Comparison of Brewer ultraviolet irradiance measurements with total ozone mapping spectrometer satellite retrievals

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Abstract. Comparison of measured UV irradiance with estimates from satellite observation is potentially effective for the validation of data from the two sources. Summer data from ten Canadian Brewer sites were compared in this study with noon UV irradiance estimated from total ozone mapping spectrometer (TOMS) measurements. In general, TOMS estimates can successfully reproduce long-term and major short-term UV variations. However, there are some systematic differences between the measurements at the ground and satellite-retrieved UV irradiance. From 3 to 11% of the Brewer-TOMS difference can be attributed to the Brewer angular response error. This error depends on the solar zenith angle and cloud conditions, and is different from instrument to instrument. When the angular response of the Brewer instrument is considered and applied, the Brewer data are still lower than TOMS-estimated UV irradiance by 9 to 10% on average at all sites except one. The difference is close to zero at one station (Saturna Island), possibly due to its much cleaner air. The bias can be seen in clear sky conditions and at the 324-nm wavelength, i.e., it is not related to local cloud conditions or absorption by ozone or SO_2. [DOI: 10.1117/1.1516818]

Subject terms: UV irradiance; Brewer; total ozone mapping spectrometer; cloud amount.

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1 Introduction

Satellite measurements are widely used to estimate UV irradiance at the ground.[1–9] Spaceborne observation can provide information on two key parameters that determine UV irradiance: total ozone amount and the cloud transmittance or reflectivity. Radiative transfer or statistical models can then derive UV irradiance at the ground from these satellite observations. The total ozone mapping spectrometer (TOMS) is an important source of derived UV data, because it has provided both total ozone and cloud reflectivity measurements since the late 1970s. Recently developed methods can include the effect of UV absorption by atmospheric aerosols[10] in the derivation.

Validation of satellite-estimated UV irradiance is a complicated task, because of the variety of possible sources of discrepancies with ground-based measurements. They range from errors in absolute instrument calibrations to a largely different spatial and temporal resolution for ground-based and satellite measurements. It has been found that TOMS produces systematically higher UV irradiance values than are measured at the ground at northern midlatitudes.[10,11] Better agreement has been found at one site in the southern hemisphere.[11] It was suggested[11] that the UV absorption by tropospheric gasses (ozone, SO_2, NO_2) or by absorbing aerosols has not been adequately taken into account in the satellite retrievals, and the better agreement in the southern hemisphere is related to a much lower level of pollutants there.

Systematic differences between UV irradiance measured at ten Canadian Brewer sites and UV estimates from TOMS measurements have been analyzed in this study. The nonideal angular response of the Brewer spectrophotometer can cause an underestimation of UV irradiance. Theoretical and practical aspects of correction for this response error are also discussed. The comparison between UV irradiance measured by the Brewer and derived from TOMS data at wavelengths with strong (305 nm) and weak (324 nm) ozone absorption was performed to determine possible ozone-related effects on the difference between the measured and TOMS-derived UV irradiance. Meteorological cloud amounts measured at or close to Brewer sites were also used to study effects of the cloud conditions on the difference.

2 Instruments and Data Sets

UV irradiance measurements made by single monochromator Brewer spectrophotometers at the Canadian ozone and UV monitoring network stations between 1989 and 2000 were used. The Brewer instrument measures horizontal spectral UV irradiance with a spectral resolution of approximately 0.55 nm, full width at half maximum (FWHM). The data were corrected for instrumental stray light as described in Ref. 12. In its normal UV routine, the

Brewer scans from 290 to 325 nm and then back to 290 nm. The integration time is approximately 1 sec for each wavelength, the sampling interval is 0.5 nm, and the double scan takes about 8 min. The reported units are $\mathrm{mWm^{-2}nm^{-1}}$. There are normally from one to four such measurements performed every hour throughout the day from sunrise to sunset. The measurements on the network stations were less frequent from 1989 to 1994, typically ~20 per day increasing in 1995 to 1999 to up to 50 per day. The erythemal action spectrum used here was determined by the Commission Internationale de l'Éclairage (CIE). All data are available from the World Ozone and Ultraviolet Radiation Data Center (WOUDC) in Toronto (http://www.msc-smc.ec.gc.ca/woudc/).

The current TOMS UV algorithm is based on calculated clear-sky UV irradiance F_{clear} with corrections for cloud/nonabsorbing aerosols or absorbing aerosols. The calculation of F_{clear} from satellite-derived extraterrestrial spectral solar irradiance and NASA's TOMS measurements of total column ozone, aerosols, and surface reflectivity and estimates of various error sources have been described elsewhere.[10,13] The corrections to the irradiances and the daily exposure values are based on the cloud transmission factor C_T estimated from the single TOMS measurement at the near-noon overpass; diurnal variation in the C_T factor is disregarded. The type of correction (specific C_T algorithm) is selected based on the two threshold values of the TOMS aerosol index (AI) (calculated from 340 and 380-nm radiances for the Nimbus 7 TOMS and from 331 and 360 nm for the Earth Probe TOMS) and the Lambertian equivalent reflectivity (LER) (360 or 380 nm). The surface albedo is estimated using the TOMS monthly minimum Lambertian effective surface reflectivity (MLER) global database.[14–16]

Only summer (June through August for Churchill, May through August for all other stations) data were analyzed in this study to avoid problems related to effects of high snow albedo on the TOMS UV retrievals. Systematic diurnal variations in cloud cover may yield a bias between the ground measurements and daily UV irradiation derived from TOMS single noon overpasses at some sites. Therefore, the main part of the comparison with observations was made only for times close to local noon, so that the results would be less affected by temporal changes of cloud cover. The Brewer data comprised the average UV irradiance measurements made between 11 am and 1 pm local solar time. The compared quantities are the irradiances at 305 and 324 nm and the erythemally weighted irradiance. Mean noon UV irradiances were also derived from TOMS observations. The mean zenith angle of the Brewer measurements, TOMS total ozone, aerosol index, and reflectivity were used as input parameters for the TOMS UV irradiance calculation at the Brewer sites. Using the mean zenith angle instead of calculating UV irradiances at the exact times of the Brewer measurements and averaging the calculated values is a simplification that may introduce some systematic error (up to 1 to 2%), but this error is small compared to the other sources of the Brewer-TOMS differences described here. Hourly meteorological cloud amount data recorded at or close to Brewer sites were used as an independent source of information on cloud conditions for the interpretation and analysis of the comparison.

3 Angular Response Error of Brewer UV Measurements

Dependence of responsivity on the direction of incident radiation is a well-known source of measurement uncertainty in spectroradiometers.[17,18] This unwanted dependence is present in Brewer instruments but it is disregarded in the algorithm, which is used to compute the measurement values from the signals. The Brewer is calibrated for normal incidence and the algorithm divides the signal by this responsivity, thereby introducing error into the measurement. This angular response error can be calculated from the angular response of the instrument and the angular distribution of the radiation field, but information on both is usually highly limited. In most Brewers the responsivity is higher at normal incidence than for all other directions and, consequently, the Brewer irradiance measurements are biased low, i.e., the error is negative. It has been shown to be in the range of 2 to 7% for Brewer 86, depending on solar elevation, cloud cover, aerosol content, etc.[17] Methods to correct this angular response error, also known as "cosine error," have been described in the literature.[17,19–21] They are typically based on nearly simultaneous measurements of direct or diffuse components of global UV irradiance by the same[17] or a different[21] instrument.

