार्षिक, 2-3 वर्ष) तथा क्यू.टी.ओ. (अर्द्धत्रैवार्षिक, 3-4 वर्षों) दोलनों के उल्लेखनीय महत्वपूर्ण आयामों का पता चला है। मूल मानों से इसे घटाने पर स्पष्ट रूप से सहज परिवर्तन देखा गया है जिसमें 1986 में अन्तर 260 डी.यू. से 1996 में अन्तर 230 डी.यू. (बारह महीने के निरंतर माध्यों में अन्तर 12 प्रतिशत की कमी) तक का ह्रास हुआ है तथा इसके पश्चात् लगभग यह स्तर स्थिर पाया गया है। इस प्रकार दक्षिणी ध्रुव में नेट ओज़ोन परिवर्तन के दो भाग हैं (i) 1996 तक दीर्घावधि एक समान अधोमुखी प्रवृति और तत्पश्चात् स्थिर स्तर, तथा (ii) क्यू.बी.ओ. - क्यू.टी.ओ. दोलनों की प्रधानता। ऐसे समय में रसायनिक विनाशकारी प्रभाव के शीघ्र समाप्त होने की संभावना नहीं होती है किन्तु प्रमुख ज्वालामुखी विस्फोटों अथवा संवर्धित समतापमंडलीय शीतलन हस्तक्षेपों जैसे ग्रीन हाऊस के प्रभावों के कारण इनमें वृद्धि भी हो सकती है। यदि दीर्घावधि स्तर (i) स्थिर रहते हैं उस समय क्यू.बी.ओ-क्यू.टी. ओ. पैटर्नों के बहिर्वेशन से यह पता चलता है कि लगभग 1999 की समाप्ति से लेकर लगभग 2001 के प्रारम्भ होने तक की अवधि में ओज़ोन स्तर में वृद्धि हो सकती है। इस विश्लेषण का उद्देश्य यह बताना है कि यदि 20-30 डी.यू. में इस प्रकार की वृद्धि होती है तो इसे रसायनिक विनाश के कारण हुई कमी नहीं मानना चाहिए जबकि वैज्ञानिक मॉनट्रीयल प्रोटोकोल से जुड़े होने के कारण हाल ही के वर्षों में हेलोजन भार में आई कमी के कारण की तत्परता से प्रतीक्षा कर रहे हैं। एक अथवा दो वर्षों के पश्चात् (वर्ष 2002 में) वर्हिवेशित क्यू.बी.ओ.-क्यू.टी.ओ. दोलनों को 1999 की समाप्ति के स्तर तक पुनः ओज़ोन स्तर पर वापस लाया जा सकता है जिससे हालात में प्रत्यक्ष बहाली असत्य सिद्ध हो सकती है।

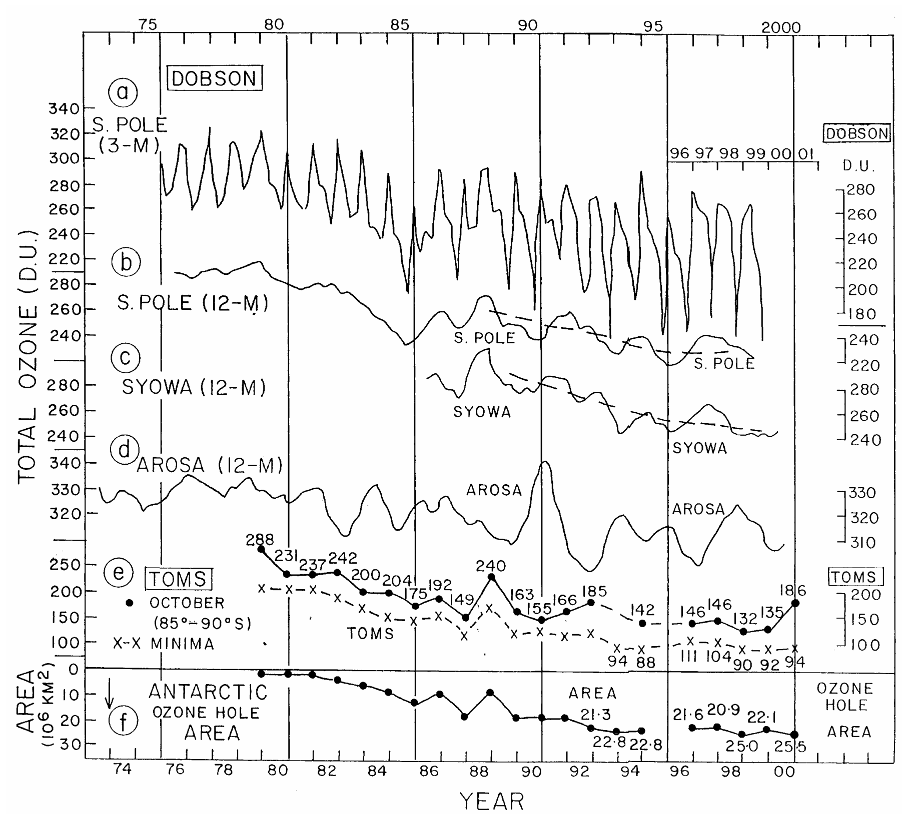
ABSTRACT. Since 1976, and more so since 1985, the Antarctic ozone level has suffered considerable depletion (termed as Antarctic ozone hole), attributed to the destructive effects of CFC compounds leaking into the atmosphere from man-made gadgets. The 12-month running means of South Pole Dobson ozone (monthly means, upto 1999 end only) were subjected to spectral analysis, which showed considerable, significant amplitudes for QBO (Quasi-biennial, 2-3 years) and QTO (Quasi-triennial, 3-4 years) oscillations, with a total range of 20-30 DU. When subtracted from the original values, a fairly smooth variation was seen, with a decrease from ~260 DU in 1986 to ~230 DU in 1996 (~12% decrease in 12-month running means), and an almost steady level thereafter. Thus, the net ozone variation at South Pole consists of two parts, (*i*) a long-term monotonically downward trend upto 1996 and a steady level thereafter and (*ii*) a superposed QBO-QTO oscillation. The chemical destruction effect is not likely to disappear soon, and may even increase if greenhouse effects, major volcanic eruptions or enhanced stratospheric cooling intervene. If the long-term level (*i*) remains steady, an extrapolation of the QBO-QTO patterns indicates that the ozone level is due for an increase from about 1999 end to about 2001 beginning. The purpose of the present analysis is to point out that, if such an increase of 20-30 DU occurs, it should not be misinterpreted as due to a decrease in chemical destruction, which scientists are eagerly awaiting due to the indication of a reduction in the halogen load in recent years due to adherence to the Montreal Protocol. After one or two years (in 2002), the extrapolated QBO-QTO oscillation may bring down the ozone level back again to the 1999 end level, and the apparent recovery may turn out to be a false signal.

