Solar UV, stratospheric ozone and UVB

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सार – समतापमंडलीय ओज़ोन की विविधता और धरातल पर प्रेक्षित यू.वी.बी. की तुलना सौर सूचकांकों के साथ की गई। 27 दिवसीय दोलनों के अनुक्रमों के दौरान एक्स-रे का बहुत अधिक आयाम (50% से अधिक) ई.यू.वी. लगभग 30 एन.एम. का ~20%, लाइमैन अल्फा 121.6 एन.एम. ~10%, एम.जी. II 280 एन.एम. ~5% और कान्टीनुआ 180–210 एन.एम. ~2%, 210–240 एन.एम. ~1–5%, 240–300 एन.एम. ~1%, 300–350 एन.एम. ~0.5% रहा। इन सभी में अनुमानतः लगभग 27 दिनों के अंतराल में अलग उँचाईयाँ देखी गई। समतापमंडलीय ओज़ोन पर प्रभाव डालने वाले संबद्ध तरंगदैर्घ्य मुख्यतः कान्टीनुआ में हैं। 27 दिवसीय अनुक्रम में, एरोसा (47° उ., 10° पू.) के डॉब्सन ओज़ोन में अनेक उँचाईयों के साथ अधिक उतार चढ़ाव (~50%) का पता चला परंतु ये उँचाईयाँ सौर सूचकांकों की उँचाईयों के अनुरूप नहीं रही। ऐसे एक 27 दिवसीय अनुक्रम के दौरान कागोशिमा, जापान (33° उ., 121° पू.) के ऊपर टी.ओ.एम.एस ओज़ोन और कागोशिमा में प्रेक्षित किए गए यू.वी.बी. (295-325 एन.एम.) से दिन प्रतिदिन के उतार चढ़ाव में अधिकता का पता चला, ओज़ोन के लिए ~20% यू.वी.बी के लिए ~50%, अथवा यू.वी.बी., परंतु ओज़ोन और यू.वी.बी. की ऊँचाईयाँ न तो एक दूसरे के अनुरूप रहीं और न ही सौर सूचकांकों के अनुरूप रहीं अतः इससे यह पता चला कि इनका कारण अंततः विभिन्न प्रक्रियाएँ हैं। एरोसा डाब्सन ओज़ोन के दीर्घावधि परिवर्तनों में, सबसे अधिक उतार चढ़ाव मौसमी परिवर्तनों (~40%, रेंज, शिखर से द्रोणी तक) में और उसके बाद क्यू.बी.ओ. (अर्ध द्विवार्षिक दोलन, ~7%, शिखर से द्रोणी तक) रहा। 1980 में आरंभ हुए भूमंडलीय अवक्षय के कारण ओज़ोन (शिखर से द्रोणी तक) के सौर चक्र विविधता रेंज चक्र 19 में (सूर्यधब्बा अधिकतम संख्या 210) ~2.6%, चक्र 20 (सूर्यधब्बा अधिकतम संख्या 111) में ~3.5% और उसके बाद अनिश्चित रहा। वर्ष 1991–97 के संबंध में थेसालोनिकी, ग्रीस (40° उ. 23° पू.) में ओज़ोन के मासिक मान 305 एन.एम .यू.वी.बी (1% ओज़ोन में कमी ~2% यू.वी.बी. में वृद्धि के अनुरूप रही) के साथ प्रति सहसंबद्ध रहे परन्तु 325 एन.एम .यू.वी.बी के साथ येन केन प्रकारेण सहसंबद्ध रहे जिससे ज्ञात होता है कि ओज़ोन यू.वी.बी. संबंध तरंग दैर्घ्य पर अधिक निर्भर रहा। तथापि,, जबकि सौर सूचकांक 1991 में अधिकतम तथा 1996 में न्यूनतम रहे तब भी न तो ओज़ोन और न ही यू.वी.बी. 305 एन.एम. और 325 एन.एम दोनो में से कोई एक सौर सूचकांक में होने वाली विविधता के अनुरूप रहे। विशेष रूप से, 1991 में ओज़ोन स्तर अधिक था परन्तु अगले दो वर्षों (1993 तक) में अत्याधिक कम रहा। एरोसा (47° उ.) और स्योवा (69° द.) में ओज़ोन की तुलना से पता चला है कि यह कमी सौर चक्र से संबंधित नहीं है अपितु ओज़ोन के भूमंडलीय अवक्षय के कारण हुई है।

ABSTRACT. The variations of stratospheric ozone and UVB observed at ground were compared with those of solar indices. During sequences of 27-day oscillations, X-ray had very large amplitudes (exceeding 50%), EUV near 30 nm had ~20%, Lyman alpha 121.6 nm ~10%, Mg II 280 nm ~5%, and continua 180-210 nm ~2%, 210-240 nm ~1.5%, 240-300 nm ~1%, 300-350 nm ~0.5%. There were distinct peaks seen in all of these, with spacing of roughly about 27 days. For effects on stratospheric ozone, the relevant wavelengths are mostly in the continua. In the 27-day sequences, the Dobson ozone at Arosa (47° N, 10° E) showed large fluctuations (~50%) with many peaks, but the peaks did not match with the peaks of solar indices. During one such 27-day sequence, the TOMS ozone overpass over Kagoshima, Japan (32° N, 121° E) and the UVB (295-325 nm) observed at Kagoshima showed large day-to-day fluctuations, ~20% for ozone, ~50% or UVB, but the peaks of ozone and UVB did not match with each other, nor with the peaks of solar indices, thus indicating altogether different mechanisms as their causes. In long-term changes for Arosa Dobson ozone, the largest fluctuations were the seasonal variation (~40% range, peak to trough) and the next largest were the QBO (Quasi-biennial oscillation, ~7%, peak to trough). Solar cycle variation ranges of ozone (peak to trough) were only ~2.6% in cycle 19 (sunspot maximum number 210), ~3.5% in cycle 20 (sunspot maximum number 111) and uncertain thereafter, because of the global depletion which started in 1980. For 1991-1997, the monthly values of ozone at Thessaloniki, Greece (40° N, 23° E) were anti-correlated with 305 nm UVB (1% ozone decrease corresponded to ~2% UVB increase), but poorly correlated with 325 nm UVB, indicating that ozone-UVB relationship was highly wavelength-dependent. However, whereas solar indices had a maximum in 1991 and a minimum in 1996, neither ozone nor any of the two UVB 305 nm and 325 nm showed resemblance with the solar index variations. In particular, ozone level was high in 1991 but decreased considerably within two years (by 1993). A comparison with ozone at Arosa (47° N) and Syowa (69° S) showed that this drop is not related to solar cycle but is due to the global depletion of ozone.

Key words – Solar UV, Stratospheric ozone, UVB, Total ozone.

