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ABSTRACT

This document describes the parameterization of longwave radiation in the UCLA/GLAS general circulation model. Transmittances have been computed from the work of Arking and Chou for water vapor and carbon dioxide and ozone absorptances are computed using a formula due to Rodgers. Cloudiness has been introduced into the code in a manner in which fractional cover and random or maximal overlap can be accomodated. The entire code has been written in a form that is amenable to vectorization on CYBER and CRAY computers. Sample clear sky computations for five standard profiles using the 15- and 9-level versions of the model have been included.

1. INTRODUCTION

The parameterization of longwave radiation for general circulation models is currently under extensive study. Several experiments have shown that model integrations over long periods are very sensitive to the particular methods used in calculating the radiative terms. However, because of the spectral nature of radiation, an accurate description of the radiation field requires a summation over several spectral bands. Moreover, since the interaction paths are very long, transmittances between each atmospheric level and all other levels must be computed and carried through the spectral integration. Because of this, the computation of longwave radiation is the most time consuming step in the integration of a general circulation model. One common practice is to use a fairly detailed and accurate representation of the radiation, but to update the model infrequently, say every five hours, even if the physics is updated every half hour or hourly. The problem with this approach is that the life-cycle of clouds is often less than the time-interval of the update, and so there can be no interaction between radiation and cloudiness on shorter time scales. The need, therefore, is for a fast yet accurate treatment of longwave radiation.

2. RADIATIVE TRANSFER

For a clear atmosphere, the upward and downward fluxes at pressure level p, integrated over the spectral range $\Delta\nu$, can be written as

$$F_{clr}{\uparrow}(p) = \int_{\Delta\nu} d\nu \, [B_\nu(T_s)\, \tau_\nu(p,p_s) + \int_{p_s}^{p} B_\nu(T(p'))\, \frac{d\tau_\nu(p,p')}{dp'}\, dp'] \qquad (1a)$$

and

$$F_{clr}{\downarrow}(p) = \int_{\Delta\nu} d\nu \, [\int_{p_t}^{p} B_\nu(T(p'))\, \frac{d\tau_\nu(p')}{dp'}\, dp'] \qquad (1b)$$

where $B_\nu(T)$ is the blackbody flux at temperature T and wavenumber ν, $\tau_\nu(p,p')$ is the diffuse transmittance between the levels p and p', and the subscripts s and t denote the surface and the top of the atmosphere, respectively. In order to use Equations (1a, b) as written, the spectral interval must be very narrow, since τ_ν varies very rapidly with wavenumber. In practice, models avoid this problem by resorting to certain assumptions regarding the distribution of spectral lines in the various absorption bands and constructing approximate band models.

We have adopted the method described by Chou and Arking (1980) and Chou (1984) for the water vapor bands, Chou and Peng (1983) for carbon dioxide and Rodgers (1968) for ozone. Table 1 lists the spectral regions covered for each of the bands in the model. Apart from line absorption in the various bands, there is also water vapor continuum absorption over a wide spectral region that overlaps with water vapor line absorption as well as the carbon dioxide and ozone absorption bands. This continuum absorptance, computed from a formula given by Roberts *et al.*, (1976) is multiplied by the line transmittances where appropriate. Details are given in Chou and Kouvaris (1981).

An alternate form of the flux equations is obtained through integration by parts of (1a,b) reducing them to

$$F_{clr}\uparrow (p) = B(T(p)) + G(p,p_s,T_s) - G(p,p_s,T(p_s)) + \int_{T(p)}^{T(p_s)} \partial G(p,p',T(p'))/\partial T \; dT(p') \; , \tag{2a}$$

$$F_{clr}\downarrow (p) = B(T(p)) - G(p,p_t,T(p_t)) + \int_{T(p)}^{T(p_t)} \partial G(p,p',T(p'))/\partial T \; dT(p') \; , \tag{2b}$$

where

$$G(p,p',T) = \int_{\Delta\nu} \tau_\nu (p,p') \, B_\nu(T) d\nu \quad , \tag{2c}$$

$$\partial G(p,p',T)/\partial T = \int_{\Delta\nu} \tau_\nu(p,p') \, \partial B_\nu (T)/\partial T \; d\nu \quad . \tag{2d}$$

In the 9.6 µm and 15 µm bands, the spectral width of the band is sufficiently narrow such that a mean value of the Planck function may be used. That is,

$$G(p,p',T) = \int_{\Delta\nu} \tau_\nu (p,p') d\nu/\Delta\nu \cdot \int_{\Delta\nu} B_\nu(T) d\nu \tag{3}$$

For carbon dioxide, the spectral integration is performed separately over the band center from 620-720 cm^{-1} and the band wings from 540-620 cm^{-1} and 720-800 cm^{-1}. The transmittance in the ozone band is obtained by scaling the band absorptance given by Rodgers (1968), assuming that all absorption by ozone is confined to the 980-1100 cm^{-1} region. For water vapor, the variation of B_ν and τ_ν in (2c) is accounted for over the various spectral ranges. Details of the technique used to compute transmittances may be found in the references quoted above.

For cloudy skies, if an assumption is made that the clouds are black at thermal wavelengths, the above equations can be written very easily for a completely overcast sky by replacing the limits on the exchange integral, since transmission through a black cloud is zero. However, we have retained the possibility of allowing fractional cloud cover in the various model layers or partial transmittance through high tenuous clouds. Therefore, a slightly different computational approach has been used utilizing the probability of a clear line of sight between each layer and all other layers, the ground and the top of the atmosphere. This will be explained in the description of the code.

The final result required by the dynamic model is the radiative cooling rate, or the divergence of the net flux. In terms of the quantities computed by Eqs. (2a, b) the cooling rate is

$$-\frac{dT}{dt} = \frac{g}{C_p}\frac{d}{dp}(F\downarrow - F\uparrow) \qquad (4)$$

Of course, all other fluxes are available and the net flux at the surface is needed to perform the surface energy balance. For diagnostic purposes, the upward flux at the top of the atmosphere is also retained as output of the radiation model.

3. RADIATION CODE

In principle, if the atmospheric parameters such as temperature and mixing ratio of water vapor, carbon dioxide and ozone are given, the various transmittances required for the flux computation can be obtained using the theory covered in the various references cited earlier. In general, the transmittance depends on the atmospheric temperature, presure and amount of absorbing gas. The atmosphere, however, is inhomogeneous in that the absorber amount, pressure and temperature are functions of altitude, and the absorbing path has to be suitably scaled in order to compute the transmittance. Again, the references cited explain the theory and techniques utilized. Practical difficulties arise when the exchange integrals in (2) are to be set in a numerical procedure to compute fluxes. The dynamic atmospheric model provides only the surface temperature and layer mean temperatures and mixing ratios for the model layers. However, the flux integrals are over a continuous atmospheric path, and the modeler is faced with the familiar problem of discretization. Since transmittance is a non-linear function of atmospheric path, widely varying results can be obtained depending on the assumptions made regarding the structure of temperature and mixing ratio between model levels. This problem of interpolation has been dealt with in various ways. Usually, the dynamic model layers are further subdivided and assumptions made about the profiles within the layer. Even after this, different quadrature schemes can yield different results, especially over paths where the transmittance varies rapidly.

In the radiation code that we have designed, we have side-stepped the interpolation problem by computing absorber amounts assuming that the mixing ratio of absorbing gas in each atmospheric layer is constant. The flux computations require that the temperature be known at the layer interface (each level of the model). For this, we interpolate the temperature linearly in the logarithm of pressure for all levels except the top and bottom of the planetary boundary layer which is the lowest layer of the model. The temperature at the top and bottom of this layer is computed by following the appropriate adiabat. The dynamic model furnishes information up to the highest layer in the model, but there is some residual opacity in the upper atmosphere that, if ignored, could influence fluxes and cooling rates in the upper layers of the model. Usually, some radiation layers are inserted above the model layers and climatological information regarding temperature and mixing ratios supplied to the radiation code. In the 15-level UCLA model, the uppermost layer is centered at 1.4 mb with its bottom at 1.9 mb, and its upper boundary at 1 mb. We insert one radiation layer between 0 and 1 mb, and specify the temperature and mixing ratios in this layer, for example that they are the same as those in the top layer of the model.

The description of the radiation code is given below in separate sections for each subroutine and a listing is attached in the appendix. The code as presented is designed for clarity rather than optimization. It is also written so that it can be vectorized quite easily for use on CYBER and CRAY machines. Only key statements are explained with references to the papers from which the equations were obtained.

SUBROUTINE RADIR

This is the driving program of the longwave radiation code. The input to this code is the atmospheric profile of temperature and gaseous constituents. The input parameters passed to the subroutines are copied into internal variables. NDATA is the number of layers in the model which is 15 for the 15-level UCLA GCM. The other variables are as follows.

PU = pressure at each level of the model

PA = pressure at the middle of each layer

TA = mean temperature of the layer defined at pressure PA

TS = surface temperature

WA = water vapor mixing ratio of the layer defined at pressure PA

OA = ozone mixing ratio of the layer defined at pressure PA

CSS = random overlap cloud fraction

CCU = maximum overlap cloud fraction

The pressure at the top and bottom of the extra layer inserted on top of the dynamic model is designated PU(1) and PU(2) and defined. The cloud fraction in this layer is 0.0 and all other cloud fractions are constrained to lie between 0.0 and 1.0. After calls to the other subroutines, the fluxes at each level are returned to RADIR for the computation of cooling rates using (4). The term FAC is a conversion factor and since fluxes are in c.g.s. units, a conversion is also applied to obtain the upward flux at the top of the atmosphere (ULWTOP), the downward flux at the surface (DLWBOT) and the net upward flux at the surface (RS) in Wm^{-2}. The cooling rates in the 15 model layers are returned to the main program and are in °C day^{-1}.

SUBROUTINE INDATA

When the program is run for the very first time, data is read in through this subroutine call. The data concerns the G-function and temperature corrections in the water vapor bands and is stored in tables. There is a subroutine call to a table look up program that computes the relevant numbers. This will discussed later.

SUBROUTINE SETUP

This routine does some housekeeping on the input variables and also performs the temperature interpolation and computes scaled absorber amounts. At the end of the interpolation, the variables are on a vertical grid as shown in Figure 1. The amount of water vapor and ozone in each layer is computed from

$$U(p_1,p_2) = \frac{1}{g} \int_{p_1}^{p_2} q \, dp \approx \frac{q}{g} \; \Delta p_{1,2} \qquad (5)$$

where q is the mixing ratio.

A factor of 1.02 is used to convert the pressure to c.g.s. units and divide in the acceleration constant. Some points to note are that there is a lower limit on the allowed mixing ratio. This is to prevent numerical problems at later stages.

