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Comparison of satellite-derived UV irradiances with ground-based measurements at four European stations

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[1] Satellite-derived ultraviolet (UV) irradiances may form the basis for establishing a global UV climatology, provided that their accuracy is confirmed against ground-based measurements of known quality. In this study, quality-checked spectral UV irradiance measurements from four European stations (Sodankyla, Finland; Bilthoven, Netherlands; Ispra, Italy; and Thessaloniki, Greece) are compared with those derived from TOMS, based on the (version 8) data set. The aim of this study is to validate the TOMS UV irradiances and to investigate the origin of disagreements with ground-based data. Comparisons showed that TOMS overestimates summertime noon CIE-weighted irradiances from 6.6% at the high-latitude site of Sodankyla up to 19% for the three other sites. The influence of clouds and aerosols on the observed differences was investigated. For the other three sites (Bilthoven, Ispra, and Thessaloniki), TOMS overestimates the irradiance at 324 nm by almost 15% even under conditions with cloud optical depth of less than 5. For cloud-free days at Ispra and Thessaloniki, differences ranging between 3% and 20% are well correlated with aerosol optical depth.

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1. Introduction

[2] During the last decade, satellite observations from the Total Ozone Mapping Spectrometer (TOMS) have been extensively used in combination with radiative transfer or statistical models to derive UV irradiances at the ground [e.g., *Herman et al.*, 1999; *Krotkov et al.*, 1998; *Krotkov et al.*, 2001]. Since 1978, satellite-derived UV products are available over the globe so that global climatology of surface UV irradiance could be established and possible trends could be examined.

[3] Validation of satellite UV estimates with ground-based measurements is a complicated task, since the spatial distribution of solar UV irradiance received at the ground is mainly controlled by the variability of total ozone and clouds and therefore may vary strongly from place to place. Other parameters, such as aerosols, air pollution, and local weather patterns, are also capable in modifying the UV field. Except from ozone, the impact of all these factors is more or less localized, producing a different UV field at locations even a few kilometers apart. Hence ground-based measurements are not always representative of a typical satellite measurement pixel (TOMS ground FOV ~50 km in nadir). The daily averaged UV reduction factors due to clouds derived from ground-based pyranometer data and satellite measurements was examined by *Matthijsen et al.* [2000] and *Williams et al.* [2004]. They showed that a good correspondence between space-born and ground-based UV reduction factors can be achieved when combining several ground-based stations per satellite grid cell. Comparisons of TOMS UV estimates with ground-based measurements showed that in summertime the TOMS retrievals overestimate UV radiation, with some exceptions over a few unpolluted sites [e.g., *Eck et al.*, 1995; *Fioletov et al.*, 2002; *Fioletov et al.*, 2004; *McKenzie et al.*, 2001].

[4] In this study, noon spectral irradiances from the latest (version 8) TOMS UV retrieval algorithm were compared with ground-based spectral measurements at four European stations, representing different geographical and environmental conditions. The influence of cloud and aerosol variability on the bias is examined.

2. Ground-Based Measurements and Satellite Data

[5] The four European stations that were used in this study are listed in Table 1, with information on the instru-

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Table 1. Information on Measurement Sites at the Ground and Instruments Used in This Study

Site/Country	Instrument ID	Latitude, °N	Longitude, °E	Altitude, m	Instrument Type	Number of Days	Site Characterization
Sodankyla, FI	FIS	67.4	26.6	179	MKII Brewer #037	963	Remote
Thessaloniki, GR	GRT	40.6	22.9	60	MKIII Brewer #086	689	Urban
Ispra, IT	ISP	45.8	8.6	214	MKII Brewer #066	1185	Rural
Bilthoven, NL	NLR	52.1	5.2	9	Dilor 2.XY.50	977	Rural