Key words – Antarctic ozone hole, QBO, QTO

1. Introduction

Since 1976, and more so since 1985, the stratospheric ozone level in the Antarctic has decreased considerably (Farman *et al*., 1985). In recent years, more than 50% of the ozone layer has been destroyed over the entire Antarctic region each spring (McPeters *et al*., 1996). The decreased level (termed as ozone hole) leads to significant increases in surface ultraviolet radiation (UVR) and may also affect the midlatitude ozone layer (Cariolle *et al*., 1990; Prather and Jaffe 1990) and cause ill effects on fauna and flora due to increased UVR. The depletion is attributed to the destructive effect of CFC compounds (halogen chemistry, Anderson *et al*., 1991) which leak into the atmosphere from man-made gadgets like refrigerating units, hair sprays etc. As per the Montreal Protocol, efforts are under way to reduce or eliminate the use of CFC compounds and some results are visible. Montzka *et al.* (1996) noted a decline in the CFCs in the troposphere. ClO measurements from HALOE seem to indicate that the decline might have reached the stratosphere (Richard McPeters 2000, personal communication). The scientific community would certainly be eager to note a recovery of the Antarctic ozone depletion, if it is due to a reduction of halogen load in obeisance to the Montreal Protocol. However, ozone changes could as well be due to other causes unrelated to the halogen load as such and, these causes need to be taken into consideration before concluding that the reduction in halogen load is causing desirable effects. Severe depletion may be worsened by green-house gas increases (Shindell *et al*., 1998a,b). The heterogeneous halogen chemistry destroying ozone is very sensitive to temperature. During austral winter and spring, temperatures within the polar vortex are low enough to produce polar stratospheric clouds (PSCs) and particle and droplet surfaces convert chlorine from reservoir species into active forms that destroy ozone. The degree of chlorine activation can be strongly influenced by small temperature variations (near the threshold), by any mechanism. Performing simulations with the Goddard Institute of Space Studies GCM and using a physically realistic parameterization of the heterogeneous chemistry responsible for polar ozone loss, Shindell *et al.* (1997) showed that random, unforced interannual variability in the propagation of tropospheric wave energy into the stratosphere could modulate temperatures and influence the severity of the Antarctic ozone hole by as much as 20%. Further, Shindell *et al.* (1999) included a prescribed quasi-biennial oscillation (QBO) applied at a constant maximum value and found that the maximum variability in total ozone loss would increase still further, from 20% to ~50%. However, the QBO effects have a long, complicated history, briefly as follows.

The QBO was first detected in low-latitude stratospheric zonal winds almost simultaneously by Reed *et al.* (1961), Veryard and Ebdon (1961) and Angell and Korshover (1962). For several months, the winds remain westerly or easterly, but switch from one to the other rapidly within a few months. The durations of the westerlies and easterlies change with altitude and latitude. Detailed characteristics (effect of seasons etc.) have been reported by several workers (Naujokat, 1986 and references therein). If 12-month running averages are plotted, the plot with western (positive) and eastern (negative) wind speeds is smooth, but the spacing between successive maxima seems to have changed steadily but significantly with time, being ~26 months in early 60s to ~30 months in the 90s. Dunkerton and Delisi (1985) developed a climatology of the latitudinal structure of the QBO at 50 and 30 hPa. The maxima occur later at lower altitudes, by 10-12 months. This QBO is 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 mixed Rossby-gravity waves. Plumb and Bell (1982) developed a numerical model, which reproduces many of the observed features of this wind QBO. For many years, the term QBO was used only to imply the stratospheric low-latitude wind QBO. Even today, some workers do so. However, many diverse phenomena like geomagnetic activity, rainfalls in some locations, El Niño etc., apparently unrelated to stratospheric winds, seem to have a QBO (Kane 1997a,b and references therein). Hence the term QBO is now considered in its literary sense and represents any variation in any parameter, with a periodicity of 2-3 years. Soon after the discovery of QBO in low-latitude stratospheric winds in 1961, a QBO was discovered in total column ozone near the equator by Funk and Garnham (1962) and at middle and high latitudes by Angell and Korshover (1962). The latitudinal structure was examined by several workers, more recently by Yang and Tung (1995 and extensive references therein) who summarized the situation as, (a) the QBO signal was strongest in the middle and high latitudes and was present mainly in the winter-spring season, (b) 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 (west wind maxima coinciding with ozone maxima, east wind maxima coinciding with ozone minima), and (c) there was no gradual phase propagation from low to high latitudes. Kane (1998) extended this study by spectral analysis of total ozone measured by TOMS at different latitudes and emphasized the curious presence of a ~4 year periodicity at latitudes exceeding 50°, probably related to sea surface temperature (El Niño occurrence frequency). Such a periodicity was earlier reported by Hasebe (1980) from the ground-based network ozone data of 15 years and was confirmed later by Hasebe (1983), using Nimbus 4 BUV data. Since the periodicity is not exactly 4 years and may be anywhere in the range 3-4 years, it will be termed hereafter as a QTO (Quasi-triennial oscillation, 3-4 years), similar to the term QBO (Quasi-biennial oscillation, 2-3 years). In the Antarctic ozone, an apparent QBO-like oscillation was first noted by Bojkov (1986) and Stolarski *et al*. (1986). Soon after, Garcia and



Figs. 1(a-f). Plots of the Dobson ozone level at (a) South Pole, 3-month means (DJF, MAM, JJA, SON), (b) South Pole, 12-month running means, (c) Syowa, 12-month running means, (d) Arosa, 12-month running means. Plots of TOMS ozone at (e) 85°-90° S, full line representing zonal October means and crosses representing minimum daily values, in each year. (f) Plots of the Antarctic ozone hole area (in units of million square kilometres) on the dates when the ozone minimum occurred (not necessarily the maximum area of that year), plotted upside down, as larger areas imply lesser ozone levels

Solomon (1987) used the equatorial wind speed at 50 hPa during October and showed for 1979-1986 that the total ozone amounts in Antarctica were relatively low (high) during the westerly (easterly) phase of the wind. Further, Lait *et al.* (1989) used the August-September average of both 50 and 30 hPa equatorial winds and found a higher correlation between 30 hPa winds and the September Antarctic total ozone hole decline rates. However, it was soon noticed that whereas strong ozone variations were well correlated with September 30 hPa wind phase during 1986, 1987, 1988, the correlations were less clear for 1989, 1992, 1993. Gray and Ruth (1993) concluded that there is not a unique variable such as wind at a particular level in any month that can be correlated definitely with ozone hole, probably because of the irregular descent rates of the QBO phase and the month of phase changes. On the other hand, Bodekar and Scourfield (1995) asserted that the strength of the ozone hole was strongly correlated with 30 hPa winds, with a phase-shift of +12 months. In the face of these contradictory results, Shindell *et al.* (1999) show in (Fig. 1) plots of 30 and 50 hPa winds and ozone mass over the Antarctic vortex period (19 July-1 December) one below the other for 1980-1996 and mention that whereas "observations do suggest some periodicity in the ozone hole severity, a definitive correlation with the QBO (of low-latitude stratospheric wind) remains tantalizingly elusive". Thus, whereas the ozone hole severity may have a QBO, it does not seem to be related directly to the wind QBO, particularly in phase. The simulations by Shindell *et al.* (1999) give a quantitative estimate of the QBO effect, which may increase the effect of random, unforced runs from 20% to 50% of the ozone hole area, and mention that the daily total mass of ozone depleted in the Antarctic region during September was (in units of 10^{10} kg), 8.7 in the QBO easterly maximum, 12.0 in the westerly maximum, and 10.3 in the unforced case. Thus, a considerable difference between the easterly and westerly phases is envisaged, but this difference is not seen in actual observations shown in the Fig. 1 of Shindell *et al.* (1999). In short, what is happening in the Antarctic is not in complete conformity with the simulations, particularly the phase relationship with wind QBO. Recently, on the basis of both the magnitude and autocorrelation of the noise from Nimbus 7 TOMS ozone measurements, Weatherhead *et al.* (2000) gave estimates of the time required to detect a fixed trend in ozone at various locations around the world. If no intervening factors such as major volcanic eruptions or enhanced stratospheric cooling occur, their results indicate that recovery of total column ozone is likely to be detected earliest in the Southern Hemisphere near New Zealand, southern Africa, and southern South America and the range of time expected to detect a recovery for most regions of the world is between 15 and 45 years (or more if greenhouse emissions increase). This is a grim prospect. In the present communication, we concentrate only on the Antarctic region, and attempt a simple, perhaps naive, but certainly more practical, empirical approach to guess what to expect on short term time scales (few months to few years), not by taking hints from elsewhere (low-latitude stratospheric wind patterns etc.) but enquiring what the Antarctic ozone data themselves suggest in the form of regular periodicities in the 2-4 year region (not needing to know their underlying physical mechanisms), and if these are significant, extrapolating these to see whether there is likely to be a upturn or downturn in total ozone values in near future. In the case of a downturn, the ozone hole would look to be intensified further, but in the case of a upturn, a hole recovery may be seen which would be unrelated to decreases in halogen loads but could be misinterpreted as a ozone hole recovery due to the Montreal agreement, eagerly awaited by the scientific community. The main assumption in the present analysis is that the periodicities seen in the past data should give meaningful, reliable results when extrapolated for future intervals.

