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Comparison of daily UV doses estimated from Nimbus 7/TOMS measurements and ground-based spectroradiometric data

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Abstract. During recent years, methods have been developed for estimating UV irradiance reaching the Earth's surface using satellite-measured backscattered UV radiances. The NASA-developed method is based on radiative transfer calculations and satellite measurements of parameters affecting UV radiation: extraterrestrial solar irradiance, atmospheric ozone, cloud reflectivity, aerosol amounts, and ground albedo. In this work a comparison is made between daily UV erythemal doses estimated from Nimbus-7/TOMS measurements (from 1991 to May 1993) and those calculated from ground-based spectroradiometer data. Three stations operated by the National Science Foundation were chosen for this comparison: Ushuaia, Argentina (for 573 days), Palmer, Antarctica (for 450 days), and San Diego, California, (for 149 days). These stations were selected to illustrate the differences between ground-based measurements using the same type of instrument, SUV-100 double monochromator spectroradiometers, and satellite estimates of surface UV irradiance under three different environmental conditions (mountains and snow, nearly continuous snow cover, and midlatitude urban sea level conditions). Averaging the measured and TOMS-estimated doses over periods from 1 week to 1 month improves the agreement. The daily or monthly mean bias increases during months when there is snow/ice on the surface. TOMS has a larger estimate of the UV irradiance by 25% at San Diego (no snow), in agreement with the summer-month analysis of Toronto irradiances [*Herman et al.*, 1999]. TOMS underestimates the average daily-UV dose at Ushuaia (monthly mean bias of −13%) and at Palmer (−35%) consistent with snow/ice with cloud effects not being properly accounted for in the TOMS algorithm. When the reflectivity at all three sites is low (no snow), the TOMS irradiance estimate is larger than the SUV-100 measurements consistent with previously analyzed Brewer data at Toronto. The effects of local fog or clouds smaller than the satellite field of view and undetected UV-absorbing aerosols near the ground are discussed. In addition to uncertainties in radiometric calibrations of the spectrometers, none of the SUV-100 data are corrected for deviations of diffuser-transmittance from true cosine response.

1. Introduction

Changes in the Earth's atmosphere caused by anthropogenic and natural pollutants has led to the well-documented decline in ozone and the corresponding small increase in UV irradiance at the Earth's surface at higher latitudes greater than about 40° [*Herman et al.*, 1996]. These increases can affect the human health, crop yields, ocean productivity, and materials aging.

In addition to the satellite estimation of UV irradiance, there has been a long-term well-established network of ground-based instrumentation. The ground-based network has the advantage that it more accurately represents the local conditions of the region than the currently large-pixel (100 km) estimates from TOMS (total ozone mapping spectrometer). Ground-based instruments provide a direct measure of the surface irradiance (aside from calibration issues) as opposed to the calculated estimates from satellite data.

UV radiation at ground level is traditionally measured using a variety of ground-based instruments. However, the network of high-quality ground-based UV instruments is not dense enough for a monitoring of the global distribution of solar UV radiation and is almost completely lacking over the oceans. Because of this limitation, methods using satellite measurements of extraterrestrial solar radiation, atmospheric ozone, cloud reflectivity, aerosol amounts, and ground albedo combined with radiative transfer modeling are needed to estimate the daily global distribution of UV irradiance. It is important that the satellite estimates of surface UV irradiance are validated under the widest set of conditions.

The longest continuous time series of satellite-based surface UV data has been calculated using the Nimbus-7/TOMS measurements for the period 1978–1993 [*Eck et al.*, 1995; *Herman et al.*, 1996; *Krotkov et al.*, 1997; 1998; *Herman et al.*, 1999; *N. A. Krotkov et al.*, unpublished data, 1999 (hereinafter referred to as K99)]. Other ways of estimating the UV irradiance at ground level using satellite data have been introduced by *Madronich* [1992], *Lubin and Jensen* [1995; 1997]; *Meerkoetter et al.* [1997]; and *Nunez et al.* [1997].

In this work a comparison is made between daily UV ery-

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themal doses calculated with the NASA TOMS UV algorithm (see ftp://jwocky.gsfc.nasa.gov/pub/n7toms) and those calculated from UV measurements with a single type of spectroradiometer and discusses possible causes for the differences. The comparison of daily doses is important, because in many cases daily doses are of primary interest to the biological or materials impact studies. Three stations operated by the National Science Foundation (NSF) were chosen for this comparison: Palmer (Antarctica, 64°46′S, 64°03′W), Ushuaia (Argentina, 54°49′S, 68°10′W), and San Diego (California, 32°45′N, 117°11′W).

Earlier TOMS validation papers [*Eck et al.*, 1995; *Krotkov et al.*, 1998; *Herman et al.*, 1999] provide detailed comparisons with the well-calibrated Brewer 14 instrument located at Toronto, Canada. The current study compares data with three stations (using SUV-100 spectrometers) located in places with widely varying environmental conditions (Palmer, snow covered most of the year; Ushuaia, mountain terrain with snow cover part of the year; San Diego, a sea level urban environment that never has snow cover).

The data are described in section 2. The comparison of the NSF and the TOMS UV data is presented in section 3. Reasons for the differences between the data sets are discussed in section 4.

2. Data

2.1. TOMS UV Data

The TOMS instrument is NASA's second-generation backscatter UV ozone sounder, designed to study ozone concentrations in the Earth's atmosphere. Nimbus-7/TOMS-measured direct solar radiation and backscattered radiation from the Earth-atmosphere system in six 1 nm wide UV channels, centered at 313, 318, 331, 340, 360, and 380 nm [*Eck et al.*, 1987]. The shortest two wavelength bands are strongly absorbed by ozone, while the four longest wavelengths are only weakly absorbed. Nimbus 7/TOMS had a slowly-drifting Sun-synchronous orbit, with an observation time of 1130 LT in 1979 and 1030 LT in 1993 for each satellite field of view (FOV) [*Herman and Celarier*, 1997]. For each scan, the TOMS instrument made 35 side-looking measurements along a cross-track scan. At the nadir the measurement footprint was 50×50 km^2, while at the most extreme slant angle (51° from the nadir), the footprint increased to 150×200 km^2 [*Herman et al.*, 1997].