mentation, the data availability, and characteristic details for each station. The stations extend from 40.6°N to 67.4°N and correspond to different cloud and aerosol regimes. We used ground-based measurements for the time period 1991–2003, when data from the TOMS instruments on Earth Probe (1996–2003) and Nimbus 7 (1978–1993) satellites were available. Only summer (May through September) data were analyzed to avoid the problems of the TOMS algorithm in distinguishing between snow cover and clouds at Sodankyla, [*Fioletov et al.*, 2004; *Kalliskota et al.*, 2000]. Snow depth observations from FIS site have been also used to exclude days with snow-covered surface. The SHICrivm algorithm was applied to all spectra, to correct for any wavelength shifts and to exclude spectra with nonnatural spikes or distortions in spectral shape [*Slaper et al.*, 1995]. Additionally, all spectra were standardized to a triangular slit function with 0.55 nm full width at half maximum (FWHM) to match the spectral resolution of the irradiances produced by the TOMS UV algorithm. Averages of global irradiance at selected wavelengths (305, 310, and 324 nm) and of erythemal (CIE weighted) irradiance between 1100 and 1300 hours true solar time were calculated for each day and for all sites. To minimize the influence of the solar zenith angle variation during this interval, the average solar zenith angle was calculated for each day and used in the TOMS UV retrieval algorithm. The expected error form this simplification is up to 2%, which is considered small compared to errors from other sources that determine the differences between satellite-derived and ground-based UV measurements [*Fioletov et al.*, 2002].

[6] The database of TOMS UV irradiances (1978 to 2003) has been expanded to include five new products (noon irradiance at 305, 310, 324, and 380 nm convolved with the same triangular slit function, and noon erythemal-weighted irradiance), in addition to the existing CIE daily exposure, which permit direct comparisons with ground-based measurements from the above-mentioned UV spectroradiometers. New TOMS ozone and reflectivity (Version 8) data, as well as average solar zenith angles for ground measurements were used as input to version 1.5 TOMS UV software to produce customized UV time series for these locations [*Herman et al.*, 1999; *Krotkov et al.*, 2002; *Krotkov et al.*, 1998; *Krotkov et al.*, 2001]. The calculated effective cloud optical depth was used to examine the effect of spatial and temporal variability of clouds on differences between satellite estimates and ground-based measurements.

3. Instrument-Related Differences

[7] In the frame of the EC-funded project "Quality Assurance of Spectral Ultraviolet Measurements in Europe through the development of a transportable unit" (QASUME) (http://lap.physics.auth.gr/qasume/) a traveling reference spectroradiometer (TRS) was developed with the aim to provide quality assurance to spectral solar UV measurements conducted by spectroradiometers operating in Europe [*Gröbner et al.*, 2005]. The TRS provided colocated and synchronized measurements under various atmospheric conditions with the local site instruments at 25 sites all over Europe, including the sites where ISP, FIS, GRT, and NLR spectroradiometers that are used in this study operate. Detailed reports about the on-site intercomparisons can be found in the work of *Gröbner et al.* [2003a], *Gröbner et al.* [2003b], and *Gröbner et al.* [2004].

[8] An overview of the comparisons results is presented in Table 2, which shows percentage differences of spectral irradiances at selected wavelengths measured by the local instruments from those measured by the TRS. The data used in these comparisons were measured at solar zenith angles, which cover a range representative for the data that are used for the comparisons with TOMS estimates. Since a direct comparison of the four spectroradiometers that were used in this study was not possible, their differences against the well-calibrated and maintained traveling instrument were used to demonstrate the level of agreement among them. The four instruments agree to within 6% at 305 nm and 8% at 324 nm. The two double monochromator spectroradiometers (GRT and NLR) have a rather constant bias with the traveling spectroradiometer. These differences are mainly due to the different calibration standards to which each instrument traces its calibration. The wavelength dependence of the other two instruments (3% for FIS and 4% for ISP), which are both single monochromators, could be caused partly by stray light in the UVB wavelengths and the weak sensitivity at the high wavelengths. Nevertheless, with the exception of FIS, these differences are rather small compared to the bias of these instruments with TOMS, as will be discussed in the following.

