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Validation of Spectral and Broadband UV-B (290 - 325 nm) Irradiance for Canada

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Abstract

Stratospheric ozone depletion, as a result of increasing chlorofluorocarbons in the stratosphere, allows more UV-B irradiance (290 - 325 nm) to reach the earth's surface with possible detrimental biological effects. Because there are few UV-B radiation stations, irradiance models are useful tools for estimating irradiances where measurements are not made. Estimates of spectral and broadband irradiances from a numerical model are compared with Brewer spectrophotometer measurements at nine Canadian stations (Alert, Resolute Bay, Churchill, Edmonton, Regina, Winnipeg, Montreal, Halifax and Toronto) and 26 years of data. The model uses either the discrete ordinate radiative transfer (DISORT) or the delta-Eddington algorithms to solve the radiative transfer equation for a 49-layer, vertically inhomogeneous, plane-parallel atmosphere, with cloud inserted between the 2 and 3 km heights. Spectral calculations are made at 1 nm intervals. The model uses extraterrestrial spectral irradiance, spectral optical properties for each atmospheric layer for ozone, air molecules, and aerosol and surface albedo. A fixed broadband cloud optical depth of 27 was satisfactory for calculating cloudy sky irradiances at all stations except in the arctic.

Comparisons are made both for daily totals and for monthly averaged spectral and broadband irradiances. The delta-Eddington method is shown to be unsuitable for calculating spectral irradiances under clear skies, at wavelengths less than 305 nm where absorption by ozone is high, and at large solar zenith angles. The errors are smaller for overcast conditions. The method is adequate for daily total and monthly averaged spectral (≥ 305 nm) and broadband calculations for all sky conditions, although consistently overestimating irradiances. There is a good agreement between broadband measurements and calculations for both daily totals and monthly averages with mean bias error mainly less than 5% of the mean measured daily irradiance and root mean square error less than 25%, decreasing to below 15% for monthly averages.

Keywords: Modelling UV-B Radiation, DISORT, Delta-Eddington, Spectral and Broadband Radiation, Brewer Spectrophotometer, UV-B Measurements in Canada

1. Introduction

Human made chemicals, including chlorofluorocarbons and other halocarbons, have damaged the stratospheric ozone layer that protects people, plants, and animals from harmful biologically active ultraviolet (UV-B) irradiance. The effective UV-B waveband is from 290 to 325 nm, which is the wavelength range of the Canadian Brewer spectrophotometer measurements. Even though the UV-B band is biologically important, it contains little energy, constituting only 1.8% of the total solar radiation at the top of the atmosphere, and no more than 1% at the earth's surface [1].

Within the UV-B band the atmosphere becomes more transparent with increasing wavelength since ozone absorption decreases by two orders of magnitude as wavelength increases between 290 - 325 nm [2]. Over this wavelength range the irradiance at the ground may vary through eleven orders of magnitude. Biological effects are not constant across the waveband. In general, the shorter the wavelength is, the greater the biological effect [3]. Therefore, spectral measurements are essential for biological applications.

UV-B irradiance measurements are rare in Canada and the world. Radiative transfer models are potentially very important tools to supplement the spatially sparse network. The DISORT and delta-Eddington algorithms have been used widely to model irradiance [4-7]. Delta-Eddington uses a two-term expansion of the scattering phase function but DISORT allows for any number of expansions of the phase function, therefore, it is potentially an exact solution. Comparisons between both methods for model atmospheres for UV transmittance (290 - 400 nm) for various amounts of absorption and scattering have been made by Forster and Shine [8]. Here, we present the first extensive comparison of the two methods for real atmospheres in the UV-B waveband.

Forster and Shine [8] showed that the delta-Eddington is not suitable for calculating spectral values for clear skies and at large solar zenith angles but for overcast skies it may be suitable. For thick scattering cloud layers, the two-term expansion is sufficient because multiple scattering is dominant and not too sensitive to detailed phase function structure [9,10]. Erlick and Frederick [11] compared the delta-Eddington flux calculations with the 22-stream DISORT model for an isolated optically-thick cloud layer (τ = 40) at 290 nm with zero surface albedo. They found that transmission and reflection from these two methods were closely matched except for large zenith angles greater than 60˚ where the delta-Eddington transmissivity and reflectivity were too high and too low (by 10%) respectively. Lubin *et al*. [12] argued that the uncertainties in spectral irradiance calculations using the delta-Eddington approximation instead of DISORT are less than the uncertainties involved in treating clouds as plane parallel layers.

Validation studies that have compared model calculations with measurements are mostly restricted to data for just a few days and cloudless skies [13-15]. Few studies have validated surface-based models for all sky conditions [6,16,17]. This is the first comprehensive study for Canada. A pilot study was performed by Davies *et al*. [7] at four Canadian stations (Bedford, Toronto, Winnipeg, Edmonton) using a small amount of data.

Comparison between UV-B irradiance calculated by DISORT model and measurements have been presented by Wang and Lenoble [5], Zeng *et al*. [14] and Pachart *et al*. [18] for clear sky conditions. Wang and Lenoble [5] concluded that the variation of the ratio between measurement and model spectral results exceeds ±20%, but the agreement is better than ±6% when the ratio is averaged over intervals of 10 nm. Zeng *et al*. [14] compared measured spectral irradiances with 8-stream DISORT results. They found that UV-B irradiances could be predicted to within 8% if the input parameters were well known. These differences are due to calibration errors either in the instrument or in the extraterrestrial spectral irradiance.

Our study is important because scientists in Canada-have found that an average ozone depletion of about 6% has been observed over five Canadian monitoring stations (Toronto, Goose Bay, Edmonton, Churchill and Resolute Bay) since the late 1970s [19]. In Toronto (43˚47'N, 79˚28'W) Kerr and McElroy [20] reported decreases in the ozone levels between 1989 and 1993 of 4.1% and 1.8% per year in winter and summer, respectively.

This paper evaluates a numerical model for UV-B irradiance for all sky conditions, validates spectral and broadband irradiances using Brewer spectrophotometer measurements, and assesses the relative usefulness of the DISORT and delta-Eddington algorithms in calculating spectral and broadband irradiances.

Section 2 and 3 describe the irradiance and ozone measurements. Section 4 introduces the model and the input parameters. Section 5 presents the model validation results. Section 6 gives conclusions, emphasizes the contributions of this research and details some of the future research needs.

2. The Brewer Measurements

Spectral UV-B irradiance measurements in Canada began in March 1989 and are made at 13 locations with the Canadian designed single monochromatic Brewer spectrophotometer. Nine of these locations, which have the necessary meteorological data for radiative transfer calculation, are used in this study (**Figure 1**). The Brewer instrument allows the calculation of daily ozone depth and measures spectral irradiance for wavelengths between 290 and 325 nm at a resolution of 0.5 nm. Each spectral measurement consists of the average of a forward and backward scan across the wavelength range, which takes about 8 minutes to complete [20]. Measurements of the radiation intensity that falls on a horizontal diffusing surface are made once or twice each hour throughout the day from sunrise to sunset at irregular times in GMT. These spectral measurements were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC).

The Brewer instruments have known uncertainties. They receive stray light from longer wavelengths adjacent to the one being measured [21,22] which affects measurements below about 305 nm where the light intensity is very small. Also, they are subject to cosine error such that measurements usually underestimate the horizontal global irradiance by up to 8% depending on clouds, aerosols, and solar zenith angle [23,24]. Each