Although (5) gives the amount of water vapor in a column of air from p_1 to p_2 as mentioned earlier, it is necessary to scale this amount to compute the transmission. In the routine we have defined three scaled water vapor absorption paths, one each for the band centers and band wings and one for e-type absorption. The path for band absorption is of the form

$$w_1 \, (p_1,p_2) = \int_{p'}^{p} (p''/p_r)^m \, R \, [T(p''),T_r] \; q(p'') \; dp''/g \qquad (6)$$

and for e-type absorption is

$$w_3 \, (p_1,p_2) = \int_{p'}^{p} e(p''). \; \exp[1800 \; (1/T(p'') - 1/T_0)] \; q(p'') \; dp''/g. \qquad (7)$$

The temperature dependent function R in (6) is written as SZ1 for the band center and SZ2 for the band wings and is given by

$$R(T,T_r) = \exp \; [r(T - T_r)] \quad , \qquad (8)$$

where $r = 0.005$, $T_r = 225°K$ for the band centers and $r = 0.016$ and $T_r = 256°K$ for the wings. The reference pressure, p_r, is 275 mb for the center and 550 mb for the wings and $m = 1$ for both. In (7), $e(p'')$ is the water vapor partial pressure in atmospheres and $T_0 = 296°K$. The equation is coded as XX = ... with UBAR denoting the scaled path length, w_3, from each pressure level to the top of the atmosphere. The factor 630 in the code converts mixing ratio to vapor pressure in atmospheres and is (0.622*1013) and explained in Chou and Kouvaris (1981).

VBAR and WBAR are respectively, the scaled path lengths in the band center and wings. UBARM, VBARM and WBARM are the means of path lengths from two adjacent layers to the top, a quantity that is required later in the computation of transmission.

The scaled amount of carbon dioxide denoted by PSCALV for the band center and PSCALW for the wings is obtained from (6) with c(p") replacing q(p") where the concentration of CO_2 is in ppm. A conversion factor of 0.26 for 330 ppm is used here. Any other concentration can be used by changing the number accordingly since scaling in c is linear. The reference pressure, p_r, is 30 mb in the center and 300 mb in the wings while m = 0.85 in the center and 0.5 in the wings. For pressures $p<p_c$, the pressure scaling is (p_c/p_r) where $p_c = 1$ mb. The temperature scaling $R(T,T_r)$ is written as in (8) with r = 0.0089 in the center and 0.025 in the wings; $T_r = 240°K$ for both regions. As in water vapor, the mean scaled path lengths PSCAMV and PSCAMW are also computed.

The ozone amount is given by (5) without any temperature scaling replacing q by the ozone mixing ratio. Additionally a quantity called the effective broadening pressure for a path is required and this is given by

$$\tilde{p} = \int_{p_1}^{p_2} q\ p\ dp / \int_{p_1}^{p_2} q\ dp \qquad (9)$$

The ozone amount is coded as V while the numerator of (9) is coded as U in the subroutine. Additionally mean quantities UM and VM are also computed.

SUBROUTINE IRFLUX

This subroutine computes the fluxes in each of the bands in turn and adds them up. The various terms in (2a,b) are computed by calls to other subroutines that calculate the appropriate transmission functions.

The G-functions for water vapor defined by (2c,d) are computed here. As explained in Chou (1984),

$$G(w_1,w_3;T) = \tau\,(w_1,w_3;T)\;B\,(T) \tag{10}$$

where w_1, w_3 are defined by (6) and (7) and B(T) is the Planck function at T integrated over the wavelength interval in question. The transmission, $\tau(w_1,w_3;T)$ is itself parameterized as

$$\tau\,(w_1,w_3;T) = \tau\,(w_1,w_3;\,250)[1 + \alpha\,(w_1,w_3)(T - 250) + \beta\,(w_1,w_3)(T - 250)^2] \tag{11}$$

The quantities, $\tau\,(w_1,w_3;\,250)$, α and β are obtained from a table lookup through a call to subroutine TABLE or a parameterization in subroutine GFUNC. For the band center, only w_1 is needed whereas for the band wings both w_1 and w_3 are needed. Note that w_1 is scaled differently for the center and wings, such that the passing argument to TABLE or GFUNC contains three path lengths UBAR,VBAR and WBAR.

The downward flux is computed from (2b) for which the terms $G(p,p_t,T(p_t))$ and $\sum_{p}^{p_t} \Delta G(p,p',T(p'))$ are required. In the code, $G(p,p_t,T(p_t)$ is called SHT and is computed for each level in the model starting with the second level and proceeding down to the surface. By definition, the downward flux at the topmost radiation level, 0 mb, is zero and so no computations are performed for that level. For each level, the term ΔG is computed with respect to all other layers following an approximation given in Chou and Kouvaris (1981). Basically, the approximation states that the contribution to the exchange integral at level I from a layer J is the product of the change in Planck function across the layer J and the transmission from the middle of layer J to level I hence the need for computations of mean absorber amounts in SETUP. The terms ΔG are called SG in the code for both upward and downward fluxes. Note that SG is two-dimensional and only one half of the array is used for the downward flux, whereas the other half is used for the upward flux. For the upward flux, $[G(p,p_s,T_s) - G(p,p_s,T(p_s))]$ is called SHU and is computed for each level except the surface.

The Planck function integrated over the spectral range in each band is computed by linear interpolation from tables given by DATA statements. The nomenclature is

SV = Planck function in water vapor band center

SW = Planck function in water vapor band wings

BAI = Planck function in 15 μm region

BWI = Planck function in 9.6 μm region

SH = Planck function integrated over entire spectrum

The terms in the flux equation in the 9.6 and 15 μm region are computed after calls to subroutine TRCO3 which returns the transmission in the 15 μm region as TAUF and in the 9.6 μm region as TXUF. These, when multiplied by the appropriate difference in Planck function across the layer are added to the SG calculated for water vapor.

After G and ΔG are computed, the upward and downward fluxes, FU and FD are calculated. For the clear sky, all cloud parameters CS, CC and CH are unity and the fluxes are simply summations of ΔG over the appropriate layers. The variable SG is summed in SUM and the downward flux is written as

$$\mathrm{FD = SUM - SHT + SH}$$

while the upward flux is written as

$$\mathrm{FU = SUM + SHU + SH}$$

following (2a,b). The upward flux at the surface is the black body flux since the surface is assumed to have unit emissivity in this code. Therefore, for the surface, FU = SH.

SUBROUTINE TRCO3

This subroutine computes the transmittance in the CO_2 and O_3 regions given the scaled atmospheric paths for the various absorbers.

The transmittance in the 15μm region is expressed as

$$\tau\ (w_1,w_2,w_3) = \tau\ (w_1) \cdot \tau(w_2) \cdot \tau\ (w_3) \tag{12}$$

where subscripts 1, 2 and 3 refer to water vapor line, CO_2 line, and water vapor e-type absorption, respectively and the multiplicative property of transmittances has been used. Expressions for $\tau\ (w_1)$ and $\tau\ (w_3)$ in this region are given in Chou (1984) and are

$$\tau\ (w_1) = \exp\ [-6.7w_1/(1 + 16w_1{}^{0.6})] \tag{13}$$

and

$$\tau\ (w_3) = \exp\ (-27w_3{}^{0.83}) \tag{14}$$

The CO_2 band transmittance is expressed as

$$\tau\ (w) = \exp\ [-aw/(1 + bw^n)] \tag{15}$$

for both the band center and wings. The values of a, b and n are given in Chou and Peng (1983). Note that the wide band model has been used here. The transmittance $\tau\ (w_2)$ is given by suitably weighting (15) in the band center and wings, i.e.

$$\tau\ (w_2) = \frac{1}{\Delta\nu}\ [\tau_c\ \Delta\nu_c + \tau_w\ \Delta\nu_w] \tag{16}$$

where c and w refer to the center and wings respectively. For the model used here, $\Delta\nu_c$ = 100 cm^{-1} and $\Delta\nu_w$ = 160 cm^{-1} and the ratio of weights is therefore 5:8. The transmittance is denoted by TAUF and passed back to IRFLUX.

The transmittance in the 9.6μm region is computed by a modification of the band absorptance formulation given in Rodgers (1968). If we assume that all the ozone absorption is restricted to the 980-1100 cm^{-1} interval, then the average transmittance in that interval based on Rodgers' formula is

$$\tau_{O_3} = 1 - \frac{81.21}{120.0} [1 - \exp (-4.398 \tilde{p} \{\sqrt{1 + 4 (\frac{345.28 U_{O_3}}{0.876 \tilde{p}})} - 1\}] \tag{17}$$

where U_{O_3} is the column amount of ozone expressed in gcm^{-2} and $\tilde{p}$ is the effective broadening pressure in atmospheres. If $\bar{p}$ is the mean pressure of the atmospheric layer and Δp is the pressure thickness of the layer in mb and X is the ozone mixing ratio in g/g in the layer, then

$$U_{O_3} = 1.02 \; X \; \Delta p \tag{18}$$

for each layer and the path through several contiguous layers is

$$U_{O_3} = \sum_i 1.02 \; X_i \; \Delta p_i \quad . \tag{19}$$

The effective broadening pressure in atmospheres, for a path through several contiguous layers is

$$\tilde{p} = [\frac{\sum X_i p_i \Delta p_i}{\sum X_i \; \Delta p_i}]/1013.25 \tag{20}$$

The ozone amounts and the numerator of (20) were calculated in SETUP and are passed from IRFLUX. A note of caution here is that if OZAI in SETUP is very small, there is a danger of computational overflow in using (20). This can be rectified by setting a small non-zero value for OZAI if OZAI is zero or very nearly so. If the model is to be run without ozone, XZ = 1.0 in the subroutine.

The transmittance in the ozone band has to be multiplied by the transmittance in the water vapor continuum that overlaps this region. The weak water vapor line absorption is neglected so only w_3 computed by (7) is needed. The transmittance is given in Chou (1984) and is

$$\tau(w_3) = \exp (-9.79 w_3) \tag{21}$$

and is denoted by TXUF.

SUBROUTINE TABLE

Calls to this subroutine are made to compute $\tau(w_1,w_3; 250)$, $\alpha(w_1,w_3)$ and $\beta(w_1,w_3)$ as defined by (11). Tables are read in at the start of the program and during an integration the values are interpolated and returned to the calling subroutine. A description of the table and the tables themselves are given in Chou (1984). The table is used only for the water vapor bands. For the band center, the quantities are a function only of VBAR which is w_1 for the center, called B in the subroutine. τ, α and β are given at regular intervals in $\log_{10} w_1$; there are 22 values from $\log_{10} w_1 = -6.0$ to $\log_{10} w_1 = 0.3$. Extrapolation is permitted for larger values of $\log_{10} w_1$ but a check is made to ensure that $\tau \geq 0.0$. τ, α, β are returned as WV, YV, ZV, respectively.

For the band wings, both w_1 and w_3 determine τ, α and β and so the table is two-dimensional with 22 values of $\log_{10} w_1$ from $\log_{10} w_1 = -5.4$ to $\log_{10} w_1 = 0.9$ and 19 values of w_3 from 0.0 to 0.054. The scale for w_3 is linear unlike that for w_1. In the wings, w_1 is WBAR, called A in the subroutine, while w_3 is VBAR, call C in the subroutine. Again a check is made to ensure that $\tau \geq 0.0$ The two-dimensional table lookup is linear in $\log_{10} w_1$ and w_3. τ, α, β are returned as WW, YW, ZW, respectively.

Since the table lookup procedure cannot be vectorized very easily, we have tried to replace the table by polynomial fits valid in the range of the table. This subroutine called GFUNC is also provided in the code and has the same input and output arguments as TABLE.

