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Sensitivity of UV-B Irradiance to Cloud Optical Depth and Droplets Equivalent Radii

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Abstract

The DIScrete Ordinate Radiative Transfer (DISORT) and the delta-Eddington models were used to evaluate the relationship between cloud optical depth, τ_c and direct, diffuse and global transmitted irradiances in the UV-B region for various solar zenith angles (SZAs), two values of cloud droplet equivalent radius, r_e (7μm and 10μm) and two cases of low (α = 0.05) and high (α = 0.75) albedos under overcast conditions. The study shows that the delta-Eddington model is not suitable for calculating direct and diffuse components separately but it is suitable for calculating diffuse irradiances for overcast conditions for two cases only at northern latitudes where SZAs are large and at southern Canada where τ_c values are always greater than 10. The delta-Eddington model is accurate when calculating the global fluxes anywhere, although it overestimates by an average of 6%. Global transmittance is greater by 7% for smaller droplet sizes (r_e = 7μm) for both cases of low (α = 0.05) and high (α = 0.75) albedos.

Keywords: cloud equivalent radius, cloud optical depth, delta-Eddington algorithm, 8-stream DISORT algorthim, solar zenith angle, UV-B transmitted irradiance

1. Introduction

Most biological damage at the surface is caused by biologically active ultraviolet, UV-B band (280 to 325 nm) and, to a lesser extent, the UV-A band (325 to 400 nm). Although the irradiance in the UV-C band (200 to 280 nm) is potentially the most damaging to organisms, it is absorbed completely by the atmosphere so that negligible amounts reach the earth's surface. UV-B irradiance in wavelengths between 280 and 290 nm is mainly absorbed by stratospheric ozone and does not reach the earth's surface, even after large reductions in atmospheric ozone such as occur over Antarctica in spring (Frederick et al., 1993). The effective UV-B waveband is from 290 to 325 nm, which is the wavelength range of the Canadian Brewer spectrophotometer measurements (Binyamin et al., 2011). Even though the UV-B band is biologically important, it constitutes only 1.8% of the total solar radiation at the top of the atmosphere, and no more than 1% at the earth's surface (Frederick et al., 1989).

Stratospheric ozone depletion due to human-made chemicals allows more UV-B irradiance to reach the ground causing harmful biological effects such as eye cataracts, skin cancer and DNA damage. It also reduces crop yields, damages aquatic life and affects animal growth (Tevini, 1993). A 1% decrease in total column ozone is expected to cause an increase of 1.3% in erythemally active UV-B irradiance (McKinlay & Diffey, 1987; McKenzie et al., 2003) and 2% in those wavelengths implicated in non-melanoma skin cancer (Kelfkens et al., 1990). However, the UV–B radiation band does not pose biological problems only during periods of reduced stratospheric ozone. Biological concerns for UV–B damage existed before depletion of stratospheric ozone.

Overcast skies generally reduce the amount of UV-B irradiance reaching the surface (up to 80%) and the magnitude of attenuation depends highly on cloud optical depth (τ_c, which is the integral of the extinction (absorption plus scattering) coefficients), the single scattering albedo (ω_c, defined as the ratio of the scattering to extinction coefficients), the asymmetry factor (g_c, the average direction of scattering), the size of droplet equivalent radii (r_e, is a weighted mean of the size distribution of cloud droplets,), solar zenith angle (SZA, the angle between the local vertical and the center of the solar disc) and possible in-cloud absorbers (especially tropospheric ozone) (McKenzie et al., 2003; Calbo et al., 2005). These dependencies make it difficult to set a quantitative relationship between cloud optical properties and the actual UV-B irradiance field.