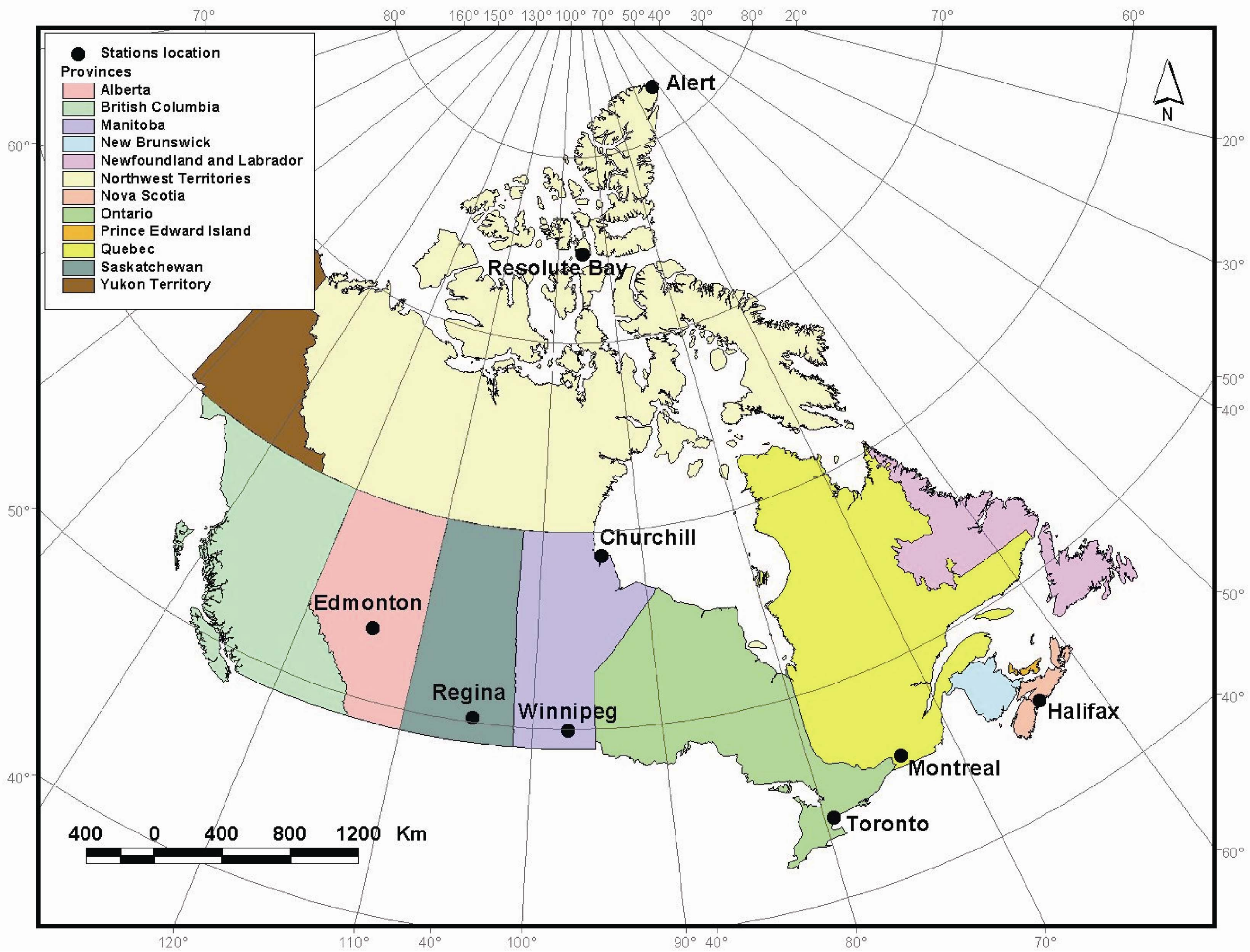


Figure 1. Location of Canadian stations used in the study.

instrument has its own cosine error, which can vary from 2% to 20% [e.g., 24,25].

Calibration uncertainty for the Brewer instruments ranges from ±5 – 7% [26,27]. The Brewer instrument is also affected by ambient temperature and humidity variations [21]. It is provided with a temperature-stabilized enclosure but this does not totally eliminate the temperature variability. The temperature effect is greater at shorter wavelengths and can produce mean errors ranging from –2% to 2% in winter and summer, respectively over the Brewer spectral range [23]. However, Cappellani and Kochler [28] have found that for winter days (temperature range 9.8˚ to 21.7˚C) and for summer days (temperature range 21.7˚ to 42˚C), the Brewer values should be increased by 2% and 8%, respectively.

Some quality control procedures are performed by the Meteorological Service of Canada (MSC). These include: calibration with 1000-watt standard lamps that are traceable to the US National Institute of Standards and Technology; daily radiometric stability that is maintained with an internal 20-watt quartz halogen lamp; a wavelength check is made several times per day using a mercury discharge lamp; and a correction for stray light [23]. However, corrections for the effect of cosine error on the UV-B spectra and a wavelength-dependent temperature effect are not applied. In this study an increase of 6% was applied to the Brewer data to compensate for the cosine error effect on the basis of research by Krotkov *et al.* [29] and Wang *et al.* [27].

3. Other Measurements

Daily total ozone column measurements from the Brewer instrument were obtained from the WOUDC for the stations shown in **Figure 1**. Hourly (local standard time) measurements of total cloud opacity, surface temperature, pressure and relative humidity were provided by the MSC. Values were linearly interpolated for the irradiance measurement times in GMT. Solar zenith angles for each measurement time and the ratio of actual to mean

Sun-Earth distance were calculated following Michalsky [30]. Daily snow depth measurements were provided by the MSC.

4. Davies Model Description

Surface irradiance G is expressed as a cloudiness- scaled combination of cloudless sky irradiance G_o and overcast sky irradiance $G_\otimes$:

$$G = (1-C)G_O + CG_\otimes, \quad (1)$$

where C is the fraction of the sky that is cloud covered. G_o and $G_\otimes$ are calculated spectrally at 1 nm intervals using either the DISORT [31] or the delta-Eddington [32] solutions to the radiative transfer equation.

This model can be applied anywhere where there are daily measurements of column ozone and snow depth and hourly cloud cover observations. Radiative transfer calculations of G_o and $G_\otimes$ require the spectral UV-B irradiance emitted by the sun and the spectral optical properties for each atmospheric layer for ozone absorption, Rayleigh scattering, aerosol extinction, and cloud scattering and surface albedo.

In this study, the atmosphere is divided into 49 layers with constant scattering and absorbing properties within each. The layers are thin (1 km) in the lower atmosphere, intermediate (2.5 km) in the middle atmosphere and thick (5 km) in the upper atmosphere. Each layer is regarded as horizontally homogeneous and the curvature associated with sphericity of the earth is ignored. Layer values of spectral optical depths, single scattering albedos and asymmetry factors were calculated as layer averages. These spectral optical properties were combined for each wavelength and layer. The cloud is placed in one layer (between 2 and 3 km) and in this plane-parallel atmosphere radiation transfer is considered only in the vertical. In the calculation, cloud optical properties replace optical properties for the cloudless layer between 2 and 3 km.

The model uses solar spectral extraterrestrial irradiances from the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) instrument on board the third Atmospheric Laboratory for Applications and Science (ATLAS-3) space shuttle mission launched on Nov. 13, 1994 (D. Prinz, personal communication, 2007), ozone absorption coefficients from Paur and Bass [33], Rayleigh scattering cross sections following Elterman [34], aerosol optical properties from Shettle and Fenn [35]. Since the Brewer instrument measures irradiance through a triangular filter with a base of 1.1 nm (full width at half maximum of 0.55 nm), the high spectral resolution (full width at half maximum ~ 0.15 nm, sampled approximately every 0.05 nm) SUSIM data were averaged to mimic the Brewer. SUSIM measurements for average Sun - Earth distance were selected from the 289.45 and 326.55 nm wavelength range at a 0.05 nm interval, and averaged for each nanometer from 290 to 325 nm.

Since there are few measured atmospheric vertical profiles of ozone, temperature, pressure and humidity, standard model atmospheres containing these vertical profiles for 50 atmospheric levels from the surface to 120 km in LOWTRAN 7 [36] were used for the model in this study. Summer and winter midlatitude and subarctic model atmospheres were used to calculate Rayleigh and ozone optical depths. Urban aerosol optical properties for 50 km and 36.5 km visibilities were used for the boundary layer for both Toronto and Montreal and a 50 km visibility rural aerosol was used for all other stations. Ozone concentrations were scaled by the ratio of total measured to total model atmospheric ozone depth.

For this study, Broadband values of cloud single scattering albedo ω and asymmetry factor g_c were set at 0.999997 and 0.8709, respectively, for equivalent radius of 7 μm (for arctic stations) and 0.999995 and 0.8587, respectively, for equivalent radius of 10 μm (for midlatitude and subarctic stations) at all wavelengths [37]. Broadband cloud optical depths τ_c were calculated iteratively from overcast irradiance measurements for snow free conditions to eliminate irradiance increase from multiple scattering between cloud and snow [37].

Surface albedo measurements for the UV-B band are not available in Canada. Albedo was calculated following Davies *et al*. [7] as a linear function of daily snow depth measurement between 0.05 for a snow free ground [38] and 0.75 for a snow cover of 30 cm or greater. Albedo is independent of wavelength and the effects of melting and snow contamination are ignored.