2. Data

To illustrate the QBO-QTO waves, the data used are (*i*) Dobson ozone measurements at South Pole (90° S), Syowa (69° S, 40° E) and Arosa (46° N, 9° E), for which, data were obtained from the Web site (www.tor.ec.gc.ca/woudc) of The World Ozone and Ultraviolet Radiation Data Centre (WOUDC), Downsview, Ontario, Canada, and (*ii*) Total Ozone Mapping Spectrometer (TOMS) measurements for the south polar latitude range 85°–90° S, for which data were obtained from the TOMS Home page (http://toms.gsfc.nasa.gov). Some consolidated data were supplied privately by Dr. Richard McPeters, principal investigator for Earth Probe TOMS at the Goddard Space Flight Center, Maryland, USA. Data for low latitude stratospheric wind and ENSO (El Niño/Southern Oscillation) were obtained from the NOAA Climate Prediction Center Website (http://www.cpc.ncep.noaa.gov/data/indices).

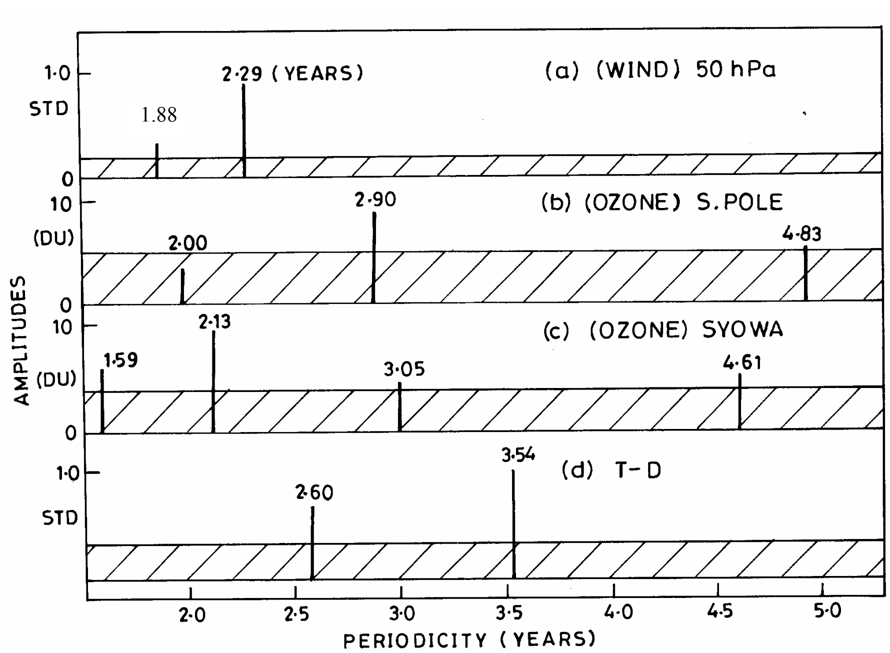
3. Plots for Dobson ozone

In the Antarctic, the Sun is well above horizon only during October, November, December, January and February. Hence, the TOMS data are available only for these months. For the Dobson measurements, moonlight can be used in the dark months March, April, May, June, July, August and September. Such data have large uncertainties, but are better than no data, and are needed for evaluating 12-month running means.

Fig. 1(a) shows a plot of the 3-month means (DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November) of the Dobson ozone values at the South Pole. As can be seen, there is a large seasonal variation. Up to 1984, the values ranged between 230-330 DU (Dobson Unit, milliatmosphere.cm), but since 1985, there has been depletion, with seasonal values ranging between 160-290 DU. In recent years, the October values dropped below 150 DU, and the minimum daily values during September-October dropped below 100 DU. Fig. 1(b) shows the 12-month running means. The seasonal variation is almost eliminated and an irregular variation is seen with a range of ~40 DU. During 1980-1985, there were almost no oscillations, only a down trend, but in later interval, there were oscillations with peak spacings of 24-50 months (Quasi-biennial and/or quasi-triennial oscillations). It is interesting to note that there was a large QBO wave during 1986-1989 but later, it changed to a QTO, indicating that these QBOs and QTOs are not long-lasting and may give contradictory results in different intervals, as seems to have happened. Fig. 1(c) shows the plots for Syowa which has variations almost (but not exactly) similar to those at South pole, indicating considerable latitude dependence even inside the Antarctic region. Fig. 1(d) shows the plot for Arosa, a location in northern middle latitude (Switzerland), far away from the Antarctic region. Whereas the QBO-QTO is seen at Arosa, the amplitudes and peak positions are different from those in the Antarctic. Here again, the QBO-QTO patterns are transient, with large amplitudes during 1980-1985 and then again near 1990-1991. Latitude dependence of QBO-QTO characteristics is discussed in detail elsewhere (Bowman, 1989; Kane *et al.*, 1998, and references therein), but those are, of course, *average* characteristics and may be slightly different for different time intervals.

4. Plots for TOMS ozone

Fig. 1(e) shows the plots for TOMS ozone values (average of all the values) in the 85°-90° S latitude zone.

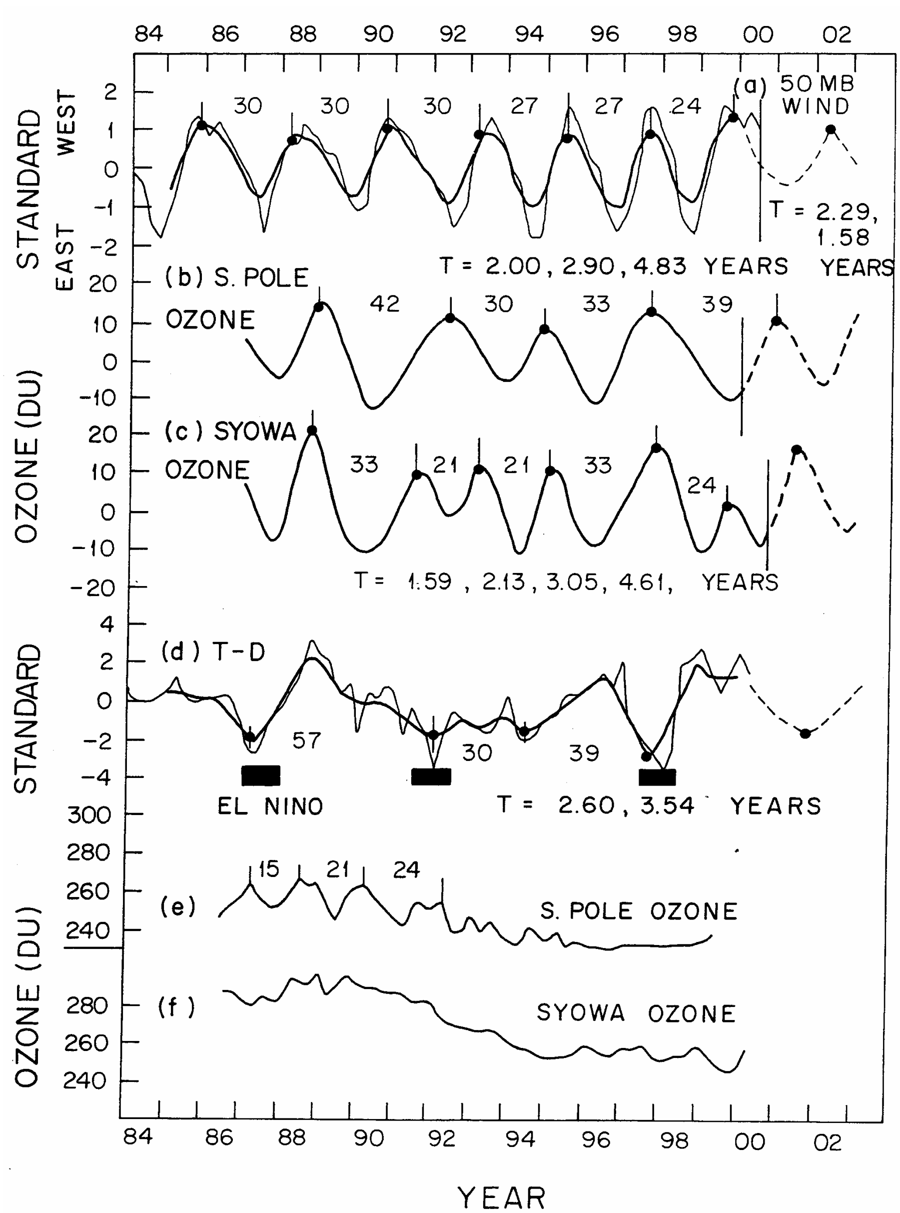


Figs. 2(a-d). Amplitudes of the various periodicities (in years, as indicated) seen in (a) 50 hPa wind, (b) South Pole Dobson ozone, (c) Syowa Dobson ozone and (d) Southern Oscillation Index (T-D). The hatched portions are the 2σ limits

