Spectral distribution of UV-B irradiance derived by synthetic model compared with simulation results of TUV and ground measurements

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ABSTRACT

Multifilter rotating shadowband radiometers are deployed in the United States, Canada, and New Zealand by the USDA (United States Department of Agriculture) UV-B (ultraviolet-B) Monitoring and Research Program to measure UV-B irradiances at seven discrete wavelengths. A synthetic model is used to construct the continuous spectral distribution, from which irradiance integrals can be performed for various purposes. The derived spectral data are posted for public use through a web accessible database. Although the synthetic model has been validated with a certain data set, few works have been seen to compare the results of the synthetic model with simulations of other widely accepted models such as TUV. Through this comparison the validation of the synthetic model can be further confirmed and alternative techniques for constructing spectral irradiances from discrete narrowband measurements can also be explored.

In this study the data from the USDA UV-B Monitoring and Research Program are used to evaluate the synthetic model and to explore the capability of the TUV model for constructing continuous spectra from discrete measurements. Simulations of the TUV model are compared with discrete measurements, erythema-weighted broadband measurements, and the results of the synthetic model. Good agreements between derived results by using TUV model and the synthetic model with measurements in general further confirm the validation of the synthetic model. Generally, the spectral irradiances constructed by using synthetic model are lower than those by using the TUV model at very shorter wavelengths (<301 nm) and at the wavelengths of 315-342 nm, but are higher at other wavelengths. The ratio of erythemal doses derived by using the TUV simulation to broadband measurements varies between 0.87-1.02. Constructed erythemal doses by using the TUV simulation are closer to broadband measurements than those obtained by using the synthetic model. These results suggest that the TUV model may be a good alternative to accurately estimate continuous spectral distributions from discrete measurements.

Keywords: UV-B radiation, spectrum retrieval, synthetic model, TUV

1. INTRODUCTION

Observations and model results have found a close correlation between the decrease in stratospheric ozone and the increase in solar ultraviolet (UV) radiation reaching the Earth's surface under clear skies[1-4]. Numerous studies have reported that elevated UV radiation is harmful to plants, terrestrial and marine ecosystems, and humans[5-13]. High doses of UV radiation are considered to be responsible for the development of skin cancer and cataracts. UV radiation can weaken the human immune system, cause the loss of crop yield, and affect the phytoplankton activities. Therefore, it is important to monitor the variation of UV radiation over large areas of the Earth's surface in the situation of climate change and depletion of stratospheric ozone.

The multi-filter rotating shadowband (narrowband) radiometer (MFRSR)[14] has been deployed by the USDA UV-B Monitoring and Research Program (UVMRP) to make long term measurements of total horizontal and direct normal solar irradiances at seven wavelengths over the U.S.A. domain (nominal 2 nm FWHM bandwidth)[15-16]. Diffuse irradiances at these seven wavelengths are also derived directly from the measurements. This instrument provides more

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spectral information than a UV-B broadband Pyranometer, with a much lower cost and less operational complexity than a UV spectroradiometer. The continuous spectral distribution of solar UV radiation is important to many scientific disciplines. For example, converting discrete irradiance measurements into continuous spectra allows the construction of weighted doses, predicting irradiance integrals for arbitrary action spectra, and comparisons with collocated spectroradiometer measurements. Several techniques have been proposed to accurately retrieve continuous spectral data from a few discrete measurements[17-21]. The synthetic model was proposed by Min and Harrison[22] and developed by Davis and Slusser[23] to derive UV spectrum based on the MFRSR measurements at seven different wavelengths. Comparison of UV synthetic spectra with broadband and spectroradiometer measurements showed a good agreement[24-25]. It is currently used by UVMRP for online retrieval of continuous spectral data of UV-B radiation from the MFRSR measurements at seven different wavelengths. However, several discrete measurements are required to construct a continuous spectrum using synthetic model since it is based on a best curve fit with the measurements. In addition, this model works well only if there are at least five valid measurements. Usually, the solar zenith angle must be less than 70° for this condition to be met. The computation will overflow or under-flow for the cases of large solar zenith angles since the signals are too weak in these cases. The TUV radiative transfer model was developed to simulate the continuous spectrum of UV irradiance in the troposphere[26-28] and it has been used in various studies[29]. Comparison between results of different models with measurements is an approach to test the validation of the models in accurately constructing solar UV irradiance from MFRSR measurements. It also provides a means of exploring alternatives for this spectrum retrieval purpose.

