

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

Comparison of Brewer UV irradiance measurements with TOMS satellite retrievals

Vitali Fioletov, James Kerr, David Wardle, Nickolay Krotkov, Jay Herman

Vitali E. Fioletov, James B. Kerr, David I. Wardle, Nickolay A. Krotkov, Jay R. Herman, "Comparison of Brewer UV irradiance measurements with TOMS satellite retrievals," Proc. SPIE 4482, Ultraviolet Ground- and Space-based Measurements, Models, and Effects, (17 January 2002); doi: 10.1117/12.452952

SPIE.

Event: International Symposium on Optical Science and Technology, 2001, San Diego, CA, United States

Comparison of Brewer UV irradiance measurements with TOMS satellite retrievals

Vitali E. Fioletov*, James B. Kerr, and David I. Wardle

Meteorological Service of Canada, Toronto, Canada

N. Krotkov,

Goddard Earth Sciences and Technology Center, Univ. of Maryland Baltimore County

J.R. Herman

NASA Goddard Space Flight Center

ABSTRACT

Comparison of measured UV irradiance with estimates from satellite observation is potentially effective for the validation of the data from the two sources. Data from 10 Canadian Brewer sites were compared in this study with noon UV irradiance estimated from TOMS measurements. In general, TOMS estimates can successfully reproduce long-term and major short-term UV variations, although there are some systematic differences between the measurements at the ground and satellite-retrieved UV irradiance. Up to 9% of the Brewer-TOMS difference can be attributed to the Brewer cosine response error. This error depends on the solar zenith angle and cloud conditions, and is different from instrument to instrument. When the cosine response of the Brewer instrument is considered and applied, the Brewer data are still lower than TOMS-estimated UV irradiance at most of the sites by 10% on average. The bias for clear-sky condition is smaller, about 4%, than for overcast conditions (about 20% on average) with some wavelength dependence. The bias was close to 0 at one station (Saturna Island), possibly due to its much cleaner air.

Keywords: UV irradiance, Brewer, TOMS, cloud amount.

1. INTRODUCTION

Satellite measurements are widely used to estimate UV irradiance at the ground¹⁻⁹. Space borne 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 a compelling choice among satellite instruments used for UV retrieval. TOMS can provide both total ozone and cloud reflectivity data from the late 1970s. Recently developed methods can also account for UV absorption by atmospheric aerosols¹⁰.

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 hemisphere¹¹.

Systematic differences between UV irradiance measured at 10 Canadian Brewer sites and UV estimates from TOMS measurements have been analyzed in this study. Meteorological cloud amount data measured at or close to Brewer sites were also used to study effects of the cloud conditions on the difference between the measured and TOMS-derived UV irradiance.

*Vitali.Fioletov@ec.gc.ca; fax 1 416 739 4281; <http://exp-studies.tor.ec.gc.ca>; Meteorological Service of Canada (ARQX), 4905 Dufferin Street, Downsview, Ontario, M3H 5T4, Canada

2. INSTRUMENTS AND DATA SETS

UV irradiance measurements made by 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). In its normal UV routine, the Brewer scans from 290 to 325 nm and then back to 290 nm. The integration time is approximately one second for each wavelength, the sampling interval is 0.5 nm and the double scan takes about 8 minutes. The reported units are $\text{mWm}^{-2}\text{nm}^{-1}$. 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 in 1989-1994, typically, ~20 per day increasing in 1995-1999 to up to 50 per day. The erythemal action spectrum used here was determined by the Commission internationale de la 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 corrections to calculated clear-sky UV irradiance F_{clear} . The calculation procedure is based on table lookup and cloud/non-absorbing aerosol correction or absorbing aerosol correction. Calculation of F_{clear} in the UV range from satellite-derived spectral extraterrestrial solar irradiance and NASA's TOMS measurements of total column ozone, aerosols and surface reflectivity was previously described in the literature^{10,12}, including estimates of the various error sources. The exact correction would require complete characterization of the optical state of the atmosphere and the surface during the course of the day (for daily exposure calculations). The complete information is never available from the satellite data alone. Therefore, the correction factor (C_T) has to be estimated using limited information available from the single satellite measurement at the near-noon overpass time. The TOMS UV algorithm estimates daily exposures assuming no diurnal changes in C_T factor ("frozen clouds and aerosols"). The type of correction (specific C_T algorithm) is selected based on the two threshold values of the TOMS aerosol index (AI) (calculated from 340nm and 380nm radiances in case of Nimbus 7 TOMS and from 331nm and 360nm in case of Earth Probe TOMS) and Lambertian Equivalent Reflectivity (LER) (360nm or 380nm). The surface albedo is estimated using the TOMS monthly Minimum Lambertian Effective surface Reflectivity (MLER) global database^{13,14,15}.

