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# Satellite estimation of spectral UVB irradiance using TOMS derived total ozone and UV reflectivity

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**Abstract.** A method for satellite remote sensing of spectral UVB radiation incident at the earth's surface for snow and/or ice free areas has been developed. Measurements of total ozone and UV reflectivity from the Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) instrument have been applied to this technique. Comparison of satellite estimates with ground based measurements of spectral UVB irradiance show differences which are comparable to differences between near simultaneous measurements made with two or more ground based co-located instruments.

## Introduction

Due to decreasing concentrations of stratospheric ozone resulting largely from destruction by chlorofluorocarbons [Stolarski *et al.*, 1992; Turco *et al.*, 1990] there is concern over the potential increases in biologically harmful ultraviolet-B radiation (UVB; 290-320 nm) incident at the earth's surface. This has led to increased ground based measurement and monitoring of both spectral and broadband UVB at surface stations located throughout the world [Kerr and McElroy, 1993; Frederick *et al.*, 1993; Bais *et al.*, 1993; Webb, 1992].

However, surface monitoring stations are often widely spaced geographically, sometimes are limited to a short time duration of recorded measurements, and sometimes limited to broadband measurements, thus lacking spectral information. Remote sensing of UVB irradiance from satellite has the potential advantage of giving full daily global coverage of spectral UVB estimates. In addition, since we are utilizing measurements made by the Nimbus-7 TOMS instrument, there exists a long time series of data record (November 1978 - May 1993) from which UVB irradiance may be inferred, thus potentially enabling analysis of geographical, seasonal, and interannual variability. The individual effects of trends in total ozone and variability in cloud properties may also be analyzed with this data set. However, since there is only 1 overpass per day of the Nimbus-7 TOMS, the estimates will be most accurate for mid-day irradiance which is the time period for maximum irradiance.

## Instrumentation and Data

The retrieved values of total ozone and UV reflectivity for Toronto in 1990 from the Nimbus-7 TOMS instrument are being used as inputs to our UVB irradiance model. The version

6 TOMS data applied here have been shown to have almost no relative drift in calibration with time when compared to 39 Dobson stations [McPeters and Komhyr, 1991]. There is a bias, however of overestimation of total ozone by the Nimbus-7 TOMS compared to Dobson stations [McPeters and Komhyr, 1991]. In this current study, we reduce the TOMS total ozone amounts by a constant 1.5% in order to account for the bias as compared to the Dobson and Brewer instruments which are both located in Toronto.

The TOMS UV reflectivity values which we utilize in this study are the mean of measurements made at 360 and 380 nm. The time series trend of UV reflectivity shows mainly higher minimum values of reflectivity for the months of January-March and for December. This can be attributed to the presence of snow cover on the ground, which was verified with observations made at Toronto Pearson International airport.

The observations of ground based spectral UVB irradiance, which we compare to our satellite estimates, were made with the Brewer instrument number 14 [Kerr and McElroy, 1993] located in Toronto (44°N, 79°W). This instrument measures UVB intensity at wavelength intervals of 0.5 nm between 290 and 325 nm with a resolution of about 0.5 nm. It takes approximately 8 minutes for the instrument to complete a forward and backward wavelength scan which are then averaged. These measurements are made once or twice each hour from sunrise to sunset. Analysis of the calibration records of this instrument show that the measured responsivity of the instrument varied by +2.7% at 300 nm and +2.5% at 325 nm between 1989 and 1993. These variations are representative of the overall uncertainty of the calibration process combined with variations in instrument sensitivity. The data have been adjusted to account for these measured changes in instrument responsivity. Stray light effects are reduced by use of a band limiting filter that removes light at wavelengths greater than 340 nm and by subtracting stray light measured near 290 nm where there is negligible radiation. Noontime (TOMS overpass) values of stray light are estimated to be near zero for wavelengths greater than 302 nm in summer and 305 nm in winter. At 300 nm these estimated values increase to about 2% in summer and 5% in winter.