SUBROUTINE CLOUDS

In the longwave, clouds are considered to be non-reflecting and are assumed to completely fill a model layer in the vertical. In the horizontal, clouds are permitted to occupy a fraction of the grid box or to be partially transmitting. In either case the cloud fraction is expressed as a number between 0.0 and 1.0, with 0.0 corresponding to clear skies and 1.0 to a completely filled opaque cloud. A completely filled layer of thin clouds of given emissivity is designated by the same parameter between 0.0 and 1.0 since for non-reflecting clouds, partial filling and partial transmission are interchangeable. The cloudy sky fluxes are computed from the same set of equations as the clear sky with certain multiplicative cloudiness factors depending on probabilities of clear line of sight between levels. These probabilities are computed in SUBROUTINE CLOUDS, the input to which specifies cloud fraction in each level and also whether the clouds are randomly overlapped or maximally overlapped. In the program the two kinds of cloudiness are specified independently, with CSS referring to random overlap fraction and CCU to the maximum overlap fraction.

The flux equations for partially cloudy skies are given below for the simple case illustrated in Figure 2. Consider a 5 layer model with a cloud in layer 3. If that is the only cloudy layer and fractional cover is N, then (2b) for the downward flux at a level below the cloud can be written as

$$F_{cld}\downarrow(p) = B(T(p)) - (1 - N)\, G(p,p_t,T(p_t)) + (1 - N) \int_{T(p)}^{T(p_t)} \partial G(p,p',T(p'))/\partial T \, dT(p')$$

$$+ N \int_{T(p)}^{T(p_{c_b})} \partial G(p,p',T(p'))/\partial T \, dT(p') \qquad (22)$$

where p_{c_b} is the level of the cloud base, in this case, level 4. But (22) can be written as

$$F_{cld}\downarrow(p) = B(T(p)) - (1 - N)\, G(p,p_t,T(p_t)) + (1 - N) \int_{T(p_{c_b})}^{T(p_t)} \partial G(p,p',T(p'))/\partial T \, dT(p')$$

$$+ \int_{T(p)}^{T(p_{c_b})} \partial G(p',p',T(p'))/\partial T \, dT(p') \qquad (23)$$

by splitting the limits of the first integral. Noting that $G(p,p_t,T(p_t))$ involves the transmittance between level p and the top of the atmosphere, p_t, it is evident that (1 - N) is the probability of a clear line of sight between

p and p_t since p is below cloud base. Similarly for all levels between p_{c_b} and p_t, the probability between p and p' is also $(1 - N)$. For levels between p and p_{c_b} the probability is 1.0. Therefore (23) can be written as

$$F_{cld}\downarrow(p) = B(T(p)) - C(p,p_t)\ G(p,p_t,T(p_t)) + \int_{T(p)}^{T(p_t)} C(p,p')\ \partial G(p,p',T(p'))/\partial T\ dT(p') \tag{24}$$

where $C(p,p')$ is the probability of a clear line of sight from p to p'. Comparing (24) with (2b), we see that the form is the same except for the multiplication of the factors $C(p,p_t)$ and $C(p,p')$. These are coded as CH and CS respectively. It can be shown that the upward flux above the cloud layer is given by

$$\begin{aligned} F_{cld}\uparrow(p) = {} & B(T(p)) + C(p,p_s)[G(p,p_s,T_s) - G(p,p_s,T(p_s))] \\ & + \int_{T(p)}^{T(p_s)} C(p,p')\ \partial G(p,p',T(p'))/\partial T\ dT(p') \end{aligned} \tag{25}$$

The probability of a clear line of sight from level p to the surface is coded as CC. These cloud factors CH, CC and CS are passed back to IRFLUX for flux computations.

If there are clouds in more than one layer, (24) and (25) can still be used but the cloudiness factor will depend on the fraction in each layer and cloud overlap. The problem of fractional cloud overlap is still under study and there is no consensus on the preferred form of overlap in general circulation models. This question is only of academic importance in models that assume either clear skies or complete overcast. In the current radiation code we allow for two kinds of overlap, random and maximum. These are illustrated in Figs. 3 and 4.

Only some selected probabilities of clear lines of sight will be illustrated. In Figs. 3 and 4 for example, N_1, N_2 and $N_5 = 0.0$, and $C(6,1)$ can be seen to be

$$C(6,1) = \mathrm{MIN}\ [(1 - N_3), (1 - N_4)] \qquad (26)$$

for maximum overlap, where MIN is the minimum function. For random overlap,

$$C(6,1) = (1 - N_3) * (1 - N_4) \qquad (27)$$

In obtaining C for downward flux, the probabilities are computed starting from the top going down using equations like (26) and (27). In general, cloud factors are of the form $C_{i,j}$ where i is the level at which the flux is to be computed and j is the level to which the probability of a clear line of sight is needed. For the downward flux, j = 1 corresponds to the factor CH in the code while for the upward flux if j is the lowest level of the model (surface), then the factor is CC in the code. The downward cloud factors are computed by

$$C_{i,j} = \mathrm{MIN}\ [(1 - N_j), (1 - N_{j+1}), (1 - N_{j+2}) \ldots\ldots\ldots (1 - N_{i-1})], \qquad (28)$$

for maximum overlap and

$$C_{i,j} = (1 - N_j) * (1 - N_{j+1}) * (1 - N_{j+2}) *\ldots\ldots\ldots* (1 - N_{i-1}) \qquad (29)$$

for random overlap. The upward cloud factors are computed by

$$C_{i,j} = \mathrm{MIN}\ [(1 - N_{j-1}), (1 - N_{j-2}), (1 - N_{j-3}), \ldots\ldots\ldots (1 - N_i)], \qquad (30)$$

for maximum overlap and

$$C_{i,j} = (1 - N_{j-1}) * (1 - N_{j-2}) * (1 - N_{j-3}) *\ldots\ldots\ldots* (1 - N_i) \qquad (31)$$

for random overlap. The cloud factors for maximum and random overlap are computed separately and then multiplied to give the final probability of clear line of sight. It is possible to have a maximum overlap cloud fraction and random overlap cloud fraction assigned to the same layer but it is unlikely that a model will be able to make such specifications. We anticipate that the most common usage will be for layers of maximally overlapped cloud fractions in consecutive layers overlapped with a broken cloud layer or cirrus layer separated by clear layers. For example in Fig. 3, if N_1 was the fraction of randomly overlapped clouds in layer 1 with N_3 and N_4 the maximum overlap cloud fractions in layers 3 and 4 respectively and $N_2 = 0$ signifying a clear layer 2, then (26) would read

$$C(6,1) = \mathrm{MIN}\ [(1 - N_3),\ (1 - N_4)] * (1 - N_1) \tag{32}$$

However, if the downward flux at level 3 was needed, the appropriate factor would be C(3,1) and this would be given by

$$C(3,1) = (1 - N_1) \tag{33}$$

The cloud fractions in layers 3 and 4 would not enter into the computations since level 3 is above the two layers. This simple example illustrates the usage of SUBROUTINE CLOUDS.

4. SAMPLE COMPUTATIONS

The radiation code has been used to compute fluxes and cooling rates using five standard profiles shown in Tables 2-6. The input profiles are currently being used in an intercomparison project in which GLAS is a participant. The input parameters have been interpolated to the levels corresponding to the 15- and 9-layer versions of the UCLA/GLAS GCM.

The momenclature used in the tables is as follows.

PA = pressure at the middle of each layer in mb
PU = pressure at the bottom of each layer in mb
TA = temperature of the layer defined at pressure PA in Kelvin
QL = water vapor mixing ratio in layer in g/g
O3 = ozone mixing ratio in layer in g/g
UP15 = upward flux at each level in 15-layer model in Wm^{-2}
UP9 = as above in 9-layer model
DN15 = downward flux at each level in 15-layer model in Wm^{-2}
DN9 = as above in 9-layer model
NT15 = net upward flux at each level in 15-layer model in Wm^{-2}
NT9 = as above in 9-layer model
CR15 = cooling rate in each layer in 15-layer model in Celsius/day
CR9 = as above in 9-layer model

The same profiles have been used for the two models. The 9-layer model has the same vertical structure as the nine lowest layers of the 15-layer model. The top of the 15-layer model is at 1.0 mb whereas the top of the 9-layer model is at 51.8 mb. Fluxes and cooling rates have been presented such that the values in layers or levels at the same pressure are in the same row in the table. Of course, results are not presented for the six upper layers missing in the 9-layer model. The cooling rates computed for the 9-layer model do not differ substantially from the 15-layer results except for the top one or two layers of the model where the cooling rate itself is quite small. These results also compare favorably with results obained for 31 layers using the same profiles. The version of the code used to obtain the results in the five tables used SUBROUTINE TABLE for the water vapor transmittance and computed the temperature at the top and bottom of the boundary layer by following a dry adiabat. However, the code given in the appendix uses interpolated temperatures for these two levels.

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TABLE 1

Spectral regions in the longwave radiation scheme.

	H_2O band centers	H_2O band wings	CO_2 band center	CO_2 band wings	O_3 band
Spectral range (cm^{-1})	0-340 1380-1900	340-540 800-980 1100-1380 1900-3000	620-720	540-620 720-800	980-1100

TABLE 2

TROPICAL PROFILE

L	PA	PU	TA	QL	O3
1	1.4	1.9	267.8	0.325E-05	0.557E-05
2	2.7	3.7	258.2	0.325E-05	0.890E-05
3	5.2	7.2	247.6	0.325E-05	0.105E-04
4	10.0	13.9	237.8	0.325E-05	0.123E-04
5	19.3	26.8	228.6	0.325E-05	0.101E-04
6	37.3	51.8	216.3	0.325E-05	0.505E-05
7	72.0	100.0	201.4	0.325E-05	0.920E-06
8	125.7	152.6	202.0	0.331E-05	0.216E-06
9	187.2	223.4	218.3	0.742E-05	0.149E-06
10	268.2	314.9	233.9	0.786E-04	0.999E-07
11	372.1	431.4	249.3	0.443E-03	0.751E-07
12	502.2	575.5	265.0	0.143E-02	0.656E-07
13	662.1	751.6	279.6	0.398E-02	0.588E-07
14	855.7	963.0	291.2	0.109E-01	0.541E-07
15	987.9	1013.0	298.7	0.158E-01	0.490E-07

SURFACE TEMPERATURE = 300.0

	FLUXES WATTS PER SQUARE METER						COOLING RATES DEGREES / DAY	
L	UP15	UP9	DN15	DN9	NT15	NT9	CR15	CR9
1	297.1		1.1		296.0		5.79	
2	297.0		1.6		295.4		5.28	
3	296.7		2.4		294.2		3.71	
4	296.2		3.5		292.7		2.37	
5	295.9		5.1		290.8		1.16	
6	296.0		7.0		289.1		0.01	
7	297.6	296.7	8.5	5.2	289.0	291.5	-0.03	0.04
8	299.6	299.6	10.3	8.3	289.2	291.3	0.09	0.17
9	302.5	302.5	13.8	12.3	288.7	290.2	0.43	0.47
10	308.1	308.1	23.0	21.8	285.1	286.3	1.79	1.81
11	318.3	318.3	52.7	51.6	265.6	266.7	2.39	2.39
12	336.5	336.5	103.8	102.8	232.7	233.7	2.17	2.17
13	364.5	364.5	168.9	167.9	195.6	196.6	2.18	2.19
14	400.2	400.2	250.2	249.2	150.0	151.0	2.47	2.48
15	447.2	447.2	359.0	358.3	88.2	88.9	3.53	3.55
16	459.3	459.3	392.0	391.4	67.3	67.9		

