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# New observations of ultraviolet radiation and column ozone from Socorro, New Mexico

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**Abstract.** Measurements of surface ultraviolet irradiances are presented for the period of June 1997 to December 1998 from Socorro, NM (34°N, 107°W). The observations are used with results of radiative transfer calculations to retrieve total column ozone. Mean differences between Socorro daily ozone measurements and Earth Probe TOMS satellite data are -1.8 DU and 0.6 DU for 1997 and 1998, respectively. Unusually low ozone was observed in late November and December of 1998, with levels near or below the lowest ozone in the 17-year Nimbus-7 and Earth Probe TOMS record for this location. The clear-sky correlation between the UV Index at 60° solar zenith angle and total ozone is well described by a power law, with an exponent (Radiation Amplification Factor) of $0.97 \pm 0.16$. One exception occurred during a 10-day period in December 1997 and January 1998 in the aftermath of a heavy snow storm, when the UV Index exhibited clear-sky enhancements of up to 30%. Increases in downwelling ultraviolet radiation were related to a higher effective surface albedo with maximum estimated values between 0.7 to 0.9.

## Introduction

The amount of solar ultraviolet radiation penetrating to the Earth's surface is critically important to the health of biological systems. The sensitivity of living organisms to ultraviolet radiation increases rapidly for wavelengths less than 320 nm. Much of the harmful UV-B (280-320 nm) radiation is absorbed by stratospheric ozone, although downward trends recently observed in total column ozone, particularly at high latitudes, imply significant increases in surface UV exposure [e.g., *Herman et al.,* 1996]. The anticorrelation between total column ozone and surface UV radiation is a complex function of many variables, including solar zenith angle, surface elevation, cloud cover, aerosol loading and optical properties, surface albedo, and vertical profile of ozone [*Madronich,* 1993]. Ground-based observations can play an important role in improving the understanding of some of these effects.

This paper describes the first results from measurements of global (direct plus diffuse) ultraviolet irradiances using a moderate band filter radiometer deployed in Socorro, New Mexico. The frequent availability of clear skies at this site in the southwestern US provides the opportunity to monitor cloud-free relationships between UV exposure and total ozone, and to establish a baseline for examining effects of other atmospheric and surface variables.

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## Observations

The observations were made using a five channel, temperature controlled UV radiometer (Biospherical Inc., GUV-511C), which measures downwelling, global irradiances in four UV channels near 305, 320, 340, and 380 nm. Nominal bandwidths are 10 nm. The radiometer has been in rooftop operation since June 1997 at the New Mexico Institute of Mining and Technology in Socorro, NM (34°N, 107°W, elevation 1426 m).

Radiometer sensors detect light impinging on a single quartz flat plate diffuser; the directional response of individual sensor channels follow a cosine curve to within about 5% from 0 to 70° incident angle. Sensors are located in an insulated housing and an active temperature controller maintains an operating temperature of $50° \pm 0.5°$C for detector stability. The instrument is located so that the diffuser plate is level to within 0.25° and the field of view is unobstructed over nearly $2\pi$ sr in the upward facing hemisphere. Data are recorded as 5-minutes averages between the hours of 6 am to 6 pm local time.

Sensor outputs in each channel are directly proportional to the integral of the product of filter response and incident spectral irradiance. Relating sensor outputs to the spectral irradiance at the peak of the filter bandpass is relatively straightforward for the 320, 340, and 380 nm channels where the incident irradiance varies slowly over the spectral width of the filter. For the 305-nm channel, the combination of a solar blind detector and interference filter provides a peak spectral response at 300 nm, with an out-of-band rejection of $10^6$ for $\lambda > 320$ nm. Products of the detector-filter response with typical solar spectra show that the peak sensitivity may vary between 305 and 308 nm, depending on ozone amount and solar zenith angle (SZA) [*Dahlback,* 1996]. Comparisons of GUV response with measurements using a high resolution scanning spectrometer (SUV-100) over a wide variety of cloud and SZA indicate that the 305 nm irradiance is most appropriate for obtaining a uniform correlation between 0 and 70° SZA [*Booth et al.,* 1994].

