JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D20, PAGES 24,051–24,062, OCTOBER 27, 2001

Satellite retrievals of erythemal UV dose compared with ground-based measurements at northern and southern midlatitudes

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Abstract. In recent years, estimates of UV radiation at the Earth's surface have been obtained from satellite retrievals. These retrievals have been compared with ground-based measurements at a few sites, but so far there have been few comparisons from unpolluted sites. This study compares differences between satellite-derived estimates of UV and ground-based measurements at a clean air site in the Southern Hemisphere with those from more polluted sites in the Northern Hemisphere, to investigate the extent to which boundary layer extinctions are taken into account by frequently used satellite retrievals. It is found that the hemispheric differences inferred from the ground-based measurements are much larger than those derived from the satellite retrievals. Since international intercomparison campaigns have shown the ground-based spectroradiometers to be in agreement, it is concluded that differences in tropospheric extinctions (e.g., by ozone and aerosols) are not adequately taken into account in the satellite retrievals of UV radiation examined so far.

1. Introduction

Estimates of surface UV radiation based on Total Ozone Mapping Spectrometer (TOMS) satellite data have been used extensively in the last decade to establish global climatologies of UV radiation and to examine possible trends due to stratospheric ozone depletion. While the retrieval algorithms are rather simple, they do address the main factors responsible for UV variability: solar zenith angle (SZA), clouds, aerosols, surface albedo, and ozone. The satellite-derived UV has been compared with ground-based measurements from Toronto, and was found to be approximately 20% greater than the observed values [*Herman et al.*, 1999a].

Several groups are now using satellite products to derive surface UV. Some use cloud reflectivities from TOMS, others use cloud retrievals from different satellite instruments (e.g., Earth Radiation Budget Experiment (ERBE)) [*Lubin et al.*, 1998], while others derive cloud extinctions from precipitable water [*Verdebout*, 2000] in addition. For high spatial resolution of the cloud field advanced very high resolution radiometer (AVHRR) data were used in addition to ozone values from the Global Ozone Monitoring Experiment (GOME) [*Meerkoetter et al.*, 1997]. *Zerefos et al.* [2001] used satellite overpasses at Thessaloniki and San Diego to identify the signal of quasi-biennial oscillation (QBO) on UV-B irradiances. An algorithm to retrieve instantaneous UV irradiances [*Li et al.*, 2000] has been validated against data from several sites in Canada [*Wang et al.*, 2000]. The agreement between retrievals from the TOMS METEOR 3 instrument and ground-based measurements over the period 1992 to 1994 is encouraging. As with the TOMS retrievals [*Herman et al.*, 1999a], there is a tendency for the satellite-derived values to be greater than the measured values. Because the orbit of the METEOR 3 satellite is not Sun synchronous with noon overpasses, the maximum erythemally weighted irradiances tested are only up to relatively low values ~0.19 W m^{-2} (UV index = 6.8). In some cases the satellite-derived retrievals of UV have been made accessible to the community through the Internet.

Under conditions where the surface albedo is large, there can be difficulties in separating cloud reflectivity from surface reflectivity [*Wang et al.*, 2000]. In that case even the sign of the correction based on reflectivity would be incorrect. Quantification of this effect has been attempted by comparing satellite retrievals with ground-based measurements from three National Science Foundation instruments maintained by Biospherical Instruments at San Diego, Ushuaia, and Palmer Station [*Kalliskota et al.*, 2000]. It was found that the satellite-derived daily erythemal UV doses at San Diego were typically 25% more than the measurements. At the other sites the satellite retrievals were often lower when the surface was snow covered. During periods with no snow cover, the retrievals at the Southern Hemisphere sites showed good agreement with measurements. However, the sites were widely different in latitude, so that a SZA dependence in the satellite retrievals could mask or amplify differences.

A weakness of all satellite retrievals is that the backscattered radiation reflected back to the instrument does not penetrate fully to the surface, so assumptions must be made about aerosol and ozone extinctions in the atmospheric boundary layer. In densely populated or industrialized regions, these aerosol extinctions can be large [*Gonzales et al.*, 2000] and reduce UV appreciably [*Verdebout*, 2000; *Kylling et al.*, 1998]. One purpose of the present study is to determine the extent to which differences in tropospheric

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Paper number 2001JD000545.
0148-0227/01/2001JD000545$09.00

Table 1. Details of Measurement Sites

Site and Country	Latitude, °N	Longitude, °E	Altitude, m	Pressure, hPa	Correction (SUSPEN)[a]	Laboratory[b]	Start Date
Toronto, Canada	43.78	-79.47	198	995	1.03	MSC	March 1, 1989
Thessaloniki, Greece	40.52	22.97	50	1013	1.01	LAP	Jan 26, 1991
Garmisch- Partenkirchen, Germany	47.48	11.07	730	930	0.99	IFU	April 30, 1992
Lauder, New Zealand	-45.04	169.68	370	970	1.00	NIWA	Jan 11, 1990

[a] Factors required to bring all measurements to a common scale, based on results from the SUSPEN campaign.

[b] Abbreviations are as follows: MSC denotes Meteorological Service of Canada, LAP denotes Laboratory for Atmospheric Physics, IFU denotes Fraunhofer Institute for Environmental Research, and NIWA denotes National Institute of Water and Atmospheric Research

aerosols can affect the accuracy of the retrievals at midlatitude sites. This is achieved by comparing erythemal UV measured at a pristine Southern Hemisphere site, Lauder, New Zealand, with more polluted Northern Hemisphere sites (Toronto, Canada; Garmisch-Partenkirchen, Germany; and Thessaloniki, Greece). The 1 μm aerosol optical depth at Lauder, New Zealand, is typically 0.02, whereas in unpolluted regions of the Northern Hemisphere, corresponding values of around 0.1 to 0.2 are typically assumed. Other indicators of atmospheric pollution, such as black carbon and SO_2, also differ by a factor of 20 between New Zealand and populated regions of the Northern Hemisphere due to differences in anthropogenic contributions [*Cooke and Wilson*, 1996; *Schult et al.*, 1997; *Charlson et al.*, 1991; *Langner and Rodhe*, 1991]. Model calculations show that these differences can have a large effect on UV irradiance [*Erlick and Frederick*, 1998a, 1998b]. Observational studies comparing UV between Lauder, New Zealand, and Garmisch-Partenkirchen have also demonstrated that tropospheric extinctions are an important contributor to the observed differences [*McKenzie et al.*, 1993; *Seckmeyer and McKenzie*, 1992].

Differences in surrounding topography can also have an influence on the satellite retrievals because they represent averages over areas of ~30 km x 30 km or more. This is a particular issue with data from Garmisch-Partenkirchen, which is surrounded by high mountains. The Lauder site is also affected in this way, but to a lesser extent.

2. Ground-Based Measurements

Spectral measurements over decadal time spans are now available with well-calibrated UV spectroradiometers from several sites (e.g., see Table 1). Data from the groups responsible for data at the sites in Table 1 have been intercompared through various international efforts to standardize ultraviolet spectroradiometry [e.g., *McKenzie et al.*, 1993; *Seckmeyer et al.*, 1994; *Bais et al.*, 2001]. Especially in the latter [*Bais et al.*, 2001] (the Standardization of Ultraviolet Spectroradiometry in Preparation of a European Network (SUSPEN) intercomparison campaign in Greece in July 1997) they have been found to agree to within 2-3% for some instruments when corrections are applied to account for errors in the cosine response of those instruments [*Gardiner and Kirsch*, 1998; *Bais et al.*, 2001]. Measurements taken over longer periods may, of course, be subject to larger uncertainties than in an intercomparison campaign [*Bernhard and Seckmeyer,* 1999]. Nevertheless, all data from the contributing groups were normalized to a common scale using the correction factors derived from this intercomparison campaign [*Bais et al.*, 2001] and were provided in the form of daily doses of erythemally weighted UV irradiances [*McKinlay and Diffey*, 1987]. Measurements from the Brewer instruments (Greece and Canada) included small corrections based on extrapolation algorithms that had been tested against other instruments to allow for the relatively small contribution to erythemal UV from wavelengths longer than the sampled region. In the early period of overlap with Nimbus 7 TOMS, data from Greece and Canada were from single monochromators rather than double monochromators. Double monochromators were used for all measurements at Lauder and Garmisch-Partenkirchen.