Summer (June-August for Churchill, May-August for all other stations) data only were analyzed in this study to avoid problems related to effects of high snow albedo on the TOMS UV retrievals. Meteorological cloud amount data measured at or close to Brewer sites were also used as an independent source of information on cloud conditions. Cloud amount is measured every hour.

To avoid problems related to changes of the cloud cover throughout the day we compare Brewer measurements around noon with TOMS-derived UV irradiance. TOMS overpass values of erythemally weighted UV and UV irradiance at 305 and 324 nm calculated for the Brewer sites were analysed. The average UV irradiance measured by the Brewer instruments between 11 am and 1 pm local solar time was used in the comparison. The mean zenith angle of the Brewer measurements, TOMS total ozone, aerosol index and reflectivity were used as input parameters for the TOMS overpass UV irradiance calculation. The use of the mean Brewer zenith angle instead of calculation UV irradiances at the exact time of the Brewer measurements with averaging the calculated values may introduce some systematic error (up to 1-2%), but this error is small compared to the other sources of the Brewer-TOMS differences described here.

3. COSINE RESPONSE ERROR OF BREWER UV MEASUREMENTS

One source of potential systematic errors in the Brewer measurements is well known and is related to the cosine response error¹⁶. The angular response of the Brewer instrument is different from an ideal cosine function. In many cases it results in underestimation of the measured irradiances, and requires a special correction. Depending on the wavelength and on the aerosol and cloud condition, the cosine correction was previously estimated¹⁶ for Brewer instrument 86 to be in the range from 2% to 7%. The error, however, could be different from one instrument to another. The cosine response function of Brewer instrument 14 was measured for this study. Brewer 14 is the main instrument for UV measurements in Toronto and it provides a continuous record of spectral UV irradiance data from 1989. It was found that the response of the Brewer 14 instrument illuminated by direct source can be approximated by $\cos^{1.195}(Z)$ function, where Z is the vertical incidence angle of the direct source. This approximation makes it pos-

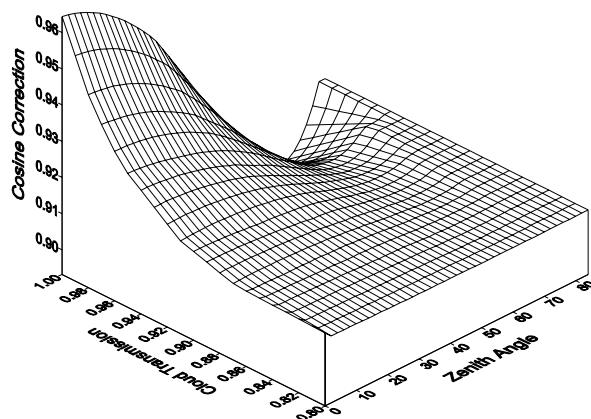


Figure 1. Calculated cosine correction for Brewer #14 as a function of cloud transmittance function and solar zenith angle.

or a thin cloud that reduces UV irradiance by less than 10% result in constant cosine error (about 9%) and independent of the solar zenith angle. For clear sky conditions the error is from 4% at $\text{SZA}=0^\circ$ to about 11% at $\text{SZA}=65^\circ$. The results of Figure 2 can be used to correct the Brewer measurements. The measured cloud transmittance is, however, not the same as the transmittance used in Figure 2, because the measured irradiance has not yet been corrected for the cosine error. Therefore, the results of Figure 2 should be used recursively.