The raw voltage outputs from each sensor are converted to irradiances at a fixed wavelength through the use of a linear calibration function. Calibration constants were determined through solar intercomparison to a reference GUV radiometer in April 1997, and again in September 1998. The reference GUV calibration is constrained by solar intercomparison with an SUV-100 having a NIST-traceable calibration using a 200 W FEL Standard of Spectral Irradiance. Solar intercomparison-based calibrations of GUV-511s involve typical standard errors of 1 to 2% for SZA less than 60°, and the repeatability of calibrations normally is within ±4% in the 305 nm channel and ±3% in the 320 nm channel [*Booth et al.,* 1994]. The September 1998 calibration of

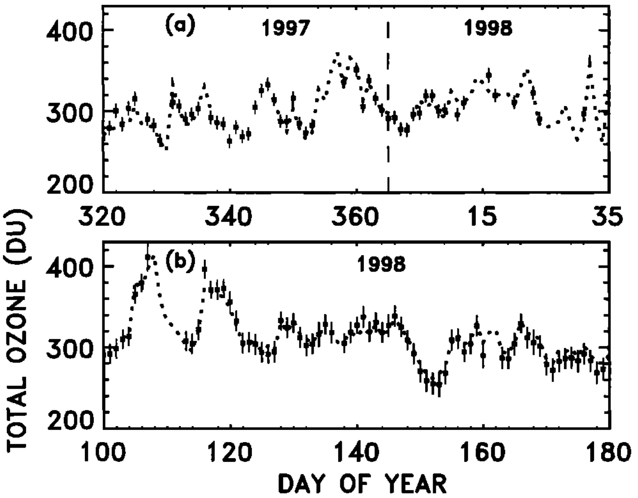

**Figure 1.** Column ozone over Socorro, NM for (a) 12/97-1/98, and for (b) 5/98-6/98. Error bars are RMS fit errors to irradiance ratios and calibration uncertainties in 305 and 320-nm channels. Also shown are coincident EP-TOMS ozone values (dotted curve) for Albuquerque overpass ($\sim$100 km N of Socorro).

the Socorro GUV-511 indicated a 7% increase in sensitivity since April 1997 for 305-nm sensor, and less than 0.5% changes at other wavelengths. A linear correction factor has been applied to the 305-nm data over the 15-month period between calibrations. A ±6% overall uncertainty is adopted for the 305-nm channel and ±3% uncertainties are assumed at other wavelengths.

## Total Column Ozone

The differential absorption method for measuring gas column abundances is a well-developed procedure which has been used extensively to monitor total ozone [e.g., *Dobson*, 1931; more recently in *Slusser et al.*, 1999]. We use the Tropospheric Ultraviolet-Visible Radiation Model (TUV) [*Madronich et al.*, 1996] to simulate global UV irradiances for retrieving column ozone. Application of the differential absorption method for GUV measurements involves use of the 305 nm channel for the irradiance strongly affected by ozone absorption, and the 320 nm channel for the irradiance weakly impacted by ozone.

The approach adopted here takes advantage of the range of irradiance ratios ($F_{305}/F_{320}$) measured over a diurnal timespan. Total ozone is determined independently for AM and PM by minimizing RMS differences between measured and modeled log irradiance ratios versus secant SZA for angles less than 70°. Diurnally-averaged ozone is determined from the weighted mean of AM and PM ozone, with weightings inversely proportional to uncertainties in the measurements.

The presence of optically thick clouds in the direct solar beam can decrease irradiance ratios in a way which is SZA dependent, potentially contaminating derived ozone [*Mayer et al.*, 1999]. The ozone retrieval excludes cloudy data based on irradiances from the 380-nm channel, using an empirical SZA relationship derived from an average of eighteen full days of clear-sky data. Ozone is calculated only if more than one hour of clear-sky measurements is available. This criteria has resulted in loss of ozone data for about 10% of Socorro GUV time series.