4. Comparison and Results

[9] Mean percentage differences between ground-based measurements at the four sites and the corresponding TOMS estimates for noon irradiances at 305, 310, 324 nm and for erythemal irradiance are presented in Table 3. The

Table 2. Percentage Differences, %, Between Instruments at Selected Sites and the Traveling Reference Spectroradiometer at Selected Wavelengths[a]

		Differences to TSR, %		
Instrument ID	Campaign Years	305 nm	310 nm	324 nm
FIS	2003	5.9	5.0	3.1
GRT	2002	4.3	4.1	3.8
ISP	2003	0.0	−1.5	−4
NLR	2002, 2003, 2004	1.8	1.8	2.0

[a]Average differences are presented for sites where more than one comparison campaigns exist.

Table 3. Mean Percentage Difference With Standard Deviation (in Parenthesis) Between Ground Measurements and Satellite UV Estimates

Site Name	Differences Between TOMS and GB Derived Irradiances (%)			
	305 nm	310 nm	324 nm	CIE
Sodankyla (FIS)	11.6 (26.6)	7.8 (26.0)	5.1 (26.5)	6.6 (26.1)
Bilthoven (NLR)	22.4 (21.0)	20.1 (20.1)	14.3 (21.4)	19.1 (20.7)
Ispra (ISP)	21.5 (23.7)	18.5 (22.7)	13.0 (23.2)	18.3 (23.1)
Thessaloniki (GRT)	21.9 (16.4)	16.7 (16.2)	11.7 (16.6)	18.6 (16.3)

differences for Sodankyla are considerably lower (by about 12%) compared to the differences at the other three sites, probably as a result of lower tropospheric aerosol abundances over this high-latitude site and it is in agreement with relevant studies [e.g., *Arola et al.*, 2005; *McKenzie et al.*, 2001].

[10] At all sites, the differences decrease with increasing wavelength. This is consistent with that expected from small errors in the determination of O_3 and SO_2 columns and aerosol optical depth that show up primarily at the shorter wavelengths. The standard deviation decreases with decreasing latitude being almost 10% higher in Sodankyla compared with that at Thessaloniki, mainly as an effect of differences in cloudiness, which increases from south to north in the summer months that are considered in this study. Only one spectroradiometer (NLR) is capable in recording irradiance at 380 nm; the mean difference and standard deviation with TOMS (not shown in Table 3) is 11.6% and 24.4%, respectively.

[11] The absolute differences between TOMS-derived and ground-based UV irradiances that are presented here agree with results from similar studies that were conducted for other locations in the northern hemisphere. *McKenzie et al.* [2001] reported that measurements of daily CIE erythemal dose at two European sites (Garmisch-Partenkirchen, Germany, and Thessaloniki, Greece) are 20–30% lower than the TOMS estimates, while measurements in Toronto, Canada, are lower by only 15%. *Fioletov et al.* [2002] compared summertime noon TOMS UV estimates and Brewer measurements at the sites of the Canadian ozone and UV monitoring network. It was found that the mean TOMS-Brewer bias at 324 nm was 9.5% for clear skies and 6.9% for cloudy conditions. Similar values were found for the CIE irradiance, while for 305 nm the bias was 11.9% and 10.1%, respectively [*Fioletov et al.*, 2004]. Results of our study for Sodankyla confirm previous findings that TOMS estimates are in better agreement with ground-based measurements at remote and less polluted sites [e.g., *McKenzie et al.*, 2001].

[12] Mean summertime (May through September) differences between TOMS and ground-based measurements of spectral UV irradiances for each year of the period 1990–2003 are presented in Figure 1. Only years with more than 30 common days of measurements during the 5-month period were considered. Despite the differences in sampling between years, there is a constant bias for each site through the period of study. The variability of the differences is similar each year; the standard deviations for each year are within ±3% from those presented in Table 3.

