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Abstract Increases in ultraviolet fluxes (300 nm to 340 nm) reaching the ground between 1979 and 1992 are estimated using measured stratospheric ozone amounts and reflectivity data from Nimbus-7/TOMS (Total Ozone Mapping Spectrometer). The UV-increases are estimated from an ozone data set obtained using a new algorithm incorporating improved in-flight instrument calibration. The 380 nm radiance data are used to show that there were no changes in ultraviolet atmospheric albedo due to clouds and aerosols from 1979 to 1992 within the 1% uncertainty of the measurements. Linear least squares fits to the monthly and annual increases in UV exposure since 1979 are given for 3 wavelengths (300 nm, 310 nm, and 320 nm) that are strongly, moderately, and weakly absorbed by ozone. The estimated linear changes for the 3 wavelengths become significant (2 standard deviations) poleward of about 40° latitude. In the 45° ± 5° latitude band, the slope of linear fits to the annual zonally averaged changes for these wavelengths are about 13%, 3%, and 1% per decade in the southern hemisphere, and 10%, 3%, and 1% per decade in the northern hemisphere. Similarly derived values are estimated for DNA, plant, and erythema action spectra. Monthly values of exposure changes are larger towards higher latitudes and during the spring and winter months (e.g., 8.6%, 9.8%, and 5.1% per decade during April at 45°N). Erythema UV-increases obtained from TOMS data disagree with previously determined ground based UV-decreases from an average of 8 U.S. Robertson-Berger sites.

Introduction.

The short wavelength portion of the UV-B range (290 nm to 320 nm) that is strongly absorbed by ozone in the atmosphere should show an increase at the Earth's surface corresponding to the reported decreases in ozone amount [Stolarski *et al.*, 1991; Gleason *et al.*, 1993; Herman and Larko, 1994] using TOMS (Total Ozone Mapping Spectrometer) data. Estimates of UV-B increases have been made by Madronich [1992] based on clear-sky radiative transfer calculations. The relationship of noontime UV-damage increases and interannual cloud variability based on Version 6 TOMS ozone and ERBE (Earth Radiation Budget Experiment) cloud estimates has been discussed by Lubin and Jensen [1995]. Changes in the amount of ultraviolet flux (UV-flux) at the earth's surface have been investigated through the use of ground based data [Scotto *et al.*, 1988; Frederick and Weatherhead, 1992; McKenzie *et al.* 1992; Justus and Murphy, 1994]. The Scotto *et al.* [1988] analysis of the US portion of the

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Robertson-Berger meter data (approximating the 290 nm to 330 nm erythral spectrum) found an average decrease in UV levels for 1974 - 1985 of -0.69%/year for 8 U.S. sites. Similarly, *Frederick and Weatherhead*, [1992] found decreasing UV levels from a study at 3 US Dobson sites. The decreasing UV amounts have been attributed to tropospheric changes in meteorological conditions including the presence of absorbing aerosols and increases in tropospheric ozone [Grant, 1988; Scotto *et al.*, 1988; Bruhl and Crutzen, 1989; Justus and Murphy, 1994]. *Blumthaler and Ambach* [1990] found the erythral exposure to be increasing at about 1% per year from 1981 to 1989 at a high clear-air site in the mountains (Swiss Alps at 3.6 km). Increases in the UV-B radiation have been reported for Toronto [Kerr and McElroy, 1993; 1994] that are related to observed changes in stratospheric ozone amounts over a relatively short data record. *Basher et al.*, [1994] have found evidence of UV-B increases for a clean-atmosphere site on the south coast of New Zealand.

In this work we extend recent estimates of UV penetration to the earth's surface by using the new Version 7 TOMS ozone and reflectivity data. We show changes in UV-B that includes daily estimates of cloud effects [Eck *et al.*, 1987; Eck and Dye, 1991; Eck *et al.*, 1995], the effect of local terrain height, and the ozone decreases between January 1979 and December 1992 (the end of the TOMS data record is May 1993). Version 7 corrects a progressively worsening TOMS in-flight calibration problem that became significantly larger after 1990, and corrects a wavelength calibration error that led to a constant +4% offset in the Version 6 ozone amounts present since November 1978. Using radiative transfer calculations that include multiple scattering [Dave, 1965], we estimate surface UV-flux changes from measured changes in stratospheric ozone amounts and tropospheric cloud and aerosol effects. Daily time series of exposure to UV flux are constructed to estimate changes that have occurred since the beginning of the TOMS ozone data set including the portion of the Mt. Pinatubo ozone perturbation occurring between 1991 and 1992. The Mt. Pinatubo aerosol did not appreciably alter the total UV irradiances at the ground [McKenzie *et al.*, 1995].