The UV irradiance reaching the Earth's surface is calculated in two steps [*Krotkov et al.*, 1997, 1998; *Herman et al.*, 1999]. First, the solar UV irradiance at the ground is calculated for clear sky (cloud and aerosol free) conditions with a radiative transfer model based on the work of *Dave* [1964, 1965]. The model takes into account scattering by the molecular atmosphere, absorption by ozone, reflection from the Earth's surface, and the effects of terrain altitude and the solar zenith angle. Extraterrestrial solar irradiance was obtained from UARS/SOLSTICE (Solar Stellar Irradiance Comparison Experiment) [*Rottman et al.*, 1993]. TOMS total ozone values [*McPeters et al.*, 1996] and climatological ozone profiles based on solar backscatter ultraviolet (SBUV) (aboard Nimbus 7) measurements and on balloon ozonesonde measurements [*Wellemeyer et al.*, 1997] are used in the UV algorithm. Normally, surface altitude is taken from a terrain height database [*Wieser*, 1987]. However, in this study, the actual altitudes of the ground-based instruments have been used in the TOMS UV algorithm.

The surface reflectivity is obtained from the climatological surface reflectivity (R_s), data set calculated from TOMS 380 nm backscattered radiances [*Herman and Celarier*, 1997]. Usually R_s varies between 2 and 4% over land (no ice or snow) and 4 to 8% over water. For land areas covered by ice and snow, R_s is much larger, approximately 20 to 95% [*Feister and Grewe*, 1995] depending on the age, depth, and purity of the snow, with the highest reflectivities occurring for clouds over fresh snow. Because the reflectivity of clouds can be as much as 80% [*Eck et al.*, 1987], the TOMS UV algorithm is unable to distinguish between snow and clouds. If snow is misinterpreted as a cloud, it causes underestimation of the surface UV irradiance [*Herman et al.*, 1999; K99]. The current TOMS UV algorithm attempts to balance between these two effects by introducing an empirical probability of the occurrence of cloud over snow to reduce the error when averaged over periods of a month.

The attenuation of UV radiation due to clouds is estimated using a cloud correction factor (ratio of cloudy-sky to clear-sky irradiance) [*Krotkov et al.*, 1997; *Herman et al.*, 1999; K99]. The cloud correction factor is determined using TOMS 380 nm reflectivities measured during the daily satellite overpass and radiative transfer simulations [*Dave*, 1964; *Stamnes et al.*, 1988]. The cloud correction factor is calculated using a plane-parallel cloud model, in which it is assumed that the cloud layer is always homogeneous and located between 700 and 500 hPa. Finally, the UV irradiance at the Earth's surface is calculated as the product of the clear-sky irradiance and the cloud correction factor. UV-absorbing aerosols (volcanic ash, smoke, soot, and dust) are taken into account as described by *Herman et al.* [1999] and *Krotkov et al.* [1998]. However, the absorption properties of aerosols are detected only if the aerosol layer is about 1.5 km above the surface [*Herman et al.*, 1999]. Reflecting aerosols (e.g., sulfates or low-altitude absorbing aerosols) are included in the cloud correction based on measured reflectivity [*Krotkov et al.*, 1998].

The assumptions in the TOMS UV algorithm related to estimating cloud transmittance from the measured scene reflectivity are discussed in several papers [*Herman et al.*, 1996; *Krotkov et al.*, 1997; *Herman et al.*, 1999; Krotkov et al., K99]. Calculated UV doses for clear-sky days are more likely to be accurate than for cloudy days because of the possible errors involved in assuming a continuous plane-parallel cloud cover to represent the average reflectivity for a TOMS scene that may contain a distribution of broken clouds. This is true only in the absence of undetected absorbing aerosols that can cause significant UV attenuation (~10%) in urban areas [*Krotkov et al.*, 1998; *Herman et al.*, 1999].

2.2. Ground-Based Spectroradiometer Data

The ground-based data used in this study are obtained from instruments in the NSF network consisting of SUV-100 double monochromator spectroradiometers manufactured by Biospherical Instruments Inc. Three stations were chosen for this comparison: Ushuaia, Palmer, and San Diego. Measurements at Palmer and Ushuaia started in May and in November 1988, respectively. The San Diego station has been in operation since November 1992. During the first operational years at Palmer and at Ushuaia the accuracy of the data was not of the highest quality (J. C. Ehramjian, personal communication, 1998). Consequently, these years were ignored in the comparison.

Corrections for wavelength, stray light, and dark current have been performed on the NSF spectroradiometer data [*Booth et al.*, 1993]. In addition, frequent calibrations have

been carried out to reduce errors caused by system changes and long-term drifts. The SUV-100 system is temperature-stabilized, so no separate temperature correction is required. Cosine corrections for the diffuser plates of the three instruments have not been made, which in Brewer spectrometers were shown to cause underestimation of surface UV irradiance especially at high solar zenith angles [*Seckmeyer and Bernhard*, 1993; *Ireland and Sacher*, 1996; *Bernhard and Seckmeyer*, 1997]. If this is true for the SUV-100 spectrometers, then it is partially offset by the fact that the proportion of diffuse radiation increases with increasing solar zenith angle (i.e., increasing latitude). In the Nordic intercomparison of ultraviolet and total ozone instruments at Izaña, 1996, the error, due to a nonideal cosine response, has been estimated to be about 5–10% [*Blumthaler and Bais*, 1997]. These numbers may not be valid for the cosine correction of the NSF instruments, because this correction is specific to each instrument. In the near future the cosine correction will also be included in the corrections of the NSF data (J. C. Ehramjian, personal communication, 1998).

