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Solar spectral weight at low cloud tops

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Abstract. The spectral distribution of the incoming solar irradiance varies substantially from the top of the atmosphere to the surface. This occurs because of the selective spectral attenuation by the various atmospheric constituents. Using a line-by-line and doubling-adding solar radiative transfer model, we formulate a prescription that accounts for this variation in the spectral solar irradiance and thereby determine the appropriate spectral weights for low clouds. The results are sufficiently general with respect to cloud top heights ranging from 680 to 860 mbar, while the range of applicability in terms of the solar zenith position extends to sun angles less than 75°. On the basis of the results here we suggest a reference cloud top height of 760 mbar and a reference zenith angle of 53°. The error in the radiative quantities relative to the "benchmark" calculations is generally less than 5% in most of the spectral bands. As a simple application, it is found that the enhancement of cloud absorption in a two band cloud optical properties parameterization can be largely avoided by using this simple modification of the solar spectral irradiance incident at the top of low-lying clouds.

Introduction

Solar spectral distribution at the top of the atmosphere (TOA) is an accurately measured value. However, the solar spectral distribution at a cloud top is highly variable with dependence on cloud top height, solar zenith angle, and atmospheric profile [*Davies et al.*, 1984; *Ramaswamy and Freidenreich*, 1992]. The solar spectral distribution at a cloud top is necessary for obtaining the cloud radiative properties. For example, the solar cloud reflection to direct incidence radiation is defined as

$$R = \int F_\nu^{\uparrow}\, d\nu \bigg/ \int F_\nu^{\downarrow}\, d\nu \tag{1}$$

where $F_\nu^{\uparrow\downarrow}$ is the upward (downward direct) solar flux for frequency ν at the cloud top. For a scheme in which the solar spectrum is divided into n bands, (1) becomes

$$R = \sum_{i=1}^{n} S_i^{\uparrow} \bigg/ \sum_{i=1}^{n} S_i^{\downarrow} = \sum_{i=1}^{n} R_i\, w_i \tag{2}$$

where $S_i^{\uparrow\downarrow} = \int_{\Delta\nu_i} F_\nu^{\uparrow\downarrow}\, d\nu$ is the band spectral integrated fluxes, $\Delta\nu_i$ is the spectral interval of band i, $R_i = S_i^{\uparrow}/S_i^{\downarrow}$ is the reflection for band i, and $w_i = S_i^{\downarrow}/\Sigma_{j=1}^{n} S_j^{\downarrow}$ is the weight of solar irradiance in the ith band. A similar formulation holds for cloud transmission to direct incident radiation, while the absorbed flux can be obtained in the usual way.

If the spectral interval of band i is fine enough, the reflection R_i can be obtained by considering a single-frequency value or the average of a few frequency values of $F_\nu^{\uparrow}/F_\nu^{\downarrow}$ within the ith band, since the spectrally dependent variation of radiative properties for water droplets is relatively uniform over broad frequency intervals [*Davies et al.*, 1984]. Therefore the key point in obtaining the cloud reflection is the weight of the solar spectrum in the different bands at the top of the cloud. These weights, in general, cannot be evaluated in a simple way by considering only a few monochromatic values in a band. This is because the selective attenuation at the different spectral frequencies by the gaseous constituents has distinct characteristics [*Ramaswamy and Freidenreich*, 1992].

In models with complete column radiation algorithms the band weight appropriate at the cloud top can be obtained by solving explicitly for the solar radiative transmission through the atmosphere. However, problems involving status cloud simulations, such as studies with cloud resolving models, demand that the solar radiation incident at cloud top be accounted for in a simple but accurate manner, without invoking a detailed column radiative transfer algorithm. In the measurement of cloud reflection it is very difficult to measure solar flux at an adequate number of wavelengths in order to obtain the required band weights accurately. In finite cloud radiation studies, for example, Monte Carlo simulations, [*McKee and Cox*, 1974], there is considerable interest in only the cloud layer, and the atmosphere above the cloud is usually ignored. Such problems also demand that a simple accurate prescription of the solar irradiance at cloud top be specified. In the Monte Carlo work of *Li et al.* [1994], the solar spectral weight at the TOA was used to represent that at the cloud tops. Also, it is imperative that future calculations involving finite low clouds use the appropriate low cloud top solar flux.