In this work a new method of estimating the angular response error has been developed and used to correct the Brewer measurements prior to making the comparison with the TOMS data. The method expresses the error as a function of just two variables, the solar zenith angle and the ratio of the measurement to a modeled clear-sky irradiance. It depends also on the Brewer angular response function, which may be different from one instrument to another. The method does not account for any azimuth dependency of the response function, and it relies on a number of other simplifying assumptions, which are described in what follows. It was also assumed that the directional distribution of diffuse sky radiance is isotropic. This assumption is commonly used for correcting the angular response error.[22] Although spatial variations of the intensity of the sky radiance up to a factor of 2 have been observed,[23] the error in global irradiance introduced by the anisotropy of the radiance is small.[17]

The angular response function $f_b(\theta)$, defined as the responsivity at incidence angle θ relative to the normal incidence responsivity, was measured for this study on Brewer 14, which has been operating almost continuously at Toronto since 1989. It was found that $f_b(\theta)$ can be approximated by $(\cos\theta)^{0.195}$, as shown in Fig. 1.

Due to the division by responsivity in the algorithm, for beam radiation (radiation originating from a single direction) the angular response function describes the ratio between the Brewer measurement E^m_{beam}, and the corrected (true) value E^c_{beam}, which would have been obtained if the correct responsivity, specific to that incidence angle θ, had been used in the algorithm. Thus following the nomenclature in Ref. 17, $f_b(\theta)$ is also a correction factor defined by:

$$f_b(\theta)=E^m_{\mathrm{beam}}/E^c_{\mathrm{beam}}. \tag{1}$$

The equivalent correction factor for diffuse isotropic radiation,

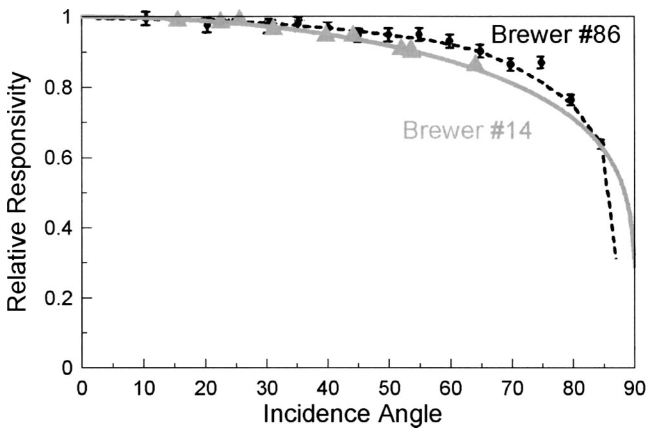

Fig. 1 Measured angular response of the instruments Brewer 14 and 86. The black dots connected by the dashed lines indicate previously published[16] angular responses of Brewer 86. Results of the measurements for Brewer 14 are shown by gray triangles. The gray line represents the $\cos^{1.195}(\theta)$ function, where θ is the vertical incidence angle.

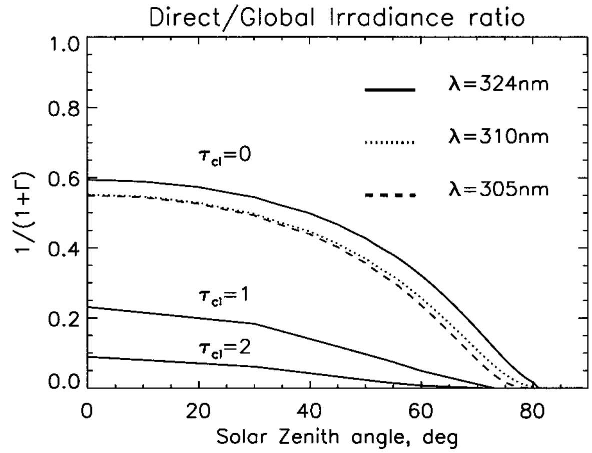

Fig. 2 Calculated ratio of direct-to-global surface irradiance as a function of the solar zenith angle at three wavelengths: 305, 310, and 324 nm for clear skies ($\tau_{Cl}=0$) and at 324 nm for cloud optical depth $\tau_{Cl}=1$ and 2. The surface pressure is assumed to be 1 atm, and surface albedo 5%.

$$f_d = E_d^m / E_d^c,$$

can be calculated from $f_b(\theta)$ as follows.

$$f_d = \int f_b(\theta)\cos(\theta)\partial\Omega \bigg/ \int \cos(\theta)\partial\Omega$$
$$= \int \cos^{1.195}(\theta)\partial\Omega/\pi$$
$$= 2\int_0^{\pi/2} \cos^{1.195}\theta d(\cos\theta) = \frac{2}{2.195} = 0.911, \quad (2)$$

where Ω is a solid angle and the integration is over the upward hemisphere. The calculated correction factors for the angular response of Brewer 14 for direct and diffuse illumination are equal at a solar zenith angle of about 50 deg $[f_b(50\,\text{deg}) = f_d = 0.911]$.

The correction factor for global irradiance (direct plus diffuse) f_g is given by a weighted sum of direct (f_b) and diffuse (f_d) factors:

$$f_g = E_g^m / E_g^c = f_b(1+\Gamma)^{-1} + f_d\Gamma(1+\Gamma)^{-1}, \quad (3)$$

where Γ is the diffuse to direct irradiance ratio, which in turn depends on the solar zenith angle, wavelength, surface pressure and reflectivity, and atmospheric conditions (ozone, aerosol, clouds). Among the various interdependent ratios between diffuse, direct, and global irradiance, we have used Γ here because of the availability of parameterizations of $\Gamma(\lambda,\theta)$ at the ground for clear-sky conditions (no aerosols and clouds) as a function of wavelength (300 to 340 nm) and solar zenith angles (0 to 70 deg).[10] These parametrizations are based on radiative transfer calculations for a Rayleigh atmosphere with a 325 DU midlatitude ozone profile using the DISORT radiative transfer code.[24]

Figure 2 shows the ratio of direct to global irradiance $[1/(1+\Gamma)]$ for two cloud amounts. The results agree qualitatively with previous measurements[17] for low aerosol conditions. Figure 3 demonstrates the angular response error of Brewer 14 calculated from the clear-sky results shown in Fig. 2. As expected the error does not depend on wavelength if the solar zenith angle is about 50 deg.

Even clouds of small optical thickness quickly reduce the direct component and enhance the diffuse component of the surface irradiance, so that the angular response error will approach its value for diffuse illumination. As shown in Fig. 3, clouds (and aerosols) mainly flatten out the solar zenith angle dependence of the angular response. It should be emphasized that the results discussed here and the correction algorithm is applicable for uniform clouds, and that the results could be different for broken clouds.