TABLE 3

MIDLATITUDE SUMMER PROFILE

L	PA	PU	TA	QL	O3
1	1.4	1.9	274.7	0.400E-05	0.606E-05
2	2.7	3.7	264.8	0.400E-05	0.103E-04
3	5.2	7.2	252.5	0.400E-05	0.134E-04
4	10.0	13.9	241.5	0.400E-05	0.147E-04
5	19.3	26.8	232.2	0.400E-05	0.104E-04
6	37.3	51.8	222.1	0.400E-05	0.583E-05
7	72.0	100.0	216.9	0.400E-05	0.270E-05
8	125.7	152.6	216.1	0.400E-05	0.955E-06
9	187.2	223.4	217.7	0.819E-05	0.471E-06
10	268.2	314.9	233.1	0.113E-03	0.240E-06
11	372.1	431.4	248.0	0.402E-03	0.151E-06
12	502.2	575.5	262.4	0.103E-02	0.103E-06
13	662.1	751.6	275.6	0.292E-02	0.756E-07
14	855.7	963.0	287.8	0.731E-02	0.582E-07
15	987.9	1013.0	293.1	0.110E-01	0.515E-07

SURFACE TEMPERATURE = 294.0

	FLUXES WATTS PER SQUARE METER						COOLING RATES DEGREES / DAY	
L	UP15	UP9	DN15	DN9	NT15	NT9	CR15	CR9
1	288.2		1.2		287.0		6.81	
2	288.1		1.8		286.2		6.31	
3	287.7		2.8		284.9		4.41	
4	287.1		4.0		283.1		2.83	
5	286.5		5.7		280.8		1.66	
6	286.2		7.9		278.3		0.68	
7	286.7	286.3	10.4	8.2	276.3	278.1	0.22	0.32
8	289.2	289.2	14.2	12.9	275.0	276.3	0.14	0.20
9	291.9	291.9	17.8	16.9	274.1	275.0	0.36	0.38
10	296.5	296.5	25.4	24.6	271.1	271.9	1.86	1.87
11	307.5	307.5	56.6	55.9	250.9	251.6	1.98	1.98
12	324.8	324.8	101.2	100.6	223.6	224.2	1.87	1.87
13	348.5	348.5	156.8	156.2	191.7	192.3	1.95	1.96
14	380.3	380.3	229.3	228.8	151.0	151.6	2.01	2.01
15	414.8	414.8	314.0	313.6	100.8	101.2	3.25	3.26
16	423.5	423.5	342.0	341.5	81.5	81.9		

TABLE 4

MIDLATITUDE WINTER PROFILE

L	PA	PU	TA	QL	O3
1	1.4	1.9	258.1	0.400E-05	0.779E-05
2	2.7	3.7	243.0	0.400E-05	0.113E-04
3	5.2	7.2	227.8	0.400E-05	0.116E-04
4	10.0	13.9	220.6	0.400E-05	0.108E-04
5	19.3	26.8	218.4	0.400E-05	0.921E-05
6	37.3	51.8	215.3	0.400E-05	0.691E-05
7	72.0	100.0	215.7	0.400E-05	0.355E-05
8	125.8	152.9	217.5	0.446E-05	0.165E-05
9	187.7	224.1	218.7	0.902E-05	0.871E-06
10	269.2	316.1	221.6	0.223E-04	0.347E-06
11	373.6	433.3	234.7	0.986E-04	0.150E-06
12	504.6	578.3	247.5	0.410E-03	0.848E-07
13	665.4	755.3	259.8	0.110E-02	0.550E-07
14	860.1	968.0	267.6	0.200E-02	0.467E-07
15	992.9	1018.0	271.5	0.257E-02	0.462E-07

SURFACE TEMPERATURE = 272.2

	FLUXES WATTS PER SQUARE METER						COOLING RATES DEGREES / DAY	
L	UP15	UP9	DN15	DN9	NT15	NT9	CR15	CR9
1	236.4		1.0		235.4		5.10	
2	236.2		1.3		234.9		3.99	
3	235.9		1.9		234.0		2.20	
4	235.6		2.5		233.1		1.45	
5	235.5		3.5		232.0		1.19	
6	235.6		5.5		230.1		0.78	
7	236.3	236.3	8.5	8.0	227.8	228.3	0.49	0.53
8	238.2	238.2	13.2	13.0	225.0	225.3	0.39	0.39
9	240.3	240.3	17.7	17.4	222.6	222.8	0.45	0.45
10	243.1	243.1	24.4	24.1	218.8	219.0	0.67	0.67
11	248.1	248.1	36.7	36.5	211.5	211.7	1.33	1.33
12	258.3	258.3	65.3	65.1	193.0	193.2	1.68	1.68
13	273.9	273.9	109.7	109.5	164.2	164.4	1.47	1.47
14	291.9	291.9	158.5	158.3	133.4	133.6	1.07	1.07
15	306.9	306.9	200.5	200.3	106.4	106.6	1.53	1.53
16	311.5	311.5	214.2	214.0	97.3			

TABLE 5

SUBARCTIC SUMMER PROFILE

L	PA	PU	TA	QL	O3
1	1.4	1.9	277.5	0.400E-05	0.570E-05
2	2.7	3.7	269.4	0.400E-05	0.979E-05
3	5.2	7.2	255.7	0.400E-05	0.132E-04
4	10.0	13.9	243.3	0.400E-05	0.119E-04
5	19.3	26.8	234.6	0.400E-05	0.811E-05
6	37.3	51.8	225.1	0.400E-05	0.519E-05
7	72.0	100.0	225.1	0.400E-05	0.368E-05
8	125.6	152.5	225.0	0.401E-05	0.163E-05
9	186.9	223.0	225.1	0.111E-04	0.787E-06
10	267.6	314.1	225.0	0.422E-04	0.314E-06
11	371.1	430.2	240.7	0.292E-03	0.145E-06
12	500.8	573.9	256.0	0.102E-02	0.997E-07
13	660.2	749.3	268.7	0.251E-02	0.689E-07
14	853.1	960.0	279.6	0.489E-02	0.515E-07
15	984.9	1010.0	286.0	0.697E-02	0.418E-07

SURFACE TEMPERATURE = 287.0

	FLUXES WATTS PER SQUARE METER						COOLING RATES DEGREES / DAY	
L	UP15	UP9	DN15	DN9	NT15	NT9	CR15	CR9
1	270.3		1.3		269.0		7.18	
2	270.1		1.9		268.2		6.93	
3	269.7		3.0		266.7		4.85	
4	269.0		4.3		264.7		2.91	
5	268.3		5.9		262.4		1.83	
6	267.8		8.2		259.6		0.97	
7	268.0	268.0	11.3	10.0	256.8	258.0	0.55	0.65
8	270.2	270.2	16.6	15.9	253.6	254.3	0.39	0.41
9	272.3	272.3	21.1	20.6	251.2	251.7	0.51	0.53
10	275.0	275.0	28.1	27.7	246.9	247.4	1.01	1.02
11	280.6	280.6	44.7	44.3	236.0	236.4	1.93	1.93
12	296.3	296.3	86.8	86.4	209.5	209.8	1.90	1.90
13	318.8	318.8	141.6	141.3	177.2	177.5	1.70	1.70
14	346.0	346.0	204.2	203.9	141.8	142.1	1.45	1.45
15	376.8	376.8	271.1	270.8	105.7	106.0	2.26	2.27
16	384.9	384.9	292.7	292.4	92.3	92.5		

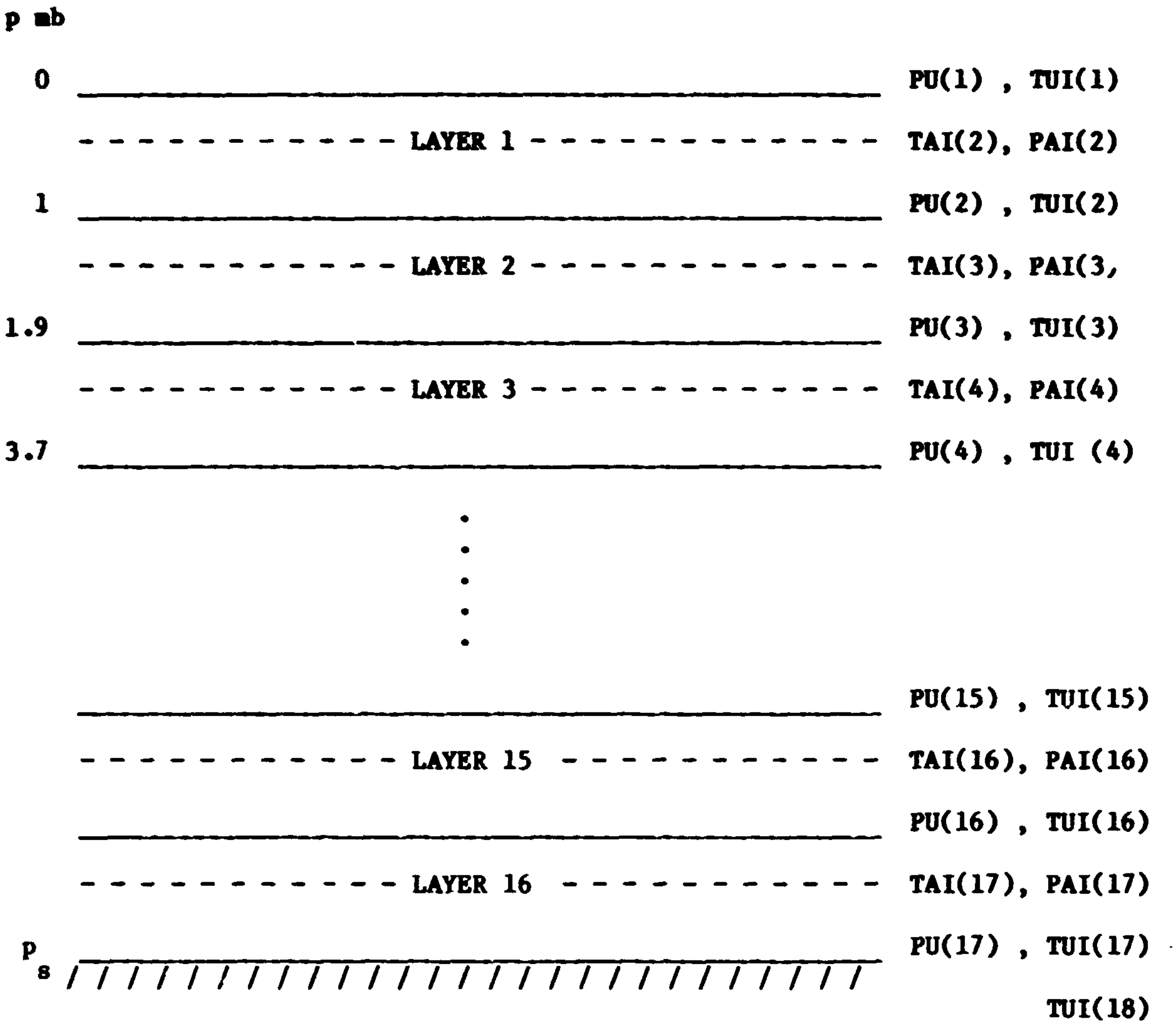
TABLE 6

SUBARCTIC WINTER PROFILE

L	PA	PU	TA	QL	O3
1	1.4	1.9	245.9	0.400E-05	0.932E-05
2	2.7	3.7	234.2	0.400E-05	0.124E-04
3	5.2	7.2	222.7	0.400E-05	0.121E-04
4	10.0	13.9	216.5	0.400E-05	0.920E-05
5	19.3	26.8	214.3	0.400E-05	0.871E-05
6	37.3	51.8	213.1	0.400E-05	0.780E-05
7	72.0	100.0	215.7	0.400E-05	0.528E-05
8	125.7	152.6	217.3	0.509E-05	0.249E-05
9	187.2	223.4	217.3	0.989E-05	0.129E-05
10	268.2	314.9	217.3	0.169E-04	0.428E-06
11	372.1	431.4	225.8	0.463E-04	0.131E-06
12	502.2	575.5	239.6	0.272E-03	0.649E-07
13	662.1	751.6	251.7	0.742E-03	0.474E-07
14	855.7	963.0	258.3	0.997E-03	0.355E-07
15	987.9	1013.0	257.5	0.898E-03	0.307E-07