The solar spectral weight inside the atmosphere varies with height and solar zenith angle. It is therefore not easy to predict a general governing formula. This paper shows that under certain circumstances the spectral weight in different bands

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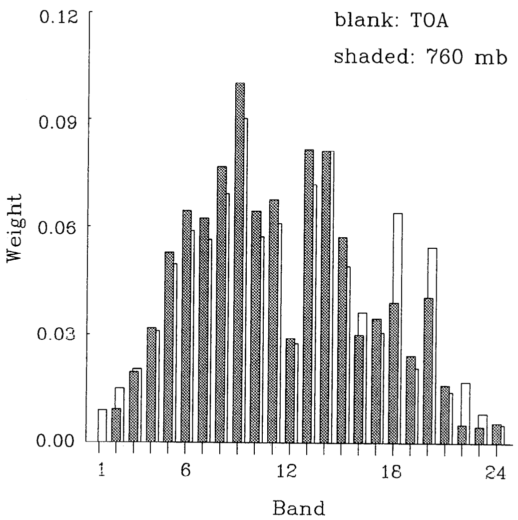

Figure 1. Twenty-four band solar spectral weights at the top of the atmosphere (TOA) in the tropics and at a pressure of 760 mbar, with solar zenith angle equal to 0°.

across the total spectrum can be evaluated with a reasonable accuracy. We focus on the problem as it applies to atmospheres containing low clouds, which incidentally have a very large influence on the radiation budget in the atmosphere.

Results

We consider first a low cloud embedded in a tropical atmosphere [*McClatchey et al.*, 1972]. The cloud top is set at 760 mbar. The solar spectrum value at the TOA is based on the data of *Labs and Neckel* [1970], and a solar zenith angle of 0° is assumed. The precise method of line by line plus doubling and adding is used to account for the gaseous transmission and Rayleigh scattering. We employ here the Geophysical Fluid Dynamics Laboratory line-by-line model [*Ramaswamy and Freidenreich*, 1991; *Freidenreich and Ramaswamy*, 1993], with water vapor, carbon dioxide, oxygen, and ozone included. Figure 1 illustrates the clear-sky weights of the solar spectral irradiance at the TOA and at a cloud top of 760 mbar, under overhead sun conditions. Figure 1 demonstrates the variation of solar spectral weight with altitude. The 24-band scheme of *Slingo* [1989], widely applied in climate models, is used for the solar spectrum range of 0.25–4 μm (the band intervals are shown in Table 1). It is found from Figure 1 that the band weight of the downward solar spectrum at 760 mbar is quite different from that at the TOA. In band 1 the downward solar flux is almost totally depleted at 760 mbar because of ozone absorption and Rayleigh scattering. Also, large differences occur in the highly absorbing bands in the near-infrared region due to the absorption by water vapor and carbon dioxide. In Figure 1 the large decrease in weight in some bands at 760 mbar causes an increase of weight in other bands; this is because of the normalization of the band weights to unity.

The tops of low clouds (stratus, stratocumulus, and cumulus) are generally lower in altitude than 680 mbar (~2.5 km) [*Rossow and Schiffer*, 1991]. We assume that the low cloud tops are located at an altitude higher than 860 mbar (~1 km), which is close to the atmospheric lifting condensation level. Further, we choose the level of 760 mbar (~1.9 km) as the standard level to show the deviations of solar spectral weight in such low

Table 1. Weights of Solar Spectrum at Top of the Atmosphere and Weights of Solar Spectrum for Tropics, Middle-Latitude Summer, and Sub-Arctic Winter at an Altitude of 760 mbar With Solar Zenith Angle Equal to 53° and Surface Albedo Equal to 0