1.   Introduction

The Sun emits a wide variety of radiations, originating in different parts (photosphere, chromosphere, transition region, corona) of the solar atmosphere. Solar ultraviolet (UV) irradiance (115-420 nm) originates mostly in the solar photosphere and chromosphere. When absorbed in the Earth's atmosphere, it plays a dominant role in the temperature distribution, photochemistry, and overall momentum balance in the stratosphere, mesosphere, and lower thermosphere. The irradiance at and below 300 nm is completely absorbed by O_2 and O_3 in the Earth's atmosphere (15-120 km), affecting the balance of ozone in the stratosphere and the mesosphere (McPeters and Chandra, 1994) and causing ionization at various altitudes. Thus, the variability of the solar UV irradiance needs to be estimated accurately, to decipher the natural and anthropogenic effects.

The solar UV spectrum below 300 nm was first obtained by a V-2 rocket in October 1946 (Baum *et al.*, 1946), followed by extensive observations using rockets, balloons, aircraft, and short-lived (shuttle) and long-duration satellites as observational platforms (Tousey, 1963; Heath, 1980). The different observations differed by more than 20% for wavelengths less than 200 nm and 10-20% for longer wavelengths, mostly due to inaccuracies of the photometric calibrations of the early instruments. Significant improvements were made in succeeding years (Rottman, 2000).

On 12 September 1991, the Upper Atmosphere Research Satellite (UARS) was launched. Descriptions of the satellite, its mission, and the instruments and some early results have been presented in the June 1993 issues of Journal of Geophysical Research and Geophysical Research Letters. The solar UV data are measured by two UARS instruments, namely Solar Ultraviolet Spectral Irradiance Monitor (SUSIM), and SOLar STellar Irradiance Comparison Experiment (SOLSTICE). The UARS-SOLSTICE measurements started on 3 October, 1991 and provide data for ~119-420 nm. Details about the SOLSTICE instrument, operation, calibrations, and a validation of the SUSIM and SOLSTICE measurements by comparing these with same-day measurements by two solar instruments on the shuttle Atmospheric Laboratory for Applications and Science (ATLAS) missions are given in Rottman (2000).

Stratospheric ozone has been studied by analysing ground-based (Dobson and Umkher) records for the last several decades. An in-phase solar cycle variation of global mean total ozone with amplitude of several percent from solar minimum to solar maximum has been reported by several workers (Angell, 1989; Reinsel *et al.*, 1987;

Dütsch *et al.*, 1991; Zerefos *et al.*, 1997). Satellite measurements of global column ozone (*e.g.*, TOMS) covering 13 to 15 years also indicate an in-phase solar cycle variation with amplitude of 1.5 to 2% (Chandra, 1991; Hood and McCormack, 1992; Chandra and McPeters, 1994). Direct solar mechanisms for causing ozone perturbations include changes in ultraviolet (UV) irradiance and in the flux of precipitating energetic particles. The latter is probably important only at high latitudes and the effects at lower latitudes are relatively small (Jackman, 1991). Solar UV at wavelengths less than 242 nm directly modify the rate of photo dissociation of molecular oxygen and, hence of ozone production in the upper stratosphere (Hood, 1997). Estimates of changes from solar minimum to maximum for irradiances near 200 nm are reported to be in the range 6 to 10% (Donnelly, 1991; Cebula *et al.*, 1992; DeLand and Cebula, 1993; Rottman and Woods, 1995) and, during solar maximum conditions, comparable amplitudes are estimated on the solar rotation (27-day) time scales (Donnelly, 1991; London *et al.*, 1993). Observational evidence for solar UV effects on stratospheric ozone at low and middle latitudes for both solar cycle and solar rotation timescales is presented by many workers [Hood (1997) and references therein]. Variations of ozone at different stratospheric levels were studied from Umkehr data which showed that most of the variation occurred near the concentration maximum in the 20-30 km altitude range (Dütsch *et al.*, 1991). Satellite SBUV and SBUV/2 data (Hood *et al.*, 1993; Chandra and McPeters, 1994) indicated solar cycle variations of 4 to 7% near 2 mbar (~45 km altitude), decreasing to negligibly small values by 6 mbar (~35 km altitude). Two-dimensional model calculations predicted only 1.5 to 2.5% between 3 and 6 mbar, decreasing to less than 1.5% below 20 km altitude. (Brasseur, 1993; Fleming *et al.*, 1995; Haigh, 1994). Hood (1997) applied multiple regression methods to zonal mean and total ozone data and lower stratospheric temperature and geopotential heights and found for the SBUV-SBUV/2 data that most of the 1.5-2% solar cycle variation of global mean total column ozone occurred in the lower stratosphere (altitudes below 28 km). There were geographical similarities between solar coefficients of total ozone and stratospheric temperature and geopotential heights, suggesting that changes in lower stratospheric dynamics from solar minimum to maximum may play an important role in driving the observed total ozone solar cycle variation. In recent model studies, Austin *et al.* (2000) and Labitzke *et al.* (2002) used the UK Met. Office coupled chemistry-climate model having 64 levels from the ground to 0.01 mbar and resolution in three dimensions. For a 27-day oscillation, the model is reported to have captured correctly the observed tropical ozone sensitivity and downward phase propagation. Rozanov *et al.* (2001) applied a 1-D radiative-convective model with interactive

photochemistry to estimate the sensitivity of the temperature and ozone to an increase of the extraterrestrial solar flux. It was found that ozone and temperature are most sensitive to the variations of solar flux variation in the wavelength range 200 to 220 nm and the correlation with ozone is positive, mainly due to the ozone build-up in the stratosphere due to the molecular oxygen photo dissociation by the Herzberg continuum. However, between 260-300 nm, the ozone-solar flux correlation is negative because of the enhanced ozone destruction due to enhanced ozone photolysis in the Hartley ozone band. The effects of these two wavelength bands are such as to cancel each other, but variability of solar flux strongly decreases with increasing wavelengths. Hence, the positive effect of the 200-220 nm range is more prominent and is expected to prevail over the negative effect of the 260-300 nm range.

In the SOLSTICE data, there are flux values for four continuum ranges: 180-210 nm; 210-240 nm; 240-300 nm; 300-350 nm. In this communication, the variations of the day-to-day fluxes of these ranges are examined for intervals having strong 27-day oscillations and compared with the day-to-day variations of stratospheric ozone. Long-term changes are also examined.

2. Plots of solar emission lines for a short interval (132 days)

In another study (Kane *et al*., 2001), the daily values of solar UV fluxes for the 26-month interval October 1997-July 1999 were divided into 6 intervals for short-term study as :

Interval I, 1 June – 10 October 1997,

Interval II, 11 October 1997 – 19 February 1998 (has 27-day oscillations),

Interval III, 20 February – 1 July 1998 (has 27-day oscillations),

Interval IV, 2 July - 10 November 1998,

Interval V, 11 November 1998 – 22 March 1999 (has 27-day oscillations),

Interval VI, 23 March – 31 July 1999 (has 27-day oscillations).