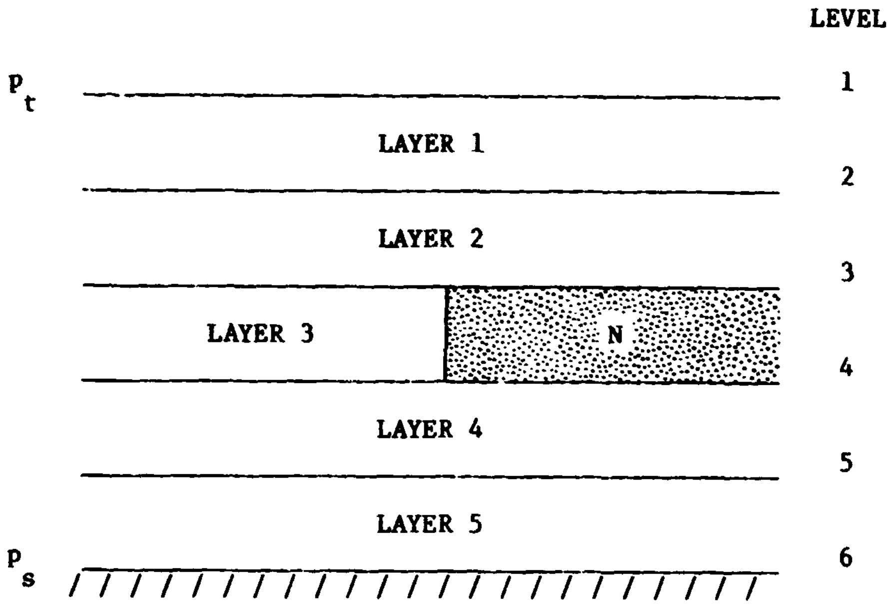
SURFACE TEMPERATURE = 257.1

	FLUXES WATTS PER SQUARE METER						COOLING RATES DEGREES / DAY	
L	UP15	UP9	DN15	DN9	NT15	NT9	CR15	CR9
1	202.2		0.8		201.4		3.90	
2	202.1		1.1		201.0		3.22	
3	201.9		1.6		200.3		1.98	
4	201.6		2.1		199.5		1.35	
5	201.5		3.1		198.4		1.15	
6	201.6		4.9		196.7		0.86	
7	202.2	202.4	8.1	8.2	194.1	194.2	.63	0.65
8	203.7	203.7	13.1	13.2	190.5	190.5	0.49	0.48
9	205.1	205.1	17.6	17.6	187.5	187.5	0.51	0.51
10	207.0	207.0	23.9	23.8	183.2	183.2	0.52	0.52
11	210.2	210.2	32.7	32.7	177.5	177.6	0.82	0.82
12	217.3	217.3	51.1	51.0	166.2	166.2	1.57	1.57
13	230.5	230.5	91.2	91.1	139.3	139.4	1.36	1.36
14	243.9	243.9	133.1	133.0	110.9	111.0	0.78	0.78
15	246.5	246.5	155.1	155.1	91.4	91.4	1.04	1.04
16	248.0	248.0	162.8	162.7	85.2	85.2		



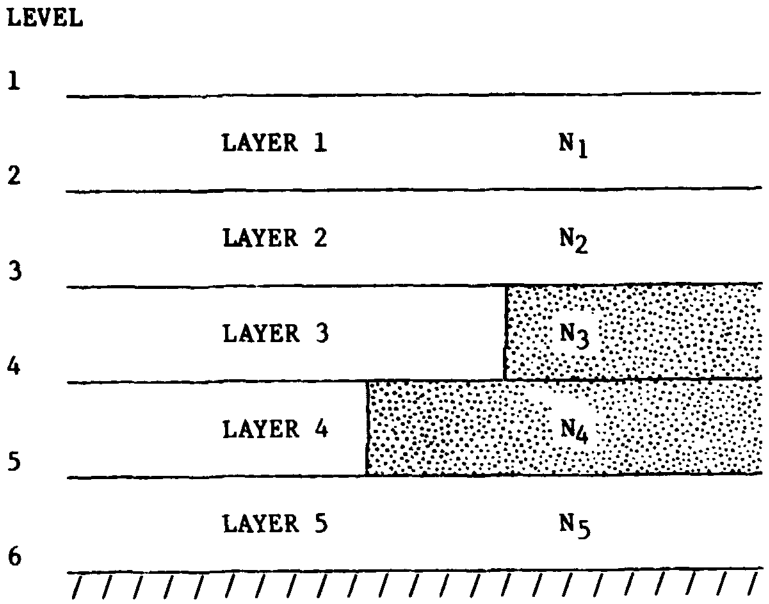
Levels in the Radiation Model

FIG. 1



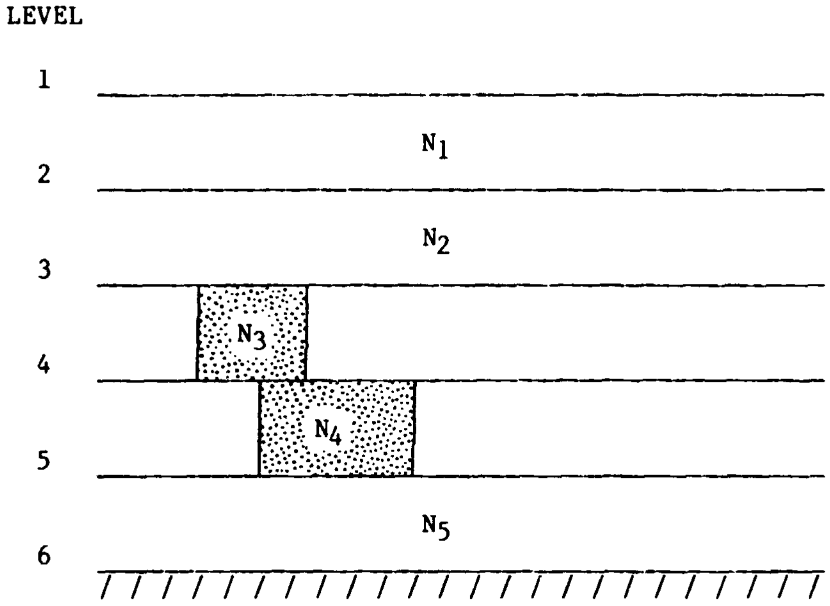
Schematic showing partial cloudiness in one layer

