Optical Depth for Overcast Clouds from ERBE Bidirectional Reflection Distribution Functions

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Abstract

Mean values of overcast cloud optical depths τ implied by the Earth Radiation Budget Experiment (ERBE) bidirectional reflection distribution functions (BRDFs) are compared with a corresponding value derived from surface pyranometer measurements made across Canada during summer. In so doing, it is assumed that the form of the frequency distribution for τ over the entire earth is the same as its Canadian summer subset. It is also assumed that azimuthally averaged ERBE BRDFs for overcast clouds can be modeled using plane-parallel theory. With these assumptions, it is shown that mean τ for overcast clouds implied by the ERBE BRDFs is ~40 while the corresponding value inferred from Canadian pyranometer data is ~30. Though independent estimates of these particular quantities have not been reported as yet, the difference seems reasonable. Moreover, it seems likely, though definitely not conclusive, that this difference could not be used ultimately to support the existence of anomalous absorption of solar radiation by clouds.

Introduction

There have been very few objections raised regarding the integrity of mean top of atmosphere (TOA) reflected broadband solar fluxes inferred from ERBE observations. This could be interpreted, in turn, to imply that on average least, ERBE BRDFs are thought to be reasonably sound (Brooks et al. 1986). Moreover, the most reliable BRDFs are likely those for overcast skies. Therefore, assuming that the ERBE azimuthally averaged BRDFs for overcast clouds can be modeled well with plane-parallel theory, and that a suitable distribution of cloud optical depth τ can be found, it should be possible to estimate a likely range of mean optical depth $\bar{\tau}$ for overcast cloud as seen by ERBE's forerunner Nimbus-7. Thus, the purpose of this paper is to estimate a likely range of $\bar{\tau}$ implied by the ERBE BRDFs and compare it to estimates derived from Canadian pyranometer data.

Methodology

Define the azimuthally averaged BRDF as

$$\left\langle \Omega\left(\mu^{i}, \mu_0^{j}; \tau\right) \right\rangle = \frac{1}{2\pi} \int_0^{2\pi} \Omega\left(\mu^{i}, \phi, \mu_0^{j}; \tau\right) d\phi ,$$

where $\Omega\left(\mu^{i}, \phi, \mu_0^{j}; \tau\right)$ is the full hemispheric BRDF, μ^{i} and μ_0^{j} represent the *i*th and *j*th range of cosine of viewing and solar zenith angles, ϕ is relative azimuth angle, and τ is cloud optical depth. Figure 1 shows broadband $\mu^{i} \left\langle \Omega\left(\mu^{i}, \mu_0^{j}; \tau\right) \right\rangle$ as a function of τ (for reference at 0.5 μm) for plane-parallel, homogeneous clouds. These were produced by a Monte Carlo algorithm (Barker et al. 1998a) using 1-km thick clouds with bases at 1 km imbedded in the mid-latitude summer (MLS) atmosphere with a spectrally invariant (Lambertian) surface albedo of 0.15. Also, cloud droplets were assumed to be liquid spheres with an effective radius of 10 μm. Analysis was restricted to these ranges of μ_0 because they were the most frequent in the Canadian dataset. The dashed lines on Figure 1 are corresponding ERBE BRDF values. It is likely that the moderate variability of cloud structure, characteristic of overcast cloud, within Nimbus-7's field-of-view (FOV) had little influence on $\left\langle \Omega\left(\mu^{i}, \mu_0^{j}; \tau\right) \right\rangle$ (N. Loeb, personal communication 1997). However, it is unclear to what extent ice crystals influenced ERBE's $\left\langle \Omega\left(\mu^{i}, \mu_0^{j}; \tau\right) \right\rangle$.

On the basis of Figure 1, for $\mu_0 \in [0.4, 0.5]$, typical values of τ that went into the construction of ERBE BRDFs appear to