An NSF SUV-100 instrument took part in a comparison campaign with four other similar instruments in August 1994 at Garmisch-Partenkirchen, southern Germany [*Seckmeyer et al.*, 1995]. During the campaign the differences between the instruments were at the ±7% level, when spectra were weighted by the erythemal-weighting function. However, over a longer period, the calibration uncertainty is usually larger. The NSF instruments used in this study do not necessarily have the same performance as the campaign instrument. Also, the Sun angles were different from those at San Diego, Palmer, or Ushuaia, so the cosine correction errors are likely to be different.

The spectral UV measurements have been carried out once an hour during the daytime. Each wavelength scan takes about 10 min. Cloud-cover changes during the scans were neglected because in a long data set they are not likely to cause any systematic error but will increase the effective scatter of the data. Daily Comm. Int. de l'Eclairage (CIE) weighted doses [*McKinlay and Diffey*, 1997] were calculated from the hourly irradiances by multiplying the single-wavelength irradiances by the CIE weighting factors at each nominal wavelength [*Booth et al.*, 1993].

3. Results

This section will discuss the comparison of the ground-based CIE-weighted dose and with the corresponding TOMS-estimated dose. The differences from TOMS for each location will be given and a list of possible reasons for these differences. This paper will not perform the analysis of the individual instruments or their local meteorological environment at the time of the measurements.

Comparisons of the daily CIE-weighted UV doses from TOMS and NSF ground-based data were made for Ushuaia (from April 16, 1991 to May 6, 1993), Palmer (from August 26, 1991 to May 6, 1993), and San Diego (from October 31, 1992 to May 6, 1993). Mean and root-mean-square (rms) differences between the TOMS-estimated and the ground-based data are shown in Figure 1, both on an absolute scale (J/m^2) and on a relative scale (%). For Ushuaia the correlation coefficient (0.94) between TOMS-estimated and ground-based UV data is fairly high. The mean (−13%) is closest to TOMS estimates, and the rms difference (29%) is the smallest among the stations. For Palmer the agreement is worse, with quite a low correlation coefficient (0.80) and large mean (−35%) and rms differences (45%).

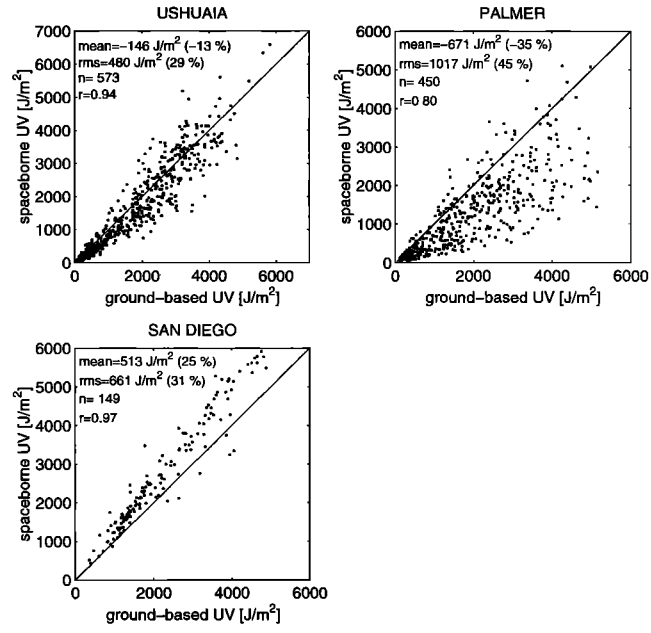

Figure 1. Comparison of daily CIE-weighted UV doses retrieved using the TOMS UV algorithm and National Science Foundation (NSF) spectroradiometric data for Ushuaia (top left), Palmer (top right), and San Diego (bottom left). Mean and rms differences between these two data sets are shown in the top left corner of each panel as absolute values, TOMS-NSF (J/m^2), and as percentages (TOMS-NSF)/NSF; shown in parentheses, n is the number of days and r is the correlation coefficient.

At Ushuaia and at Palmer the TOMS UV algorithm gives lower doses, on the average, than the ground-based data. The difference is opposite in sign from the comparison to San Diego data, where the TOMS UV estimates exceeds the ground-based data by an average of 25%. The shift of about 55% relative to TOMS implies a physical reason for the systematic difference between the data sets (Palmer versus San Diego). Figure 2 shows the comparison of the ground-based daily UV doses from the San Diego SUV-100 data and the TOMS UV data. Generally, the day-to-day variation of the UV doses is similar, but the values of the UV doses are different. A correlation has also been observed between the day-to-day variation of TOMS and ground-based daily UV doses at Ushuaia and Palmer but not so clearly as for San Diego.

The differences between the TOMS-estimated and the ground-based UV data seem to have a seasonal dependence. This can be seen in Figure 3, where the ratio of the TOMS-estimated and the ground-based UV are shown as a function of time for Ushuaia (top), for Palmer (middle), and for San Diego (bottom). The TOMS UV data are in better agreement with the ground-based data in summer than in winter. At Palmer and Ushuaia the seasonal differences are correlated with changes in solar zenith angle θ and the climatological presence of snow. At both stations the underestimation by the TOMS UV algorithm is most severe at large noontime θ. For example, the mean difference at Palmer was −17% for noontime $\theta \leq 42°$ and −47% for $\theta > 67°$. At San Diego the time series is only about half a year for a location without snow, for which reason no similar seasonal variation can be found.