[13] The positive bias of TOMS can be attributed mainly to the spatial and temporal variability of clouds, and under cloud-free conditions to the unaccounted aerosol absorption in the boundary layer. In the following paragraphs, we discuss separately these two effects.

4.1. Effect of Clouds

[14] The algorithm of TOMS that is used for UV retrievals provides an average UV irradiance over a wide area (pixel size ~50 km in nadir to >100 km off-nadir). Because of the spatial and temporal distribution of clouds, the UV radiances sensed by TOMS when looking at a certain pixel are inhomogeneous. On the other hand, a ground-based spectroradiometer measures the cosine weighted irradiance, and therefore most of the signal originates from a much smaller than the subsatellite pixel area. Therefore the different geometries of the two measurements introduce a large uncertainty in their comparison.

[15] To investigate the effect of cloudiness distribution on the positive bias of TOMS, we studied the dependence of this bias from the effective cloud optical depth (COD) that is calculated from TOMS UV algorithm. UV irradiances at 324 nm were selected, to minimize the effects from ozone and SO_2 absorption. Ground-based measurements from only three instruments (ISP, NLR, and GRT) were used because their differences from TOMS are of similar magnitude (see Table 3). Mean differences of TOMS from all instruments were calculated for different classes of COD (between 0 and 15 in steps of 1 and 15 and 45 in steps of 5) and are shown in Figure 2. All averages were calculated from at least 30 measurements. This condition could not be fulfilled for most of the cloud classes for Sodankyla preventing a separate analysis for this site, which was excluded from Figure 2 because of its significant differences from TOMS.

[16] The average differences of Figure 2 show no particular dependence on cloud optical depth, considering also their large standard deviations. For clear skies and for light or scattered clouds (COD < 5) the TOMS bias is higher by 14–17%. For higher cloud classes (between 5 and 15, where most of overcast cases are included) the mean bias of TOMS seems to decrease and in a few cases approaches zero. In these COD classes there are numerous cases of ground-based measurements that are higher than TOMS and the variability of the differences increases. For thick clouds (COD > 15, where mostly cases with tower cumulus clouds are included), the spatial and temporal variability of clouds become more important, and the chances for ground-based measurements under rain are higher. Thus the standard deviation of the differences increases remarkably and the average TOMS bias varies between 5 and 20%.

[17] The relative percentage of differences between TOMS and ground-based measurements at 324 nm in intervals of 10% are shown in Figure 3 separately for clear skies (COD < 1) and heavy clouds (COD > 15). Under clear skies the majority of the differences lie between 5 and 25%, and the standard deviation is relatively small. Under optically thick clouds, the variability increases and there are plenty of cases where ground-based measurements are higher than TOMS estimates. Occasionally, ground-based measurements may be enhanced even more by side reflections on cumulus clouds. As a result, the range of differ-

