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Documentation of the Solar Radiation Parameterization in the GLAS Climate Model

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Documentation of the Solar Radiation Parameterization in the GLAS Climate Model

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Preface

This technical memorandum has been prompted by recent changes to the way in which solar radiation is modelled in the general circulation model (GCM) at the Goddard Space Flight Center's Laboratory for Atmospheric Sciences (GLAS).

The revised solar radiation treatment combines a direct-diffuse radiative transfer model, developed by the author, with much of the orginal model, developed by A. A. Lacis and J. E. Hansen. It is a pleasure to acknowledge the substantial contribution to the present form of the code that has been made by Drs. Lacis and Hansen. Much of their original code remains unaltered. The author, however, accepts sole responsibility for any errors or omissions that may be present in this documentation.

I would like to express my appreciation to Dr. M. Halem and Dr. J. Shukla for providing the encouragement and opportunity to complete this work.

R.D.

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1. INTRODUCTION

The differential absorption of solar radiation by the earth-atmosphere system initiates various dynamical and physical processes responsible for maintaining the general circulation of the atmosphere as well as local climatic regimes. In any numerical model which attempts to directly simulate these processes, it is therefore necessary to include as a subset of the model a parameterization scheme for the absorption of solar radiation which is both accurate and efficient.

The general circulation model (GCM) in use at the Goddard Laboratory for Atmospheric Sciences (GLAS) generates most of the interactive atmospheric variables that affect solar radiation; namely cloud cover, humidity, temperature and pressure. These variables are supplemented in the parameterization scheme described here with climatological values of ozone and surface albedo to yield absorption values for the surface and nine atmospheric layers on a 4^o latitude by 5^o longitude horizontal grid.

The absorbed solar radiation is then incorporated into the diabatic terms of the next time step of the GCM, and a new round of atmospheric variables are generated. In practice, the solar radiation routines are called every third time step, corresponding to 30 mins. of model time, in the interests of computational efficiency.

This memorandum documents the parameterization as developed by mid 1981. The development rests heavily on the work of Lacis and Hansen (1974), with extensions to account for solar zenith angle effects on the earth surface and a revised radiative transfer treatment in clouds.

Briefly, the current parameterization allows for ozone, water vapor and surface absorption under a variety of conditions and for arbitrary sun angle. Rayleigh scattering by the clear atmosphere is parameterized and multiple scattering by cloud droplets calculated layer by layer. The spectral integration for regions with water vapor absorption is reduced to a summation over five terms using a probability distribution. Limitations to the current scheme include ignoring the effect of aerosols, absorption by cloud droplets and the spectral nature of the surface albedo.

In the description that follows, the scientific background for the radiation calculations is first summarized, followed by a description of the FORTRAN code. Comparative results between the old and new parameterizations are then presented.

2. SCIENTIFIC OVERVIEW

This section discusses the scientific basis on which the radiation routines have been developed. Much of the original treatment of Lacis and Hansen (1974) remains unaltered, and is therefore simply summarized. Developments to the parameterization scheme since the Lacis and Hansen version are discussed fully.

2.1 Input Variables

Before the transfer of solar radiation can be modelled, a number of input variables describing the extraterrestrial insolation and the radiatively active components of the earth-atmosphere system must first be defined. The usual input variables in the GLAS GCM, with their FORTRAN counterparts in parentheses, are:

- ϕ, (LAT) - latitude in degrees.
- d, JDAY - time of year, in Julian days.
- t_h, (TOFDAY) - local apparent time, either specified explicitly or obtained from GMT, longitude and the Equation of Time.
- $\bar{A}_g$, (AG) - conventional surface albedo
- (CL) - type of cloud, if any, present at each level of the atmosphere.

q, (SHL) - specific humidity at each level of the atmosphere.

T, (TL) - mean temperature (K) for each level of the atmosphere.

P_g, (PRESS) - surface pressure, (mb).

The following additional variables may then be readily derived:

μ_o, (COSZ) - cosine of the solar zenith angle. See section 2.2.

$\mu_o S_o$, (SCOSZ)- the extraterrestial irradiance (ly/day). See section 2.2.

M, (COSMAG) - a magnification factor to account for the slant path and refraction of the direct beam. Given by

$$M = 35/(1224\mu_o^2 + 1)^{\frac{1}{2}}.$$

U_n, (OZALE) - the ozone amount in cm (NTP) above each atmospheric level. Determined from climatological values using subroutine OZONE2, with JDAY and LAT as independent variables.

P_n, (PLE) - pressure (mb) at the top of the nth atmospheric level, determined by
$P_n = P_1 + (n-1)(P_g - P_1)/N$, where, typically, $P_1 = 10$mb and $N = 9$.

y_n, (SWALE) - the effective water vapor amount above each atmospheric level. See section 2.4.

A_g, (RSURF) - the solar zenith angle dependent component of the surface albedo. See section 2.5.

τ_n, (TAUC) - the cloud optical thickness in each atmospheric level. See section 2.6.

2.2 Astronomy

The extraterrestrial solar irradiance, S_o, and the solar declination angle, δ, vary slowly with the time of the year. Following Paltridge and Platt (1976), Ch. 3, for example, the time of the year may be expressed in radians as

$$\Psi_n = 2\pi d_n/365 \qquad 2.2.1$$

where d_n ranges from 0 on Jan 1 to 364 on Dec 31.

An approximate expression for δ, accurate to 0.0006 radians is then

$$\begin{aligned}\delta = {} & 0.006918 - 0.399912 \cos\Psi + 0.070257 \sin\Psi \\ & - 0.006758 \cos 2\Psi + 0.000907 \sin 2\Psi \\ & - 0.002697 \cos 3\Psi + 0.001480 \sin 3\Psi\end{aligned} \qquad 2.2.2$$

The extraterrestrial solar irradiance when the earth is at a distance R^* from the sun is given by

$$S_o = 2823.9\ (\bar{R}^*/R^*)^2, \qquad 2.2.3$$

where $\bar{R}^*$ is the mean earth-sun distance and the solar constant has been taken as 1368 W/m^2 from Willson et al. (1981). The factor $(\bar{R}^*/R^*)^2$ in eq. 2.2.3 may be determined to an accuracy better than 10^{-4} by

$$(\bar{R}^*/R^*)^2 = 1.000110 + 0.034221 \cos\Psi + 0.001280 \sin\Psi + 0.000719 \cos 2\Psi + 0.000077 \sin 2\Psi \qquad 2.2.4$$

A further astronomical variable of interest is the Equation of Time, Eq, given in radians by

$$Eq = 0.000075 + 0.001868 \cos\Psi - 0.032077 \sin\Psi - 0.014615 \cos 2\Psi - 0.040849 \sin 2\Psi, \qquad 2.2.5$$

from which local apparent time is given by

$$\text{local apparent time} = \text{local mean time} + Eq. \qquad 2.2.6$$

Given the local apparent time t_h, in radians, measured from local apparent noon, the solar zenith angle Θ_o for latitude ϕ is given by

$$\cos\Theta_o = \sin\delta \sin\phi + \cos\delta \cos\phi \cos t_h. \qquad 2.2.7$$

2.3 Absorption by Ozone

The absorption of solar radiation by ozone closely follows the original treatment of Lacis and Hansen (1974), making use of the assumptions that

(a) ozone absorption takes place above any levels of significant scattering.

(b) ozone absorption and water vapor absorption occur in separable spectral regions.

Absorption is then a function of the effective path x, traversed by the radiation through the ozone layers. If x is in cm (NTP), this function is given empirically by

$$A_{oz}(x) = 0.02118/(1 + 0.042x + 0.000323x^2) + 1.082/(1 + 133.6x)^{0.805} + 0.0658/[1 + (103.6x)^2] \qquad 2.3.1$$

where the first term on the r.h.s. refers to absorption of visible radiation by the Chappuis band, and the other terms to absorption of ultraviolet radiation by the Hartley and Huggins bands.

The effective path traversed by the direct beam to reach level n is $x_n = MU_n$ (section 2.1), and the effective path traversed by radiation reflected from the atmosphere beneath the ozone layers is $x_n^* = MU_t + 1.9\ (U_t - U_n)$, where the factor of 1.9 accounts for diffuse transmission, and U_t refers to the total ozone amount. The total absorbed radiation in each layer containing ozone is then given from eq. 2.3.1 by

$$A_n = \mu_o S_o\ \{A_{oz}(x_{n+1}) - A_{oz}(x_n) + \bar{R}[A_{oz}(x_n^*) - A_{oz}(x_{n+1}^*)]\} \qquad 2.3.2$$

where $\bar{R}$ refers to the albedo of the underlying atmosphere to visible radiation and is determined for a cloudy atmosphere as in section 2.8. For cloud free conditions, however, an empirical formula for $\bar{R}$, chosen explicitly to be consistent with eq. 2.3.1 is used as follows:

$$\bar{R} = R_1 + (1-R_1)(1-R_2)\ A_g/(1-\bar{A}_g R_2) \qquad 2.3.3$$

where $R_1 = 0.2186/(1+0.816\mu_o)$

and $R_2 = 0.144$.

2.4 Absorption by Water Vapor

The fractional absorption for solar radiation traversing an effective water vapor amount x (centimeters of precipitable water vapor) was found empirically by Lacis and Hansen (1974) to be given by

$$A_{w.v.}(x) = 2.9/[(1+141.5x)^{0.635} + 5.925x] \qquad 2.4.1$$

The effective water vapor amount above each level is found by integrating the specific humidity with respect to pressure, making a rough scaling correction for the effects of temperature and pressure on absorption. That is,

$$y_n = \frac{1}{g} \int_o^{P_n} q(P/1013)(273/T)^{\frac{1}{2}}\ dP \qquad 2.4.2$$

The direct solar beam then traverses an effective water vapor amount

$$x_n = M\, y_n \qquad 2.4.3$$

to reach the top of layer n, and radiation reflected from the surface traverses an amount

$$x_{n+1}^* = My_N + 5/3\,(y_N - y_{n+1}) \qquad 2.4.4$$

to reach the bottom of layer n.

If we ignore scattering, the total absorption due to water vapor in each layer is given by

$$A_n = \mu_o S_o\{A_{w.v.}(x_{n+1}) - A_{w.v.}(x_n) + A_g[A_{w.v.}(x_n^*) - A_{w.v.}(x_{n+1}^*)]\} \qquad 2.4.5$$

Eq. 2.4.5 is used only when the atmosphere is cloud-free. For cloudy atmospheres there is usually significant scattering of solar radiation at those wavelengths where water vapor absorption is also significant, and a different approach is used, with eq. 2.4.1 being replaced by

$$A_{w.v.}(x) = 1 - \sum_{i=1}^{5} p(k_i)e^{-k_i x} \qquad 2.4.6$$

where p(k)dk is the fraction of incident flux associated with an absorption coefficient between k and k+dk. The values of $p(k_i)$ and k_i in the current version of the GLAS GCM are given in Table 2.4.1.

Table 2.4.1

Discrete probability distribution of water vapor absorption coefficients

i	k_i	$p(k_i)$
1	0.005	0.107
2	0.041	0.104
3	0.416	0.073
4	4[illegible]52	0.044
5	72.[illegible]9	0.025

The absorbing optical thickness due to water vapor in layer n is then given for each $i=1,2,\ldots,5$ by $\tau_{w.v.,n,i} = k_i(y_{n+1} - y_n)$ 2.4.7

The absorption optical thickness due to water vapor, $\tau_{w.v.}$, and the scattering optical thickness due to clouds, τ_c, are then combined to give the total optical thickness for each layer and each value of i. That is.

$$\tau_{n,i} = \tau_{w.v.,n,i} + \tau_{c,n}, \qquad 2.4.8$$

with the effective single scatter albedo for the layer being given by

$$a_{n,i} = \tau_{c,n}/\tau_{n,i} \qquad 2.4.9$$

and the subsequent radiative transfer problem is solved as discussed in sections 2.7 and 2.8.

2.5 Absorption by the Earth's Surface

The surface albedo is divided into two components, one of which, $\bar{A}_g$, is applied to the diffusely incident radiation, and the other, $A_g(\mu_o)$, is applied only to the direct solar beam. The two components are related (see for instance Paltridge and Platt, 1976) by

$$A_g(\Theta_o) = \bar{A}_g + (1-\bar{A}_g) \exp\left[-0.1(90^o-\Theta_o)\right] \qquad 2.5.1$$

For cloudy skies, the surface is treated as if it were a non-transmitting atmospheric layer in sections 2.7 and 2.8, and for cloud free conditions separation of the scattering and absorbing portions of the spectrum is again assumed so that

$$\text{surface absorption} = \mu_o S_o\{0.647(1-\bar{R}_{RAY}) + [0.353 - A_{w.v.}(x_{N+1})][1-A_g(\mu_o)]\} \qquad 2.5.2$$

where the first term on the r.h.s. refers to absorption of radiation in the scattering (by Rayleigh atmosphere) portion of the spectrum and the second term to absorption of radiation in the same spectral regions as water vapor absorption. The combined albedo of the surface and Rayleigh atmosphere, R_{RAY}, is given empirically by

$$\bar{R}_{RAY} = R_1 + \frac{(1-R_1)(1-R_2)A_g(\mu_o)}{(1-R_2\bar{A}_g)} \qquad 2.5.3$$

where $R_1 = 0.433/(1 + 6.43\mu_o)$ 2.5.4

and $R_2 = 0.093.$ 2.5.5

2.6 Intensive Cloud Properties

The GLAS GCM currently generates four types of clouds, namely: "supersaturation" clouds in any layer except layer 1, "low level convective" clouds in layer 7 or 8, "mid level convective" clouds in layer 5 or layer 6, and "penetrating convective" clouds in any four consecutive layers except layer 1 or layer 2. The only difference in the intensive radiative properties of these cloud types is in their optical thickness, τ_c, as given in Table 2.6.1.

Table 2.6.1

Optical Thickness of Different Cloud Types

Cloud Type	Cloud Layer	τ_c
Supersaturation	2,3,4,5,6,7,8 or 9	1,2,4,6,6,8,8,8 (respectively)
Low Level Convective	7 or 8	16
Mid Level Convective	5 or 6	8
Penetrating Convective	4 consecutive layers between 3 and 9	8 in each of the four layers

The other intensive properties, required for the radiative transfer calculations of section 2.7, namely the single scatter albedo a_c and the asymmetry factor g_c of the phase function for scattering by the cloud droplets, are assumed to be constant for all cloud types. Current values in the GLAS GCM are a_c=1 and g_c=0.85.

2.7 Radiative Properties of a Single Layer

This section describes how the reflection and transmission characteristics of a single atmospheric layer are determined, given as inputs the total optical thickness τ, the single scatter albedo a, the asymmetry factor g, and the solar zenith angle $\mu_o = \cos^{-1}\theta_o$. For convenience, we may also introduce an extinction coefficient k and a vertical depth Z_o to the layer, so that $\tau = kZ_o$.

The transfer of solar radiation through a single homogeneous layer is shown schematically in Fig. 2.7.1. The direct beam gives rise to diffuse irradiance reflected upwards at z=0, UO, and transmitted downwards at $z=Z_o$, DO, as well as a depleted direct beam of irradiance

$$\mu_o S_o' = \mu_o S_o \exp\left[-\tau \sec \theta_o\right] \qquad 2.7.1$$

For $\tau \geq 8$, UO and DO are found using the Delta Eddington approximation of Joseph *et al* (section 2.7.1), with the Coakley and Chylek version of the two stream approximation being used for $\tau < 8$ (section 2.7.2).

The transmittance, TL, and the reflectance, RL, of the layer to diffusely incident radiation is also required, and here the Sagan and Pollack (1967) version of the two stream approximation is retained.