5. Validation of Model Irradiances

The section assesses the model's performance in calculating spectral and broadband irradiances using the extraterrestrial solar spectrum, the calculated spectral optical parameters, and the broadband cloud optical depths given in Binyamin *et al.* [37]. Although the results in Binyamin *et al.* [37] showed that the DISORT 8 and delta-Eddington algorithms yielded very similar cloud optical depths for all stations in the study it is also important to examine how well irradiances from the two methods compare since the delta-Eddington method is an approximate solution of the radiative transfer equation whereas the DISORT 8 method is close to an exact solution.

5.1. Performance Measures

Model performance is assessed using the mean bias error

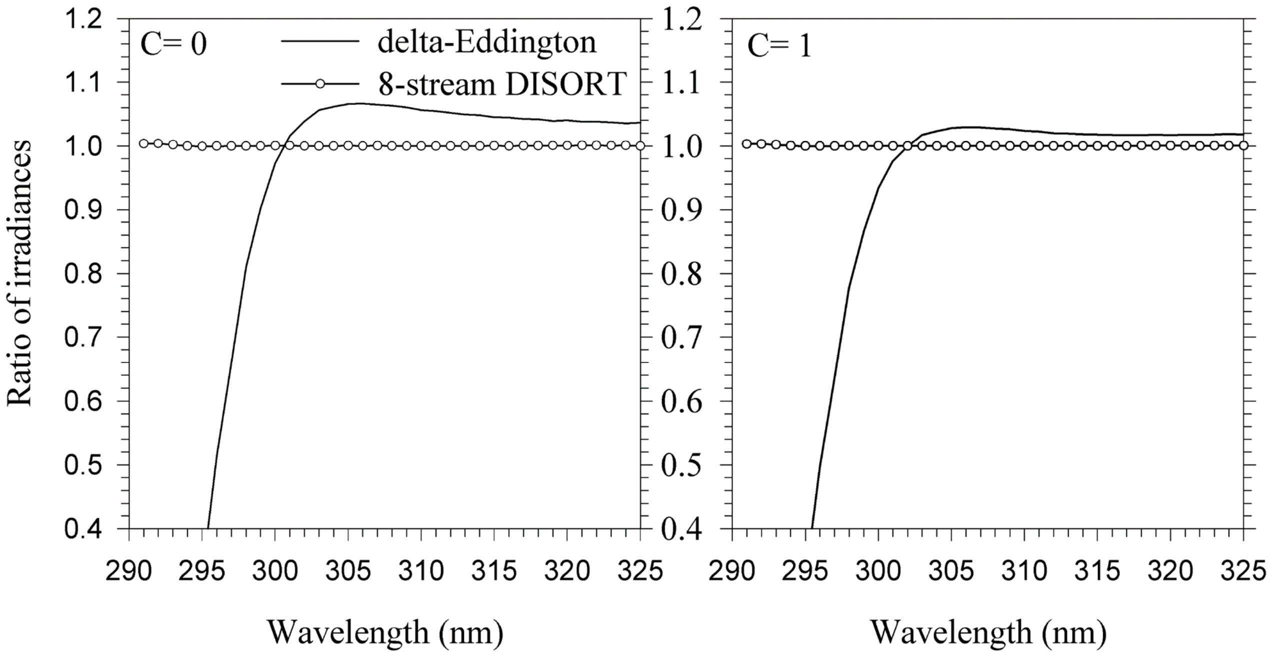


Figure 2. Ratio of spectral irradiance calculated by delta-Eddington and 8-stream DISORT methods to that of 16-stream DISORT method for solar zenith angle of 64.4˚ for clear (C = 0) and overcast (C = 1) sky conditions for Toronto on June 24, 1993 with 302 DU total ozone column and a surface albedo of 0.05.

(MBE), which measures systematic error, and the root mean square error (RMSE), which includes both systematic and non-systematic error [39]. When MBE is small, the RMSE measures mainly the non-systematic error. If d_i is the difference between calculated and measured irradiances (daily or monthly), MBE and RMSE are defined from the variance of d

$$\sigma_d^2 = \frac{\sum d_i^2}{N} - \left(\frac{\sum d_i}{N} \right)^2 = (\text{RMSE})^2 - (\text{MBE})^2, \quad (1)$$

where N is the number of data points. The performance measures are expressed as percentages of the mean measured irradiance for the relevant period.

The main source of random error stems from the cloud cover data. Since cloud cover is only reported once an hour, cloudiness variations between hours are missed. Linear interpolation of cloud cover for the Brewer instrument's measurement time only improves the validity of cloud estimates if the real variation of cloudiness between hourly observations is linear. Intuitively, errors arising from interpolation are expected to be random although initial errors in observer cloud estimates are probably systematic since observers tend to overestimate cloud cover because the earth curvature leads to an impression of greater cloudiness toward the horizon in non-overcast sky conditions [40].

5.2. Comparisons of Irradiances from the Delta-Eddington and DISORT Methods

The numerical experiments by Forster and Shine [8] revealed systematic overestimation by the delta-Eddington method. Here, their analysis has been applied to a real atmosphere (June 24, 1993 at Toronto) for both cloudless and overcast skies.

Figure 2 shows ratios of spectral irradiances calculated by both the delta-Eddington and 8-stream DISORT methods to irradiances calculated by a 16-stream DISORT method for a solar zenith angle of 64.4˚, as used by Forster and Shine [8]. The DISORT ratio is close to one at all wavelengths in both cloud cases while, the delta-Eddington values decrease rapidly below 302 nm. The delta-Eddington model agrees to within 2% with DISORT for the overcast case at wavelengths greater than 302 nm but the error increases to 7% for the cloudless sky cases, respectively, at 305 nm. Delta-Eddington values also fall off sharply for wavelengths below about 300 nm in both cloudless and overcast cases.

Figure 3 compares ratios of delta-Eddington to 8-stream DISORT spectral irradiances at seven solar zenith angles for the June 24, 1993 atmosphere and simulated cloudless and overcast skies. In the cloudless case, the delta-Eddington method generally overestimates spectral irradiances at wavelengths greater than 305 nm and underestimates it at wavelengths below 300 nm at solar ze-

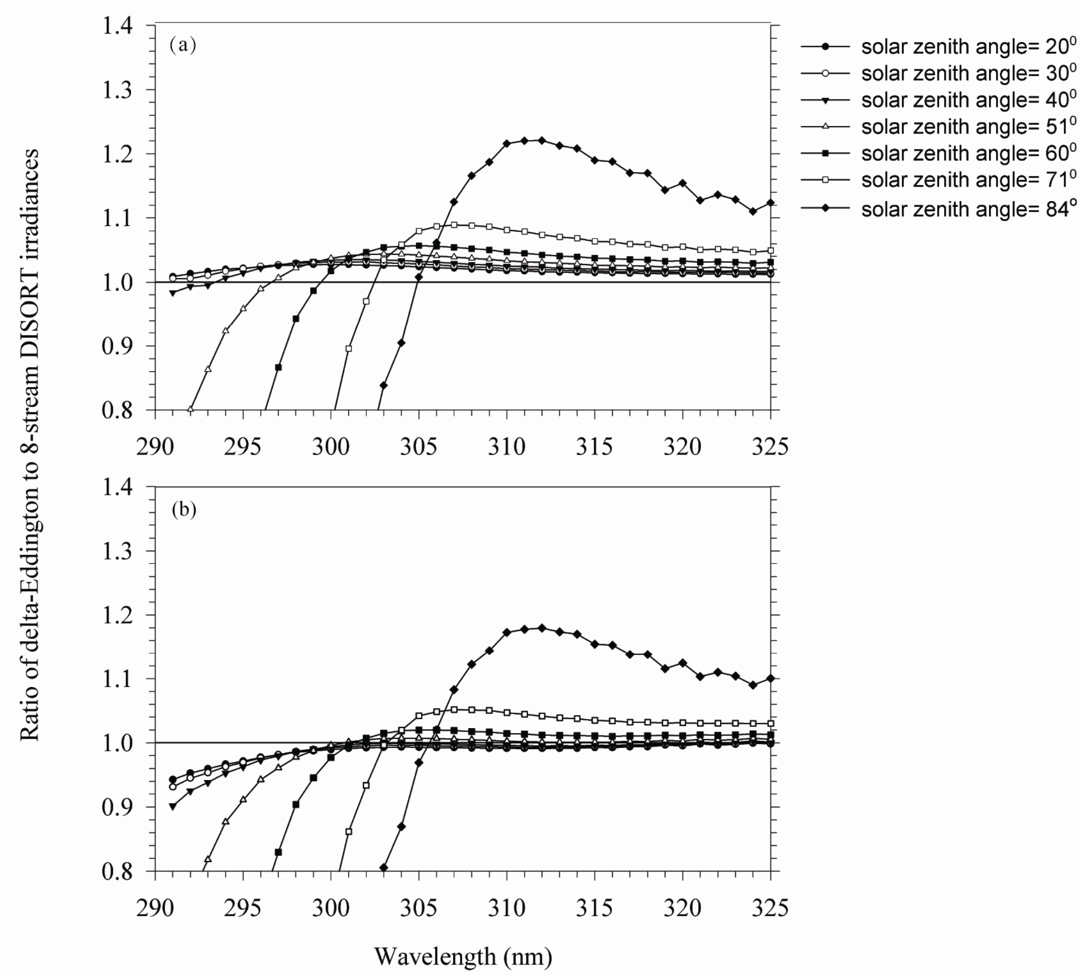


Figure 3. Ratio of spectral irradiance calculated by delta-Eddington and 8-stream DISORT method for solar zenith angle of 64.4˚ for clear (C = 0) and overcast (C = 1) sky conditions for Toronto on June 24, 1993 with 302 DU total ozone column and a surface albedo of 0.05.