FIG. 2



Schematic showing maximum overlap

FIG. 3



Schematic showing random overlap

FIG. 4

APPENDIX

CODE LISTING

NOTE: Several loops diagnosed by the compiler as being non-vectorizable can in fact be vectorized by using vector functions or slight restructuring. Since these are usually system-specific, the user is expected to make the necessary changes. A fully vectorized half-precision version of the code designed for the CYBER-205 that is currently being used in the GCM is available from the authors upon request.

```
      SUBROUTINE RADIR(LM,PL,PL20,TL,TG,QL,O3L,CLD,CLU,
     1                 ATLX,RS,ULWTOP,DLWBOT)
C
C**********   INPUT PARAMETERS   ***********
C
C     LM.......NUMBER OF LAYERS
C     PL.......LAYER MIDDLE PRESSURE IN MB
C     PL20.....LAYER BOTTOM PRESSURE IN MB
C     TL.......LAYER MIDDLE TEMPERATURE IN KELVIN
C     TG.......SURFACE TEMPERATURE IN KELVIN
C     QL.......WATER VAPOR MIXING RATIO IN G/G
C     O3L......OZONE MIXING RATIO IN G/G
C     CLD......RANDOM OVERLAP CLOUD FRACTION
C     CLU......MAXIMUM OVERLAP CLOUD FRACTION
C
C**********   OUTPUT PARAMETERS   **********
C
C     ATLX.....LAYER COOLING RATE IN CELSIUS/DAY
C     RS.......NET UPWARD FLUX AT SURFACE IN W/M**2
C     ULWTOP...UPWARD FLUX AT TOP OF ATMOSPHERE IN W/M**2
C     DLWBOT...DOWNWARD FLUX AT SURFACE IN W/M**2
C
      DIMENSION PL(72,20),PL20(72,20),TL(72,20),TG(72)
      DIMENSION QL(72,20),O3L(72,20),CLD(72,20),CLU(72,20)
      DIMENSION ATLX(72,20),RS(72),ULWTOP(72),DLWBOT(72)
      DIMENSION FE(72,20),COOLR(72,20)
      COMMON/FLUX/FD(72,20),FU(72,20)
      COMMON/AMHN/TA(72,20),PA(72,20),WA(72,20),OA(72,20)
     1,NDATA,TS(72)
      COMMON/CSC/CSS(72,20),CCU(72,20),CH(72,20),CC(72,20)
     1,CS(72,20,20)
      COMMON/PRESS/PU(72,20),DP(72,20)
      COMMON/INIT/NP,NPP1,NPM1
C
      LOGICAL FIRST/.TRUE./
      IF(.NOT.FIRST) GO TO 10
      FIRST=.FALSE.
      CALL INDATA
C
   10 CONTINUE
      NDATA=LM
      FAC=3.6*24./10030.*.98
      DO 20 I=1,72
      PU(I,1)=0.
      PU(I,2)=1.
      CSS(I,1)=0.
      CCU(I,1)=0.
      TS(I)=TG(I)
   20 CONTINUE
      DO 30 J=1,NDATA
      DO 30 I=1,72
      PA(I,J)=PL(I,J)
      PU(I,J+2)=PL20(I,J)
      TA(I,J)=TL(I,J)
      WA(I,J)=QL(I,J)
      OA(I,J)=O3L(I,J)
      CSS(I,J+1)=CLD(I,J)
      CCU(I,J+1)=CLU(I,J)
      CSS(I,J+1)=AMAX1(AMIN1(CSS(I,J+1),1.0),0.)
```

```
0035          CCU(I,J+1)=AMAX1(AMIN1(CCU(I,J+1),1.0),0.)
0036     30   CONTINUE
        C
0037          CALL SETUP
        C
0038          DO 40 IP=1,NP
0039          DO 40 IL=1,72
0040          FE(IL,IP)=FD(IL,IP)-FU(IL,IP)
0041     40   CONTINUE
0042          DO 50 I=1,72
0043          ULWTOP(I)=FU(I,1)*0.001
0044          DLWBOT(I)=FD(I,NP)*0.001
0045          RS(I)=-FE(I,NP)*0.001
0046     50   CONTINUE
0047          DO 60 IP=2,NP
0048          DO 60 IL=1,72
0049          COOLR(IL,IP)=(FE(IL,IP)-FE(IL,IP-1))*FAC/DP(IL,IP)
0050     60   CONTINUE
0051          DO 70 J=1,NDATA
0052          DO 70 I=1,72
0053          ATLX(I,J)=COOLR(I,J+2)
0054     70   CONTINUE
0055          RETURN
0056          END

UNCOLLAPSIBLE LOOPS      REASON FOR NON-VECTORIZATION
-------------------      -----------------------------
LINE 0026                LINE 0035   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0025                LINE 0026   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0018                LINE 0019   LHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES

NUMBER OF LOOPS IN ROUTINE    = 0010

NUMBER OF VECTORIZABLE LOOPS = 0007

NUMBER OF STACKLIBED LOOPS    = 0000
```

```
0001          SUBROUTINE INDATA
        C
        C*********      READ IN DATA      ***********
        C
0002          COMMON/H2O/GL(30,20),COEFF(30,20,2)
0003          COMMON/INDAT/NUP1,NW
0004          NUP1=20
0005          NW=22
0006          READ(5,10)DUMMY
0007       10 FORMAT(A1,/,A1,/)
0008          READ(5,10)DUMMY
0009          READ(5,20)((GL(IW,IU),IW=1,NW),IU=1,NUP1)
0010          READ(5,10)DUMMY
0011          READ(5,20)(((COEFF(IW,IU,I),IW=1,NW),IU=1,NUP1),I=1,2)
0012       20 FORMAT(11F7.4)
0013          RETURN
0014          END
```

```
UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ---------------------------
LINE 0011               LINE 0011   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP
LINE 0011               LINE 0011   STATEMENT IS NOT AN ASSIGNMENT STATEMENT
LINE 0009               LINE 0009   STATEMENT IS NOT AN ASSIGNMENT STATEMENT

NUMBER OF LOOPS IN ROUTINE    = 0003

NUMBER OF VECTORIZABLE LOOPS = 0000

NUMBER OF STACKLIBED LOOPS    = 0000
```

```
  0001          SUBROUTINE SETUP
          C
          C
  0002          DIMENSION PRE(2),PR(2)
  0003          DIMENSION X2(72,20),X4(72,20),SZ1(72,20),SZ2(72,20),XX(72,20)
  0004          DIMENSION RV(72,20),RW(72,20),PM(72,20),PMV(72,20),PMW(72,20)
  0005          DIMENSION DPI(72,20),PAI(72,20),TAI(72,20),RAWI(72,20)
               *          ,OZAI(72,20)
  0006          COMMON/PRESS/PU(72,20),DP(72,20)
  0007          COMMON/TEMP/TUI(72,20)
  0008          COMMON/INIT/NP,NPP1,NPM1
  0009          COMMON/SH20/UBAR(72,20),VBAR(72,20),WBAR(72,20),UBARM(72,20),
               1            VBARM(72,20),WBARM(72,20)
  0010          COMMON/SC0203/PSCALV(72,20),PSCALW(72,20),U(72,20),V(72,20),
               1              PSCAMV(72,20),PSCAMW(72,20),UM(72,20),VM(72,20)
  0011          COMMON/AMHN/TA(72,20),PA(72,20),WA(72,20),OA(72,20),NDATA
               1,           TS(72)
  0012          DATA PRE/275.,550./,PR/30.,300./,PP/1./
  0013          NP=NDATA+2
  0014          NPP1=NP+1
  0015          NPM1=NP-1
  0016          DO 10 IP=2,NP
  0017          DO 10 IL=1,72
  0018          DP(IL,IP)=PU(IL,IP)-PU(IL,IP-1)
  0019          DPI(IL,IP)=DP(IL,IP)*1.02
  0020       10 CONTINUE
          C
          C****** TEMPERATURE AND HUMIDITY INTERPOLATIONS *************
          C
  0021          DO 20 J=1,NDATA
  0022          DO 20 I=1,72
  0023          WA(I,J)=AMAX1(WA(I,J),0.1E-12)
  0024          OA(I,J)=AMAX1(OA(I,J),0.1E-12)
  0025       20 CONTINUE
  0026          DO 30 J=3,NP
  0027          DO 30 I=1,72
  0028          PAI(I,J)=PA(I,J-2)
  0029          TAI(I,J)=TA(I,J-2)
  0030          RAWI(I,J)=WA(I,J-2)*DPI(I,J)
  0031          OZAI(I,J)=OA(I,J-2)*DPI(I,J)
  0032       30 CONTINUE
  0033          DO 40 J=3,NPM1
  0034          DO 40 I=1,72
  0035          X2(I,J)=ALOG(PU(I,J)/PA(I,J-2))
```

```
      X4(I,J)=ALOG(PA(I,J-1)/PA(I,J-2))
      TUI(I,J)=TA(I,J-2)+X2(I,J)/X4(I,J)*(TA(I,J-1)-TA(I,J-2))
   40 CONTINUE
      DO 50 I=1,72
      X2(I,NP)=ALOG(PU(I,NP)/PU(I,NPM1))
      X4(I,NP)=ALOG(PA(I,NDATA)/PU(I,NPM1))
      TUI(I,NP)=TUI(I,NPM1)+X2(I,NP)/X4(I,NP)*(TA(I,NDATA)
     1          -TUI(I,NPM1))
      TUI(I,NPP1)=TS(I)
      DPI(I,1)=0.
      PAI(I,1)=0.
      PAI(I,2)=0.5*PU(I,2)
   50 CONTINUE
      DO 60 J=1,2
      DO 60 I=1,72
      TAI(I,J)=TA(I,1)
      TUI(I,J)=TA(I,1)
      RAWI(I,J)=WA(I,1)*DPI(I,J)
      OZAI(I,J)=OA(I,1)*DPI(I,J)
   60 CONTINUE
C
C********** COMPUTE SCALED WATER VAPOR AMOUNTS*********
C
      DO 80 IL=1,72
      UBAR(IL,1)=0.
      VBAR(IL,1)=0.0
      WBAR(IL,1)=0.0
   80 CONTINUE
      DO 90 IP=2,NP
      DO 90 IL=1,72
      SZ1(IL,IP)=EXP(0.005*(TAI(IL,IP)-225.0))
      SZ2(IL,IP)=EXP(0.016*(TAI(IL,IP)-256.0))
      VBAR(IL,IP)=VBAR(IL,IP-1)+RAWI(IL,IP)*SZ1(IL,IP)*
     1              (PAI(IL,IP)/PRE(1))
      WBAR(IL,IP)=WBAR(IL,IP-1)+RAWI(IL,IP)*SZ2(IL,IP)*
     1              (PAI(IL,IP)/PRE(2))
      XX(IL,IP)=(PAI(IL,IP)/630.)*RAWI(IL,IP)*RAWI(IL,IP)/DPI(IL,IP)
      XX(IL,IP)=XX(IL,IP)*EXP(1800./TAI(IL,IP)-6.0811)
      UBAR(IL,IP)=UBAR(IL,IP-1)+XX(IL,IP)
      UBARM(IL,IP)=0.5*(UBAR(IL,IP)+UBAR(IL,IP-1))
      VBARM(IL,IP)=0.5*(VBAR(IL,IP)+VBAR(IL,IP-1))
      WBARM(IL,IP)=0.5*(WBAR(IL,IP)+WBAR(IL,IP-1))
   90 CONTINUE
C
C********* COMPUTE SCALED CO2 AMOUNTS **********
C
      DO 100 IL=1,72
      PSCALV(IL,1)=0.
      PSCALW(IL,1)=0.
  100 CONTINUE
      DO 110 IP=2,NP
      DO 110 IL=1,72
      RV(IL,IP)=EXP(0.0089*(TAI(IL,IP)-240.0))
      RW(IL,IP)=EXP(0.025*(TAI(IL,IP)-240.0))
      PM(IL,IP)=AMAX1(PAI(IL,IP),PP)
      PMV(IL,IP)=(PM(IL,IP)/PR(1))**0.85*RV(IL,IP)
      PMW(IL,IP)=(PM(IL,IP)/PR(2))**0.5*RW(IL,IP)
C
C********** 0.26 IS FOR CO2=330 PPMV ***********
C
```

```
  0084          PSCALV(IL,IP)=DP(IL,IP)*PMV(IL,IP)*0.26+PSCALV(IL,IP-1)