Figure 2 illustrates the effect of cosine correction. For this plot all Brewer measurements of UV irradiance at 324 nm at Toronto under clear sky (cloud amount=0) were compared to the model calculations for clear sky conditions. Figure 2 shows the ratio between the measurements and the model as a function of solar zenith angle. The ratio for non-corrected (the left panel) and for cosine 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 1. It is also likely to have

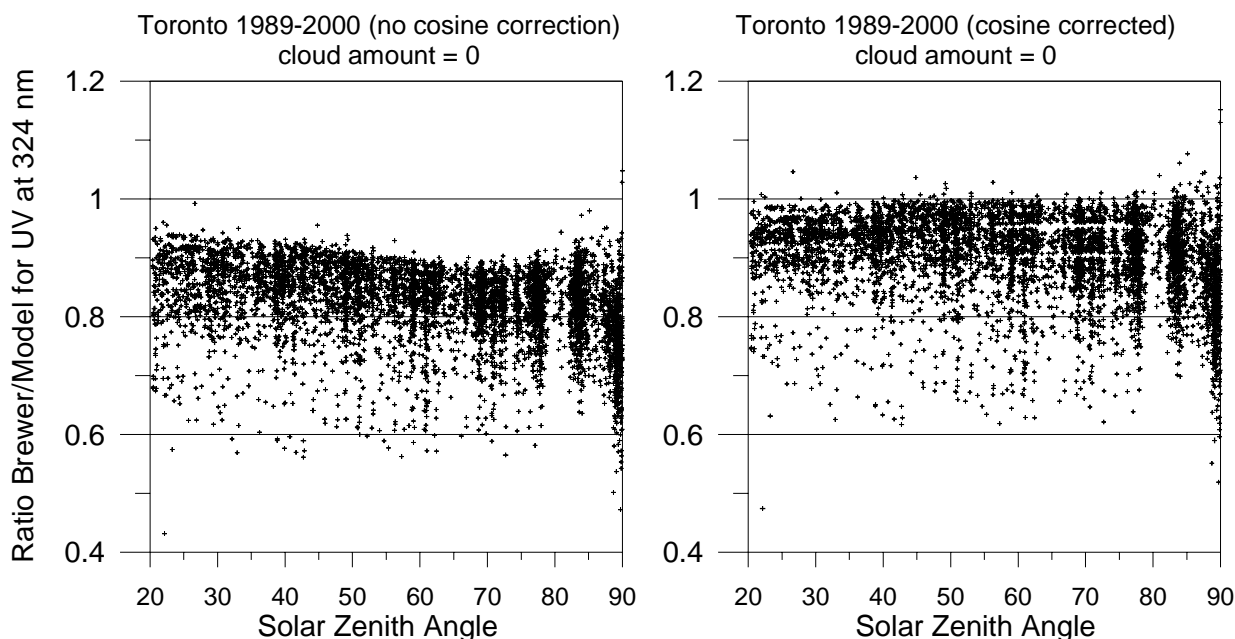


Figure 2. Ratio between the measured and modeled UV irradiance for Toronto clear sky conditions (cloud amount=0).

sible to calculate the error in the measurements for different cloud conditions and then correct the data. The calculations were done for different optical thickness of the uniform clouds ranging from 0 to 5. It is more convenient from the practical point of view to express the correction factor as a function of cloud transmittance (i.e., the ratio of the irradiance to its clear sky value) instead of cloud optical thickness. Figure 1 shows the cosine correction factor as a function of the solar zenith angle (SZA) and cloud transmittance. The correction factor has small dependence on wavelength that was neglected in this study. Even an aerosol layer

