CHAPTER -4

SOLAR UV-B RADIATION AND ATMOSPHERIC OZONE

RESULTS AND DISCUSSION

This chapter discusses the results of the direct solar UV-B flux measurements carried out from 1982 to 1992. The diurnal and annual variations in the UV flux have been studied. The measured flux has been compared with theoretical estimates. During the period, October-December, the UV flux shows variations, indicating possible links with the Antarctic ozone hole phenomenon. A three dimensional contour representation of the flux received over an year is made. Using the UV data, the long term trends in the flux are derived. The measured UV flux is inverted to derive the total ozone content. The long term trend in the derived ozone in the light of the satellite measurements is presented and discussed.

The amount of solar radiation reaching the earth's surface depends on diverse factors like the latitude, altitude above sea level of the site, the time, season of the year, activity of the sun, natural and anthropogenic disturbance to the atmosphere etc. Here the results of the measurement of solar UV-B radiation at the surface are at first examined in terms of their diurnal behaviour.
Fig. 4.1. Diurnal variation in the solar flux at 320, 310, 300, and 290 nm on a clear day (Feb 12, 1992). A polynomial is fitted to the measured data.
In Fig 4.2., the flux computed following Dave and Halpern, (1976) are shown along with the measured flux at 310 and 320 nm. These computed flux are for an ozone overburden of 300 matm-cm (Dobson Unit, D.U) with a constant Rayleigh molecular scattering optical depth. A constant aerosol optical depth is also assumed in the computations of flux. The variation of the measured flux with zenith angle follows the computed profile.

4.2. SEASONAL VARIATION IN THE SOLAR UV-B RADIATION:

For studying the features in the seasonal variation of the solar UV-B radiation, flux at a specific zenith angle was selected. Throughout the year, the flux measurements at the 30° zenith angle exist for all wavelengths. Therefore, flux at 30° zenith was chosen to study the seasonal variations in the measured flux. The variations in the solar UV-B radiation received over an year at the surface at 320, 310, 300 and 290 nm channels are shown for the year, 1990, in Fig 4.3. The variations have been observed to be similar over other years also. India Meteorological Department (IMD) has been monitoring the direct, diffuse and global components of the total solar radiation (visible to near IR) at about 145 stations in India (Mani & Rangarajan, 1982). From this data, the monthly mean radiation data for Trivandrum is taken. The direct component of the total radiation in kW/m² for an average clear sky noon
Fig. 4.2. Variation in the measured and computed flux at 320 and 310 nm with solar zenith angle from 0 to 70°. The forenoon (FN) and afternoon (AN) measured flux shows good agreement with theory.
conditions has been chosen and is also shown in Fig. 4.3. A fourth degree polynomial is fitted to the IMD solar radiation data.

It can be seen that the pattern of variation is similar in all the cases. Annual variation in the direct component of the total solar radiation can, in general, be attributed to a change in the sun-earth distance during the course of an year. As far as the direct component of radiation is concerned, the sun behaves as a point source. However, a closer look at the data reveals that the minimum occurring in the solar radiation has a wavelength dependence. The direct component of the total solar radiation data is mostly visible radiation with a small amount of near IR radiation. This spectrum peaks at about 450 nm wavelength. The annual behaviour of this radiation indicates a low around day number 180. This period coincides with the summer solstice (June 21) and the farthest annual position of the earth (apogee) with respect to the sun. When the UV-B data is examined, it is found that the 320 nm behaves similar to the total solar radiation, except for a slight shift in the minimum. But the 310, 300 and 290 nm radiation come to a minimum around the day number 125. The 290 nm channel has mostly radiation in the wavelength region above 295 nm, behaves similar to the 300 nm radiation. A closer examination of the data for other years also reveals that the 310 annual minimum is between those of 300 and 320 nm. The UV radiation is absorbed by the atmospheric species while the total solar
Fig. 4.3. Solar UV-B flux at 290, 300, 310 and 320 nm at 30° zenith measured for an year, 1990, is shown. The direct component of the total solar radiation is also shown with a polynomial fit.
radiation is relatively attenuated less.

The 320, 310, 300 and 290 nm radiations emanate from different depths of the solar photosphere. The lower wavelength radiations emanate from deeper layers. Therefore, the instantaneous position of the earth with respect to the sun and the solar azimuth are found to affect the UV-B insolation at the earth's surface, apart from the absorbing species in the earth's atmosphere. The percentage variation of the solar flux corresponding to the variation in sun earth distance indicate that a 6.6 % change between January 3 and July 7 exist as depicted in Fig 4.4.

It can be noted from the Fig. 4.3, that the variation in the flux at all the UV wavelengths is not smooth during the October- December period. This variation is discussed in detail in the next section.