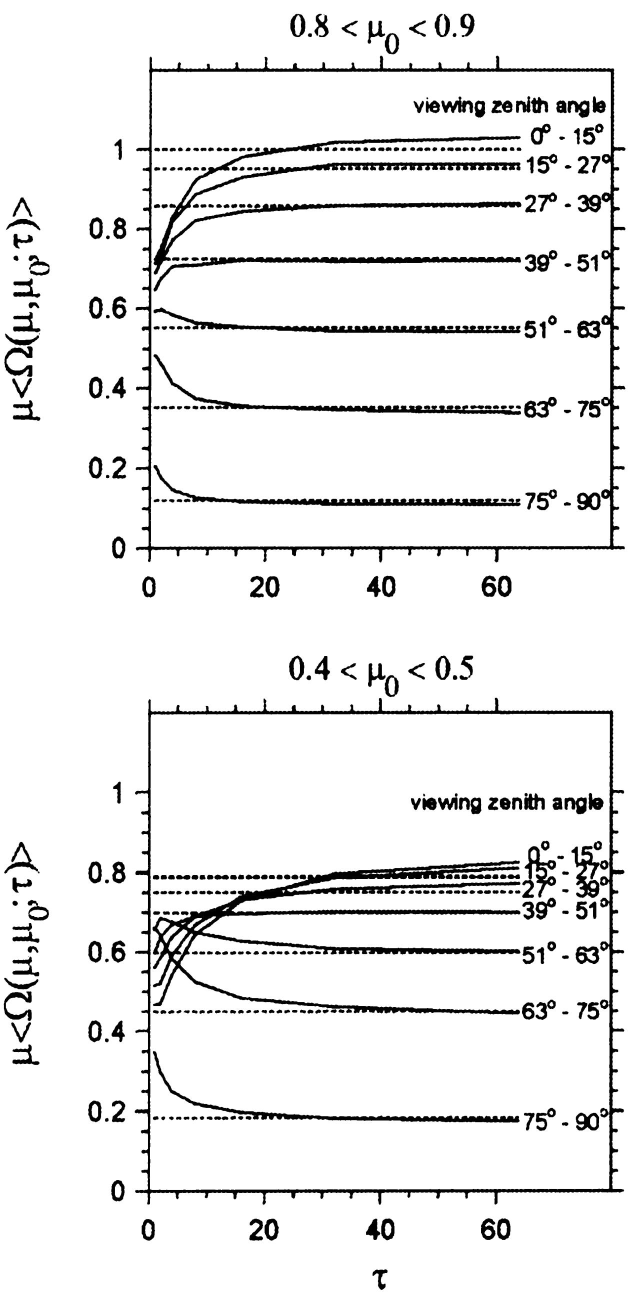

Figure 1. Solid lines are model-generated azimuthally averaged BRDFs as a function of τ for two ranges of solar zenith angles as listed on the top of each graph. Each line represents a specific range of viewing zenith angles as listed on the graphs. Horizontal dashed lines are corresponding ERBE BRDF values. For a concentrated view, (Ω) were scaled by μ.

have been ~30; as for $\mu_0 \in [0.8,0.9]$, typical values of τ seem to have been ~20. The mean optical depth $\overline{\tau}$ of clouds that went into the making of the ERBE BRDFs can, however, be solved for with somewhat greater accuracy as discussed next.

Assume that for given ranges of μ^i and μ_0^j, mean values of $\left\langle \Omega\left(\mu^i,\mu_0^j;\tau\right)\right\rangle$ are

$$\overline{\left\langle \Omega\left(\mu^i,\mu_0^j\right)\right\rangle} = \int_0^\infty \left\langle \Omega\left(\mu^i,\mu_0^j;\tau\right)\right\rangle p_{\mu^i,\mu_0^j}(\tau)\,d\tau, \qquad (1)$$

where $p_{\mu^i,\mu_0^j}(\tau)$ are normalized conditional probability distributions of mean cloud optical depth in Nimbus-7's FOV [i.e., ~(50 km)^2]. Following from Figure 1, assume that for most overcast scenes, $\left\langle \Omega\left(\mu^i,\mu_0^j;\tau\right)\right\rangle$ can be approximated by

$$\left\langle \Omega\left(\mu^i,\mu_0^j;\tau\right)\right\rangle \approx a\tau^b, \qquad (2)$$

where a and b are coefficients determined by least-squares regression.

Using hourly integrated surface irradiance measurements from 21 sites across Canada during summer, Barker et al. (1998b) found that for each site, $p(\tau)$ can be approximated extremely well by

$$p_\Gamma(\tau) \approx \frac{1}{\Gamma(\nu)}\left(\frac{\nu}{\overline{\tau}}\right)^{\nu} \tau^{\nu-1}\, e^{-\tau\nu/\overline{\tau}}, \qquad (3)$$

where $\overline{\tau}$ is mean τ for all overcast scenes, and ν is related to var(τ). Figure 2 shows the overall $p_\Gamma(\tau)$ for all 21 stations in which $\overline{\tau}$ = 28.4 and ν computed by the maximum likelihood estimate and method of moments is 1.59 and 1.82, respectively. Note that because these τ were inferred from hourly flux data and a plane-parallel radiative transfer model, they are (as are values inferred from the ERBE BRDFs) necessarily effective values in which it is fully expected that

$$\overline{\tau} = \int_0^\infty \tau p(\tau)\,d\tau \le \int_0^\infty \tau P(\tau)\,d \qquad (4)$$

where $P(\tau)$ is the unknown intrinsic density function of τ (Cahalan et al. 1994). It is anticipated, however, that by restricting the analysis to overcast clouds, the inequality in Eq. (4) is minor (Barker et al. 1996; R. Pincus, personal communication 1998).