Thus for $a < 1$

$$RL = (u^2-1)(1-e^{-2\lambda\tau})/\text{den} \qquad 2.7.2$$

and $$TL = 4ue^{-\lambda\tau}/\text{den} \qquad 2.7.3$$

where $$\lambda = \{3(1-a)(1-ag)\}^{\frac{1}{2}}, \qquad 2.7.4$$

$$u = (1-ag)^{\frac{1}{2}}(1-a)^{-\frac{1}{2}}, \qquad 2.7.5$$

and $$\text{den} = (u+1)^2 - (u-1)^2 e^{-2\lambda\tau} \qquad 2.7.6$$

For the conservative case of $a = 1$, we have

$$TL = \{1 + \frac{3^{\frac{1}{2}}}{2}(1-g)\tau\}^{-1} \qquad 2.7.7$$

and

$$RL = 1 - TL \qquad 2.7.8$$

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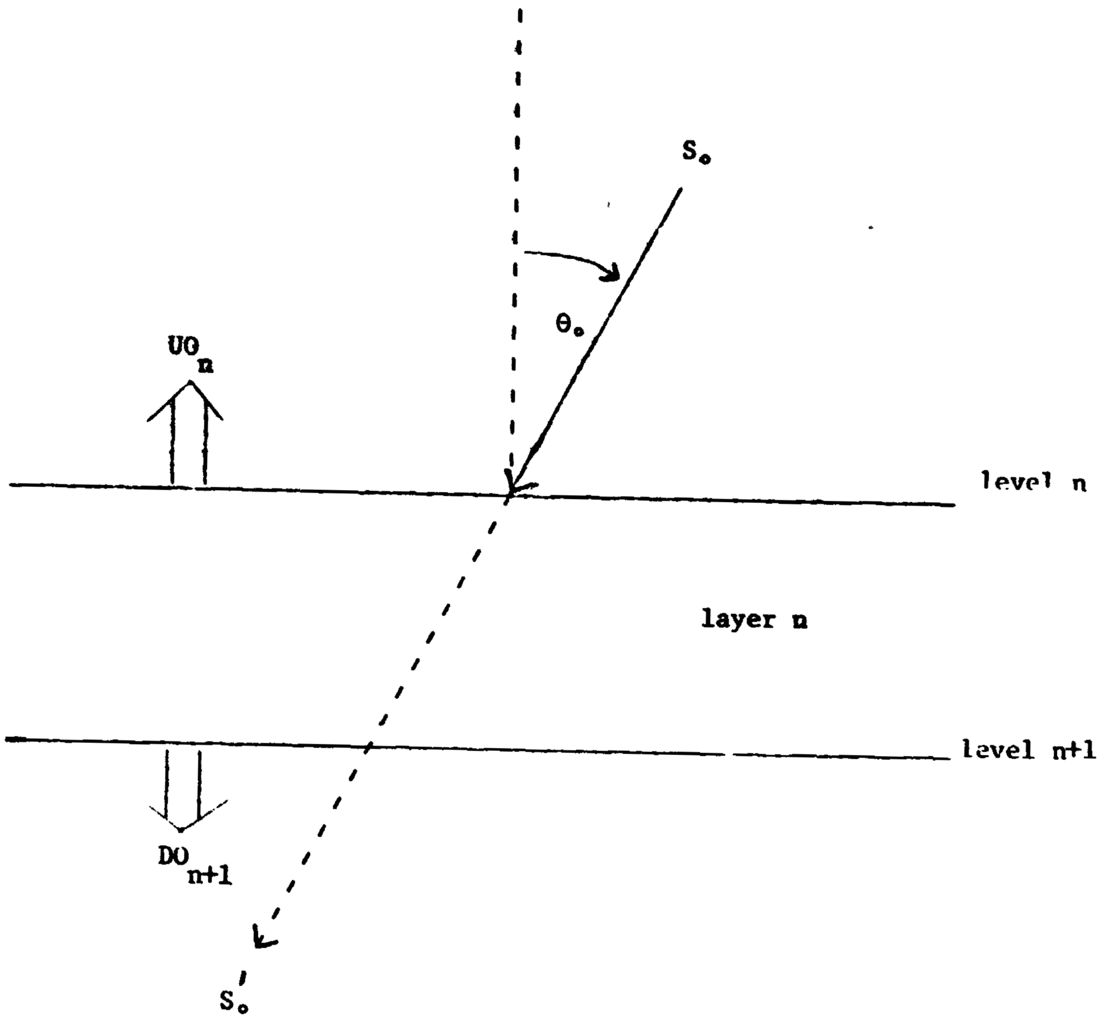

fig. 2.7.1

2.7.1 Delta-Eddington approximation

For $\tau \geq 8$ the Delta-Eddington approximation of Joseph *et al* (1976) appears superior to alternative simple approximations and has been adopted for use in the GCM.

The intensive parameters are first scaled so that

$$k' = k(1 - af) \qquad 2.7.9$$

$$a' = a(1 - f)/(1 - af) \qquad 2.7.10$$

$$g' = (g - f)/(1 - f) \qquad 2.7.11$$

where $f=g^2$.

The resulting solutions for UO and DO are then given by

$$UO = 2\pi\ I_o(0)\ S_o, \qquad 2.7.12$$

and

$$DO = 2\pi\ I_o(Z_o)\ S_o, \qquad 2.7.13$$

where

$$I_o(0) = \alpha_1 \exp(-\eta Z_o) + \alpha_2 + \alpha_3, \qquad 2.7.14$$

$$I_o(Z_o) = \alpha_1 + \alpha_2 \exp(-\eta Z_o) + \alpha_3 \exp(-k'Z_o/\mu_o) \qquad 2.7.15$$

and

$$\eta = \{3k'^2(1 - a'g')(1 - a')\}^{\frac{1}{2}} \qquad 2.7.16$$

$$\alpha_1 = \{v_1 w_2 - u_1 w_1 \exp(-\eta Z_o)\}/\{\det\} \qquad 2.7.17$$

$$\alpha_2 = \{v_1 w_1 - u_1 w_2 \exp(-\eta Z_o)\}/\{\det\} \qquad 2.7.18$$

$$\alpha_3 = -3k'^2 a'[1 + g'(1 - a')]/4\pi(k'^2/\mu_o{}^2 - \eta^2) \qquad 2.7.19$$

and

$$\det = v_1{}^2 - w_1{}^2 \exp(-2\eta Z_o) \qquad 2.7.20$$

$$u_1 = h - \eta \qquad 2.7.21$$

$$v_1 = h + \eta \qquad 2.7.22$$

$$w_1 = -(h + k'/\mu_o)\alpha_3 - 3k'\mu_o a'g'/4\pi \qquad 2.7.23$$

$$w_2 = -[(h - k'/\mu_o)\alpha_3 - 3k'\mu_o a'g'/4\pi] \exp(-k'Z_o/\mu_o) \qquad 2.7.24$$

and

$$h = 3k'(1 - a'g')/2 . \qquad 2.7.25$$

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2.7.2 The Two Stream Approximation

For small optical thicknesses, the Delta-Eddington approximation is less precise than the two stream approximation of Coakley and Chylek (1975), which tends to the single scatter approximation as $\tau \to 0$.

A generallized form of the two stream approximation leads to

$$UO = S_o \{\alpha_1^- e^{-\lambda\tau} + \alpha_2^- + \alpha_3^-\} \quad 2.7.26$$

and

$$DO = S_o \{\alpha_1^+ + \alpha_2^+ e^{-\lambda\tau} + \alpha_3^+ e^{-\tau/\mu_o}\} \quad 2.7.27$$

where $\lambda = p(1 - a)^{\frac{1}{2}}(1 - a + 2a\beta_1)^{\frac{1}{2}}$ 2.7.28

$$\alpha_3^{\pm} = \eta^{\pm}/(\mu_o^{-2} - \lambda^2) \quad 2.7.29$$

$$\alpha_1^+ = \{\alpha_3^+(c_1 - c_2)e^{-\lambda\tau} - \alpha_3^- a\beta_1 e^{-\tau/\mu_o}\}/\{c_1 + c_2 - (c_1 - c_2)e^{-2\lambda\tau}\} \quad 2.7.30$$

$$\alpha_1^- = \alpha_1^+(c_1 + c_2)/a\beta_1 \quad 2.7.31$$

$$\alpha_2^+ = -\alpha_3^+ - \alpha_1^+ e^{-\lambda\tau} \quad 2.7.32$$

$$\alpha_2^- = \alpha_2^+ (c_1 - c_2)/a\beta_1 \quad 2.7.33$$

$$\eta^+ = -a\{p\, a\beta_1 + (1 - \beta_2)[p(1 - a) + \mu_o^{-1}]\} \quad 2.7.34$$

$$\eta^- = -a\{p\, a\beta_1 + \beta_2[p(1 - a) - \mu_o^{-1}]\} \quad 2.7.35$$

$$c_1 = 1 - a + a\beta_1 \quad 2.7.36$$

and

$$c_2 = \lambda/p \quad 2.7.37$$

The Coakley-Chylek approach has been further modified to allow for an optimal choice of the backscattered fraction based on Wiscombe and Grams (1976), and to make a delta-scaling of τ, a and g to τ', a' and g' analogous to the Delta-Eddington scaling.

Thus for $\tau \leq 1$

$$p = 1/\mu_o \quad 2.7.38$$

$$\beta_1 = \beta_2(\mu_o) \quad 2.7.39$$

and for

$$\tau > 1$$

$$p = 2 \qquad 2.7.40$$

$$\beta_1 = 1/2(1 - \frac{7}{8}g') \qquad 2.7.41$$

where $\beta_2(\mu_o)$ is chosen numerically from Fig. 3 of Wiscombe and Grams (1976).

2.8 Multi-Layer Solution

At each grid point of the GCM, the following quantities are first determined for each layer, n, taken in isolation, using the methods of section 2.7.

SO_n - the direct solar irradiance through level n.

UO_n - the upwelling irradiance through level n due to SO_n.

DO_n - the downwelling diffuse irradiance through level n due to SO_{n-1}.

R_n - the reflectivity of layer n to unit diffuse irradiance.

T_n - the transmissivity of layer n to unit diffuse irradiance.

These quantities are then combined in the following scheme to give the total upwelling and downwelling irradiances, U_n and D_n, through each level, from which the absorption in each layer is given by

$$A_n = D_n - U_n - (D_{n+1} - U_{n+1}) \qquad n = 1, 2, \ldots, N \qquad 2.8.1$$

where

N is the total number of atmospheric layers.

The scheme used is similar to that of Grant and Hunt (1968), with UO_n, DO_{n+1} acting as internal sources, and with some simplification due to the fact that the radiation is treated as though it were diffuse.

We define DI_n and UI_n to be, respectively, the downwelling and upwelling diffuse irradiances due to all radiation crossing level n which has not previously crossed level n + 1. Dl_n and Ul_n may then be obtained recursively from

$$Dl_n = (Dl_{n-1} + UO_{n-1} CR_{n-1})\, M_{n-1} T_{n-1} + DO_n \qquad n = 2, \ldots, N \qquad 2.8.2$$

and

$$Ul_n = (Dl_n R_n + UO_n)\, M_n \qquad n = 1, \ldots, N \qquad 2.8.3$$

where CR_n is the composite reflectivity of diffuse upwelling irradiance at level n due to all layers above level n, and is given recursively by

$$CR_n = R_{n-1} + T_{n-1} CR_{n-1}\, T_{n-1} M_{n-1} \qquad n = 2, \ldots, N \qquad 2.8.4$$

and M_n is the magnification factor for multiple reflections at level n between layer n and all layers above level n. M_n is given by

$$M_n = 1 \,/ (1 - CR_n\, R_n) \qquad 2.8.5$$

Note that $CR_1 = 0$, $DO_1 = 0$, and $Dl_1 = 0$.

Once Dl and Ul have been found for all n, the total irradiances crossing each level, D_n and U_n, are found recursively be evaluating

$$U_n = Ul_n + U_{n+1} T_n\, M_n \qquad n = N-1, N-2, \ldots, 1 \qquad 2.8.6$$

$$D_n = Dl_n + U_n CR_n + SO_n \qquad n = N, N-1, \ldots, 1 \qquad 2.8.7$$

Note that $U_N = Ul_N$ and that the direct irradiance at each level has been included in D_n.

3. COMPUTATIONAL OVERVIEW

This section discusses the general flow of the solar radiation code and the function of the various subroutines.

3.1 Initialization

The input variables for the solar radiation code come from a number of sources, depending mainly on their time dependence. This is reflected in the schematic flow diagram of fig. 3.1.

Climatological, or otherwise predetermined, variables enter the radiation code by way of DATA statements in the relevant subroutines or may be read in from tape at the start of GCM run.

Slowly varying quantities such as the solar declination angle and the mean earth-sun distance are updated at the start of each new Julian day by a call to SRDATE.

Rapidly changing quantities such as temperature, pressure, humidity and clouds are calculated at each time step of the GCM and are available to the solar radiation code by way of COMMON blocks.

As shown in fig. 3.1 a call to the solar radiation code involves looping over each horizontal grid element, determining the solar zenith angle for that element, and calling SOLAR1 to find the absorbed radiation at each vertical level, given a daytime situation.

3.2 SOLAR1

Subroutine SOLAR1 controls most of the flow for calculating absorption at a single grid point. It also performs the absorption calculations directly in the case of a cloud free atmosphere.

As shown schematically in fig. 3.2, the water vapor amount above each level, scaled for pressure and temperature effects, is determined first. The levels

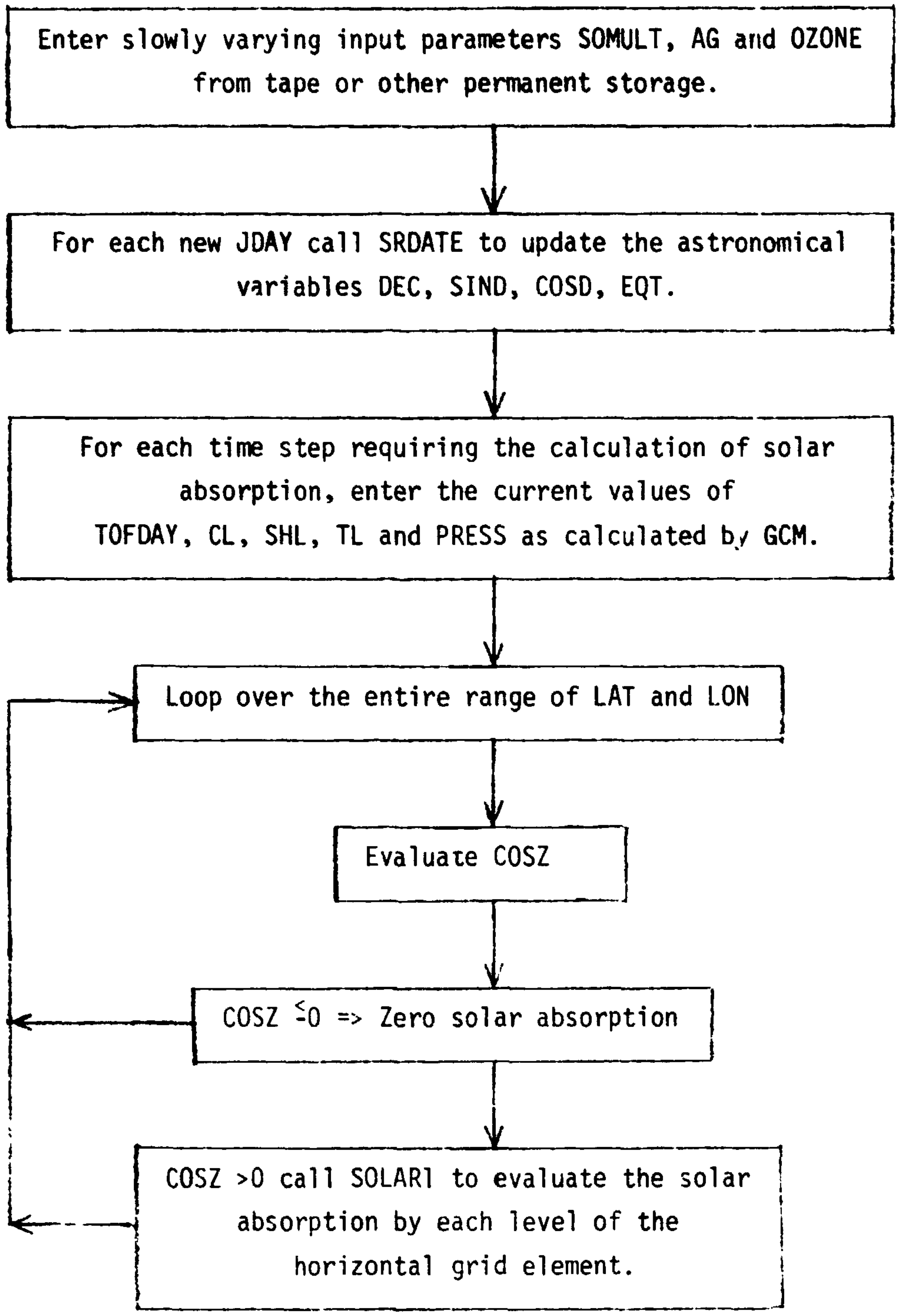

Fig. 3.1 Schematic flow diagram of initialization and call to SOLAR1.

