Effect of aerosols on surface UV at Socorro, New Mexico: Measurements based on global irradiances and a direct sun photometer

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ABSTRACT

Measurements of aerosol UV optical depths are described as part of an ongoing study of surface ultraviolet irradiances over the southwestern United States. Global UV irradiances are continuously monitored using a moderate-bandwidth radiometer (Biospherical, GUV-511), which has been in operation since June 1997. Irradiances at 305 and 320 nm are used to derive column ozone; erythemal doses are determined with the additional consideration of 340 and 380-nm irradiances. The clear sky relationship between ozone and UV dose is well characterized by a power law with an exponent that decreases with increasing solar zenith angle, from 1.12 to 0.99 between solar zenith angles of 20 and 60 degrees. Most recently, aerosol optical depths at 340 nm have been estimated using standard direct sun techniques applied to model corrected global measurements. These are compared with direct sun measurements (Solar Light, Microtops II) over a five month period. Mean values agree well, but daily observations show differences in aerosol optical depths of up to 0.1, with direct sun measurements indicating larger variability. Aerosol optical depths inferred from global irradiances vary between a minimum of about 0.03 in winter and a maximum of 0.10 in summer.

Keywords: UV Radiation, Aerosols, Ozone

1. INTRODUCTION

There are many factors that determine the intensity of solar ultraviolet radiation reaching the Earth's surface, primarily ozone absorption, solar zenith angle, molecular, aerosol and cloud scattering, and cloud and aerosol absorption.[1] Ground-based measurements have established the expected anticorrelation between ozone and UV exposure under clear skies.[2,3] Reductions in surface UV due to clouds (typically 20 to 60%) are more variable both temporally and spatially,[4,5] and in some situations clouds may even induce local increases in UV.[6] The UV reduction in the presence non-absorbing aerosols is expected to be smaller on average, about 10% for an aerosol optical thickness of one.[7] Absorbing aerosols and dust may produce larger reductions, however. Under certain circumstances, changes in surface UV albedo can play an important role.[8]

We report here on measurements of global UV irradiances at Socorro, New Mexico, located in the U.S. desert southwest. The high frequency of clear skies permit a baseline to be established for examining effects of clouds and aerosols. A technique is described for estimating aerosol optical thickness using global UV irradiances.

2. MEASUREMENTS

Continuous measurements of UV irradiances at 305, 320, 340, and 380 nm, with subsequent determination of column ozone and erythemal UV, have been made from Socorro, NM (34°N, 107°W), from June 1997 to present. Data is collected using a moderate-bandwidth UV radiometer (Biospherical GUV 511C) which senses downwelling, global (direct plus diffuse) irradiances incident on a horizontal Teflon-quartz diffuser. The radiometer is temperature stabilized at 50°C. Nominal spectral bandwidths of the four UV filter/detectors are 10 nm.

Detector outputs are proportional to the integral of the product of filter responses and incident spectral irradiances. Voltages from each sensor are converted to irradiances at a fixed wavelength through the use of a linear calibration function, with calibration constants determined through a solar intercomparison to a reference GUV instrument at Biospherical Instruments, which is ultimately tied to a NIST-traceable 200W FEL Standard of Spectral Irradiance. The Socorro GUV was initially calibrated in April 1997, with recalibrations in September 1998 and April

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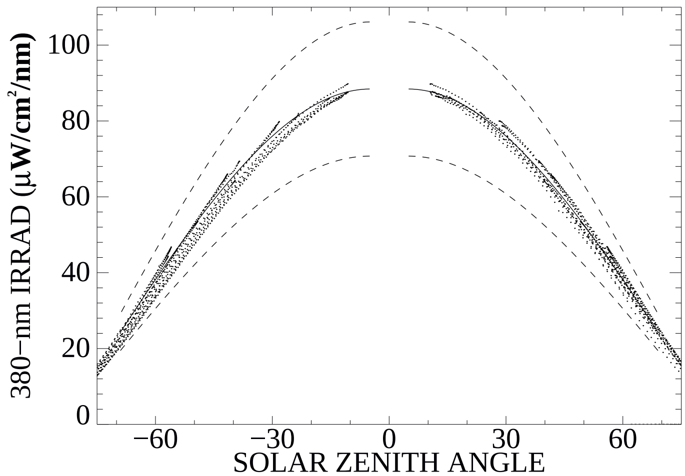

Figure 1. 380-nm irradiances versus solar zenith angle, where negative angles are morning and positive are afternoon. Also indicated are a cubic fit (solid), and ±20% irradiance thresholds for cloud discrimination.