Thus, the angular response error can be estimated and corrected if direct and diffuse irradiance are known.[17] In

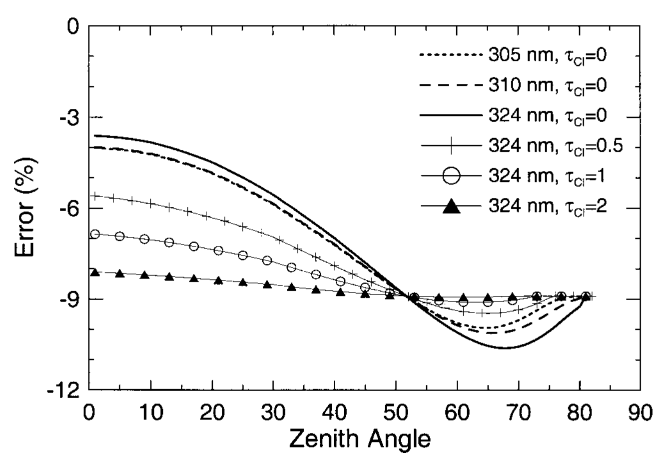

Fig. 3 Calculated error due to the angular response of Brewer 14 for a particular global irradiance measurement as a function of solar zenith angle at 305, 310, and 324 nm for clear skies ($\tau_{Cl}=0$) and at 324 nm for cloud optical depth $\tau_{Cl}=0.5$, 1, and 2 for 325 DU ozone amount. The spectral dependence of the angular response error is weak at UVB wavelengths. Therefore, it is possible to use the correction factor at, for example, 324 nm to correct at Brewer measurements at all wavelengths.

the case of the Canadian UV network, the only information available is Brewer measurements of spectral global irradiance, and a method that allows estimation of the response error directly from global irradiance is needed. Radiative transfer model calculations were used in this study to model global, direct, and diffuse solar radiation for different cloud conditions. The angular response error was then estimated and Brewer measurement results were simulated using the model output. Finally, a relationship between simulated measurements and the response error was established and applied to correct real Brewer measurements.

The angular response error is a function of the solar zenith angle (θ) and the ratio of direct to diffuse radiation that is determined by cloud optical thickness (τ). As shown in Fig. 3, angular response has little wavelength dependence and all calculations were performed for a 324-nm wavelength, and then the correction factor was applied to all Brewer wavelengths. The radiative transfer calculations[14] were done for different optical thicknesses of the uniform clouds, with τ ranging from 0 to 2 with a 0.5 increment, and the solar zenith angles from 0 to 80 deg with a 1-deg increment. The model provides values of global irradiance $E_{324}(\tau,\theta)$ at 324 nm with its direct and diffuse components. Angular response to global irradiance $f_g(\tau,\theta)$ is then calculated using Eq. (3). Cloud transmittance $[C_T = E_{324}(\tau,\theta)/E_{324}(0,\theta)]$ is also derived from the model output. Measured cloud transmittance at 324 nm $[M_T(\tau,\theta)]$ or the ratio of the irradiance that would be measured by the Brewer $[f_g(\tau,\theta)E_{324}(\tau,\theta)]$ to $E_{324}(0,\theta)$ was also estimated from the model:

$$M_T = f_g(\tau,\theta)E_{324}(\tau,\theta)/E_{324}(0,\theta) = f_g C_T .$$

Brewer measurements should be multiplied by the factor $F = 1/f_g$ to adjust for the angular response error. To correct for the error, F should be expressed as a function of the Brewer measurements, for example, as a function of M_T and θ.

Figure 4 illustrates the results of the model calculations. Plots of C_T and f_g as a function of cloud optical depth at different solar zenith angles are shown in Figs. 4(a) and 4(b). Calculations demonstrate that M_T is a monotonic function of τ. Therefore, τ can be expressed as a function of M_T, as shown in Fig. 4(c). The other characteristics can also be represented as functions of M_T. The factor F can also be expressed as a function M_T [Fig. 4(d)], making it possible to derive F from M_T and θ, i.e., from the measurements. Under simplifying assumptions made here, the model calculations show that an aerosol layer or a thin cloud that reduces UV irradiance by 10% or more yields a nearly constant angular response error (about 9%) that is the same for all solar zenith angles. Therefore, F is nearly constant for all zenith angles if $M_T < 0.81$. Figure 5 illustrates the dependence of F on M_T and θ for Brewer 14 as a three-dimensional surface for $M_T > 0.8$.

To correct Brewer data, it is convenient to express the relationship between F, M_T, and θ in a form of parameterization derived from the model calculations. The following parametrization of the factor F from θ (in degrees) and M_T was used:

$$\begin{aligned} &F = 1.096 \quad \text{for } M_T < 0.8 \text{ or } \theta > 80\,\text{deg, otherwise} \\ &F = 1.096 - 2.37(M_T - 0.8)^2 + 0.0805\theta(M_T - 0.8)^2 \\ &\quad - 0.00653\cdot\theta^2\cdot(M_T - 0.8)^2 + 0.000193\cdot\theta^3\cdot(M_T - 0.8)^2 \\ &\quad - 0.00000146\cdot\theta^4\cdot(M_T - 0.8)^2. \end{aligned} \tag{4}$$

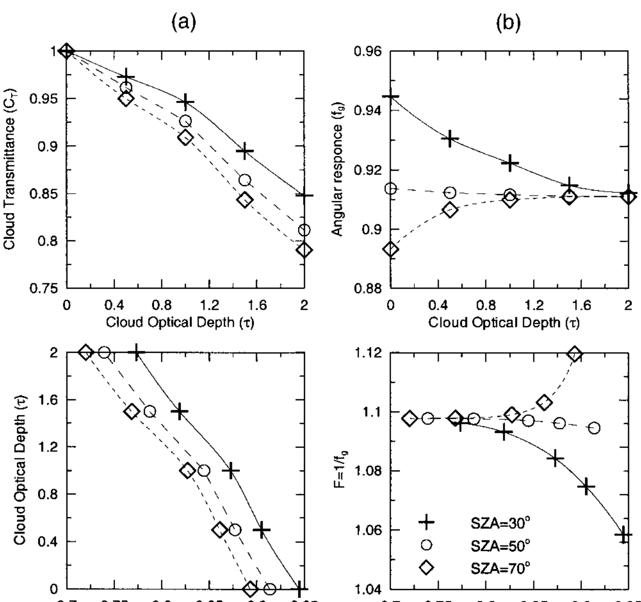

Fig. 4 (a) Calculated from a radiative transfer model cloud transmittance (C_T) and (b) angular response to global irradiance (f_g) as a function of cloud optical depth (τ) at 30, 50, and 70-deg solar zenith angles. Calculations show that measured transmittance (M_T), i.e., the ratio of measured UV irradiance to modeled clear sky irradiance, is a monotonic function of τ. Therefore, (c) τ can be expressed as a function of M_T. Other characteristics including (d) the Brewer correction factor ($F = 1/f_g$) can be also expressed as functions of M_T. Model calculations were performed for τ values between 0 and 2 with 0.5 step.

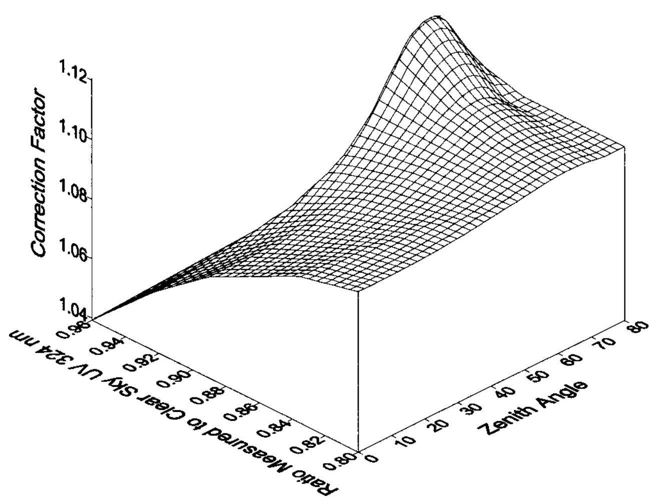

Fig. 5 Calculated correction factor for the Brewer instrument as a function of solar zenith angle and ratio of measured clear-sky UV irradiance at 324 nm. Brewer measurements should be multiplied by the correction factor to correct for the angular response error.