Errors in daily doses can arise from insufficient sampling from the ground-based instruments. At Lauder there are typically only 30 scans per day in summer and fewer in winter (one scan every 5° of SZA, plus four to six scans over the midday period). The relatively small number of scans means that if there are large temporal differences in cloud cover, their effects may not always be captured in the daily integrals derived from these measurements. A similar sampling strategy is used at Thessaloniki for the period after 1993, while in the beginning of the record (1991) fewer scans were acquired during each day. Where spectroradiometer data were missing, data from a broadband erythemal UV sensor were used as a proxy. At Toronto, about one or two measurements were made each hour during the early part of the record [*Kerr and McElroy*, 1993], increasing to about double the frequency for the later part of the record [*McArthur et al.*, 1999]. At Garmisch-Partenkirchen the sampling is more complete, with scans being repeated continuously at intervals of approximately 8 min.

In a previous study, daily integrals were accepted for Lauder data whenever there were 10 or more scans per day [*McKenzie et al.*, 2000]. However, the comparison with satellite data revealed occasional outlier data points. While these outliers did not influence the conclusions, the correlations can be improved by constraining the acceptance criteria more tightly. Here, we require that there are at least five scans in the morning and five in the afternoon, but with extra conditions to ensure data were sampled close to the midday period which dominates the UV dose. We achieved this by requiring at least one scan within 1° of the minimum SZA, three within 5°, and five within 15°. For the Nimbus 7 TOMS period this procedure resulted in less than 50% of the data being retained. However, for the Earth Probe TOMS period when the instrument automation was improved, data losses were less than 5%. A similar screening of data was also performed for the Toronto measurements, although with the more complex integration scheme used for this data set, the changed criteria had very little effect. There was no need for

Table 2. Details of Satellite-Derived UV Estimates[a]

TOMS Satellite	Start Date	End Date	Footprint Minimum to Maximum Dimensions, km E-W x km N-S
Nimbus 7	day 305, 1978	day126,1993	(50 x 50) to (150 x 100)
Earth Probe	day 198, 1996	day 50, 2000	(26 x 26) to (60 x 33) to Dec, 1997 (38 x 38) to (99 x 52) from Dec, 1997

[a] Between December 5 and 12, 1997, the orbital altitude of the Earth Probe satellite was boosted from ~500 km to 740 km.

any further screening of data from Thessaloniki or Garmisch-Partenkirchen. Apart from occasional short gaps, daily doses of erythemal UV were available continuously at all four ground sites from the start dates listed in Table 1.

3. Satellite Data

Satellite overpass data were made available from the TOMS instruments on Nimbus 7 (N7) and from Earth Probe (EP) satellites by Jay Herman of NASA Goddard. The periods analyzed and satellite footprint dimensions are listed in Table 2.

The satellite overpass data include the following variables: modified Julian day, four-digit year number (yyyy), day number (doy), UT seconds from midnight, scan position, field-of-view (fov) latitude, fov longitude, distance from fov center to site, terrain pressure at fov center, solar zenith angle, total ozone, reflectivity at 380 nm, aerosol index, sulfur oxide index, diurnal erythemal exposure, irradiance clear overpass, irradiance cloudy overpass, irradiance clear noon, irradiance cloudy noon. Although TOMS ozone data were available for much of the period between the N7 and EP satellites, it is less suitable for UV retrievals because the orbit of the satellite (METEOR 3) was not Sun-synchronous so that in general there was no overpass close to local solar noon.

Details of the retrieval algorithm are given elsewhere [*Herman et al.*, 1999a]. The treatment of cloud effects is quite simple. The reflectivity at 380 nm (R_{380}) is used to deduce an effective cloud transmission factor (CT_E)

$$CT_E = 1 - (R_{380} - R_G) / (1 - 2 R_G), \qquad (1)$$

where R_G represents the reflectivity derived from a climatology and is usually in the range 2-4% [*Herman et al.*, 1999a]. The computed clear-sky UV irradiance is multiplied by this factor to estimate the cloud-modulated UV irradiance.

At any instant throughout the day it is unlikely that the cloud fraction above any given measurement site will match the area-averaged cloud fraction derived from satellite data. However, there is a higher probability that the mean cloud over any site cover over the course of a day will match the satellite-derived estimate. This will not always be the case: for example, if there are orographically induced cloud patterns. Nevertheless, for the purposes of intercomparing satellite and ground-based data, it is most useful to consider derived daily doses rather than instantaneous irradiances. Cloud effects that occur over the midday period when UV irradiances are high will be of prime importance. Thus there is a need for good collocation of satellite and ground-based data.

It has been shown previously that while one satellite overpass per day is not sufficient to reliably derive a daily dose, it can provide useful data for statistical comparisons. The uncertainty of the monthly mean was less than 5% if only one midday value of cloud transmission is available instead of its full diurnal variation [*Martin et. al.*, 2000].

The collocated satellite overpass data were merged with cross-calibrated ground-based data from the four sites. The criteria for acceptance of satellite data could be varied. Initially, for the comparison of time series (Figures 1 through 9), we used the following acceptance criteria: (1) the center of satellite observation footprint is within 50 km of the observation site; (2) all cloud reflectances are accepted (0 to 100%); (3) data from all surrounding quadrants are accepted; (4) all satellite SZAs are accepted (0° < SZA < 90°); and (5) data from both N7 and EP TOMS periods are included. In subsequent sections dealing with detailed statistical studies,

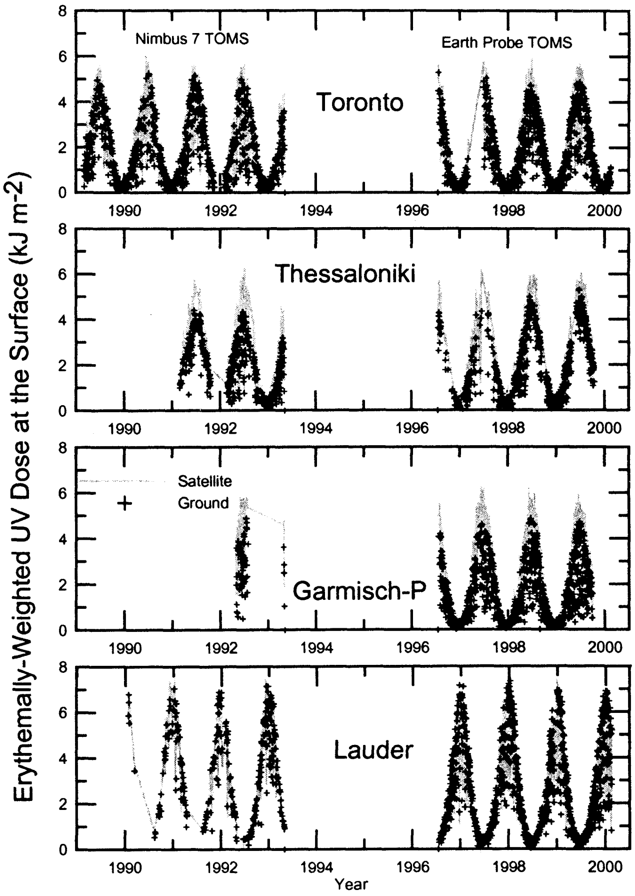

Figure 1. Time series showing a comparison between erythemally weighted UV daily dose measured from the ground and derived from satellite within 50 km of the four sites. Data points represent the ground-based measurements and the shaded region shows the range of corresponding satellite-derived overpass measurements.

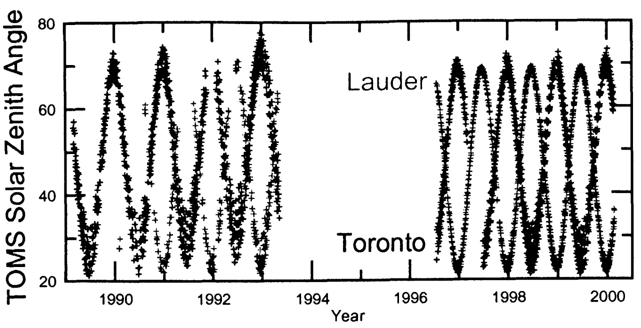

Figure 2. Time series of solar zenith angle (SZA) of daily satellite overpass data for Lauder and Toronto.

we investigate the sensitivity to changing these acceptance criteria.