The full line represents the monthly means for the month of October only, with a value as low as 132 DU in October 1998. The crosses represent the *minimum daily value* in that year, usually occurring in the end of September or early October. It may not be exactly at the South Pole and could be as far away as 10°-20°, when the polar vortex is not pole centered. The minimum values are, of course, much smaller than the October averages. The minimum daily value was as low as 90 DU on September 30, 1998, 92 DU on October 1, 1999 and 94 DU on September 29, 2000. Fig. 1(f) shows a plot of the size of the Antarctic ozone hole area in units of million square kilometers, on the day in each year when the level was minimum. (As seen later, this may not be the maximum area for that year, but is near the same). In 1998, the area was 24.99 units on September 30; in 1999, it was 22.08 units on October 1 and in 2000, it was 25.50 on September 29. (However, this was not the maximum area in 2000. That occurred earlier on September 10, with a value 29.2; see discussion later). Thus, from 1998 to 1999, the area decreased from 24.99 to 22.08 units (-12%), while the minimum daily value increased from 90 to 92 DU (+2%), and the October mean value increased from 132 to 135 DU (+2-3%). From 1999 to 2000, the area increased from 22.08 to 25.50 (+15%) but the minimum daily value also increased from 92 to 94 DU (+2%) and the October value increased from 135 to as high as 184, giving contradictory indications, namely, worsening (expansion) of the hole area but recovery of the near-polar ozone levels (explanations discussed later on).

5. Spectral analysis and predictions from extrapolated values

Can the plots be extrapolated to know the possible QBO-QTO wave in near future? For this, the data for the last 13 years (1987-1999, 4 values every year, 52 seasonal 12-month running means, centered 3 months apart) were subjected to MESA (Maximum Entropy Spectral Analysis) to obtain the prominent periodicities and further to MRA (Multiple Regression Analysis) to obtain the amplitudes and phases of these periodicities (Kane *et al.*, 1998). Fig. 2 shows the amplitudes. The top plot [Fig. 2(a)] is for low-latitude stratospheric wind speed at 50 hPa and shows one highly significant periodicity at 2.29 years and a minor but significant periodicity at 1.88 years. For South Pole ozone [Fig. 2(b)], there is a significant peak at 2.90 years, a barely significant peak at 4.83 years, and an insignificant peak at 2.00 years. For Syowa ozone [Fig. 2(c)], the most significant peak is at 2.13 years, the next significant at 1.59 years (~20 months, mentioned by Bowman, 1989) and smaller, barely significant peaks at 3.05 and 4.61 years. Note that the Syowa peaks are not exactly similar to those of south pole and the 20 month peak is only in Syowa. However, none of the ozone peaks are



Figs. 3(a-f). Plots of 12-month running means (full lines) and their extrapolated values (dashed lines) as reconstructed from the QBO-QTO periodicities T, as indicated, for (a) 50 hPa wind, (b) South Pole Dobson ozone, (c) Syowa Dobson ozone (d) (T-D). The numbers between successive maxima are spacings in months. If values of plot (b) are subtracted from the 12-month running means of South Pole ozone, a long-term trend remains as shown in (e). Similarly, (f) represents the long-term trend for Syowa ozone

similar to the wind peak of 2.29 years. The bottom plot [Fig. 2(d)] is for the sea surface phenomenon ENSO (El Niño/Southern Oscillation). El Niños occur abruptly at intervals of 2-7 years. However, these are intimately associated with the parameter (T-D), a pressure difference between the locations Tahiti (T) in the Pacific and Darwin (D) in Australia, and the minima of (T-D) coincide with El Niño occurrences. Thus, (T-D) is a very good representative of the ENSO phenomenon. Here, the major periodicity is at 3.54 years, but the smaller peak at 2.60 years is also highly significant. Thus, (T-D) has both, a QBO and a QTO. However, these periodicities have *changed considerably with time* (see details in Kane, 1998). For example, in the 21-year interval 1953-1974, the 50 hPa wind had two prominent peaks at 2.38, 2.95 years and (T-D) had two peaks at 2.88 (minor), 3.73 (major) years. In the next 21-year interval 1974-1995, 50 hPa wind had just one prominent peak at 2.49 years and (T-D) had 2.44 (smallest), 3.34 (medium), 4.51(largest) years. But none of these are anywhere near the South Pole or Syowa ozone peaks. Thus, an attempt to associate Antarctic ozone changes with stratospheric low-latitude wind or sea surface ENSO cannot give fruitful results. In that case, the origin of the ozone peaks remains a mystery, more so because these peaks seem to be transient, with the QBO dominant in some time intervals and QTO in others. However, for the purpose we have in mind, their exact origin need not be known. Using the amplitudes and phases of the ozone peaks as obtained from the data from 1985 onwards up to date, *one can reconstruct the series and extrapolate it to several months ahead*. Fig. 3 shows the results of the extrapolations.

(*i*) Fig. 3(a) refers to the 50 hPa wind (thin line, monthly values; thick line, 12-month running means) with west wind as positive and east wind as negative. The plot shows about seven QBO cycles. Surprisingly, whereas the spacing in the first four cycles is 30 months, the spacing reduces to 27 months in the next two cycles and further to 24 months recently. Using the amplitudes and phases of the average periodicities T = 2.29 and 1.88 years as indicated in Fig. 2(a), a west wind maximum seems to have occurred at the end of year 1999, and a shift towards east winds (dashed line) has started which may terminate as east wind maximum in the beginning of year 2001, rising to a west wind maximum again by the beginning of year 2002.

(*ii*) Fig. 3(b) refers to the South Pole total ozone. The maxima of the 12-month running means show spacings of 42, 30, 33, 39 months, the unevenness being due to the superposition of more than one periodicities. Using the amplitudes and phases of the average periodicities T = 2.00, 2.90, 4.83 years as indicated in Fig. 2(b), the extrapolated values (dashed line) indicate a ozone maximum by the end of year 2000, followed by a fall up to the beginning of year 2002, followed by a rise again thereafter.

(*iii*) Fig. 3(c) shows plots for Syowa total ozone and indicates a complicated structure. Using the average periodicities T = 1.59, 2.13, 3.05, 4.61 years as indicated in Fig. 2(c), the extrapolated values (dashed line) indicate a minimum at the end of year 2000, followed by a rise up to the middle of year 2001, followed by a fall up to the end of year 2002. Note that this pattern is roughly the same as that of the South Pole ozone but delayed by about 6 months. It will also be tempting to say that the extrapolation pattern for South Pole ozone is just the reverse of that of the 50 hPa wind, *i.e.*, winds shifting from westwards to eastwards cause a rising trend in ozone. However, this would be misleading as ozone has a QTO and QBO, while wind has only a QBO and hence, this apparent association will not survive in future.