The difference between F values from parametrization in Eq. (4) and estimates of the radiative transfer model is less than 0.005.

Brewer measurements divided by $E_{324}(0,\theta)$ give the M_T values used in Eq. (4). Clear-sky UV irradiance at 324 nm estimated for the Brewer slit function and for the Sun-Earth distance of 1 AU, 1013.25 mb surface pressure, 3% surface reflectivity, TOMS midlatitude (55 °N) profile, 300 DU total ozone, and $\tau=0$ can be parametrized as:

$$E_{324}(0,\theta)=0.5018-4.799\cdot 10^{-6}\cdot \theta-0.000107\cdot \theta^2 +1.333\cdot 10^{-7}\cdot \theta^3+1.455\cdot 10^{-10}\cdot \theta^4 +4.4418\cdot 10^{-11}\cdot \theta^5.$$

The difference between the radiative transfer model output and this parametrization is less than 0.05% for $\theta<64$ deg, less than 0.2% for $\theta<78$ deg, and less than 4% at 89 deg.

Our calculations are for uniform cloud conditions and they do not apply when the UV irradiance exceeds the clear-sky value due to reflection from relatively thick but scattered clouds. Therefore when the value of M_T exceeds $f_g(0,\theta)$, it is replaced in Eq. (4) by $f_g(0,\theta)$. The following parameterization was used for $f_g(0,\theta)$:

$$f_g(0,\theta)=0.9651-0.0004431\cdot \theta+1.1036\cdot 10^{-5}\cdot \theta^2 -9.114\cdot 10^{-7}\cdot \theta^3+9.069\cdot 10^{-9}\cdot \theta^4.$$

Figure 6 (top) illustrates the effect of the angular response correction. All May through August Brewer measurements of UV irradiance at 324 nm at Toronto under a clear sky (cloud amount=0) were compared to the model calculations for clear-sky conditions for this plot. Figure 6 shows the ratio between the measurements and the model as a function of solar zenith angle. The ratio for noncorrected data (the left panel) and for angular response-corrected data (the right panel) is shown. The clear-sky model estimates should represent the upper limit of all measured data, i.e., the ratio should be lower than or equal to 1. It is also expected to have days with clean atmosphere when the ratio should be close to 1. Figure 6 demonstrates that the corrected data have much better agreement with the clear-sky model than the noncorrected data. Angular response measurements were available at the time of this study for only one instrument, Brewer 14. We applied the angular response correction estimated for Brewer 14 to all the other Canadian Brewers. It appears this gives reasonable results as, for example, shown in Fig. 6 (bottom) for Saturna Brewer 12. Nevertheless, some difference in angular response from instrument to instrument is expected, and further measurements of the response of different instruments are required.

4 Difference Statistics

UV irradiance derived from TOMS overpass measurements demonstrates reasonably good agreement when compared to Brewer UV observations that have been corrected for the angular response error. Figure 7 shows daily CIE irradiation (or daily exposure, i.e., irradiance integrated over the entire day) measured by two different Brewer instruments (14 and 15) at Toronto and estimated from TOMS observations in May through June 2000. TOMS-estimated UV reflects large day-to-day variability of daily UV irradiation measured at the ground, although some systematic difference with Brewer data is evident from the plot. The average bias between the UV irradiation derived from TOMS and measured by Brewer 14 is about 9% if the bias is calculated as a mean of the daily percentage differences, and 5.5% if the bias is calculated as a percentage difference between the mean TOMS irradiation values and the mean Brewer values. The correlation coefficient between the Brewer and TOMS irradiation data plotted in Fig. 7 is 0.9. For comparison, the correlation coefficient between the two Brewer sets

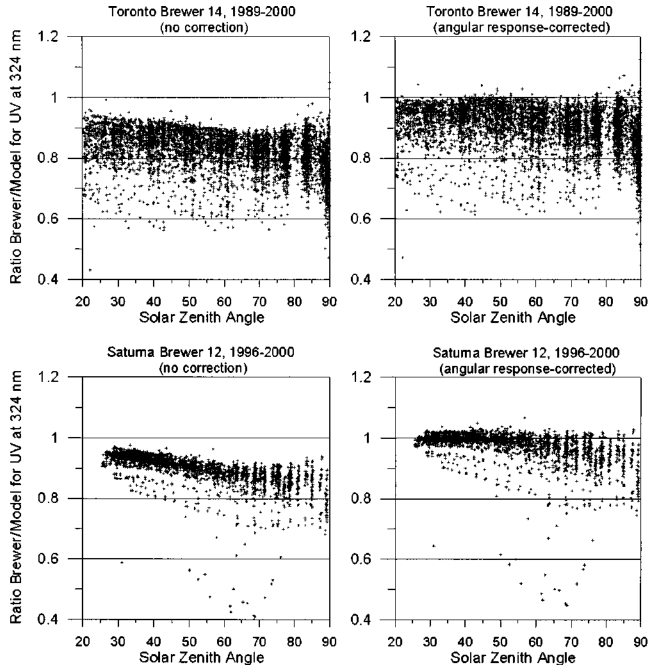

Fig. 6 (top) Ratio between the measured and modeled UV irradiance for Toronto (Brewer 14) and (bottom) Saturna (Brewer 12) clear-sky conditions (cloud amount=0).

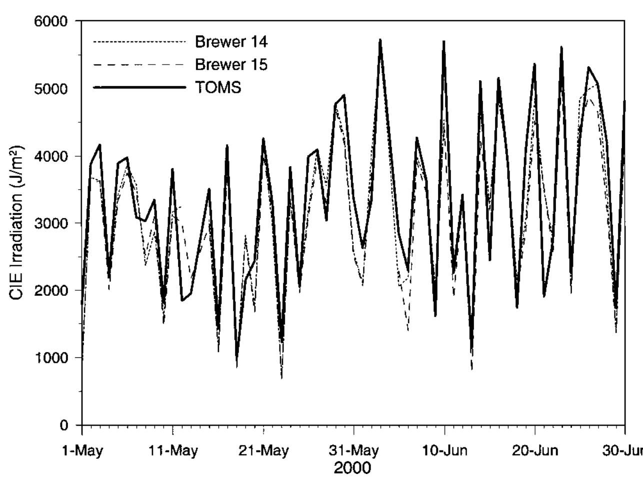

Fig. 7 Daily CIE irradiation measured by Brewer 14 and 15 and estimated from TOMS observations at Toronto in May through June 2000. The correlation coefficient between the measured and derived TOMS irradiation plotted here is 0.9. The standard deviation of the difference between the measured and derived UV is about 16%.