	Band																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
μm	0.25–0.30	0.30–0.33	0.33–0.36	0.36–0.40	0.40–0.44	0.44–0.48	0.48–0.52	0.52–0.57	0.57–0.64	0.64–0.69	0.69–0.75	0.75–0.78	0.78–0.87	0.87–1.00	1.00–1.10	1.10–1.19	1.19–1.28	1.28–1.53	1.53–1.64	1.64–2.13	2.13–2.38	2.38–2.91	2.91–3.42	3.42–4.00
TOA	8939	14,980	20,412	31,037	49,587	58,865	56,371	69,225	90,401	57,138	61,110	27,552	72,007	81,458	49,189	36,491	30,717	64,203	20,948	54,615	14,133	17,128	8311	5172
TRO	10	7126	18,344	30,727	52,338	64,680	63,107	77,663	101,455	65,940	68,960	29,397	84,330	80,768	59,483	28,202	35,765	36,421	25,165	39,541	16,747	4016	3963	5838
MLS	3	6326	18,101	30,466	51,886	64,065	62,334	76,242	99,378	65,075	69,017	29,134	84,179	82,773	59,152	30,061	35,759	38,895	24,977	40,553	16,739	4460	4516	5899
SAW	0	5011	17,247	29,322	49,920	61,516	54,479	71,736	93,024	61,972	68,141	28,114	82,545	88,280	57,355	35,987	35,207	49,835	24,094	45,444	16,459	6598	6744	5958

TOA, top of the atmosphere; TRO, tropics; MLS, middle-latitude summer; SAW, sub-Arctic winter. Weights are ($\times 10^6$).

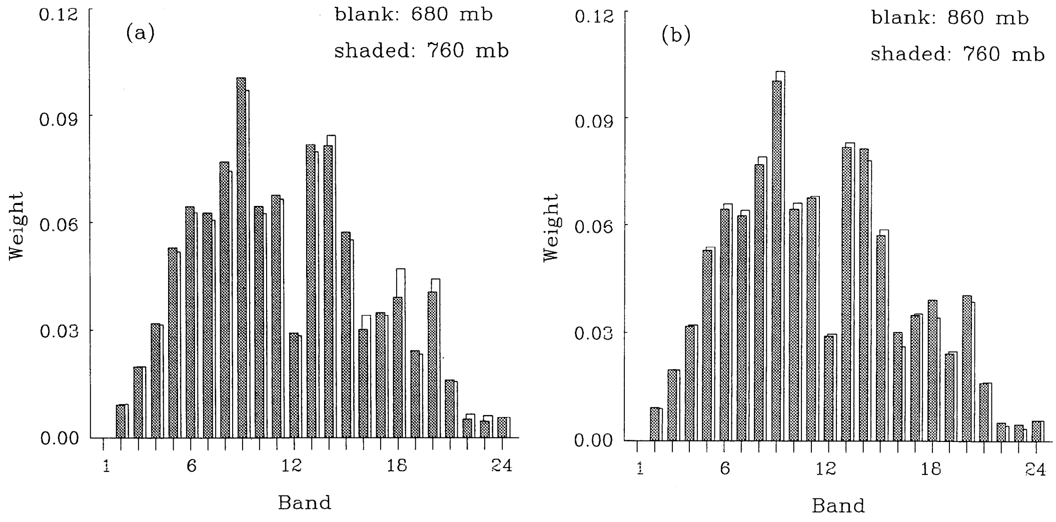

Figure 2. (a) Same as Figure 1, except at 680 and 760 mbar in a tropical atmosphere; (b) same as Figure 2a except at 760 and 860 mbar.

cloud top regions. We plot the downward solar spectrum band weights at 680 and 760 mbar in tropics in Figure 2a and the weights at 760 and 860 mbar in Figure 2b, again for overhead sun. In comparison with Figure 1 the deviations in solar spectral distribution from that of 760 mbar are small in the region between 680 and 860 mbar, less than 5% in most of bands. We therefore suggest using the solar spectral band weight value at 760 mbar as a nominal value for low clouds with tops at altitudes of 680 mbar or lower.

Next, we consider the influence of the solar zenith angle. The spectral attenuation in the atmosphere above the cloud is sensitive to the sun angle. In Figure 3a the downward solar spectral weights at 760 mbar are plotted for solar zenith angles of 0° and 53° (which is approximately the diurnal mean solar zenith angle). It can be found that the difference between the two cases is very small. Only band 2 has a difference larger than 10%. Therefore, taking the weights corresponding to the daily-mean solar zenith angle can be expected to represent the solar spectral distribution at cloud tops with reasonable accuracy, without the necessity to consider the diurnal variation in the solar zenith angle. Of course, for very large solar zenith angles, the results would deviate considerably from the results using the daily-mean solar zenith angle. In Figure 3b the weights of solar spectrum at 760 mbar in tropics are plotted for a solar zenith angle of 75°. Large deviations (>10%) occur in bands 2, 3, and 23. We are not motivated to formulate a parameterization for the variation with respect to the solar zenith angle as it would complicate the problem. The solar weights in bands 2, 3, and 23 are relatively very small, and the difference in this region would have only a small influence on the weight distribution over the whole solar spectrum. We don't expect the standard results of 53° to be applicable to solar zenith angles beyond 75°.