For these estimates, the average atmospheric properties for UV scattering, cloud amounts, and ground reflectivity within a $1^\circ \times 1.25^\circ$ latitude x longitude box are estimated from TOMS 380 nm reflectivity measurements. Monthly and annual changes in UV exposure (expressed as a linear fit slope in percentage change per decade) are developed from time-series analysis as a function wavelength (300 - 340 nm) and 10° latitude bands (-65° to $+65^\circ$). Error estimates for the linear-fit calculations include effects of tropospheric perturbations in ozone amounts on UV intensity, and the variability caused by clouds and stratospheric ozone. By December 1992 the Mt. Pinatubo ozone perturbation causes only a small change in the linear-fit slope since it was significant for only a few months out of 14 years (Herman and Larko, 1994).

UV Flux at The Earth's Surface

The solar UV flux at the earth's surface for clear-sky conditions can be estimated from a multiple scattering calculation [Dave, 1965] using a spherical geometry ray path for the absorption and scattering of the primary beam and a plane parallel atmosphere for the scattered component. This semi-spherical method is accurate up to moderately large solar zenith angles ($\theta > 85^\circ$) that occur at high latitudes and near sunrise and sunset. The semi-spherical method has been checked against a full spherical geometry calculation for both direct and scattered flux (spherical code developed by *B. Herman* [1995], private communication). An exception to use of the semi-spherical method occurs for high latitudes during the late autumn through early spring time period when the solar zenith angles can be greater than 85° for the entire day.

The effects of atmospheric scattering are represented using solutions of the semi-spherical radiative transfer equation for a plane parallel atmosphere with absorption, scattering, and corrections for cloud effects. The total UV flux on a horizontal surface at the ground, F_s , is given by the clear-sky solution for zero ground reflectivity times a correction for ground reflectivity (4% - 5% with no snow [Eck *et al.*, 1995]) and cloud reflectivity, $C(R_{TOMS})$. R_{TOMS} is the measured radiance to irradiance ratio minus the calculated effect of a pure Rayleigh scattering atmosphere. R_{TOMS} is a function of ground reflectivity, cloud and aerosol optical depth, and the viewing geometry. The cloud correction is obtained by setting $C(R_{TOMS})$ to the factor $(1 - R_{TOMS})f_c$. Radiative transfer calculations show that f_c depends on the viewing geometry and weakly on the cloud optical depth and ground reflectivity. For cloud optical depths between 0 and 50, $1 \geq f_c \geq 1.2$ with almost no dependence on cloud height. Since the Nimbus-7/TOMS viewing geometry was approximately constant between its 1978 launch and 1993, f_c is almost constant and is not significant for UV-change calculations. As shown later, for zonal averages R_{TOMS} has no significant change over the measurement period so that the assumption $f_c = \text{constant}$ is accurate. R_{TOMS} is approximately 5 times more sensitive to changes in cloud or aerosol amounts than f_c .

Since f_c is approximately constant in time, the simpler cloud correction of $C(R_{TOMS}) = [1 - (R_{TOMS} - 0.05)/0.90]$ [Eck *et al.*, 1995] can be used for estimating UV-changes. In this case, when R_{TOMS} is greater than 0.5, the ground reflectivity is set to 0 and $C(R_{TOMS})$ is set to $[1 - R_{TOMS}]$. Using TOMS ozone and reflectivity data and the extraterrestrial solar flux, good agreement with ground based UV-flux measurements at Toronto, Canada [Kerr and McElroy, 1993] has been obtained as a function of wavelength and day of the year [Eck *et al.*, 1995].

Surface UV-flux tables were made from radiative transfer calculations for the wavelength range 300 to 340 nm in steps of 0.5 nm, for ozone amounts from 225 DU to 475 DU in steps of 50 DU, for zenith angles 0° to 80° in steps of 10° and the additional zenith angle of 88° , and for the altitude range 1 km to 5 km. Intermediate values are obtained by low-order polynomial interpolation from the generated tables for use in the following sections. Using these tables, daily UV-fluxes are computed on a $1^\circ \times 1.25^\circ$ global grid from TOMS data. The resulting UV-fluxes are integrated for each day of the year to obtain UV-exposures.