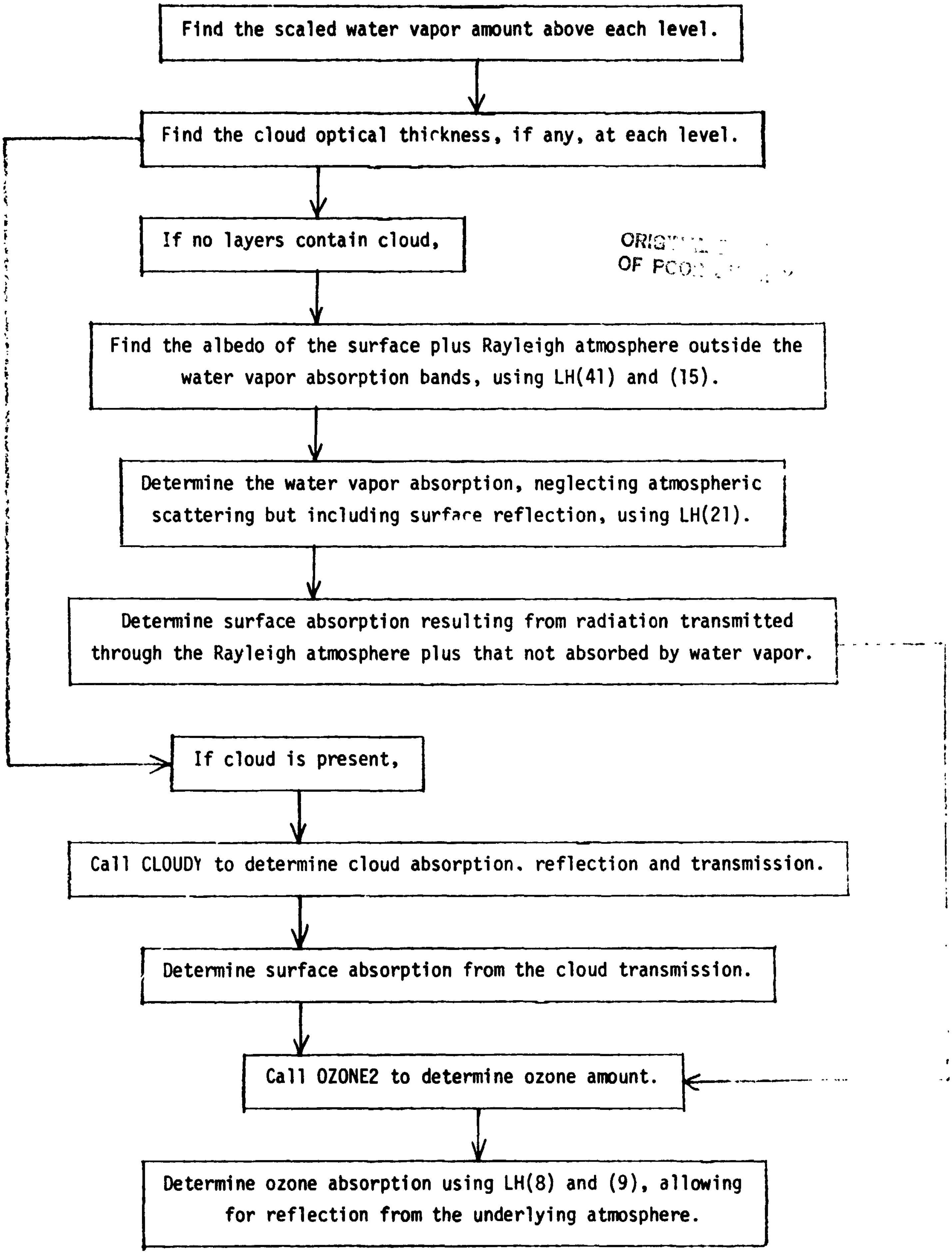

Fig. 3.2 Schematic flow diagram for SOLAR1

are then examined for cloud content and cloud optical thicknesses assigned based on cloud type. Should cloud be present at any level the flow turns to subroutine CLOUDY for determination of the cloud properties, otherwise absorption due to water vapor in Rayleigh atmosphere is calculated directly.

SOLAR1 finally determines the albedo of the earth-troposphere and calculates the ozone absorption in the upper levels.

3.3 CLOUDY

Subroutine CLOUDY controls the calls to the radiative transfer routines and the wavelength integration when clouds are present.

The effect of clouds in the visible is handled simply by adding all the cloud layers together and assuming no atmospheric absorption, so that a single call to LAYER and one to ADDER with N=2 to add in the surface albedo is all that is needed.

In the solar infrared, water vapor absorption is included by first determining the total intrinsic radiative properties for each layer arising from both the cloud and the water vapor, making a call to LAYER and repeating this procedure for each layer. ADDER is then called to combine the effects of all the cloud layers and the surface, and this process is repeated for each wavelength interval.

3.4 LAYER

Subroutine LAYER evaluates the reflection and transmission of a single or composite cloud layer, both for unit diffuse irradiance on the cloud top and for a given irradiance from a specified solar zenith angle.

The cloud properties are scaled using 2.7.9 to 2.7.11 if $\tau > 1$. For $\tau < 8$, the Coakley-Chylek two stream approximation of section 2.7.2 is used. Otherwise, for $\tau \geq 8$, the delta Eddington approximation of section 2.7.1 is used, as depicted in the schematic of fig. 3.4.

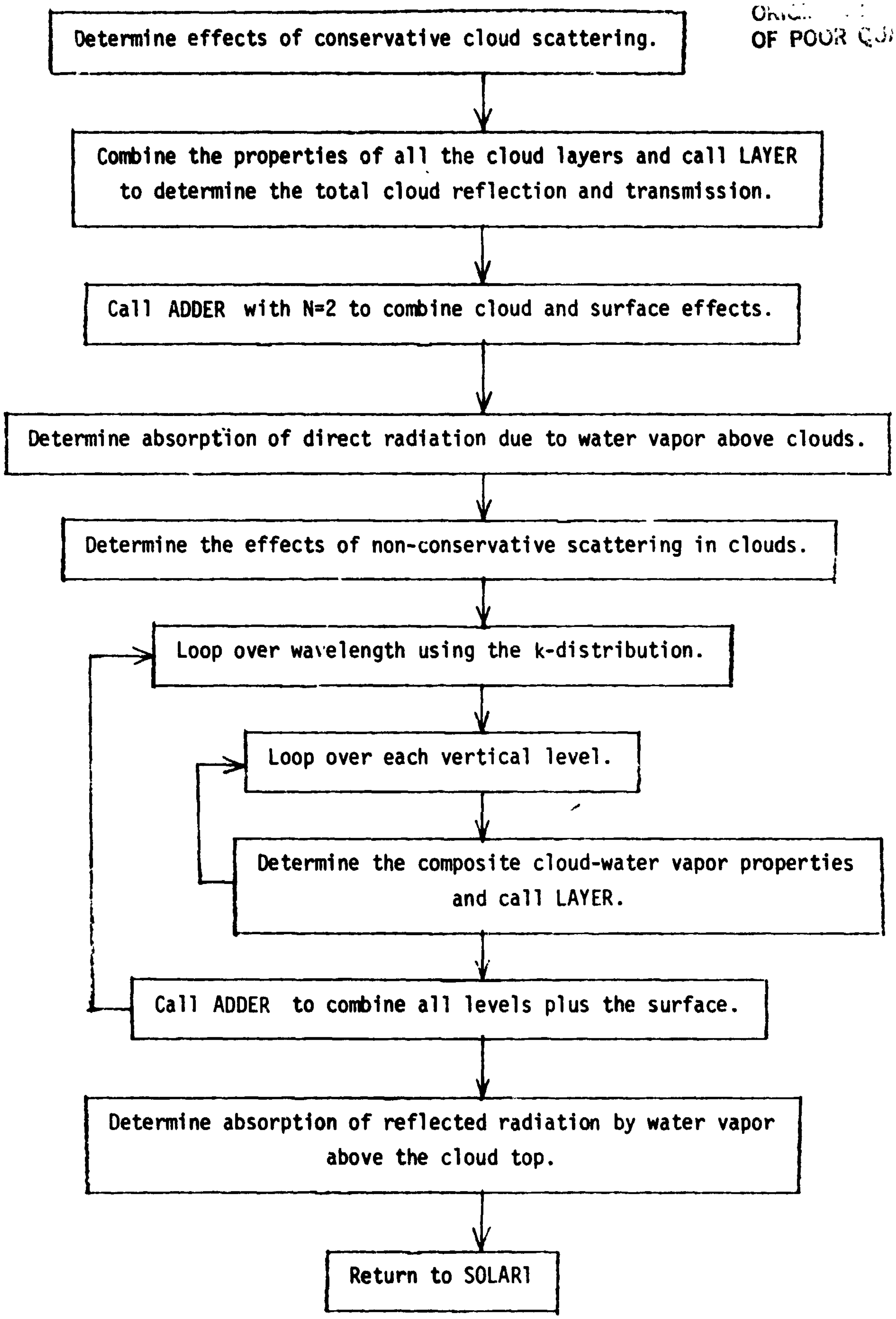

Fig. 3.3 Schematic flow of subroutine CLOUDY

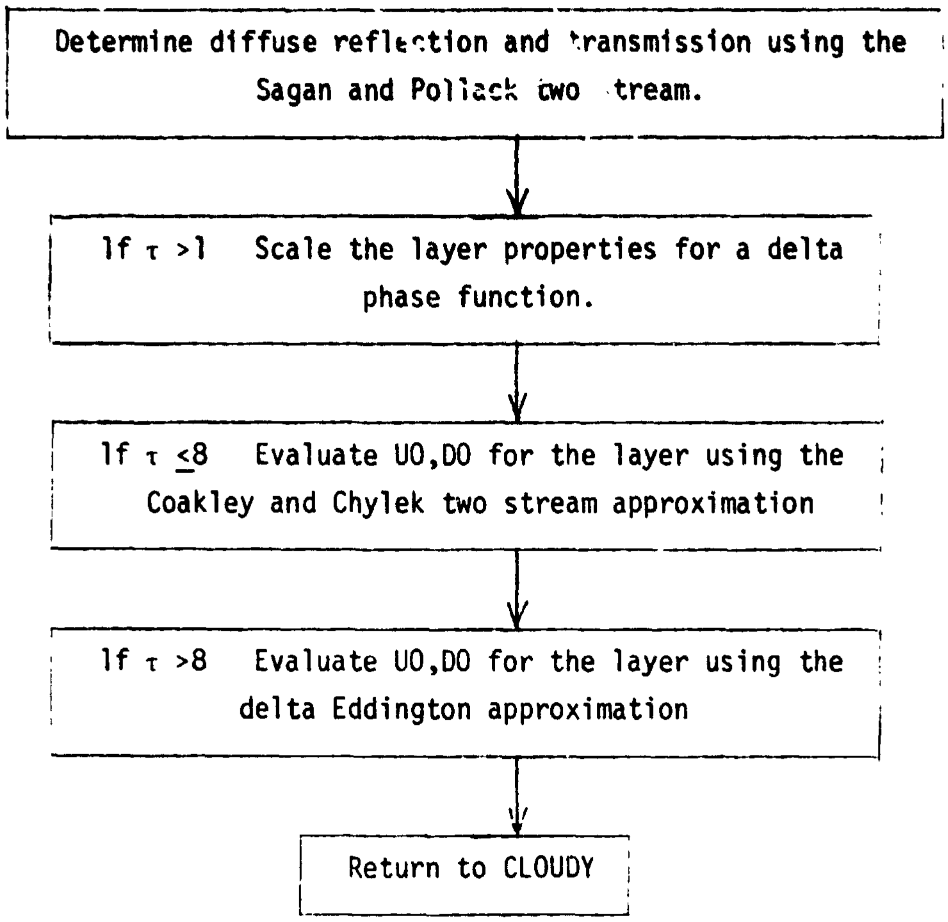

Fig. 3.4 Schematic flow diagram for subroutine LAYER

3.5 OZONE2, ADDER , AOZONE and AWATER

Subroutine OZONE2 interpolates from a stored data set to find the climatologically expected ozone amount above each level, based on the time of year and the latitude.

Subroutine ADDER combines the effect of different cloud levels and/or the surface. It follows section 2.8 closely.

Functions AWATER and AOZONE determine the absorption due to a given path of water vapor or ozone, determined from LH(21) and LH(8), (9) respectively.

3.6 SUBROUTINE SUMMARIES

3.6.1 AOZONE

Real Function AOZONE (X)

This function calculates the fraction of incident radiation that is absorbed by an ozone amount of X cm (NTP), using LH(7) and (9).

There are no external references.

3.6.2 AWATER

Real Function AWATER (X)

This function calculates the fraction of incident radiation that is absorbed by X cm of precipitable water vapor, using LH(21).

3.6.3 ADDER

Subroutine ADDER (NL1)

COMMON/ ADD / SOL(10), UO(10), DO(10), RL(10), TL(10), UL(10), DL(10), ABSL(10).

Input Variables

NL1 - Integer - The number of layers to be combined.

$2 < NL1 < 10$

SOL - Real Array - Vertical component of the direct solar beam crossing each level.

UO - Real Array - Upwelling irradiance at the top of each layer due to the direct solar beam on that layer.

DO - Real Array - Downwelling irradiance at the base of each layer. due to the direct solar beam.

RL - Real Array - Reflectivity of each layer to diffuse irradiance.

TL - Real Array - Transmissivity of each laver to diffuse irradiance.

Output Variables

UL - Real Array - The total upwelling irradiance through each level.

DL - Real Array - The total downwelling irradiance through each level.

ABSL - Real Array - The solar radiation absorbed by each layer.

Notes

1. This subroutine is called from CLOUDY for each spectral interval to evaluate the absorption due to interactions between layers.
2. The computer variables generally have names which compare directly with the symbols of section 2.8.
3. The first part of ADDER is for NL1=2, which takes a particularly simple form. The section is entered to evaluate the total cloud effect in the nonabsorbing portion of the spectrum.