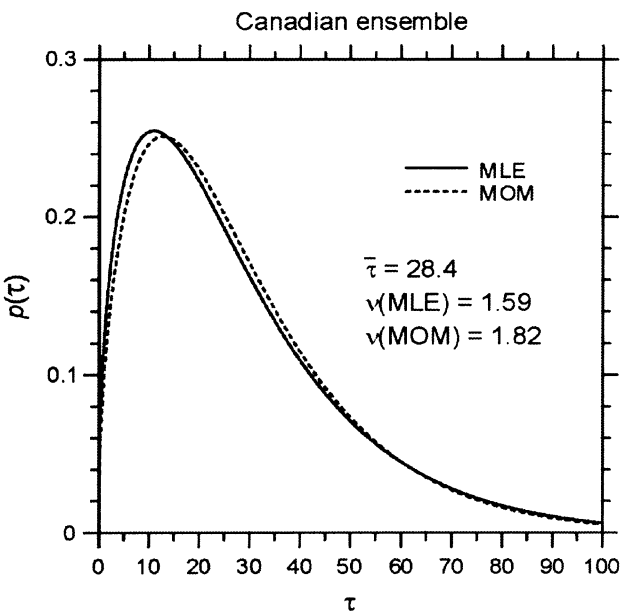

Figure 2. Probability density functions fit to over 75,000 values of overcast cloud τ inferred from hourly pyranometer measurements made at 21 sites across Canada during summer. Values of ν were obtained by the maximum likelihood estimate (MLE) and the method of moments (MOM). Values listed on the plot are parameters for Eq. (3).

Although the gamma distribution describes the Canadian summer data almost perfectly, there is no guarantee that it is applicable to the entire global population. For the time being, however, assume that it is. This is not as strict as it sounds and the gamma distribution does provide a simple analytic model to work with. Hence, substituting Eq. (2) and Eq. (3) into Eq. (1) and using the ERBE azimuthally averaged BRDFs gives

$$\overline{\left\langle \Omega\left(\mu^{i},\mu_0^{j}\right)\right\rangle} \approx \frac{a}{\Gamma(\nu)}\left(\frac{\nu}{\bar{\tau}}\right)^{\nu}\int_0^{\infty}\tau^{\nu+b-1}e^{-\tau\nu/\bar{\tau}}\,d\tau,$$

which when solved for $\bar{\tau}$ yields

$$\bar{\tau}\left(\mu^{i},\mu_0^{j}\middle|\nu\right) \approx \left[\frac{\overline{\left\langle \Omega\left(\mu^{i},\mu_0^{j}\right)\right\rangle}}{a}\;\frac{\Gamma\nu}{\Gamma(\nu+b)}\right]^{1/b}, \qquad (5)$$

where it is now clear that the solution for a particular viewing-illumination geometry depends on the value assumed for ν.

Figure 3 shows $\bar{\tau}$ estimated by Eq. (5) for ERBE BRDFs as a function of ν for values of μ^{i} in which the fit in Eq. (2) had a coefficient of determination $R^2 > 0.9$. It is unlikely that $\bar{\tau}(\nu)$ vary much as a function of μ^{i} and indeed the disparity in $\bar{\tau}(\nu)$ for a given ν is rather narrow at about ±5. On the