These intervals, in the rising part of the present solar cycle 23, were chosen, as there were uninterrupted, continuous data for both line emissions and radio emissions. Among these, Interval II, III, V and VI had strong 27-day oscillations. Fig. 1 shows a plot of the daily

values of X-rays ~0.1-1.0 nm, EUV 26-34 nm, Lyman alpha 121.6 nm, Mg II 280 nm, (plots 1-4) and four continua: 180-210 nm; 210-240 nm; 240-300 nm; 300-350 nm. (plots 5-8) (percentage deviations from their respective means) for Interval II-III (about 260 continuous days). As can be seen, there are 9 distinct peaks near days 25, 50, 78, 108, 134, 160, 180, 209, 240 (marked by vertical lines), with spacing of 20-31 days. For ozone, only the continua are relevant. Whereas the amplitudes of other wavelengths are large, (trough to peak ranges 500% for X-rays; 20 % for EUV 26-34 nm; 10% for Lyman alpha, 5% for MG II), those for continua are small: ~2% for 180-210 nm; ~1% for 210-240 nm; ~0.6% for 240-300 nm; ~0.3% for 300-350 nm. For 200-220 nm reported by Rozanov *et al*. (2001) as most appropriate for ozone, the ranges would be ~1.5%. To examine the behaviour of stratospheric ozone in this interval, daily Dobson data for the middle latitude location Arosa (47° N, 10° E) are plotted as plot 9, daily values (thin line) and 5-day moving averages (superposed thick line). There are peaks in the moving averages (marked by dots) but not all of these are prominent, and most of these do not match with the solar flux peaks (vertical lines). Since the expected solar effects are only ~1-2%, these could have been suppressed in the large ordinate scale for ozone. Hence, the ozone scale was expanded and the plot is shown for days 1-90 on the left side, just below the plot 9. As can be seen, ozone shows prominent peaks at days 16, 33, 53, 66, 77, 88 (spacing 11-20 days), only one of these matching the vertical line near day 78. Thus, in these 90 days, ozone had variations as large as 5%, not matching with the solar continua peaks. During the 260-day interval, ozone had an increase from –20% in October 1997 to +30% in April 1998, which is the well-known seasonal change at Arosa. However, superposed on this seasonal change, there were very large short-term variations (35-50%, lasting for a few days) around days 125 and 180. Thus, the solar effects on stratospheric ozone are negligibly small and there are other much larger day-to-day variations, besides the large seasonal variations.

Are these large variations very local? Plot 10 (thin line) shows the TOMS ozone values for an overpass above Arosa. The plot is very similar to plot 9. However, the superposed thick line representing ozone in a broad latitude range 45-60° N does not show the variations of plot 9. It seems, therefore, that the large variations above Arosa are confined to a very small latitude belt and are probably due to some very local circulation effects. The bottom plot 11 in Fig. 1 shows the variations in a TOMS overpass over the location Ahmedabad (23° N, 73° E). There are a few peaks but these do not match with those of Arosa. Thus, large variations of 15% or more in a few days can occur differently at different latitudes, and are obviously unrelated to solar effects.
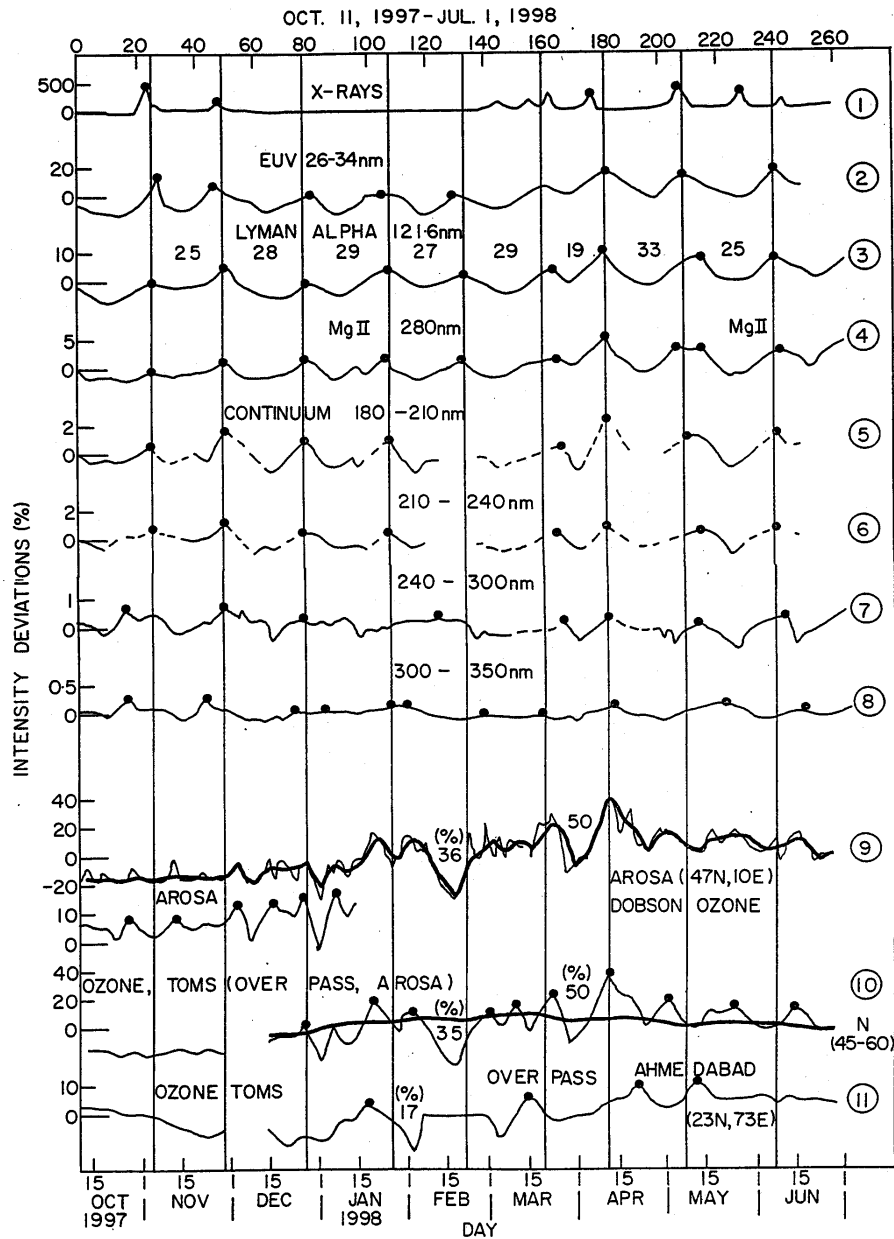
Fig. 1. Evolution of various solar lines emissions during the 263-day interval 11 October, 1997 –
1 July, 1998. Plot 9 is for Dobson ozone at Arosa, Switzerland, while plots 10 and 11 are for
TOMS ozone (overpass data) for Arosa and Ahmedabad

Fig. 2 shows a plot of daily values of ozone at levels 1 to 10 in the stratosphere (Umkehr observations, above Arosa) for January-February, 1998 (days 80 to 140 of Fig. 1), when large day-to-day changes occurred. The top plot is for total ozone (sum of all levels) and does not show a peak at the arrow which marks a peak in solar fluxes (day 108 of Fig. 1). Instead, two peaks are seen, one near 22 January and another near 2 February, 1998. The drop from 22 to 27 January is ~24% for total ozone.