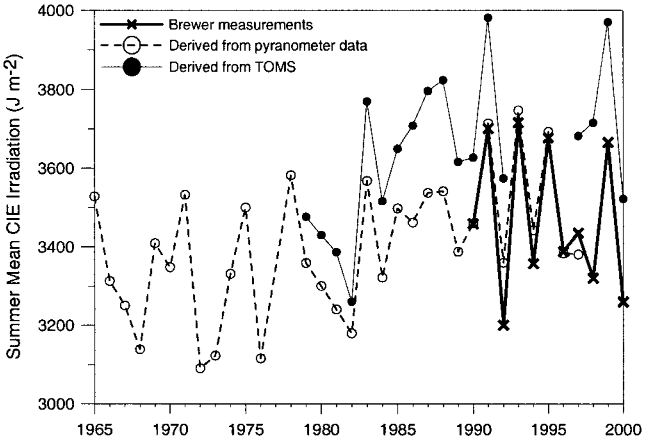

Fig. 8 Summer (May through August) mean daily erythemal (CIE) irradiation at Toronto measured by the Brewer (corrected for angular response data), estimated from TOMS observations and derived from total ozone and pyranometer data.[24,25]

of measurements is 0.99. The standard deviation of the difference between the UV measured by Brewer 14 and the UV derived from TOMS is about 16%. There is also a 2% bias between the two Brewer instruments (Brewer 15 data are lower) that could be explained by a small systematic calibration error, a difference in the instrument angular response, as well as by a random error due to some discrepancy in the measurement schedules of the two instruments.

Summer (May through August) mean values of daily erythemal irradiation measured by the Brewer instrument and estimated from TOMS for Toronto are shown in Fig. 8. The measured summer values in different years are from 5 to 12% lower than the TOMS-derived UV irradiation and the average bias is about 9%. The standard deviation of the difference between the two data sets is about 4%. Good agreement over a longer time interval is seen between TOMS-derived UV and UV irradiance estimated from ground-based total ozone and global solar radiation (pyranometer) measurements using the method described in Refs. 25 and 26. Thus, Fig. 8 demonstrates that the satellite data successfully reproduces year-to-year fluctuation and long-term changes of UV irradiation, although some systematic bias is present.

These examples indicate that even angular response-corrected Brewer UV irradiance measured at Toronto is systematically lower than TOMS-derived UV. Most of the Canadian Brewer sites show a similar bias with TOMS. Table 1 summarizes the differences between Brewer measurements and TOMS overpass erythemal UV irradiance for ten Canadian Brewer sites. The percentage difference in Table 1 is given in percent of TOMS mean irradiation. The standard deviation of the difference between Brewer and TOMS-derived UV is about half that of the natural variability of UV irradiance, confirming that TOMS provides valuable information about variations of UV irradiance. The bias between Brewer and TOMS data also is evident from the table, and its magnitude is different from station to station ranging from 6 to 14.6%, except for one station, Saturna, which shows a slightly negative bias with TOMS.

There are many possible explanations for the bias. It could be caused by Brewer instrument-related problems or site-specific albedo or cloud conditions, as well as by some residual effects of ozone, SO_2, or by aerosol absorption unaccounted for by the TOMS algorithm. Separation of those different effects would help us to understand the nature of the TOMS-Brewer difference. Some separation can be achieved by looking at the TOMS-Brewer differences at different wavelengths and for different cloud conditions. Two wavelengths, 305 nm with very strong ozone absorption, and 324 nm with negligible ozone absorption were

Table 1 Summer (June through August for Churchill and May through August for all others) noon CIE irradiation statistics for Brewer stations. Summer time mean noon (11 am to 1 pm) erythemal (CIE) spectrally weighted irradiance data for Canadian stations. Average of TOMS data were used for days when several overpasses were available. The percent values in columns 9, 10, and 11 represent the mean TOMS-Brewer difference (column 7), the standard deviation of the difference, and the standard deviation of UV variability expressed in percentage of the mean TOMS noon irradiance (column 6).

Station	Latitude	Longitude	Mean Brewer irradiation (mW/m^2)	Brewer standard deviation (mW/m^2)	Mean TOMS irradiation (mW/m^2)	Mean TOMS-Brewer difference (mW/m^2)	Standard deviation of the TOMS-Brewer difference (mW/m^2)	Mean TOMS-Brewer difference (%)	Standard deviation of the TOMS-Brewer difference (%)	Brewer standard deviation (%)
Churchill	58.8 °N	94.1 °W	95.3	36.8	101.4	6.1	19.9	6.0	19.6	36.3
Edmonton	53.6 °N	114.1 °W	122.4	44.4	132.1	9.8	21.5	7.4	16.3	33.6
Goose Bay	53.3 °N	60.4 °W	93.6	42.3	107.2	13.6	23.8	12.7	22.2	39.5
Saskatoon	52.1 °N	106.7 °W	126.0	44.9	140.9	14.9	28.8	10.5	20.4	31.8
Regina	50.2 °N	104.7 °W	138.6	48.7	150.6	12.0	26.9	7.9	17.9	32.4
Winnipeg	49.9 °N	97.2 °W	129.1	45.4	142.7	13.6	25.5	9.5	17.9	31.8
Saturna	48.8 °N	123.1 °W	144.4	51.1	143.6	−0.8	24.0	−0.6	16.7	35.6
Montreal	45.5 °N	73.8 °W	138.3	52.8	146.6	8.4	25.6	5.7	17.5	36.0
Halifax	44.7 °N	63.6 °W	135.3	54.9	148.7	13.4	28.8	9.0	19.4	37.0
Toronto	43.8 °N	79.5 °W	143.6	54.8	164.6	21.0	30.6	12.8	18.6	33.3

analyzed in this study in addition to the erythemally weighted UV irradiance.

The Brewer and TOMS measure different physical characteristics. The Brewer provides nearly instantaneous measurements of spectral UV irradiance at a single point, while the TOMS-based algorithm gives an estimate on the average UV irradiance over a large, up to 100×100 km, area. As a result, the distribution of UV irradiance values measured by the Brewers is different from the distribution of the TOMS-derived values. Figure 9 shows the histogram of different cloud transmittance values (C_T) at 324 nm for Brewer and TOMS values. The number of Brewer measurements is higher for almost every bin if $C_T<1$. TOMS estimates heavy clouds ($C_T<0.25$) less than half as frequently as the Brewer. Figure 9(b) is based on data from nine Canadian stations. Histograms for individual stations show similar distributions, as shown by the histogram for Toronto [Fig. 9(a)]. Heavy clouds that cause very low C_T values at the ground do not cover the entire TOMS field of view, and TOMS C_T is therefore higher. For rare cases when Brewer $C_T>1$ due to reflection from broken clouds, TOMS-derived UV is lower than the ground measurements.

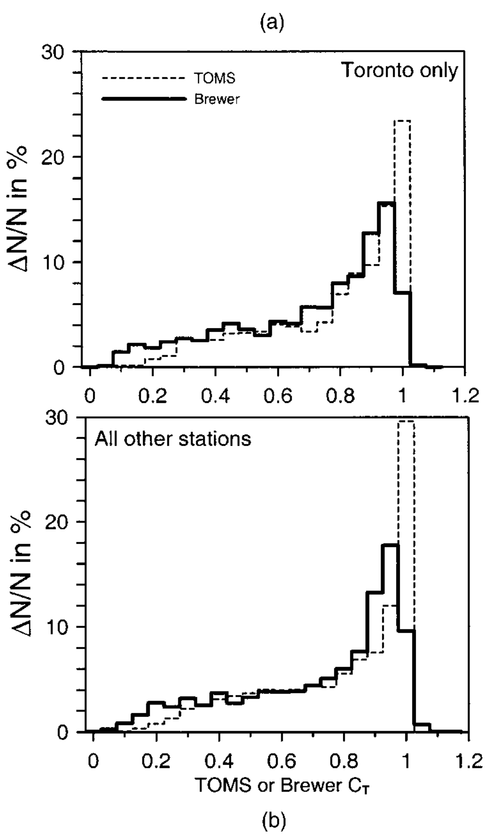

Fig. 9 Relative frequency of different C_T values in Brewer and TOMS observations estimated using Brewer measurements ±1 h around noon and TOMS overpasses for Canadian stations. Relative numbers of TOMS observations for different TOMS C_T values and relative number of Brewer measurements for different Brewer C_T values are plotted using the same horizontal axes. Data are binned with 0.05 step by C_T. The histograms were produced using 2,200 pairs of Brewer measurements and TOMS overpass estimates for Toronto (a) and 11,941 pairs for nine other Canadian stations (b).