4. Comparisons With Time Series of Daily Overpass Data

Figure 1 shows the daily doses of erythemally weighted UV from ground-based measurements for which the acceptance criteria with available satellite data were met. During the period between 1993 and 1996, no satellite data were made available. Doses are greatest at Lauder. As will be shown, while there is good agreement between satellite-derived UV dose and measured UV dose at Lauder, the satellite-derived doses are significantly greater than the ground-based measurements at the Northern Hemisphere sites.

Figure 2 shows the SZA for the satellite measurements at Lauder and Toronto. The satellite overpasses are Sun-synchronous and close to local solar noon, although there is less day-to-day variability in SZA for Lauder than at the Northern Hemisphere sites. The range of SZA is similar at all sites because all are at similar latitudes. Since the sites are all at midlatitudes, a threshold SZA = 45° can be used to separate the data between "summer" and "winter" periods.

Figure 3 shows the satellite-derived ozone measurements at each site. Ozone values for all three Northern Hemisphere sites are similar, but in Lauder the ozone amounts are significantly lower. It should be noted that there are systematic differences in ground-measured ozone from satellite-measured ozone, with satellite-measured ozone being significantly larger, especially in the Southern Hemisphere. In New Zealand the TOMS instruments tend to read about 10 Dobson units (DU) high in the summer months. Differences are slightly smaller at northern midlatitudes. These differences are examined in more detail by *Bodeker et al.* [2001].

The satellite-measured reflectivity (Figure 4) shows significant differences in the apparent cloud distributions between the sites. Thessaloniki appears to have the greatest proportion of days with low cloud reflectivity. At the other end of the scale, Garmisch-Partenkirchen seems to have few days with low cloud reflectivity in spring and summer. Although cloudless days at this site are more common in the winter, the satellite-derived reflectivities are maximum in this

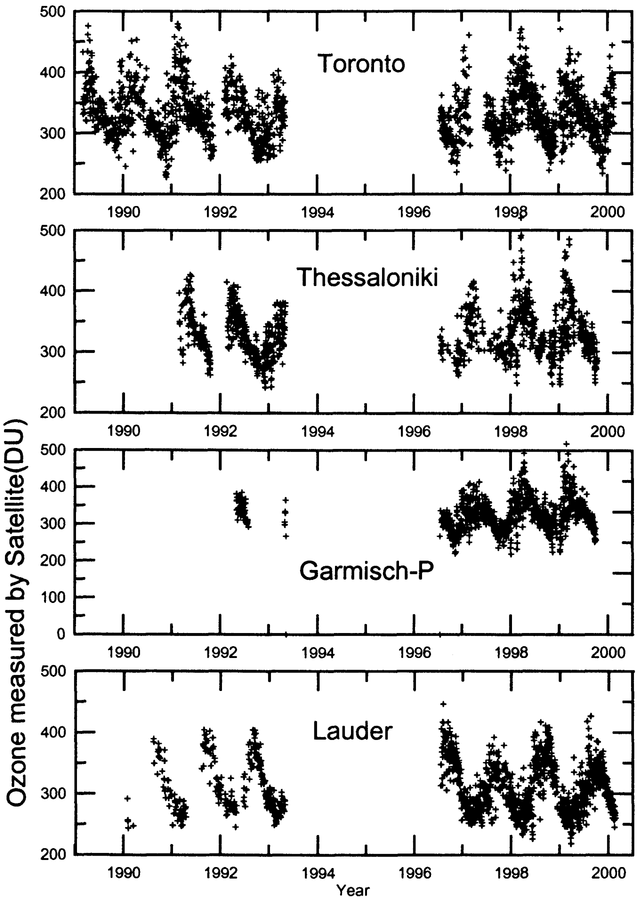

Figure 3. Time series of satellite-measured ozone for the overpass data shown in Figure 1.

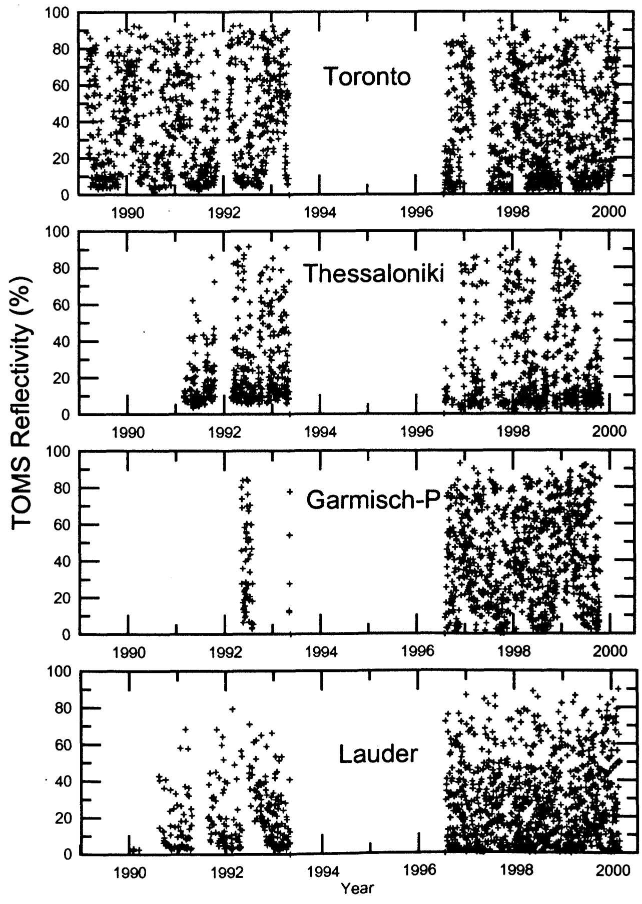

Figure 4. Time series of satellite reflectivity of the overpass data shown in Figure 1.

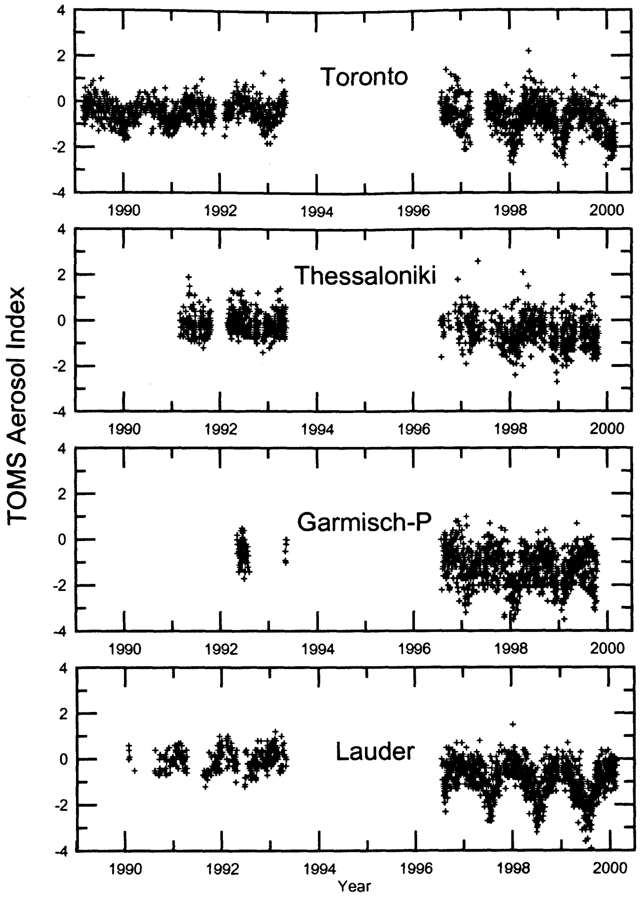

Figure 5. Time series of satellite aerosol index from the overpass data shown in Figure 1.