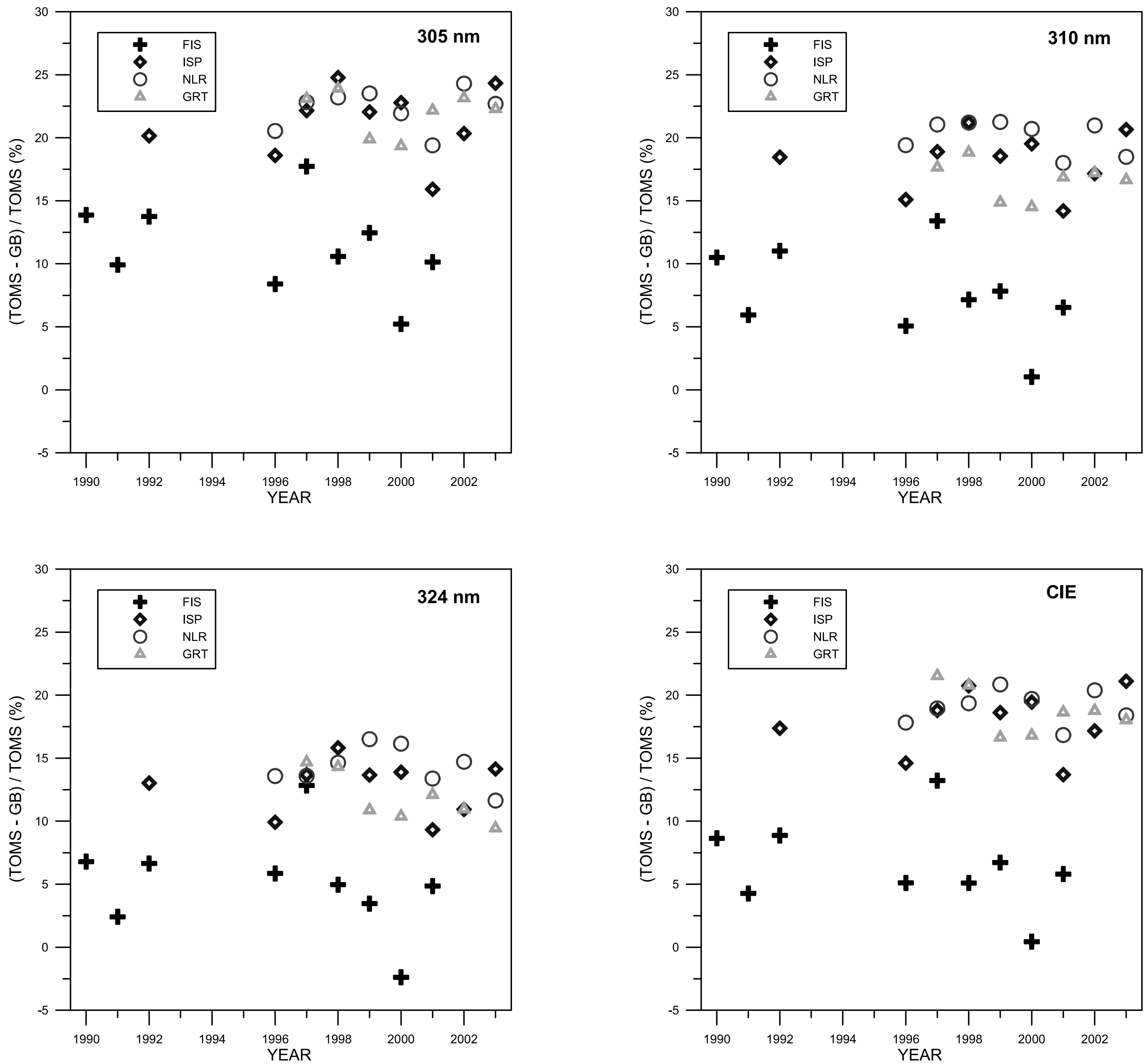

Figure 1. Differences between ground-based measurements and TOMS estimates for noon global UV irradiances at 305 nm (upper, left), 310 nm (upper, right), and 324 nm (lower, left) and for noon CIE dose (lower, right).

ences is much larger (between about −150 and 70%), but the average bias of TOMS is again in the order of 25%.

4.2. Effect of Aerosols

[18] Aerosol absorption in the boundary layer is not properly taken into account in the TOMS UV algorithm because they do not appear as absorbing aerosols in the TOMS AI data. This additional error has been shown to be the reason for the observed positive bias between TOMS-derived UV and ground-based measurements. [e.g., *McKenzie et al.*, 2001; *Arola et al.*, 2005; *Krotkov et al.*, 2005; *Krotkov et al.*, 2004]. Here the dependence of TOMS bias on AOD is examined using the measurements from Thessaloniki and Ispra, for which collocated aerosol measurements were available.