2000. Based on the repeatability of GUV-511 calibrations[9] and the stability of the Socorro instrument, we adopt a ±6% overall uncertainty for the 305-nm channel and ±3% uncertainties are assumed at other wavelengths.

The daily mean column ozone is obtained using the diurnal variation in the measured ratio $ln(F_{305})/ln(F_{320})$, where F_{305} and F_{320} are the irradiances at 305 and 320 nm, respectively. The best fit ozone is found by minimizing RMS differences between measured and modeled log irradiance ratios versus secant of the solar zenith angle, with model output from the TUV radiative transfer model.[10] Complete details can be found in Ref. 3. In addition, the UV Index (CIE erythema dose rate in W m^{-2} multiplied by 40) is determined using a multiple linear regression of irradiances at 305, 320, and 340 nm. Simulations of GUV-511 response using over 13,000 SUV-100 spectra at six sites, ranging from the South Pole to San Diego, demonstrate that the UV Index can be reproduced to ± 2% with this technique.[11]

3. UV INDEX, OZONE AND CLOUDS

Discrimination from cloud effects is accomplished using irradiances from the 380-nm channel. Figure 1 shows measurements from eighteen clear-sky days that cover a range of seasons and years. A cubic function of solar zenith angle represents an empirical clear-sky relationship that is used to identify clouds for all measurements. The RMS deviation between the data and cubic fit is 5%. Also shown are ±20% thresholds used for removing cloudy data in the calculation of total ozone, where a minimum of one hour of clear-sky measurements over the course of each day are required to obtain adequate solar zenith angle coverage. This criterion has resulted in loss of ozone data on only 10% of available days.

The anticorrelation between ozone and UV Index for a solar zenith angle of 50° is displayed in Fig. 2. The relationship is described well using a power law,

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

where I is the UV Index, N is total ozone, and K and RAF are constants that are functions of solar zenith angle. The RAF is a Radiation Amplification Factor that is useful for expressing small changes in UV exposure to changes in ozone,

$$\frac{\delta I}{I} = -RAF \cdot \frac{\delta N}{N}\,. \tag{2}$$

The best fit values of $K = 1306$ Dobson Units (DU) and $RAF = 1.03$ are derived from these measurements, implying a near 1:1 anticorrelation between percent changes in UV and ozone at 50° solar zenith angle, We find similar behavior in all other data, with both K and RAF growing larger with decreasing solar zenith angle. The maximum RAF is 1.12 for 20° solar zenith angle.

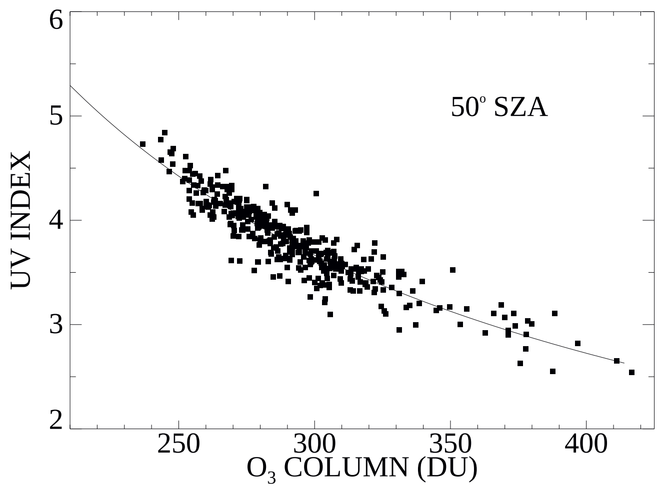

Figure 2. IV Index and total ozone for clear sky, solar zenith angle of 50°. Solid line is a least-squares fit using the power law relation of Eq. (1).

An accurate description of sun angle variations in the relationship between surface UV and ozone, one based on observations over a 3-year period, permits a quantitative analysis of the effect of clouds on surface UV. We define a Cloud Reduction Factor, CRF= I(O_3,observed)/I(O_3,clear), where I(O_3,clear) refers to the UV Index obtained from clear sky observations of UV Index versus total ozone. Annual mean values of the CRF are 0.89, 0.89, .88, and .87 for 1997, 98, 99, and 2000, respectively. Our annual mean CRF's agree to with 2% with values calculated from EP-TOMS reflectivity at 360 nm for the Socorro overpass, using the relation developed in Ref. 12. Comparison of daily values, where the ground-based data is averaged over one hour centered on the time of EP-TOMS overpass, show considerably larger differences averaging about ±30%.