## Cloudless Sky - Aerosol Free Model

The solar flux at the ground for clear, cloudless conditions,  $F_{clr}$ , has been calculated using the expression:

$$F_{clr} = F_d(1+r)/(1-RS_b), \quad (1)$$

where  $F_d$  is the direct solar flux reaching the surface (on a horizontal plane),  $r$  the ratio of diffuse to direct radiation,  $R$  the surface reflectivity, and  $S_b$  the fraction of reflected radiation backscattered to the surface by the atmosphere. These calculations are made in an atmosphere that contains Rayleigh scatterers and ozone, but no aerosols or other Mie

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scatterers. Correction for Mie scattering effects are made using the procedure described in the next section. Given the extraterrestrial solar flux at 1 AU ( $F_0$ ), Sun-Earth distance  $d$  (in AU), ozone absorption coefficient per unit ozone amount ( $\alpha$ ), Rayleigh scattering coefficient per unit pressure ( $\beta$ ), surface pressure  $p$  in atm., solar zenith angle  $\theta$ , and total column ozone amount  $\Omega$ ;  $F_d$  is given by

$$F_d = F_0 \cos(\theta) \exp[-\sec(\theta)(\alpha\Omega + \beta p)] / d^2 \quad (2)$$

Alpha,  $\alpha$ , values are calculated by applying 0.5 nm triangular slit averaging to the laboratory measurements of Bass and Paur (1984), assuming a nominal atmospheric temperature of -50C.  $\beta$  values are based on the work by Bates [1984]. For this study, we used the solar flux,  $F_0$ , data acquired by the SOLSTICE [Woods et al., 1993; Rottman et al., 1993] instrument on NASA's Upper Atmospheric Research Satellite (UARS). High spectral resolution SOLSTICE data was degraded to 0.5 nm Brewer spectral resolution using a triangular bandpass function. The diffuse to direct ratio  $r$  is calculated by solving auxiliary equations of radiative transfer [Dave, 1964] that accounts for all orders of scattering and polarization effects. Earth's sphericity effects are accounted for the primary scattering but not for higher order scattering.  $S_b$  is calculated by assuming that the surface is lambertian. Calculations show that the  $r$  is extremely insensitive (~1%) to either the total ozone amount or to its vertical distribution, for solar zenith angles of <60 degrees. Therefore  $r$  is calculated using a mid latitude standard profile containing 325 DU of ozone.

### Attenuation of UVB Due to Clouds

The presence of clouds and the variation in their optical properties is a dominant factor which affects the amount of UVB radiation incident at the surface of the earth. The TOMS instrument UV reflectivity is utilized to approximate the cloud albedo and thus the attenuation of UVB radiation due to cloud. Eck et al. [1987] have shown that the cloud-free TOMS UV reflectivity of land surfaces is uniformly low, typically ranging from 2-7%. In comparison they found that the average reflectivity of cloud filled fields of view for the region from 60° N to 60° S for a one week period was 56.1%. Because the reflectivity of snow and ice is also high in the UV, it is not possible to distinguish between clouds and clear regions covered by snow or ice. We have therefore limited our analysis to the snow-free months of April through November 1990.

In our technique for the estimation of the cloud attenuation of UVB we make three simplifying assumptions. First, that clouds are non-absorbing in the UV region, and therefore potential UVB either reaches the surface or is backscattered to space before reaching the surface. Second, that cloud reflectivity is constant across the UV region and thus measurements of TOMS reflectivity at 360 and 380 nm are representative of the UVB spectral region. Third that the TOMS measured UV bi-directional reflectivity is representative of cloud spectral hemispherical albedo. Since the Nimbus-7 overpass is near to local noon, the TOMS instrument scans nearly perpendicular to the principal plane of the sun, thus minimizing direct forward or backscattering view directions. Broadband measurements (0.2-4.5 nm) from the Nimbus-7 Earth Radiation Budget instrument show that cloud

anisotropy is much less in the plane perpendicular to the solar principal plane than in the solar principal plane [Taylor and Stowe, 1984]. In addition, some effects of cloud anisotropy may average out over extended time periods as view angles and solar zenith angles change.