nith angles greater than 60˚. In the overcast case, delta-Eddington estimates are closer to DISORT values except at smaller wavelengths (below 302 nm) at larger solar zenith angles (greater than 50˚). Also, the irradiance drop below unity increases for larger solar zenith angles and with overcast. **Figures 2** and **3** show that the delta-Eddington method can be expected to overestimate spectral irradiances at most wavelengths in most cases.

At large solar zenith angles and shorter wavelengths (less than 305 nm) where ozone absorption is high, the delta-Eddington method did not perform well because of the truncation of the scattering phase function to two terms. Forster and Shine [8] showed that this also applies to a two stream DISORT. Although the amount of irradiance is very small at these short wavelengths it may nevertheless be important because this is the portion of the spectrum where biological sensitivities are maximum for many processes. Therefore, the 8-stream DISORT method should be used for spectral irradiances at wavelengths below 305 nm.

Figure 4 shows the variation of the ratio of irradiances of the delta-Eddington and 8-stream DISORT methods with ozone amount and sun angle for cloudless and overcast conditions at 295 nm and 305 nm. At 295 nm, the delta-Eddington error increases strongly with ozone amount, especially at larger solar zenith angles (greater than 50˚). Cloud reduces the range of the ratio values and they never exceed unity. At 305 nm, the delta-Eddington error depends only slightly on ozone except at solar zenith angles larger than 70˚. Under overcast, the ratio range is mainly between 1 and 1.05 except at a zenith angle of 84˚ where it is similar to the cloudless ratio at the same angle. Therefore, for wavelength ≥ 305 nm, and when considering daily total spectral irradiances, errors in the delta-Eddington approximation are less important. This is because the times of day with smaller solar zenith

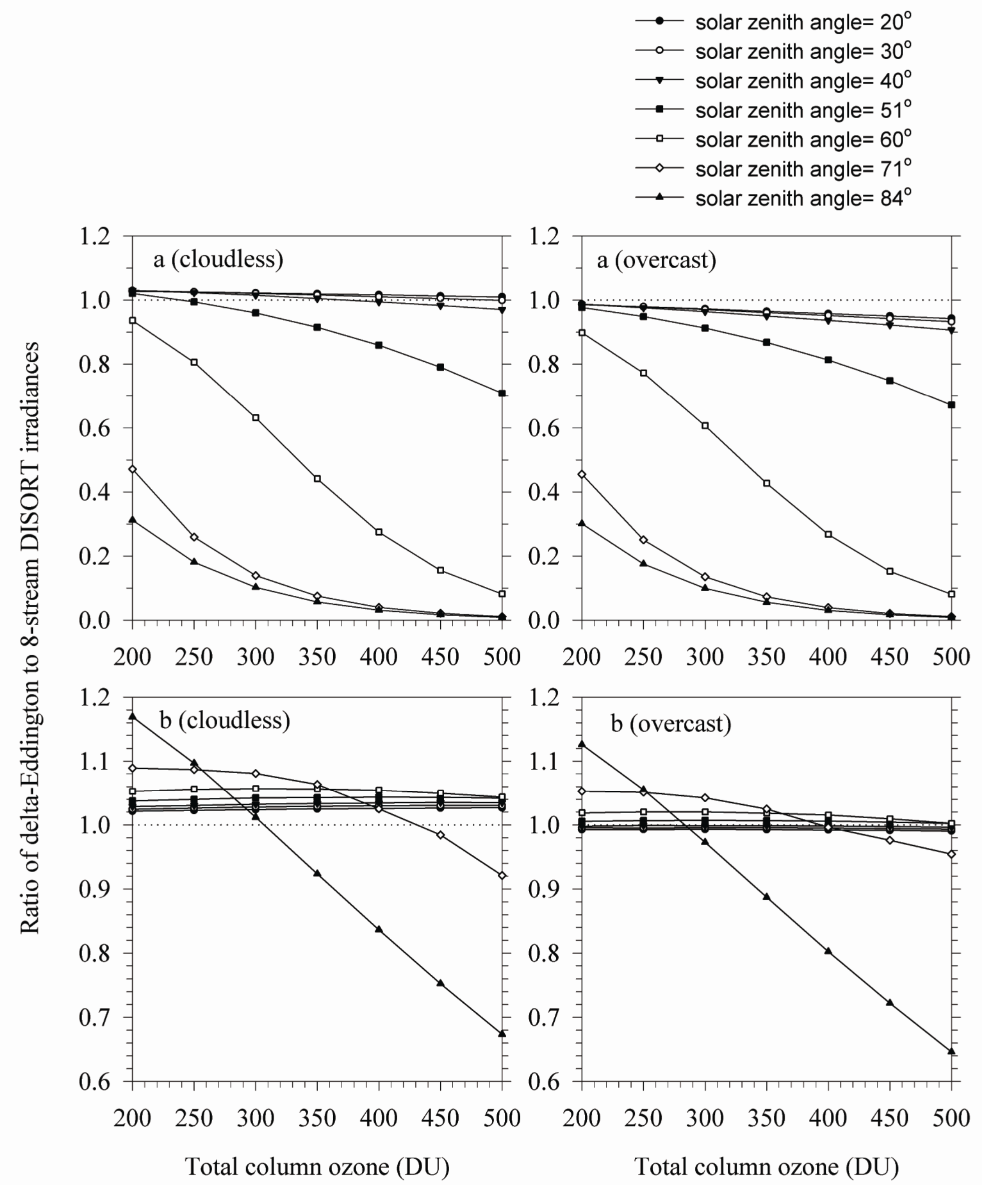


Figure 4. Ratio of irradiances calculated by delta-Eddington method to 8-stream DISORT method as a function of total column ozone and solar zenith angle for a wavelength of 295 nm(a) and 305 nm (b) for Toronto on June 24, 1993 for cloudless and overcast sky conditions with a surface albedo of 0.05.

angles contribute most to the total irradiances.

Daily values of spectral and broadband irradiances from the delta-Eddington and DISORT models were compared for all sky conditions using annual values of cloud optical depth for each station showed in **Table 1** [37].

Seven wavelengths (295, 300, 305, 310, 315, 320 and 325 nm) were selected to demonstrate model spectral performance for Resolute, Churchill, Winnipeg and Toronto for 1993. **Table 2** shows MBE and RMSE for 295 nm and 305 nm. Statistics for 300 nm are similar to those for 295nm and statistics for all other wavelengths are similar to those for 305 nm and therefore are not shown. In general, the delta-Eddington irradiances exceed DISORT's values by 3 - 7% with the exception of Resolute at 295 nm. RMSE values are mainly within 3 - 14%. These differences are within the uncertainty of the Brewer instrument (±10%) and are smaller than the differences between irradiances measured with different instruments [41-43].

Resolute is an exception. At 295 nm, delta-Eddington underestimates irradiance by 23%. This is attributed to high cloudiness and large solar zenith angles (**Figure 3**). Forster and Shine [8] have shown that the delta-Edding-

Table 1. Characteristics of the inferred cloud optical depth for the nine Canadian datasets. N is the number of data points.