4. AEROSOL OPTICAL DEPTHS

The method of using the slope of the direct sun log irradiance versus secant of solar zenith angle has long been applied to determined extinction optical depths in the atmosphere (e.g., Ref.13). The method adopted here relies on model calculations of the ratio of direct to total global irradiance at 340 nm. Results from TUV are shown in Fig. 3, using the U.S. Standard Atmosphere, no clouds, vertical distribution of aerosol optical depth from Ref. 14, single scattering albedo of 0.99, and asymmetry parameter of 0.70. These results are not particularly sensitive to the choice of aerosol properties, but are impacted more by a change from sea level to 1426 m elevation. As indicated in Fig. 3, the direct beam contribution to the global field at 340 nm varies from 70% at overhead sun to as little as 30% for 70° solar zenith angle.

Measured global irradiances are multiplied by the calculated direct fraction to estimate the direct flux, and a further $\cos(\theta)$ correction is applied to yield the normal component. The slope of the direct flux as a function of $\sec(\theta)$ is the total extinction optical depth, τ,

$$\ln(F) = \ln(F_o) \; - \; \tau \sec(\theta) \, . \tag{3}$$

We use clear sky data for $\theta \leq 70°$ to avoid cloud effects and errors due to departures from an exact $\cos(\theta)$ response at larger angles. An example of data for one day is shown in Fig. 4. Morning and afternoon data are fitted separately, with calculated slopes of 0.686 and 0.709, respectively. Uncertainties of about 7% arise from the deviations from linearity and assumed errors in the direct fraction correction. These slopes are the mean extinction optical depths for AM and PM. At 340 nm, the Rayleigh optical depth is 0.608 at 1426 m elevation; the remaining extinction is assumed to be due to aerosol, resulting in a mean aerosol optical depth of 0.09 ± 0.05.

The near linear behavior shown in Fig. 4 indicates that the corrections to our global field measurements are appropriate. Small deviations from linearity may be related to the cosine response error of the radiometer (up to 5% at 70° incident angle). Nevertheless, large relative uncertainties exist in our aerosol optical depths due to the dominance of molecular scattering (85-95%) in the total extinction.

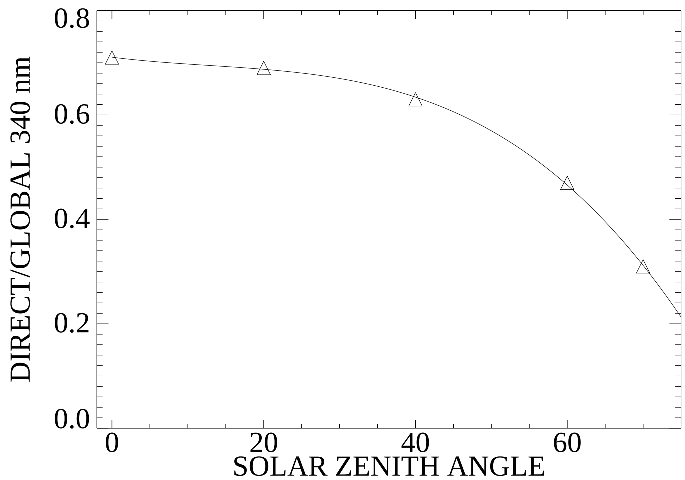

Figure 3. Model calculated ratio of direct solar irradiance at 340 nm to global (direct plus diffuse) irradiance, with atmospheric conditions and surface elevation as described in the text.

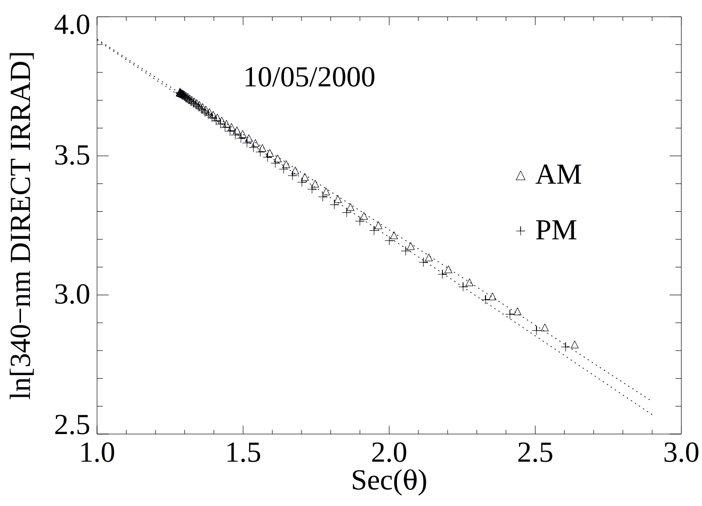

Figure 4. Log of direct solar irradiances inferred from measured global field at 340 nm, plotted against secant of solar zenith angle. Dotted lines represent least squares linear fits for morning and afternoon data.