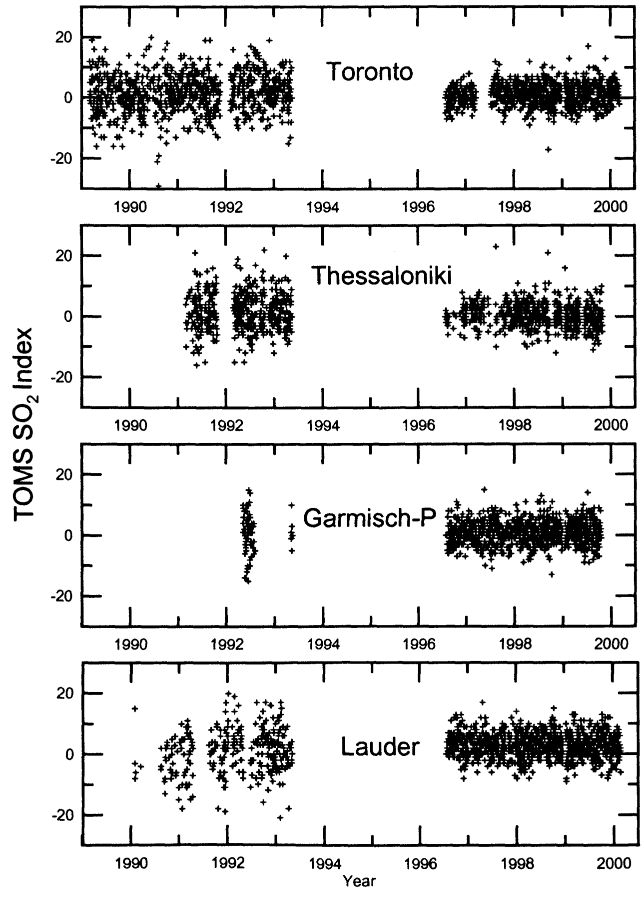

Figure 6. Time series of satellite SO_2 index from the overpass data shown in Figure 1.

period, showing that at this site, at least, reflection from snow-covered terrain may provide a lower limit to these reflectivities. The minimum reflectivity is increased by smaller amounts during winter at the other sites.

Surprisingly, there are no significant differences in the satellite-derived aerosol index and SO_2 index parameters, even before and after the Pinatubo eruption in June 1991 (Figures 5 and 6). This suggests a low sensitivity to these parameters. In the case of the aerosol index, there is a clear summer maximum at all four sites, and there is a tendency toward lower values and larger annual variation in more recent years. The only noteworthy feature of the SO_2 index data is that there is a greater variability in the N7 period. These parameters relevant to tropospheric extinctions (sulfur dioxide index, aerosol index) are not significantly different between the pristine site (Lauder) and more polluted sites.

Figures 7 and 8 show detailed day-to-day variations over shorter periods during the summer and winter months. In the winter months (Figure 8), the maximum doses are typically only 10% of those in the summer. For the most part, the satellite product shows a remarkable ability to model the effects of cloud changes on daily-integrated UV dose from a single observation per day. Seasonal differences are apparent at Toronto and Garmisch-Partenkirchen. In Toronto the agreement is better in summer, whereas in Garmisch-Partenkirchen the agreement is better in winter. These sites both experience snow during the winter, and it is possible that reflections from snow-covered terrain are being interpreted as

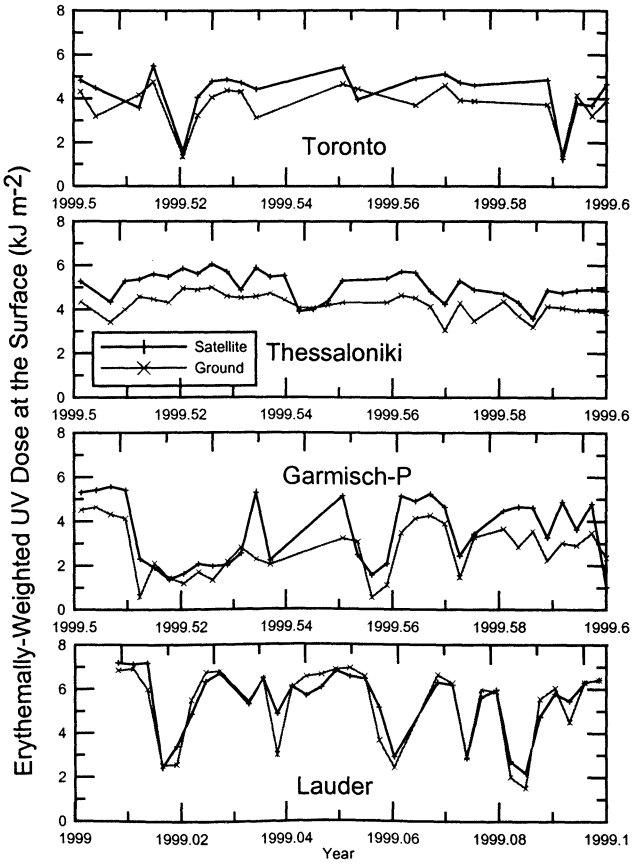

Figure 7. Time series showing a day-by-day comparison between erythemally weighted UV daily dose measured from the ground and derived from satellite within 50 km of the four sites over a short summer period. Dates shown include the fraction of the year completed.

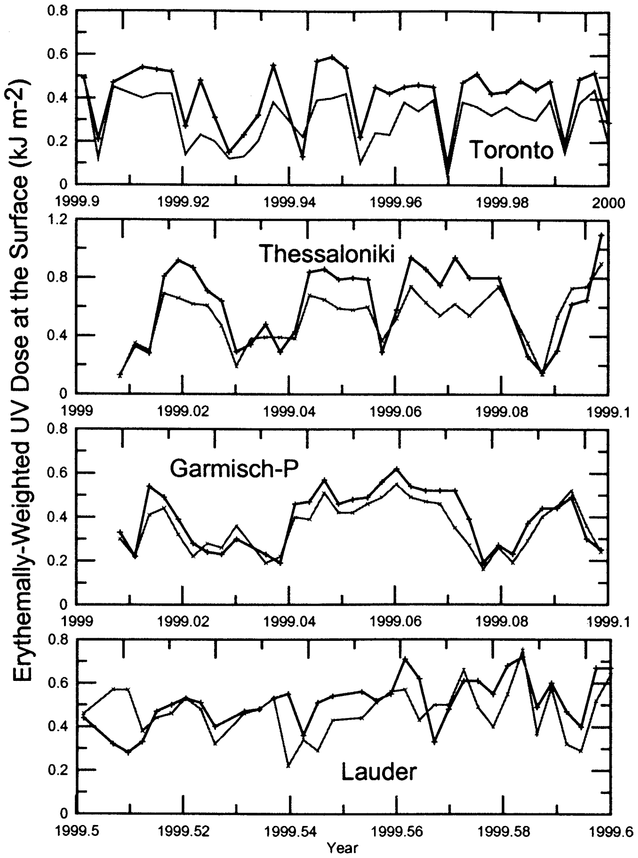

Figure 8. Time series showing a day-by-day comparison between erythemally weighted UV daily dose measured from the ground and derived from satellite within 50 km of the four sites over a short winter period.

cloud effects in the satellite retrievals. Clouds have the effect of reducing UV, whereas snow-covered surfaces have the effect of increasing UV. This is consistent with the seasonality seen at Toronto, but is inconsistent with that seen at Garmisch-Partenkirchen. At Garmisch-Partenkirchen, other factors that may influence the results are: (1) more tropospheric ozone in summer, or (2) more boundary layer aerosols in summer. The former is further supported by the fact that the effect of tropospheric ozone on UV irradiance is nonlinear in the presence of clouds [*Mayer et al.,* 1998].

5. Monthly Means

Monthly means of collocated data were formed, using a selection criterion that monthly means are valid only if daily doses from more than 10 days per month were available. Again it should be noted that because of differences in sampling, these plots should not be used for trend analysis. Figure 9 shows monthly mean ratios of satellite-derived UV to ground-based values. Note the large seasonal swing at Garmisch-Partenkirchen, which is probably due to seasonal changes in snow cover.

At Thessaloniki, the discrepancy between satellite and ground-based data was larger for the N7 period. These larger differences may indicate a calibration issue since the ground-based measurements were made with a single Brewer only in that period, or they may result from the more polluted troposphere during that period, as has been discussed previously [*Zerefos et al.,* 1997; *Herman et al.,* 1999b]. However, the characteristics of the differences between ground-based measurements and satellite estimates at the other three sites are generally constant over the time period, indicating reasonable long-term stability in calibration.