Clouds effect on radiation has been commonly shown by the cloud modification factor (CMF), which is the ratio of the measured or simulated irradiance at the surface under overcast skies to calculated cloudless irradiance under the same atmosphere (Calbo et al., 2005). Most studies showed a large variability in CMF values for the same cloud cover due to its variable optical properties (Calbo et al., 2005; Esteve et al., 2010, Lopez et al., 2010, Mateos et al., 2010, Aun et al., 2011). The two most important cloud parameters needed to calculate the amount of UV-B irradiance reaching the surface are: τ_c and r_e. Several studies using radiative transfer models have investigated the effect of τ_c on UV radiation (Wang & Lenoble, 1996; Mayer et al., 1998; Nichol et al., 2003; Bernhard et al., 2004; Calbo et al., 2005; apart from a study by Binyamin et al. (2011), it has not studied for the UV-B band. Generally τ_c and r_e effect on UV-B irradiance is a fairly new field, without extensive literature on their effect, instruments, models, and their performance. The objective of this research is to examine the effect of variable τ_c, SZAs, r_e and surface albedo (α) on direct, diffuse and global UV-B transmittance under overcast conditions.

2. The Model

Global transmitted irradiance is the sum of direct beam and diffuse component. The direct beam spectral radiation $S_\lambda(\tau, \mu_0, \phi_0)$ at the ground is described by Beer's law:

$$S_\lambda(\tau, \mu_0, \phi_0) = \mu_0 \left[\frac{S_\lambda(0)}{(d/\bar{d})^2}\right] \exp(-\tau/\mu_0), \tag{1}$$

where λ is the wavelength, μ_0 the cosine of the solar zenith angle, ϕ_0 the solar azimuth angle (is the horizontal angle between the sun and a standard direction, north or south), $S_\lambda(0)$ is the extraterrestrial solar flux at Sun-Earth distance of 1 Astronomical Unit (AU, is the average Sun-Earth distance (1.495×10^{11}m) and is assigned a value of 1), d the actual daily Sun-Earth distance, $\bar{d}$ its average annual value and τ is the total optical depth for the atmosphere.

The diffuse irradiance is the downward component of atmospheric scattering. For a direction specified by μ and ϕ, the spectral radiance $I_\lambda(\tau, \mu, \phi)$ is given by:

$$\mu \frac{dI_\lambda}{d\tau_\lambda}(\tau_\lambda, \mu, \phi) = -I_\lambda(\tau_\lambda, \mu, \phi) + \frac{\omega_\lambda}{4\pi}\int_0^{2\pi}\int_{-1}^{+1} P(\mu, \phi; \mu', \phi') I_\lambda(\tau_\lambda, \mu', \phi')\, d\mu' d\phi' + \frac{\omega_\lambda}{4} S_{0\lambda} P_\lambda(\mu, \phi; \mu_0, \phi_0) e^{(-\tau_\lambda/\mu_0)}, \tag{2}$$

where $P_\lambda(\mu,\phi;\mu',\phi')$ is the scattering phase function that defines the light scattered from the direction μ',ϕ' into the direction μ,ϕ. The first term on the R.H.S. is the diffuse intensity attenuated by absorption and scattering, the second represents multiply scattered radiation from the direction μ',ϕ' into μ,ϕ, and the third represents scattering from the direct beam from μ_0,ϕ_0 into the direction μ,ϕ.

Eq. (2) is an integro-differential equation, which, in general, cannot be solved analytically. The DIScrete Ordinate Radiative Transfer (DISORT) and delta-Eddington algorithms have been used to model irradiance under clear and cloudy skies (Liu et al., 1991; Madronich, 1992; Tsay & Stamnes, 1992; Forster et al., 1995; Subasilar, 2008; Binyamin et al., 2011; Nielsen et al., 2013). The irradiance transmittance in this study was calculated using either the discrete ordinate radiative transfer (DISORT) (Stamnes et al., 1988) or the delta-Eddington (Joseph et al., 1976) solutions of the radiative transfer equation for theoretical model atmospheres for a single layer of variable cloud optical depths irradiated from above solely by direct beam radiation of quantity μ_0 for two cases of low (α = 0.05) and high (α = 0.75) albedos. Cloud single scattering albedo ω_c and asymmetry factor g_c were computed from Mie theory for two values of equivalent droplet radius; 7 µm for arctic stations and 10 µm for midlatitude and subarctic stations (Binyamin et al., 2009). ω_c and g_c were set at 0.999997 and 0.8709, respectively, for equivalent radius of 7 µm and 0.999995 and 0.8587, respectively, for equivalent radius of 10 µm following Binyamin et al. (2009). Clouds are assumed to be composed of spherical droplets of virtually pure water of known radii using the spectral complex refractive index data of Hale & Querry (1973). The ice crystal and mixed-phase clouds were neglected because ω_c and g_c for these clouds are roughly equal to those for liquid clouds (Tsay & Stamnes, 1992; Barker et al., 2002). A fixed surface UV-B albedo of 0.05 and 0.75 were used in all simulations. The 8-stream (8 degrees of expansion of the phase function) DISORT algorithm was used to achieve acceptable accuracy. Min & Harrison (1996) reported that the uncertainty in inferring τ_c using DISORT with 8 streams is 1%.