Station	Year	Aerosol type	Mean and Median cloud optical depth				
			δ -Eddington		DISORT 8		
			Mean	Median	Mean	Median	N
Alert (NWT)	1995	Rural + 50 km	13.6	9.0			271
Resolute (NWT)	1993	Rural + 50 km	22.9	16.7	22.3	15.9	294
	1994		22.9	16.9			271
	1995		36.8	22.9	36.3	22.4	313
	1996		25.2	16.6			283
	Station		27.2	18.0			1161
Churchill (Man.)	1993	Rural + 50 km	39.8	27.5	39.7	26.7	170
	1994		78.1	34.2			216
	1995		48.3	26.6			216
	1996		37.9	23.4			454
	Station		48.6	27.1			1056
Edmonton (Alta.)	1993	Rural + 50 km	34.7	24.8			112
	1994		40.4	30.6			127
	1995		51.0	33.5			149
	1996		33.9	24.8			211
	Station		39.7	27.9			599
Regina (Sask.)	1994	Rural + 50 km	40.7	25.4			246
	1995		54.7	26.4			113
	Station		45.1	25.9			359
Winnipeg (Man.)	1993	Rural + 50 km	37.4	26.9	37.6	27.4	405
Montreal (Que.)	1993	Urban + 50 km	53.0	34.7			215
	1994		49.5	28.9			239
	Station		51.1	29.6			454
	1993	Urban + 36.5 km	43.5	29.3			
	1994		41.7	24.6			
Halifax (NS)	1993	Rural + 50km	48.9	31.7			516
	1994		39.3	27.6			531
	1995		40.5	27.4			609
	1996		34.2	25.6			613
	Station		40.5	27.8			2269
Toronto (Ont.)	1993	Urban + 50 km	43.9	26.8	43.7	26.7	405
	1994		44.7	31.0			765
	1995		53.0	29.7			583
	1996		53.7	38.4			880
	Station		49.4	32.6			2633
	1993	Urban + 36.5 km	37.89	22.8			590
	1995		47.1	25.2			705

Table 2. Comparison of daily spectral irradiances from the delta-Eddington and 8-stream DISORT methods for the period indicated for each station. N is the number of data points and $\bar{M}$ is the mean annual daily spectral irradiance calculated by DISORT ($J \cdot m^{-2} \cdot day^{-1} \cdot nm^{-1}$). Values of MBE and RMSE are given as percentages of $\bar{M}$. Positive MBE values indicate delta-Eddington overestimation.

Statistics	Resolute Bay 1993	Churchill 1993	Winnipeg 1993	Toronto 1993
		295 nm		
N	89	136	136	192
$\bar{M}$	0.07	0.46	0.83	1.37
MBE	–23.00	6.92	5.72	6.61
RMSE	26.44	13.94	9.00	10.25
		305 nm		
N	141	178	228	250
$\bar{M}$	180.45	347.49	370.41	474.93
MBE	7.40	3.71	3.15	3.31
RMSE	11.11	3.26	3.32	4.41

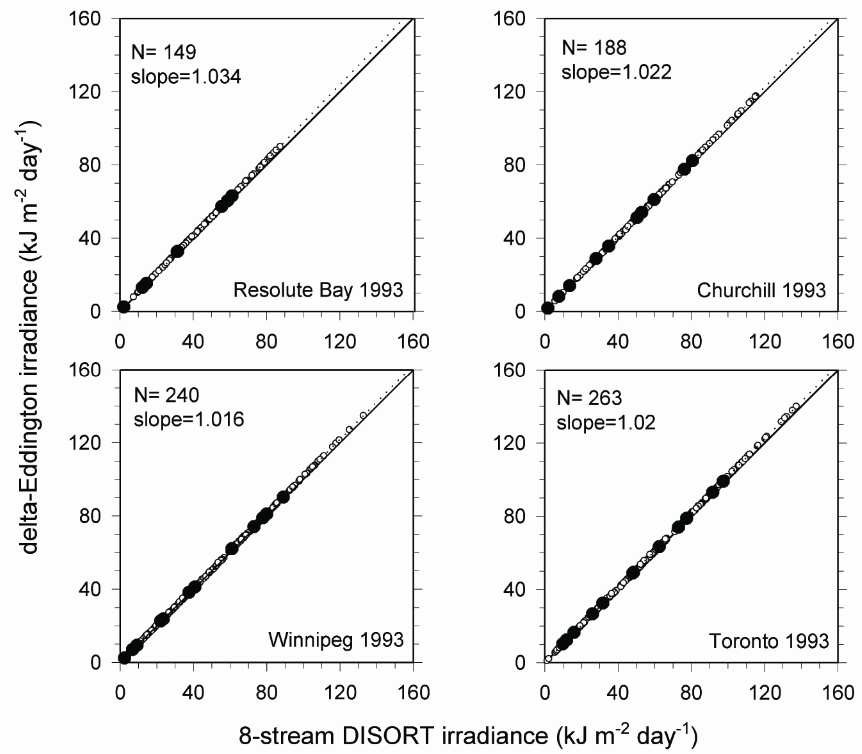


Figure 5. Comparison of 8-stream DISORT and delta-Eddington daily totals (white circles) and monthly averages (black circles) broadband irradiances using annual values of cloud optical depth for each station (Table 1) at Resolute Bay, Churchill, Winnipeg and Toronto. The dotted lines represent linear regressions constrained to pass through the origin.

ton method underestimates the multiple scattering of cloud by up to 14%. The underestimation is not apparent at the lower latitude stations where cloudiness is less and sun angles are higher.

For broadband irradiances, Forster and Shine [8] showed for a theoretical atmosphere that the average delta-Eddington transmittance exceeds 16 stream DISORT estimates by 5% at a sun angle of 60˚. We confirm this for real atmospheres for 1993 at Resolute, Churchill, Winnipeg and Toronto (**Figure 5**) using 8-stream DISORT. The overestimates are less than 4%. The irradiances represent the wide range of solar zenith angles and sky conditions found in midlatitude, subarctic and arctic stations.

5.3. Comparisons of Model Calculations with Measurements

5.3.1. Spectral Results

Comparison statistics of daily spectral irradiances between models and measurements is given in **Table 3** for the two wavelengths (295 nm and 305 nm used previously) for one year at nine stations. For wavelengths ≧ 305 nm the MBE for the two methods is mainly within 5% of the mean measured irradiance. This is well within the uncertainty of the Brewer instrument. Biases for delta-Eddington are mainly positive while those for DISORT are mainly negative. This follows from section 5.2 which showed that the delta-Eddington method, generally, produces larger spectral irradiances than DISORT. The better MBE for delta-Eddington (the inferior model) at longer wavelengths may suggest systematic overestimation by Brewer instruments.

The comparisons between model estimates and measurements are poorer at wavelengths below 305 nm although DISORT estimates match measurements closer than the delta-Eddington estimates as expected (**Table 3**). The larger magnitude of the MBE values at 295 nm at most stations for both models may be attributed in part to the difficulty in measuring within this spectral region. In this range, very low light levels and increased stray light scattering increase the instrumental uncertainty (E. Wu of MSC, personal communication, 2007).

Delta-Eddington's rapid decrease in irradiance at 295 nm, shown in section 5.2, is only detectable at the arctic stations as a result of the greater cloudiness and solar zenith angles. At the other stations, except Halifax, delta-Eddington's MBE values are positive. This follows from flux overestimation in cloudless skies that are more common than in the arctic (**Figure 3**). At Halifax, the

Table 3. Comparison of daily spectral irradiances from the delta-Eddington (DE) and 8-stream DISORT (D8) methods against measurements for the period indicated for each station. N is the number of data points and $\bar{M}$ is the mean annual measured daily spectral irradiance ($J \cdot m^{-2} \cdot day^{-1} \cdot nm^{-1}$). Values of MBE and RMSE are given as percentages of $\bar{M}$ Positive MBE alues indicate model overestimation.