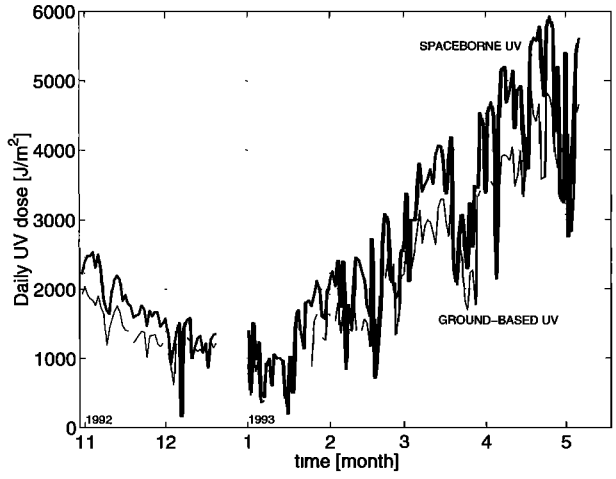

Figure 2. Daily UV doses at San Diego from October 31, 1992 to May 6, 1993. The thick line is the TOMS-estimated UV and the thin line is the ground-based UV.

The ratio of the TOMS-estimated and the ground-based daily UV doses at different 380 nm reflectivity values for Ushuaia (top), for Palmer (middle), and for San Diego (bottom) are shown in Figure 4. The mean and rms differences are also shown for different 380 nm reflectivity classes. The number of clear days ($R_{380} < 10\%$) is low at Ushuaia, because of frequent clouds [*Booth et al.*, 1993]. For Palmer the snow cover decreases the number of low-reflectivity cases. The main feature is that the ratio between the measured and the TOMS-estimated irradiance decreases when reflectivity increases at both Ushuaia and Palmer. For San Diego the dependence was not so obvious. When the reflectivity is low for all three sites (no snow), the ratio is greater than 1 (TOMS greater than the SUV-100), and is consistent with previously analyzed Brewer 14 data at Toronto [*Herman et al.*, 1999].

3.1. TOMS Reflectivity and Cloud Fraction Data

The TOMS 380 nm reflectivity is related to snow/ice, cloud fraction (measured in oktas, 1/8, 2/8, . . . , 8/8 cloud fraction), and to cloud optical depth. In the absence of snow cover on the ground, there should be an increase in TOMS reflectivity with increasing cloud fraction (SYNOP surface weather data from the National Center for Atmospheric Research (NCAR) and National Meteorological Center (NMC).

The mean and rms differences were calculated for various ranges of SYNOP total cloudiness: $N_{AV} \leq 1$, $N_{AV} = 1$ to 4, $N_{AV} = 4$ to 7, and $N_{AV} \geq 7$. N_{AV} is the average of the available daytime SYNOP total cloudiness values for each day. The number of days used in this analysis was smaller than in the previous analysis, because of some missing SYNOP observations. The mean differences between satellite and ground UV doses were largest during the clear days ($N_{AV} \leq 1$) at Ushuaia (−15%) and at Palmer (−40%). This is a direct indication that the TOMS algorithm treats high reflectance from snow as cloud cover, which in turn causes the underestimation of the UV dose. In other N_{AV} ranges, the differences were almost the same. At San Diego the mean and rms differences were smallest for $N_{AV} = 1$ to 4 and largest for $N_{AV} \geq 7$. The best correlation coefficient (1.00) was obtained during clear-sky conditions (34 days) at San Diego, when the mean and rms differences were 25 and 26%, respectively.

The SYNOP total cloudiness versus 380 nm TOMS reflectivity for Ushuaia (top) and for San Diego (bottom) in 1992–1993 are shown in Figure 5. At Ushuaia there is snow cover during the winter months, which causes the higher reflectivities than those seen at San Diego. From the comparison shown in Figure 5 the TOMS 380 nm reflectivity is only weakly correlated with the SYNOP cloud fraction at San Diego. In addition, there is considerable scatter in the cloud-fraction data, especially as the cloud fraction increases. For Ushuaia the correlation is worse and the scatter is greater, because the cloud-fraction data include snow on the ground.

3.2. Weekly and Monthly Average Dose Comparisons

Because the satellite estimation of cloud transmittance is an average over a region of 100 × 100 km^2, it has been demonstrated for Toronto data [*Herman et al.*, 1999; K99] that better agreement between ground observations and satellite estimates occur when the data are averaged over weekly or monthly periods. Time averaging the satellite and ground-based comparisons for daily dose is even more important than for comparison with measured irradiances near the time of the satellite overpass. TOMS obtains only a single near-noon point every day at a given Earth location. Because of this there can be differences in measured and estimated UV daily or time-average doses because of systematic changes in cloudiness between morning and afternoon. For example, in the summer, afternoon cloudiness frequently increases relative to morning cloudiness as moisture evaporates from the surface. In this case, differences between satellite and ground-based UV doses will remain even after averaging over a month.

The differences between the TOMS and the ground-based UV doses were calculated for weekly and monthly average UV doses. The daily rms differences (at Ushuaia 29%, at Palmer 45%, and at San Diego 31%) were larger than the weekly (22, 41, and 25%) and monthly (20, 40, and 25%) rms differences. The scatter of the daily data is substantially reduced in the weekly or monthly average doses for all stations (see Figure 6 showing time-averaged UV doses, daily, weekly, and monthly, for Ushuaia). The mean biases of the weekly and monthly averaged doses were almost the same as for daily doses. This shows that the biases are not random but represent real biases between the TOMS algorithm and the ground-based measurements for specific local conditions.