6. Statistical Analyses

Figure 10 shows scatterplots for the N7 TOMS period of satellite-derived daily erythemal UV dose versus measured values for the four sites (left panels). Statistics for the regression lines are shown in Table 3a.

For this period the number of collocated data points is rather small, especially for Garmisch-Partenkirchen. At Toronto the satellite-derived UV is about 15% more than that measured at the ground. At Thessaloniki the discrepancy is more than 30%. At Lauder the two are in good agreement.

In the intervening period between the N7 and EP TOMS satellites there were significant improvements in data quality and data frequency from ground-based measurements of UV irradiance doses at the sites under study. Consequently, we restricted the detailed statistical analysis to the EP TOMS period only. Scatterplots for this restricted data set are shown in the right panels of Figure 10. They show the same general patterns as for the N7 period, but the scatter is improved significantly. Statistics of the regression lines are shown in Table 3b. As in the N7 comparison, there is good agreement at Lauder, but overestimations by the satellite at the more

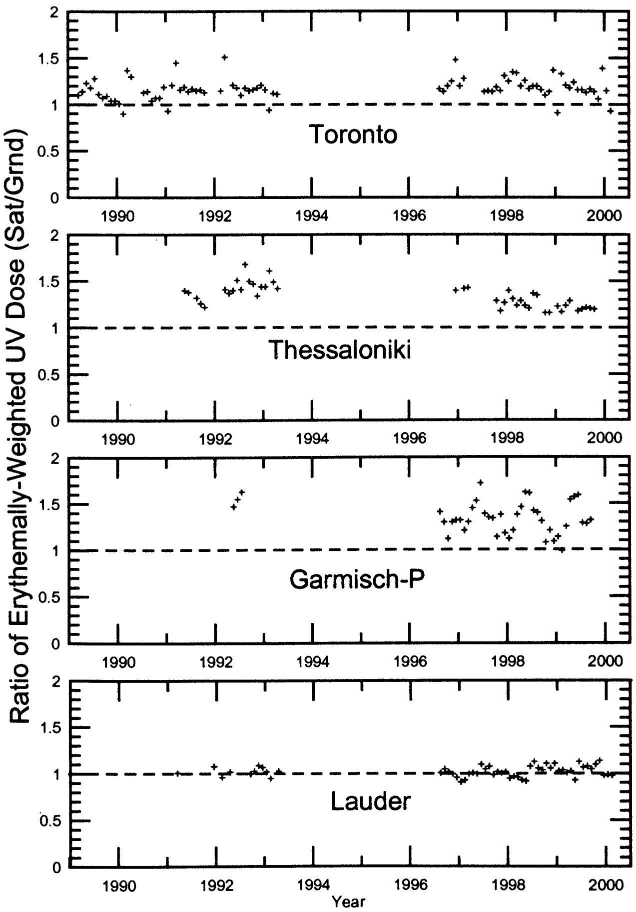

Figure 9. Time series of monthly means of the ratio of satellite-derived to ground-measured erythemally weighted UV daily dose.

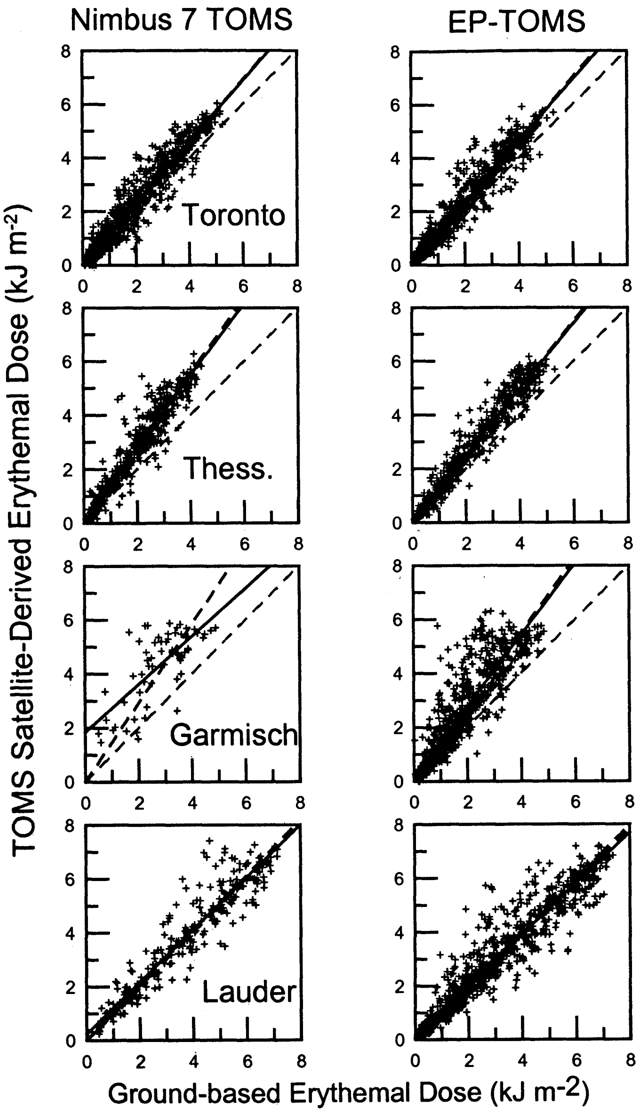

Figure 10. Scatterplot of satellite-derived versus ground-measured erythemally weighted UV daily dose at four sites. The panels on the left are for the Nimbus 7 Total Ozone mapping Spectrometer (TOMS) overlap period, and the panels on the right are for the Earth Probe (EP)TOMS overlap period. The solid line is the least squares linear regression line, and the dashed line is the linear regression line constrained to pass though the origin. The lighter diagonal dashed line is the ideal regression of unit slope.

Table 3a. Regression Statistics for the Nimbus 7 TOMS ($r < 50$ km) Overpass Data[a]

Site	N	R^2	Gradient	y Intercept
Toronto	886	0.929 (0.973)	1.14 (1.15)	0.033
Thessaloniki	456	0.906 (0.976)	1.32 (1.39)	0.177
Garmisch-Partenkirchen	65	0.511 (0.942)	0.89 (1.46)	1.837
Lauder	288	0.903 (0.977)	0.97 (1.02)	0.239

[a] Numbers in parentheses are statistics for the regression lines constrained to pass though the origin.

Table 3b. Regression Statistics for the Earth Probe TOMS Period ($r < 50$ km) Overpass Data[a]

Site	N	R^2	Gradient	y Intercept
Toronto	940	0.941 (0.977)	1.142 (1.167)	0.071
Thessaloniki	661	0.957 (0.985)	1.220 (1.249)	0.087
Garmisch-Partenkirchen	936	0.838 (0.938)	1.317 (1.377)	0.146
Lauder	1082	0.927 (0.971)	0.941 (0.982)	0.68

[a] Numbers in parentheses are statistics for the regression lines constrained to pass though the origin

polluted sites. At Thessaloniki the differences are smaller in the EP TOMS period, as noted earlier.

Despite the similarity in latitude, the measured UV doses for Lauder are much greater than at the other three sites. Again the systematic differences noted previously can be seen. Differences between satellite-derived UV and measured UV can be large. The spread of deviations is noticeably smaller for Thessaloniki. It appears that day-to-day cloud effects may be smaller here and that the agreement between satellite estimates and ground-based measurements is

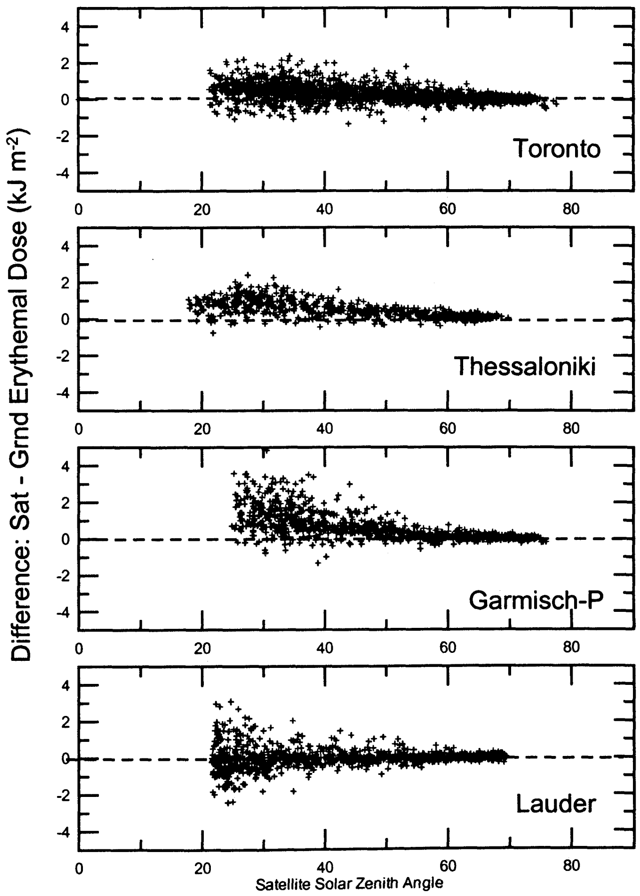

Figure 11. Scatterplot of differences between satellite-derived and ground-based measurements of erythemally weighted UV daily dose as a function of satellite solar zenith angle at the time of the overpass measurement (EP TOMS).