Statistics	Alert 1995	Resolute 1995	Churchill 1993	Edmonton 1994	Regina 1994	Winnipeg 1993	Montreal 1994	Halifax 1993	Toronto 1993
					295 nm				
N	12	80	136	135	204	136	154	206	192
$\bar{M}$	0.02	0.05	0.46	0.62	0.84	0.84	0.72	0.80	1.25
MBE (DE)	–39.93	–3.54	5.25	71.62	1.99	10.50	43.94	–12.31	20.22
MBE (D8)	33.46	24.46	–1.21	51.60	–9.06	–0.42	27.90	–19.67	9.41
RMSE (DE)	85.71	88.09	51.14	87.31	49.19	32.28	70.22	45.18	38.84
RMSE (D8)	64.40	90.81	51.47	75.81	45.56	34.21	51.34	51.89	32.08
					305 nm				
N	31	154	178	274	211	228	212	231	250
$\bar{M}$	121.09	155.68	355.85	340.43	497.54	405.60	475.38	425.44	494.14
MBE (DE)	–1.88	14.37	5.72	5.07	5.23	–1.26	0.28	–6.15	2.85
MBE (D8)	–11.58	7.85	–2.35	–2.15	–1.73	–6.68	–6.39	–10.68	–3.89
RMSE (DE)	26.69	23.50	25.11	25.08	20.13	14.18	12.82	13.76	11.83
RMSE (D8)	29.50	25.30	23.28	20.18	17.77	18.40	13.14	17.55	12.15

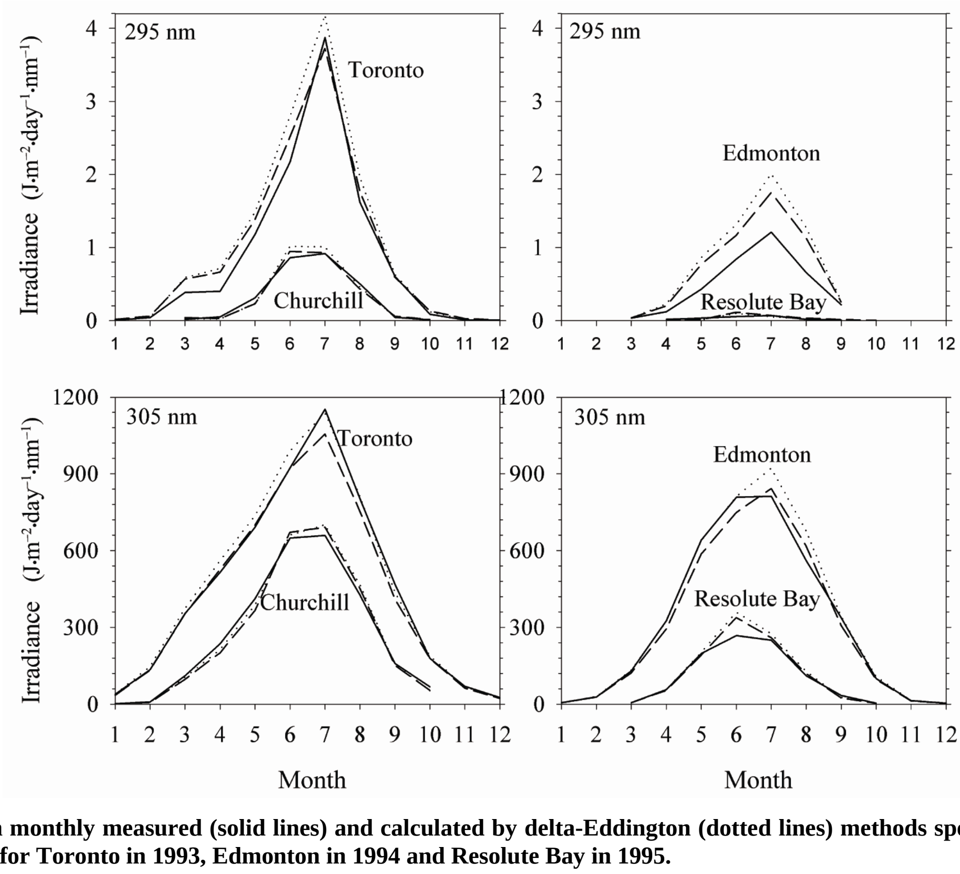


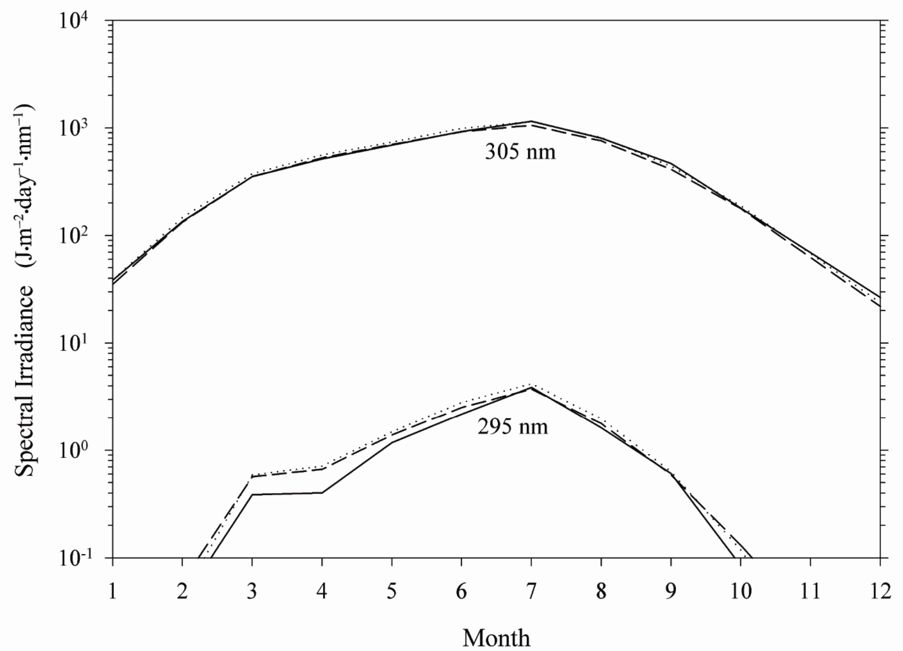
Figure 6. Mean monthly measured (solid lines) and calculated by delta-Eddington (dotted lines) methods spectral irradiance at 295, 305 nm for Toronto in 1993, Edmonton in 1994 and Resolute Bay in 1995.

negative MBE for both models suggests a systematic error in the Brewer instrument.

RMSE values for wavelengths greater than 300 nm are mainly within 12% to 25%. These decrease with length of averaging period for both models to below 10% for 30-day averaging periods, which is similar to decreases for broadband solar radiation estimates [44].

Mean monthly measured and calculated spectral irradiances for 295 nm and 305 nm are plotted for four stations (Resolute, Churchill, Edmonton and Toronto) in **Figure 6**. Both model estimates follow measurements well but at 295 nm the delta-Eddington method consistently overestimates irradiances.

Figure 7 shows the annual variation of measured and



		Delta-Eddington			DISORT 8		
Wavelength	M	Slope	MBE%	RMSE%	Slope	MBE%	RMSE%
295 nm	0.87	1.207	20.70	30.39	1.103	10.29	18.47
305 nm	446.02	1.030	2.97	6.56	0.962	- 3.83	8.02

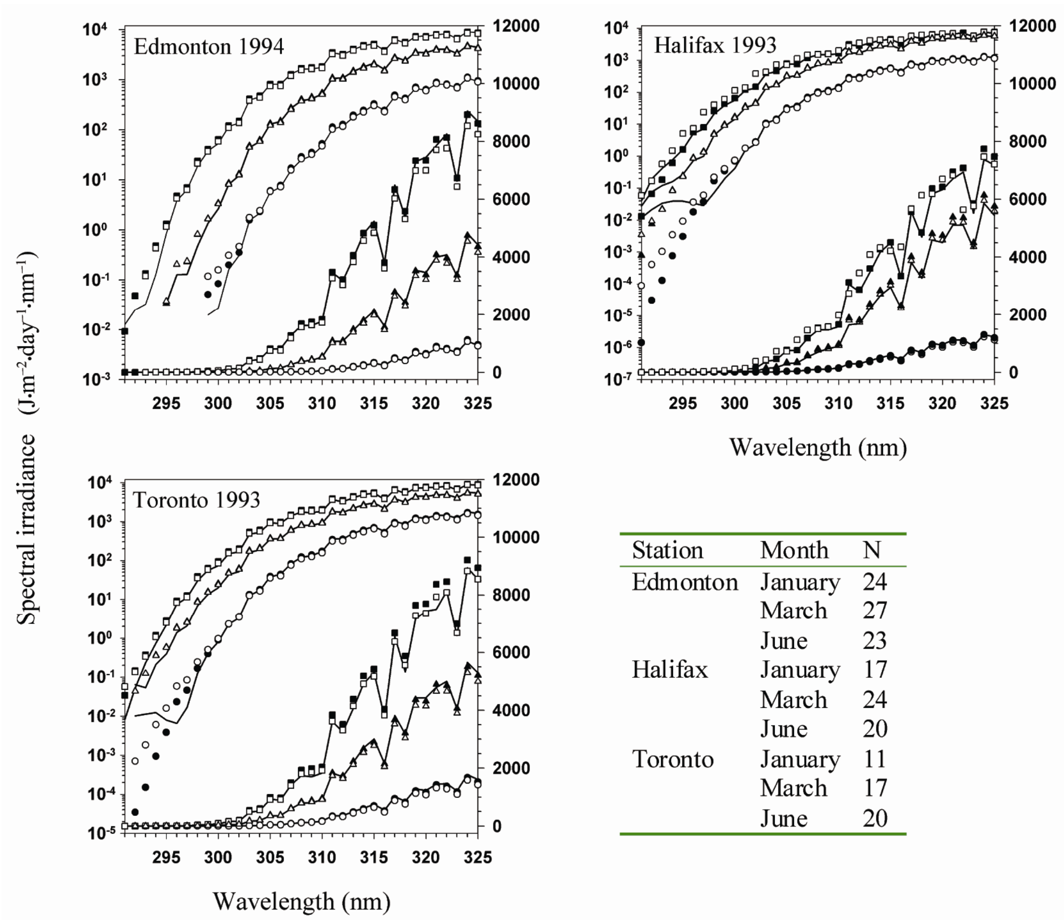
Figure 7. Mean monthly measured (solid lines) spectral and calculated by the delta-Eddington (dotted lines) and DISORT (dash lines) models for various wavelengths for Toronto 1993. Table gives relative MBE and RMSE values with positive MBE indicating model overestimation. M is the mean monthly measured irradiance.