4. Possible Reasons for Differences and Discussion

The differences in measured and TOMS-estimated UV irradiance are much larger than the TOMS calibration accuracy [*Herman et al.*, 1999] or the expected radiometric accuracy of the SUV-100 spectrometers but agree with the errors discussed in the next subsections. The accuracy of the TOMS UV estimates over snow-/ice-free surfaces has been estimated to be better than 5% in clear-sky conditions [*Krotkov et al.*, 1998; *Herman et al.*, 1999]. Similar accuracies apply for snow-/ice-free pixels covered with a homogeneous cloud layer. When local conditions for snow/ice and aerosols are fully taken into account, the differences between the ground-based measured and satellite-estimated irradiances are reduced to within the error estimates for both types of instruments [*Herman et al.*, 1999; K99].

The main sources of bias are as follows: (1) the presence of snow or ice on the ground that is not properly represented in

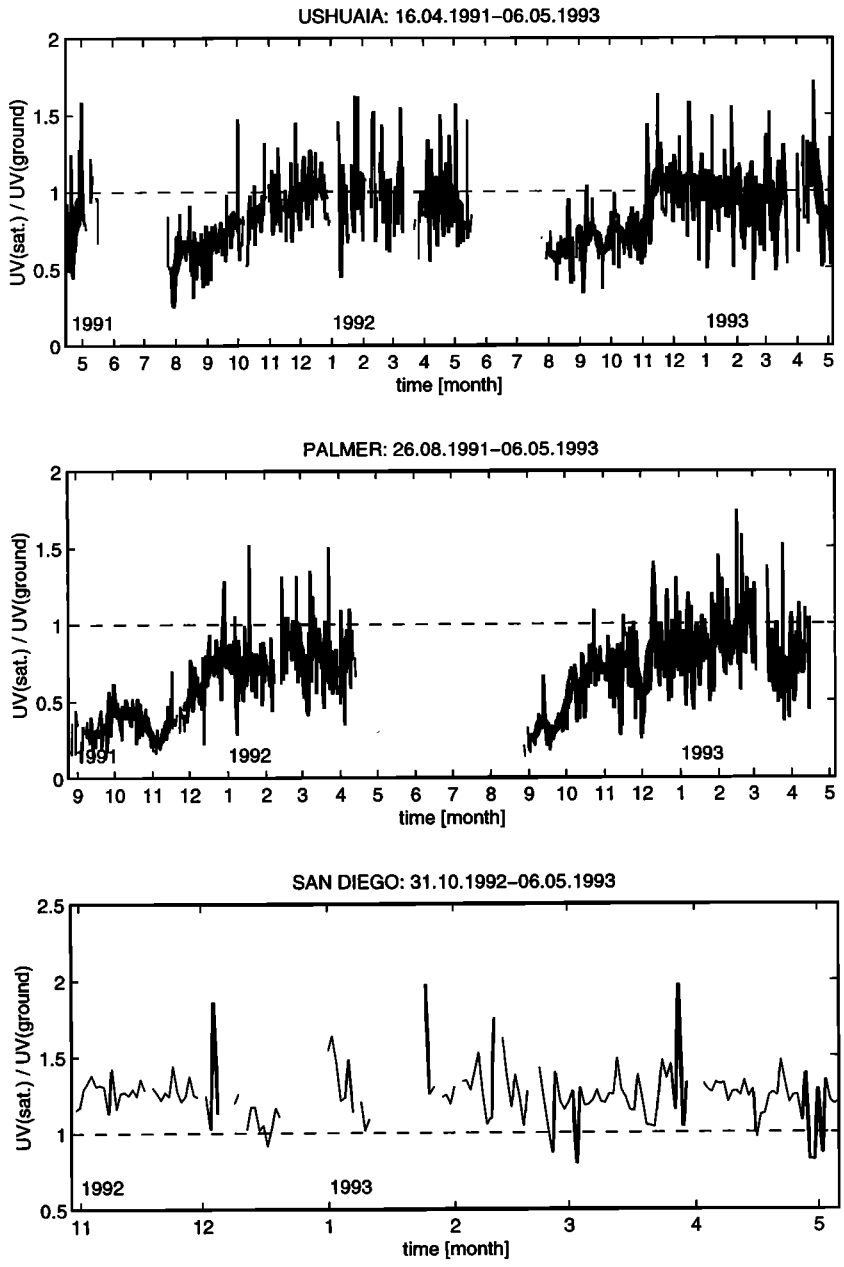

Figure 3. Ratio of TOMS-estimated and ground-based daily UV doses as a function of time for Ushuaia (top), for Palmer (middle), and for San Diego (bottom). The thick curve shows the 10 day running mean.

the TOMS algorithm (very important for Palmer and Ushuaia but not for summer months or for San Diego during all seasons); (2) the presence of undetected (by TOMS) absorbing aerosols over the ground-based site (more important for San Diego); (3) sampling errors from the representation of the entire day's cloud cover based on a single near-noon measurement of reflectivity with a different field of view (FOV) than the ground-based site (important for all three sites); (4) cosine error for the ground-based instruments (important for all sites).

4.1. Uncertainties in Measured and Estimated UV Irradiances

The uncertainties in the radiative transfer parameters are shown in Table 1 along with an estimation of how the uncertainty in a specific input parameter may affect the calculated UV irradiances. Some of the estimated model errors in calculated UV irradiance depend on the solar zenith angle and on the wavelength. The impact of errors in the input parameters can be enhanced in certain circumstances, the most of which is the case with clouds over snow [*Herman et al.*, 1999]. The rms differences found in this study (Figure 1) are larger than the total rms error for cloud-free conditions shown in Table 1. Clouds together with snow increase the error. In addition, the table values are not directly applicable to this study, because here the daily CIE-weighted doses have been used. However, the table gives a good estimate of the various sources of errors and their relative importance.