(*iv*) Fig. 3(d) shows the plot of the ENSO parameter (T-D). Here, the patterns are very much different. The minima coincide with El Niño years (marked by full rectangles) and the spacings of the (T-D) *minima* are very irregular (57, 30, 39 years). Using the average periodicities T = 2.60, 3.54 years as indicated in Fig. 2(d), the extrapolated values (dashed line) indicate a drop, from the present high level to the end of year 2001 and a rise thereafter. As such, an El Niño may develop by the end of year 2001.

If the QBO-QTO pattern shown in Fig. 3(b) is subtracted from the 12-month means of the South Pole ozone values, the difference should not have any QBO-QTO and should show a monotonic decline of the ozone level. Fig. 3(e) shows a plot of this difference. The plot still has some wiggles, especially during 1985-1991, indicating that the QBO-QTO has not been completely eliminated (the wiggles have spacings of 15, 21, 24 months). But in the later interval, there is an almost smooth fall and a steady level in recent years (1996 onwards). The same is true for Syowa ozone shown in Fig. 3(f). If the prediction of Weatherhead *et al*. (2000) comes true, the plots in Fig. 3(e&f) should show horizontal traces for atleast a decade and may show a very slow recovery thereafter. If unusual events like volcanoes etc. occur, these patterns will be disturbed, most probably, in an unpredictable way.

In geophysical parameters, prediction is always hazardous, and there is no guarantee as such that any prediction will necessarily come true. (Nature has its own quirks and often behaves unexpectedly). For South Pole ozone, the ozone level in future will be determined by the combination of, (*i*) the trend of the monotonic fall in Fig. 3(e) and (*ii*) the extrapolated curve in Fig. 3(b). If 3(e) remains steady, 3(b) will imply a rise up to 2000 end, followed by a fall up to 2001 end, followed by a rise thereafter. If the level in Fig. 3(e) remains steady, oscillations due to QBO-QTO should be seen as in Fig. 3(b). Whether the maxima and minima would occur at the indicated times, is anybody's guess. But ozone level oscillations with a range of about 20-30 DU are certainly expected to occur. As such, a recovery due to lessening of chemical destruction due to reduced halogen load can be claimed with some confidence only if the ozone level rises more than 20–30 DU above the present level. This is the main conclusion of the present investigation. This applies to the ozone levels at South Pole and Syowa only for which monthly data were available, or could be

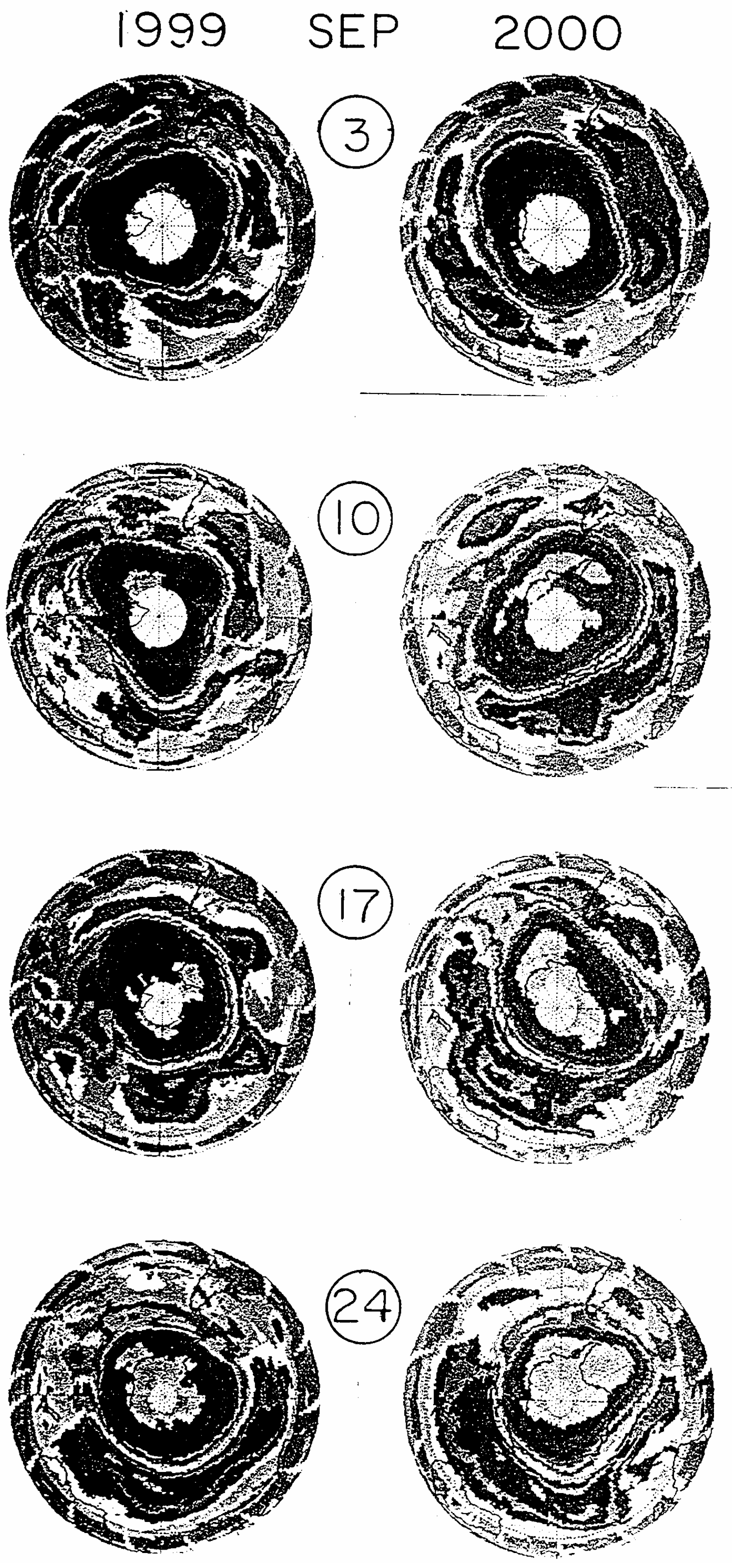
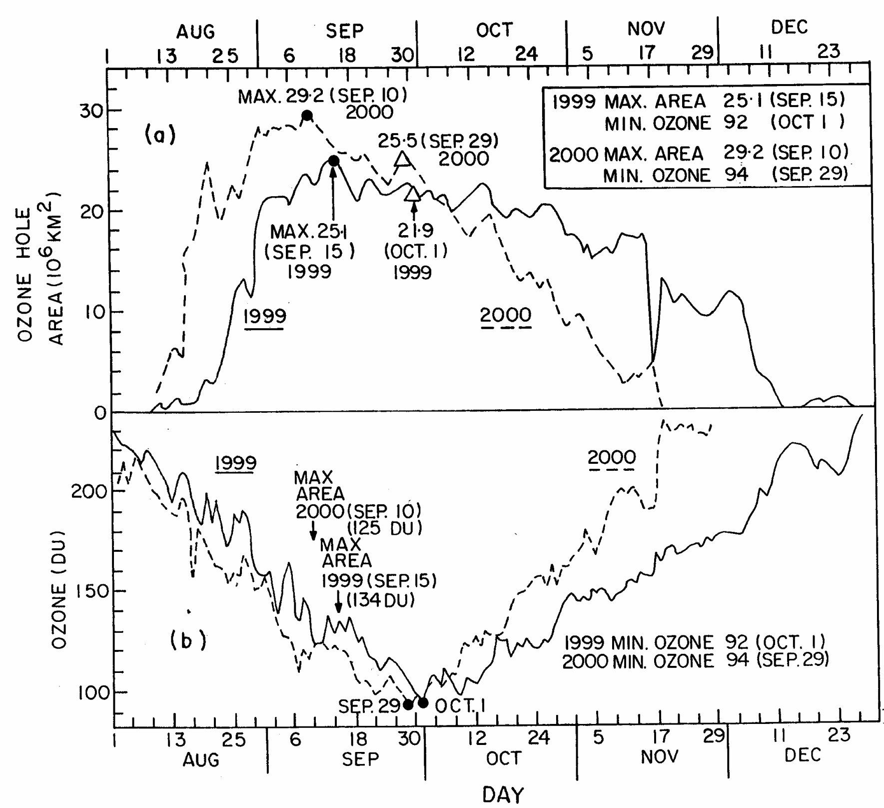