In this study, we compare the spectral irradiances derived by using synthetic model and TUV simulation with discrete measurements of MFRSR. The derived irradiances are then weighted with an erythemal weighting function and integrated over the UV wavelengths to compare with broadband measurements. The results show good agreements between model results and measurements. The erythemal doses derived by using TUV simulation are closer to broadband measurements than those calculated by using synthetic spectrum. In the rest of this presentation, we will first explain the methodology and material exploited in this study. Results are presented in Section 3. Section 4 concludes this work.

2. METHODOLOTY AND DATA

2.1 Synthetic model

In the synthetic spectra model, the incident irradiance at the Earth's surface is expressed in terms of the extraterrestrial solar irradiance and other factors as follows[22-23, 25].

$$I(\lambda) = I_0(\lambda)\exp\left[-\left(mX(\lambda) + C_1\lambda^{-1} + C_2\lambda^{-2} + C_3\lambda^{-3} + C_4\lambda^{-4}\right)\right] \qquad (1)$$

Where:
λ is the wavelength in nm
$I(\lambda)$ is the irradiance at the ground
$I_0(\lambda)$ is the extraterrestrial irradiance
m is the path length
$X(\lambda)$ is the optical depth due to column ozone
C_1, C_2, C_3, and C_4 are coefficients accounting for molecular, aerosol, and cloud scattering and absorption and the terms correspond to the attenuations of these factors to the irradiance.

The coefficients were determined by a best curve fit technique with the discrete MFRSR measurements at seven different wavelengths. The spectral irradiances can then be computed using Equation (1) after the coefficients have been determined.

2.2 Spectrum constructed with TUV model

There are two steps in constructing solar spectral irradiance using the TUV radiative transfer model. First, the spectrum data are simulated using the TUV model with the input of daily column ozone. Clouds and aerosols are assumed to be zero and the USA standard atmosphere is assumed. This spectral irradiance can be considered as the irradiance due to ozone absorption under some kind of standard atmospheric conditions (e.g., standard atmospheric density and temperature profiles) and is denoted by $I_{o3}(\lambda)$. Then the actual irradiance $I(\lambda)$ is determined using the following equation.

$$I(\lambda) = I_{o3}(\lambda) \times f(\lambda) \quad (2)$$

Where $f(\lambda)$ is a factor to correct the deviation of $I_{o3}(\lambda)$ from $I(\lambda)$. Taking MFRSR measurements as standard references, $f(\lambda)$ is the ratio of $I(\lambda)$ to $I_{o3}(\lambda)$. At the wavelengths where irradiances are measured by MFRSR, the TUV simulation results and the measurements can be used to compute the values of $f(\lambda)$. For wavelengths, at which the irradiances are not measured, $f(\lambda)$ can be determined by an interpolation/extrapolation technique. In this study, linear interpolation and extrapolation are exploited to compute the values of $f(\lambda)$ at wavelengths where irradiances are not measured.

2.3 Erythemal weighting function

In order to compare the retrieved continuous spectral data using Equations (1) and (2) with broadband measurements, the standardized erythema action spectrum[30] is used as a weighting function to integrate the UV spectrums. For the convenience of readers, the erythemal weighting function is given below.

$$fery(\lambda) = \begin{cases} 1, & \lambda < 298nm \\ 10^{0.094\times(298-\lambda)}, & 298nm \le \lambda < 328nm \\ 10^{0.015\times(139-\lambda)}, & 328nm \le \lambda < 400nm \\ 0, & \lambda \ge 400nm \end{cases} \quad (3)$$

Where $fery(\lambda)$ is the weight at wavelength λ. Equation (3) is used as the erythemal weighting function in the TUV model and in this study, and it is used as the calibration factor for the UVB-1 broadband radiometer as well[31].

2.4 Data

Observations at Pawnee (40.790° N, 104.750° W, 1641 m above sea level), Colorado, USA, which is a site in the UVMRP UV-B monitoring network, in May and June, 2006 are used. This selection of data is only for convenience and to use the most recent data. The Multi-Filter Rotating Shadowband Radiometer and UVB-1 broadband radiometer from Yankee Environmental Systems were used in the observation. The MFRSR measured irradiances at the wavelengths 300, 305, 311, 317, 325, 332, and 368 nm[14], while the UVB-1 broadband radiometer measured the UV-B radiation from approximately 280 to 320 nm with an accuracy of 6-10% for different solar zenith angles[32] and was calibrated for erythemal UV radiation measurements[31]. MFRSR measurements were made every 20 seconds and UVB-1 measurements were taken every 15 seconds. These real-time measurements were then aggregated to 3-minute averages online. These averages are used in this study for comparison.