The values of clouds, aerosols, and the climatological surface albedo R_s detected by TOMS do not necessarily represent the conditions at a station, because the former values are an

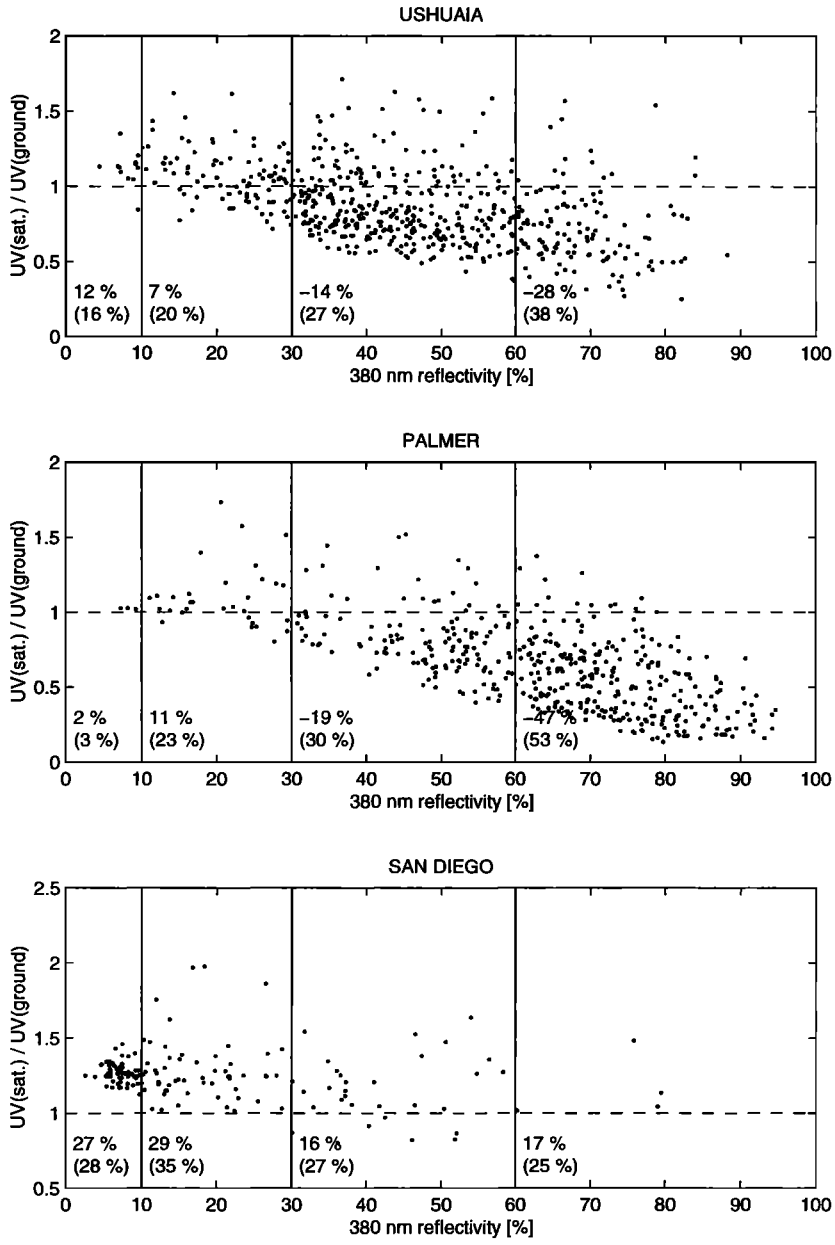

Figure 4. Ratio of the TOMS-estimated and ground-based daily UV doses as a function of 380 nm reflectivity for Ushuaia (top), for Palmer (middle), and for San Diego (bottom). Mean and rms differences (in parentheses) are shown for different 380 nm reflectivity classes: $R_{380} \leq 10\%$, $10 < R_{380} \leq 30\%$, $30 < R_{380} \leq 60\%$, and $R_{380} > 60\%$.

average over the TOMS FOV (50×50 to 150×200 km^2). Both Palmer and San Diego are located near the sea, and it is likely that this affects the value of R_s as seen by TOMS. However, the effect is small for conditions free of ice and snow. At Palmer, where both snow and a glacier are present, the sea may decrease R_s. This can cause an underestimation of the calculated TOMS UV values. The effect of an inhomogeneous surface albedo on UV irradiance has been studied by *Degünther et al.* [1998].

The Ushuaia station is located in the foothills of the Andes, so the variations in surface type and elevation around Ushuaia are large within the area covered by the TOMS FOV. A systematic bias can occur if the altitudes of the ground-based instrument and the TOMS footprint differ. When high mountains are present in the TOMS FOV, as in Ushuaia, the ozone value used to represent the ozone column above the station may be systematically too small.

An additional error occurs if the wrong terrain altitude (pressure) is used to represent the Rayleigh scattering. A 10 mbar pressure uncertainty becomes a ~0.7% uncertainty in 310 nm irradiance and ~1.2% at 295 nm [*Krotkov et al.*, 1998]. However, the surface altitude is not an error source in this work, because the TOMS UV data have been calculated by using the known altitude of the spectroradiometers. However, the terrain height used in the TOMS ozone algorithm may not give a value that represents the actual ozone amount over the

instrument site. When the ozone error is combined with the Rayleigh-scattering error, the uncertainty is increased to ~1% error at 310 nm and ~2% at 295 nm. The error at 310 nm approximately corresponds to the expected error for erythemal irradiance considered here.

Highly localized fog banks, which are occasionally observed at San Diego [*Booth et al.*, 1993], are averaged within the TOMS 100 km footprint and so do not represent conditions observed by the spectrometer. It is also probable that there are urban absorbing aerosols present which TOMS cannot detect. In Toronto the values ranged up to optical depths of 0.3 [*Krotkov et al.*, 1998]. This amount of undetected absorbing aerosols can cause a TOMS UV irradiance overestimate of 10%, especially on otherwise clear days.