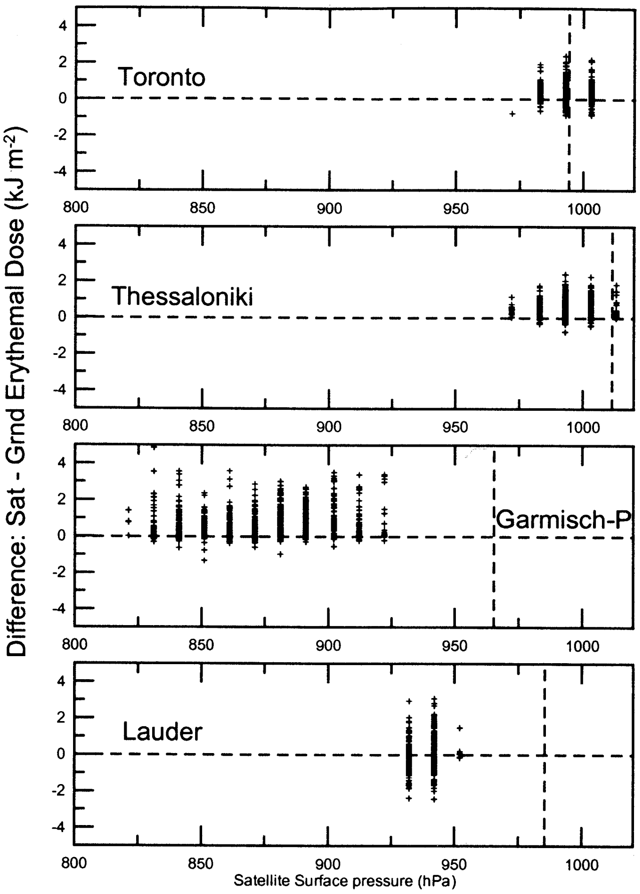

Figure 12. Scatterplot of differences between satellite-derived and ground-based measurements of erythemally weighted UV daily dose as a function of satellite surface pressure at the center of the field of view at the time of the overpass measurement (EP TOMS). The dashed vertical lines show the mean surface pressure measured at each site.

improved under these clearer sky conditions. Snow effects are also likely to be smaller at this site. The largest discrepancies occur at Garmisch-Partenkirchen.

Statistics of the regression of EP TOMS satellite derivation as a function of ground-based measurements based on these scatterplots are shown in Table 3b. The numbers in parentheses are statistics for the regression lines constrained to pass through the origin. Generally, the regression statistics are similar, but the latter are more appropriate since measurement uncertainties (from both sources) are generally larger in winter when irradiances are small and when snow cover is more likely.

The Lauder and Garmisch-Partenkirchen sites appear to show greater variability from day to day, which is not always captured by the satellite data. This may be because of peculiarities of the measurement site. For example, Lauder is located in a valley with very low rainfall, but with regions of much heavier rainfall surrounding the site (especially to the west). Similarly, there is much higher precipitation in the mountainous surroundings of the Garmisch site. While at some sites the fractional cloud cover in a single daily satellite image may be an accurate representation of the average cloud cover over a particular site within the scene, this is not the case for these sites [*Uddstrom et al.*, 2000].

Winter measurements are associated with larger SZA, so we plotted differences in UV between satellite and ground-based measurement as a function of SZA, to see the extent to which snow may affect the correlations (Figure 11). Largest differences occur in the summer when absolute amounts are a factor of 10 greater. When ratios rather than differences are plotted (not shown) this SZA dependence is reversed, with larger deviations in ratios at large SZA in winter when snow cover is present at some sites. At Lauder the differences show little systematic dependence on SZA. However, at the other sites there is a tendency for larger differences at the smaller SZA, especially for Garmisch-Partenkirchen.

Table 4. Effect on Statistics of Changing the Coincidence Criteria for Earth Probe TOMS Data[a]

Subset of Overpass Data	Number of Days	Correlation Coefficient (R^2)	Regression Gradient
	Toronto		
All	1030	0.976	1.169
100 km	972	0.976	1.170
50 km	940	0.977	1.170
10 km	83	0.973	1.201
50 km, *z*>45	529	0.964	1.158
50 km, *r*<20	372	0.988	1.190
50 km, *z*<45	411	0.978	1.169
50 km, *z*<45, *r*<20	236	0.988	1.192
50 km, *z*>45, *r*<20	136	0.991	1.172
	Thessaloniki		
All	738	0.984	1.248
100 km	686	0.985	1.246
50 km	661	0.985	1.249
10 km	67	0.984	1.277
50 km, *z*>45	319	0.980	1.259
50 km, *r*<20	408	0.990	1.263
50 km, *z*<45	343	0.986	1.248
50 km, *z*<45, *r*<20	248	0.990	1.261
50 km, *z*>45, *r*<20	160	0.992	1.289
	Garmisch-Partenkirchen		
All	1013	0.936	1.376
100 km	967	0.937	1.376
50 km	936	0.938	1.377
10 km	106	0.952	1.342
50 km, *z*>45	511	0.956	1.259
50 km, *r*<20	231	0.985	1.278
50 km, *z*<45	426	0.985	1.396
50 km, *z*<45, *r*<20	139	0.985	1.282
50 km, *z*>45, *r*<20	92	0.985	1.251
	Lauder		
All	1167	0.967	0.974
100 km	1112	0.970	0.981
50 km	1082	0.971	0.982
10 km	107	0.982	0.970
50 km, *z*>45	535	0.970	1.004
50 km, *r*<20	515	0.990	0.991
50 km, *z*<45	547	0.971	0.981
50 km, z<45, *r*<20	267	0.990	0.991
50 km, *z*>45, *r*<20	248	0.990	0.995

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[a] The criterion *z*>45 corresponds to data selected at SZA > 45°, corresponding to winter data, whereas *z*<45 corresponds to summer data (see Figure 2). The criterion *r*<20 corresponds to selecting only data with reflectivity less than 20% to avoid complications of overcast conditions or snow-covered terrain.

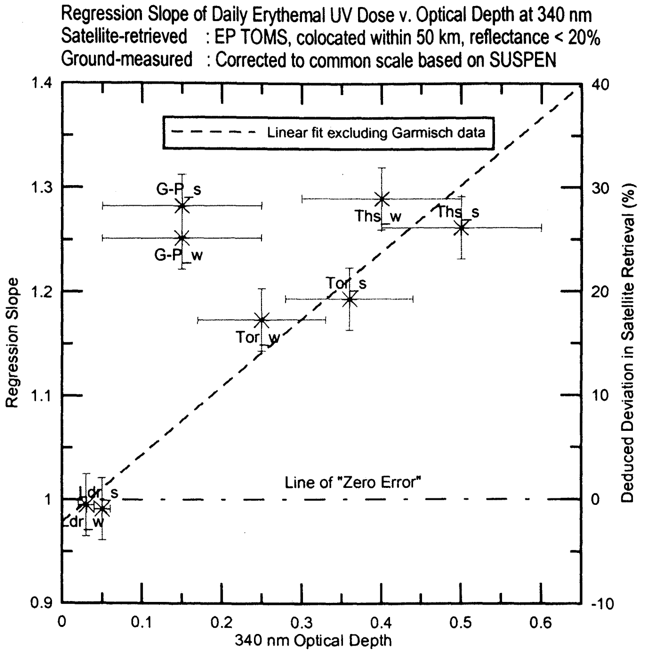

Figure 13. Regression slope of satellite-derived UV versus ground-measured UV as a function of the estimated aerosol optical depth at 340 nm. Percentage deviations in satellite retrieval from ground-based measurements are also shown on the right axis. Data points are labeled by site and season. For example "Ths_w" and "Ths_s" are Thessaloniki winter and summer, respectively.