3.6.4 CLOUDY

Subroutine CLOUDY (RCLOUD, NLAY, NTOP)

COMMON/RADCOM/

COMMON/CLDCOM/

COMMON/ADD /

Input Variables

NLAY	- Integer	- Number of layers in model.
NTOP	- Integer	- Layer number of the highest layer containing cloud
TAUL(16)	- Real Array	- Cloud optical thickness of each layer. (CLDCOM)
FSCAT	- Real	- Fraction of incident radiation (visible) that is not subjected to atmospheric absorption (CLDCOM).
COSZ	- Real	- Cosine of the solar zenith angle (RADCOM).
RSURF	- Real	- Surface albedo with respect to direct beam (CLDCOM).
AG	- Real	- Surface albedo with respect to diffuse radiation(CLDCOM)
SWALE(16)	- Real Array	- Scaled water vapor amount above each level (CLDCOM).
COSMAG	- Real	- Refraction magnification factor (CLDCOM).
SCOSZ	- Real	- Solar irradiance normal to top of atmosphere (CLDCOM).
SWIL(16)	- Real Array	- Scaled water content within each layer (CLDCOM).

Output Variables

TOPABS	- Real	- Absorption above level 1 (CLDCOM).
AL(16)	- Real Array	- Absorption in each layer (CLDCOM).
RCLOUD	- Real	- Cloud albedo in the visible.

Notes

1. This subroutine first evaluates the effect of all the cloud layers in the visible by a single call to LAYER and one call to ADDER .
2. The variables required for ADDER a transferred using COMMON/ ADD /.
3. This subroutine is called by SOLAR1 and in turn makes use of LAYER and ADDER.

3.6.5 LAYER

Subroutine LAYER (SCOSZ, COSZ, TAU, PIO, SO1, UP, DN, RL, TL)

Input Arguments

- SCOSZ - Real - Vertical component of direct solar irradiance on top surface of layer.
- COSZ - Real - cosine of the solar zenith angle.
- TAU - Real - Layer optical thickness.
- PIO - Real - Single scatter albedo.

Output Arguments

- SO1 - Real - Vertical component of transmitted direct solar irradiance.
- UP - Real - Irradiance reflected from the direct beam by the layer.
- DN - Real - Irradiance transmitted through the layer from the direct beam.
- RL - Real - The reflectivity of the layer to diffusely incident radiation.
- TL - Real - The transmissivity of the layer to diffusely incident radiation.

Notes

1. This subroutine is called by CLOUDY to evaluate the reflection and transmission characteristic of any layer, such as a cloudy layer, that contains scatterers.
2. The output from LAYER is utilized by ADDER.
3. Subroutine LAYER is self-contained, with no external references.
4. The computer variables generally have names which compare directly with the symbols of section 2.7.

3.6.6 OZONE2

Subroutine OZONE2 (NLAYO1, XDAY, XLAT)

COMMON/RADCOM/

COMMON/CLDCOM/

Input Variables

NLAYO1	- Integer	- The number of pressure levels above which ozone is to be considered. SOLAR1 sets NLAYO1 = 6.
XDAY	- Real	- GARP reference day. XDAY = JDAY + 63.
XLAT	- Real	- Latitude in degrees.
PLE (16)	- Real Array	- in RADCOM. - the pressure (mb) at the top of each level of the GCM.

Output Variables

OZALE (16)	- Real Array	- in CLDCOM. - the amount of ozone above the top of each model layer.

Notes

1. This subroutine is called once per grid point via SOLAR1 to calculate the ozone amounts based on climatology above each level of the model.
2. There are no external references.
3. The subroutine first finds the total ozone (TOTOCM) by interpolating from quarterly climatological values based on latitude. It then uses TOTOCM to set up a fine scale vertical distribution of ozone from which it interpolates to obtain the values of OZALE.

3.6.7 SOLAR1

Subroutine SOLAR1 (NLAY, XDAY, XLAT)

COMMON/RADCOM/

COMMON/CLDCOM/

Input Variables

NLAY	- Integer	- The number of atmospheric layers.
XDAY	- Real	- GARP reference day. XDAY = JDAY + 63.
XLAT	- Real	- Latitude in degrees.
COSZ	- Real	- Cosine of solar zenith angle. (RADCOM)
RSURF	- Real	- Surface albedo for direct radiation from COSZ. (CLDCOM)
AG	- Real	- conventional surface albedo.
SO	- Real	- Solar irradiance at top of atmosphere (RADCOM).
PLE (16)	- Real Array	- pressure (mb) at each atmospheric level (RADCOM).
TL (15)	- Real Array	- Temperature at mid-pt. of each layer (RADCOM).
SHL (15)	- Real Array	- Humidity of each layer (RADCOM).
CL (15)	- Real Array	- cloud information, coded to indicate presence and type. (RADCOM)

Output Variables

AS (15)	- Real Array	- absorption in each atmospheric layer (RADCOM)
SG	- Real	- absorption at surface. (RADCOM)
SWALE (16)	- Real Array	- scaled water vapor above each level. (CLDCOM)
SWIL (16)	- Real Array	- scaled water vapor amount in each layer. (CLDCOM)

Notes

1. The water vapor is scaled for temperature and pressure effects as in LH(24).
2. The cloud optical thickness in each level is found by decoding the array CL and follows section 2.6.
3. The cloud free situation is treated directly, firstly for the non-absorbing Rayleigh atmosphere, and secondly for water vapor absorption in the absence of scattering.
4. This subroutine is called at each grid point to evaluate solar absorption. It calls in turn CLOUDY, if clouds are present, and OZONE2 for ozone amounts.

3.6.8 SRDATE

Subroutine SRDATE (JDAY, SOMULT, SO, DEC, SIND, COSD, EQT, ALBEDO)

Input Arguments

JDAY	- Integer	- The Julian day number, = 1 on Jan. 1st.
SOMULT	- Real	- A multiplier of the solar constant. SOMULT = 1 for units of ly/day. SOMULT = 0.4844 for units of W/M^2. SOMULT can also be varied to perturb the solar constant.

Output Arguments

SO	- Real	- The extraterrestrial solar irradiance.
DEC	- Real	- The solar declination angle (radians).
SIND	- Real	- SIN(DEC).
COSD	- Real	- COS(DEC).
EQT	- Real	- Equation of time (radians).
ALBEDO (46,72)	- Real Array	- Conventional surface albedos.

Notes

1. This subroutine is called once per day to update slowly varying astronomical variables and surface albedos.
2. A solar constant of 1368 W/m^2 is used.
3. The equations used are discussed in section 2.1.
4. The surface albedos are read in from unit 10 as IALB (46,72) - Integer *2 in free format.

Calling Routine: Main Program

External References: Logical Unit 10.

4. Comparative Results

Results from the new code for the transmittance of a single cloud layer as a function of sun angle are compared in Fig. 4.1 (taken from Davies, 1980) with results from the Lacis and Hansen (LH) code and precise results from a doubling model (Hansen, 1971). While the new code compares well with the doubling model, the LH version underestimates transmission for high solar elevations and overestimates it for low solar elevations.

In addition to specific case comparisons between the old and new codes, which generally show large differences, it is of interest in the GCM context to compare averaged results to see if the differences might be significantly reduced. The GCM output was therefore analyzed off-line to provide such averages. The input parameters to the radiation routines obtained during a given GCM run were stored and the absorbed radiation was recalculated with both the old and new codes. Since the new code did not interact with other aspects of the GCM, a direct comparison of code differences was therefore possible, circumventing the immediate effects of model noise.

The off-line recalculation of absorbed solar radiation using the LH code was of course redundant, the values agreeing with those used in the original on-line calculations of the complete GCM. The recalculation did, however, serve as a diagnostic check and conveniently reformatted the old results.

Figs. 4.2-4.4 show results from the new code (solid lines) and the differences with the LH code (dashed lines: LH result-new result). The absorbed solar radiation has been zonally averaged and also averaged for the mouth of February, for a GCM run which was initialized on January 1. Fig. 4.2

shows the radiation absorbed by both the surface and atmosphere. Fig. 4.3 and Fig. 4.4 show, respectively, the surface and atmospheric absorption. The LH code is seen to systematically overestimate absorption at almost all latitudes. The differences vary somewhat with latitude, depending on sun angle and cloud cover. On a globally averaged basis, the overestimate is 7% in total absorption, 4% in surface absorption and 17% in atmospheric absorption. The corresponding results for zonally averaged planetary albedo are shown in Fig. 4.5. The LH code systematically underestimates albedo with the differences increasing at high latitudes. Fig. 4.6 shows similar results, but for an average over April. If the time average is relaxed and zonal averages at a single time step are compared, as in Fig. 4.7 for mid-February, the functional dependence on latitude is less regular, but the systematic differences persist.

Finally, since the largest percentage differences were in atmospheric absorption, the vertical distribution of absorbed solar radiation by model level is presented in Fig. 4.8 for the global average and a zonal average at 46°S. The two codes show their greatest differences in levels 4 and 5, presumably due to the effects of thick cloud.

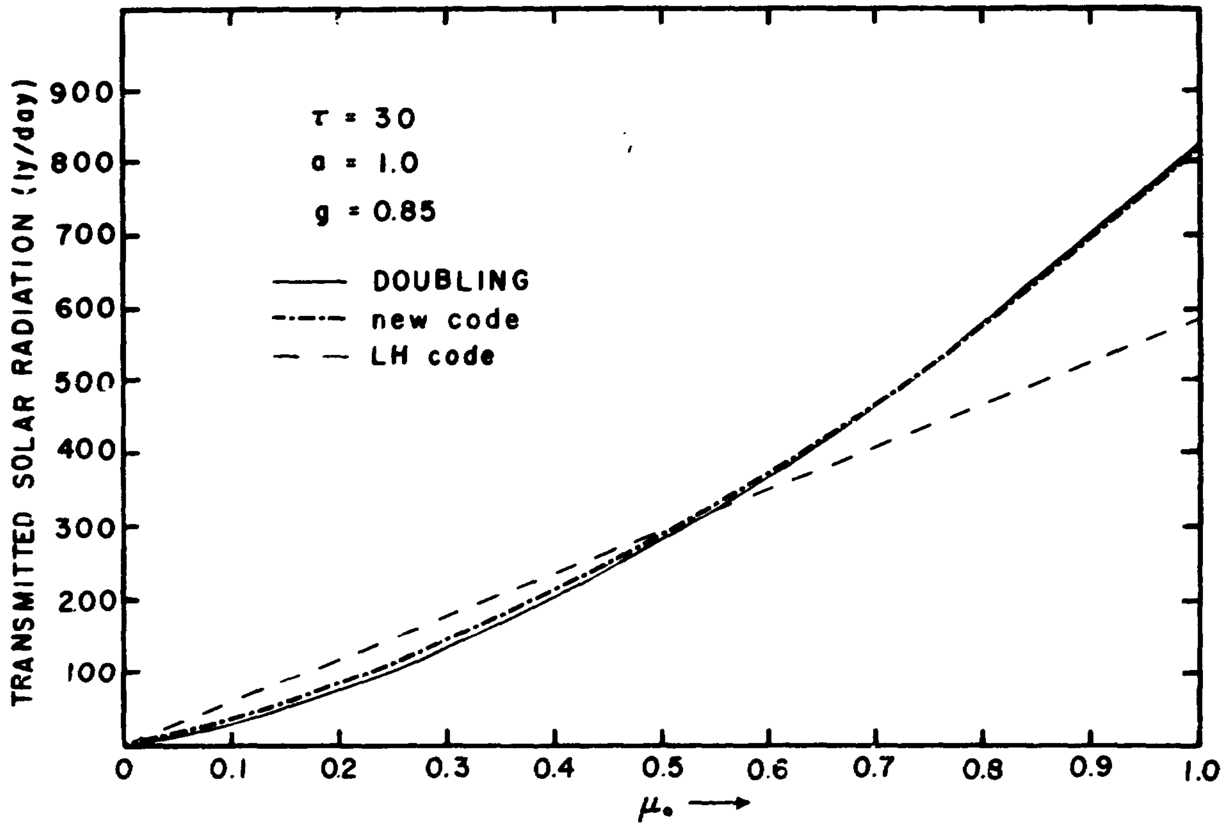

Fig. 4.1 Transmitted solar irradiance as a function of $\mu_o \cdot F_o = 2880$ ly/day.

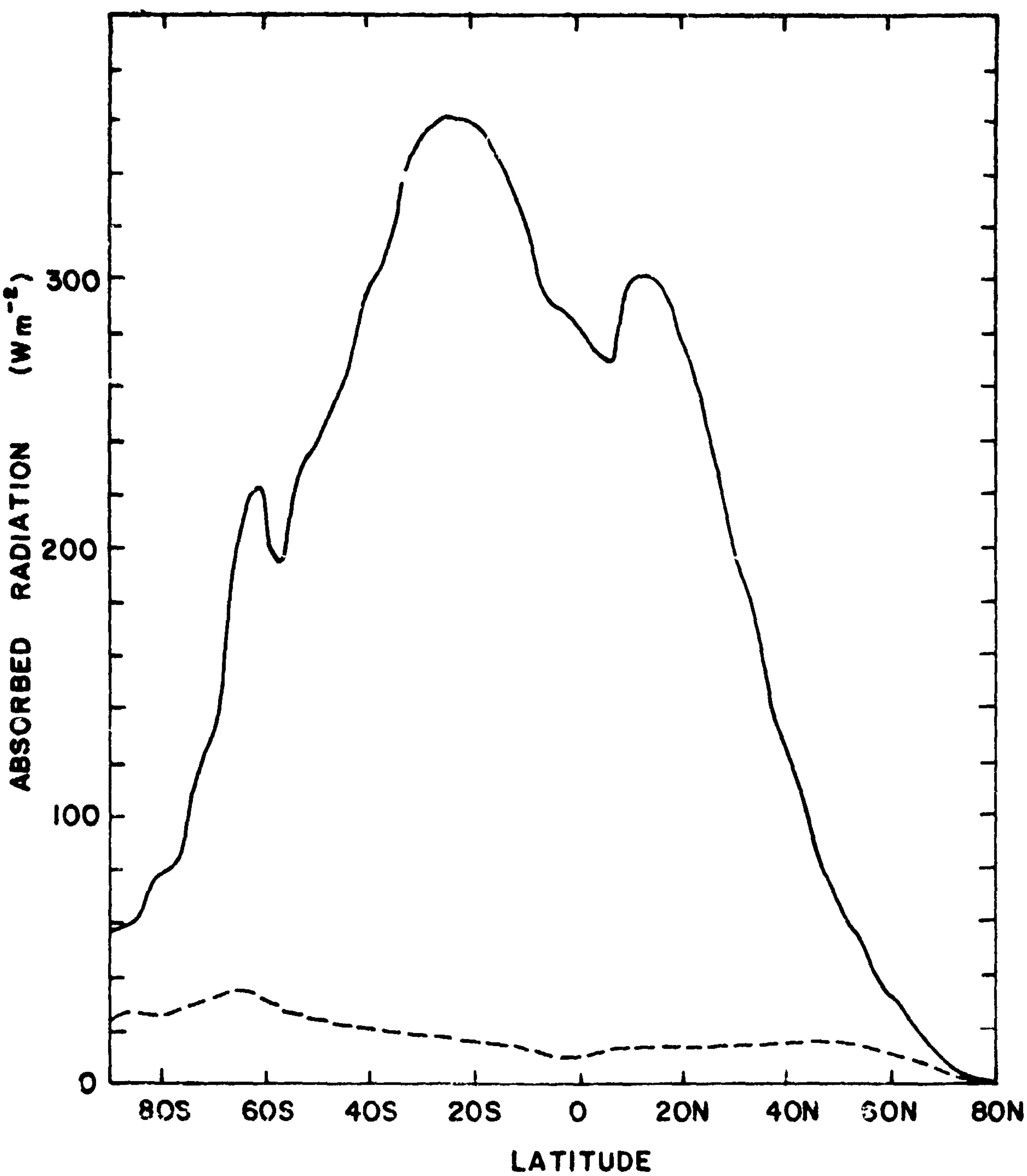

Fig. 4.2 Zonally averaged solar radiation absorbed by the surface plus atmosphere. February average.
——— New code results. -- -- -- LH code - New code.