3. Results and Discussion

3.1 Sensitivity to Cloud Optical Depth (τ_C)

The influence of τ_c on direct and diffuse transmitted broadband irradiances from both the delta-Eddington and DISORT models is shown in Figure 1. This shows model calculations of transmitted irradiance through a single layer of variable optical depth irradiated from above solely by direct beam radiation of quantity μ_0. When μ_0 is small (e.g., 0.2), sun's rays pass through a thicker atmosphere, hence more radiation attenuation and less reaching the surface and when μ_0 is large (e.g., 0.9), the atmospheric attenuation is small and more radiation reaches the surface. Therefore, at mid- and high latitudes the UV-B irradiances in winter are much smaller than in the summer.

Both models show that the direct beam irradiance at the surface becomes smaller with increasing τ_c and SZAs ($\mu_o \leq 0.4$); the relationship is nonlinear. It also shows that when τ_c is greater than 3 or 10 for the DISORT and delta-Eddington models, respectively, the direct beam drops to virtually zero and the surface irradiance is diffuse. There are also discrepancies in the direct and diffuse components between the two models at smaller τ_c and smaller SZAs or high sun ($\mu_0 \geq 0.6$). This is because the delta-Eddington model uses the scaled optical depth in calculating the direct beam, which makes the direct irradiance larger than the actual direct irradiance (Joseph et al., 1976). Also the direct beam includes diffuse radiation that travels in the same direction as the direct beam resulting in overestimation of the direct beam and underestimation of diffuse irradiance. This is evidently not a problem in the calculation of global fluxes. To confirm this, the globally transmitted irradiance is plotted against τ_c in Figure 1c and shows that the delta-Eddington values compare well with that of DISORT at small τ_c and higher solar elevation ($\mu_0 \geq 0.6$). Therefore, the delta-Eddington model is accurate when calculating the global fluxes anywhere, although it overestimates by an average of 6%. Similar results were found by Nielsen et al. (2013) that the relative error increases by 4% for τ_c = 5 and solar zenith angle of 53.0°. For very high optical thicknesses (τ_c > 50) the biases are insignificant because the total transmittance and consequently the absolute error is very low (Nielsen et al., 2013).

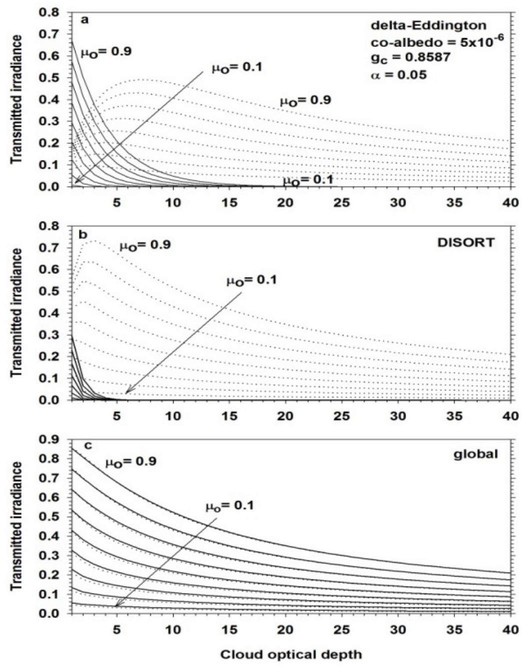

Figure 1. The variation of direct beam (solid line) and diffuse (dotted line) transmitted irradiance with cloud optical depth and cosine of the solar zenith angle (μ_0). (a) calculated by delta-Eddington and (b) by DISORT. Figure c shows the global (direct+diffuse) transmitted irradiance calculated by delta-Eddington (solid line) and DISORT (dotted line). g_c is the cloud asymmetry factor and α is the surface albedo.