In Table 1 the solar spectral weights for low clouds are presented. As discussed above, the cloud top height is set at 760 mbar, and the daily-mean solar zenith angle of 53° is

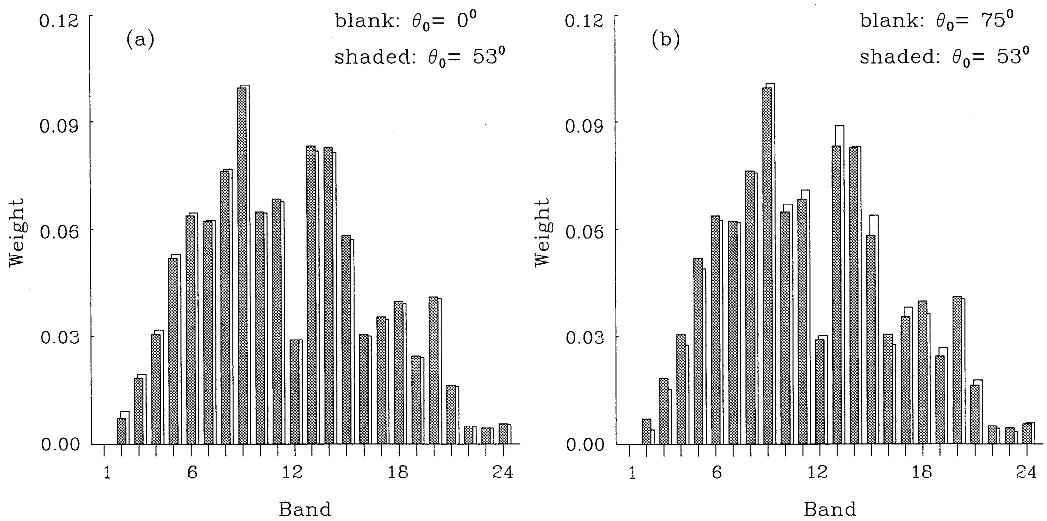

Figure 3. (a) Twenty-four band solar spectral weights for a tropical atmosphere at a pressure of 760 mbar, with solar zenith angles equal to 0° and 53°, respectively; (b) same as Figure 3a except for solar zenith angles of 53° and 75°.

Table 2. Weight of Solar Spectrum for Middle Latitude Summer Conditions at an Altitude of 760 mbar, With Solar Zenith Angle Equal to 53° and Surface Albedo Equal to 0.1

Band	MLS
1	3
2	6450
3	18,442
4	30,900
5	52,393
6	64,469
7	62,562
8	76,357
9	99,328
10	64,966
11	68,830
12	29,050
13	83,900
14	82,448
15	58,916
16	29,930
17	35,607
18	38,724
19	24,868
20	40,373
21	16,664
22	4440
23	4495
24	5873

employed. The effect of atmospheric profiles is considered by showing separately the results of tropics, midlatitude summer, and sub-Arctic winter [*McClatchey et al.*, 1972]. Also, the solar spectral weight at the top of the atmosphere is shown, which differs slightly from that in the work of *Slingo* [1989] because of the different reference atmospheres used. It is worth noting that the deviations from the standard values of midlatitude summer and sub-Arctic winter in Table 1 are smaller compared to that in the tropics (Figures 2 and 3). This is mostly because of the lesser water vapor density in midlatitude summer and sub-Arctic winter, together with considerably less effects due to the other atmospheric constituents. We also would like to point out that the differences among the three atmospheric profiles are relatively smaller than the difference between TOA and each of the atmospheric profiles. Therefore we can set a global climatological value of the solar spectral weight at the low cloud tops by performing an average of the results for the three atmospheric profiles.

Discussions

Our results are based on clear-sky conditions with zero-surface albedo. If there exist high clouds, the data presented in Table 1 are no long applicable. Also, a nonzero surface albedo and the existence of low clouds will cause multiple reflections which would exert a further effect on the downward solar flux, mostly in the UV and visible spectrum due to Rayleigh scattering. We find that this influence is very small. In Table 2 the solar spectral weight for midlatitude summer is shown with surface albedo equal to 0.1, cloud top height of 760 mbar, and solar zenith angle equal to 53°. We can find that the difference caused by a nonzero surface albedo is very small, less than 1% in most of the bands.