UV irradiance distribution within the TOMS pixel is inhomogeneous, and Brewer measurements at different places within the TOMS pixel yield different results. An ideal way to compare ground-based and satellite data would be to install a large number of ground-based sensors within the TOMS pixel and compare their average to the TOMS-derived UV. In practice this is very difficult. Instead, TOMS UV irradiance estimated for the same conditions can be compared to the average of corresponding Brewer measurements. UV irradiance depends mostly on ozone, cloud conditions, and the solar zenith angle. Ozone absorption effects can be neglected if UV irradiance at 324 nm is considered. Dependence on the solar zenith angle can be accounted for if cloud transmittance (C_T) is considered instead of the irradiance itself. The average of all Brewer C_T values measured at a given value of the TOMS C_T should be equal to that TOMS C_T if there is no systematic difference between Brewer and TOMS UV data. The scatter in the relationship is caused by the inhomogeneous cloud distributions as well as measurement and algorithm deficiencies.

Figure 10 shows the average and the median of the TOMS-Brewer difference to TOMS UV irradiance ratio plotted as a function of TOMS C_T. The data are binned by C_T with 0.05 increment. The average difference shows little dependence on C_T, and TOMS in general overestimates Brewer-measured UV by 5 to 10%. The median value, however, has a different behavior. The median value is lower than the mean for $C_T>0.6$, i.e., for clear sky and light, or broken clouds and higher than the mean for $C_T<0.5$. For heavy clouds ($C_T<0.4$), the majority of Brewer measurements are 15 to 20% lower than TOMS, although in some cases the Brewer UV is much higher than TOMS, bringing the overall average to about 7% level (Fig. 11).

The asymmetry of the TOMS-Brewer difference distribution makes the result of the comparison very sensitive to how the two data sets are compared, and subject to possible misinterpretation. Figure 12 shows the same plot as Fig. 10, but for the difference relative to the Brewer values. It

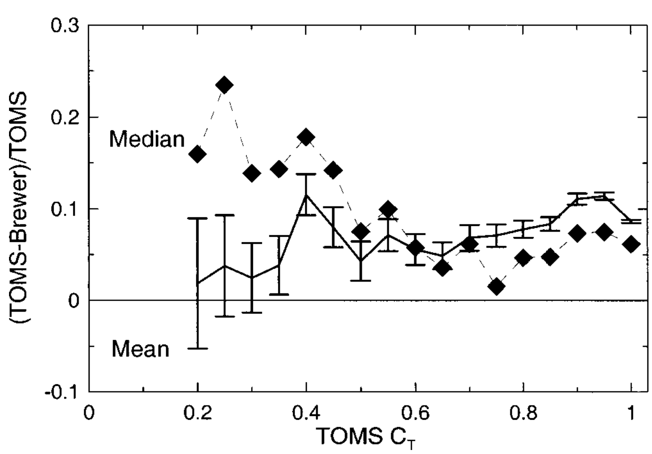

Fig. 10 The mean and median TOMS-Brewer difference of the noon UV irradiance at 324 nm divided by TOMS-estimated UV irradiance as a function of TOMS cloud transmission (the ratio between measured and clear-sky UV irradiance). The data are binned by C_T values with 0.05 increments. At least 30 pairs of measurements were required for each bin. The error bars indicate one standard error interval. All stations except Saturna were used for the plot.

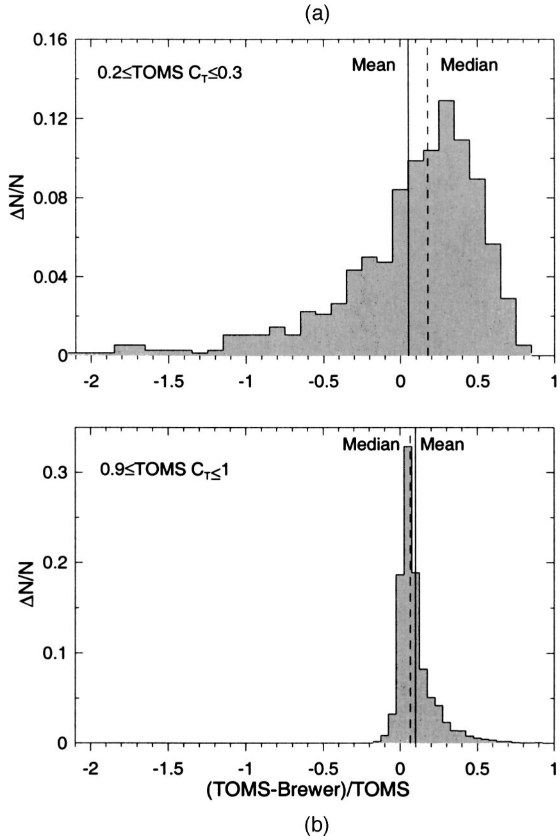

Fig. 11 (a) Relative frequency of different values of the TOMS minus Brewer difference devided by TOMS estimates for UV at 324 nm for TOMS cloud transmittance between 0.2 and 0.3 (heavy clouds) and (b) between 0.9 and 1 (mostly clear sky). The mean and median values are also shown. About 1% of all data is located between −3 and −2 and are not shown in the plot. All stations except Saturna were used for the plot.

shows that the bias could be as high as 40%. Caution should be also exercised if the relationship between ground-based measured and satellite-derived UV irradiance is established using linear regression with parameters estimated with the least squares method. The method is sensitive to asymmetry of the distribution. It should be mentioned that the error bars in Figs. 10 and 12 were calculated assuming that the errors are independent. It was obviously not true, because a part of the TOMS-Brewer difference is caused by the Brewer calibration uncertainties that are highly autocorrelated.

Brewer UV irradiance can be much higher than the TOMS-estimated UV under mostly cloudy skies if a Brewer measurement is taken during a break in the clouds. In the majority cases, however, Brewer values are lower than TOMS. This can be seen if the cases of broken clouds are excluded. The TOMS-Brewer difference was calculated for different cloud amounts [Fig. 13(b)]. The difference is between 0.04 and 0.06 if the cloud amount is less then 8, i.e., it is nearly the same as for clear-sky conditions and below the average. For overcast conditions (cloud amount =10), the difference is more than 0.12. This again reflects the fact that the Brewer measured and TOMS-derived UV irradiances are different physical parameters. The latter represents UV irradiance estimated over a large area. There is always a possibility of clouds within the TOMS pixel when the sky is clear over the Brewer site and the TOMS-derived irradiance is on average lower than the clear-sky irradiance. Similarly, TOMS-derived UV irradiance on average is higher than the average under overcast conditions at the measuring site. Figure 13 also shows the mean ratio of Brewer measured irradiance to the modeled clear-sky irradiance as a function of the cloud amount and the mean cloud optical depth estimated from TOMS measurements as a function of the cloud amount.