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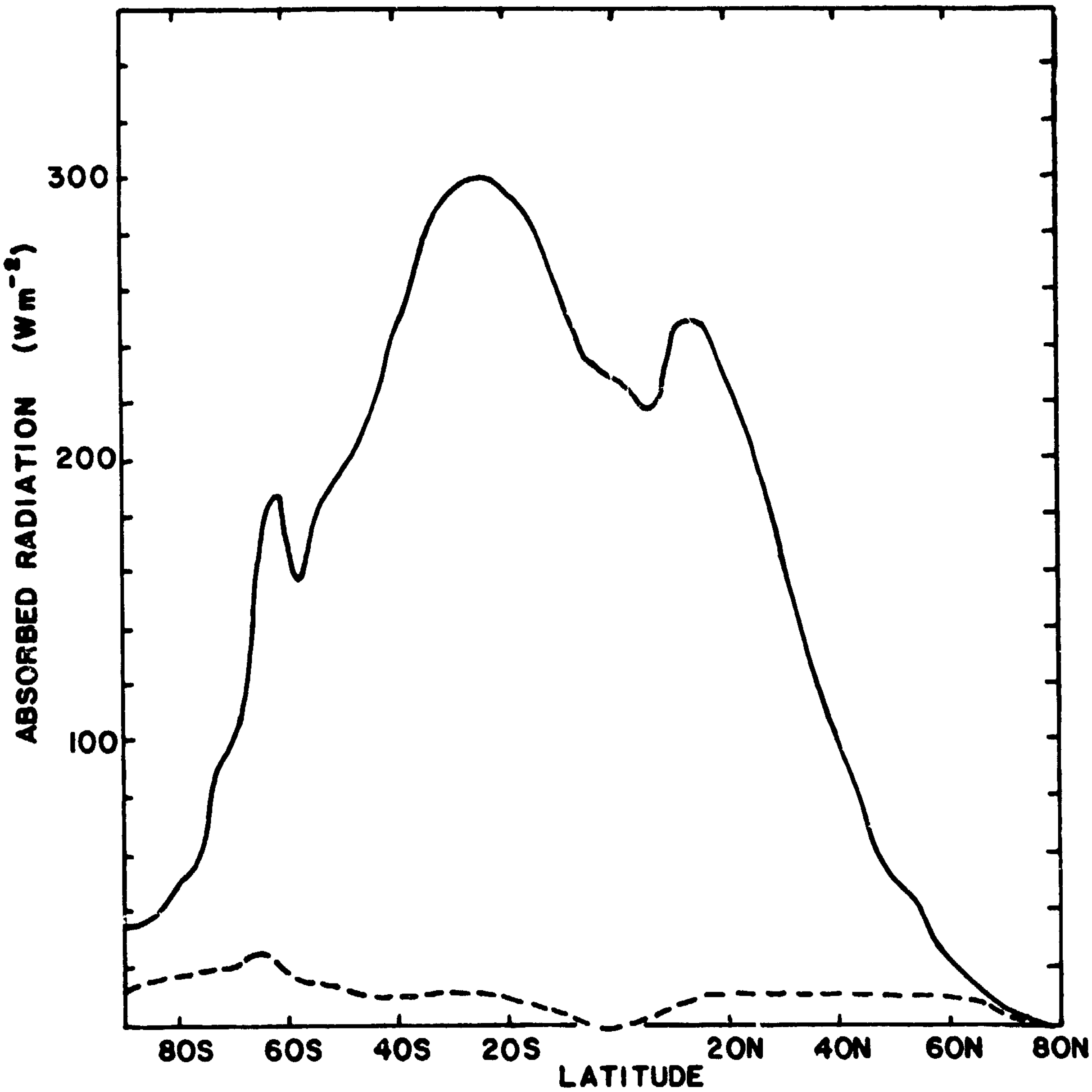

Fig. 4.3 Same as Fig. 4.2 but for surface absorption only.

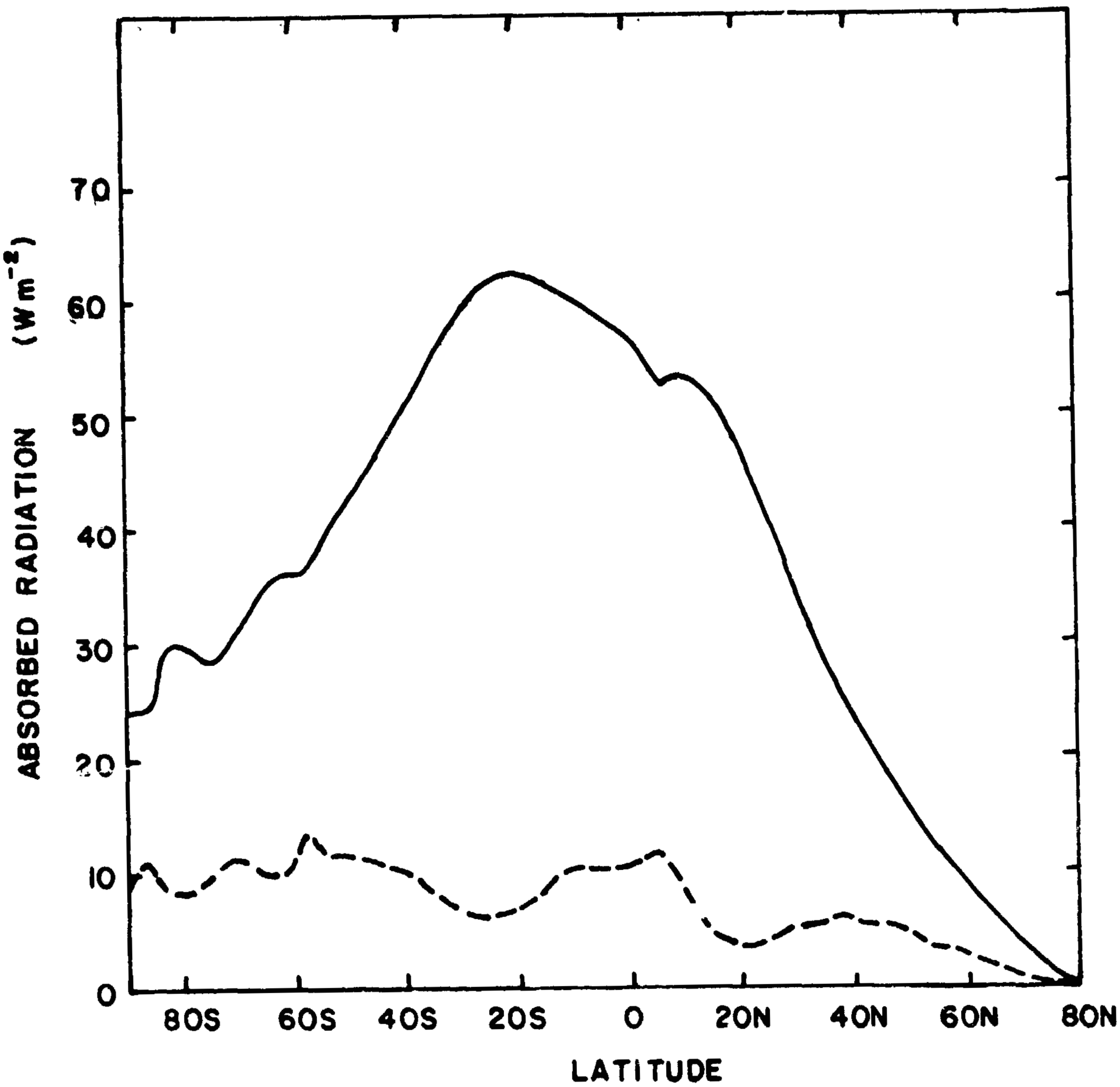

Fig. 4.4 Same as Fig. 4.2 but for atmospheric absorption only.

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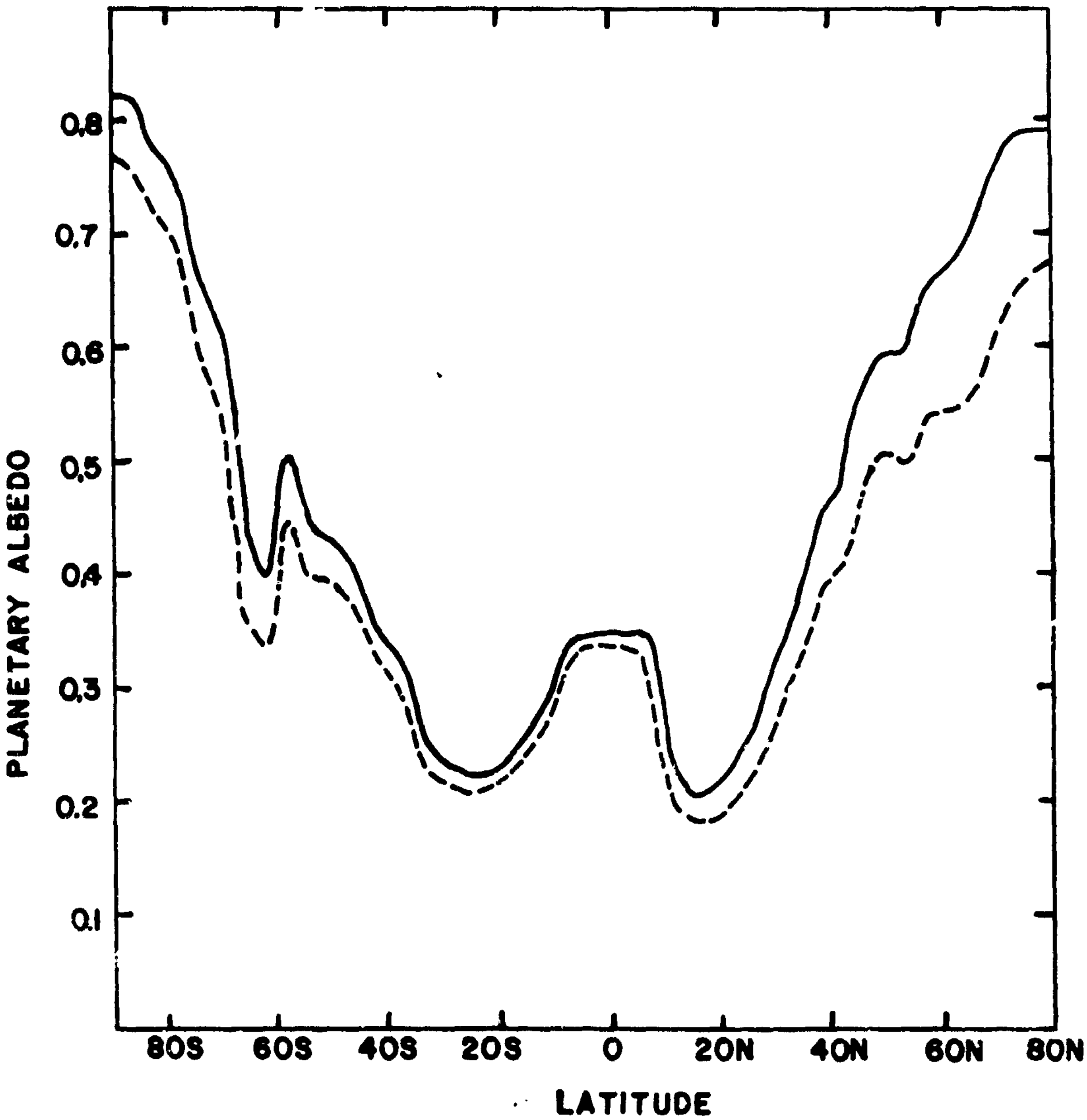

Fig. 4.5 Zonally averaged planetary albedo. February average. ——— New code. — — — LH code.

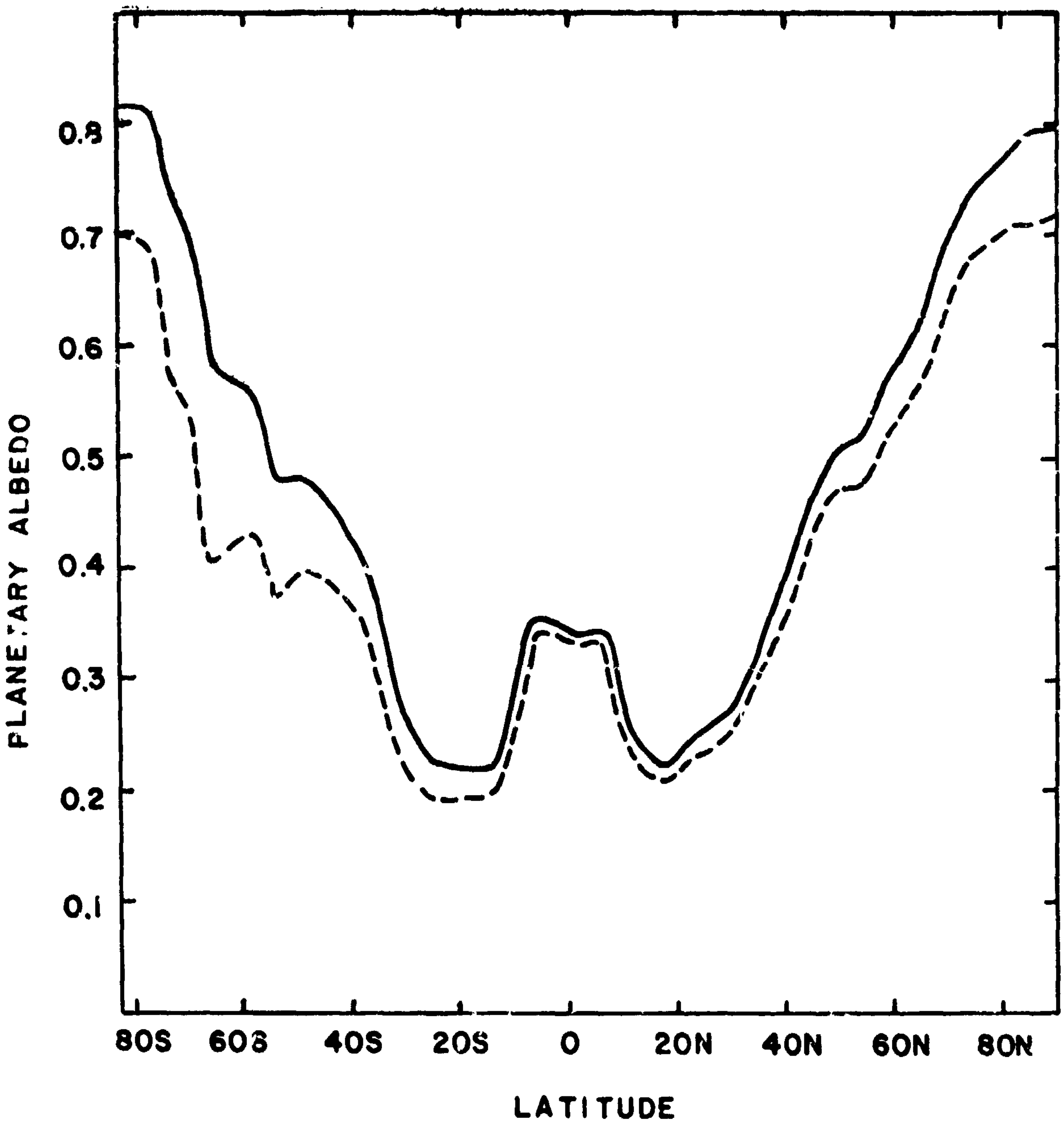

Fig. 4.6 Same as Fig. 4.5 but for April average.