At the individual levels 1-10, the first peak near 20 January is seen at all levels, but the second peak near 2 February is not seen at levels 9, 8, 7. Also, the drop from 22 to 27 January is very different at the various levels and the top plot of total ozone resembles that of levels 3 and 4, which are at the ozone maximum near 25-30 km. Thus, this particular feature of double peaks is unrelated to solar peaks and has a different profile at different levels, indicating a local dynamical origin.
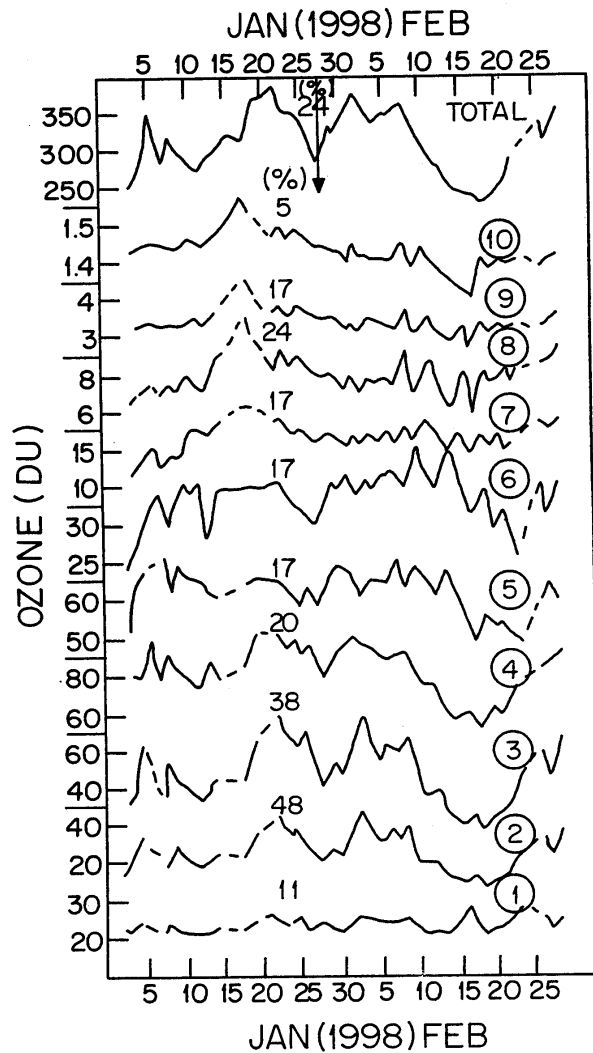
Fig. 2. Ozone at different stratospheric levels (1-10) above Arosa, for January-February, 1998. The open numbers are percentage changes from 22-27 January, 1998. The top plot is for total ozone

Fig. 3. Same as Figure 2, for 18 March - 30 April, 1998

Fig. 3 shows a similar plot of Umkehr observations for March-April, 1998 (days 160 to 200 in Fig. 1). In the total ozone (top plot), there are two major peaks, one near 22 March, 1998 and another larger one near 10 April, 1998, with a separation of only 19 days (not ~27 days). The magnitudes of the changes from peak to trough and trough to peak are large (30-50%). These are similar to, and seem to be contributed mainly by level 2, 3, and 4. At other levels, the peaks are displaced and the magnitudes are different. None of these are related to the variations of the solar flux and, strong local dynamical processes seem to be involved.

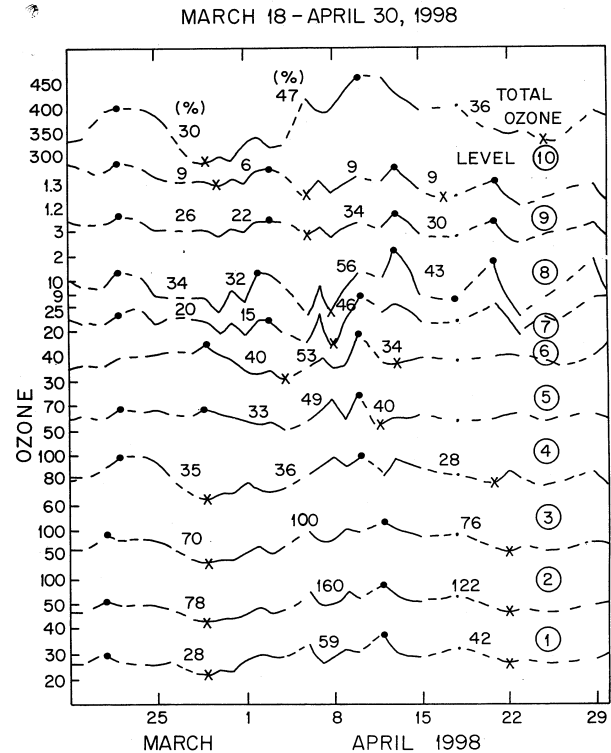Fig. 4 shows a plot of TOMS ozone in different latitude bands of 15° width, from south pole (90°S to