The variation of the diffuse transmittance calculated by both delta-Eddington and DISORT models with τ_c is presented in Figure 2. The disagreement between the two models for $\mu_0 \geq 0.6$ and when τ_c < *10* is apparent. However, both models show that transmitted irradiance changes little with τ_c for larger solar zenith angles ($\mu_o \leq$ 0.5) and becomes constant beyond τ_c = 30. Therefore, the above comparisons suggest that the delta-Eddington model is not suitable for calculating direct and diffuse components separately but is suitable for calculating diffuse irradiances for cloudy conditions for two cases only at northern latitudes where SZAs are large and at southern Canada where τ_c values are always greater than 10.

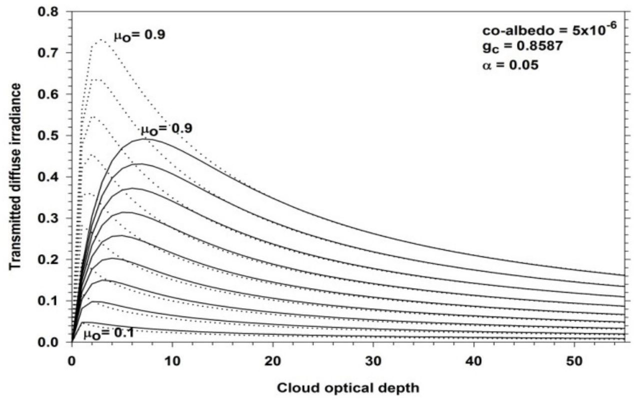

Figure 2. The sensitivity of diffuse UV-B irradiance calculated by delta-Eddington (solid line) and DISORT (dotted line) to cloud optical depth and cosine of the solar zenith angle (μ_0). g_c is the cloud asymmetry factor and α is the surface albedo.

3.2 Sensitivity to Equivalent Radius (r_e)

The sensitivity of total irradiance to τ_c for different r_e, α and SZAs is shown in Figure 3. For smaller droplet sizes ($r_{e\,=}$ 7μm), the transmitted flux increases by an average of 7% due to larger values of ω_c and g_c and τ_c is smaller by 10% than that for r_e = 10 μm. Leontieva et al. (1994) found that the variations in r_e from 5μm to 15μm can produce an uncertainty of about 15% in retrieved τ_c for the whole solar irradiance. r_e has varying impact on irradiances. Rawlins & Foot (1990) stated that increasing the value of r_e results in greater forward scattering by the cloud layer and an increase in transmitted solar irradiance. Similarly, Hu & Stamnes (2000) found that an increase in the size of r_e decreases its reflectivity of solar radiation and warms the Earth's surface. This is true only for low surface albedo but for larger albedo ≥ 0.8 the transmitted irradiance at the surface is larger with smaller r_e (Leontyeva & Stamnes, 1994). However, this study shows that the total UV-B transmitted irradiance is always larger with smaller r_e for both cases of low (α =0.05) and high (α =0.75) albedos (Figure 3). Long photon path lengths in clouds with r_e = 10 μm can increase absorption by tropospheric ozone, resulting in a sharp decrease in transmitted irradiance (Fredrick & Lubin, 1988; Mayer et al., 1998). The effect of surface albedo is more obvious in Figure 4 where transmitted diffuse irradiance is shown for one solar zenith angle (60°) and two different r_e values. Multiple reflections between the snow surface with high albedo (i.e., α = 0.75) and cloud base can double the surface radiation (Figure 4).