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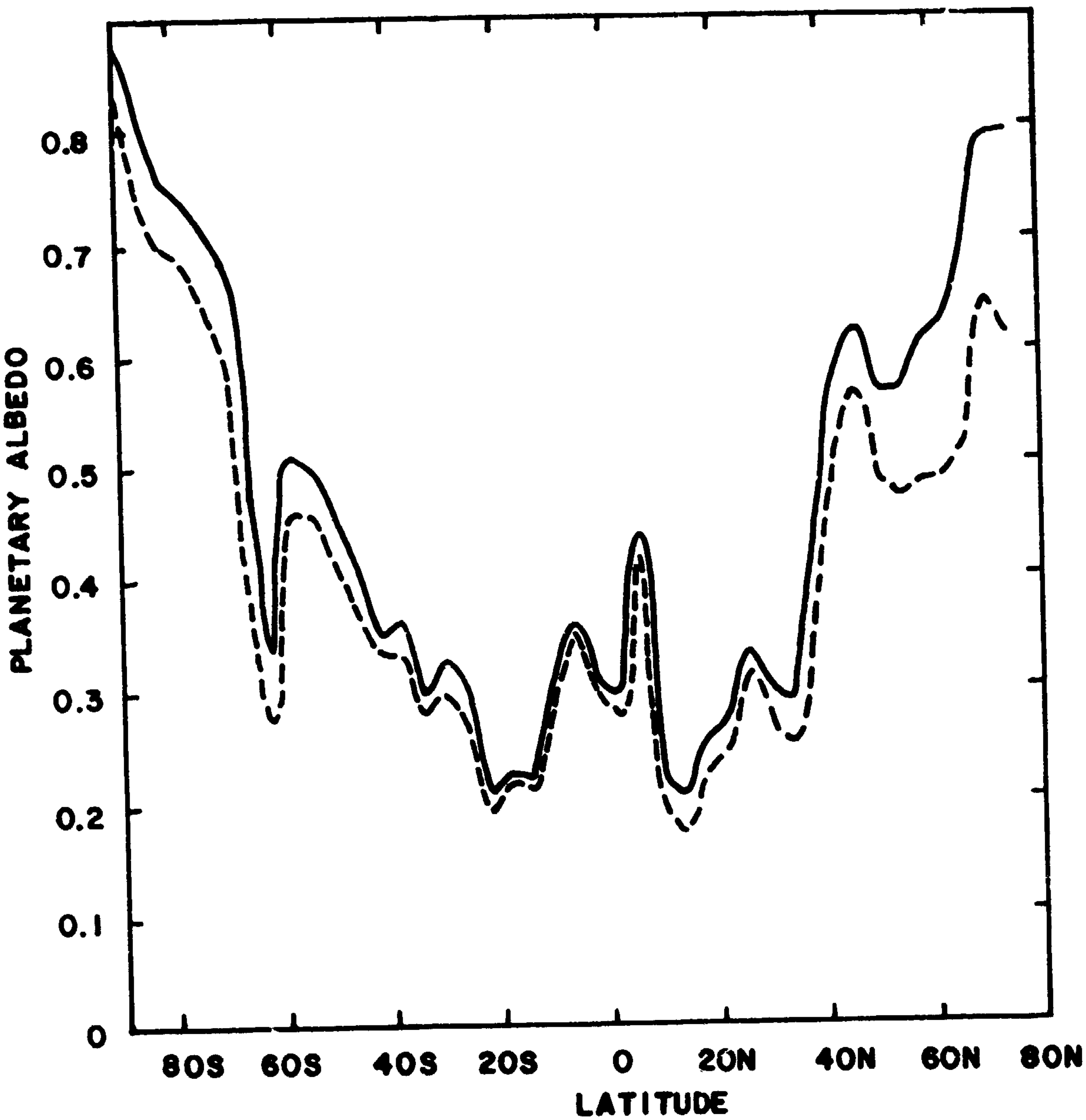

Fig. 4.7 Same as Fig. 4.5 but for single time step at mid-February.

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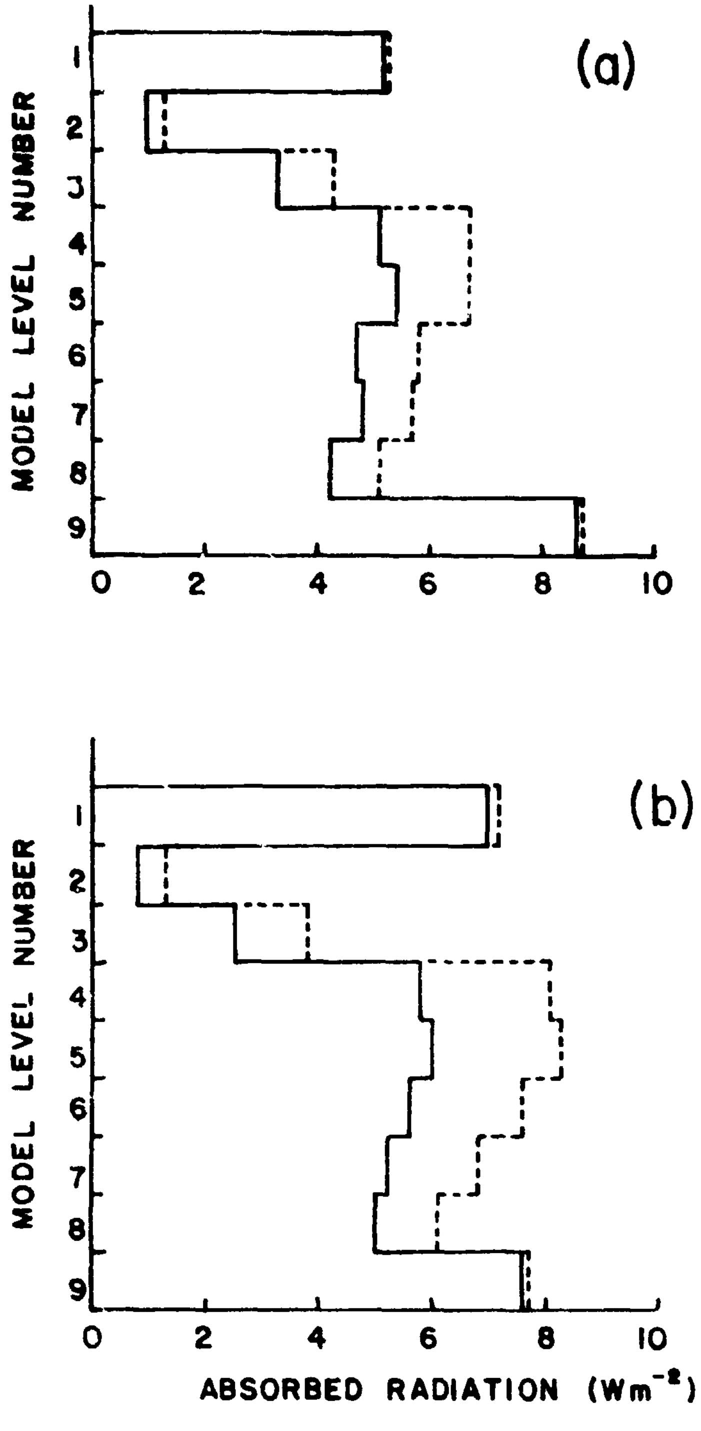

Fig. 4.8 Atmospheric absorption by model level. February averages. ——— New code. -- -- -- LH code.

(a) Global average (b) Zonal average at 46°S

5. Summary

The new solar radiation code described in this report yields significantly different values of absorbed solar radiation by the atmosphere and surface when compared to the original Lacis and Hansen code. These differences appear greatest for conditions of large solar zenith angle, and consequently, depend on latitude and season.

While the new code follows the physics of radiative transfer quite faithfully, as evidenced by comparison with even more precise (yet slower) models, there undoubtedly remains some room for improvement. A spectrally dependent surface albedo, and the effect of a background aerosol, should be included, but the most substantial improvement will be in the treatment of cloud propoerties, especially the treatment of fractional cloud cover. A substantial amount of original research on the radiative properties of multi-layered broken clouds is first needed, however, before they can be successfully considered in a GCM.

6. References

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Lacis, A. A., and J. E. Hansen, 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere. J. Atmos. Sci., 31, 118-133.

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Wiscombe, W. J., and G. W. Grams, 1976: The backscattered fraction in two-stream approximations. J. Atmos. Sci., 33, 2440-2451.