Contour plots of the UV flux at all the four wavelengths are given for the year 1991, as a typical case, in Fig 4.5 (a) and (b). These represent the annual pattern of the UV radiation with zenith angle also. These contours indicate that the variation in flux is large at lower zeniths (shorter paths) than at longer path lengths for all the wavelengths. The influence of the atmosphere in attenuating the solar radiation is evident from these contours. The highs in flux correspond to broad peaks. The contour plots do not show marked changes from one year to another. Since the contour intervals are large, the variation in flux at larger zeniths is not evident.
Fig. 4.4. Variation % of the solar flux corresponding to the variation of the sun-to-earth distance: 6.6% variations are noted between January 3 and July 7.
Fig. 4.5. Contour plots of the solar flux at 320, 310, 300 and 290 nm for the year 1991.
4.3. VARIATIONS IN THE DIRECT SOLAR UV-B FLUX DURING OCTOBER - DECEMBER PERIOD:

Continuous observation of the direct solar UV-B flux at Trivandrum, a tropical site, over a decade shows that the variation in the flux during the period October-December is not smooth. In the case of 320 nm, the radiation decreases after the day number 270 and then slightly increases to reach a maximum towards the end of the year. In the 310 and 300 nm channels, the decrease is prominent and the recoupment is clear only in certain years. In Fig.4.6., the measured solar UV-B flux at 320, 310 and 300 nm is shown for the period 1982 to 1992. From the figure, it can be seen that this feature is regular and appears every year, though the exact nature of variation shows a change from one year to another.

This unique set of data clearly shows that the UV flux reaching the surface decreases and then increases during the period October to December every year. The possible reasons for this behaviour have to be considered. As mentioned earlier, the direct component of the total solar radiation increases from around day number 180 and reaches a maximum towards the end of the year. Therefore, it would be reasonable to expect that the UV radiation also should show a similar behaviour, unless the absorbing species introduce such a variation. It can also be seen that the decrease in the flux is more pronounced in 300 nm channel than in the 320 nm
Fig 4.6  Long term solar flux at 300, 310 and 320 nm from 1982 March to 1992 May. The Dobson spectrophotometer data on total ozone at Syowa station in Antarctica is also shown in the plot.
channel. The absorption due to ozone is higher in the 300 nm channel. This strengthens the view that the flux could vary due to a change in total ozone.

There may be two possibilities for such a change in ozone to occur. The first one could be the existence of local sources of ozone production and depletion and the second, transport. No known mechanism exists that could account for an increased production of ozone that would introduce discernible amounts in total ozone. Therefore, ozone transport has to be considered. Since the chemical lifetime of odd oxygen in the lower stratosphere is long compared to the time constants associated with transport by the mean meridional circulation, transport by mean meridional advection can play an important role in determining ozone distribution. The vertical distribution of ozone peaks at different heights at different latitudes. Much of the change in total column abundance is due to differences found in the altitudinal profiles below about 20 km. This behaviour is related to ozone transport in cyclones and anticyclones which propagate into the lower stratosphere. Therefore, transport plays an important role in the ozone distribution. The period, October to December, is meteorologically active with the onset and withdrawal of the north-east monsoon in this region. The linkage between the ozone rich air brought in by the winds associated with this monsoon and the ozone change has to be examined in detail. It is possible that the ozone produced over the tropics was not transported to the other
regions and caused an initial ozone accumulation which later got removed by transport. These possibilities have to be looked into with the help of meteorological data, eddy diffusion coefficient and mass transport in the troposphere and stratosphere.

It is known that during the same period, the Antarctic ozone is depleted by large amounts. When the measured UV flux is compared with the total ozone at Syowa, an Antarctic station, the two parameters showed a remarkable anticorrelation, as shown in Fig.4.7. This anticorrelation suggests that when the ozone hole recoups, the tropical ozone also shows an increase.

Studies indicate the possibility of the extension of the Antarctic ozone hole to lower latitudes in the South American region (Kane, 1991). Therefore, if the ozone hole is felt near the tropics, then its subsequent recouping could also be effective. To understand this, it becomes necessary to know whether the tropical regions exhibit such a depletion in ozone. The ozone derived from the measured flux is shown for four years, 1988 to 1991, in Fig.4.8. It can be seen that the ozone does go through a minimum before starts increasing around the day number 270. The derived ozone variation over an year resembles a midlatitude situation up to about the day number 270. The increase in ozone after that is also followed by a decrease which is not seen in the midlatitude profile. Compared to a normally expected ozone distribution over a tropical region.
Fig. 4.7. Syowa total ozone during the years 1983, 1985, 1988, 1989, 1990 and 1991, with the 300 nm UV flux measured at Trivandrum during that period. Ozone is expressed in atm-cm for compatible representation on the same graphs. A remarkable anticorrelation is seen.
Fig. 4.8. The average total ozone derived from the flux at the four wavelengths is shown for the years 1988 to 1991.
from the Dobson data, the ozone measured using the UVB radiometer is less during the ozone hole period. Therefore, measurements of solar UVB at different latitudes using a standardized system is needed to understand this.