We investigated the sensitivity of the regression statistics as functions of the parameters available in the TOMS overpass data. Generally, the sensitivities were small. However, the scatter of error between satellite-derived and ground-measured UV did show a possible dependence on satellite footprint pressure, as shown in Figure 12. Systematic differences due to differences in station altitude are apparent, and differences in the variability also occur. At Garmisch-Partenkirchen there is a wide range of pressure differences, and the mean surface pressure is approximately 60 hPa less than at the observatory mean pressure of 930 hPa. This corresponds to an altitude discrepancy of ~300 m, which could be responsible for systematic differences in UV of a few percent, since altitude sensitivities of ~20% per kilometer have been reported [*Blumthaler et al.*, 1997; *Seckmeyer et al.*, 1997]. However it has been shown that the dependence on altitude can not be described by a single number, but is a function of season, albedo, and air pollution [*Seckmeyer et al.*, 1997]. Smaller differences in pressure are also observed at Lauder, but since aerosol extinctions are small at this site, we can be more confident that the altitude difference does not lead to a significant error. At Toronto and Thessaloniki the pressure differences are small. At all sites the pressure differences show little sensitivity to these selection criteria. Topographical effects will be discussed in further detail later.

7. Constraining Acceptance Criteria

In the complete set of the overpass data supplied, the maximum separations sometimes exceed 300 km, and all cloud conditions corresponding to reflectivities from 0 to 100% and all satellite solar zenith angles are included. The effects of constraining the domain of satellite measurements were investigated. Using more stringent acceptance limits reduced the number of days included, but in most cases had little effect on the conclusions, as shown by Table 4.

As the selection criteria are tightened, the number of points included decreases, as expected, and correlation coefficients increase. While at most sites the relationship between satellite-derived UV and measured UV is insensitive to these selection criteria, an exception is at Garmisch-Partenkirchen, where the gradients are smaller during the winter months (SZA > 45°), or for cloud- and snow-free conditions (reflectivities < 20%). It appears that at this site the high surrounding terrain contributes significantly to the deviations. However, at the other sites, errors arising from these selection criteria are not important. There were no significant changes in satellite footprint pressure when using different selection criteria.

8. Relationship Between Satellite Deviations and Aerosol Optical Depth

The satellite-derived UV is not a direct measurement of UV at the surface. It is a product derived from a radiative transfer model, using UV radiation that is backscattered from the troposphere. Because the radiation does not penetrate fully through the boundary layer, there is a potential for the satellite product to overestimate UV, particularly in regions where aerosol and tropospheric ozone concentrations are greater so that the effective backscatter altitude is higher. Absorbing aerosols, such as those present over more densely populated regions, can lead to larger systematic differences in the UV derived from satellite measurements [*Binenko and Harshvardhan,* 1993]. These can dramatically increase the effective albedo as measured from space, leading to a reduction in inferred UV in nominally clear-sky conditions. On the other hand, the presence of absorbing aerosols can reduce cloud reflectivities appreciably (perhaps by a factor of 2), leading to increases in the inferred surface UV under cloudy conditions [*Twomey*, 1991]. Even in remote locations the absorption coefficient of aerosols is much greater in the Northern Hemisphere than the Southern Hemisphere.

The calculated effect of aerosols on UV irradiance can be appreciable [*Liu et al.*, 1991]. Model to measurement comparisons by *Kylling et al.* [1998] have shown that aerosols in Greece can easily reduce the erythemal UV by 20% or even more; *Mayer* [1997] has shown that at Garmisch-Partenkirchen, aerosol reductions in global UV irradiance are typically 10%. However, much larger extinction losses are possible at this site [*Gröbner et al.*, 2000]. *Kerr* [1997] showed that aerosol reduces global UV irradiance values at Toronto typically by 5-10%. Here we attempt to relate the errors in satellite retrievals to estimates of climatological mean aerosol optical depths measured at each site.

In Figure 13 the gradient of the regression line between satellite-derived UV and measured UV is plotted as a function of the estimated aerosol optical depth at 340 nm. To minimize collocation errors and uncertainties arising from snow reflections, the data in this plot are restricted to those within 50 km of the ground station, and to reflectances less than 20% (as shown in Table 4). The separation into summer and winter is achieved on the basis of the SZA of the satellite observation, with SZA < 45° being taken as summer, and SZA > 45° being taken as winter (see Figure 2).

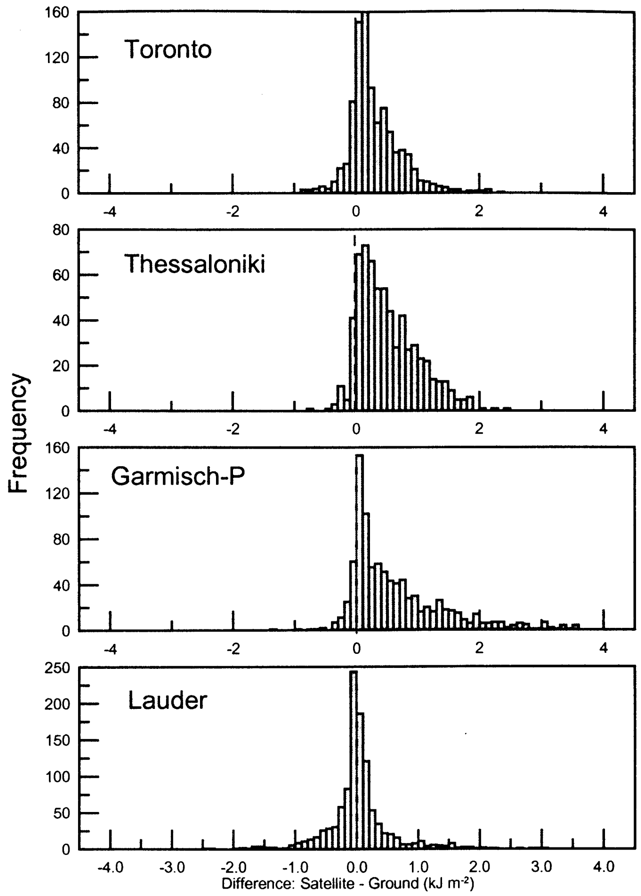

Figure 14. Histogram of EP TOMS overpass disparities (the difference between satellite-derived minus ground-measured values).

While agreement is excellent at Lauder, the gradients are too large in the Northern Hemisphere sites, especially the two sites in Europe where the satellite overestimates UV doses by 20-30%. Apart from Garmisch-Partenkirchen, there appears to be a good correlation between this error and the optical depth. Measurements of aerosol optical depth in surrounding regions [*Ingold et al.,* 2001] suggest that those derived for Garmisch-Partenkirchen [*Mayer,* 1997] may be too small, and as discussed below, the complex surrounding topography may also contribute to the apparent discrepancy.

Boundary layer aerosols could affect the agreement between ground-based measurements in two ways. First, they reduce the erythemally weighted UV irradiance reaching the surface by scattering the radiation through longer path lengths. Greater reductions at the surface would result if the aerosols were absorbing. Such absorbing aerosols are perhaps more likely over populated regions, due to the carbon content of combustion products. It has also been shown that extinctions from aerosols can be greater when the relative humidity is high [*Shettle and Fenn,* 1979]. In addition, multiple scattering by aerosols increases the optical path length in the troposphere, thus increasing extinctions by tropospheric ozone, whose concentrations also tend to be elevated in polluted regions.

Second, aerosols could increase or decrease satellite-derived UV by changing the observed reflectance. In the UV region the surface reflectance is usually small (albedo <5%). However, Rayleigh backscattering from the intervening atmosphere acts to increase the reflected energy sensed. With increased aerosol, the scattering is increased further. In general, one would expect that this would increase the deduced reflectance and thus lead to reduced surface UV. However, if the aerosols were absorbing, then backscattered radiation sensed at the satellite could be less than for a pure Rayleigh atmosphere. This would be interpreted as reduced cloud, leading to an increase in retrieved UV.

