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Comparison of UV-B Broadband Brewer Measurements with Irradiances from Surface-Based and Satellite-Based Models

Jacqueline Binyamin[1], John Davies[2], Bruce McArthur[3]
[1]*Department of Geography, University of Winnipeg, Winnipeg, Canada*
[2]*School of Geography and Earth Sciences, McMaster University, Hamilton, Canada*
[3]*Air Quality Research Branch, Meteorological Service of Canada, Toronto, Canada*
E-mail: j.binyamin@uwinnipeg.ca
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Abstract

UV-B irradiance can be estimated from surface meteorological data or from satellite measurements. This paper compares irradiance estimates from the Davies surface-based radiation model and the Canada Centre for Remote Sensing (CCRS) satellite model with Brewer spectrophotometer measurements for all sky conditions at six Canadian stations (Edmonton, Regina, Winnipeg, Montreal, Halifax and Toronto). The Davies model is applied with both the discrete ordinate radiative transfer (DISORT) and the delta-Eddington algorithms to solve the radiative transfer equation.

Both models' estimates are compared with instantaneous Brewer measurements. Both perform similarly with mean bias errors within 6% of the mean measured irradiance for the measurement period and root mean square errors between 25% and 30%.

Keywords: UV-B Irradiance, Brewer Spectrophotometer, DISORT, Delta-Eddington, TOMS, Satellite-Based Models, Surface-Based Models

1. Introduction

Stratospheric ozone depletion increases the amount of harmful UV-B (290 - 325 nm) irradiance reaching the earth's surface [1]. Instruments such as the Brewer spectrophotometer measure spectral irradiance [2], but measurements in Canada and internationally are spatially s--parse and are generally of short duration. Radiation mdels can estimate irradiance for locations and times without measurements and can predict irradiances for possible changes in ozone concentrations.

Radiation models use either surface meteorological data or satellite measurements. Models, which use surface data, apply algorithms, which vary from simple approximations [3] to rigorous solutions of the radiative transfer equation. The two most widely used radiative transfer solutions are the discrete ordinate radiative transfer (DISORT) model [4] and the delta-Eddington model [5]. Since these use local data, they should represent point conditions more accurately than the large area estimates from satellite.

Satellites measure reflected radiances at the top of the atmosphere which, combined with radiative transfer calculations or inversion algorithms, provide estimates of the irradiance at the surface [6-8]. Although satellite measurements provide extensive spatial coverage they usually provide, unless they are sun synchronous, one measurement each day, which prohibits the calculation of daily total irradiance.

Comparisons of model calculations with measurements are mostly restricted to data for a few cloudless days [9-12]. Few studies have validated surface-based models for all sky conditions [13-17].

This paper compares broadband irradiances (290 - 320 nm) from a surface-based model [16,17] and from the Canada Centre for Remote Sensing (CCRS) Meteor-3/ total ozone mapping spectrometer (TOMS) satellite based-model [6-8] with Brewer spectrophotometer measurements in Canada.

2. Irradiance Measurements

Brewer spectrophotometer measurements for six Can

Table 1. Canadian UV-B monitoring stations used in the study.

Station	Latitude, °N	Longitude, °W	Elevation, m	Years of data
Edmonton (Alta.)	53°33′	114°06′	766	1993-1994
Regina (Sask.)	50°13′	104°40′	592	1994
Winnipeg (Man.)	49°55′	97°14′	239	1993
Montreal (Que.)	45°28′	73°45′	24	1993-1994
Halifax (NS)	44°44′	63°40′	31	1993-1994
Toronto (Ont.)	43°47′	79°23′	198	1993-1994

dian locations, for which there were simultaneous satellite-based irradiances, are used in this study (**Table 1**). This instrument allows for the calculation of daily ozone depth and measures spectral irradiance for wavelengths between 290 and 325 nm at a resolution of 0.5 nm. Radiation measurements are made once or twice each hour from sunrise to sunset at irregular times in GMT [18]. Following Krotkov *et al*. [12] and Wang *et al*. [19] the Brewer values were increased by 6% to compensate for the cosine error.

3. The Davies Model

The model developed by Davies *et al*. [16] and modified by Binyamin *et al.* [17] is used in this study. Surface irradiance G is calculated as a linear combination of clear G_{O} and overcast $G_{\otimes}$ sky irradiances weighted with cloud fraction C :

$$G = \left(1 - C\right) G_{\text{O}} + C G_{\otimes}. \quad (1)$$

G_{O} and $G_{\otimes}$ are calculated spectrally at wavelength interval of 1 nm using either the DISORT [4] or the delta-Eddington [5] solutions to the radiative transfer equation for a vertically inhomogeneous 49-layer, 120 km, plane parallel atmosphere, with cloud inserted between 2 and 3 km heights. The model uses spectral values of the extraterrestrial irradiance from the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) ATLAS-3 space shuttle mission (D. Prinz, personal communication, 2002), ozone absorption coefficients from Paur and Bass [20], Rayleigh scattering cross sections following Elterman [21], aerosol optical properties from Shettle and Fenn [22], a fixed cloud optical depth of 27 [17,23], and a fixed surface albedo of 0.05 [24]. Hourly total cloud opacity observations were obtained from the Meteorological Service of Canada.