75° S to north pole (75° N to 90° N), for 11 October, 1997 to 1 July, 1998. The bottom plots show averages for the northern (NH) and southern (SH) hemispheres and for global ozone, as given in the NASA website http://toms.gsfc.nasa.gov/eptoms/ep.html. The most prominent variation seems to be the seasonal variation, with minimum in October and maximum in April in the northern hemisphere and an almost reverse pattern (maximum in October and minimum in April) in the southern hemisphere, both with ~15% change. In the global average, the percentage change should be almost zero, but a pattern similar to the northern hemisphere is seen, with a change of ~6%, probably because more data of the northern hemisphere were available for the global average. In the other plots, some small maxima are seen (marked by dots) but these are often obscure and do not match with the solar flux maxima (vertical lines). Thus, solar effects, if any, are very small (1 or 2%) and ambiguous, while oscillations of ~5% unrelated to solar activity and lasting a few days are seen mostly in the northern hemisphere. For wider latitude bands, the magnitudes are much smaller than those at an individual location (Arosa, shown in Figs. 2 & 3), indicating that such variations are of a much localized origin.
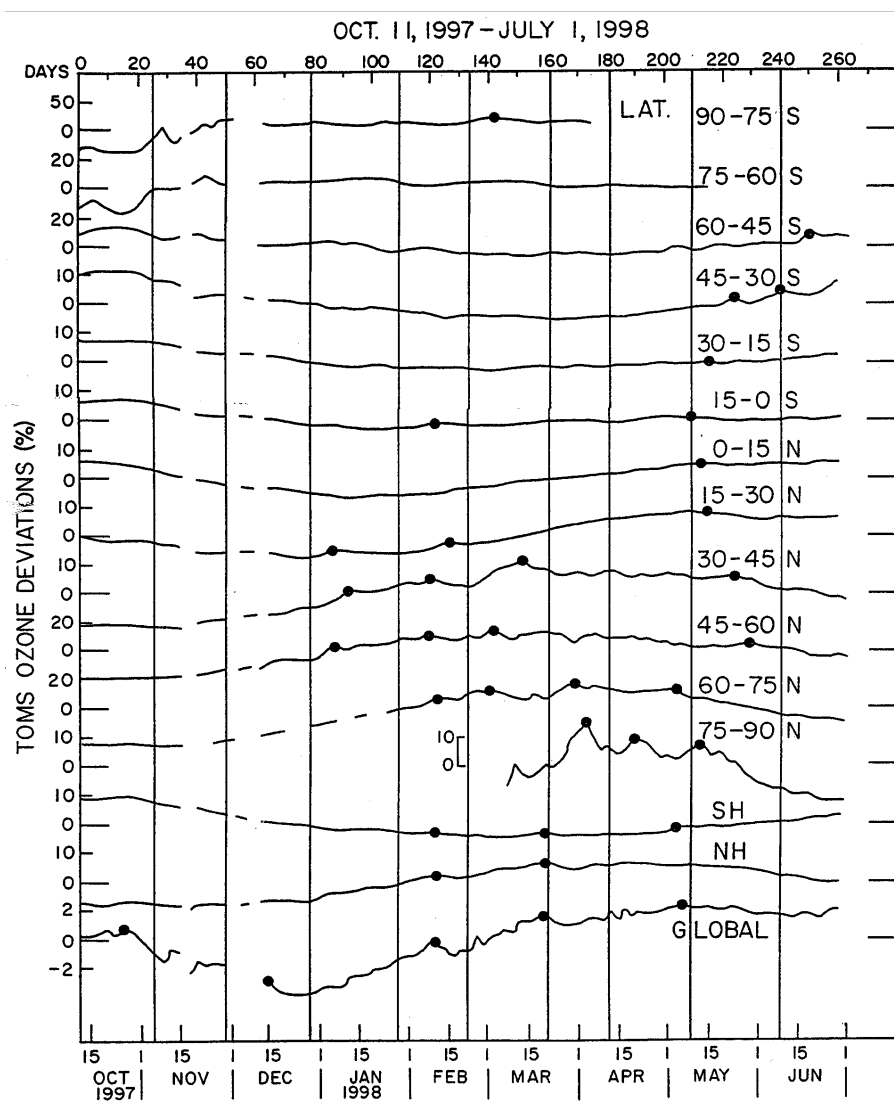
Fig. 4. Plots of TOMS ozone in different latitude belts during the 263-day interval 11 October, 1997 – 1 July, 1998. The bottom plots are for northern (NH), southern (SH) hemispheres and the global ozone

3.   Comparison with UVB changes

Solar UV radiation (100-400 nm) is subdivided into three bands, UV-A (400-320 nm), UV-B (320-280 nm), UV-C (280-100 nm). The UV-C is totally absorbed in the terrestrial atmosphere and wavelengths shorter than ~240 nm are mainly responsible for producing the stratospheric ozone. UV-A is not absorbed efficiently by any atmospheric constituent, reaches the Earth's surface almost unaltered, and is only mildly harmful to terrestrial life. UV-B is very strongly absorbed by ozone, suffers large variations, and is harmful to plant and human life (can cause skin cancer). The most effective biological

wavelength for producing skin erythema on typical Caucasian skins is 297 nm (Koller, 1965). Though UV-B has been measured on a long-term basis by some groups (Scotto *et al.*, 1988; Blumthaler and Ambach, 1988, 1990; Correll *et al.*, 1992), the measurements are not fully reliable and consistent with each other (Kane, 1991, 1998). For example, Correll *et al.* (1992) mentions that from 1975 to 1985, the 305 nm UVB increased by a factor of 4 (the primary solar intensity in 290-330 nm had increased only by 1-5%). If true, there should have been a colossal increase (more than 500%) in skin cancer incidence in some succeeding decade (1% increase in UVB is expected to cause ~2% increase in skin cancer
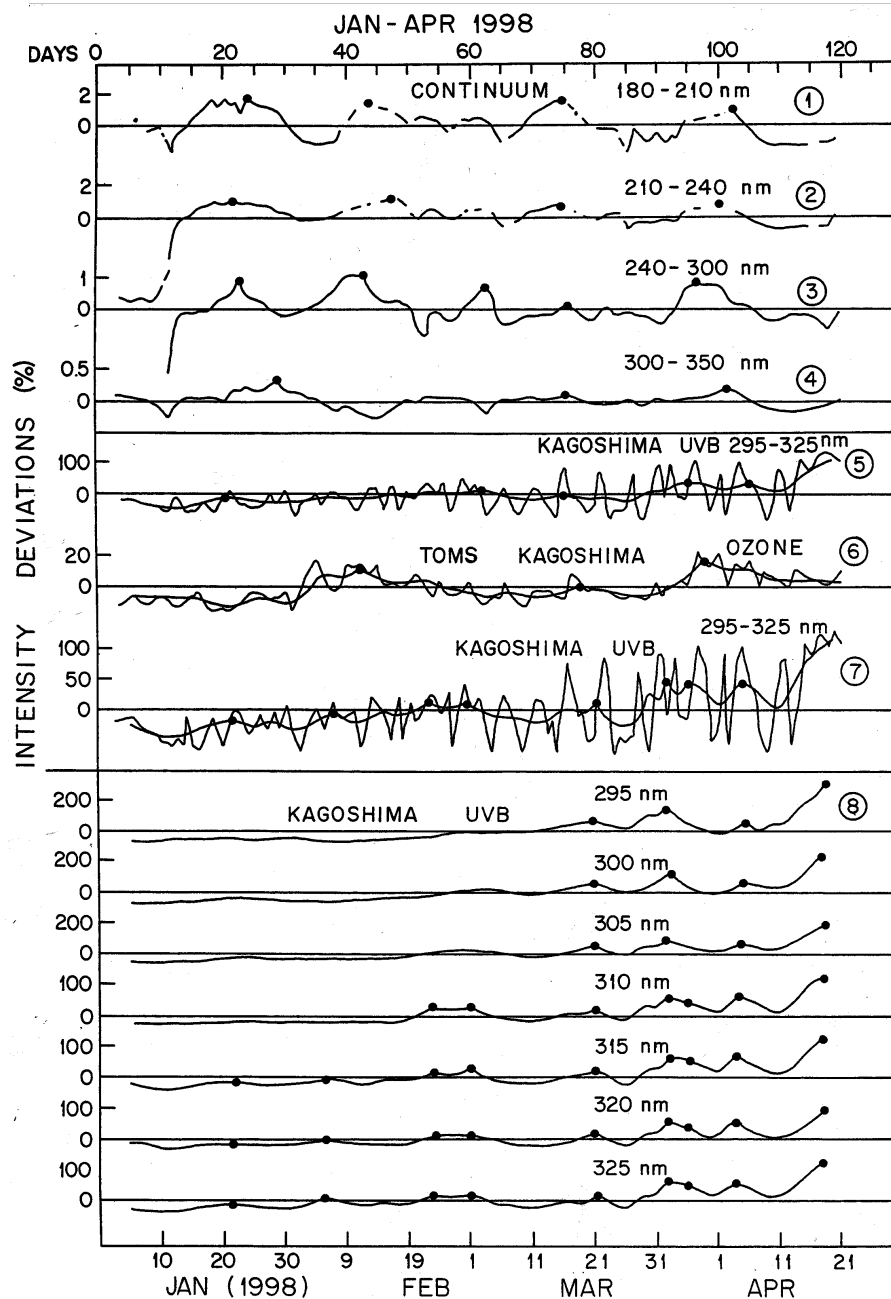
Fig. 5. Evolution of various solar continua emissions (Plots 1-4) during the 263-day interval 11 October, 1997 - 1 July, 1998. Other plots are for TOMS ozone overpass above Kagoshima, Japan (32° N, 131° E) (plot 6) and UVB (295-325 nm) measured at Kagoshima (plots 5, 7 and 8)