  0085          PSCALW(IL,IP)=DP(IL,IP)*PMW(IL,IP)*0.26+PSCALW(IL,IP-1)
  0086          PSCAMV(IL,IP)=0.5*(PSCALV(IL,IP)+PSCALV(IL,IP-1))
  0087          PSCAMW(IL,IP)=0.5*(PSCALW(IL,IP)+PSCALW(IL,IP-1))
  0088      110 CONTINUE
          C
          C********** COMPUTE SCALED OZONE AMOUNTS ********
          C
  0089          DO 120 IL=1,72
  0090          U(IL,1)=0.
  0091          V(IL,1)=0.
  0092      120 CONTINUE
  0093          DO 130 IP=2,NP
  0094          DO 130 IL=1,72
  0095          U(IL,IP)=PAI(IL,IP)*OZAI(IL,IP)+U(IL,IP-1)
  0096          V(IL,IP)=OZAI(IL,IP)+V(IL,IP-1)
  0097          UM(IL,IP)=0.5*(U(IL,IP)+U(IL,IP-1))
  0098          VM(IL,IP)=0.5*(V(IL,IP)+V(IL,IP-1))
  0099      130 CONTINUE
          C
  0100          CALL IRFLUX
          C
  0101          RETURN
  0102          END

UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ---------------------------
LINE 0094               LINE 0096   RHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
LINE 0093               LINE 0094   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0078               LINE 0085   RHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
LINE 0077               LINE 0078   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0061               LINE 0068   RHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
LINE 0060               LINE 0061   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0048               LINE 0053   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                    VECTORIZATION OF LOOP
LINE 0039               LINE 0045   LHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
LINE 0022               LINE 0024   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0021               LINE 0022   NONVECTORIZABLE LOOP NESTED WITHIN LOOP

NUMBER OF LOOPS IN ROUTINE    = 0020

NUMBER OF VECTORIZABLE LOOPS  = 0010

NUMBER OF STACKLIBED LOOPS    = 0000



  0001          SUBROUTINE IRFLUX
          C
          C
  0002          DIMENSION SV(72,20),SW(72,20),TUI1(72,20),TUI2(72,20)
  0003          DIMENSION BAI(72,20),BWI(72,20)
  0004          DIMENSION X1(72,20),X2(72,20),X3(72,20),X4(72,20),X5(72,20),
               1          X6(72,20),X7(72,20),X8(72,20)
  0005          DIMENSION BH20V(25),BH20W(25),BLKCO2(25),BLKWIN(25)
  0006          DIMENSION FH(72,20),DH(72,20),F1(72,20),IT(72,20)
  0007          DIMENSION SH(72,20),SG(72,20,20),SHT(72,20),SHU(72,20),SUM(72)
  0008          DIMENSION A(72,20),B(72,20),C(72,20),WV(72,20),YV(72,20),
```

```
     1          ZV(72,20),WW(72,20),YW(72,20),ZW(72,20)
      DIMENSION D(72,20),E(72,20),F(72,20),TAUF(72,20),TXUF(72,20)
      COMMON/SH20/UBAR(72,20),VBAR(72,20),WBAR(72,20),UBARM(72,20),
     1             VBARM(72,20),WBARM(72,20)
      COMMON/SC0203/PSCALV(72,20),PSCALW(72,20),U(72,20),V(72,20),
     1              PSCAMV(72,20),PSCAMW(72,20),UM(72,20),VM(72,20)
      COMMON/INIT/NP,NPP1,NPM1
      COMMON/FLUX/FD(72,20),FU(72,20)
      COMMON/CSC/CSS(72,20),CCU(72,20),CH(72,20),CC(72,20)
     1,          CS(72,20,20)
      COMMON/TEMP/TUI(72,20)
      DATA TEMP1/190./,DT/5./,NT/25/
C
C******* H2O PLANCK FUNCTION **********
C
      DATA BH20V/22661.,24086.,25575.,27135.,28775.,30506.,32339.,
     *    34286.,36361.,38578.,40954.,43505.,46248.,49203.,52388.,
     *    55824.,59532.,63533.,67849.,72502.,77516.,82913.,88717.,
     *    94952.,101640./
      DATA BH20W/30708.,34405.,38417.,42763.,47461.,52529.,57985.,
     *    63850.,70141.,76880.,84088.,91784.,99990.,108726.,118016.,
     *    127881.,138344.,149429.,161160.,173561.,186659.,200478.,
     *    215046.,230390.,246539./
C
C******* WINDOW PLANCK FUNCTION **********
C
      DATA BLKWIN/1944.,2377.,2877.,3450.,4102.,4838.,5664.,6585.,
     *              7606.,8733.,9969.,11320.,12788.,14380.,16097.,
     *              17944.,19923.,22038.,24292.,26685.,29221.,31902.,
     *              34729.,37703.,40825./
C
C******* CO2 PLANCK FUNCTION *********
C
      DATA BLKC02/18606.,21145.,23884.,26826.,29973..33325.,36883.,
     *             40647.,44617.,48792.,52170.,57750.,62530.,67509.,
     *             72683.,78050.,83609.,89354.,95285.,101397.,107686.,
     *             114155.,120794.,127601.,134574./
      DO 10 IP=1,NP
      DO 10 IL=1,72
      SHT(IL,IP)=0.
      SHU(IL,IP)=0.
   10 CONTINUE
      DO 15 IP=1,NP
      DO 15 IX=1,NP
      DO 15 IL=1,72
      SG(IL,IX,IP)=0.
   15 CONTINUE
      DO 20 IP=1,NPP1
      DO 20 IL=1,72
      FH(IL,IP)=(TUI(IL,IP)-TEMP1)/DT+1.5
      IT(IL,IP)=FH(IL,IP)
      IT(IL,IP)=MAX0(MIN0(IT(IL,IP),NT-1),1)
      F1(IL,IP)=FLOAT(IT(IL,IP)-1)
      DH(IL,IP)=TUI(IL,IP)-(TEMP1+F1(IL,IP)*DT)
      SV(IL,IP)=BH20V(IT(IL,IP))+(BH20V(IT(IL,IP)+1)-BH20V(IT(IL,IP)
     1          ))*DH(IL,IP)/DT
      SW(IL,IP)=BH20W(IT(IL,IP))+(BH20W(IT(IL,IP)+1)-BH20W(IT(IL,IP)
     1          ))*DH(IL,IP)/DT
      BAI(IL,IP)=BLKC02(IT(IL,IP))+(BLKC02(IT(IL,IP)+1)-BLKC02(IT
     1      (IL,IP)))*DH(IL,IP)/DT
```

```
      BWI(IL,IP)=BLKWIN(IT(IL,IP))+(BLKWIN(IT(IL,IP)+1)-BLKWIN(IT
     1     (IL,IP)))*DH(IL,IP)/DT
   20 CONTINUE
      DO 30 IP=1,NPP1
      DO 30 IL=1,72
      SH(IL,IP)=SV(IL,IP)+SW(IL,IP)+BAI(IL,IP)+BWI(IL,IP)
      TUI1(IL,IP)=TUI(IL,IP)-250.
      TUI2(IL,IP)=TUI1(IL,IP)*TUI1(IL,IP)
   30 CONTINUE
C
C*****************                *****************
C*****************       H2O      *****************
C*****************                *****************
C
      DO 40 IP=2,NP
      DO 40 IL=1,72
      A(IL,IP-1)=ABS(UBAR(IL,IP))
      B(IL,IP-1)=ABS(VBAR(IL,IP))
      C(IL,IP-1)=ABS(WBAR(IL,IP))
   40 CONTINUE
      JP=NPM1
C
C     CALL TABLE(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
      CALL GFUNC(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
C
      DO 45 IP=2,NP
      DO 45 IL=1,72
      X1(IL,IP)=WV(IL,IP-1)*SV(IL,1)
      X2(IL,IP)=1.+YV(IL,IP-1)*TUI1(IL,1)+ZV(IL,IP-1)*TUI2(IL,1)
      X3(IL,IP)=WW(IL,IP-1)*SW(IL,1)
      X4(IL,IP)=1.+YW(IL,IP-1)*TUI1(IL,1)+ZW(IL,IP-1)*TUI2(IL,1)
      SHT(IL,IP)=X1(IL,IP)*X2(IL,IP)+X3(IL,IP)*X4(IL,IP)
   45 CONTINUE
      DO 50 IP=1,NPM1
      DO 50 IL=1,72
      A(IL,IP)=ABS(UBAR(IL,NP)-UBAR(IL,IP))
      B(IL,IP)=ABS(VBAR(IL,NP)-VBAR(IL,IP))
      C(IL,IP)=ABS(WBAR(IL,NP)-WBAR(IL,IP))
   50 CONTINUE
      JP=NPM1
C
C     CALL TABLE(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
      CALL GFUNC(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
C
      DO 55 IP=1,NPM1
      DO 55 IL=1,72
      X1(IL,IP)=WV(IL,IP)*SV(IL,NPP1)
      X2(IL,IP)=1.+YV(IL,IP)*TUI1(IL,NPP1)+ZV(IL,IP)*TUI2(IL,NPP1)
      X3(IL,IP)=WW(IL,IP)*SW(IL,NPP1)
      X4(IL,IP)=1.+YW(IL,IP)*TUI1(IL,NPP1)+ZW(IL,IP)*TUI2(IL,NPP1)
      X5(IL,IP)=WV(IL,IP)*SV(IL,NP)
      X6(IL,IP)=1.+YV(IL,IP)*TUI1(IL,NP)+ZV(IL,IP)*TUI2(IL,NP)
      X7(IL,IP)=WW(IL,IP)*SW(IL,NP)
      X8(IL,IP)=1.+YW(IL,IP)*TUI1(IL,NP)+ZW(IL,IP)*TUI2(IL,NP)
      SHU(IL,IP)=X1(IL,IP)*X2(IL,IP)+X3(IL,IP)*X4(IL,IP)-
     1           X5(IL,IP)*X6(IL,IP)-X7(IL,IP)*X8(IL,IP)
   55 CONTINUE
C
C*********DOWNWARD FLUX SG(IX,IP)************
C
```

```
      DO 75 IP=2,NP
      DO 60 IX=2,IP
      DO 60 IL=1,72
      A(IL,IX-1)=ABS(UBAR(IL,IP)-UBARM(IL,IX))
      B(IL,IX-1)=ABS(VBAR(IL,IP)-VBARM(IL,IX))
      C(IL,IX-1)=ABS(WBAR(IL,IP)-WBARM(IL,IX))
   60 CONTINUE
      JP=IP-1
C
C     CALL TABLE(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
      CALL GFUNC(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
C
      DO 70 IX=2,IP
      DO 70 IL=1,72
      X1(IL,IX-1)=WV(IL,IX-1)*SV(IL,IX-1)
      X2(IL,IX-1)=1.+YV(IL,IX-1)*TUI1(IL,IX-1)+ZV(IL,IX-1)
     1           *TUI2(IL,IX-1)
      X3(IL,IX-1)=WW(IL,IX-1)*SW(IL,IX-1)
      X4(IL,IX-1)=1.+YW(IL,IX-1)*TUI1(IL,IX-1)+ZW(IL,IX-1)
     1           *TUI2(IL,IX-1)
      X5(IL,IX-1)=WV(IL,IX-1)*SV(IL,IX)
      X6(IL,IX-1)=1.+YV(IL,IX-1)*TUI1(IL,IX)+ZV(IL,IX-1)*TUI2(IL,IX)
      X7(IL,IX-1)=WW(IL,IX-1)*SW(IL,IX)
      X8(IL,IX-1)=1.+YW(IL,IX-1)*TUI1(IL,IX)+ZW(IL,IX-1)*TUI2(IL,IX)
      SG(IL,IX-1,IP)=X1(IL,IX-1)*X2(IL,IX-1)+X3(IL,IX-1)*X4(IL,IX-1)
     1              -X5(IL,IX-1)*X6(IL,IX-1)-X7(IL,IX-1)*X8(IL,IX-1)
   70 CONTINUE
   75 CONTINUE
C
C*********UPWARD FLUX SG(IX,IP)*********
C
      DO 95 IP=1,NPM1
      IP1=NP-IP
      DO 80 IX=1,IP1
      DO 80 IL=1,72
      A(IL,IX)=ABS(UBAR(IL,IP)-UBARM(IL,IX+IP))
      B(IL,IX)=ABS(VBAR(IL,IP)-VBARM(IL,IX+IP))