4. The CCRS Satellite Model

The CCRS satellite algorithm for retrieving surface irradiance [6] is based on a linear relationship between TOA albedo at 360 nm and surface absorbed irradiance. The surface irradiance is given by:

$$G = \frac{S_0 \cos\theta T_{03} \left(1 - 0.196 - 0.798\alpha_{360} - a_d\right)}{(1 - \alpha_s) + a_u \alpha_s} \quad (2)$$

where S is the extraterrestrial irradiance; θ the solar zenith angle ; T_{03} the band-mean transmittance due to ozone absorption; α_{360} the albedo for the earth-atmosphere system at 360 nm; α_s surface albedo; and a_d and a_u represent aerosol absorption for the downwelling and upwelling irradiance.

The extraterrestrial irradiance was taken from Fröhlich and London [25]. Total ozone amount was taken from the TOMS data set. Surface albedo was assumed to be 0.04 for Toronto and 0.03 for other stations. Aerosol optical depth τ_a measurements were available for Toronto [19] and a value of 0.31 was substituted for missing days. For Winnipeg and Edmonton τ_a was assumed to be 0.2, and 0.1 for the remaining stations. Aerosol single scattering albedo was assumed to be 0.95 for all stations. The model can only be used for days without snow cover.

5. Comparison of the Davies Model and CCRS Model Results

The Meteor 3 reflectance measurements were made at different local times, with usually once per day, with a maximum of two values per day that matched the times of Brewer measurements (Pubu Ciren, CCRS, personal communication, 2007). Each CCRS model estimate is compared with a simultaneous Brewer measurement and a calculation from the Davies model using both the delta-Eddington and DISORT methods. There is a small difference in the spectral integration range used by CCRS and the Davies model. CCRS presents irradiances integrated over the 290 - 320.5 nm wavebands in 0.5 nm steps while the Davies irradiances were integrated in 1 nm steps over the 290 - 320 nm range. In this section, both models are compared with Brewer measurements integrated to the upper wavelength limit appropriate to the model.

Comparison of the Davies model broadband irradiances and the simultaneous satellite-based results with Brewer measurements made at six stations (Edmonton, Regina, Winnipeg, Montreal, Halifax and Toronto) in 1993 and 1994 (**Table 1**) are presented in **Figure 1**. They represent 10 station years of instantaneous data mainly between May and September, with 605 data points in total. Generally, the agreement between the three is visually good for all stations. The MBE (mean difference) values correspond to less than 0.04 $W \cdot m^{-2}$ on average for individual stations and pooled data for both surface-based and satellite-based methods.