modeled spectral irradiances for 295 nm and 305 nm for Toronto 1993. The table below **Figure 7** indicates larger MBE and RMSE at 295 nm. Both models perform well at wavelengths 305 nm with greatly reduced MBE and RMSE.

Figure 8 shows mean monthly measured spectral irradiance and corresponding model values with both linear and logarithmic plots for three months (January, March and June) for Edmonton in 1994, Halifax in 1993 and Toronto in 1993. The linear plot illustrates more clearly the agreement of measured and calculated irradiances at larger wavelengths while the logarithmic plot is better for showing the agreement at smaller wavelengths. Model values follow measurements well except below 300 nm. This may be attributable as stated earlier to the difficulty of measuring such low irradiance levels and to the light leakage problem even though a correction has been applied to irradiances for wavelengths less than 305 nm [23]. Model calculations show the same spectral variation as the Brewer measurements at wavelengths greater than 295 - 298 nm. The Halifax and Toronto data show evidence of stray light leakage in the corrected Brewer measurements.

5.3.2 Broadband Results

Performance statistics for daily total and monthly averaged broadband irradiances are given in **Table 4** for one year at nine stations. In general, both models perform well for broadband calculations with MBE mainly less than 5% and RMSE less than 25%, which is similar to values obtained from comparisons for global irradiance [45] and the preliminary UV-B irradiance study for Canadian stations by Davies *et al*. [7]. This comparison shows that the delta-Eddington algorithm is adequate for estimating surface broadband UV-B irradiance under all sky conditions from mid-latitudes to the arctic. The method is faster computationally than the DISORT algorithm. Three sets of irradiances were calculated and compared to show the sensitivity of the model to τ_c. Daily and monthly broadband irradiances from delta-Eddington algorithm were calculated separately using (a) annual τ_c for each station, (b) one τ_c for each station, and (c) one τ_c for all non-arctic stations. Agreement in all three cases is good and the results are very similar. MBE is less than 7% and daily RMSE less than 25%, decreasing to less than 15% for monthly averages



Station	Month	N
Edmonton	January	24
	March	27
	June	23
Halifax	January	17
	March	24
	June	20
Toronto	January	11
	March	17
	June	20

Figure 8. Mean monthly measured (solid lines) and calculated by delta-Eddington (Black circles, triangles and squares) and 8-stream DISORT (white circles, triangles and squares) spectral irradiance on a logarithmic (upper lines, left axis) and linear (lower lines, right axis) scale for January (circles), March (triangles) and June (squares) for Edmonton in 1994, Halifax in 1993 and Toronto in 1993. Table gives N which is the number of days used for each month.

Table 4. Summary of delta-Eddington (DE) and 8-stream DISORT (D8) performance measures against measurements for daily total and monthly averaged broadband irradiances for the period indicated for each station. N is the number of data points and $\bar{M}$ is the mean annual measured daily total irradiance ($KJ \cdot m^{-2} \cdot day^{-1}$). Values of MBE and RMSE are given as-percentages (italic) of $\bar{M}$. Positive MBE values indicate model overestimation.

Statistics	Alert 1995	Resolute 1995	Churchill 1993	Edmonton 1994	Regina 1994	Winnipeg 1993	Montreal 1994	Halifax 1993	Toronto 1993
Daily total									
N	31	154	178	274	211	228	212	231	250
$\bar{M}$	38.26	51.28	60.32	49.66	63.23	54.14	62.66	54.80	60.15
MBE (DE)	–0.45	3.13	–0.47	5.55	6.30	3.73	–1.19	–1.10	1.92
MBE (D8)	–7.59	–0.98	–5.95	–0.50	0.57	–1.52	–7.07	–5.75	–2.96
RMSE (DE)	23.24	11.37	18.09	19.21	16.58	13.34	14.33	17.76	14.78
RMSE (D8)	24.67	11.30	18.78	15.88	14.25	12.60	15.18	18.94	14.61
Monthly average									
N	4	8	10	12	10	12	12	12	12
$\bar{M}$	38.27	39.76	49.09	46.33	55.02	47.79	50.17	52.18	55.81
MBE (DE)	–2.18	2.80	–1.85	5.10	5.30	3.25	–1.50	–1.20	1.77
MBE (D8)	–9.02	–1.51	–7.31	0.91	–0.49	–2.00	–7.53	–5.88	–3.21
RMSE (DE)	10.64	8.13	14.15	10.41	9.37	5.34	6.79	9.28	4.88
RMSE (D8)	15.14	6.55	15.23	7.49	5.86	3.79	10.00	11.59	5.35

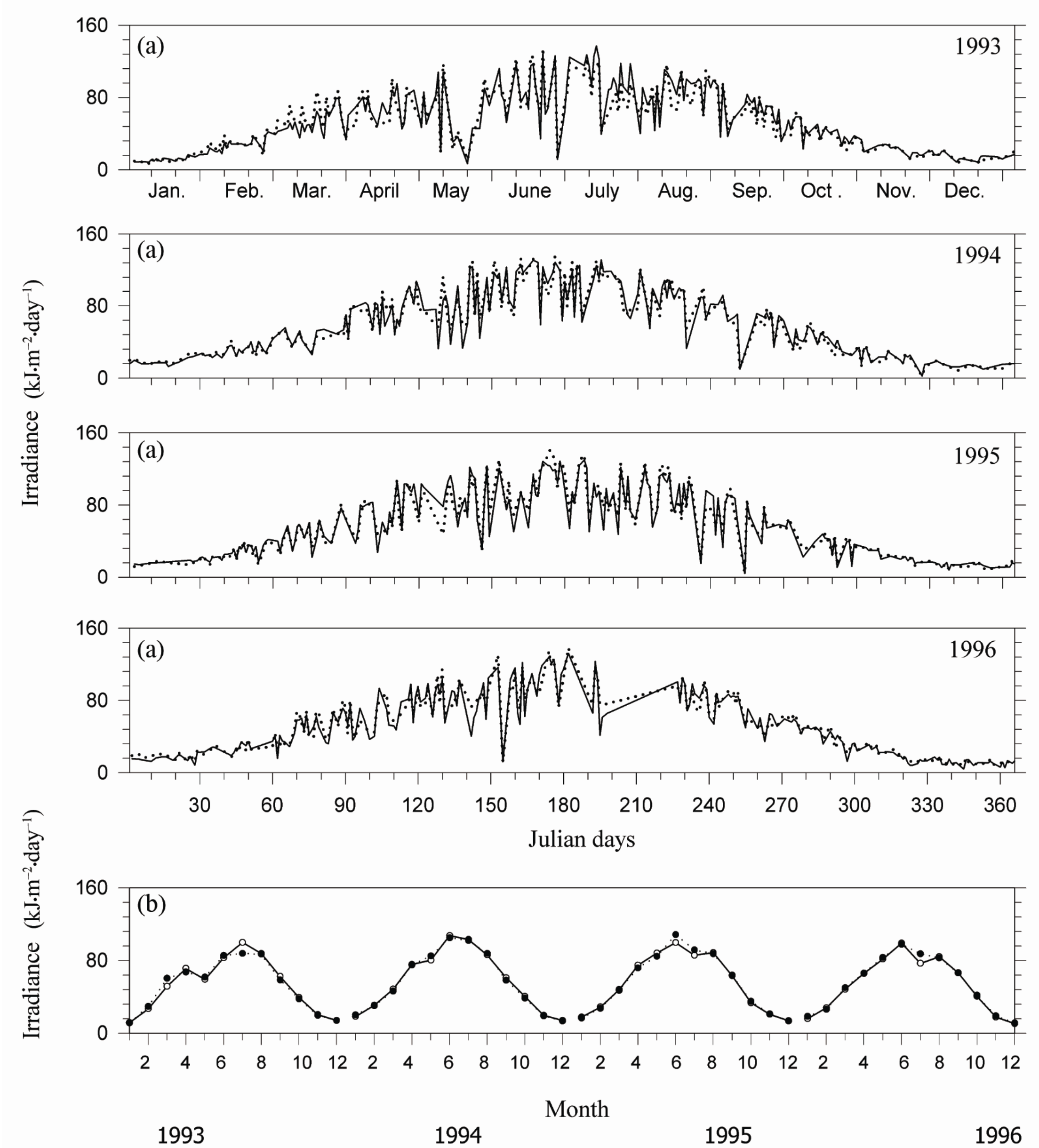


Figure 9. (a) Daily total measured (solid lines) and calculated (dotted lines) broadband irradiances for Halifax (1993-1996) and (b) Monthly average broadband irradiances measured (line and white circles) and calculated by delta-Eddington model (dotted and black circles) for Halifax for years 1993-1996.