The TOMS-Brewer difference expressed in percent of the TOMS-derived irradiance (or the Brewer to TOMS ratio) does not have a strong dependence on the TOMS C_T, which suggests examining the TOMS-Brewer bias in two classes of C_T or reflectivity values, rather than analyzing it as a function of C_T. The whole dataset was therefore divided into two nearly equal subsets: clear-sky or thin cloud conditions with the TOMS reflectivity less than 0.2, and cloudy conditions with reflectivity greater than 0.2. The

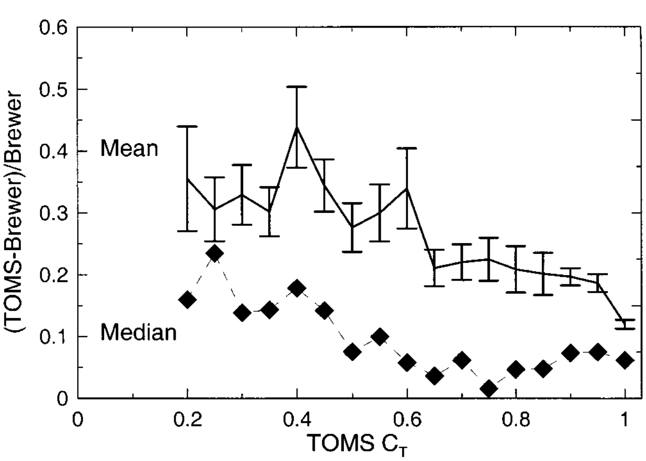

Fig. 12 Same as Fig. 10, but for the difference divided by Brewer-measured UV irradiance.

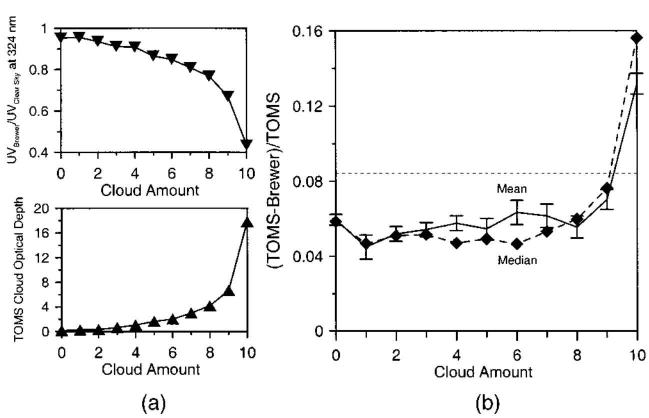

Fig. 13 (a) The ratio between Brewer measurements and clear sky irradiance and cloud optical depth estimated from TOMS observation as a function of the cloud amount (b). The mean and median TOMS-Brewer difference of the noon UV irradiance at 324 nm relative to TOMS-estimated UV irradiance as a function of the cloud amount. The error bars indicate one standard error interval. The dashed line indicates the average value. All stations except Saturna were used for the plot. About one third of all measurements were taken under overcast (cloud amount=10) conditions.

Table 2 Summer (June through August for Churchill and May through August for all others) mean TOMS-Brewer difference in noon irradiation in percent of TOMS UV irradiation. Summer time mean noon (11 am to 1 pm) erythemal (CIE) spectrally weighted irradiance data for Canadian stations. The average and the standard deviations were calculated using all stations except Saturna.

Station	Number of days	324 nm	305 nm	CIE	Number of days	324 nm	305 nm	CIE
	Data with TOMS reflectivity <0.2				Data with TOMS reflectivity $\geqslant 0.2$			
Churchill	190	9.2	12.1	9.3	250	2.0	4.7	1.3
Edmonton	345	9.7	11.8	9.6	299	4.8	7.1	4.3
Goose Bay	111	9.4	11.5	9.4	273	13.9	16.7	13.8
Saskatoon	306	10.5	13.6	11.9	246	7.1	10.7	8.5
Regina	310	9.5	10.6	9.2	214	5.8	8.3	5.8
Winnipeg	308	9.9	12.4	10.7	253	6.9	8.8	6.9
Saturna	384	1.9	1.8	0.9	379	−2.4	−3.0	−4.1
Montreal	251	8.5	8.1	6.1	244	5.4	7.1	4.0
Halifax	252	8.6	12.5	10.1	271	4.8	10.0	6.8
Toronto	502	10.1	14.5	12.2	460	11.2	17.1	14.0
Average		9.5	11.9	9.8		6.9	10.1	7.3
Standard Deviation		0.7	1.8	1.8		3.6	4.3	4.3

results are shown in Table 2 for noon UV irradiance at 305 and 324 nm and erythemally weighted UV.

For clear skies (TOMS reflectivity <0.2), the Brewer-TOMS bias at 324 nm is about 9.5% for the subset for all stations except Saturna. The spread of the bias values in this subset for UV at 324 nm is very small, from 8.5 to 10.5%. This 2% spread can be easily attributed to the instrument calibration uncertainties or to the difference in angular response for individual Brewer instruments. No significant difference was found when Nimbus 7 and Earth probe TOMS data were examined separately.

The bias is slightly (insignificantly) smaller for cloudy conditions (TOMS reflectivity >0.2), and the spread between the Brewer sites is higher than in clear-sky conditions. The difference in the angular response between Brewers could be one of the factors responsible for higher spread, because effects of angular response error are higher for diffuse radiation than for direct solar radiation at low zenith angles seen in summer at noon. Enhancement of UV absorption within the cloud by aerosols and local cloud conditions, such as the lake effect at Toronto, also could be contributing factors.

It is unlikely that the negative bias at the Saturna Island station is caused by the Brewer instrument problems (e.g., calibration error, different angular response error), because three different Brewer instruments have been used at that site between 1990 and 2000, and they all show similar differences with TOMS. All annual mean TOMS-Brewer bias values for noon UV irradiance at 324 nm are between 5 and −1%. For comparison, the same numbers for Toronto are 14 and 8%. The relatively clean air with low aerosol and urban pollution loading at this island site on the West Coast of British Columbia is most probably the cause of relatively higher levels of UV irradiance there.

The bias is greater at 305 nm than at 324 nm, indicating some wavelength dependence in the reduction of clear-sky UV irradiance caused by pollution or aerosol absorption. The difference is the smallest at Saturna Island and the largest at Toronto and Halifax. The last two sites are located in polluted urban areas. The difference between UV irradiance 305 and 324 nm can be explained by, for example, small (1 to 2 DU) amounts of SO_2 in the lower troposphere that cannot be detected from TOMS. This explanation is viable because relatively high amounts of SO_2 were commonly seen at Toronto as well as at the Halifax site, which is located 3 km from a power plant. In addition to SO_2, the absorbing aerosols have spectral dependence of their transmittance.

Figure 6 demonstrates that the measured UV irradiance can sometimes be 10 to 30% lower than the modeled clear-

Table 3 Summer (June through August for Churchill and May through August for all others) mean TOMS-Brewer difference in noon irradiation in percent of TOMS UV irradiation. Tau=0, cloud amount=0. Summer time mean noon (11 am to 1 pm) erythemal (CIE) spectrally weighted irradiance data for Canadian stations. The average and the standard deviations were calculated using all stations except Saturna.