APPENDIX

CODE LISTING

```
      REAL FUNCTION AOZONE(X)
C
C***   THIS IS THE LACIS-HANSEN PARAMETERIZATION OF OZONE ABSORPTION.
C
      IF(X.LE.0. )GOTO 1
      AOZONE=.021180*X/(1.0+0.042*X+0.000323*X*X)+1.08173*X/(1.00+
     1        138.57*X)**0.805+0.0658*X/(1.00+(103.63*X)**3)
      RETURN
C
1     AOZONE=0.0
C
      RETURN
      END
      REAL FUNCTION AWATER(X)
C
C***   THIS IS THE LACIS-HANSEN PARAMETERIZATION FOR WATER VAPOR
C      ABSORPTION.
C
      IF(X.LT.0. )GOTO 1
      AWATER=2.9*X/((1.+141.51*X)**.635+5.925*X)
      RETURN
C
1     AWATER=0.0
C
      RETURN
      END
      SUBROUTINE ADDER(NL1)
C
C      COMBINES THE SOLUTIONS OBTAINED PREVIOUSLY FOR ISOLATED LAYERS,
C      BY SUCCESSIVE APPLICATION OF THE INTERACTION PRINCIPLE
C
C      DESIGNED BY ROGER DAVIES (PURDUE UNIVERSITY), 1981.
C
C      NL IS THE NUMBER OF ISOLATED LAYERS TO BE ADDED, INCLUDING
C      THE SURFACE, AND NL1 IS NL+1.
C
C      ASSUMES THAT NL1 IS BETWEEN 2 AND 10, AND THAT UO,DO,SOL,RL
C      AND TL HAVE BEEN SET UP BY CLOUDY. UL,DL AND ABSL ARE FOUND
C      HERE.
C
C      THE TEN'S BELOW ARE NLAY+1, AND SHOULD BE CHANGED IF THE
C      NUMBER OF MODEL LAYERS IS CHANGED.
C
      REAL M(10),CR(10),VM(10),VP(10)
C
      COMMON/ADD/SOL(10),UO(10),DO(10),RL(10),TL(10),
     1            UL(10),DL(10),ABSL(10)
C
      NL=NL1-1
      M(2)=1./(1.-RL(1)*RL(2))
      IF(NL.GT.1 )GOTO 10
      UL(2)=(UO(2)+DO(2)*RL(2))*M(2)
      UL(1)=UO(1)+UL(2)*TL(1)
      DL(2)=SOL(2)+DO(2)+UL(2)*RL(1)
      ABSL(1)=SOL(1)+UL(2)-UL(1)-DL(2)
      ABSL(2)=DL(2)-UL(2)
      RETURN
C
10    CR(1)=0.0
```

```
      CR(2)=RL(1)
      M(1)=1.
      DO 1 J=2,NL
         CR(J+1)=RL(J)+TL(J)*TL(J)*CR(J)*M(J)
 1       M(J+1)=1./(1.-CR(J+1)*RL(J+1))
      VP(2)=DO(2)
      VP(1)=0.0
      VM(1)=UO(1)
C
      DO 2 J=1,NL
         VP(J+1)=TL(J)*M(J)*(VP(J)+CR(J)*UO(J))+DO(J+1)
 2       VM(J+1)=M(J+1)*(VP(J+1)*RL(J+1)+UO(J+1))
      UL(NL1)=VM(NL1)
      DL(NL1)=VP(NL1)+UL(NL1)*CR(NL1)+SOL(NL1)
      ABSL(NL1)=DL(NL1)-UL(NL1)
C
      DO 3 J=1,NL
         K=NL1-J
         UL(K)=VM(K)+UL(K+1)*TL(K)*M(K)
         DL(K)=VP(K)+UL(K)*CR(K)+SOL(K)
 3       ABSL(K)=DL(K)-UL(K)-(DL(K+1)-UL(K+1))
C
      RETURN
      END
      SUBROUTINE CLOUDY(RCLOUD,NLAY,NTOP)
C
C***   THIS SUBROUTINE FIRST CREATED BY R. DAVIES 11/14/79
C
C      IT EVALUATES THE ABSORPTION DUE TO WATER VAPOR IN A CLOUDY
C      ATMOSPHERE, CALLING LAYER AND ADDER IN THE PROCESS.
C      THE EXISTENCE OF CLOUD IN AT LEAST ONE LEVEL BELOW THE TOP
C      LEVEL IS ASSUMED.
C
      COMMON/RADCOM/AS(15),RE(16),PL(15),PLE(16),PLK(15),PLKE(16),TT(15)
     *,TLE(16),TG,TH(15),SHL(15),SHLE(16),SHG,CLOUD(15),COSZ,SO,SG,CXL,
     * OCEAN,ICE,SNOW
C
      LOGICAL OCEAN,ICE,SNOW
C
      COMMON/CLDCOM/SWALE(16),SWIL(15),AL(16),TAUL(16),OZALE(16),TOPABS,
     1              COSMAG,SCOSZ,FSCAT,RSURF,AG
C
      COMMON/ADD/SOL(10),UO(10),DO(10),RL(10),TL(10),
     1             UL(10),DL(10),ABSL(10)
      DIMENSION FK(5),XK(5)
      DATA FK/0.107,0.104,0.073,0.044,0.025/
      DATA XK/0.005,0.041,0.416,4.752,72.459/
      DATA NFK/5/,EPS/1./
C
      NLAY1=NLAY+1
      NCLEAR=NTOP-1
C
C      EVALUATE THE CONSERVATIVE PORTION OF THE CLOUD ALBEDO.
C
      TAU=0.0
      DO 1 N=NTOP,NLAY
 1       TAU=TAU+TAUL(N)
      SOL(1)=FSCAT
C
      CALL LAYER(SOL(1),COSZ,TAU,0.9999,SOL(2),UO(1),DO(2),RL(1),TL(1))
```

```
C
      U0(2)=RSURF*SOL(2)
      RL(2)=AG
C
      CALL ADDER(2)
C
      RCLOUD=UL(1)/FSCAT
C
C      EVALUATE ABSORBED INCIDENT FLUX ABOVE CLOUDS.
C
      W=SWALE(1)*COSMAG
      DB=AWATER(W)
      TOPABS=DB*SCOSZ
C
      DO 2 N=1,NCLEAR
         W=SWALE(N+1)*COSMAG
         DA=AWATER(W)
         AL(N)=(DA-DB)*SCOSZ
2        DB=DA
C
C      EVALUATE ABSORPTION WITHIN AND BELOW CLOUDS.
C
      DO 3 N=NTOP,NLAY1
3        AL(N)=0.0
C
C      LOOP OVER WAVELENGTH USING THE K-DISTRIBUTION.
C
      DO 4 K=1,NFK
         WK=W*XK(K)
         WK=AMIN1(WK,75.0)
         SOL(1)=EXP(-WK)*FK(K)*SCOSZ
         IF(SOL(1).LT.EPS )GOTO 4
         DO 5 N=NTOP,NLAY
            M=N-NCLEAR
            TAUAB=XK(K)*SWIL(N)
            TAU=TAUL(N)+TAUAB
            PIO=TAUL(N)/TAU
            IF(PIO.GT.0.1 )GOTO 7
            ARG=AMIN1(TAUAB*COSMAG,75.0)
            SOL(M+1)=SOL(M)*EXP(-ARG)
            U0(M)=0.0
            DO(M+1)=0.0
            RL(M)=0.0
            ARG=AMIN1(1.66*TAUAB,75.0)
            TL(M)=EXP(-ARG)
            GOTO 5
C
7           CALL LAYER(SOL(M),COSZ,TAU,PIO,SOL(M+1),U0(M),DO(M+1),RL(M),
     1                 TL(M))
5           CONTINUE
         M=NLAY1-NCLEAR
         U0(M)=RSURF*SOL(M)
         RL(M)=AC
C
         CALL ADDER(M)
C
         DO 8 N=NTOP,NLAY1
            M=N-NCLEAR
8           AL(N)=AL(N)+ABSL(M)
C
```

```
C        EVALUATE ABSORPTION OF REFLECTED FLUX ABOVE THE CLOUDS.
C
         FKK=UL(1)
         N=NTOP
9        IF(FKK.LT.EPS )GOTO 4
         N=N-1
         ARG=AMIN1(1.66*SWIL(N)*XK(K),75.0)
         DA=(1.0-EXP(-ARG))*FKK
         AL(N)=AL(N)+DA
         IF(N.GT.1 )GOTO 9
         ARG=AMIN1(1.66*SWIL(1)*XK(K),75.0)
         TOPABS=TOPABS+FKK*(1.0-EXP(-ARG))
4        CONTINUE
C
      RETURN
      END
      SUBROUTINE LAYER(SCOSZ,COSZ,TAU,PIO,SO1,UP,DN,RL,TL)
C
C***   THIS CALCULATES THE REFLECTION, ABSORPTION, AND TRANSMISSION
C      OF AN ISOLATED CLOUD LAYER, USING THE DELTA-EDDINGTON OR
C      TWO-STREAM APPROXIMATIONS, DEPENDING ON LAYER THICKNESS.
C
C      SCOSZ IS THE COSINE-WEIGHTED INCIDENT SOLAR FLUX FOR THE LAYER.
C      COSZ IS THE COSINE OF THE SOLAR ZENITH ANGLE.
C      TAU IS THE LAYER'S OPTICAL THICKNESS.
C      PIO IS THE SINGLE-SCATTERING ALBEDO FOR THE LAYER.
C
C      SO1 IS THE DIRECT FLUX TRANSMITTED BY THE LAYER.
C      UP IS THE UPWARD DIFFUSE IRRADIANCE AT THE TOP OF THE LAYER,
C          IN UNITS OF SCOSZ.
C      DN IS THE DOWNWARD DIFFUSE IRRADIANCE AT THE BASE OF THE LAYER,
C          IN UNITS OF SCOSZ.
C      RL IS THE REFLECTANCE OF THE LAYER.
C      TL IS THE DIFFUSE TRANSMITTANCE OF THE LAYER.
C
      REAL KP,KS,IOO,IOZ,LAMDA,LAMDA2
C
      REAL BA(12`,BB(12)
C
      DATA PI/3.141592654/,F/0.7225/
C
      DATA BA/0.5,.32,.2,.14,.11,.09,.07,.06,.05,.045,.04,.04/
C
      DATA BB/.5,.47,.43,.38,.36,.32,.29,.265,.24,.215,.19,.19/
C
      DATA G/0.85/
C
      SECZ=1./COSZ
      ZO=TAU
      A=PIO
C
C      FIRST CALCULATE THE DIFFUSE REFLECTANCE AND TRANSMITTANCE,
C      USING THE SAGAN-POLLACK TWO-STREAM APPROXIMATION.
C      A=1 IMPLIES CONSERVATIVE SCATTERING (NO ABSORPTION).
C
      IF(A.LT.1.0)GOTO 12
      TL=1./(1.+0.13*ZO)
      RL=1.-TL
      GOTO 13
C
```

```
C     SCATTERING PLUS ABSORPTION.
C
12    U2=(1.-A*G)/(1.-A)
      U=SQRT(U2)
      DL=SQRT(3.*(1.-A)*(1.-A*G))
      DS=DL*ZO
      IF(DS.GT.75.)DS=75.
      DO=EXP(-DS)
      DO2=DO*DO
      DEN=(U+1.)*(U+1.)-(U-1.)*(U-1.)*DO2
      RL=(U2-1.)*(1.-DO2)/DEN
      TL=4.*U*DO/DEN
C
C      NOW CALCULATE THE REFLECTION AND TRANSMISSION DUE TO THE
C      DIRECT BEAM.
C
C      IF TAU IS LESS OR EQUAL TO 1, WE USE THE COAKLEY-CHYLEK
C      TWO-STREAM APPROXIMATION, WITHOUT SCALING.  IF TAU IS
C      GREATER THAN 1 AND LESS THAN OR EQUAL TO 8, USE THE
C      COAKLEY-CHYLEK TWO-STREAM APPROXIMATION, WITH SCALING.
C      FOR TAU GREATER THAN 8, USE THE DELTA-EDDINGTON
C      APPROXIMATION.
C
13    IF(TAU.GT.1. )GOTO 1
C
      P=SECZ
      GOTO 2
C
1     ZO=TAU*(1.-PIO*F)
      G=0.45945946
      A=PIO*0.2775/(1.-PIO*F)
2     DS=ZO*SECZ
      IF(DS.GT.75.)DS=75.
      EO=EXP(-DS)
      SO1=SCOSZ*EO
C
      IF(TAU.GT.8. )GOTO 3
C
      BETA=0.5-0.4375*G
      IR=10*COSZ
C
      IF(TAU.GT.1. )GOTO 4
C
      BETA2=BA(IR+1)-(10.*COSZ-IR)*(BA(IR+1)-BA(IR+2))
      BETA1=BETA2
      GOTO 5
C
4     BETA2=BB(IR+1)-(10.*COSZ-IR)*(BB(IR+1)-BB(IR+2))
      BETA1=BETA
C
      P=2.0
C
5     LAMDA2=P*P*(1.-A)*(1.-A+2.*A*BETA1)
      EP=-A*(P*A*BETA1+(1.-BETA2)*(P*(1.-A)+SECZ))
      EM=-A*(P*A*BETA1+BETA2*(P*(1.-A)-SECZ))
      T=SECZ*SECZ-LAMDA2
      GP=EP/T
      GM=EM/T
C
C     CHECK FOR CONSERVATIVE SCATTERING.
```

```
C
      IF((1.-A).LE.0.0)GOTO 6
C
      LAMDA=SQRT(LAMDA2)
      DS=LAMDA*Z0
      IF(DS.GT.75.)DS=75.
      D0=EXP(-DS)
      A1=1.-A+A*BETA1
      B1=LAMDA/P
      DEN=A1+B1-(A1-B1)*D0*D0
      AP=(GP*(A1-B1)*D0-GM*A*BETA1*E0)/DEN
      AM=AP*(A1+B1)/(A*BETA1)
      BP=-GP-AP*D0
      BM=BP*(A1-B1)/(A*BETA1)
      UP=(AM*D0+BM+GM)*SCOSZ*SECZ
      DN=(AP+BP*D0+GP*E0)*SCOSZ*SECZ
      GOTO 10
C
6     SP=-GP
      SM=(-GP*P*BETA1*Z0-GM*E0)/(1.+P*BETA1*Z0)
      RHO=P*BETA1*(SM-SP)
      UP=(GM+SM)*SCOSZ*SECZ
      DN=(GP*E0+RHO*Z0+SP)*SCOSZ*SECZ
      GOTO 10
C
3     T=1.-A
C
C      CHECK FOR CONSERVATIVE SCATTERING.
C
      IF(T.LT.1.E-10 )GOTO 8
C
      DL2=3.*(1.-A*G)*T
      DL=SQRT(DL2)
      DS=DL*Z0
      IF(DS.GT.75.)DS=75.
      D0=EXP(-DS)
      TEMP=SECZ*SECZ-DL2
      FSUN=3.*COSZ*A*G/(4.*PI)
      AL3=-3.*A*(1.+G*T)/(4.*PI*TEMP)
      H=1.5*(1.-A*G)
      U1=H-DL
      V1=H+DL
      W1=-(H+SECZ)*AL3-FSUN
      W2=-E0*((H-SECZ)*AL3-FSUN)
      DET=V1*V1-U1*U1*D0*D0
      AL1=(V1*W2-U1*W1*D0)/DET
      AL2=(V1*W1-U1*W2*D0)/DET
      I00=AL1*D0+AL2+AL3
      I0Z=AL1+AL2*D0+AL3*E0
      UP=2.*PI*I00*SCOSZ*SECZ
      DN=2.*PI*I0Z*SCOSZ*SECZ
      GOTO 10
C
8     AL=COSZ*((3.*COSZ-2.)*E0-3.*COSZ-2.)/(4.*PI)
      AL=AL/(Z0+4./(3.*(1.-G)))
      BETA=COSZ*(3.*COSZ+2.)/(4.*PI)+AL/(1.5*(1.-G))
      UP=-1.5*COSZ*COSZ+2.*PI*BETA
      DN=-1.5*COSZ*COSZ*E0+AL*Z0*2.*PI+2.*PI*BETA
C
C      SAFETY NET.  DON'T ALLOW NEGATIVE RADIATION.
```

```
C
10    IF(UP.LT.0.) UP=0.0
      IF(DN.LT.0.) DN=0.0
      IF(RL.LT.0.) RL=0.0
      IF(TL.LT.0.) TL=0.0
C
      RETURN
      END
      SUBROUTINE OZONE2(NLAYO1,XDAY,XLAT)
C
C***   LACIS-HANSEN OZONE ROUTINE.  USES CLIMATOLOGICAL OZONE
C      DISTRIBUTION, INTERPOLATED BY LATITUDE, SEASON, AND ALTITUDE.
C
      LOGICAL ICE,OCEAN,SNOW
C
      COMMON/RADCOM/AS(15),RE(16),PL(15),PLE(16),PLK(15),PLKE(16),TL(15)
     *,TLE(16),TG,TH(15),SHL(15),SHLE(16),SHG,CLOUD(15),COSZ,SO,SG,CXL,
     * OCEAN,ICE,SNOW
C
      COMMON/CLDCOM/SWALE(16),SWIL(15),AL(16),TAUL(16),OZALE(16),TOPABS,
     1              COSMAG,SCOSZ,FSCAT,RSURF,AG
C
      REAL OLJAN(19),OLAPR(19),OLJUL(19),OLOCT(19)
C
      REAL OCM22(23),OCM30(23),OCM38(23),OCM46(23),PROCM(23)
C
      REAL TOTOZ(4),CDATE(6),OCMXX(23)
C
C      TOTAL OZONE AMOUNTS AS A FUNCTION OF LATITUDE AND SEASON.
C      VALUES ARE GIVEN EVERY 5 DEGREES OF LATITUDE FROM THE EQUATOR
C      TO 90 DEGREES.  SYMMETRY ACROSS THE EQUATOR IS ASSUMED.
C      OLJAN IS FOR NORTHERN HEMISPHERE JANUARY AND SOUTHERN HEMISPHERE
C      JULY, ETC.  UNITS ARE CM AT STP.
C
      DATA OLJAN/.2292,.2308,.2354,.2417,.2521,.2646,.2783,.2942,.3042,
     *    .3121,.3204,.3292,.3404,.3496,.3542,.3575,.3579,.3567,.3558/
C
      DATA OLAPR/.2375,.2408,.2475,.2583,.2725,.2879,.3062,.3250,.3429,
     *    .3608,.3762,.3925,.4075,.4200,.4287,.4333,.4342,.4329,.4312/
C
      DATA OLJUL/.2387,.2454,.2508,.2583,.2658,.2746,.2837,.2950,.3067,
     *    .3187,.3275,.3329,.3354,.3358,.3337,.3321,.3283,.3229,.3175/
C
      DATA OLOCT/.2346,.2358,.2383,.2425,.2479,.2525,.2567,.2608,.2646,
     *    .2679,.2717,.2754,.2792,.2829,.2867,.2883,.2896,.2896,.2883/
C
C      FOUR DISTRIBUTIONS OF TOTAL OZONE, FROM A MAX OF 0.22 TO A MAX OF
C      0.46, IN CENTIMETERS AT STP.
C
      DATA OCM22/.00008,.00657,.01830,.03353,.05614,.08685,.10930,
     *   .14029,.16624,.17797,.18492,.18867,.19120,.19384,.19645,