(**Table 5**).

Binyamin *et al.* [37] showed that τ_c values for mid-latitudes and subarctic showed little variation with latitude. Therefore, values of τ_c for non-arctic stations were combined to produce a pooled median value of 27. **Table 5** shows that on average the irradiance changes by less than 0.2% when this pooled median value is used. This agreement suggests that in this range of climate τ_c variation is similar and possibly representative of other midlatitudes and sub-arctic climates. This obviates the need for extensive computation to retrieve τ_c for each station and year.

An example of the daily variation in model performance is shown in **Figure 9** for Halifax (1993-1996). Model irradiances follow the variation of measurements well with no indication of seasonal biases, which implies that a constant τ_c can be used satisfactorily. **Figure 9** also shows the model performance of monthly averaged irradiance for Halifax. Most irradiances compare to within 10%. Larger differences (up to 15%) occur in a few summer months but they change in sign from year to year. Similar results were found by Norsang *et al.* [46] in

Table 5. Summary of delta-Eddington performance measures for daily total and monthly average irradiances using annual τ_c, station τ_c and pooled τ_c. N is the number of data points and $\bar{M}$ is the mean daily measured broadband irradiance ($kJ \cdot m^{-2} \cdot day^{-1}$). Values of MBE and RMSE are given as percentages of $\bar{M}$. Positive MBE values indicate model overestimation.

Statistics	Alert	Resolute	Churchill	Edmonton	Regina	Winnipeg	Montreal	Halifax	Toronto
				Annual τ_c					
Daily total									
N	31	574	603	947	373	228	288	855	833
$\bar{M}$	38.26	47.09	58.51	51.47	58.79	54.14	66.12	57.57	66.05
MBE	–6.24	–8.35	–1.26	–0.88	–0.46	–3.37	–6.88	–8.15	–7.57
RMSE	25.74	20.73	22.19	19.39	17.01	15.29	16.94	19.34	19.76
Monthly average									
RMSE	11.94	14.47	13.8	7.15	4.46	5.98	7.81	10.44	9.27
				Station τ_c					
Daily total									
MBE		–8.04	–0.91	–0.69	0.26		–6.35	–8.02	–8.33
RMSE		20.89	21.55	19.42	16.6		16.63	19.19	20.13
Monthly average									
RMSE		14.56	12.99	7.53	4.28		7.16	10.27	9.57
				Pooled τ_c					
Daily total									
MBE			–1.18	–0.47	–1.42	–3.69	–5.31	–7.9	–5.81
RMSE			21.65	19.31	18.03	15.54	15.06	19.10	18.37
Monthly average									
RMSE			13.01	7.49	4.52	6.31	6.24	10.15	7.24

Table 6. Comparisons between measured and calculated (delta-Eddington) daily total and monthly average broadband irradiances for two aerosols loading. N is the number of data points and $\bar{M}$ is the mean measured irradiance ($kJ \cdot m^{-2} \cdot day^{-1}$). Values of MBE and RMSE are given as percentages of $\bar{M}$ Positive MBE values indicate model overestimation.

Statistics	Montreal 1993	Montreal 1994	Toronto 1993	Toronto 1995
		Light aerosol		
Daily total				
N	76	212	250	153
$\bar{M}$	75.72	62.92	60.34	75.20
%MBE	–0.63	–1.20	1.94	6.28
%RMSE	14.58	14.31	14.76	18.48
Monthly average				
N	8	12	12	10
$\bar{M}$	58.15	53.78	59.53	58.16
%MBE	1.35	–2.36	1.92	5.47
%RMSE	7.49	6.00	4.77	9.61
		Heavy aerosol		
Daily total				
%MBE	–2.34	–3.20	0.08	–0.86
%RMSE	14.72	13.99	14.28	15.29
Monthly average				
%MBE	–0.70	–4.45	–0.01	–1.70
%RMSE	7.30	6.93	4.31	5.61

Lhasa, Tibet for clear sky irradiances.

5.4. Comparisons of Two Different Aerosol Loadings

In this section we show the effect of changing boundary layer aerosol from light (50 km visibility) to heavier (36.5 km visibility), which is the average of 50 km and 23 km models for Montreal (1993 and 1994) and Toronto (1993 and 1995). Separate values of τ_c were calculated for each station and year. The heavier aerosol reduced τ_c by an average of 15%. Fluxes from the two urban aerosol loadings are compared with measurements at both stations. The heavier aerosol reduces irradiances by about 2% at Montreal and by 2 - 7% at Toronto (**Table 6**). This agrees well with the findings of Chertock *et al.* [47] and Wang *et al.* [48] who found that aerosols could reduce daily solar irradiance up to 3 - 5%. For Montreal there is better agreement between the light aerosol model results and measurements with MBE less than 2.5% for daily total and monthly average broadband irradiances (**Table 6**). For Toronto, the heavier aerosol model shows better agreement with MBE less than 2%.

6. Conclusions

This study evaluated the relative performance of the delta-Eddington and DISORT algorithms within a numerical model for estimating spectral and broadband UV-B irradiances for Canadian conditions and to validate model results with Brewer spectrophotometer measurements.

The most important findings are:

• The delta-Eddington method produces daily total spectral irradiances for all sky conditions, which are generally 3 - 7% larger than those from the 8-stream DISORT method. The fractional overestimation decreases as wavelength increases. Irradiances are acceptable for wavelengths ≥ 305 nm. This method is unsuitable for wavelengths below 305 nm where ozone absorption is high due to the truncation of the scattering phase function to two terms. At longer wavelengths its performance varies with solar zenith angle and cloudiness. For clear skies, the method always overestimates irradiances at all sun angles with the error increasing as the solar zenith angle increases. For cloudy skies the errors are much smaller.

• The delta-Eddington method performs very well for broadband calculations for both daily total and monthly averaged irradiances.

• Comparison of spectral estimates from both models with measurements indicate uncertainties in the Brewer measurements at wavelengths < 305 nm.

• At wavelengths ≥ 305 nm better agreement with measurements by the delta-Eddington than by DISORT suggests overestimation by the Brewer spectrophotometer.

• Model estimates for broadband irradiances for both daily totals and monthly averages have a MBE less than 5% and RMSE less than 25% deceases to less than 15% for monthly averages. These statistics compare favourably with those obtained for global radiation [45].

• A constant τ_c value of 27 is adequate for all stations except the arctic. This is important because it suggests that further estimation of τ_c is not necessary.

• A light boundary layer aerosol model was suitable for Montreal and a heavy aerosol model for Toronto.

This research is the first to provide extensive evaluation for spectral and broadband irradiances for a large data set, which includes midlatitude, subarctic, and arctic stations. The spectral information is important to biologists who can combine it with various an action spectrum to determine potential biological exposure.

This physically-based model can be applied anywhere. Refinements to the extraterrestrial solar spectrum, Rayleigh scattering cross sections and ozone absorption coefficients are unlikely to be large and the model's linear combination of cloudless and overcast components has been shown to work in a wide range of Canadian conditions. The greatest restriction to its use is the availability of cloud cover information. Future applications of the model should use satellite measurements of ozone and cloud.

The Brewer instrument data sets have not been corrected for the cosine error of the diffuser, temperature errors, as well as absolute radiometric calibration errors. In fact, the 6% increase made to the Brewer data in this study was an approximate correction to remove the systematic cosine error but the actual correction should be made depending on the solar zenith angle and sky illumination conditions [23].

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