Results for daily ozone from two periods in the winter of 1997 and early summer of 1998 are shown in Figure 1. Also indicated are near coincident data from the Earth Probe - Total Ozone Mapping Spectrometer (EP-TOMS). The level of agreement is good despite temporal (diurnal average versus 10-12 LT overpass) and spatial (ground-based versus 40 km field of view) differences in data sets. Mean differences between the two ozone measurements (Socorro GUV minus EP-TOMS) are -1.8 and +0.6 DU for 1997 and 1998, respectively. The Socorro GUV ozone tends to display slightly larger variations than EP-TOMS ozone; the RMS difference between data sets is 9 DU.

## Ozone and UV Index

Total ozone and the noon UV Index for all Socorro data are shown in Figure 2. The UV Index is the CIE erythema dose rate in W $m^{-2}$ multiplied by 40, consistent with the recommendation of the World Meteorological Organization [*WMO*, 1994]. The scale typically ranges from 0 to 10, with values above 7 considered high exposure. The UV Index is calculated using a multiple linear regression of GUV measured irradiances at 305, 320, and 340 nm. Modeled GUV responses using over 13,000 SUV-100 spectra at six sites ranging from the South Pole to San Diego indicate that the index can be reproduced to ± 2% using the linear regression [*Booth et al.*, 1994].

Values of the UV Index in Figure 2 show primarily the impact of changing noon SZA between summer and winter. The effect of clouds is apparent also in the scatter toward lower UV Index values. The influence of changing ozone amounts is clearly visible in certain cases. For example, the very high index of 13 on July 1, 1997 (day 182) corresponds to a relatively low 255 DU column ozone. Similarly, an index of 12.5 was recorded on June 2, 1998 (day 153) when measured total ozone was 254 DU.

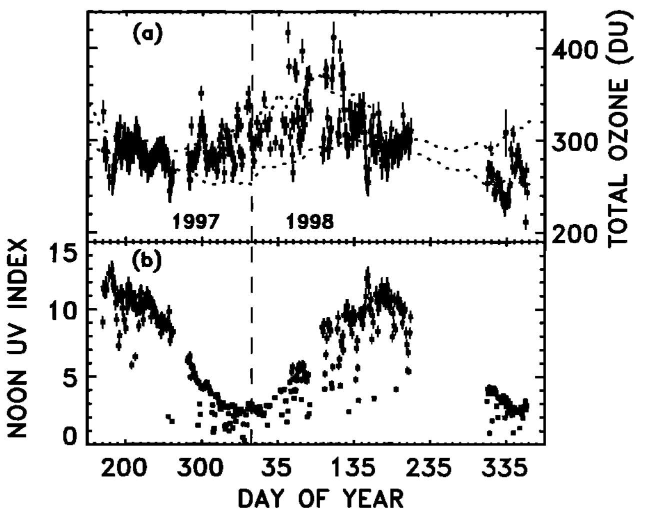

**Figure 2.** Time series of (a) total ozone and (b) noon UV Index. Dotted curves in (a) are mean±1-sigma of 10-day averages of 1978-1993 Nimbus-7 TOMS ozone. Error bars in (b) are the sum of spectrally weighted uncertainties in 305, 320, and 340-nm calibrations.

Column ozone in Figure 2 shows an expected seasonal variation, with higher values and larger variability during spring. Shown also is the mean range of Nimbus-7 TOMS data from 1978 to 1993. Ten-day running averages of GUV total ozone generally fall within the range of the TOMS climatology, with the exception of an extended period of seasonally high ozone near day 300 in 1997, and more recently during a period of unusually low ozone near day 335 in 1998. An extremely low value of 211 DU was measured on December 26, 1998. This falls below the smallest ozone (220 DU) in the Nimbus-7 and EP-TOMS overpass database spanning over seventeen years. NCEP analyses indicate a localized region of significant cooling ($\sim$ 10 K) on the 50 mb surface, coincident with the presence of a strong tropospheric high over New Mexico. These suggests a dynamical origin for the anomalously low ozone.