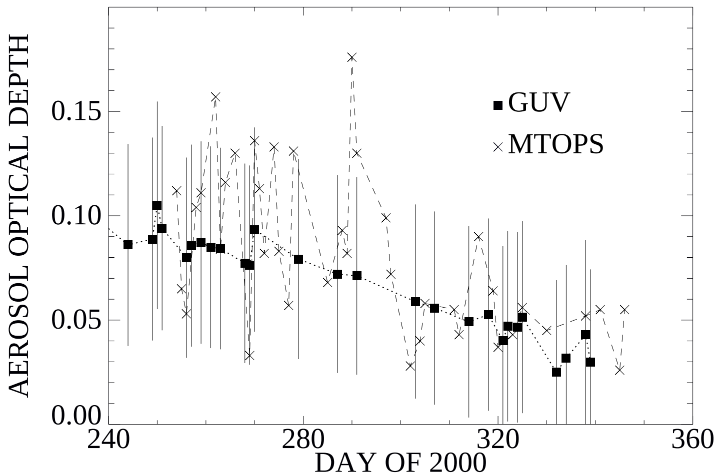

Figure 5. Aerosol optical depths at 340 nm from the GUV global irradiance, daily mean (squares), and from near instantaneous measurements using a sun photometer (x's).

In Fig. 5 we compare aerosol optical depths from the GUV with co-located measurements using a hand held sun photometer (Solar Light Microtops II). The sun photometer provides a near instantaneous measure of aerosol optical depth at 340 nm based on surface pressure, solar zenith angle, and sensor calibration, and requires a cloud-free field of view ($\sim 2.5°$) during the acquisition time of about 20 s. Most of the Microtops measurements were obtained during mid-morning, although on some days cloud conditions permitted observations only in the afternoon. There are more measurements from the Microtops than from the GUV during this time since the latter requires clear skies for an extended period over the day. The GUV measurements show much less variability, as may be expected due to diurnal averaging. Nevertheless, the agreement is generally within the uncertainties of the GUV observations, and both data sets indicate the same decreasing trend in optical depth over this period of about three months from September through November, 2000.

Results from all Socorro observations are shown in Fig. 6. The annual mean aerosol optical depth is 0.065, and a definite seasonal pattern is apparent where optical depths are larger and more variable from March through October. It is likely that much of the increase during the spring months of March and April results from blowing mineral dust due to high winds. In addition, mid-day relative humidities increase from 10-20% during winter to 40-50% during the monsoon season of July-September, which may contribute to a higher persistence and growth of liquid phase aerosol.

These values suggest that aerosols have an impact, but generally play a smaller role than clouds in the scattering and absorption of UV radiation at our location. Aerosol optical depths rarely exceed 0.10, and consequent reductions in the direct beam component are therefore 10% or less. In fact, part of this reduction is compensated by increases in the downward scattered component; the net effect on the global field is a reduction of 3 to 5% at wavelengths relevant for eythemal UV.

5. CONCLUSIONS

Measurements of surface UV irradiance have been used to determine erythemal UV dose, total ozone, and cloud and aerosol effects on surface UV at Socorro, New Mexico. The Radiation Amplification Factor between UV dose and total ozone varies between 1.12 and 0.99, depending on solar zenith angle. Although the instantaneous impact of clouds can be large, the annual mean reduction in UV exposure due to clouds averages about 12% at our location. Reductions due to aerosols are smaller and average about 4%.

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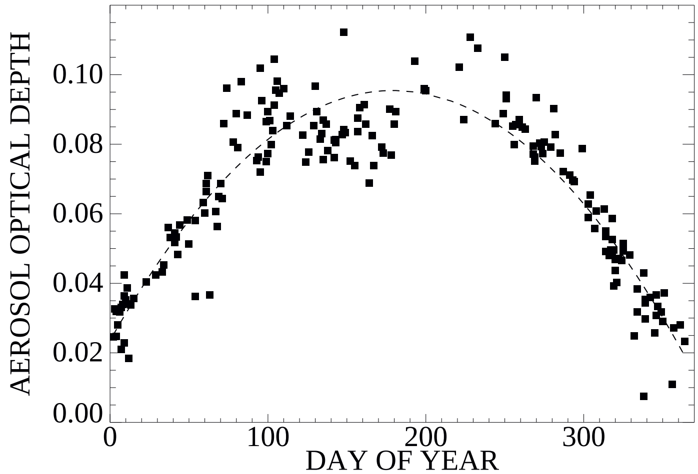

Figure 6. Aerosol optical depth at 340 nm versus day of year (squares) for 1998 to 2000. Dashed line is a harmonic fit to seasonal variation.

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