incidence). That has not happened. The relation between ozone changes and the corresponding UVB changes is largely latitude-dependent. For example, for a 1% decrease of ozone, Dahlback *et al.* (1989) reported an increase of UV dose of ~1% at 60° N, while McKenzie *et al* (1991) reported an increase of $1.25 \pm 0.20\%$ at 45° S. There have been several measurements of ozone and UVB in the last few years [Kane (1998), and references therein]

but the results are not consistent. To complicate matters, UV can be reduced by as much as 80% by clouds, and changes due to columnar SO_2 changes have their own unique spectral dependence (Bais *et al.*, 1993).

Fig. 5 shows a plot of solar continua (plots 1-4: 180-210 nm; 210-240 nm; 240-300 nm; 300-350 nm) for
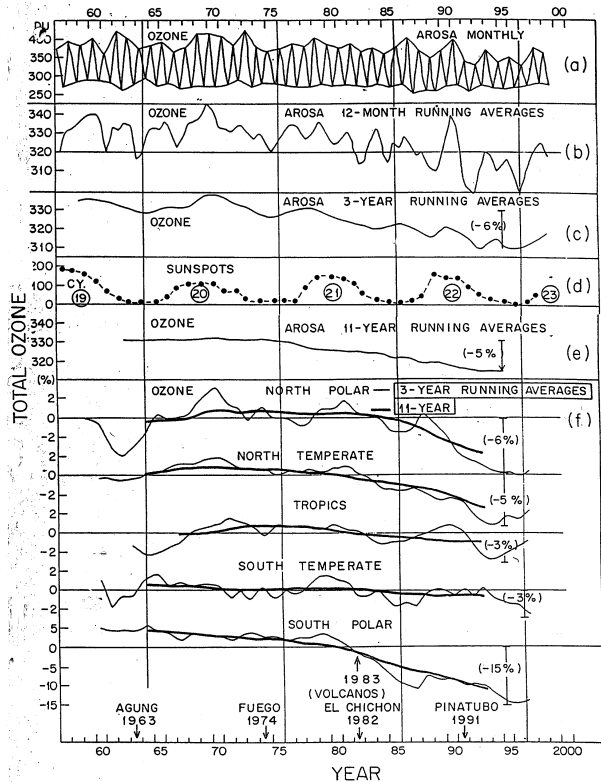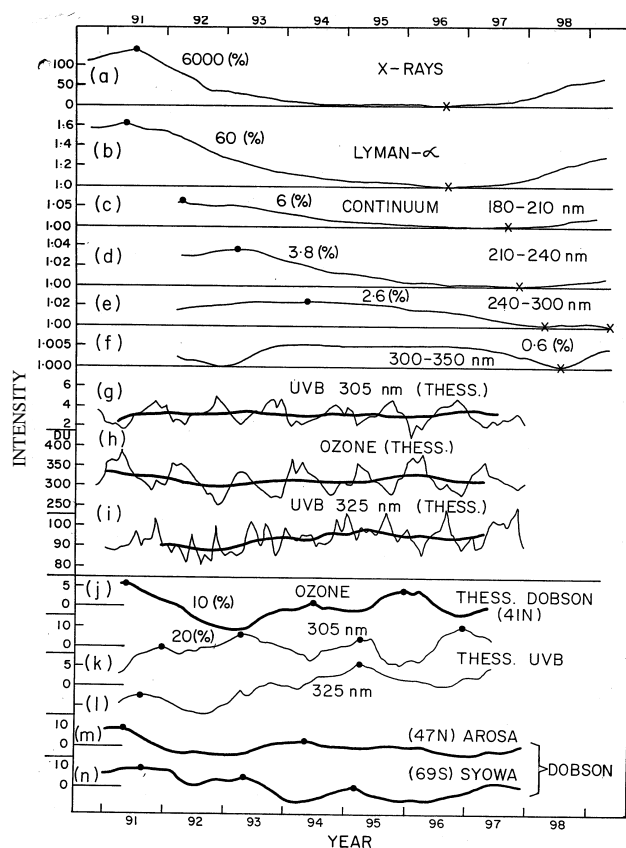
Figs. 6(a-f). Plots of (a) Arosa Dobson ozone, monthly values, (b) Arosa 12-month moving averages, (c) Arosa 3-year moving averages. (d) Sunspot numbers. (e) Arosa 11-year moving averages and (f) Plots for ozone in different latitude belts

