A Shortwave Parameterization Revised to Improve Cloud Absorption

GRAEME L. STEPHENS

CSIRO, Division of Atmospheric Research, Aspendale, Victoria, Australia, 3195

STEVEN ACKERMAN AND ERIC A. SMITH

Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO 80523

17 May 1983 and 20 October 1983

ABSTRACT

We present a modification to the parameterization scheme of Stephens which improves on the estimation of shortwave absorption by cloud. In particular, the variation of cloud absorption with solar elevation angle is improved with the modified scheme.

1. Introduction

The need to understand the role of clouds in maintaining and modifying the diabatic heating of the atmosphere and the value of cloud-radiation parameterizations in achieving this understanding scarcely needs emphasis. In view of the usefulness of such parameterizations, we consider it important to offer any improvements to existing schemes which are based on the basic theory. In this note, we revise some aspects of the shortwave parameterizations of Stephens (1978). This revision is a direct result of the large number of queries received by the author(s) concerning the specification of a number of key variables required to use the parameterization. These queries referred mainly to the use of the analytic formulas used to represent the relevant variables. Unfortunately, these formulas contained errors and better results are obtained when the parameter values are taken directly from the tables provided.

The essential aspect of the parameterization is that it demonstrates that the relevant shortwave cloud properties can be reliably described in terms of cloud liquid water path W and solar zenith angle θ_0 ($=\cos^{-1}\mu_0$). In the original scheme outlines in Stephens (1978), cloud albedo is generally well handled for most parametric ranges of W and μ_0, whereas significant errors in absorption occurred when θ_0 exceeded ~60°. Here, we present a modification to the original tables which to a large extent overcomes this problem while preserving the performance of the original scheme for cloud albedo.

2. Methodology

The starting point for the parameterization is with the two-stream version of the radiative transfer equation. The following two-stream model solutions are those used in the original scheme outlined in Stephens (1978).

(i) Nonabsorbing medium [$\tilde{\omega}_0 = 1$ ($\lambda \leq 0.75$ μm)]

$$\left.\begin{aligned} \mathrm{Re}(\mu_0) &= \frac{\beta(\mu_0)\tau_N/\mu_0}{1 + \beta(\mu_0)\tau_N/\mu_0} \\ \mathrm{Tr}(\mu_0) &= 1 - \mathrm{Re}(\mu_0) \end{aligned}\right\} . \tag{1}$$

(ii) Absorbing medium [$\tilde{\omega}_0 < 1$, ($\lambda > 0.75$ μm)]

$$\left.\begin{aligned} \mathrm{Re}(\mu_0) &= [(u^2 - 1)\exp(\tau_{\mathrm{eff}})]/R - \exp(-\tau_{\mathrm{eff}}) \\ \mathrm{Tr}(\mu_0) &= 4u/R \end{aligned}\right\} , \tag{2}$$

where the absorption is

$$A(\mu_0) = 1 - \mathrm{Re}(\mu_0) - \mathrm{Tr}(\mu_0),$$

and

$$\left.\begin{aligned} u^2 &= [1 - \tilde{\omega}_0 + 2\beta(\mu_0)\tilde{\omega}_0]/(1 - \tilde{\omega}_0) \\ \tau_{\mathrm{eff}} &= \{(1 - \tilde{\omega}_0)[1 - \tilde{\omega}_0 + 2\beta(\mu_0)\tilde{\omega}_0]\}^{1/2}\tau_N/\mu_0 \\ R &= (u + 1)^2\exp(\tau_{\mathrm{eff}}) - (u - 1)^2\exp(-\tau_{\mathrm{eff}}) \end{aligned}\right\} . \tag{3}$$

In the above equations, τ_N is the optical thickness of the cloud, $\tilde{\omega}_0$ the single-scattering albedo, and β the backscattered fraction of monodirectional incident radiation at the zenith angle μ_0. This backscattering fraction is a function of μ_0 and involves an integral over scattering phase function. The solutions (1) and (2) were chosen over the solutions of more accurate two-stream models such as the δ Eddington model for reasons of simplicity. The solutions apply for a specific wavelength or band of wavelengths in which the optical thickness τ_N and single-scattering albedo $\tilde{\omega}_0$ are assumed to be uniform. These scattering parameters are generally slowly varying functions of wavelength.