The relationship between UV Index and total ozone for all data is presented in Figure 3. A UV Index for 60° SZA (AM-PM average) is used to eliminate the seasonal dependence of noon solar zenith angle. Cloud effects are removed by considering only clear-sky data based on 380-nm irradiances. As indicated, the UV Index and ozone exhibit a negative correlation when SZA and cloud effects are excluded.

A Radiation Amplification Factor (RAF) may be defined by the power law relationship [*Madronich,* 1993]

$$I = K \cdot N^{-\mathrm{RAF}} \tag{1}$$

where $I$ is the UV dose rate, $N$ is total ozone, and $K$ and the RAF are assumed constant. The Radiation Amplification Factor is useful for relating fractional changes in UV dose and ozone, $\delta I/I = -\mathrm{RAF}\cdot\delta N/N$. A value of 0.97±0.16 is derived from a least-squares fit to the data in Figure 3, excluding ten points (solid squares) which show obvious departures from the mean relationship. The RAF uncertainty is determined primarily by the uncertainty in slope (8%) from the log-log RMS fit error, with smaller contributions originating from possible systematic errors in UV Index and ozone (5% and 4%, respectively).

Calculated values of the erythema RAF typically range between 1.0 and 1.2 [*Madronich,* 1993], and measured values have been reported at 1.33 [*Bodhaine et al.,* 1997], 1.25 [*McKenzie et al.,* 1991] (both at SZA of 45°), and most recently 1.1 [*McKenzie et al.,* 1998] (SZA of 70°). The observed RAF will be a function of SZA as well as the vertical distribution of ozone, surface albedo, and possible systematic effects such as seasonal changes in mean aerosol optical depths, particularly if such changes are in phase with the seasonal cycle of total ozone. A preliminary RAF of 1.06±0.20 at 30° SZA is obtained from the Socorro measurements based on a smaller seasonal coverage and variation in ozone.

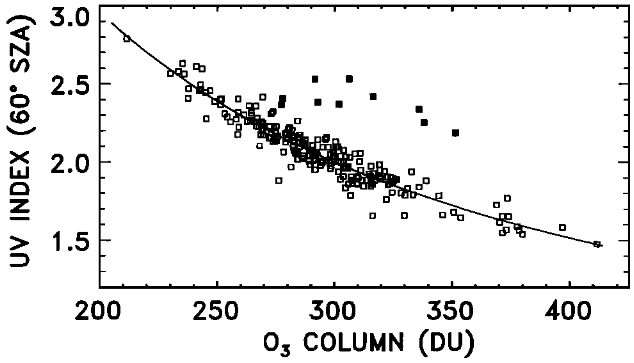

**Figure 3.** UV Index at 60° SZA versus total ozone for all clear-sky data (open squares). Observations from 12/26/97 to 1/3/98 (filled squares) were obtained after snowfall. Solid curve denotes least-squares fit using equation (1) and a RAF of 0.97.

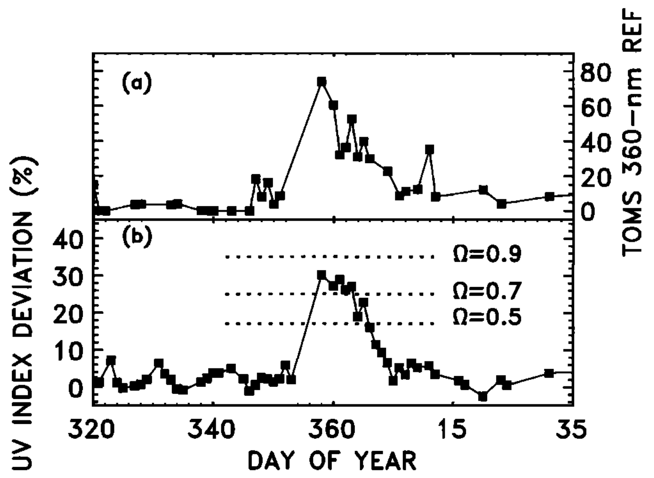

**Figure 4.** (a) Clear-sky EP-TOMS reflectivity at 360 nm. (b) Percent deviation of the UV Index from the power law relationship defined by equation (1). Dotted lines in (b) are TUV model enhancements in UV Index for assumed values of the surface albedo, Ω.