Actual UVB irradiance,  $F_a$ , was estimated by accounting for the reduction in  $F_{clr}$  due to cloud reflectance by the equation

$$F_a = F_{clr} [1 - (R - 0.05) / 0.90] \quad (3)$$

where  $R$  is the TOMS measured UV reflectivity. This is the same equation which was used by Eck and Dye (1991) for the estimation of PAR (400-700 nm) irradiance. We selected a constant threshold of 5% UV reflectivity for a cloudless scene since the minimum reflectivity values measured for Toronto in 1990 were 4% on 3 days and 5% on 5 days.

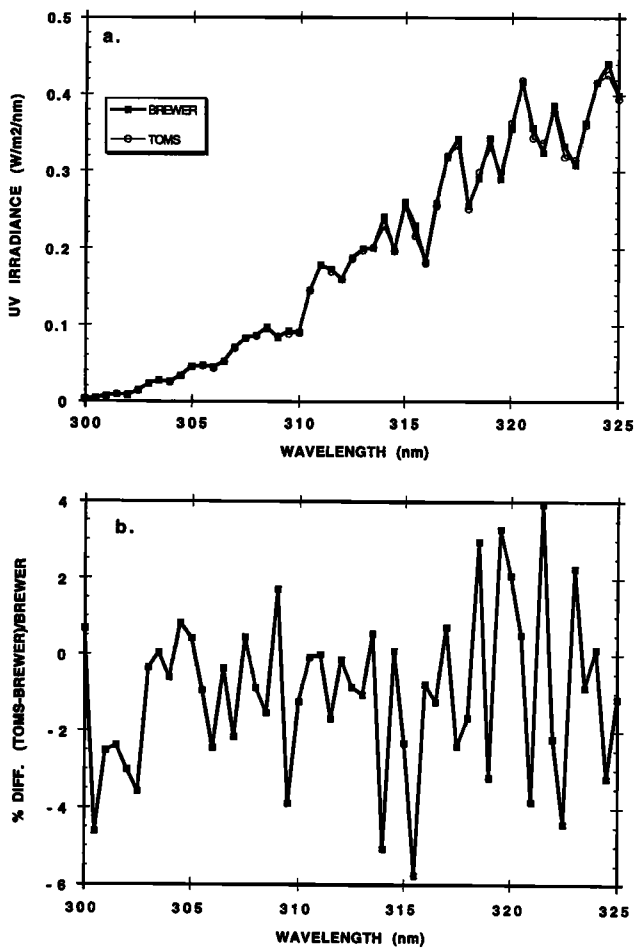
Equation (3) accounts for a decrease in the earth surface contribution to total scene reflectance as cloud reflectance increases. We use a reflectance threshold of 50% to limit the surface contribution to total scene reflectance, which approximates the reflectivity measured for 100% cloud filled TOMS field of views. For reflectances greater than 0.5, the surface background reflectance contribution is assumed to be negligible and the right hand side of Eq. (1) is multiplied by  $(1-R)$ .

### Comparison of Satellite Estimated UVB with Ground Measurements

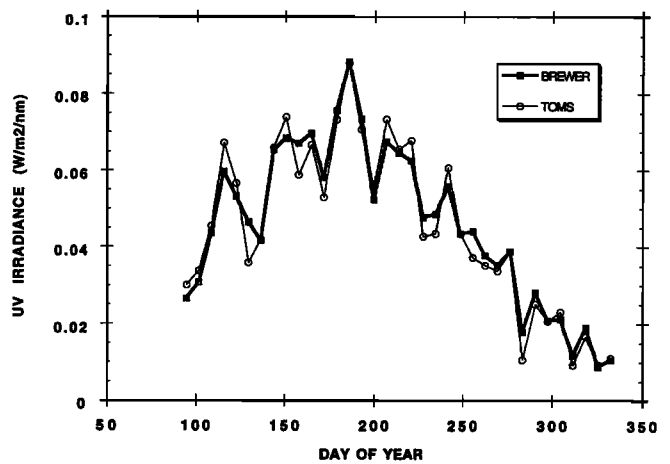
We made comparisons of UVB irradiance for daily observations which occurred in the time period 1500-1700 GMT (1000-1200 Local Standard Time (LST)) which is the time window for the Nimbus-7 overpass of Toronto in 1990. Typically the Brewer instrument made one observation per hour and thus the average of these two measurements was compared to the average of the model estimates, computed using the same solar zenith angles as the Brewer measurements.