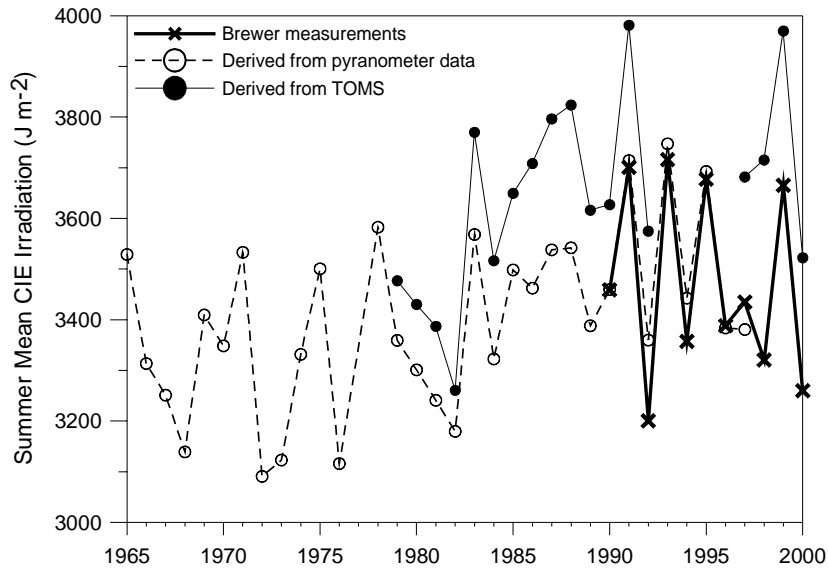


Figure 3. Summer (May-August) mean daily erythema (CIE) irradiation at Toronto measured by the Brewer (cosine-error corrected data), estimated from TOMS observations and derived from total ozone and pyranometer data. The standard deviation of the difference between measured monthly mean daily irradiation values and those derived from TOMS data is about 4%.

days with clean atmosphere when the ratio should be close to 1. Figure 2 shows that the cosine corrected data have much better agreement with the clear-sky model than non-corrected data. Cosine response measurements were available at the time of this study for only one instrument, Brewer 14. We applied the cosine-error correction estimated for Brewer 14 to all other Canadian Brewers, although some difference in cosine response from instrument to instrument is expected. Further measurements of the response of different instruments are required.

Summer mean values of erythema daily irradiation measured by the Brewer instrument and estimated from TOMS for Toronto are shown in Figure 3. TOMS can successfully reproduce year-to-year fluctuation in UV irradiation

variations, although there is a constant systematic bias. The same 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

Table 1. Summer (May-August) Noon CIE Irradiance Statistics for Brewer Stations.

Station	Latitude	Longitude	Mean Brewer Irradiation (mW/m ²)	Brewer Standard Deviation (mW/m ²)	Brewer Standard Deviation (%)*	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 (%)**	Ratio **/*
Churchill	58.8°N	94.1°W	94.3	37.6	39.9	6.5	20.3	6.9	21.5	0.54
Edmonton	53.6°N	114.1°W	121.9	45.8	37.6	10.3	22.4	8.4	18.4	0.49
Goose Bay	53.3°N	60.4°W	92.2	42.8	46.4	14.8	24.2	16.1	26.2	0.57
Saskatoon	52.1°N	106.7°W	124.6	45.2	36.3	16.0	29.6	12.8	23.7	0.65
Regina	50.2°N	104.7°W	138.3	49.5	35.8	12.6	27.7	9.1	20.0	0.56
Winnipeg	49.9°N	97.2°W	128.2	46.7	36.5	14.6	26.2	11.4	20.4	0.56
Saturna	48.8°N	123.1°W	145.8	53.8	36.9	-2.1	25.4	-1.5	17.4	0.47
Montreal	45.5°N	73.8°W	136.7	53.9	39.5	10.3	26.8	7.5	19.6	0.50
Halifax	44.7°N	63.6°W	134.0	55.8	41.6	15.1	29.5	11.3	22.0	0.53
Toronto	43.8°N	49.5°W	142.6	55.7	39.1	22.8	31.9	15.9	22.3	0.57

Summer time mean noon (11 am-1 pm) erythema (CIE) spectrally weighted irradiance data for Canadian stations. Summer data were used in order to avoid large errors in TOMS derived irradiance due to snow cover. The percent values in column 9 and 10 represent the mean Toms-Brewer difference (column 7) and the standard deviation of the difference expressed in percentage of the mean Brewer noon irradiance (column 4). The last column shows the ratio of the standard deviation of the TOMS-Brewer difference to the standard deviation of the irradiance natural variability.

Table 2. The bias in percent between TOMS and Brewer UV irradiance at 305 and 324 nm for clear sky conditions (cloud amount=0) and TOMS estimated cloud optical depth=0

Station	Number of days	UV at 324 nm	UV at 305 nm	Difference 324 vs. 305
Churchill	19	4.9	6.1	-1.2
Edmonton	38	4.5	7.3	-2.8
Saskatoon	29	7.9	10.0	-2.1
Regina	35	4.2	5.3	-1.2
Winnipeg	19	6.5	6.6	-0.2
Saturna	81	-1.7	-1.8	0.2
Halifax	25	4.1	7.3	-3.2
Toronto	26	1.7	6.3	-4.6
Average		4.0	5.9	-1.9

Note: Montreal and Goose Bay stations do not have enough data to estimate the bias.