Long-term changes in UV Exposure

Annual exposures to UV fluxes are computed over the range 300 nm to 340 nm for the period 1979 to 1992. The least-squares linear fit to zonally averaged (10° latitude bands) annual UV-exposure estimates (see Figure 1) show that below 40° latitude in the northern hemisphere, there has been no significant increase (at the 2-standard deviation confidence level) in the annual average 310 nm flux and 320 nm flux with and without cloud effects.

The change in 310 nm UV-flux at 55°N is $5.4 \pm 4\%$ per decade (or about $7 \pm 4.5\%$ between 1980 and 1992). Increases in zonal average UV in the range 300 nm to 310 nm are significant at latitudes as low as 40°N . The southern and northern hemisphere UV changes are comparable up to about 50° latitude. The changes in UV-exposure in the northern and southern hemispheres follow a similar pattern with some asymmetry caused by the appearance of the Antarctic ozone hole each spring. Aside from the larger UV exposure increases near the southern tip of Chile and Argentina, UV increases over population centers are smaller in the southern hemisphere than in the northern hemisphere because more northern cities are at higher latitudes.

The exposure change for 320 nm is only weakly sensitive to ozone changes compared to shorter wavelengths. Changes in low latitude 320 nm exposures are caused by changes in cloud transmission of UV-

Figure 1

flux. The lack of change at lower latitudes is evidence that the long-term (14-year) effect of clouds on changes in monthly average UV transmission is negligible. Similar contour plots of 330 nm and 340 nm show no changes in exposure at all latitudes between $\pm 65^\circ$. Since seasonally averaged reflectivity remains unchanged from year-to-year, long-term variability in zonal-average surface-UV intensity is controlled by the changes in atmospheric ozone amounts.

Additional contributions to long-term exposure changes can result from systematic changes in absorbing aerosols (biomass burning, volcanic ash, and desert dust) and changes in the amount of tropospheric ozone [Logan, 1985]. Analysis of the amount of absorbing aerosols seen in the TOMS data shows that the covered areas are small compared to zonal average areas, and that they are present only a small fraction of each year in most regions [Hsu et al., 1996]. While the local effects of absorbing aerosols can be large, their effects on zonal-average annual UV-exposure changes are small (less than the uncertainty from estimating the UV-changes due to ozone and cloud variability).

Possible tropospheric ozone changes are only partially seen in the TOMS data (about half the change) causing an underestimate of the corresponding UV-flux change. Examples of calculated changes caused by a 1% increase of tropospheric ozone amount in the altitude range between 1000 mb and 250 mb are a 0.5% UV flux decrease at 300 nm and 0.15% decrease at 310 nm. For changes in UV-fluxes estimated from TOMS ozone data, the errors due to possible tropospheric ozone increases would be half of the above amount (-0.25%/1% at 300 nm and -0.075%/1% at 310 nm). A similar error estimate for the erythemal or Robertson-Berger spectra yields -0.08%/1%. For the 8 U.S. Robertson-Berger sites analyzed by Scotto et al. [1988], showing an average UV-erythemal decrease of 0.69% per year, tropospheric ozone would have increased by the unlikely amount of about 14% per year (1.1/0.08) to offset the observed decrease in total ozone from TOMS data for the same 8 sites. The 8 site average erythemal increase estimated from TOMS data is about 0.41% per year. The difference is more than can be accounted for by the uncertainty in the TOMS UV estimates.

Action Spectra Weighted Exposures

The most important UV wavelengths at the earth's surface are grouped into two broad spectral bands related to their biological activity. The UV-B spectral range is defined as 290 nm to 320 nm (dependent on ozone changes) and the UV-A range from 320 nm to 400 nm (only weakly dependent on ozone changes). Using the dimensionless biological action spectrum, $W(\lambda)$ [Tsay and Stammes, 1992], the product $W(\lambda)E(\lambda)$, in the range 290 to 310 nm, contains the maximum values for causing damage in DNA molecules, plant damage, and erythema.