A comparison of the satellite estimated versus measured spectral UVB irradiance was made for a very clear, cloudless day, May 30, 1990 (Fig. 1). The TOMS UV reflectivity for this day was low, 4%, and the observer at the Toronto airport reported 0% cloud for the entire day and visibility of 40 km, which is the maximum value of visibility recorded at this location. The percentage differences between TOMS estimated and Brewer measured spectral irradiances for the 51 wavelengths at 0.5 nm steps from 300 to 325 nm ranged from +3.9% to -5.8% with an average of -1.0%. The observed wavelength-to-wavelength differences are systematic for they persist from one comparison to next. Given the sharp Fraunhofer line structure in the extraterrestrial solar spectrum, it is likely that the differences observed here are mostly due to the uncertainty in matching the correct extraterrestrial solar flux to the exact wavelength of the Brewer instrument. Mismatch of the ozone absorption coefficients due to uncertainty in instrument wavelength and uncertainty in the absorption coefficients themselves may also contribute to the spectral variability seen in the UVB comparisons.

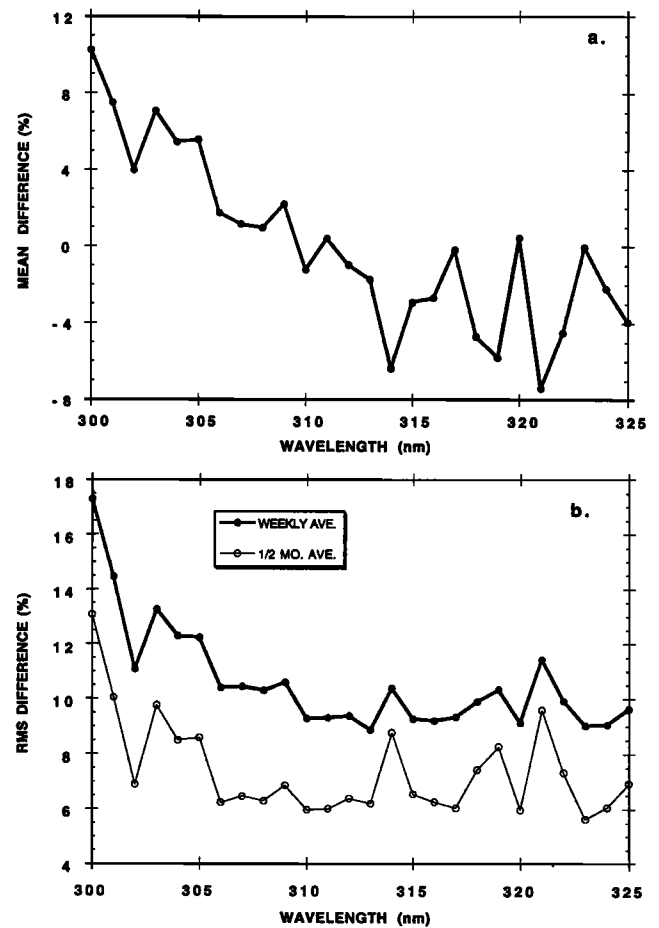
A time series of the weekly averages of UV irradiance at 310 nm measured by the Brewer instrument and estimated by our algorithm for the Nimbus-7 overpass time window for April-November 1990 is shown in Fig. 2. The agreement between the estimates and measurements is quite close, with an rms



**Fig. 1 a).** UV spectral irradiance for May 30, 1990 in Toronto measured by Brewer instrument 14 and estimated by the satellite algorithm described here. TOMS UV reflectivity on this cloudless day was 4% and the TOMS version 6 total ozone amount was 396 Dobson units. **b).** The percentage difference between the estimated and measured UV spectral irradiance for the data shown in a).



**Fig. 2.** Time series of the weekly averages of Brewer instrument measured and TOMS algorithm estimated UV irradiance at 310 nm for April through November 1990 for Toronto. Measurements and estimates are compared for the time window of the Nimbus-7 satellite overpass of 1000-1200 LST.