(pyranometer) measurements using the method described in ^{17,18}.

Table 1 summarizes the differences between Brewer measurements and TOMS overpass erythemal UV irradiance for 10 Canadian sites. The bias between Brewer and TOMS data is evident from the table and the magnitude of the bias is different from station to station. The standard deviation of the difference between Brewer and TOMS-derived UV is much smaller than the natural variability of UV irradiance, i.e., TOMS could provide valuable information even about day-to-day variations in UV irradiance.

4. DIFFERENCE IN CLEAR SKY UV IRRADIANCE

Figure 2 also shows that the measured UV irradiance can sometimes be 10-30% lower than the modeled clear-sky UV irradiance even if the cloud amount is 0. Cloud amount measurements are 1 hour 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 due to very thin clouds, haze, aerosols, or pollutions. Some of these factors affecting UV can be also 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. There are two ways to describe the bias between ground-based and TOMS UV data for clear-sky conditions. The bias can be estimated directly by considering the measurements when TOMS does not see any clouds at the ground (Table 2). It can be

also derived from the slope of the Brewer-TOMS regression line (Figure 4) for cloud amount=0 conditions.

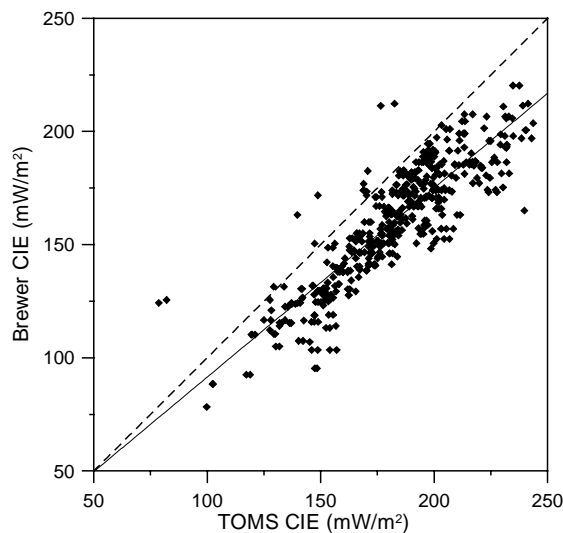


Figure 4. Scatter plot of Brewer and TOMS daily erythemal (CIE) UV noon irradiance for clear sky conditions (cloud amount=0).

The two methods give nearly identical results. A 2% to 10% bias can be seen at all stations except one. The Saturna Island station shows slightly negative bias, i.e., the measured UV irradiance is higher than UV derived from TOMS data. It is unlikely that the negative bias at the Saturna Island station is caused by the Brewer instrument problems (e.g., calibration error, different cosine response error) because three different Brewer instruments have been used at that site between 1990 and 2000. The relatively clean air at this island site off the West Coast is most probably the cause of the higher levels of UV irradiance there.

The bias is higher at 305 nm than at 324 nm that indicate some wavelength dependence of the pollution or aerosols caused the reduction of clear sky UV irradiance. 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 (1-2 DU) amount of SO₂ in the lower troposphere that cannot be detected from TOMS. This explanation is possible because high amounts of SO₂ were commonly seen at Toronto as well as at the Halifax site that is located 3 km from a power plant. In addition to SO₂ the absorbing aerosols have spectral dependence of their transmittance that is opposite to that of water clouds. Therefore, for days with cloud amount=0, but absorbing aerosol present, TOMS would treat them as cloud, overestimating their transmittance at 324 nm, but overestimating even more at 305 nm.

5. THE DIFFERENCE BETWEEN BREWER AND TOMS-DERIVED UV IRRADIANCE FOR DIFFERENT CLOUD AMOUNTS

The mean ratio between UV irradiance measured by the Brewers and estimated from TOMS data was calculated for different cloud amounts (Figure 5, right). The ratio is between 0.95 and 0.98 if the cloud amount is less than 8, i.e., it is nearly the same as for clear sky conditions. For overcast conditions (cloud amount=10) the ratio is less than 0.83. Figure 5 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. Overcast conditions reduce UV irradiance at the ground on average by more than twice.