     *   .19844,.20262,.20601,.20907,.21198,.21473,.21728,.21992/
C
      DATA OCM30/.00008,.00657,.01837,.03496,.06280,.10410,.13398,
     *   .17521,.21079,.22947,.24222,.24927,.25410,.25911,.26396,
     *   .26763,.27503,.28061,.28528,.28937,.29307,.29646,.29996/
C
      DATA OCM38/.00008,.00657,.01869,.03923,.07442,.12224,.15686,
     *   .20473,.24695,.27145,.29138,.30410,.31297,.32208,.33065,
     *   .33675,.34802,.35563,.36162,.36673,.37134,.37559,.37998/
```

```
      DATA OCM46/.00008,.00657,.01889,.04170,.07986,.12844,.16345,
     *   .21238,.25742,.28619,.31284,.33246,.34793,.36555,.38344,
     *   .39675,.41902,.43025,.43784,.44401,.44958,.45471,.46000/
C
C     REFERENCE PRESSURE LEVELS.
C
      DATA PROCM/1.,3.,5.,7.,10.,15.,20.,30.,45.,60.,80.,100.,120.,150.,
     *190.,230.,340.,450.,560.,670.,780.,890.,1013.25/
C
      DATA CDATE/-77.0,15.0,105.0,196.0,288.0,380.0/
C
      DATA TOTOZ/0.22,0.30,0.38,0.46/
C
      DATA NOZ/23/
C
C     NOTE *** CALENDAR DAY=GARP REFERENCE DAY-63 ***
C     S. HEM. OZONE DISTRIBUTION IS SEASONAL REFLECTION OF N. HEM.DISTR
C
      CDAY=XDAY-63.0
      IF(XLAT.LT.0.00) CDAY=CDAY+183.0
      IF(CDAY.GT.365.) CDAY=CDAY-365.0
      DLAT= ABS(XLAT)
      DO 100 J=1,6
      CDATEJ=CDATE(J)
      IF(CDAY.LT.CDATEJ )GOTO 110
  100 CDATEI=CDATEJ
  110 DXDATE=(CDAY-CDATEI)/(CDATEJ-CDATEI)
      DLATI=0.0
      DO 120 K=2,19
      J=K
      DLATJ=DLATI+5.0
      IF(DLAT.LT.DLATJ )GOTO 130
  120 DLATI=DLATJ
  130 DXDLAT=(DLAT-DLATI)/5.0
      I=J-1
C
C     TOTAL VERTICAL OZONE CONTENT (CM*NTP) FOR GIVEN LATITUDE AND DATE
C
      IF(CDAY.GT.15.00 )GOTO 150
  140 OD1=OLOCT(I)+DXDLAT*(OLOCT(J)-OLOCT(I))
      OD2=OLJAN(I)+DXDLAT*(OLJAN(J)-OLJAN(I))
      GOTO 200
C
  150 IF(CDAY.GT.105.0 )GOTO 170
      OD1=OLJAN(I)+DXDLAT*(OLJAN(J)-OLJAN(I))
      OD2=OLAPR(I)+DXDLAT*(OLAPR(J)-OLAPR(I))
      GOTO 200
C
  170 IF(CDAY.GT.196.0 )GOTO 190
      OD1=OLAPR(I)+DXDLAT*(OLAPR(J)-OLAPR(I))
      OD2=OLJUL(I)+DXDLAT*(OLJUL(J)-OLJUL(I))
      GOTO 200
C
  190 IF(CDAY.GT.288.0 )GOTO 140
      OD1=OLJUL(I)+DXDLAT*(OLJUL(J)-OLJUL(I))
      OD2=OLOCT(I)+DXDLAT*(OLOCT(J)-OLOCT(I))
C
  200 TOTOCM=OD1+DXDATE*(OD2-OD1)
C
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C     VERTICAL OZONE DISTRIBUTION FOR GIVEN TOTAL OZONE CONTENT
C
      TOTOZI=TOTOZ(1)
      DO 210 K=2,4
      J=K
      TOTOZJ=TOTOZ(J)
      IF(TOTOCM.LT.TOTOZJ )GOTO 220
210   TOTOZI=TOTOZJ
220   I=J-1
      DXOCM=(TOTOCM-TOTOZI)/0.08
      IF(J.GT.2 )GOTO 240
      DO 230 I=1,NOZ
230   OCMXX(I)=OCM22(I)+DXOCM*(OCM30(I)-OCM22(I))
      GOTO 280
240   IF(J.GT.3 )GOTO 260
      DO 250 I=1,NOZ
250   OCMXX(I)=OCM30(I)+DXOCM*(OCM38(I)-OCM30(I))
      GOTO 280
260   DO 270 I=1,NOZ
270   OCMXX(I)=OCM38(I)+DXOCM*(OCM46(I)-OCM38(I))
C
C     OZONE CONTENT (CM*NTP) ABOVE EACH LAYER EDGE
C
280   NP=2
      PROCMI=PROCM(1)
      DO 310 N=1,NLAYO1
      PLEN=PLE(N)
      DO 290 K=NP,NOZ
      J=K
      PROCMJ=PROCM(J)
      IF(PLEN.LT.PROCMJ )GOTO 300
290   PROCMI=PROCMJ
      PROCMI=PROCM(J-1)
300   DXPRO=(PLEN-PROCMI)/(PROCMJ-PROCMI)
      I=J-1
      PROCMI=PROCM(I)
      NP=I
310   OZALE(N)=OCMXX(I)+DXPRO*(OCMXX(J)-OCMXX(I))
      RETURN
      END
      SUBROUTINE SOLAR1 (NLAY,XDAY,XLAT,XSURF)
C
C***  ROGER DAVIES SOLAR RADIATION PARAMETERIZATION.  TAKES INTO
C     ACCOUNT THE VARIATION OF SURFACE ALBEDO WITH ZENITH ANGLE.
C     INCLUDES ABSORPTION BY OZONE AND WATER VAPOR, AS WELL AS RAYLEIGH
C     SCATTERING.  CLOUD SCATTERING IS HANDLED IN SUBROUTINE CLOUDY.
C
C     OUTPUT VARIABLES ARE AS(NLAY), THE SOLAR FLUX ABSORBED BY LAYER
C     NLAY, IN LANGLEYS PER DAY; SG, THE SOLAR RADIATION ABSORBED BY TH
C     GROUND, ALSO IN LANGLEYS PER DAY; AND TOPABS, THE SOLAR ABSORPTIO
C     ABOVE THE MODEL TOP, ALSO IN LANGLEYS PER DAY.
C
      LOGICAL ICE,OCEAN,SNOW
C
      COMMON/RADCOM/AS(15),RE(16),PL(15),PLE(16),PLK(15),PLKE(16),TL(15)
     *,TLE(16),TG,TH(15),SHL(15),SHLE(16),SHG,CLOUD(15),COSZ,SO,SG,CXL,
     * OCEAN,ICE,SNOW
C
      COMMON/CLDCOM/SWALE(16),SWIL(15),AL(16),TAUL(16),OZALE(16),TOPABS,
     1            COSMAG,SCOSZ,FSCAT,RSURF,AG
```

```
C
      REAL TCOND( 9),TPENE( 9)
C
      DATA TCOND/0.0,1.0,2.0,4.0,6.0,6.0,8.0,8.0,8.0/
C
      DATA TPENE/0.0,0.0,8.0,8.0,8.0,8.0,8.0,8.0,8.0/
C
      DATA TLOWL/16./
C
      DATA THIDL/8.0/

      DATA NLAYOZ/5/
C
      DATA SHLTOP,TLTOP,GTOPO,DELTA/0.00002,220.0,120.1612,0.00001/
C
      DATA PI/3.141592653/
C
C      GTOPO IS USED FOR SCALING WATER VAPOR ABSORPTION WITH RESPECT
C      TO A STANDARD TEMPERATURE (273.16 K) AND PRESSURE (1013.25 MB).
C
C      THE FORMULA FOR GTOPO IS:
C
C      GTOPO=2.0*0.980*1013.25/SQRT(273.16)
C
C      NIGHT-SIDE
C
C      SOLAR RADIATION ABSORBED THE THE GROUND.
C
      SG=0.0
C
C      SOLAR RADIATION ABSORBED BY LAYER N.
C
      DO 100 N=1,NLAY
100   AS(N)=0.0
C
      IF(COSZ.LT.0.01)RETURN
C
      NLAY1=NLAY-1
      RMEAN=0.0
      COSMAG=35.0/SQRT(1224.0*COSZ*COSZ+1.0)
C
C      SURFACE REFLECTIVITY.
C
C      AG IS THE SURFACE ALBEDO FOR DIFFUSE RADIATION.
C
      AG=XSURF
C
C      RSURF IS THE SURFACE ALBEDO TO DIRECT RADIATION.
C      IT INCLUDES THE SOLAR ZENITH ANGLE DEPENDENCE OF PALTRIDGE AND
C      PLATT.
C
      ARG=-18.0*(PI*0.5-ACOS(COSZ))/PI
      ARG=AMAX1(ARG,-75.0)
      RSURF=AG+(1.0-AG)*EXP(ARG)
C
C      PARTITION OF INCIDENT FLUX SUBJECT TO SCATTERING
C
      SCOSZ=S0*COSZ
      FSCAT=0.647*SCOSZ
C
```

```
C      SCALED WATER VAPOR CONTENT ABOVE EACH LAYER EDGE
C
      DB=PLE(1)**2
      SWALE(1)=DB*SHLTOP/SQRT(TLTOP)/GTOPO
      DO 120 N=1,NLAY
      M=N+1
      DA=PLE(M)**2
      SHTEM=AMAX1(SHL(N),1.0E-8)
      W=(DA-DB)*SHTEM/SQRT(TL(N))/GTOPO
      SWIL(N)=W
      SWALE(M)=SWALE(N)+W
120   DB=DA
C
C      COMPUTE CLOUD PARAMETERS:
C
C      TOP CLOUD, TOTAL AND FRACTIONAL CLOUDINESS PARAMETERS
C      WITH N=2, CLOUDS ARE EXCLUDED FROM TOP LAYER
C      FRACTIONAL CLOUDINESS IS INCLUDED, BUT NOT CURRENTLY USED.
C
      FCLOUD=0.0
      FCLEAR=1.0
      NTOPT=NLAY1
      NTOPF=NLAY1
C
      DO 140 N=2,NLAY
      XX=CLOUD(N)
C
      IF(XX.LT.0.01 )GOTO 140
      IF(XX.GT.0.99 )GOTO 130
C
      FC=AMAX1(XX,FCLOUD)
      FCLOUD=FC
      FCLEAR=1.0-FCLOUD
      IF(NTOPF.LT.NLAY )GOTO 140
      NTOPF=N
      GOTO 140
130   IF(NTOPT.LT.NLAY )GOTO 140
      NTOPT=N
      FCLEAR=0.0
140   CONTINUE
C
      IF(FCLEAR.GT.0.99 )GOTO 200
      IF(FCLOUD.LT.0.01) FCLOUD=1.00
C
C      LARGE SCALE CONDENSATION (STRATIFORM) CLOUD PARAMETERS
C
      DO 150 N=1,NLAY
      TAUL(N)=0.0
150   IF(CLOUD(N).GT.0.99) TAUL(N)=TCOND(N)
C
C      LOW LEVEL CONVECTION CLOUD PARAMETERS:
C
C              IF(NAB.EQ.1) CLOUD IS IN LAYER 7
C              IF(NAB.EQ.2) CLOUD IS IN LAYER 8
C
      NAB=CLOUD(NLAY+1)+DELTA
      IF(NAB.LT.1 )GOTO 160
      N=NAB+6
      TAUL(N)=TLOWL
C
```

```
C      MID LEVEL CONVECTION CLOUD PARAMETERS
C              IF(NBC.EQ.1) CLOUD IS IN LAYER 5
C              IF(NBC.EQ.2) CLOUD IS IN LAYER 6
C
160   NBC=CLOUD(NLAY+2)+DELTA
      IF(NBC.LT.1 )GOTO 170
      N=NBC+4
      TAUL(N)=THIDL
C
C      PENETRATING CONVECTION CLOUD PARAMETERS
C
170   NAC=CLOUD(NLAY+3)+DELTA
      IF(NAC.LT.1 )GOTO 190
      N=NAC+3
      DO 180 I=1,4
C
C      OPTICAL THICKNESS CALCULATION.
C
      TAUL(N)=TPENE(N)
180   N=N+1
190   IF(FCLEAR.LT.0.01 )GOTO 250
C
C      RAYLEIGH SCATTERING AND CLEAR ATMOSPHERE REFLECTIVITY
C
200   RBRAY=.433/(1.0+6.43*COSZ)
      RBBRAY=0.093
      RCLEAR=RBRAY+(1.0-RBRAY)*(1.0-RBBRAY)*RSURF/(1.0-RBBRAY*AG)
C
C      ABSORPTION BY WATER VAPOR IN CLEAR ATMOSPHERE
C
      W=SWALE(1)*COSMAG
      DB=AWATER(W)
      TOPABS=DB*FCLEAR*SCOSZ
      DO 210 N=1,NLAY
      W=SWALE(N+1)*COSMAG
      DA=AWATER(W)
      AL(N)=DA-DB
210   DB=DA
      TRANS=1.0-DB
      RF=TRANS*RSURF
      AL(NLAY1)=(TRANS-0.647)*(1.0-RSURF)
      IF(RF.LT.0.001 )GOTO 230
      WW=W*(1.0+1.66/COSMAG)
C
      DO 220 N=1,NLAY
      M=NLAY1-N
        WW-1.66*SWALE(M)
      DA=AWATER(W)
      AL(M)=AL(M)+(DA-DB)*RF
220   DB=DA
C
230   ACLEAR=FCLEAR*SCOSZ
C
      DO 240 N=1,NLAY
240   AS(N)=ACLEAR*AL(N)
C
C      SOLAR FLUX ABSORBED BY THE GROUND.
C
      SG=FCLEAR*(FSCAT*(1.0-RCLEAR)+SCOSZ*AL(NLAY1))
C
```

```
      RMEAN=FCLEAR*RCLEAR
      IF(FCLEAR.GT.0.99 )GOTO 290
C
C      ABSORPTION BY WATER VAPOR IN CLOUDY ATMOSPHERE
C
250   NTOP=MINO(NTOPT,NTOPF)
      CALL CLOUDY(RCLOUD,NLAY,NTOP)
      DO 260 N=1,NLAY
260      AS(N)=AS(N)+AL(N)
C
C      SOLAR FLUX ABSORBED BY THE GROUND.
C
      SG=SG+FCLOUD*FSCAT*(1.0-RCLOUD)+AL(NLAY1)
C
      RMEAN=RMEAN+FCLOUD*RCLOUD
      IF(FCLOUD.GT.0.99 )GOTO 300
      NTOP=NTOPT
      FCLOUD=1.0-FCLOUD
      DO 270 N=1,NLAY
270   IF(CLOUD(N).LT.0.99) TAUL(N)=0.0
      CALL CLOUDY(RCLOUD,NLAY,NTOP)
C
C      SOLAR RADIATION ABSORBED BY LAYER N.
C
      DO 280 N=1,NLAY
280   AS(N)=AS(N)+AL(N)
C
C      SOLAR FLUX ABSORBED BY THE GROUND.
C
      SG=SG+FCLOUD*FSCAT*(1.0-RCLOUD)+AL(NLAY1)
C
      RMEAN=RMEAN+FCLOUD*RCLOUD
      GOTO 300
C
C      EFFECTIVE CLEAR SKY RAYLEIGH ALBEDO FOR OZONE ABSORPTION
C
290   RBBROZ=0.144
      RBROZ=0.2186/(1.0+0.816*COSZ)
      RMEAN =RBROZ+(1.0-RBROZ)*(1.0-RBBROZ)*RSURF/(1.0-RBBROZ*AG)
C
C      ROUTINE PROVIDES OZONE CM ABOVE EACH LAYER EDGE
C
300   NLAYO1=NLAYOZ+1
C
      CALL OZONE2(NLAYO1,XDAY,XLAT)
C
C      COMBINED UV+VIS OZONE ABSORPTION OF INCOMING SOLAR RADIATION
C
      W=OZALE(1)*COSMAG
      DB=AOZONE(W)
      TOPABS=TOPABS+DB*SCOSZ
      DO 310 N=1,NLAYOZ
      W=OZALE(N+1)*COSMAG
      DA=AOZONE(W)
C
C      DIRECT SOLAR RADIATION ABSORBED BY OZONE IN LAYER N.
C
      AS(N)=AS(N)+(DA-DB)*SCOSZ
310   DB=DA
C
```

```
      WW=W+1.90*W/COSMAG
C
C      COMBINED UV+VIS OZONE ABSORPTION OF REFLECTED SOLAR RADIATION
C
      RF=SCOSZ*RMEAN
C
      DO 320 N=1,NLAYOZ
      M=NLAYO1-N
      W=WW-1.90*OZALE(M)
      DA=AOZONE(W)
C
C      REFLECTED SOLAR RADIATION ABSORBED BY OZONE IN LAYER N.
C
      AS(M)=AS(M)+(DA-DB)*RF
  320 DB=DA
      DA=AOZONE(WW)
      TOPABS=TOPABS+RF*(DA-DB)
C
      RETURN
      END
      SUBROUTINE SUNDAY (JDAY,SOMULT,SO,DEC,SIND,COSD,EQT)
C
C***   THIS SUBROUTINE IS USED TO INITIALIZE THE ASTRONOMICAL VARIABLES
C      THAT DEPEND ONLY ON THE TIME OF YEAR.
C
C      JDAY  IS THE JULIAN DAY, =1 FOR JAN 1ST.
C      SOMULT MULTIPLIES THE SOLAR CONST., TYPICALLY = UNITY.
C
C      SO IS THE SOLAR INSOLATION AT THE TOP OF THE ATMOSPHERE,
C         IN LANGLEYS PER DAY.
C      DEC IS THE DECLINATION ANGLE OF THE SUN, IN RADIANS.
C      SIND AND COSD ARE THE SINE AND COSINE OF DEC.
C      EQT IS THE 'EQUATION OF TIME', I.E. THE OFFSET TO LOCAL TIME, IN
C         HOURS.
C
      DATA PI/3.141592654/
C
      DTR=PI/180.
C
C      RELATIVE POSITION OF EARTH IN ORBIT.
C
      PHASE=2.*PI*(JDAY-1)/365.
      PHASE2=PHASE*2.
      PHASE3=PHASE*3.
      CP=COS(PHASE)
      CP2=COS(PHASE2)
      SP=SIN(PHASE)
      SP2=SIN(PHASE2)
C
C      EFFECT OF EARTH-SUN DISTANCE. (PALTRIDGE AND PLATT P.57)
C
      ESFCTR=1.00011+0.034221*CP+0.00128*SP+0.000719*CP2+0.000077*SP2
C
C      INCIDENT SOLAR RADIATION IN LY/DAY (WILLSON, 1982)
C
      SO=2823.9*SOMULT*ESFCTR
C
C      SOLAR DECLINATION ANGLE. (PALTRIDGE AND PLATT P.63)
C
      DEC=0.006918-0.399912*CP+0.070257*SP-0.006758*CP2+0.000907*SP2
```

```
     1       -0.002697*COS(PHASE3)+0.00148*SIN(PHASE3)
      SIND=SIN(DEC)
      COSD=COS(DEC)
C
C      THE EQUATION OF TIME (HOURS)
C
      EQT=(0.000075+0.001868*CP-0.032077*SP-0.014615*CP2-0.040849*SP2)
     1       /(DTR*15.)
C
      RETURN
      END
```