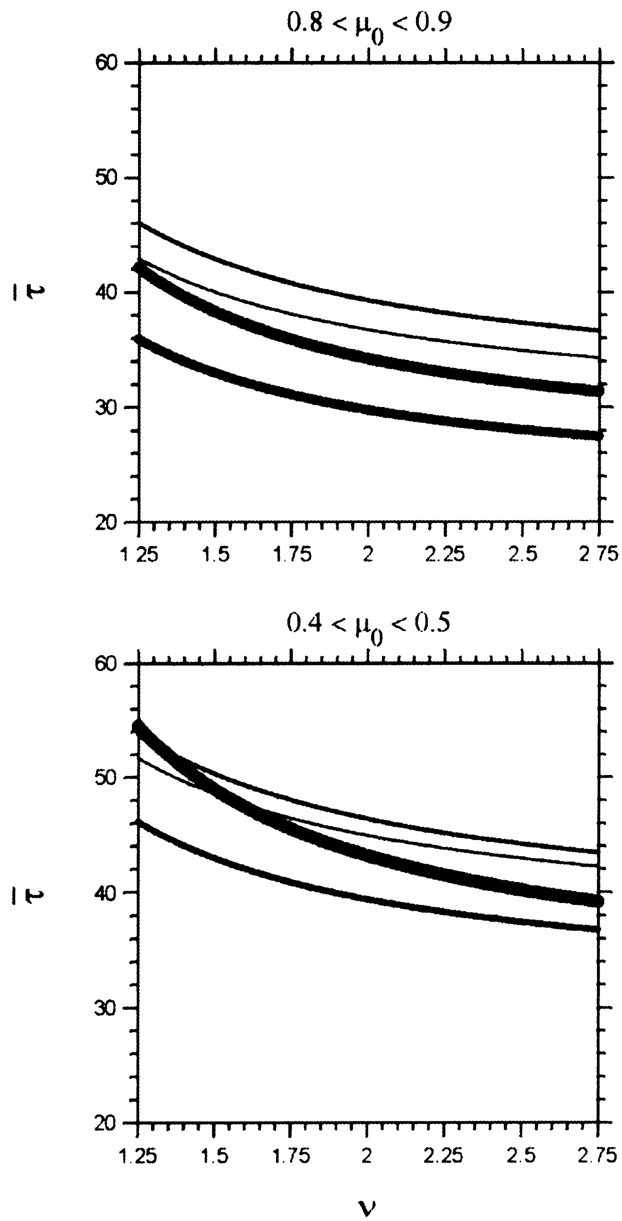

Figure 3. Solutions to Eq. (5) using values for horizontal dashed lines and regression parameters for solid curves shown in Figure 1. These are estimates of mean cloud τ as a function of unknown ν implied by the ERBE BRDFs. Line thicknesses are proportional to viewing zenith angle.

other hand, for $0.4 < \mu 0 < 0.5$, $\bar{\tau} \approx 45$ while for $0.8 < \mu_0 < 0.9$, $\bar{\tau} \approx 35$ (assuming that $\nu \approx 1.7$ as indicated by the Canadian data). Note that these values are substantially larger than the values at the points of intersection of the model and ERBE BRDF curves shown in Figure 1. It would be interesting to see if this variation in $\bar{\tau}$ with μ_0 can be corroborated with independent data or whether it is a manifestation of the assumptions made here. Note that this variation is not restricted to just time of day; latitudinal and seasonal variations are there too. Hence, it may be that the $p(\tau)$ that went into the making of ERBE BRDFs possess dependence on μ_0. If so, if for $0.8 < \mu_0 < 0.9$ $\nu \approx 1.25$, while for $0.4 < \mu_0 < 0.5$, $\nu \approx 2.75$, $\bar{\tau}$ would be roughly constant at about 40. In actuality, however, it is likely that both $\bar{\tau}$ and ν vary slightly with μ_0 (and even μ).

The monotonic increase of $\bar{\tau}$ with decreasing ν, as displayed in Figure 3, is to be expected. As ν decreases, smaller τ have increasing importance in the determination of $\left\langle \Omega\left(\mu^i, \mu_0^j; \tau\right)\right\rangle$. However, since $\left\langle \Omega\left(\mu^i, \mu_0^j; \tau\right)\right\rangle$ is fixed, $\bar{\tau}$ must be increased as a counter measure.

Discussion and Summary

Effective values of overcast cloud optical depth τ were inferred from hourly surface irradiance measurements by Barker et al. (1998b). For 21 stations across Canada during summer, they estimated $\bar{\tau}$ to be ~30, though this value is expected to be a slight underestimate relative to the true mean. Using azimuthally averaged ERBE BRDFs, it was shown here using plane-parallel theory that a corresponding global annual mean value is likely to be between 35 and 45. This agrees quite well with the Canadian estimate despite the fact that roughly 70% of Nimbus-7's measurements were over ocean.

More important, the similarity between the ERBE and Canadian estimates suggests that an anomalous absorber of solar radiation is very unlikely. Had an anomalous absorber been present, the likes of that purported by Valero et al. (1997), surface retrieved values of $\bar{\tau}$ would have been much larger than 30; the algorithm would have blindly interpreted anomalous attenuation as having come from optically thicker clouds. Likewise, $\bar{\tau}$ implied by ERBE BRDFs would have been roughly half (cf., Zender et al. 1997; Li et al. 1998) the values shown in Figure 3 (i.e., ~20); as extra attenuation would have been interpreted as thinner cloud. Furthermore, results presented here have been corroborated by a more direct comparison between overcast τ inferred from surface pyranometer data and collocated ERBE measurements (Sun et al. 1998).

The other point worth mentioning is that when Barker et al. (1998b) compared surface-inferred τ with collocated ISCCP values (Rossow and Schiffer 1991), the ISCCP values were roughly half the surface values. This, however, is at vast odds with the results shown here for ERBE and those of Sun et al. (1998).

Acknowledgments

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Other Publications in Progress

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