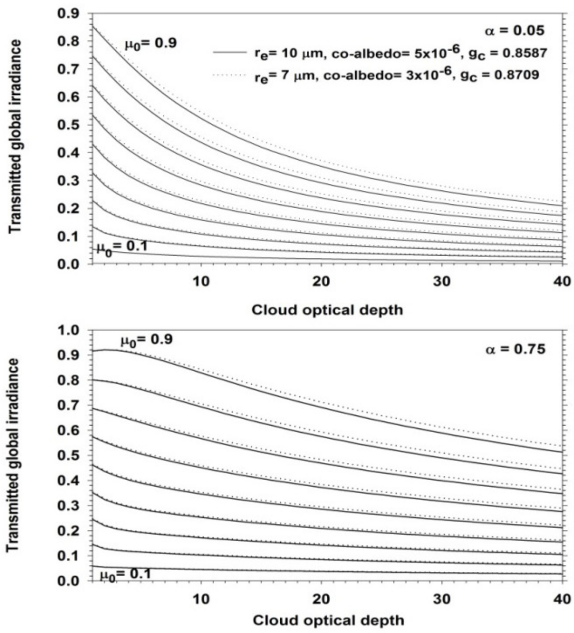

Figure 3. The sensitivity of global trasmitted UV-B irradiance to cloud optical depth for different equivalent radii (r_e), solar zenith angle cosines (μ_0) and surface albedos (α), calculated by the delta-Eddington algorithm. g_c is the cloud asymmetry factor.

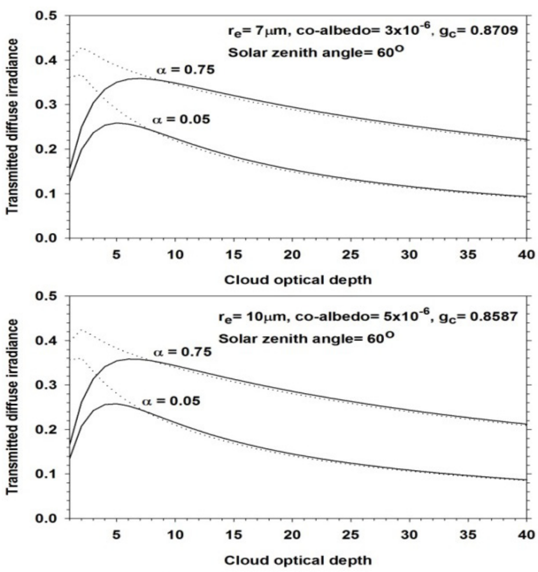

Figure 4. The sensitivity of diffuse transmitted irradiance to cloud optical depth at various surface albedos (α) and equivalent radii (r_e), computed by delta-Eddington (solid line) and DISORT (dotted line) methods. g_c is the cloud asymmetry factor.

4. Summary and Conclusions

Sensitivity analyses were made with the delta-Eddington and the DISORT 8 models for a single cloudy layer of various τ_c values and SZAs to examine the accuracy of delta-Eddington in calculating the transmitted broadband UV-B irradiances under overcast conditions and to investigate the effect of using two different drop sizes ($r_e = 7$ μm and $r_e = 10$ μm) for two cases of low ($\alpha = 0.05$) and high ($\alpha = 0.75$) albedos on the transmitted flux. The significant contributions from this research are as follows:

- The direct, diffuse and global irradiances show very strong dependence on SZA and τ_c less than 30.
- The direct beam irradiance becomes negligible with increasing τ_c and the diffuse component contributes the most to surface irradiance at $\tau_c \geq 5$ but it varies more slowly as τ_c increases.
- The delta-Eddington method is not suitable for calculating direct and diffuse components separately but is accurate for calculating the global (direct +diffuse) broadband irradiances, although it overestimates surface irradiance by an average of 6%.

- Global UV-B irradiance is very sensitive to $\tau_c \leq 10$ and as SZA decreases but the sensitivity diminishes quickly as τ_c and SZA become larger.
- Diffuse irradiances can be calculated accurately from the delta-Eddington method for two cases only at northern latitudes where SZAs are large and at southern Canada where τ_c values are always larger than 10.
- The variation of r_e from $7\mu m$ to $10\mu m$ produced smaller values of ω_c and g_c and larger τ_c values. Therefore, global transmitted UV-B irradiances decreases by 7% with increasing r_e for both cases of low ($\alpha = 0.05$) and high ($\alpha = 0.75$) albedos.

UV-B irradiance does not change the temperature of the earth's surface. There is no warming under the Antarctic ozone hole, even though the skin would burn faster. However, UV-B irradiance does reduce plant growth which leads to an increase in carbon dioxide, a gas which is a major contributor to the greenhouse effect.

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