The spectral irradiances derived by using the synthetic model are at the wavelengths of 297-369 nm inclusive with a resolution of 1 nm at 10:00-15:00 local time inclusive at every 3 minutes. For convenience, the time resolution is reduced to 15 minutes in constructing the spectral irradiances by using the TUV model simulations and the measurements. The spectral irradiances at the wavelengths of 280-400 nm inclusive with a resolution of 1 nm are estimated by using the TUV model simulations and the measurements at 9:00-15:00 local time inclusive at every 15 minutes. Therefore, in the following presentation, the data at every 15 minute are used for averages.

3. RESULTS AND DISCUSSION

Figure 1 shows the UV spectral data of MFRSR measurements compared with those constructed by using Equation (2) and the measurements. The results are averages over the observation period. Although differences can be found between the measurements and the model simulations at a specific time, a good agreement between them is obtained in average. Therefore, the erythemal weighted radiation computed with the derived spectral data agrees well with that measured by the UVB-1 broadband radiometer (Figure 2). The daily average ratio of TUV estimated erythemal radiation to broadband radiometer measurement varies between 0.87-1.02 and its average over the observation period is 0.901 (Figure 3). Compared with the results obtained by using the synthetic model[24-25], in which the ratio varied between 0.70-0.90, the erythemal doses estimated by integrating the predicted spectrum using Equation (2) are much closer to broadband measurements. Figure 4 depicts the UV spectrum of MFRSR measurements at 12:00 local time of June 1 compared with those computed using the synthetic model and Equation (2). Both the synthetic model and the TUV model can well estimate the continuous spectrum based on discrete measurements. The ratio between them varies between 0.548 and 1.16 with an average of 1.01. However, the irradiances estimated by using the synthetic model are generally lower than those retrieved by using Equation (2) at very short wavelengths (<301 nm) and at the wavelengths of 315-342 nm (Figure 5). As a result, the erythemal doses estimated by using the synthetic model are generally lower than those estimated by using the TUV model (Figure 6). Figure 7 shows the ratios of erythemal doses estimated by using the synthetic model and by using the TUV model, respectively, to broadband measurements on June 1 as well as the ratios of the synthetic model estimations to the TUV model simulations on the same day. In general, the synthetic estimations of erythemal radiation are lower than the TUV model simulations although they are very close (within 95%), and the latter are closer to broadband measurements. On this specific day, the ratio of the TUV estimation to the broadband measurement varied from 0.875 to 0.900 with an average of 0.884, while the ratio of the synthetic estimation to the broadband measurement varied from 0.849 to 0.890 with an average value of 0.871. These values are slightly different from the results in previous studies[24-25].