Station	Number of days	324 nm	305 nm	CIE
Churchill	9	6.5	8.2	5.8
Edmonton	19	5.3	7.2	5.2
Goose Bay	1			
Saskatoon	13	6.1	8.4	7.5
Regina	19	5.0	5.9	4.6
Winnipeg	11	6.3	7.7	6.6
Saturna	50	1.3	1.2	0.5
Montreal	2			
Halifax	14	5.6	9.0	7.1
Toronto	19	3.9	8.5	6.1
Average		5.5	7.8	6.1
Standard Deviation		0.9	1.0	1.0

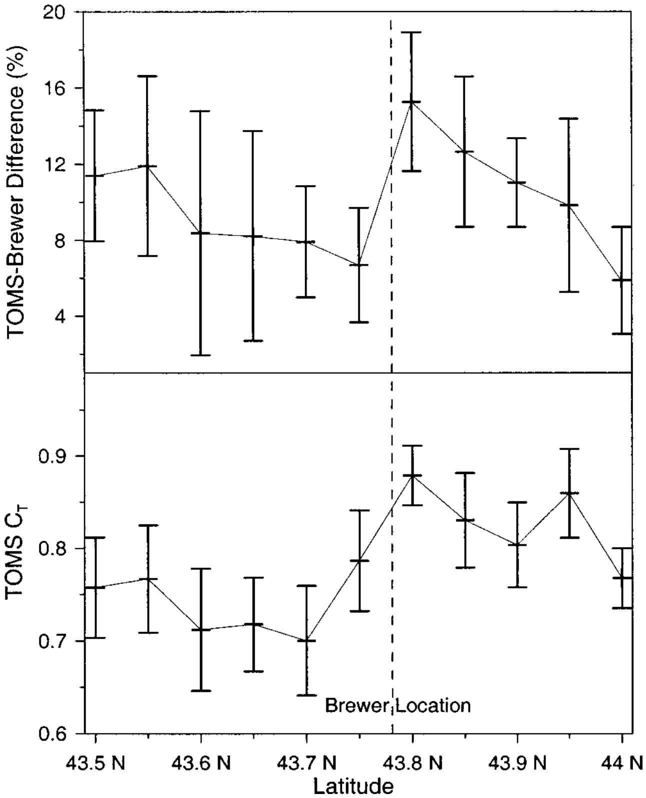

Fig. 14 Cloud transmittance over Toronto in May through August estimated from TOMS overpass data as a function of latitude. The Brewer location at Toronto is shown by the vertical dashed line. Error bars indicate one standard error interval. Overpasses taken within ±0.05 deg around the Toronto Brewer site longitude were used for the comparison. It is more common to see clouds south of the Toronto Brewer site (over Lake Ontario) than north of the site.

sky UV irradiance, even if the cloud amount is zero. Cloud amount measurements are 1 h apart. It is possible that some of the low values of the measured UV irradiance are caused by clouds being present between the cloud amount measurements. However, in most cases the difference is likely due to very thin clouds, haze, aerosols, or gaseous pollution. Some of these factors affecting the UV can also be detected from TOMS, while others, such as boundary layer aerosols, cannot. The last could cause a bias when TOMS-derived UV is compared with the measurements. The bias can be estimated by considering the measurements when TOMS does not see any clouds at the ground (Table 3).

The bias shown in Table 3 is smaller than the bias estimated for TOMS reflectivity <0.2 (Table 2). This is partially due to the distribution function asymmetry effect shown in Fig. 11: selection of cloud amount=0 conditions excludes cases of relatively low Brewer UV values caused by small clouds that have little effect on TOMS reflectivity, which is measured over a large area (up to 100×100 km).

About 4 to 6% bias for the 324-nm wavelength can be seen under clear-sky conditions at all stations except one. This bias is likely caused by aerosol absorption because ozone and SO_2 absorption is negligible at 324 nm, and cloud effects have been excluded. When absorbing aerosols occur in the absence of clouds, the TOMS algorithm treats them as clouds, overestimates their transmittance at 324 nm, and overestimates it even more at 305 nm. The Saturna Island station measurements again show a much lower difference with the TOMS-derived UV.

Table 3 shows that Toronto Brewer measurements have below average difference with TOMS under clear-sky conditions (3.9 versus 5.5% for UV at 324 nm), while in general the difference is above average at Toronto (Tables 1 and 2). The Brewer site at Toronto is located about 30-km north of Lake Ontario, which causes some asymmetry in the cloud distribution over the site. Figure 14 shows cloud transmittance over Toronto estimated from TOMS overpass data as a function of latitude. It is more common to see clouds south of the Toronto site than north of it, and it is more typical that the clouds block the southern half of the sky over Toronto, reducing the direct irradiance.

5 Summary and Discussion

TOMS can provide useful information on long-term and major short-term UV variations (Figs. 7 and 8). It was found that the standard deviation of the difference between the erythemally weighted noon UV irradiance measured by the Brewer instruments and derived from TOMS overpass data is much smaller than the natural variability of UV irradiance (Table 1).

Examples discussed in this study demonstrate that the difference between UV irradiance measured by the Brewer instruments and derived from TOMS observations depends on a number of factors. Some of them, such as the angular response error or calibration errors, are instrument-specific and could be different from one Brewer to another. Others, for example the differences in clear-sky conditions, are site specific and depend on local microclimate, surrounding terrain, local aerosol, and pollution levels. Finally, the difference in how clouds affect ground and satellite measurements yields a difference in distribution of UV irradiance values. This also can be a source of discrepancies between the two types of UV data.

A large part of the Brewer-TOMS difference can be attributed to the Brewer angular response error. This error depends on the solar zenith angle and cloud conditions, and is different from instrument to instrument. This error is about 9% for cloudy conditions and from 5 to 12% for clear skies for Brewer 14. The error can be corrected using radiative transfer model estimates if the instrument response is known.

A 6% bias between erythemally weighted UV irradiance derived from TOMS data and measured by the Brewers can be seen for clear-sky conditions at most Canadian sites, even when the data are corrected for the Brewer angular response error. However, the bias was close to zero at one station (Saturna Island), probably due to the much cleaner air there. There is a larger bias in overcast conditions.

Results of this study confirm previous findings[11] that the ground CIE UV irradiance estimates from TOMS data demonstrate better agreement with the measurements at sites with low levels of pollutions (Saturna). The systematic differences of nearly the same amplitude between Brewer and TOMS-derived UV irradiance can be seen in the CIE-integrated irradiance and in UV irradiance at 324 nm, i.e., at the wavelength where ozone and SO_2 absorption is low. This indicates that these gaseous pollutants are not the main factors causing the difference, although they do contribute to underestimation by the TOMS retrieval at sites with high levels of these pollutants (Toronto, Halifax). It is likely that difference between the Brewer-measured and TOMS-derived UV irradiance is caused by tropospheric aerosol absorption.

The difference between the Brewer-measured and TOMS-derived UV irradiance at 324 nm under mostly clear-sky conditions (TOMS reflectivity <0.2) is nearly the same at almost all Canadian sites. This suggests the difference is caused by a large scale effect that can be studied, and the results could be incorporated into a future improved TOMS algorithm.

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Biographies and photographs of the authors not available.