Fig. 4. Polar views of the evolution of the Antarctic ozone hole on 3, 10, 17, 24 September of year 1999 on the left and 2000 on the right. The white line is the 220 DU contour. The top is longitude 90° W; right, 0°; bottom, 90°E; left, 180°

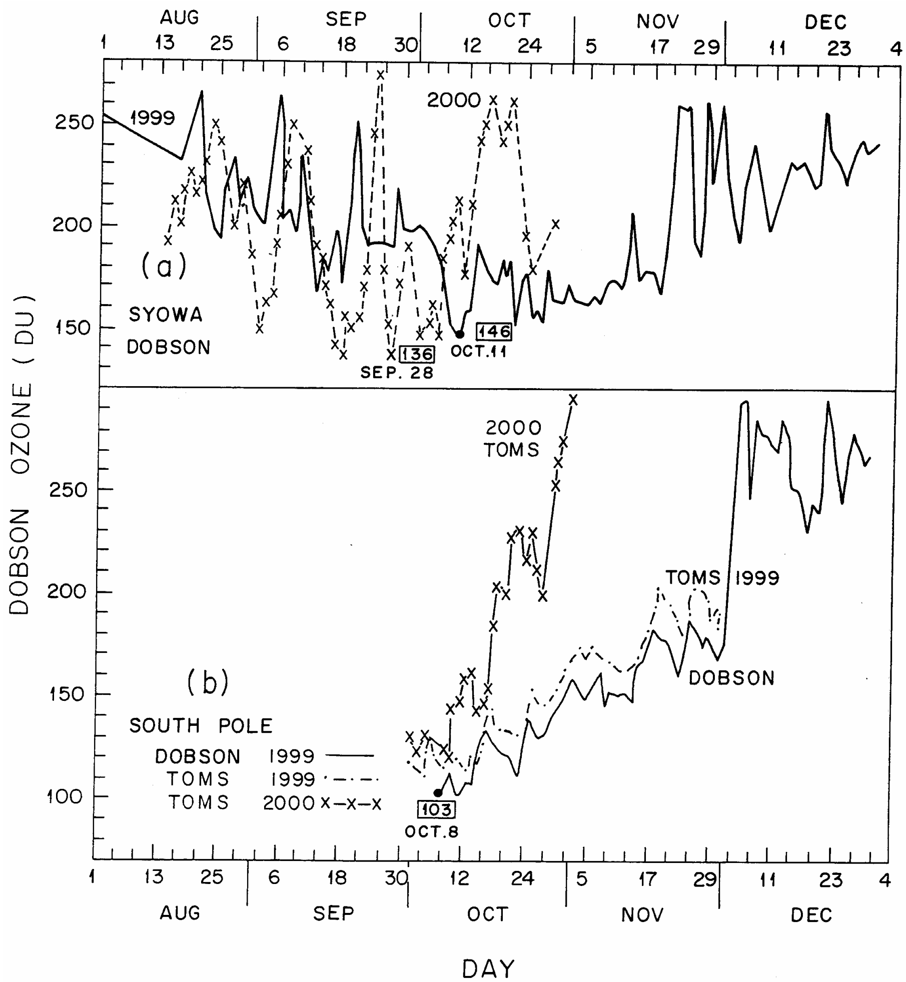


Figs. 5(a&b). Plots of daily values for August-December for 1999 (full lines) and 2000 (dashes) for (a) the ozone hole area, in units of million square kilometres and (b) the minimum ozone value in DU, mostly near the South Pole. Note that the maximum hole areas occurred several days earlier than the minimum ozone values, in both 1999 and 2000

manipulated. In case of the other parameters for which only one value per year is available, determining the characteristics of a QBO cannot be very accurate. In practical terms, alternate years would show ups and downs, with some beats missing, *e.g.*, up, down, up, down, up, up, or down, up, down, up, down, down. If there is a QTO also present, the sequence will be more complicated.

6. Dissimilarities between the variations of the various ozone parameters

In October-November, 2000, the mass media gave the sensational news that the Antarctic ozone hole in 2000 had attained its largest ever value in recent years, causing jitters in the scientific community. Were the efforts after the Montreal Protocol of no avail? On the other hand, the minimum ozone level at the South Pole was higher in 2000 (94 DU) as compared to that in 1999 (92 DU). The October values of TOMS for 85°-90°S were also much larger (186 DU) in 2000, as compared to 1999 (135 DU). Does this not imply a recovery? Then, should one get scared, or feel relieved? Obviously, considering only one parameter may be misleading, like the study of the proverbial elephant by seven blind men, each touching a different part of the elephant, and drawing a different conclusion. The Antarctic ozone hole is confined to the southern polar vortex system (90° S to 65° S), which gets isolated for 2-3 months. During the winter, the Antarctic circulation from 10 to 50 km and higher is dominated by a highly baroclinic cyclone centered close to the pole (Bojkov, 1986). The stratospheric temperature decreases toward the pole. Whereas strong westerly winds at 100 hPa and above encircle the Antarctic like an intense jet, very light winds and extremely low temperatures dominate in the central core from April through October, causing the so-called ‘winter stratospheric polar vortex’ (Labitzke and van Loon, 1972; MacIntyre, 1982). Because of the strong influence of atmospheric dynamics on the formation of the ozone hole, its shape and orientation are constantly changing throughout the spring, from nearly circular over the south pole to strongly



Figs. 6(a&b). Same as Fig. 5, for (a) Syowa Dobson ozone, full line, 1999; dashed line, 2000, and (b) South Pole Dobson ozone, full line, 1999. For 2000, the South Pole Dobson values were not yet available. Hence, in (b), the "Overpass Data" of TOMS ozone over South Pole are also plotted, the dots and dashes representing TOMS ozone for 1999 (to be compared with the full line), and the crosses representing TOMS ozone for 2000

elliptical (oval) and off-center from the pole, congruent with the polar vortex wind system, with a rotation period of about 2 to 3 weeks (Herman *et al.*, 1995a,b). Thus, locations on the periphery of the hole (Syowa) see different effects depending upon where they are with respect to the elongated ellipse. The South Pole may not always have the largest ozone depletion. In addition, the evolution of the ozone hole may be different from one year to next. Fig. 4 shows plots of the ozone hole contours observed by the Earth probe TOMS on fixed dates 3, 10, 17, 24 September with the South Pole at the center, for 1999 on the left and 2000 on the right. As can be seen, the evolutions are very different in the two years. In 1999, the patterns are mostly circular. In 2000, these are mostly elliptical, and show a rotation of about 90° in seven days, with the largest area on 10 September, 2000. Fig. 5 shows a plot of (a) the hole area in units of million square kilometres and (b) the ozone minimum in DU observed by Earth probe TOMS during August-December of 1999 (full lines) and 2000 (dashes). In general, the ozone hole is usually intense from the first week of September to about the middle or end of October. In Fig. 5(a), this pattern is seen for 1999 (full line). The maximum area (25.1 units) occurred on 15 September 1999, the values were above 20.0 from 1 September to 16 October 1999, and values remained above 15.0 units up to the middle of November, 1999. However, in 2000, the evolution was very different. The maximum area (29.2 units, larger than 25.1 units in 1999) occurred a few dates earlier (10 September 2000), values remained above 20.0 units from 25 August to