Figure 2 shows the zonally averaged action-spectra changes for $W(\lambda)E(\lambda)$ integrated over the DNA-, erythema-, and plant-damage spectra and over each day of the year. The long-term changes are based on linear least-squares fits to annual-exposure time-series from January 1979 to December 1992 in 10° latitude bands from 65°S to 65°N . The estimated UV-changes include the ozone perturbations from the eruptions of El Chichon and Mt. Pinatubo. The results show a strong UV-exposure increase for DNA and the plant spectra because of the contributions of wavelengths shorter than 310 nm. The changes in the erythemally weighted exposure integral are smaller because of the decreased sensitivity of longer wavelength fluxes to ozone changes. For 45° latitude the erythemal sensitivity is about 1:1 (a 1% decrease in ozone amount produces a 1% increase erythemal annual exposure). This is in good agreement with ground-based measurements giving the ratio $1.25:1 \pm 0.22$ [McKenzie et al., 1991] at 45°S in Lauder, New Zealand.

Figure 2

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Figure 3

Monthly UV-exposure changes (Figure 3) were obtained from daily time series for exposure from 1979 to 1992 in a manner similar to the ozone analysis of *Stolarski et al.* [1991]. The most significant difference from the ozone analysis is that the data were deseasonalized prior to the computation of the time-series coefficients. The UV-deseasonalization was accomplished by subtracting the average annual cycle from each year's data on a daily basis.

At the 2- σ level, there are no significant long-term increases in UV-exposure equatorward of 40° for processes dominated by shorter wavelengths (weighted by the DNA and plant spectra), and for spectra similar to that involved in erythema. In the southern hemisphere, the monthly 65° latitude-band changes may be incorrect because the data include high reflectivities from the south polar ice cap. If high reflectivity regions are excluded, the results are similar to the clear-sky case and to those in the northern hemisphere.

Since plant and DNA action spectra are weighted towards shorter wavelengths, the computed exposure changes are larger than for the erythema spectra at a given latitude and month. The results show that there have been significant (2- σ) increases in exposures for all months at higher latitudes (>40° for the erythema spectra, and >35° for the plant and DNA spectra).

Conclusion

Ozone and reflectivity data from Nimbus-7/TOMS have been used to estimate the expected change in zonally averaged UV exposure at the ground between 1979 and 1992 for latitudes in 10° bands between $\pm 65^\circ$. Statistically significant increases in annual UV-exposure occurred for latitudes above 40° in both hemispheres.

There have been statistically significant changes in monthly exposures at latitudes above 25°. A large portion of the annual exposure increases come from the spring and early summer months (see Figure 3). During April at 45°N the action spectra weighted UV increases are 8.6%, 9.8%, and 5.1% per decade compared to summer values of 5.3%, 5.7%, and 3.6% per decade for DNA, plant, and erythema spectra, respectively. The largest changes are at the higher latitudes in both hemispheres. At 55°N (England, Scandinavia, Germany, Russia) the annual average exposure has increased 6.8%, 8.1%, and 4.3% per decade, and at 55°S (southern portions of Argentina and Chile) the increase has been 9.9%, 11.5%, 5.6% per decade, respectively. The ozone reductions from the springtime Antarctic ozone hole cause the larger UV-B increases at high southern latitudes.

The 380 nm channel on TOMS includes the effect of ground, aerosol, and cloud reflectivity on the estimation of UV exposures at the ground. For long-term UV changes, the TOMS reflectivity data indicate there has been no significant change in zonal average aerosol plus cloudiness from 1979 to 1992 (see Figure 1). This result agrees with the independent estimate of cloud effects based on 5 years of ERBE data [*Lubin and Jensen, 1995*].

The UV-changes for the erythema spectra do not show the decrease reported by *Scotto et al.*, [1988] (an average decrease of 6.9% per decade) from the ground-based R-B meters. TOMS erythema-UV time series coincident with the R-B sites show UV increases at all 8 sites from Florida to North Dakota (an average of 4.1% per decade). The difference is more than can be accounted for by the uncertainty in the TOMS UV estimates.

Because of the presence of the Mt. Pinatubo ozone perturbation near the end of the TOMS data record, the slopes of the linear fits slightly overestimate long-term trends for UV increases.