Since the TOMS field of view is quite large, there are many cases where one pixel has partial cloud cover. This affects the instantaneous calculated UV irradiances. During a day a broken cloud field will transmit either more or less UV radiation to the ground relative to uniform overcast clouds (as assumed by the TOMS UV algorithm). Monte Carlo calculations for a typical TOMS midlatitude geometry (with $\theta = 50°$) show that broken clouds may cause errors as large as ±20% [*Geogdzhayev et al.*, 1999]. The TOMS-measured reflectivity captures the average spatial transmittance of a broken or continuous cloud field against a dark background. However, the spatial average may not represent the time integral of cloud transmittance seen by a ground-based instrument. The reflectivity error increases whenever there are systematic differences in cloudiness during a day for a given location.

The diffuser plate (or disk) cosine errors may be the largest source of error for ground-based irradiance instruments after radiometric and wavelength calibration errors. Also, the cosine error is larger in winter than in summer for the direct solar beam. However, for large θ the UV irradiance is mostly diffuse radiation that would tend to reduce the cosine error from its maximum value [*Blumthaler and Bais*, 1997]. For low θ the presence of clouds can cause an increase in cosine error relative to that for the direct solar beam.

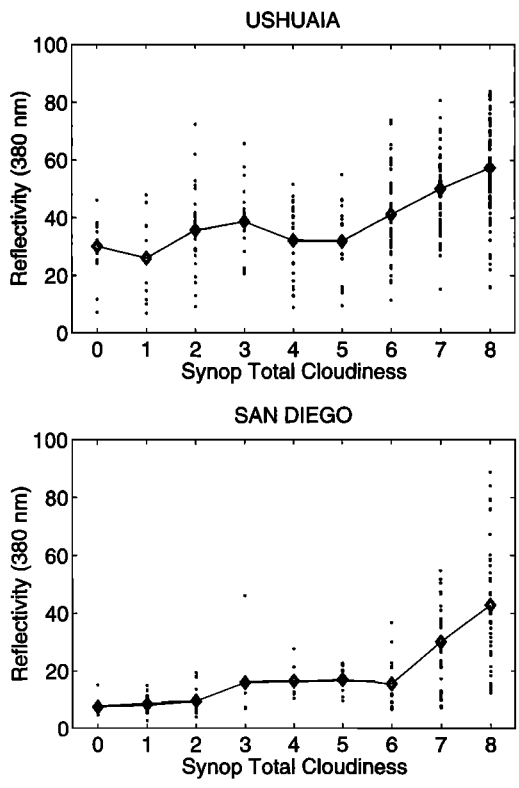

Figure 5. TOMS reflectivity versus SYNOP total cloudiness N (in oktas) for Ushuaia (top, N at 1500 UTC) and for San Diego (bottom, N at 1800 UTC) in 1992–1993. The diamonds indicate the average reflectivity.

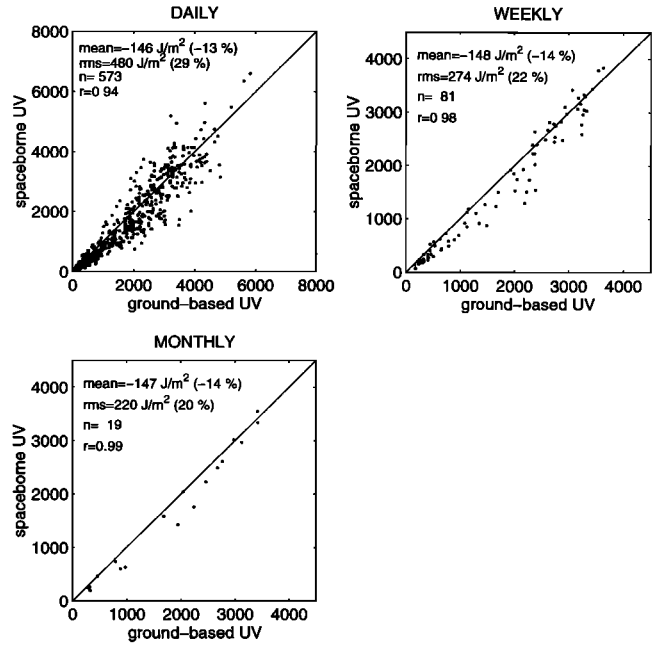

Figure 6. As Figure 1 but for daily, weekly, and monthly average UV doses at Ushuaia.

The radiative transfer code used to generate the clear-sky irradiances is less accurate at higher solar zenith angles $\theta >$ 80°, because it is not solving the fully spherical problem. Also, with $\theta > 70°$, the Umkehr effect [*Mateer*, 1965; *Fioletov et al.*, 1997; *Krotkov et al.*, 1998] complicates the modeling of the UV irradiances, because the surface irradiance becomes strongly dependent on the vertical ozone profile.

4.2. Seasonal Variation

At Palmer and Ushuaia the TOMS UV data are in better agreement with the ground-based data in summer than in winter (Figure 3). These results could be expected, since the TOMS UV algorithm is unable to distinguish between snow and clouds. This causes an underestimation of the surface UV irradiance (as seen at Ushuaia and at Palmer with snow on the ground) if the reflectivity is assumed to be from cloud cover only. Snow on the ground under clear-sky conditions increases the UV irradiance at the surface (8 to 39% at 324 nm) relative to the same conditions in the absence of snow [*Wardle et al.*, 1997]. If the ground reflectivity with snow/ice were known from outside data, the TOMS algorithm would account for the multiple scattering and reflection effects of clouds over snow/ice and give a more accurate estimate of the irradiance at the surface.