The solar spectrum is divided into two broad in-

---

tervals for the simplified scheme proposed here. The first extends from 0.3 to 0.75 μm where absorption by the cloud droplets is extremely small. The conservative scattering solutions (1) therefore apply. The absorption in the cloud is confined to the second spectral region from 0.75 to 4.0 μm. The solution expressed by (2) and (3) is applied in this region. Thus, the parameterization centers on a suitable description of the parameters of τ_N, $\tilde{\omega}_0$, β_1 and β_2. For an atmosphere heavily laden with haze or aerosol, a similar strategy to the above can be applied, but alternate parameterizations (and tuning) of the relevant optical properties ($\tilde{\omega}_0$, β_1, β_2 and τ) are required.

3. The parameterization of β and $\tilde{\omega}_0$

Stephens (1978) employed a detailed multiple-scattering model to calculate a series of values of reflection, absorption and transmission for a number of model cloud types. These calculations were used to tune the following parameters: β_1 for $\lambda < 0.7$ μm, β_2 for $\lambda > 0.7$ μm, and $\tilde{\omega}_0$ for $\lambda < 0.7$ μm. Here we present empirical modifications to the original tabulations $\tilde{\omega}_0$ which provide a better fit to the overall results of the detailed multiple-scattering model, especially when μ_0 is small. There does not appear to be any basis for this empirical correction to $\tilde{\omega}_0$ other than that it produces the correct variation of absorption with solar zenith angle. Nor does there appear to be any error in the original formulation of the $\tilde{\omega}_0$ tables which were obtained on the basis of inserting (2) and (3) although the possibility of a programming error cannot be totally discounted.

The modified values of $\tilde{\omega}_0$ are listed in Table 1(a) as a function of optical thickness and solar zenith angle. Also included are the original tables for β_1 and β_2

TABLE 1. The broadband values of ω, β_1 and β_2 used to evaluate the two-stream solutions given by (1) and (2).

τ_N	1.0	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
(a) Average values of $1 - \tilde{\omega}_0$									
1	0.0225	0.0222	0.0218	0.0208	0.0199	0.0155	0.0109	0.0059	0.0017
2	0.0213	0.0200	0.0179	0.0176	0.0156	0.0118	0.0078	0.0038	0.0010