Results of the estimates of the Brewer-TOMS difference for individual stations are summarized in Table 3. The ratio is between 0.8 and 0.9 for UV at 324 nm at all stations. As for clear sky conditions, the ratio at 305 nm is slightly lower than at 324 nm and the largest difference between the two wavelengths can be seen at Toronto and Halifax.

Analysis of the individual cases of large differences between ground measurements and TOMS-derived UV irradiances has demonstrated that TOMS overestimates UV when ground-based measurements are taken under very heavy clouds. To illustrate this effect the ratio of the TOMS-Brewer difference to the mean of TOMS and Brewer UV irradiance was estimated. Figure 6 shows the ratio values as a function of the cloud transmission (C_T) estimated from Brewer UV irradiance (left) and TOMS-derived UV (right). The data are binned by C_T . The left panel of Fig-

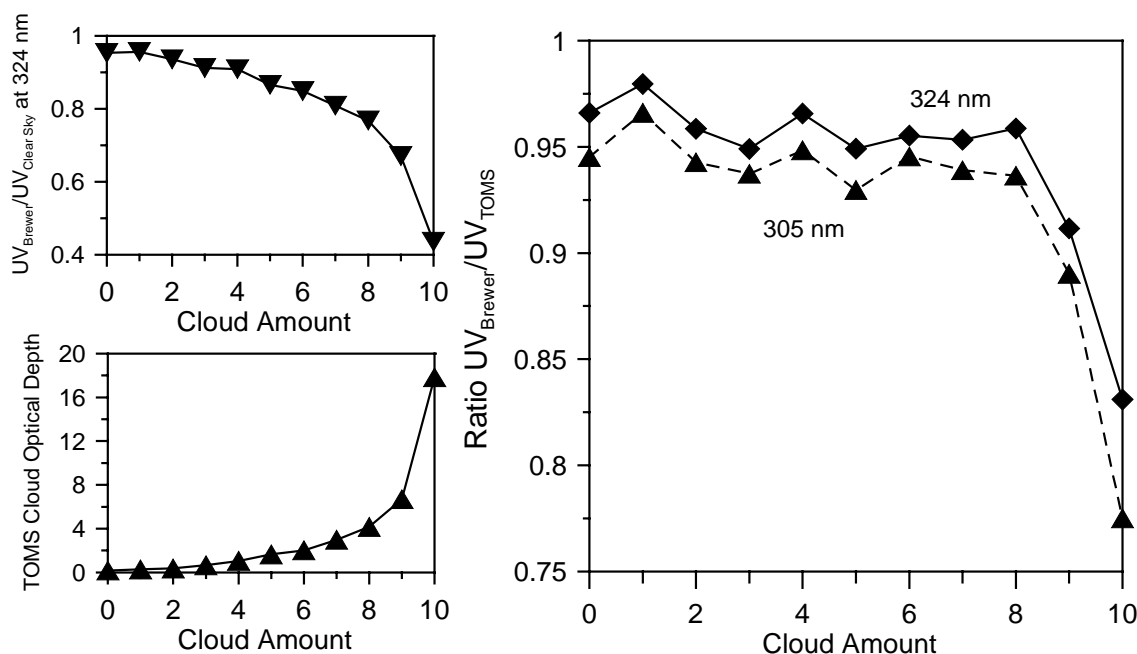


Figure 5. Ratio UV_{Brewer}/UV_{TOMS} as a function of the cloud amount (right) (overpass data from 10 stations). The ratio between measured by the Brewers and clear sky irradiance and clout optical depth estimated from TOMS observation as function of the cloud amount (left).

Table 3. Ratio between the measured Brewer and TOMS UV at 305 and 324 nm for overcast conditions (cloud amount=10).

Station	Number of days	Brewer/TOMS at 305 nm	Brewer/TOMS at 324 nm	Difference
Churchill	330	0.84	0.87	0.031
Edmonton	278	0.82	0.86	0.038
Goose Bay	271	0.68	0.74	0.055
Saskatoon	304	0.83	0.87	0.037
Regina	205	0.85	0.90	0.051
Winnipeg	240	0.77	0.83	0.054
Saturna	261	0.80	0.82	0.021
Montreal	260	0.83	0.89	0.058
Halifax	300	0.70	0.78	0.077
Toronto	457	0.68	0.77	0.088
Average		0.78	0.83	0.051

ure 6 shows that for heavy clouds (Brewer $C_T < 0.20$) TOMS always substantially overestimates UV irradiance. It is possible that the heavy cloud that caused very low C_T values at the ground does not cover the entire TOMS field of view (as large as 100 km by 100 km), and TOMS C_T is therefore higher. The presence of small amount of absorbing aerosols within the cloud could also be a contributing factor. For rare cases when Brewer $C_T > 1$ due to reflection from broken clouds, TOMS-derived UV is lower than the ground measurements. The right panel demonstrates that these effects are not seen when the data are binned by TOMS C_T .