[19] The aerosol optical depth was retrieved from direct solar irradiance measurements under cloud-free conditions for the periods 1997–2002 for Thessaloniki and 1991–1992, 1996–2002 for Ispra. For consistency with the previous part of this study we used only summertime data (May through September), when AOD is usually higher [*Gröbner and Meleti*, 2004; *Kazadzis et al.*, 2005]. Uncertainties in retrieved AOD due to measurement and methodology uncertainties have been discussed extensively by *Gröbner and Meleti* [2004] for Ispra, who reported uncertainties of 0.03 at 320 nm, and by *Kazadzis et al.* [2005] for Thessaloniki, reporting uncertainties between 0.04 and 0.06 at 340 nm. For Thessaloniki the AOD at 340 was used to minimize uncertainties due to ozone. This wavelength is not available for Ispra data because of limitations in the Brewer's spectral range. Averages of AOD between 1100 and 1300 true solar time were calculated at both sites. In this analysis we used only measurements with TOMS effective COD of less than 0.5 in order to

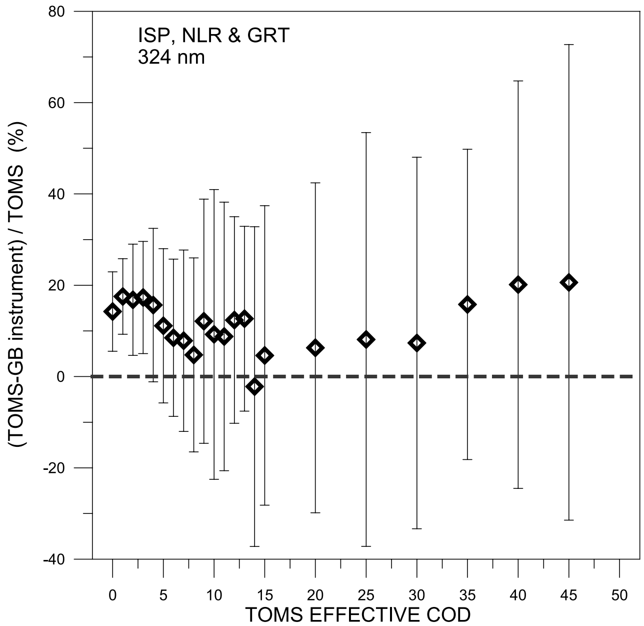

Figure 2. Average differences and standard deviation between irradiances at 324 nm derived from TOMS and from ground-based instruments as a function of TOMS-derived effective COD classes.

diminish possible impacts of clouds in the satellite radiance measurements.

[20] Differences between TOMS and ground-based measurements of irradiance at 324 nm as a function of AOD are presented in Figure 4 for the two sites, depicting and clear dependence of TOMS bias to AOD. Assuming that only aerosols are responsible for the bias of TOMS, extrapolation of linear regressions on these data to zero AOD would give an indication of the expected TOMS bias under aerosol free atmospheres, as shown by *McKenzie et al.* [2001]. These biases are calculated to 2.4% and 6.7% for Thessaloniki and Ispra, respectively. The regression slopes at both sites are similar (18.3% for Thessaloniki and 16.3% for Ispra) per unit of AOD, but they refer to different AOD wavelengths. If the AOD at 340 nm at Thessaloniki is converted to AOD at 320 nm, assuming a typical value of 1.2 for the Angstrom exponent, the slope decreases from 18.3 to 17.0% per unit AOD. This difference in the slope between the two sites may be a consequence of different nature of the aerosols prevailing at each location. The scatter around the regressions could be attributed to measurement or cloud screening uncertainties and to the absorption efficiency of aerosols [*Arola et al.*, 2005; *Cede et al.*, 2004; *Krotkov et al.*, 2005; *Krotkov et al.*, 2004]. The fact that TOMS bias is increasing with increasing aerosol load, indicates that the TOMS UV algorithm does not account correctly for the effect of aerosols on UV absorption.