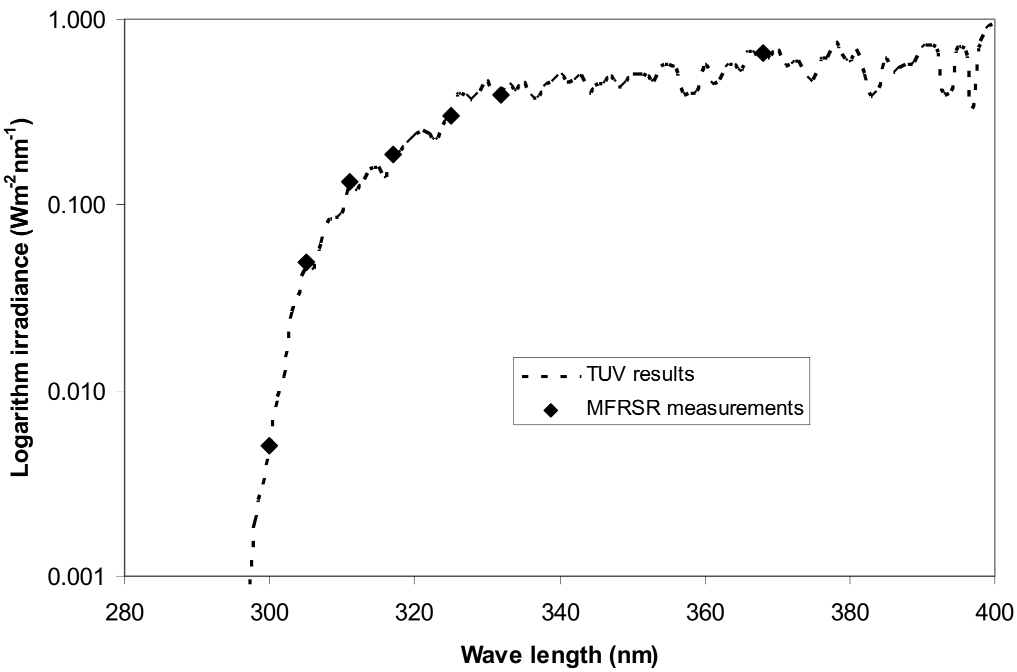

Figure 1. Solar irradiances at different wavelengths measured using MFRSR as compared with those constructed by using the TUV model simulation and the measurements through Equation (2). Results in the figure are the averages of the data at every 15 minutes from 9:00 to 15:00 local time over the observation period (May and June, 2006, Pawnee, Colorado, USA). The value axis (vertical) is plotted in a logarithm scale.

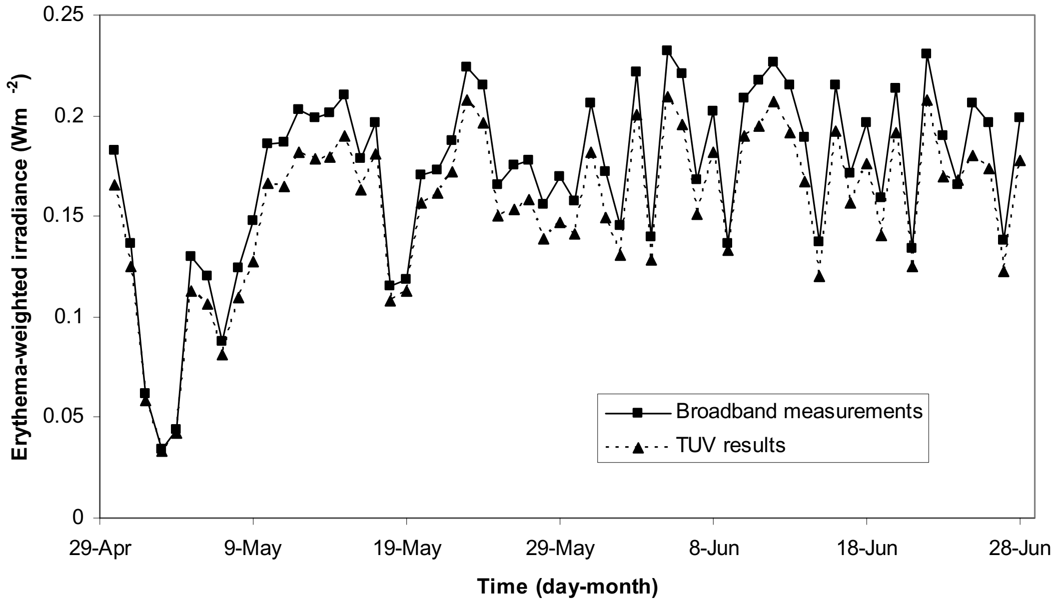

Figure 2. Daily averaged erythemal doses measured by the UVB-1 broadband radiometer compared with those constructed by using the TUV model simulation results and the erythemal weighting function, Pawnee, Colorado, USA, May-June, 2006. Daily averages are calculated using the every 15-minute data from 9:00 to 15:00 local time.