Finally, we mention a simple application of the low cloud top solar spectral band weights obtained. Climate models frequently use band schemes different from that of *Slingo* [1989]. Since the band coefficients in Slingo's parameterization are the results of the linear weighting combination of the single-wavelength values, the Slingo's 24 band scheme can be projected on to other band schemes as follows [*Slingo*, 1989]:

$$\bar{\chi}_n = \sum \chi_i w_i / \sum w_i \qquad (3)$$

where χ_i represents the coefficients of a_i, b_i, $\cdots$, f_i in Table 1 of *Slingo* [1989], the sum implies the number of neighboring bands to be combined into band n in the new scheme, and w_i is the band weight at the cloud top. Slingo's 24 band scheme is specified for low clouds with effective radius less than 15 μm. From Figure 1 it is found that at the TOA, there is a large weight in the near-infrared region than that arising at 760 mbar; further, the cloud absorption occurs mostly in the near-infrared region. Therefore a band combination based on the weights at the TOA will lead to a lesser value of single-scattered albedo and a greater absorption. Then, the ratio of solar cloud radiative forcing at the Earth's surface to that at the TOA will be much larger than unity in a general circulation model (C.-T. Chen, personal communication, 1995).

As an example, we consider a two band scheme with band intervals of 0.25–0.75 and 0.75–4 μm, which represent the visible (and UV) region and near-infrared region, respectively. The corresponding coefficients of $\bar{\chi}_n$ can be obtained by (3). Figure 4 shows the single-scattering albedos calculated by the two band scheme using standard band weight for low clouds in tropics (in Table 1) and the band weight at the TOA. We find that the single-scattering albedo is largely underestimated for the case when the TOA band weight is used. We only plot the results of near-infrared in Figure 4. In the visible region the difference in single-scattering albedo is very small for the different solar band weights used. Note that *Ramaswamy and Freidenreich* [1992] illustrate a similar bias as occurring when the near-infrared spectrum is represented as a single band. Also, *Slingo* [1989] has realized the incorrect enhancement of cloud absorption in a small number band scheme, occurring because of the band weighting of the solar spectrum at the top of the atmosphere.

In conclusion, the solar spectral weight for the different bands is an important quantity for determining cloud radiative properties. For low clouds, if the cloud top solar spectral weight is known, we can ignore the influence of the atmosphere above the cloud in a practical sense; only a single or a few frequency points per band will allow one to obtain the

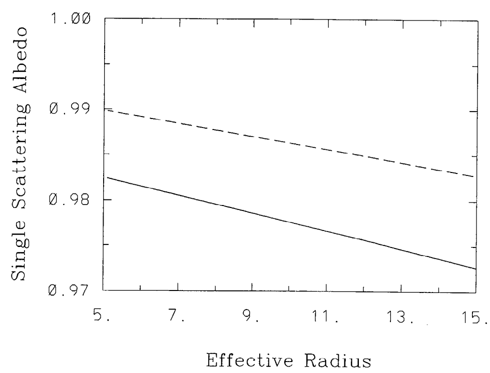

Figure 4. Single-scattering albedos for the near-infrared band in the two-band scheme, using the TOA solar band weight (solid line) and the tropical low cloud standard solar band weight (dashed line).

cloud reflection and transmission. The modification presented here with regards to the spectral irradiance at low cloud tops should be particularly useful for the modeling of radiative-microphysical-dynamical interactions, where the computational requirements necessitate a fast but accurate consideration of the solar flux incident at low cloud tops, and that has to account quite generally for the selective spectral attenuation occurring in the atmosphere. The formulation here makes it unnecessary to know the details of the interactions elsewhere in the atmosphere so that if attention is to be directed only to stratus cloud modeling, it is enough to use the precipitation here. Further, the modification here can be quite generally used in conjunction with well-known water cloud optics parameterizations [*Slingo*, 1989]. The results here are also applicable to Monte Carlo studies of low clouds with finite dimensions where, historically, the solar flux at the top of the atmosphere has been employed, but which can now be modified in a simple manner, without resorting to a full atmosphere radiation computation.

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