5	0.0195	0.0166	0.0146	0.0125	0.0096	0.0069	0.0043	0.0021	0.0005
10	0.0173	0.0138	0.0114	0.0093	0.0070	0.0049	0.0026	0.0013	0.0003
16	0.0156	0.0111	0.0090	0.0073	0.0052	0.0035	0.0019	0.0009	0.0002
25	0.0115	0.0088	0.0069	0.0052	0.0038	0.0026	0.0014	0.0007	0.00014
40	0.0104	0.0055	0.00425	0.0032	0.0023	0.00145	0.0008	0.0003	0.0001
60	0.0083	0.0050	0.0038	0.0028	0.0020	0.0013	0.0007	0.00034	0.0001
80	0.0069	0.0043	0.0035	0.0022	0.0018	0.0011	0.0006	0.0003	0.0000
100	0.0060	0.0043	0.0035	0.0022	0.0018	0.0011	0.0006	0.0003	0.0000
200	0.0044	0.0031	0.0025	0.0016	0.0011	0.00072	0.0004	0.00019	0.0000
500	0.0026	0.0018	0.0014	0.0010	0.00072	0.00048	0.00029	0.00015	0.0000
(b) Average values of β_1									
1	0.0421	0.0557	0.0657	0.0769	0.0932	0.1111	0.1295	0.1407	0.1196
2	0.0472	0.0615	0.0708	0.0803	0.0924	0.1017	0.1077	0.1034	0.0794
5	0.0582	0.0692	0.0744	0.0782	0.0815	0.0812	0.0776	0.0680	0.0483
10	0.0682	0.0726	0.0737	0.0733	0.0723	0.0685	0.0626	0.0527	0.0359
16	0.0734	0.0738	0.0728	0.0707	0.0680	0.0631	0.0564	0.0465	0.0310
25	0.0768	0.0744	0.0723	0.0691	0.0653	0.0598	0.0526	0.0427	0.0281
40	0.0791	0.0749	0.0719	0.0680	0.0636	0.0575	0.0501	0.0402	0.0261
60	0.0805	0.0752	0.0717	0.0674	0.0627	0.0563	0.0488	0.0389	0.0251
80	0.0812	0.0754	0.0717	0.0672	0.0622	0.0558	0.0481	0.0382	0.0246
100	0.0820	0.0757	0.0717	0.0670	0.0619	0.0553	0.0475	0.0376	0.0241
200	0.0831	0.0763	0.0721	0.0672	0.0619	0.0552	0.0473	0.0374	0.0241
500	0.0874	0.0800	0.0755	0.0703	0.0647	0.0576	0.0494	0.0392	0.0262
(c) Average values of β_2									
1	0.0477	0.0627	0.0734	0.0855	0.1022	0.1200	0.1379	0.1465	0.1207
2	0.0537	0.0690	0.0788	0.0886	0.1003	0.1090	0.1133	0.1065	0.0794
5	0.0660	0.0769	0.0817	0.0850	0.0871	0.0864	0.0801	0.0688	0.0474
10	0.0759	0.0793	0.0795	0.0781	0.0757	0.0705	0.0629	0.0516	0.0339
16	0.0801	0.0787	0.0766	0.0732	0.0689	0.0626	0.0543	0.0434	0.0277
25	0.0807	0.0759	0.0724	0.0678	0.0625	0.0555	0.0471	0.0368	0.0229
40	0.0770	0.0700	0.0656	0.0603	0.0545	0.0476	0.0396	0.0302	0.0184
60	0.0699	0.0621	0.0575	0.0522	0.0466	0.0401	0.0329	0.0248	0.0148
80	0.0634	0.0556	0.0510	0.0460	0.0408	0.0348	0.0283	0.0211	0.0125
100	0.0534	0.0461	0.0420	0.0376	0.0330	0.0279	0.0225	0.0166	0.0097
200	0.0415	0.0353	0.0319	0.0283	0.0246	0.0206	0.0165	0.0120	0.0068
500	0.0251	0.0208	0.0186	0.0163	0.0140	0.0115	0.0090	0.0064	0.0032