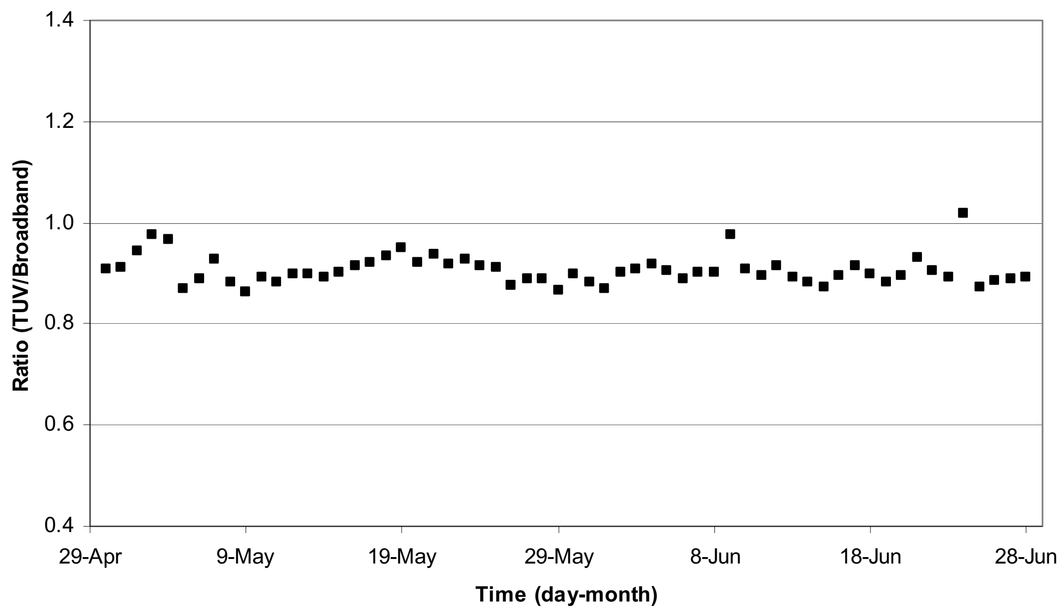

Figure 3. Ratio of daily averaged erythemal doses constructed by using the TUV simulation results to the UVB-1 broadband radiometer measurements, Pawnee, Colorado, USA, May-June, 2006. Data used for computing the ratios are the same as presented in Figure 2.

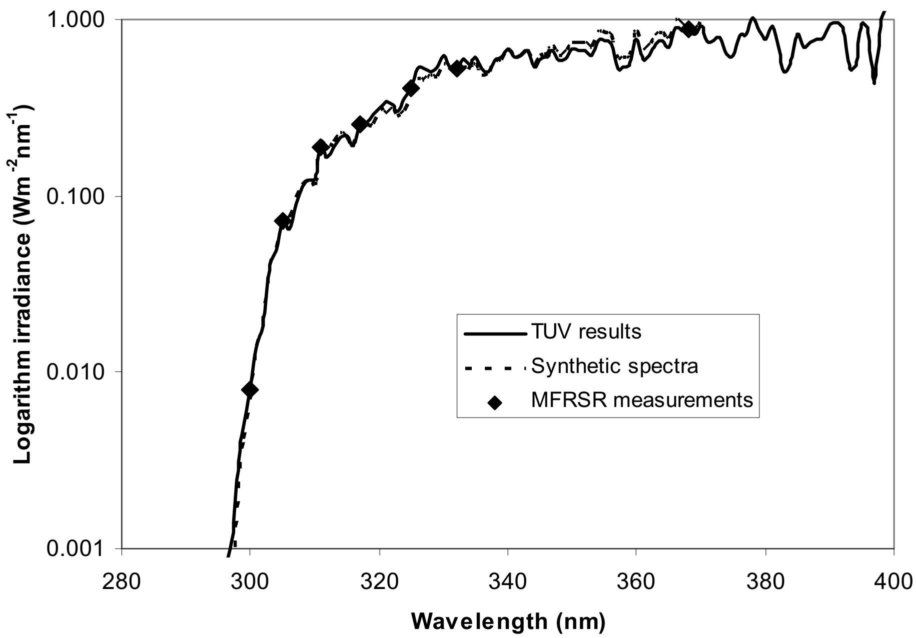

Figure 4. Irradiances at different wavelengths measured by MFRSR as compared with those retrieved by using the TUV simulation and the synthetic model at 12:00 local time at Pawnee, Colorado, USA on June 1, 2006. The values (vertical axis) are plotted in a logarithm scale.