January-April, 1998, and the UVB (Brewer) (plot 5: 295-325 nm) and TOMS ozone (plot 6), overpass above Kagoshima, Japan (32° N, 131° E). In the continua (plots 1-4), there are 4 peaks (marked by dots) near days 23, 44, 75, 102, with amplitudes of ~1-2%, lesser in larger wavelengths. In daily values (thin lines), UVB (plot 5) shows very large day-to-day changes (exceeding 50%, probably due to changes in cloudiness), while ozone (plot 6) shows changes of ~20%. In moving averages over 5 days (superposed thick lines), these changes are reduced considerably and UVB shows no prominent peaks; mostly long-term changes (seasonal?) are seen. However, ozone shows two major peaks near days 42 and 97, with a separation of 55 days, which implies two 27-day cycles, and, with a small in-between peak near 77 days, the 5-day averages of ozone show 3 peaks almost coinciding with the continua peaks near 44, 75, 102 days. The problem is that the ozone amplitudes are ~10%, far more than the continua amplitudes of ~1-2 %. How can small continua amplitudes result in large ozone amplitudes? No amplification mechanism has ever been suggested. It is suspected that the matching could be coincidental and the

ozone variations are due to causes other than solar effects. To check whether the UVB plots had smaller but significant peaks, plot 7 shows the values of UVB of plot 5, on an expanded ordinate scale. Some peaks (dots) are seen more clearly, but these do not seem to match with the continua peaks. Incidentally, the UVB changes are expected to be opposite to those of ozone, with increases of one matching with decreases of the other. No such matching is seen, and the correlation coefficient between the 5-day moving averages of UVB and ozone is +0.57, a meaningless correlation, as a negative value is expected. It seems, therefore, that the large UVB variations are mostly unrelated to ozone or to solar continua fluxes and have their own, different origins. The UVB range 295-325 is wide and it is known that all wavelengths therein do not have the same relation with ozone. To examine differences if any, the plots 8 show 5-day moving averages for individual lines 295, 300, 305, 310, 315, 320, 325 nm. Except for the ranges of the percentage variations (~200% for 295, 300, 305 nm, ~100% for 310, 315, 320, 325 nm), the variations are qualitatively alike, with no similarity with the plot 6 for ozone.

4.　Long-term changes of ozone and UVB

One of the longest series of Dobson ozone measurements is that of Arosa. Fig. 6(a) shows a plot of the monthly means. As can be seen, there is a large seasonal variation (amplitude about ±20%, peak to trough range ~40%). If this is eliminated by calculating 12-month moving averages, Fig. 6(b) shows a Quasi-biennial oscillation (QBO), with an amplitude of ~7% (range ~15%). If the QBO is minimized by calculating 3-year moving averages, Fig. 6(c) shows oscillations roughly in phase with the sunspot cycle Fig. 6(d), but the ozone ranges from sunspot maximum to sunspot minimum are small, ~2.6% in cycle 19 and ~3.6% in cycle 20. During cycle 21, near about 1980, the ozone intensity started showing a global depletion. Hence solar cycle effects are uncertain. If it is assumed that the depletion was linear with time, the solar cycle effect could be approximately estimated by calculating the average of ozone at two successive solar minima, and subtracting this average from the ozone value at the intermediate solar maximum. For cycles 21 and 22, the solar cycle effects were ~2%, with an uncertainty of ~0.5%. Incidentally, these numbers are not proportional to the sunspot number maxima. The largest smoothed sunspot number was 210 for cycle 19 and only 111 for cycle 20. The ozone changes were 2.6% for cycle 19 and larger (3.6%) for cycle 20. The other plots in Fig. 6 are for ozone levels in broad latitude belts. The thin lines are 3-year moving averages. The north-polar region ozone shows solar cycle ranges of ~3%, but other regions show much smaller solar cycle effects. The predominant variation is the long-term ozone depletion

Figs. 7(a-n). Plots of various solar line emissions for 1991-97 (a-f), for ozone at Thessaloniki, Greece (40°N) (h, j). Arosa (47° N)(m), Syowa (69° S)(n), and for UVB at Thessaloniki (305 nm, g, k; 325 nm, i, l)

references therein]. Changes in any or all of these may reduce, cancel or even reverse the UVB changes, which are otherwise expected to be opposite of those of ozone. Zerefos *et al.* (2000) have presented measurements of spectral ultraviolet irradiance and total ozone by a Brewer ozone single spectrophotometer, for Thessaloniki, Greece (40° N, 23° E). Fig. 7 shows a plot for 1991-1998. (a) X-rays show a very large change (~6000%) from solar maximum in 1991 to solar minimum in 1996. (b) Lyman alpha shows ~60%. Continua (c) 180-210 nm show 6%, (d) 210-240 nm show 3.8%, (e) 240-300 nm show 2.6%, (f) 300-350 nm show a strange pattern with a very broad maximum during 1994-1996 and a small drop of ~0.6% thereafter. The plot (g) shows the UVB at 305 nm under low cloudiness (cloud cover 2/8 or less) and plot (h) shows ozone, both measured at Thessaloniki, Greece. The thin lines are monthly means and the plots of UVB and ozone are almost reverse to each other, with a high negative correlation (-0.92). Plot (*i*) is for UVB at 325 nm. The plot is not very smooth and the correlation with ozone is only –0.19, indicating that 325 nm is almost unrelated to ozone. The thick lines are 12-month moving averages and show strange results, with no parallelism with the solar cycle. Plots (j), (k) & (l) show the moving averages on expanded ordinate scales. As can be seen, the ozone plot is not following the solar cycle at all. True, there is a maximum in 1991 (solar maximum), but there is a minimum only about one year later, in 1992-93. There is a maximum in 1995-96 at solar minimum. Thus, the long-term solar cycle effect on ozone is ambiguous. On the other hand, the 305 UVB values have a pattern opposite to that of ozone throughout 1991-97. The magnitudes of UVB changes are almost double of those of ozone (a 1% decrease of ozone is accompanied by ~2% increase of 305 nm UVB). The 325 nm UVB show an altogether different evolution pattern, somewhat parallel to that of ozone, instead of the anti-parallel of 305 UVB. The most disconcerting aspect is that 325 UVB shows a strong maximum in 1995-96 when solar activity was minimum.

The bottom plots (m) and (n) are for the 12-month moving averages of Dobson ozone at Arosa (mid-latitude) and Syowa (Antarctic). Both show a decrease from 1991 to 1992. Thus, the decrease of ozone from 1991 to 1992-93 in plot (j) is not a solar cycle effect. It reflects the global depletion of ozone due to chemical destruction by chlorofluorocarbon compounds. During 1993 to 1996, Syowa ozone (plot n) shows a substantial QBO superposed on a decline of ~20% from 1991 to 1996. Arosa ozone (plot m) shows a small QBO but the decline seems to have stopped in 1992-93 and remained at that level thereafter. The Thessaloniki ozone (plot j) shows a rise from 1992-93 onwards and the 1995-96 level is the same as that of 1991. If the data are not erroneous,

that started near 1980 and reached large depleted levels (~5% at Arosa, ~15% at the South Pole) in 1996, which seem to still continue in 2001.