4.4. LONG TERM TRENDS IN THE SOLAR UV-B RADIATION:

From the data on solar UV-B flux at different wavelengths measured here, long term trends have been arrived at all the wavelengths using a simple linear regression method and also using a Robust locally weighted regression method. Data for the entire period of analysis (1982 to 1992) is not continuous. As we have seen, the annual behaviour of the flux is not linear. However, the behaviour repeats itself over the period of observation. Various statistical techniques of analysis are available for arriving at the long term trends from such data (Davison and Hemphill, 1987). The Robust locally weighted regression method considers the entire data region as its neighbourhood for evaluation of the trend. The Robust method of trend analysis has been applied to similar problems of analysis of seasonal data as in the case of sea level rise (Walden and Prescott, 1983). This method was used for evaluating low trends in ozone by Walker, 1985. Generally, this technique is applied whereever the trends are very low.

The long term trends are obtained by linear regression analysis of the UV-B data at the four wavelengths
290, 300, 310 and 320 nm, from 1982 to 1992 May. The slopes of the regression line are positive at all the wavelengths, indicating that the UV-B radiation in general was increasing very gradually from 1982. The slopes of the regression line for different wavelengths are of the same order of magnitude. Measurements at 310 and 290 nm were started only in 1987 and hence the trends shown are for this period.

To the same data set, the Robust locally weighted regression was done. The trends are shown in Fig 4.9. In order to compare the slopes of linear regression and the Robust locally weighted regression, the correlation coefficient \( r \) between the Robust and linear regression trends was derived. These are shown in the figure.

From a low long term trend like this, the positive slope of the trend line at each wavelength is merely indicative of the increase in the flux. The closeness of the slopes in the two methods of analysis indicates that the trends are genuine.

4.5. CONVERSION OF SOLAR UV FLUX TO TOTAL OZONE:

Direct solar UV flux measurements do not exist at this latitude for comparison with the data obtained here. However, total ozone data using the Dobson spectrometer are available for tropical stations like Kodaikanal and Singapore. The UV-B flux measured here are converted to total ozone and compared with the above data. Thus, total ozone
Fig. 4.9. Long term trends in solar UV-B flux for the period 1982 to 1992. The slopes obtained by the linear and Robust locally weighted regression analysis are close as shown by the correlation coefficients.
concentration, $\Omega$, was derived using equation 8 of Chapter 3, viz.,

$$\phi_h(\lambda, \chi, \Omega) = \phi_o (r_o/r)^2 \cos \chi \exp\{- (\tau_{rs} + \tau_{aa} + \tau_{as} + \phi \Omega) \sec \chi \}. \quad (8)$$

$(r_o/r)^2$ values were linearly interpolated from the known sun earth distance on Jan 3 and July 7 or from the standard Ephemeris. $\phi_o$ was obtained from Delussi, (1975). The mean $\phi_o$ at the filter effective bandwidth is used for the computation. Rayleigh scattering coefficient was computed using equation 7 of Chapter 3 and later adopted from Deshpande and Mitra, (1983) as both were comparable. The ozone absorption coefficients are from Holina and Holina, (1986). The aerosol optical depth has been assumed from Dave and Halpern, (1976).

Fig 4.10. shows the computed total ozone on a clear day plotted as a function of the solar zenith angle $\chi$. The curve shows the average ozone computed using the flux at 320, 310, 300 and 290 nm. It can be inferred that the derived total ozone does not show any diurnal variation, as expected. The ozone derived from the flux data at different channels agree within the limits of the experimental error.

Similar computations have been carried out for all clear sky days for which observations exist. Fig 4.11. shows ozone derived for an year (1988) from all the wavelength channels. The close agreement within limits of experimental error especially among 290, 310 and 320 nm is seen here. The
Fig. 4.10. Total ozone computed for a clear observation day plotted as function of the solar zenith angle. A day near the vernal equinox, March 23, 1992, is represented.
Fig. 4.11. Total ozone computations for different channels 320, 310, 300 and 290 nm for the year 1988. The 300 nm channel discrepancy can be noted.
ozone derived using the 300 nm data shows a constant difference of nearly 8-12 D.U. compared to the mean of the ozone derived using the other 3 channels.