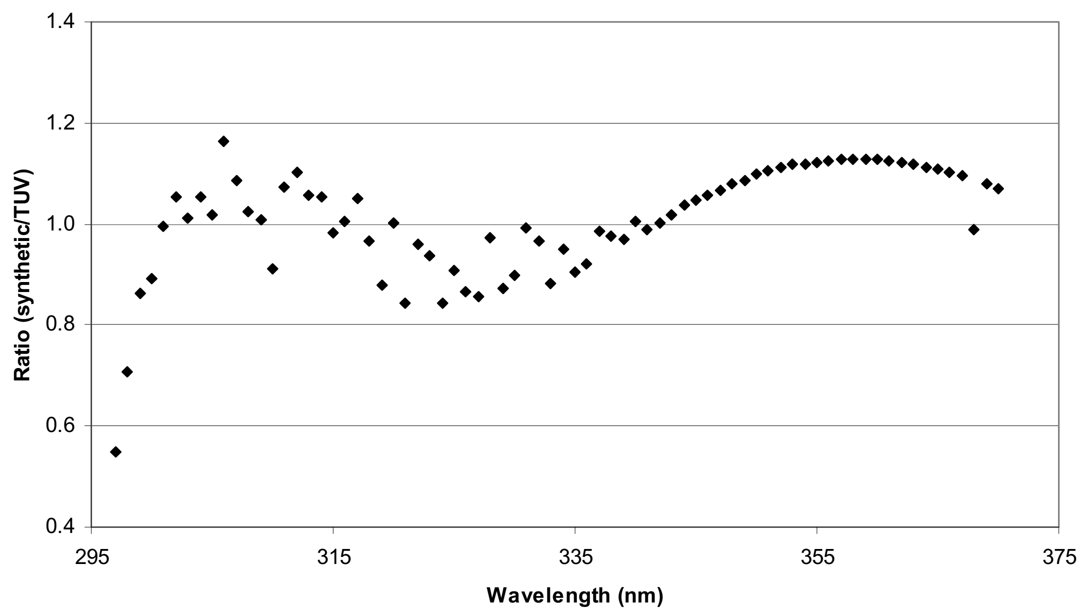

Figure 5. Ratio of spectral irradiances derived by using the synthetic model to those retrieved by using the TUV simulation at 12:00 local time at Pawnee, Colorado, USA on June 1, 2006. Data used for computing the ratios are the same as presented in Figure 4.

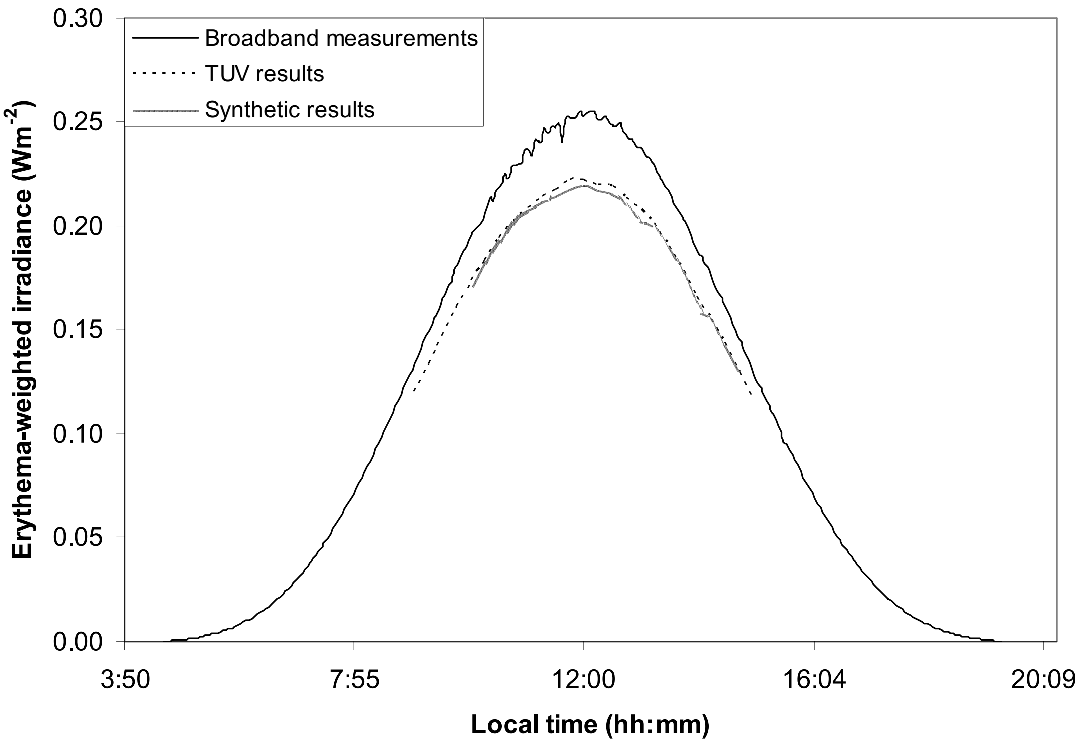

Figure 6. Diurnal pattern of the erythemal doses measured by UVB-1 broadband radiometer as compared with those constructed by using the TUV model simulation and by using the synthetic model at Pawnee, Colorado, USA on June 1, 2006. The bottom curve represents the results of the synthetic model. The up-most curve depicts the broadband measurements, and the curve between describes the results of the TUV model.