Table 2 provides performance statistics for both indi-

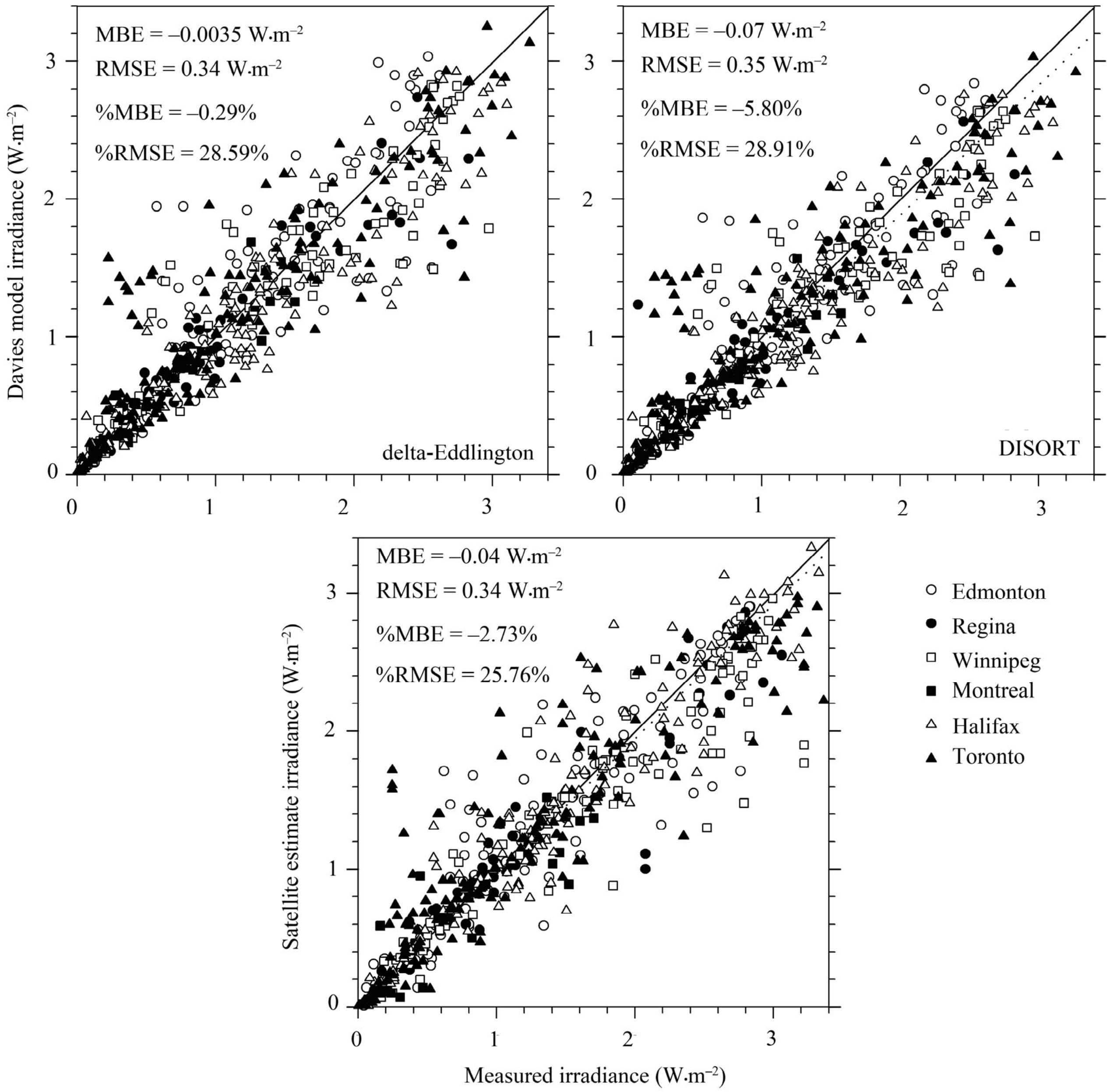

Figure 1. Comparison between Davies model calculations, CCRS satellite-based model calculations and measured UV- B irradiances for all sky conditions for Edmonton, Regina, Winnipeg, Montreal, Halifax and Toronto. The dotted lines represent linear regressions constrained to pass through the origin. A different symbol represents data for each station.

vidual stations and pooled data. For the pooled data, the Davies model with the delta-Eddington and DISORT methods and the CCRS model underestimate Brewer measurements by less than 6% of the mean measured irradiance. For the individual stations the relative MBE values range between ±6% for the delta-Eddington method, between –10% and 0.2% for the DISORT method and between –11% and 0.3% for the satellite-based method. These irradiance differences are smaller than differences between near simultaneous measurements made with different ground instruments ±10% [26-29]. The relative RMSE values for the pooled data are similar (26% and 29%) for the two methods. For the individual stations, relative RMSE values range from 24 to 34% for the Davies model and from 20 to 40% for the satellite-based model. This agrees well with the findings of Fioletov *et al.* [30] and Wang *et al.* [31] who found that differences between TOMS-estimated UV-B irradiances

Table 2. Summary of the Davies model and satellite-based method performance measures against Brewer measurements for broadband irradiances (290 - 320 nm) for each satellite time for the period indicated for each station. N is the number of data points and $\bar{M}$ is the mean measured irradiance ($W \cdot m^{-2}$). MBE and RMSE are expressed as percentages (italic) of $\bar{M}$. Positive MBE values indicate model overestimation.

Irradiance results	Edmonton 1993-1994	Regina 1994	Winnipeg 1993	Montreal 1993-1994	Halifax 1993-1994	Toronto 1993-1994	Pooled data
N	115	48	88	20	159	175	605
Davies model using delta-Eddington metho							
$\bar{M}$	1.16	1.20	1.54	0.66	1.19	1.13	1.21
MBE	6.22	–0.79	–4.97	2.13	–5.66	3.64	–0.29
RMSE	31.73	25.05	24.25	26.53	24.50	33.46	28.59
Davies model using DISORT method							
MBE	0.15	–6.62	–10.06	–5.78	–10.28	–2.38	–5.80
RMSE	28.94	25.72	25.88	27.76	25.93	33.85	28.91
Satellite method							
$\bar{M}$	1.26	1.31	1.68	0.72	1.30	1.23	1.31
MBE	0.26	–5.14	–9.75	–10.86	–1.40	0.06	–2.73
RMSE	25.49	22.30	24.11	40.05	20.45	31.03	25.76

and Brewer observations range from 3 to 11% and can be attributed to the Brewer angular response error.

6. Conclusions

This is the first study to compare the performance of satellite-based model with ground-based model estimates of UV-B irradiance. The two models perform almost identically. Differences in performance are within the uncertainties in Brewer measurements. Different fields of view of the TOMS instrument, the Brewer spectrophotometer and the Davies model seem to be inconsequential.

The satellite model can be applied virtually anywhere and does not require other observations. However, it does have two drawbacks. Firstly, because it cannot calculate irradiance throughout the day, it cannot produce daily totals. Secondly, it cannot be used over snow-covered surfaces because it is incapable of discriminating differences between cloud and surface reflections. The Davies model produces daily irradiance totals but its use is currently restricted to stations with cloud observations. Future work should examine the use of satellite cloud data. The use of the delta-Eddington method is especially appealing for calculating broadband irradiances since it is computationally less demanding than DISORT

7. References

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