Thus, as far as stratospheric ozone is concerned, the largest variations at a mid-latitude location are (a) the seasonal (~±20%), and (b) the day-to-day variations (peak to trough as much as 50%). Next biggest is the QBO (~7% peak to trough). The solar effects are (c) at the most ~3%, for long-term (solar cycle), and (d) 2 % or less for short-term (solar rotation).

For UVB, earlier data are unreliable (Kane, 1991, 1998). In later data, contradicting evidences are seen in many UVB measurements, which are attributed to overshadowing of the real UVB changes by increases in the absorbing tropospheric aerosols, ozone and changes in the meteorological conditions, in addition to effects of clouds and haze level, tropospheric minor constituents such as SO_2, and surface albedo [Zerefos *et al.* (2000) and

different long-term patterns of ozone at different latitudes are indicated, none of these matching with solar cycle. The only consistent fact is that 305 nm UVB shows variations opposite to those of ozone.

5.   Conclusions and Discussion

The variations of stratospheric ozone and UVB observed at ground were compared with those of solar indices. The following was noted:

(a)   *Short-term variations*

(*i*)   During sequences when large ~27-day oscillations occurred, X-ray fluxes near 1 nm had very large amplitudes (exceeding 50%), EUV near 30 nm had ~20%, Lyman alpha 121.6 nm ~10%, Mg II 280 nm ~5%, continua 180-210 nm ~2%, 210-240 nm ~1.5%, 240-300 nm ~1%, 300-350 nm ~0.5%. There were distinct peaks seen in all these (except in the 300-350 nm continuum where some peaks were obscure), with spacing of roughly (27±5) days.

(*ii*)   For effects on stratospheric ozone, the relevant wavelengths are mostly in the continua mentioned above. In the 27-day sequences, the Dobson ozone at Arosa (47° N, 10° E) showed large fluctuations with many peaks, but the peaks rarely matched with the peaks of solar indices. Also, the ozone fluctuations were very large, ~50% within a few days. Thus both qualitatively and quantitatively, the ozone variations were very different from those of relevant solar indices (continua). It seems that solar effects of the order of 1-2% are almost non-existent and the origin of these large fluctuations (~50%) in ozone could be in some dynamic circulations. These fluctuations were equally strong in TOMS ozone data, overpass above Arosa, but were reduced considerably when TOMS data over a broad latitude range (a few degrees around Arosa) were examined. Thus, the dynamic circulations causing these fluctuations should be fairly localized.

(*iii*)   When TOMS ozone data over broad latitude belts (15° width) were examined, some peaks were observed mostly in the northern hemisphere, but the peaks did not tally with the peaks of solar indices. Planetary waves [Salby, 1984] unrelated to solar variations might be playing an important role in causing these fluctuations.

(*iv*)   During one such 27-day sequence, the TOMS ozone overpass over Kagoshima, Japan (32° N, 121° E) and the UVB (295-325 nm) observed at Kagoshima showed large day-to-day fluctuations, ~20% for ozone, ~50% or UVB, but the peaks of ozone and UVB did not match with each other, nor with the peaks of solar indices, thus indicating altogether different mechanisms as their causes.

(b)   *Long-term changes*

(*i*)   One of the longest data series is for Arosa Dobson ozone. The largest fluctuations were the seasonal variation (~40% range peak to trough). If eliminated by calculating 12-month moving averages, the next big variation was the QBO (Quasi-biennial oscillation, ~7% peak to trough). In solar cycles 19 and 20, the overall ozone level was steady and the ozone variation ranges (peak to trough) were ~2.6% in cycle 19 (sunspot maximum number 210) and ~3.5% in cycle 20 (sunspot maximum number 111). Thus, larger sunspot number did not imply larger ozone range. During cycle 21, near about 1980, the ozone level started suffering a depletion which reached to 5-6 % percent (more in the Antarctic) in a decade's time. The solar cycle variation in cycles 21 onwards is, therefore, uncertain. But this variation is certainly less than ~2%.

(*ii*)   UVB have been measured since the 1980s, but the earlier data are unreliable and inconsistent (Kane, 1991, 1998). In the 1990s, some (hopefully) accurate measurements are available. For 1991-97, the monthly values of ozone at Thessaloniki, Greece (40° N, 23° E) were well anti-correlated with 305 nm UVB (1% ozone decrease corresponded to ~2% UVB increase), but poorly correlated with 325 nm UVB, indicating that ozone-UVB relationship was highly wavelength-dependent. However, whereas solar indices had a maximum in 1991 and a minimum in 1996, neither ozone nor any of the two UVB 305 nm and 325 nm showed resemblance with the solar index variations. In particular, ozone level was high in 1991 but decreased considerably in two years (by 1993). A comparison with ozone at Arosa (47° N) and Syowa (69° S) showed that this drop is not related to solar cycle but is due to the global depletion of ozone.

It seems therefore, that the short-term solar effect on ozone and the ground UVB is very small (1-2%) and is hardly detectable, particularly in the presence of much larger effects like the day-to-day fluctuations (~50%), and the seasonal effects (~40%). The long-term solar effects are also small (~3%) and are distorted by the QBO (~7%) and by the global depletion in recent decades. In the last two decades, considerable effort has gone in studying the solar effects on ozone and temperatures, including efforts in developing appropriate models. In the recent attempt (Labitzke *et al.*, 2002), two general circulation models (GCMs) with coupled stratospheric chemistry are used to stimulate the impact of changes in solar output on stratospheric ozone and temperature and geopotential heights. These authors report, "Comparisons between the GCM results and observations shows that the differences between solar maximum and minimum for temperature and ozone are generally smaller than observed (remember, the observed values are small, only ~3%). Also, model

predictions of the shape of the vertical profile of the ozone difference do not agree with observations and the comparisons are hindered by large statistical uncertainties in both models and observations. Nonetheless, the results are an improvement on 2-D model results in showing a larger ozone signal in the lower stratosphere". Thus, even after the efforts of about two decades, major discrepancies remain. One suspects that the modeling has reached its limits by ascertaining the regular part of the phenomenon of solar effects, and the irregular part is probably beyond its reach. In practical terms, ozone values and UVB values have so large day-to-day fluctuations that the possible contribution due to changes in solar output is comparatively very small. The effort in identifying these seems like searching a needle in a haystack, where the characteristics of the needle are not fully-known. One wonders whether the effort is of any practical value. The predictions of ozone levels based on modeling are, at the most, approximate average values. Ironically, large extreme values remain unpredicted, which is a pity, because these cause the largest damages (in every field: floods, droughts, hurricane activity, volcanic activity, tsunamies, and many others). The day-to-day changes of UVB are so large that the very high intensities on individual days can cause more physical damage than the intensities for rest of the year. Models are not able to capture this eventuality.

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