Sulphur dioxide cross absorbs in the UV-B regime. However, the difference in total ozone in the 300 nm channel is not attributable to the sulphur dioxide emission from a factory a few kilometres away from this site of observation. The absorption cross section of SO₂ peaks in the 296 region and falls off by about one decade within 305 nm. Therefore, if the change was due to the SO₂ absorption it should have interfered in the 290 channel, at least marginally. Also, the very low (ppb) levels of SO₂ does not have a annual variation of same nature.

However, the ozone derived using the 300 nm channel data will agree with the ozone derived from the data of other channels, if a possible drift in the central wavelength of the 300 nm filter by less than 0.5 nm can be assumed. Although the filter calibrations were done regularly, such a drift could not be observed since the calibration equipment does not have the required sensitivity. Assuming this possible drift, a correction for the absorption cross section from 10.66 to 11.2 (atm-cm)⁻¹ is done. The corrected profile is given in Fig 4.12. for the year 1988. The variation of ozone during an year is shown as a contour plot for the year 1991, in Fig.4.13.
Fig. 4.12. Total ozone computations at the four wavelengths after correcting the 300 nm channel.
Total ozone in 320 nm channel during 1991

Fig. 4.13. Contour plots of the ozone derived from 320 nm for the year 1991.
4.6. SENSITIVITY OF TOTAL OZONE TO MODEL PARAMETERS:

The sensitivity of the different models for ozone calculations depend on the solar flux at the top of the atmosphere, the ozone coefficients used and the aerosol optical depth. The extra terrestrial flux (ETC) has been taken from De Luissi (1975), Thekkaekara (1974), and Deshpande and Mitra (1983). The ozone coefficients are from Molina and Molina (1986) and Deshpande and Mitra (1983). The Rayleigh and aerosol optical depths have been taken from Dave and Halpern (1976). In Fig 4.14, is shown the variation of 320 and 310 nm flux reaching the surface calculated using three different models (M1, M2, M3). The figure illustrates that the UV flux received at the ground shows discernible variation from model to model.

4.7. COMPARISON WITH KODAIKANAL AND SINGAPORE OZONE:

The average total ozone computed from the four channel UV data is compared with Dobson data from other stations. Comparison with the Singapore and Kodaikanal ozone with that at Trivandrum is given in Fig 4.15. The annual amplitude at Trivandrum is ~ 50 D.U. and that at Kodaikanal is ~ 40 D.U. and at Singapore is ~25 D.U. The annual variation of the derived ozone at Trivandrum resembles that of a midlatitude station.
Fig. 4.14. Sensitivity of total ozone to model parameters. Using 3 models 320 and 310 flux have been computed and shown in the figure.
Fig. 4.15. Singapore and Kodaikanal Dobson ozone compared with the average total ozone measured at Trivandrum for one year. A large annual amplitude in Trivandrum ozone is observed.
4. 8. LONG TERM TRENDS IN TOTAL OZONE IN TRIVANDRUM AND COMPARISON WITH GLOBAL TRENDS FROM SATELLITE DATA:

Fig 4.16 gives the variation in the average total ozone derived from 320, 310, 300, and 290 nm channels for the entire period of observation. The long term trend of ozone has been derived using this data.

The trends in ozone have been derived by the linear regression and the Robust locally weighted regression techniques. The data analyses were done for the period March 1982 to May 1992. The slopes of the total ozone variation obtained by both the methods agree well within a confidence level of 90% and is 0.00777 per day with the constant 286.4 D.U.

However, this trend in ozone has not been corrected for the activity of the sun. It is known that the sunspot number, which is an index of the activity of the sun, correlates well with the total ozone (Willet, 1962, 1963, London and Haurwitz, 1963). Since the scales and units are different for total ozone and the sun spot number, both have to be normalized. Then, the slope of the sunspot number trend has to be subtracted from the total ozone slope to get the net slope of the ozone change. This value was weighted with the normalizing factor to get the actual slope for ozone. Then the annual change in the total ozone is computed. The data analysis period is from 1982 to 1989 only for which both the parameters were available. The net normalized slope derived
Fig. 4.16. Variation in the average total ozone at Trivandrum for the period March 1982 to May 1992. A linear regression line is shown in the figure. Correction for the trend in solar activity has not been incorporated here.
is -0.000023 per day. From this, the percentage change per year per average ozone works out to be 0.003132.

The long term trends in total ozone has been derived, Brasseur (1991), from satellite measurements for high and midlatitudes. This trend is interpolated linearly to the latitude, 8.5° N. For this it an ozone distribution of 250 D.U. at the equator, 350 D.U. at the mid latitude, 400 at 60° latitude and 450 D.U. at the pole has been assumed. This computation reveals a trend of -0.00325. The trends obtained from satellite and the ground based measurements agree well.