The data points in Figure 3 that deviate from the mean UV Index - ozone relationship were acquired between December 24, 1997 and January 3, 1998. It is highly unlikely, given the diurnal fitting procedure used to derive ozone, that errors in the ozone retrieval are responsible for the anomalous behavior. Ozone from EP-TOMS during this time (Figure 1a) support the validity of measured ozone. These observations were obtained under exceptionally clear skies following periods of heavy snow on December 20 and December 22-23. Snow depths averaged 6 to 8 inches; water-equivalent precipitation monitored by the New Mexico Tech Physics Club was 0.89 inches. Ground snow cover persisted over open desert areas for approximately 7-15 days after the storm.

Figure 4a shows the time series of clear-sky reflectivity measured at 360 nm by EP-TOMS, obtained using days when the Socorro GUV indicated no clouds near the time of satellite overpass. Clear-sky reflectivities peak at 74% and 68% on days 358 and 359 (December 26-27) and decline to background by day 6 in 1998. Corresponding percent deviations in UV Indices are indicated Figure 4b. A maximum elevation of 30% in the UV Index occurs on day 358 and the percent enhancement decays with time in a manner similar to EP-TOMS clear-sky reflectivities. Observed UV enhancements are consistent with increases in the mean surface albedo due to snow. This effect results from an additional contribution to the downward propagating, diffuse radiation field, due to surface reflection and subsequent atmospheric scattering back to the surface. *McKenzie et al.* [1998] recently noted UV-B enhancements of 28% at 70°

SZA due to the presence of ground snow cover at Lauder, New Zealand.

The surface within a 15 km radius of the Socorro site is predominantly open range and desert, with a mean-area reflectivity of about 2-3% at 380 nm [*Herman and Celarier,* 1997]. Figure 4b shows modeled UV Index enhancements for simulated increases in surface albedo of 0.5, 0.7, and 0.9., assuming a wavelength independent albedo and snow-free value of 0.02. Results suggest a maximum effective albedo of 0.7-0.9 within 2 to 5 days of the snowfall. Uncertainties in aerosol optical depth and single-scattering albedo, and the lack of separate measurements of the direct and diffuse radiation components, preclude a more precise determination of the mean UV albedo for this case. The range of peak values is higher than the maximum effective UV albedo of 0.57 for Tromsø, Norway, which may be partly due to the effect of open water surrounding Tromsø [*Kylling et al.*, submitted to J. Geophys. Res.]. It is also larger than the maximum derived albedo of 0.62 from New Zealand [*McKenzie et al.,* 1998]. However, the NZ value was determined 7 days after snowfall, and supplementary data from a $J_{NO2}$ actinometer indicated a UV-A albedo greater than 0.8 immediately after the snowfall. Model calculations predict a UV-B albedo of up to 0.95 for fresh snow [*Warren* 1982].

## Conclusions

New measurements of total column ozone and the relation between ozone and UV radiation from Socorro, NM have been presented. Combined effects of latitude, elevation, and frequent clear skies generate high mean UV exposure levels, with the noon UV Index routinely exceeding 10 (very high exposure) during summer. The relationship between UV Index and total column ozone shows a distinct anticorrelation under clear skies. The Radiation Amplification Factor for 60° solar zenith angle is 0.96, implying a near 1:1 relationship between percent changes in UV erythema exposure and total ozone at this location.

Enhanced levels of UV radiation were measured during a period of extensive snow cover. Maximum observed enhancements of 30% are consistent with an effective UV albedo of 0.7 to 0.9 within the first few days following the snowfall. It is noted, however, that the peak noon exposure to downwelling UV radiation under these conditions was only 25 to 30% of typical noon levels during summer, owing primarily to the seasonal difference in solar zenith angles. As pointed out by *McKenzie et al.* [1998], a greater concern may be the large increase in upwelling UV radiation over snow covered ground, leading to greater exposure to the eyes and other surfaces not normally exposed under conditions of low UV albedo.

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