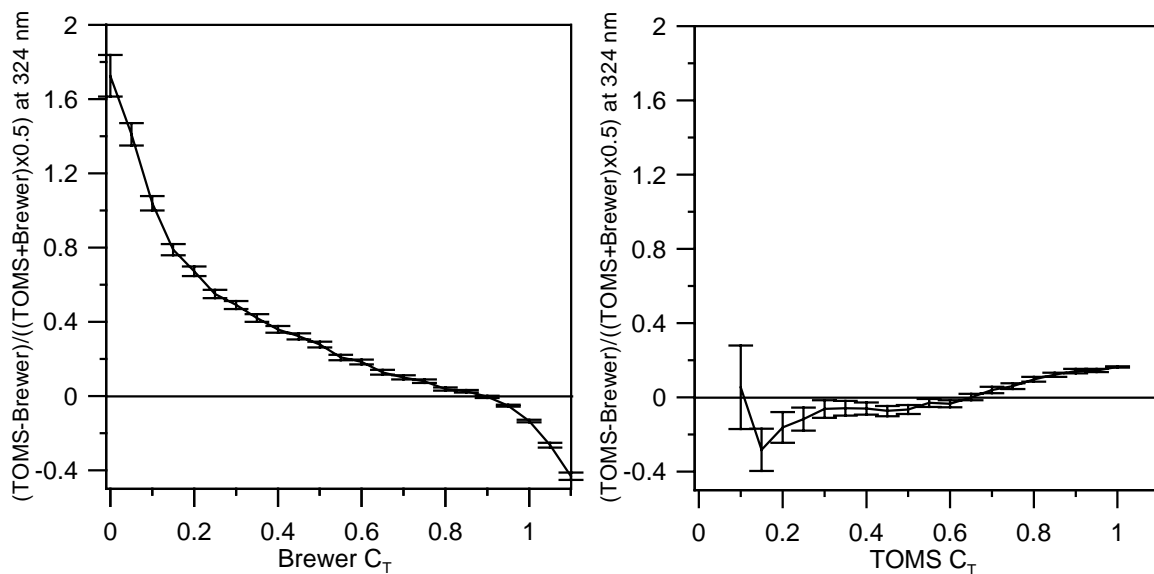


Figure 6. TOMS-Brewer difference as a function of cloud transmission (the ratio between measured and clear sky UV irradiance). The data are binned by C_T values with 0.05 increment. The error bars indicate 95% confidence intervals.

6. SUMMARY AND DISCUSSION

TOMS can successfully reproduce long-term and major short-term UV variations. It was found that the standard deviation of the difference between the measured by the Brewer instrument and derived from TOMS overpass data erythemally weighted noon UV irradiance is much smaller than the natural variability of UV irradiance.

Up to 9% of the Brewer-TOMS difference can be attributed to the Brewer cosine response error. This error depends on the solar zenith angle and cloud conditions, and is different from instrument to instrument.

A 4% bias between UV irradiance derived from TOMS data and measured by the Brewers can be seen at clear sky conditions at most Canadian sites even when the data are corrected for the Brewer cosine response error. However, the bias was close to 0 at one station (Saturna Island) probably due to much cleaner air there. A larger bias can be seen for overcast conditions.