Measurements of the single-scattering albedo and the asymmetry parameter of the aerosols would be helpful in understanding these effects. Gases that are present in pollution and absorb in the UV region (e.g., SO_2, and NO_2) may also contribute to the observed differences.

Histograms showing deviations in the differences between satellite estimations minus ground-based measurements are shown in Figure 14. The error distribution for these differences is not Gaussian, with differences tending to be skewed to larger values for the Northern Hemisphere sites, especially Garmisch-Partenkirchen. The tightest and most symmetrical distribution occurs at Lauder. Because of the large annual cycle in UV, these differences are dominated by the summer conditions and values larger than 1 kJ m^{-2} occur occasionally. When ratios rather than differences are plotted, the distribution is more Gaussian. Errors exceeding 100% (ratio < 0.5 or ratio > 2.0) occur occasionally. Again, the distribution is tightest at Lauder and broadest at Garmisch-Partenkirchen.

9. Topographic Effects

Complex surrounding topography complicates the analysis of observed differences between satellite-derived UV and ground-based measurements. At Garmisch-Partenkirchen the surrounding high terrain leads to a possible overestimation of the satellite-derived product. Also the restricted horizons reduce the field of view of the ground-based instrument, though this effect is smaller than 2% as long as the direct Sun is not obscured by the mountains.

Further, it could be speculated that the agreement between satellite-derived UV and ground-based measurements at Lauder is fortuitous since the reflectance (e.g., from clouds and snow) over the measurement site is not typical of those over the satellite footprint. Typically, the reflectivity at Lauder is lower since it is snow-free and less cloudy [*Uddstrom et al.,* 2000]. The overestimated reflectivity from the satellite leads to reductions in the deduced UV. If these reductions were as large as 20%, the discrepancies at Lauder would then have been similar to those at the other sites.

Because of the high mountain ranges running north-south in the Lauder region, there are strong gradients in rainfall and cloud cover, with regions to the SW being much cloudier than those to the NE. We investigated this effect by constraining the acceptance criteria to select data as a function of the quadrant of the TOMS footprint relative to Lauder. The results are summarized in Table 5. Gradients for satellite data in the eastern (less cloudy and flatter) quadrants are smaller than those on the western (cloudier and more mountainous) quadrants. This indicates that there are systematic differences due to cloud and/or topography. Improvements in the correspondence between satellite and ground measurements would therefore follow if higher-resolution cloud fields and topographies were used. The sector to the SE is most characteristic of Lauder both from the point of view of cloud climatology and from terrain height. However, this sector has

Table 5. Statistics for Earth Probe TOMS Data Within 50 km, Constrained by the Quadrant of the Satellite Footprint Relative to Lauder[a]

TOMS Quadrant (Bearing in Degrees)	N	R^2	Regression Gradient
All (0-360)	1082	0.971	0.98
NE (0-90)	277	0.981	0.95
SE (90-180)	299	0.980	0.94
SW (180-270	249	0.966	1.03
NW (270-360)	257	0.962	1.04

[a] All cloud reflectivities are included.

the poorest agreement, with satellite values being 7% lower than the ground-based measurements.

This apparent contradiction here is qualitatively consistent with the differences between ground-based and satellite-derived ozone, since satellite-derived ozone amounts are systematically higher than ground-based measurements at this site [*Bodeker et al.,* 2001]. The use of these larger ozone amounts tends to decrease the inferred UV (by up to 5%) and thus tends to cancel the errors due to altitude differences. This ozone underestimation in the Southern Hemisphere compared with the Northern Hemisphere may arise from differences in ozone profiles. In the Northern Hemisphere a greater proportion of ozone is in the troposphere where (1) it is more effective on a per molecule basis at absorbing UV (path factor and temperature factor), and (2) its contribution is underestimated from satellite data [*Bodeker et al.,* 2001].

The difference between the western and eastern sectors is harder to explain. It was expected that the higher cloud fractions in the west should lead to higher reflectances, which would in turn lead to reductions in the inferred UV. In fact, the opposite occurs, with satellite-derived values being nearly 10% more in the western quadrants than in the east. There are numerous possible explanations for this. It should be emphasized that the radiative transfer under cloudy skies is a complex three-dimensional-issue that should be examined by the use of 3-D radiative transfer models [*Deguenther et al.,* 1998; *Meerkoetter and Deguenther,* 2001], especially when snow albedo plays a role. However, such models still require too much CPU time to be used for the analysis of satellite data on a routine basis.

10. Conclusions

On the basis of these intercomparisons we conclude that while the TOMS retrievals are in good agreement with ground-based measurements at the pristine and dry site at Lauder, New Zealand, they systematically overestimate the UV doses in more polluted locations. Measurements from the two sites in Europe are 20-30% less than the satellite-derived values, while measurements in Toronto are approximately 15% less than the satellite-derived values. These findings are consistent with previously reported results from *Kalliskota et al.* [2000] and *Herman et al.* [1999a].

The findings may be summarized as follows: (1) Satellite-derived erythemal UV doses often represent the observed day-to-day variabilities due to changing cloud and ozone quite well. (2) However, the distribution of errors about the mean is rather large; the 2-sigma errors in ratios occur at ~0.8 and 2.0 with greatest deviations occurring at Garmisch-Partenkirchen and the smallest occurring at Lauder. (3) At the unpolluted New Zealand site there is good agreement in absolute terms; however, the agreement may be fortuitous. (4) At the three more polluted Northern Hemisphere sites, the satellite overestimates the UV doses considerably relative to that measured at the ground. (5) On a monthly basis there is good agreement in the patterns of variability at each site, but there are systematic seasonal differences at the Northern Hemisphere sites. (6) The differences observed here are similar for both the N7 TOMS and for EP TOMS periods (though uncertainties are larger for the earlier period) and are consistent with those reported previously. (7) It appears that air pollution effects either from tropospheric gases that absorb in the UV (e.g., ozone, SO_2, or NO_2) or from absorbing aerosols that attenuate UV irradiance at the surface are rather ubiquitous over large areas of the planet. To understand the effects of these better, measurements of the single-scattering albedo of aerosols would be useful. (8) In the case of Garmisch-Partenkirchen, the high-altitude surrounding terrain and the possible snow cover may compensate for the aerosol-induced deviation in the satellite data. Three-dimensional modeling studies are needed to understand these effects better. (9) Sites that represent broad geographical regions and are not influenced by snow or complex topography may reduce the complexity for scientific analysis, but they do not necessarily represent reality. (10) The stated accuracy of satellite retrievals of daily UV doses (± 12%) from TOMS retrievals of UV is overly optimistic. In three of the four sites selected, differences are larger than this. (11) Despite the increasing availability of satellite-derived products, there remains a need for high-quality ground-based measurements. (12) The use of higher spatial resolution of satellite-derived UV and cloud/terrain effects may improve the accuracy of satellite retrievals.

Acknowledgments. We thank Jay Herman and Ed Celarier at NASA Goddard Space Flight Center for providing the TOMS overpass data used in this study. For quality control of the ground-based data sets we thank Paul Johnston and Mike Kotkamp (Lauder), Tim Martin (Graz, Austria), Germar Bernhard (San Diego, California, USA), Bernhard Mayer (Oberpfaffenhofen, Germany), Tom Grajnar and Vitali Fioletov (Toronto), and Chariklea Meleti (Thessaloniki). The European Commission is thanked for their support within the framework of the SUVDAMA, SUSPEN, and EDUCE projects. The German Ministry for Education, Research and Technology is thanked for their long-term support in various research grants to support the UV measurement program at the Fraunhofer Institute for Environmental Physics at Garmisch-Partenkirchen (IFU). Monitoring of solar UV radiation at Thessaloniki is carried out by the Laboratory of Atmospheric Physics of the Aristotle University and is supervised by Christos Zerefos. This work was carried out as part of NIWA's contract C01X0033 to New Zealand's Foundation for Research Science and Technology.

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(Received February 8, 2001; revised May 23, 2001;
accepted May 29, 2001.)