5. Conclusions

[21] In this study, spectral UV irradiances measured by four UV spectroradiometers at different sites in Europe at local noon for the summer months from 1990 to 2003 are compared with those calculated from TOMS v8 data. The four locations cover a wide range of aerosol and cloudiness regimes. Comparison of the ground-based instruments with a traveling reference spectroradiometer during the period 2002–2004 revealed that the four instruments agree to with ~6% in the UV-B wavelength range.

[22] Average biases between TOMS estimates and ground-based measurements are in agreement with previous validation studies. At the three sites (Ispra, Bilthoven, and Thessaloniki), TOMS overestimates the summertime UV irradiances at 305, 310, and 324 nm and CIE dose by ~21%, 18%, 13%, and 18.5%, respectively. Average differences are considerably lower by almost 12% at the remote

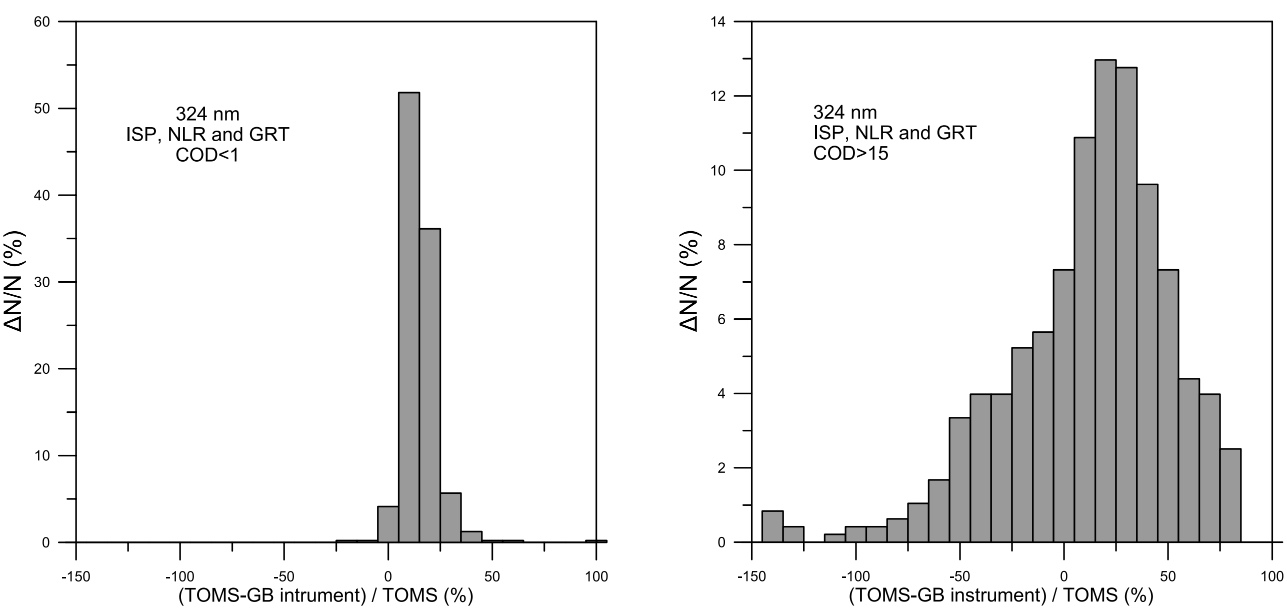

Figure 3. Distribution of relative differences between irradiances at 324 nm derived from TOMS and from ground-based instruments under clear skies (COD < 1, left panel) and thick cloud conditions (COD > 15, right panel). Ground-based measurements from Ispra, Thessaloniki, and Bilthoven were used.