REFERENCES

1. Lubin D., E. H. Jensen, and H. P. Gies, Global surface ultraviolet radiation climatology from TOMS and ERBE data, *J. Geophys. Res.*, 103, 26,061-26,091, 1998.
2. Eck, T. F., P. K. Bhartia, and J. B. Kerr, Satellite estimations of spectral UVB irradiance using TOMS derived total ozone and UV reflectivity, *Geophys. Res. Lett.*, 22, 611-614, 1995.
3. Herman, J. R., P. K. Bhartia, J. Ziemke, Z. Ahmad, and D. Larko, UV-B radiation increases (1979-1992) from decreases in total ozone, *Geophys. Res. Lett.*, 23, 2117-2120, 1996.
4. C. S. Long, A. J. Miller, H.T.Lee, J.D.Wild, R.C.Przywarty, and D. Hufford, "Ultraviolet Index forecasts issued by the National Weather Service", *Bull. Amer. Meteorol. Soc.*, 77, 729-747, 1996
5. R. Meerkotter, B. Wissinger, and G. Seckmeyer, Surface UV from ERS-2/GOME and NOAA/AVHRR data: A case study, *Geophys. Res. Lett.*, 24, 1939-1942, 1997
6. B. Mayer, C. A. Fischer, and S. Madronich, "Estimation of surface actinic flux from satellite (TOMS) ozone and cloud reflectivity measurements", *Geophys. Res. Lett.*, 25, 4321-4324, 1998
7. P. Peeters, J.F. Muller, P.C. Simon, E. Celarier, and J.R. Herman, Estimation of UV flux at the Earth's surface from GOME data, *ESA, Earth Observation*, 58, 39-40, 1998
8. J. Verdebout, "A method to generate surface UV radiation maps over Europe using GOME, Meteosat, and ancillary geophysical data", *J. Geophys. Res.*, 105, pp. 5049-5058, 2000.
9. J. Matthijsen, H. Slaper, and H.A.J.M. Reinen, G.J.M. Velders, "Reduction of solar UV by clouds: Comparison between satellite-derived cloud effects and ground-based radiation measurements", *J. Geophys. Res.*, 105, pp. 5069-5080, 2000.
10. Herman J. R., N. Krotkov, E. Celarier, D. Larko, and G. Labow, "The distribution of UV radiation at the Earth's surface from TOMS measured UV-backscattered radiances", *J. Geophys. Res.*, 104, pp. 12059-12076, 1999.
11. McKenzie R., G. Seckmeyer, A. Bias, J. Kerr, and S. Madronich, Satellite-retrievals of erythral UV dose compared with ground-based measurements at Northern and Southern mid-altitudes, *J. Geophys. Res.*, 106, 2001, in press.
12. Krotkov N. A., P.K. Bhartia, J.R. Herman, V. Fioletov, J. Kerr, "Satellite estimation of spectral surface UV irradiance in the presence of tropospheric aerosols 1. Cloud-free case", *J. Geophys. Res.*, 103, pp. 8779-8793, 1998.
13. Krotkov N.A., J. R. Herman, P. K. Bhartia V. Fioletov and Z. Ahmad, "Satellite estimation of spectral surface UV irradiance 2. Effects of homogeneous clouds and snow," *J. Geophys. Res.* 106, 2001.
14. Krotkov N. A., J. R. Herman, P. K. Bhartia, C. Seftor, A. Arola, J. Kaurola, L. Koskinen, P. Taalas, S. Kalliskota, and T. Tikkanen, "OMI surface UV irradiance algorithm" In: Ozone Monitoring Instrument (OMI) Algorithm Theoretical Basis Document, volume 3 "Aerosol, Clouds and surface UV irradiance", ed. P. Stammes, KNMI, 2001.
15. Herman J. R. and E. Celarier, "Earth surface reflectivity climatology at 340 to 380 nm from TOMS data," *J. Geophys. Res.*, 102, pp. 28003-28011, 1997.
16. Bais A. F., S. Kazadzis, D. Balis, C. Zerefos, and M. Blumthaler, Correcting global solar ultraviolet spectra recorded by a Brewer spectroradiometer for its angular response error, *Appl. Opt.*, 37, 6339-6344, 1998.

17. McArthur L. J. B., V. E. Fioletov, J. B. Kerr, C. T. McElroy, and D. I. Wardle, Derivation of UV-A irradiance from pyranometer measurements, *J. Geophys. Res.*, *104*, 30,139-30,151, 1999.
18. Fioletov, V. E., McArthur L. J. B., J. B. Kerr, and D. I. Wardle, Long-term variations of UV-B irradiance over Canada estimated from brewer observations and derived from ozone and pyranometer measurements, *J. Geophys. Res.*, *106*, 2001, in press.