TABLE 1

Values of some ozone parameters from TOMS

Year	Month	Date	Min. DU	October (85°-90°S)	Month	Date	Max.Area
1979	9	17	209	288	9	17	0.5
1980	10	15	205	231	9	30	1.5
1981	10	10	205	237	10	10	1.4
1982	9	25	189	242	10	2	7.8
1983	10	18	169	200	10	17	10.2
1984	10	3	154	204	10	3	12.3
1985	10	24	146	175	10	3	17.4
1986	10	7	159	192	10	22	13.0
1987	10	5	120	149	9	29	21.6
1988	9	19	173	240	9	20	12.3
1989	10	7	124	163	10	3	20.9
1990	10	4	128	155	9	19	20.1
1991	10	5	117	166	10	4	22.0
1992	10	10	124	185	9	27	24.4
1993	10	8	94	—	9	16	25.1
1994	9	28	88	142	9	24	24.6
1995	—	—	—	—	—	—	—
1996	10	5	111	146	9	7	26.1
1997	9	24	104	146	9	27	24.4
1998	9	30	90	132	9	19	27.3
1999	10	1	92	135	9	15	25.1
2000	9	29	94	186	9	10	29.2

8 October 2000 only, dropped below 15.0 units by 16 October 2000, and fizzled out rapidly thereafter. Adopting an arbitrary criterion of a threshold of say 2.0 units, the 1999 hole lasted from 19 August - 10 December 1999 (114 days) and had a total summed area of 1915 units, which when divided by 114 days, gives an average area of 16.8 units. In 2000, the ozone hole lasted from 11 August - 17 November 2000 (99 days) and had a total summed area of 1769 units, which when divided by 99 days, gives an average area of 17.9 units. Thus, in 2000, the hole had a slightly larger average area (17.9 against 16.8 of 1999) but lasted much less (99 days against 114 days of 1999), with a much shorter total area (1769 units against 1915 units of year 1999). Fig. 5(b) shows plots for the TOMS ozone minimum. The minima are generally very near the South Pole, but may be occasionally 10°-20° away. Here, the contrast between 1999 and 2000 is not very large. The minima occurred very near to each other, 1 October in 1999 and 29 September in 2000, much later than the dates of maximum hole area (15 September in 1999, 10 September in 2000). The starting of the hole is subjective. If a criterion of 220 DU is used (Herman *et al*., 1995a,b), the hole commenced in both years in the beginning of August, but the termination was earlier in 2000 (middle of November) than in 1999 (middle of December). The value of the minimum was larger in 2000 (94 DU) than in 1999 (92 DU).

Fig. 6 shows the plots of Dobson ozone at (a) Syowa and (b) South Pole. For Syowa [Fig. 6(a)], the minimum value was 146 DU on 11 October 1999 and 136 DU on 28 September 2000. Thus, the hole was more intense in 2000. Incidentally, as compared to 1999, the hole developed earlier in 2000 and disappeared earlier. Hence the average solar elevation should have been nearer to the horizon in 2000 and the filtered UVB radiation should have passed through larger atmospheric layers and should be weaker in intensity than in 1999, and hence, less harmful to flora and fauna in 2000. For South Pole [(Fig. 6(b)], the minimum Dobson value was 103 DU, most probably on 8 October 1999. The lesser value (103 DU) at South Pole in 1999 as compared to the Syowa

TABLE 2

Correlations during 1986-1999

	T-D	50 hPa	S.Pole 12	Syowa 12
T-D	1.00			
50 hPa	0.04	1.00		
S.Pole Oz	-0.06	0.08	1.00	
Syowa Oz	0.00	0.37	0.87	1.00

TABLE 3

Correlations during 1986-1992 (upper half) and 1993-1999 (lower half)

	T-D	50 hPa	S.Pole 12	Syowa 12
		1986-92		
T-D	1			
50 hPa	0.517806	1		
S.Pole Oz	0.392577	-0.11512	1	
Syowa Oz	0.62114	0.455314	0.723773	1
		1993-99		
T-D	1			
50 hPa	-0.35195	1		
S.Pole Oz	-0.63726	0.254617	1	
Syowa Oz	-0.67535	0.652007	0.672114	1

value (136 DU) in 1999 is because South Pole is almost near the center of the ozone hole, while Syowa is at the periphery. The values at Syowa change violently from day to day, mainly because the location becomes frequently in and out of the elliptical arm of the ozone hole. However, in Figs. 5(a&b), there are considerable day-to-day fluctuations (several percent) with spacings of a few (5-8) days. These are probably due to the effects of synoptic disturbances on total ozone through tropopause pressure changes and/or ozone mini-holes caused by the anticyclonic tropospheric forcing under the southern polar vortex (Salby and Callaghan, 1993; Orsolini *et al*., 1995, and references therein). Also, fluctuations may result from planetary or Rossby waves (wave numbers 1-3), which often accompany stratospheric warming events in polar winter and spring (Allen and Reck, 1997, and references therein). The tropospheric wave variability effects mentioned by Shindell *et al*. (1997) could also be a part of this scenario, though these authors mention essentially an interannual variability. In Fig. 6(b), data for South Pole Dobson for 2000 are not yet available on the WOUDC website. However, the TOMS website gives “Overpass data” for locations where Dobson values are available. For South Pole (Amundsen-Scott), TOMS values are available for 2000 also. In Fig. 6(b), the dots and dashes are the TOMS values for 1999 and these are similar to (slightly higher than) the Dobson values (full line), both showing recovery (values exceeding 220 DU) by November 1999 end. In contrast, for 2000 for which only TOMS values (crosses and dashes) are available, a very sharp recovery occurred much earlier, by 20 October. Table 1 gives the values of some parameters for each year since 1979.

Some salient features as seen from Table 1 and the various figures are:

(*i*) The ozone content declined and the hole area increased almost monotonically up to 1998, after which the minimum content seems to be increasing and the maximum hole area seems to be oscillating.

(*ii*) The dates of occurrence of ozone minima vary in a wide range, from 17 September to 24 October and may differ by more than 20 dates even in consecutive years. A QBO effect may exist.

(*iii*) The dates of occurrence of maximum hole areas also vary widely, from 7 September to 22 October and may vary by more than 15 days from one year to the next.

(*iv*) The ozone minima and the hole area maxima can occur on dates differing by more than 20 days, the maximum hole areas generally occurring earlier.

(*v*) The October values for 2000 are very large (186 DU) as compared to 1999 (135 DU), but this is not indicative of a spectacular recovery. The hole peaked in early September, 2000 and disappeared earlier and hence, values in October, 2000 had largely recouped.

During 2000, the different parameters showed different patterns, some showing worsening of the ozone hole in 2000, others showing a recovery. As such, conclusions based on any one parameter (maximum hole area) could be misleading. Could this mixed behaviour be a harbinger of the beginning of a recovery? In that case, a certainty of recovery could be claimed only when the ozone levels rise by more than ~30 DU, the range of the QBO-QTO. TOMS ozone minima above ~120 DU could be a certain indication of a recovery.

7. Correlations and regressions

In Fig. 3, the various parameters do not seem to be well correlated. A correlation analysis revealed the matrix shown in Table 2.

Thus, except for the ozone at South Pole and Syowa (correlation +0.87), all other correlations are negligibly small. If the 52 values (13 years, 4 seasonal values per year) are divided into two groups of 26 values each, the correlation matrices were as in Table 3.

Thus, some correlations improve but differently in the two groups, indicating essentially that the relationships are transient. Basically, it means that the correlations are poor if a large data set is used. For shorter intervals, relationships may be found as happened with Garcia and Solomon (1987) and Lait *et al*. (1989), but the relationships may disappear if larger data sets are used (Gray and Ruth, 1993). However, it is conceivable that the relationship is multiple, *i.e*., the ozone values had a relationship simultaneously with 50 hPa wind and (T-D). To check this, a bi-variate regression analysis was carried out with South Pole ozone as the independent variable and 50 hPa wind and (T-D) as dependent variables. The multiple correlation was only 0.10 and all the regression coefficients had standard errors exceeding the values of the coefficients themselves, indicating a very poor relationship. For Syowa, the multiple correlation was somewhat better (+0.37) but certainly not good enough for a meaningful relationship. Thus, even though the ozone series have significant QBO and QTO, these seem to be unrelated directly to the QBO of the 50 hPa wind or the QBO-QTO of the ENSO (T-D).