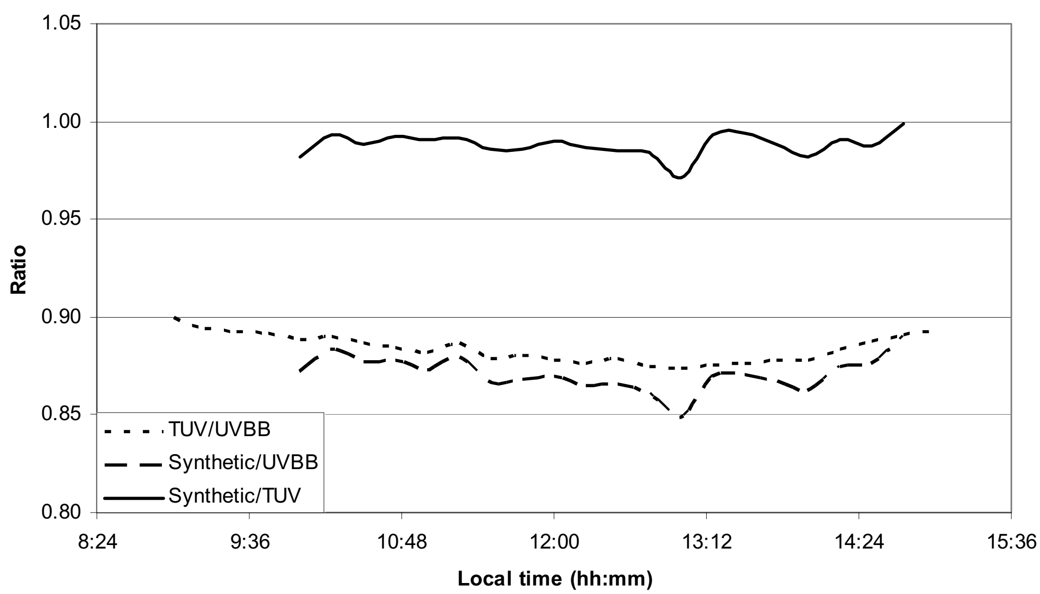

Figure 7. Diurnal pattern of ratios of the erythemal doses derived by using the TUV simulation and the synthetic model to those measured by the UVB-1 broadband radiometer as well as the ratio of the erythemal doses derived by using the synthetic model to those constructed by using the TUV simulation at Pawnee, Colorado, USA on June 1, 2006.

4. CONCLUSION AND FUTURE WORK

Both the synthetic model and the TUV model can successfully estimate continuous spectral irradiances from the MFRSR measurements at the seven wavelengths of 300, 305, 311, 317, 325, 332, and 368 nm, as demonstrated by a good agreement between the measured and the estimated data sets. The agreement between the results derived by using the synthetic model and by using the TUV simulation varies between 0.558 and 1.16 with an average of 1.01 over wavelength at 12:00 local time. Compared with the results predicted by the TUV model, the irradiances estimated by using the synthetic model are generally lower at very short wavelengths (<301 nm) and at the wavelengths of 315-342 nm. When integrated over the UV spectrum and weighted with an erythemal weighting function, the erythemal doses derived from the TUV simulation agree with broadband measurements more closely than those estimated by the synthetic model. The ratio of daily average erythemal doses predicted by using the TUV model to broadband measurements varies between 0.87 and 1.02 with an average value of 0.906.

Only a small set of data is used in this study. To further confirm the conclusion, a larger data set is required in the future. It will also be interesting if the comparison is done for different weather conditions, such as cloudy days and clear skies, and for different solar zenith angles. In this study, we use the ratio of the MFRSR measurement to the TUV simulation for the factor $f(\lambda)$ in Equation (2) and a simple linear interpolation is adopted to estimate the value of the factor for the wavelength at which a measurement is not taken. Different approaches to parameterize the factor $f(\lambda)$ and different techniques for the interpolation will be explored in the future.

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