**Fig. 3 a).** The mean percentage difference between the weekly averaged TOMS estimated UVB irradiance and similarly averaged Brewer measured values. Positive values mean that TOMS is higher than Brewer. **b).** The root-mean square (rms) differences as a percentage of the mean between TOMS estimated and Brewer measured UVB irradiances for both weekly average and one-half month average time periods.

difference of 9.3% and mean difference of -1.2% (Fig. 3). It is noted that when the measurements and estimates are averaged over the longer time period of 1/2 month, that the rms difference decreases significantly to 6.0%. This significant reduction of rms difference with increase in averaging period occurs for all of the wavelengths from 300 to 325 nm at 1 nm intervals shown in Figure 3b. This reduction of rms difference results from averaging out the random variations that are caused by the differences in spatial scale and time between the Brewer and TOMS instrument measurements. The time difference between the Brewer and TOMS measurements may be greater than 1 hour, and the Brewer takes its measurement scan over an 8 minute period with 2 readings of approximately 1 second each for each wavelength. Spectral UVB irradiance varies rapidly with time due to cloud variability, for example on June 21, 1990 measurements taken 1 hour apart by the Brewer instrument at 1541 and 1644 GMT (solar zenith angles of 28.7° and 21.6° respectively) differed by 70% to 88% from 300 to 325 nm. The spatial sampling between the two instruments also differs greatly as the Brewer instrument is measuring at a fixed point while the TOMS sensor spatial

resolution varies from 50X50 km at nadir to 150X200 km in the extreme off-nadir direction. Therefore, spatial variance in cloud cover can contribute to the differences observed. Since approximately one half of the TOMS field of view falls over water (Lake Ontario) for this station, it is possible that for some meteorological conditions that the cloud cover may differ over the two surfaces which may show contrast in surface temperature and relative humidity. Values of  $r^2$  computed between the TOMS estimates and Brewer measurements ranged from 0.975 at 300 nm to 0.943 at 325 nm. Most likely the higher values of  $r^2$  at the shorter wavelengths is due to the increasing influence of ozone relative to cloud attenuation of the UVB radiation at shorter wavelengths, since ozone variability in space and time is much smaller than cloud variability.

The average and rms differences for both the weekly and monthly time scales are systematically higher below 305 nm compared to longer wavelengths. These differences appear to be related to the difference in ozone amount seen by TOMS and Brewer in presence of aerosol and clouds, since there is little overall wavelength dependence under low reflectivity conditions. The current TOMS algorithm is known to underestimate total ozone when broken clouds are present [Seftor *et al.*, 1994]. In addition, the satellite technique is inherently insensitive to tropospheric pollutants trapped in the boundary layer [Klenk *et al.*, 1982]. Both ozone and SO<sub>2</sub> commonly found in urban smog would affect the Brewer measurements but not the TOMS measurements. This is partly because the average field-of-view of TOMS (~5000 sq. km.) is several times larger than the typical urban area with highest concentration of smog, and partly because of the atmospheric and aerosol scattering TOMS radiances are insensitive to UV absorbers close to the surface.

## Conclusions

Comparisons of ground based instruments measuring UVB spectral irradiance made simultaneously at the same locations [McKenzie *et al.*, 1993; Webb, 1992] have shown that differences between instruments were typically on the order of 5-10%. Since the rms and average differences computed for half-month averages between a Brewer instrument and the TOMS technique described here generally fall within this range, we believe that this technique has the potential to accurately monitor UVB irradiance distributions on the earth's surface.

Due to strong absorption by ozone and strong Rayleigh scattering, the diurnal distribution of UVB irradiance is strongly peaked at solar noon. Therefore the Nimbus-7 near local noon overpass time is well suited to monitoring the peak daily UVB irradiance. The Nimbus-7 TOMS data record of 14+ years of measurements has the potential to be used for global interannual studies of UVB variability.

In future work we plan to investigate whether the TOMS estimated UVB for Toronto will show the same time trend of increasing UVB radiation measured by the Brewer instrument [Kerr and McElroy, 1993] for the time period 1989-1993. We also plan to compare spectral measurements of UVB made at other ground based stations to further validate this technique.

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