The seasonal differences between the TOMS estimated doses and the ground-based dose measurements at Palmer and Ushuaia reported in this study are similar to those that have been described for Toronto [*Herman et al.*, 1999]. TOMS-

Table 1. Uncertainty in Calculated UV Irradiance From Radiative Transfer Assumptions in the Clear-sky Case

Parameter	Uncertainty in the Parameter	Impact on UV[a]	Conditions
Solar irradiance I	3% rms	3%	depends on λ
Total ozone Ω	2% rms	1–3% (10–15%)	310 nm (295 nm)
Ozone profile Ω			
stratosphere	0.25 × (low-high)[b]	1% (−1–10%)	$\theta < 50°$ ($\theta > 60°$)
troposphere	5 DU rms	0.5% (2%)	310 nm (300 nm)
Surface reflectivity R_s			
bare ground	1% rms	0.4%	320 nm
fresh snow	5% rms	3%	320 nm
Absorbing aerosols	systematic[c]	8% ± 2 systematic[c]	if neglected
Ground haze		3% ± 1 systematic[d]	
Total (310 nm, $\theta < 60°$)		11% ± 5[e]	snow free

Source: *Krotkov et al.* [1998] and *Herman et al.* [1999].
[a]Values in parentheses relate to the corresponding conditions shown in parentheses.
[b]Percent change in irradiance when the 325 DU high-latitude TOMS ozone profile replaces the 325 DU low-latitude ozone profile, dropping the ozone maximum by about 10 km. In practice, the ozone profile variability is about one fourth of this amount.
[c]TOMS will overestimate ground irradiance if aerosol absorption is not detected.
[d]Included in the TOMS-measured scene reflectivity.
[e]Systematic ± rms; $x_i = \{3, 3, 1, 0.5, 0.4, 2, 1\}$, $(\Sigma x_i^2)^{0.5} = 5$ (rms).

estimated noontime irradiances were compared to irradiances for two wavelengths 305 ± 0.5 nm and 324.5 ± 0.5 nm by using 4 years of Brewer spectroradiometric data from Toronto. They found out that the weekly averaged TOMS irradiances are systematically about 20% higher than the ground-based measurements during the summer months. In spring and autumn the agreement appears to be better. During the winter months the TOMS snow/ice causes an error opposite in sign from the error observed during the summer months. Part of the disagreement between the TOMS UV data and the Toronto Brewer data during summer months was explained by the increased presence of aerosols over Toronto, which are not seen by TOMS [*Krotkov et al.*, 1998; *Herman et al.*, 1999], and the Brewer cosine correction bias. The average degree of cloudiness is substantially less in summer than in the winter months making the effect of aerosols more important.

5. Conclusions and Future Work

During recent years, spaceborne techniques for estimating the UV radiation reaching the Earth's surface have been developed, which use measured values of extraterrestrial solar irradiance, ozone, aerosols, cloud and ground reflectivity, and radiative transfer calculations. This technique has been extensively applied to the TOMS-measured radiances by NASA (the Goddard Space Flight Center) to obtain the global distribution of UV irradiance on a daily basis since 1979.

In this work a comparison was carried out between the Nimbus-7/TOMS UV estimates and the ground-based UV measurements from three NSF instruments. The ground-based data were obtained from double monochromator spectroradiometers, SUV-100, at Ushuaia (Argentina), Palmer (Antarctica), and San Diego (California). For these instruments the lack of reliable, long-term ground-based observations limits the comparison to relatively short periods: from April 16, 1991 to May 6, 1993, for Ushuaia; from August 26, 1991 to May 6, 1993, for Palmer; and from October 31, 1992 to May 6, 1993, for San Diego.

The day-to-day variation of the UV doses (daily integrals) of both the ground-based and the TOMS-estimated data sets is similar. The correlation coefficients between the TOMS-estimated and the ground-based UV data are high for Ushuaia (0.94) and for San Diego (0.97) but lower (0.80) for Palmer. On average (1 day to monthly average daily doses), the TOMS UV algorithm seems to underestimate the daily UV doses at Ushuaia (mean difference −13%) and at Palmer (−35%) but overestimates at San Diego (25%), as compared with the ground-based measurements. For Palmer and Ushuaia the TOMS UV estimates are in better agreement with the ground-based observations in summer than in winter, because of the winter presence of snow/ice that is not properly accounted for in the TOMS UV-irradiance algorithm. When the reflectivity is low (no snow), the TOMS irradiance estimate is higher than those measured at all three sites by the SUV-100. This is consistent with the previously analyzed Brewer 14 data from Toronto.

For ground-based instruments located in mountainous regions (Ushuaia) or in coastal areas (Palmer and San Diego), the large TOMS FOV can lead to additional disagreements between the satellite estimates and the ground-based measurements. The comparison using daily doses (integral from sunrise to sunset) can also have a large variability relative to the satellite estimate caused by the once a day satellite sampling error. This is because TOMS samples the average cloud field over a 100 × 100 km^2 box only once per day (near noon) at each location. Averaging over extended time periods (from 1 week to 1 month) reduces the variance of the difference between TOMS and the SUV-100.

In addition to the uncertainties in the TOMS estimated UV dose (e.g., hourly cloud variability, undetected absorbing aerosols, and the presence of snow/ice), the ground-based SUV-100 instrument data have an error arising from the deviation of the diffuser from a pure cosine response as well as instrument-to-instrument calibration differences.

In the future the irradiances measured closest to the TOMS overpass time will be compared with the satellite-estimated values (instead of daily doses). To the extent possible, local conditions for aerosols and surface reflectivity will be incorporated into the comparison. The SUV-100 instrument uncer-

tainties will be reduced by properly accounting for the cosine response as a function of solar zenith angle and wavelength, and the proper slit function will be used in place of a simple triangle function.

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