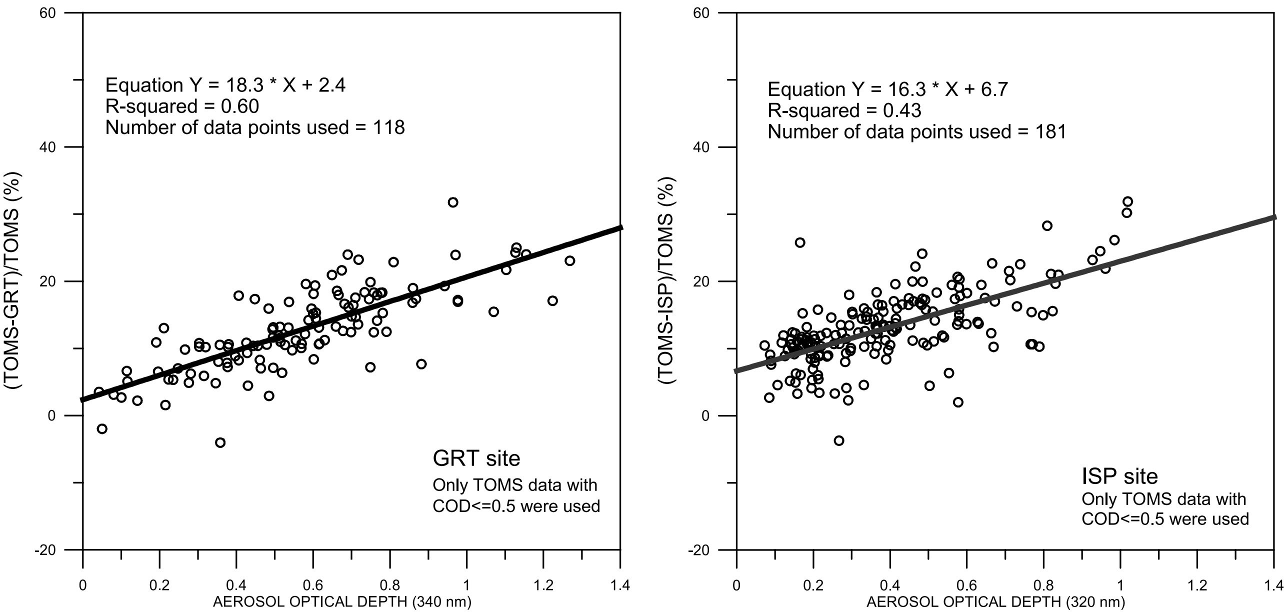

Figure 4. Percentage differences between irradiances at 324 nm derived from TOMS and from ground-based instruments as a function of AOD at Thessaloniki (left panel) and Ispra (right panel). Thick lines are linear regressions on the data.

site of Sodankyla in north Finland, while the variability is higher by about 10%, mainly because of the presence of more clouds. For all stations mean annual differences and standard deviations for the time period under study seem to be consistent with the long-term averages.

[23] The calculated effective cloud optical depth (COD) from TOMS UV algorithm for the Ispra, Bilthoven, and Thessaloniki was used as an indicator for investigating the effect of the spatial and temporal variability of clouds on the irradiance differences at 324 nm, where ozone and SO_2 absorption is low. For COD values lower than 5, TOMS overestimates UV irradiances by almost 15% with relatively low standard deviation. For higher COD values there are also many cases where ground-based measurements are higher than TOMS, and the standard deviation of the differences increases significantly.

[24] The bias TOMS UV irradiance at 324 nm under clear skies is well correlated with the aerosol optical depth (AOD) that was derived from ground-based direct irradiance measurements at Thessaloniki and Ispra. Extrapolation of linear regressions reveal that the difference between TOMS and ground-based measurements at these two sites under aerosol free conditions is about 2.4% and 6.7%, respectively. In contrast, TOMS could overestimate the UV irradiance at 324 nm by almost 20% under high aerosol loads (e.g., AOD more than 1 at 320 nm), indicating that additional correction is needed in the TOMS UV algorithm to account for aerosol absorption in the boundary layer.

[25] **Acknowledgments.** The financial support by the European Commission through the projects GOCE-CT-2004-505390, EVK2-2001-00135, and EVK2-378-2001-00130 is acknowledged.

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