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Figure Captions

Figure 1. Annual zonal average UV-exposure change for 300 nm, 310 nm, and 320 nm (Percent per Decade) computed from daily UV-exposure using a $1^\circ \times 1.25^\circ$ (latitude x longitude) grid (1979-1992). The 2 standard deviation error bars with the larger caps belong to the clear-condition plot (open squares). The larger error bars for the cloud case results from the increased variability in UV exposure relative to the clear case. The error estimates include the 1% per decade instrument uncertainty in instrument drift for Version 7 TOMS ozone data.

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Figure 2. The linear-fit slope (percent per decade) of the action-spectra weighted UV-flux exposure integral for the period 1979 to 1992 including the effects of clouds. The indicated error bars represent 2 standard deviations and are labeled with D=DNA, P=plant, and E=erythema.

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Figure 3. The monthly changes in exposure weighted by the DNA, plant, and erythema action spectra including the effect of clouds (1979 - 1992). The seasonal cycle, linear trend, QBO, and solar cycle effects are represented as separate terms in the statistical model. The contour units are percent per decade for a linear-fit slope.

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HERMAN ET AL., UV-B INCREASES (1979-1992)

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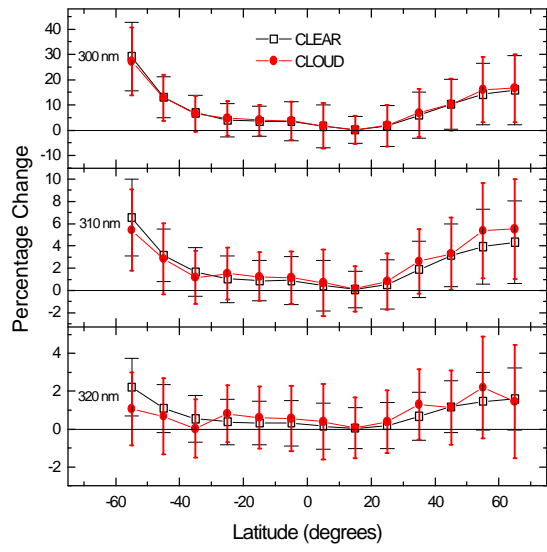


Figure 1
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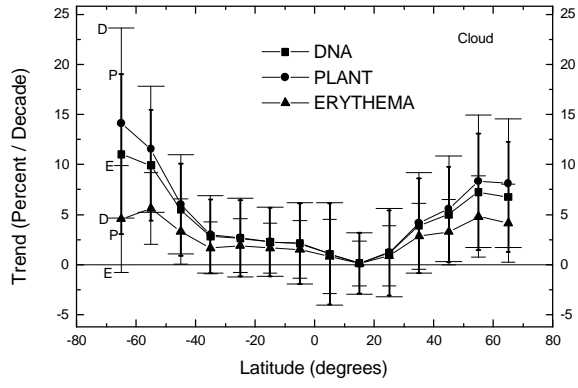


Figure 2
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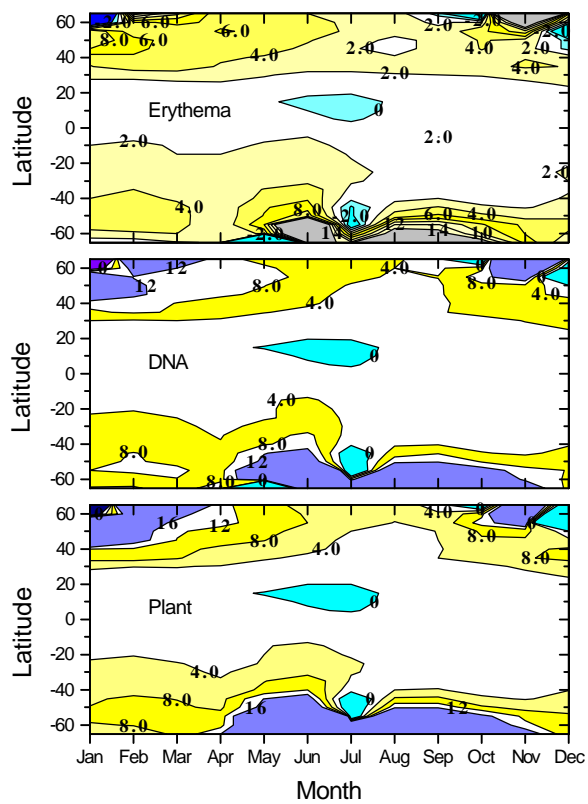


Figure 3
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