which have been smoothed slightly to provide albedos and absorptions which are smooth functions of W and μ_0. This smoothing has altered only a couple of points in each table. In the following examples, the appropriate values of β_1, β_2 and $\tilde{\omega}_0$ were interpolated from the tables using standard bilinear interpolation techniques and the given values of τ and μ_0.

4. The assessment of the modified parameterization

In the original scheme of Stephens, cloud albedo was well parameterized but errors were apparent (see his Fig. 5b) in shortwave absorption, particularly for large solar zenith angles. By employing the corrected values in Tables 1a–1c, we have been able to improve the performance of the parameterization. Figs. 1a and 1b present contours of the cloud albedo and cloud absorptance as a function of cloud liquid water and solar zenith angle. Shown on the diagrams are the contours derived from the detailed multiple-scattering model (from Stephens, and upon which the parameterizations are based), the modified parameterization and the original parameterization. The improved parameterization of cloud absorption is evident in Fig. 1b while there are no significant improvements in cloud albedo. Figs. 2a and 2b show the contours of percentage error in cloud albedo and absorptance as a function of cloud liquid water and solar zenith angle. The percentage error was defined as

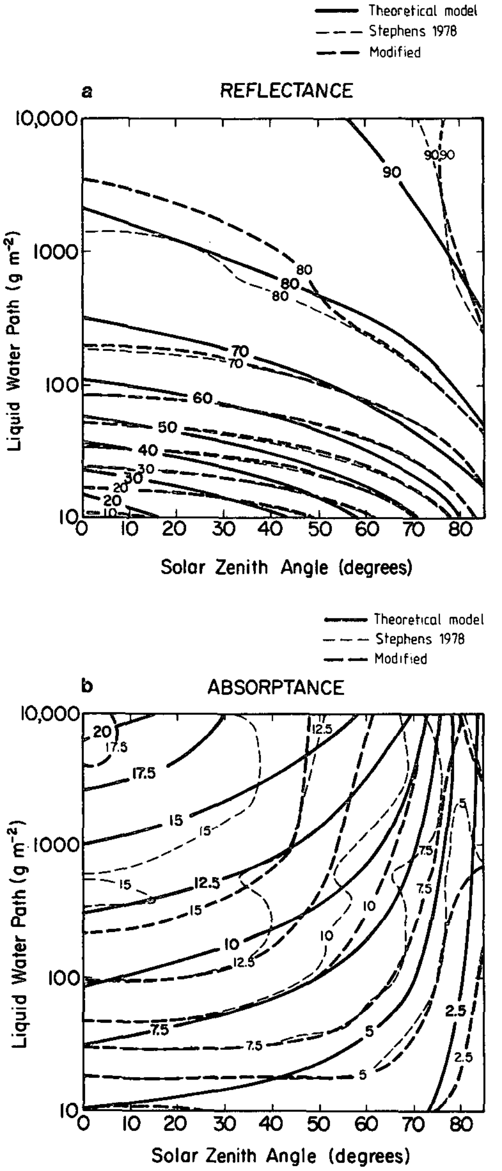

FIG. 1. The variability of (a) cloud albedo and (b) absorptance for changes of solar zenith angle and liquid water path. Contours are determined from calculations by a detailed theoretical model, from the original parameterization and from the modified parameterization.

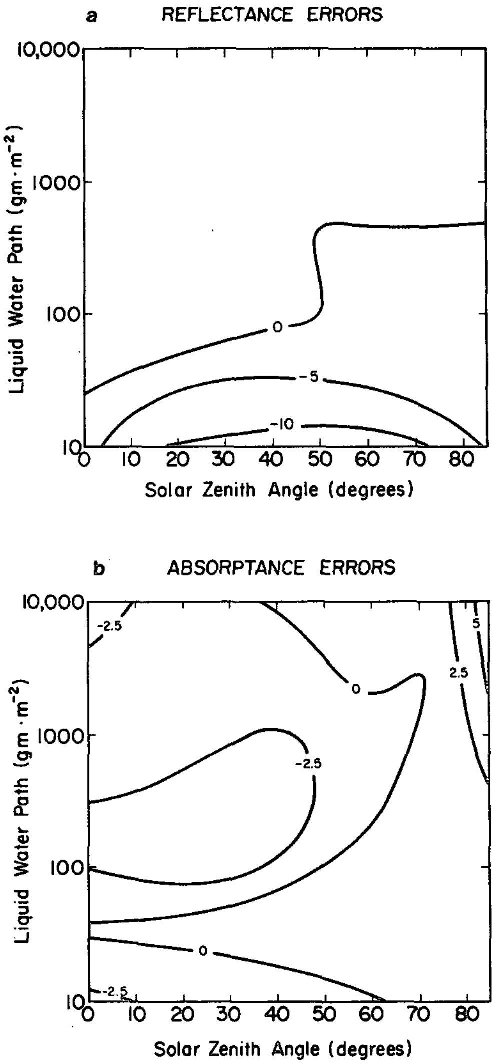

FIG. 2. Contours of the percentage difference between the modified parameterized estimates of (a) cloud albedo and (b) absorptance and the theoretical values.

$$F = [F(\text{theory}) - F(\text{parameterized})] \times 100,$$

where F(theory) corresponds to the solutions from the detailed multiple-scattering model and F(parameterized) is the reflection or absorptance determined from the present modified parameterization. Therefore, contours shown in Figs. 2a and 2b provide a rough estimate of the error that is likely to occur in the global energy balance when the parameterization is adopted. Note that the reflection errors become large when the liquid water path is small (i.e., when cloud optical depth is less than about 2). Special parameterization of reflection (and for that matter, absorption) are required for optically thin cloud such as cirrus cloud. Fig. 2b suggests that the present modified absorption parameterization accommodates the variation of absorptance with changing solar zenith angle better than in the original scheme [e.g., see Fig. 1b above and Fig. 5b in Stephens (1978)].

Acknowledgments. We gratefully acknowledge NCAR, which is sponsored by the National Science Foundation, for computer time. This work was supported by NSF Grants ATM-78-20375 and ATM-78-8010691.

REFERENCES

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. *J. Atmos. Sci.*, **35**, 2123–2132.