8. Conclusion and discussion

Stratospheric ozone at all latitudes has Quasi-biennial and/or Quasi-triennial oscillations, though these generally do not have similar characteristics at all latitudes. The 12-month running means of the ozone values at South Pole and Syowa (4 values per year centered 3 months apart, 52 values during 1986-1999) were subjected to MESA (Maximum Entropy Spectral Analysis) to detect the periodicities and to MRA (Multiple Regression Analysis) to estimate the amplitudes and phases of these periodicities. These were compared with the spectral characteristics of similar series of the 50 hPa low latitude wind and the sea-surface phenomenon ENSO (El Niño/Southern Oscillation) represented by (T-D) *i.e*., Tahiti minus Darwin atmospheric pressure, for the same interval. The following was noted:

(*i*) The stratospheric wind speed at 50 hPa showed one highly significant periodicity at 2.29 years and a minor but significant periodicity at 1.88 years. For South pole ozone there was a significant peak at 2.90 years, a barely significant peak at 4.83 years, and an insignificant peak at 2.00 years. For Syowa ozone, the most significant peak was at 2.13 years, the next significant at 1.59 years (~20 months, mentioned by Bowman, 1989) and smaller, barely significant peaks at 3.05 and 4.61 years. The Syowa peaks were not exactly similar to those of South Pole and the 20 months peak was only in Syowa. However, none of the ozone peaks were similar to the wind peak of 2.29 years. For (T-D), the major periodicity was at 3.54 years, but a smaller peak at 2.60 years was also highly significant. Thus, (T-D) had both, a QBO and a QTO. But none of these were anywhere near the South Pole or Syowa ozone peaks. Thus, an attempt to associate Antarctic ozone changes directly with stratospheric low-latitude wind or sea surface ENSO cannot give fruitful results.

(*ii*) The origin of the ozone peaks remains a mystery, more so because these peaks seem to be transient, with the QBO dominant in some time intervals and QTO in others. However, for the purpose of extrapolation that we have in mind, the exact origin need not be known. Using the amplitudes and phases of the various peaks as obtained from the data from 1985 onwards up to date, one can reconstruct the series and extrapolate it to several months ahead. The results were as follows.

(*iii*) Using the amplitudes and phases of the average periodicities T=2.29 and 1.88 years, a 50 hPa west wind maximum seemed to have occurred at the end of year 1999 and a shift towards east winds has started which may end as east wind maximum in the beginning of year 2001, rising to a west wind maximum again by the beginning of year 2002.

(*iv*) Using the amplitudes and phases of the average periodicities T=2.00, 2.90 and 4.83 years, the extrapolated values of South Pole Dobson total ozone indicate an ozone maximum by the end of year 2000, followed by a fall up to the beginning of year 2002, followed by a rise again thereafter.

(*v*) Syowa Dobson total ozone and indicated a complicated structure. Using the average periodicities T=1.59, 2.13, 3.05, 4.61 years, the extrapolated values indicated a minimum at the end of year 2000, followed by a rise up to the middle of year 2001, followed by a fall up to the end of year 2002. This pattern is roughly the same as that of the South Pole ozone but delayed by about 6 months. It will be tempting to say that the extrapolation pattern for South Pole ozone is just the *reverse* of that of the 50 hPa wind, *i.e*., winds shifting from westward to eastward cause a rising trend in ozone. However, this would be misleading as ozone has a QTO and QBO, while wind has only a QBO and hence, this apparent association will not survive in future.

(*vi*) Using the average periodicities T=2.60 and 3.54 years, the extrapolated values of (T-D) indicated a drop from the present high level to the end of year 2001 and a rise thereafter. As (T-D) minima occur in El Niño years, an El Niño may develop by the end of year 2001.

(*vii*) If the QBO-QTO patterns are subtracted from the 12-month means of the South Pole ozone values, the difference should not have any QBO-QTO and should show a monotonic decline of the ozone level. This was observed, particularly from 1991 onwards when there was an almost smooth fall and a steady level in recent years, from 1996 onwards. The same was true for Syowa ozone.

In geophysical parameters, prediction is always hazardous and there is no guarantee as such that any prediction will necessarily come true. For South Pole ozone, the ozone level in future will be determined by the combination of the trend of the monotonic fall and the observed QBO-QTO and its extrapolation. If the long-term level remains steady as envisaged by Weatherhead *et al.* (2000), the extrapolated QBO-QTO pattern implies a rise up of ozone level at South Pole up to 2000 end, followed by a fall up to 2001 end, followed by a rise thereafter. Whether the maxima and minima would occur at the indicated times, is anybody's guess. But ozone level oscillations with a range of about 20-30 DU will certainly occur. As such, a recovery can be attributed to lessening of chemical destruction due to reduced halogen load only if the ozone level rises much more than 20–30 DU above the present level. This applies to the ozone levels at South Pole and Syowa only. For other parameters with only one value per year, QBO and QTO cannot be determined accurately.

Since the main purpose of the present analysis was to determine the limit of the QBO-QTO range, which was obtained as 20-30 DU, no assumptions about the origins of these were necessary. However, an examination of the origins is academically important. For the QBO, an association with low-latitude wind QBO would be an obvious choice. Bowman (1989) mentions that 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. The problem is that the 21-month period is seen in Syowa ozone only, not at South Pole, and but the main QBO period of the wind T=2.29 years is not seen in South Pole ozone. In addition, South Pole ozone has a prominent periodicity at 4.83 years and Syowa ozone has 3.05 and 4.61 years, nowhere near the wind QBO. These are obviously of some other origin.

There is evidence to show that there is a link between planetary wave energy and the severity of the Antarctic ozone hole. Bodeker and Scourfield (1995) used TOMS data and reported a strong anti-correlation between Southern Hemisphere midlatitude total wave power and the Antarctic ozone loss on an interannual time scale. Shindell *et al*. (1997) included in the GISS GCM a physically realistic parameterization of the chemistry responsible for severe polar ozone loss and showed a similar anti-correlation, suggesting that random, unforced variability of midwinter tropospheric wave energy played a significant role and may be the best predictor of the severity of the ozone hole the following spring. Further, Shindell *et al*. (1999) also showed that though wind QBO is primarily a stratospheric phenomenon, it can modulate the amount and propagation of planetary wave energy in the troposphere as well as in the stratosphere and the dynamic activity is greater in the easterly than in the unforced case, while westerly years are dynamically more quiescent. Thus, many of the effects one sees in the Antarctic ozone hole could be related to tropospheric wave energy changes. In that case, the problem becomes of the interaction of tropospheric wave energy with the stratospheric low-latitude winds on one side and ENSO phenomenon on the other. Kodera and Yamazaki (1989) traced the variations in wave activity during 1979-1988 to variability in sea surface temperature in the South Pacific. Incidentally, whereas the ENSO has the most prominent periodicity near 4 years, it has a QBO also, of lesser but significant magnitude. Ramusson *et al*. (1990) termed it as a biennial component, but the periodicity is generally different from (more than) 2.00 years. Yasunari (1989) tried to establish a possible link between the QBOs of the stratosphere, troposphere, and the sea surface temperature in the tropics. Kane and Buriti (1997) studied the periodicities of tropospheric and stratospheric temperatures and found that temperatures at higher altitudes had QBO similar to the wind QBO, while temperatures at lower altitudes had QTO similar to eastern equatorial Pacific sea surface temperatures (ENSO). Gray *et al*. (1992) gave a hypothesized mechanism for stratospheric QBO influence on ENSO variability, while Geller (1993) and Reid and Gage (1993) discussed the troposphere-stratosphere-middle atmosphere coupling and the role of El Niño and the wind QBO. Much will depend, therefore, how the tropospheric wave energy is modified by stratospheric low-latitude winds and ENSO and whether the effects are in a distorted form. All this needs further exploration. Shindell *et al*. (1999) mention that "the impact of additional potential influences on the ozone hole, such as solar variability, volcanoes, or the El Niño-Southern Oscillation, remains to be studied".

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