      C(IL,IX)=ABS(WBAR(IL,IP)-WBARM(IL,IX+IP))
   80 CONTINUE
      JP=IP1
C
C     CALL TABLE(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
      CALL GFUNC(JP,A,B,C,WV,YV,ZV,WW,YW,ZW)
C
      DO 90 IX=1,IP1
      DO 90 IL=1,72
      X1(IL,IX)=WV(IL,IX)*SV(IL,IX+IP)
      X2(IL,IX)=1.+YV(IL,IX)*TUI1(IL,IX+IP)+ZV(IL,IX)*TUI2(IL,IX+IP)
      X3(IL,IX)=WW(IL,IX)*SW(IL,IX+IP)
      X4(IL,IX)=1.+YW(IL,IX)*TUI1(IL,IX+IP)+ZW(IL,IX)*TUI2(IL,IX+IP)
      X5(IL,IX)=WV(IL,IX)*SV(IL,IX+IP-1)
      X6(IL,IX)=1.+YV(IL,IX)*TUI1(IL,IX+IP-1)+ZV(IL,IX)
     1         *TUI2(IL,IX+IP-1)
      X7(IL,IX)=WW(IL,IX)*SW(IL,IX+IP-1)
      X8(IL,IX)=1.+YW(IL,IX)*TUI1(IL,IX+IP-1)+ZW(IL,IX)
     1         *TUI2(IL,IX+IP-1)
      SG(IL,IX+IP,IP)=X1(IL,IX)*X2(IL,IX)+X3(IL,IX)*X4(IL,IX)-
     1                X5(IL,IX)*X6(IL,IX)-X7(IL,IX)*X8(IL,IX)
   90 CONTINUE
   95 CONTINUE
```

```
C
C***********                   ***********
C***********   CO2 AND O3      ***********
C***********                   ***********
C
      DO 140 IP=2,NP
      DO 140 IL=1,72
      A(IL,IP-1)=ABS(PSCALV(IL,IP))
      B(IL,IP-1)=ABS(PSCALW(IL,IP))
      C(IL,IP-1)=ABS(WBAR(IL,IP))
      D(IL,IP-1)=ABS(UBAR(IL,IP))
      E(IL,IP-1)=ABS(V(IL,IP))
      F(IL,IP-1)=ABS(U(IL,IP))
  140 CONTINUE
      JP=NPM1
C
      CALL TRCO3(JP,A,B,C,D,E,F,TAUF,TXUF)
C
      DO 145 IP=2,NP
      DO 145 IL=1,72
      SHT(IL,IP)=SHT(IL,IP)+BAI(IL,1)*TAUF(IL,IP-1)
     1                     +BWI(IL,1)*TXUF(IL,IP-1)
  145 CONTINUE
      DO 150 IP=1,NPM1
      DO 150 IL=1,72
      A(IL,IP)=ABS(PSCALV(IL,NP)-PSCALV(IL,IP))
      B(IL,IP)=ABS(PSCALW(IL,NP)-PSCALW(IL,IP))
      C(IL,IP)=ABS(WBAR(IL,NP)-WBAR(IL,IP))
      D(IL,IP)=ABS(UBAR(IL,NP)-UBAR(IL,IP))
      E(IL,IP)=ABS(V(IL,NP)-V(IL,IP))
      F(IL,IP)=ABS(U(IL,NP)-U(IL,IP))
  150 CONTINUE
      JP=NPM1
C
      CALL TRCO3(JP,A,B,C,D,E,F,TAUF,TXUF)
C
      DO 155 IP=1,NPM1
      DO 155 IL=1,72
      SHU(IL,IP)=SHU(IL,IP)+(BAI(IL,NPP1)-BAI(IL,NP))*TAUF(IL,IP)
     1                     +(BWI(IL,NPP1)-BWI(IL,NP))*TXUF(IL,IP)
  155 CONTINUE
C
C*********DOWNWARD FLUX SG(IX,IP)************
C
      DO 175 IP=2,NP
      DO 160 IX=2,IP
      DO 160 IL=1,72
      A(IL,IX-1)=ABS(PSCALV(IL,IP)-PSCAMV(IL,IX))
      B(IL,IX-1)=ABS(PSCALW(IL,IP)-PSCAMW(IL,IX))
      C(IL,IX-1)=ABS(WBAR(IL,IP)-WBARM(IL,IX))
      D(IL,IX-1)=ABS(UBAR(IL,IP)-UBARM(IL,IX))
      E(IL,IX-1)=ABS(V(IL,IP)-VM(IL,IX))
      F(IL,IX-1)=ABS(U(IL,IP)-UM(IL,IX))
  160 CONTINUE
      JP=IP-1
C
      CALL TRCO3(JP,A,B,C,D,E,F,TAUF,TXUF)
C
      DO 170 IX=2,IP
      DO 170 IL=1,72
```

```
      SG(IL,IX-1,IP)=SG(IL,IX-1,IP)+(BAI(IL,IX-1)-BAI(IL,IX))
     1        *TAUF(IL,IX-1)+(BWI(IL,IX-1)-BWI(IL,IX))
     2        *TXUF(IL,IX-1)
  170 CONTINUE
  175 CONTINUE
C
C*********UPWARD FLUX SG(IX,IP)*********
C
      DO 195 IP=1,NPM1
      IP1=NP-IP
      DO 180 IX=1,IP1
      DO 180 IL=1,72
      A(IL,IX)=ABS(PSCALV(IL,IP)-PSCAMV(IL,IX+IP))
      B(IL,IX)=ABS(PSCALW(IL,IP)-PSCAMW(IL,IX+IP))
      C(IL,IX)=ABS(WBAR(IL,IP)-WBARM(IL,IX+IP))
      D(IL,IX)=ABS(UBAR(IL,IP)-UBARM(IL,IX+IP))
      E(IL,IX)=ABS(V(IL,IP)-VM(IL,IX+IP))
      F(IL,IX)=ABS(U(IL,IP)-UM(IL,IX+IP))
  180 CONTINUE
      JP=IP1
C
      CALL TRC03(JP,A,B,C,D,E,F,TAUF,TXUF)
C
      DO 190 IX=1,IP1
      DO 190 IL=1,72
      SG(IL,IX+IP,IP)=SG(IL,IX+IP,IP)+(BAI(IL,IX+IP)-BAI(IL,IX+IP-1))
     1        *TAUF(IL,IX)+(BWI(IL,IX+IP)-BWI(IL,IX+IP-1))
     2        *TXUF(IL,IX)
  190 CONTINUE
  195 CONTINUE
C
      CALL CLOUDS
C
      DO 210 IP=1,NP
      DO 210 IL=1,72
      FU(IL,IP)=0.
      FD(IL,IP)=0.
  210 CONTINUE
C
C***********  COMPUTE DOWNWARD FLUXES **********
C
      DO 230 IP=2,NP
      DO 215 IL=1,72
      SUM(IL)=0.
  215 CONTINUE
      IPM1=IP-1
      DO 220 IX=1,IPM1
      DO 220 IL=1,72
      SUM(IL)=SUM(IL)+SG(IL,IX,IP)*CS(IL,IX,IP)
  220 CONTINUE
      DO 225 IL=1,72
      FD(IL,IP)=SUM(IL)-SHT(IL,IP)*CH(IL,IP)+SH(IL,IP)
  225 CONTINUE
  230 CONTINUE
C
C********** COMPUTE UPWARD FLUXES ************
C
      DO 250 IP=1,NPM1
      DO 235 IL=1,72
      SUM(IL)=0.
```

```
0217     235  CONTINUE
0218          IPP1=IP+1
0219          DO 240 IX=IPP1,NP
0220          DO 240 IL=1,72
0221          SUM(IL)=SUM(IL)+SG(IL,IX,IP)*CS(IL,IX,IP)
0222     240  CONTINUE
0223          DO 245 IL=1,72
0224          FU(IL,IP)=SUM(IL)+SHU(IL,IP)*CC(IL,IP)+SH(IL,IP)
0225     245  CONTINUE
0226     250  CONTINUE
0227          DO 260 IL=1,72
0228          FU(IL,NP)=SH(IL,NPP1)
0229     260  CONTINUE
0230          RETURN
0231          END

UNCOLLAPSIBLE LOOPS      REASON FOR NON-VECTORIZATION
-------------------      ----------------------------
LINE 0214                LINE 0224   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0219                LINE 0221   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0201                LINE 0211   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0206                LINE 0208   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0177                LINE 0190   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                     NESTED WITHIN LOOP
LINE 0179                LINE 0186   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0160                LINE 0172   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                     NESTED WITHIN LOOP
LINE 0161                LINE 0168   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0156                LINE 0158   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0145                LINE 0152   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0141                LINE 0143   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0107                LINE 0117   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                     NESTED WITHIN LOOP
LINE 0109                LINE 0113   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0085                LINE 0094   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                     NESTED WITHIN LOOP
LINE 0086                LINE 0090   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0073                LINE 0082   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0065                LINE 0069   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0057                LINE 0062   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0031                LINE 0041   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                     VECTORIZATION OF LOOP
LINE 0032                LINE 0035   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0026                LINE 0027   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                     NESTED WITHIN LOOP
```

```
NUMBER OF LOOPS IN ROUTINE   = 0058

NUMBER OF VECTORIZABLE LOOPS = 0037

NUMBER OF STACKLIBED LOOPS   = 0000
```

```
      SUBROUTINE TABLE(N,A,B,C,WV,YV,ZV,WW,YW,ZW)
C
C
      DIMENSION KW(72,20),FW(72,20),KU(72,20),FU(72,20)
      DIMENSION ADEL(72,20),BDEL(72,20),WDEL(72,20)
      DIMENSION A(72,20),B(72,20),C(72,20),WV(72,20),YV(72,20),
     1             ZV(72,20),WW(72,20),YW(72,20),ZW(72,20)
      COMMON/INDAT/NUP1,NW
      COMMON/H2O/GL(30,20),COEFF(30,20,2)
      DATA SV/-6./,SW/-5.4/,DW/0.3/,DU/0.003/
      NU=NUP1-1
      DO 10 J=1,N
      DO 10 I=1,72
      B(I,J)=AMAX1(B(I,J),1.E-6)
      B(I,J)=ALOG10(B(I,J))
      KW(I,J)=(B(I,J)-SV)/DW+1.5001
      KW(I,J)=MINO(KW(I,J),NW-1)
      FW(I,J)=(B(I,J)-(SV+FLOAT(KW(I,J)-1)*DW))/DW
      ADEL(I,J)=(COEFF(KW(I,J)+1,NUP1,1)-COEFF(KW(I,J),NUP1,1))
     1           *FW(I,J)
      BDEL(I,J)=(COEFF(KW(I,J)+1,NUP1,2)-COEFF(KW(I,J),NUP1,2))
     1           *FW(I,J)
      WDEL(I,J)=(GL(KW(I,J)+1,NUP1)-GL(KW(I,J),NUP1))*FW(I,J)
      WV(I,J)=GL(KW(I,J),NUP1)+WDEL(I,J)
      WV(I,J)=AMAX1(WV(I,J),0.0)
      YV(I,J)=0.1*(COEFF(KW(I,J),NUP1,1)+ADEL(I,J))
      ZV(I,J)=0.001*(COEFF(KW(I,J),NUP1,2)+BDEL(I,J))
      KU(I,J)=A(I,J)/DU+1.5
      KU(I,J)=MINO(KU(I,J),NU-1)
      FU(I,J)=(A(I,J)-FLOAT(KU(I,J)-1)*DU)/DU
      C(I,J)=AMAX1(C(I,J),1.E-6)
      C(I,J)=ALOG10(C(I,J))
      C(I,J)=AMAX1(C(I,J),SW)
      KW(I,J)=(C(I,J)-SW)/DW+1.5001
      KW(I,J)=MINO(KW(I,J),NW-1)
      FW(I,J)=(C(I,J)-(SW+FLOAT(KW(I,J)-1)*DW))/DW
      ADEL(I,J)=(COEFF(KW(I,J)+1,KU(I,J),1)-COEFF(KW(I,J),KU(I,J),1))
     1 *FW(I,J)+(COEFF(KW(I,J),KU(I,J)+1,1)-COEFF(KW(I,J),KU(I,J),1))
     2 *FU(I,J)
      BDEL(I,J)=(COEFF(KW(I,J)+1,KU(I,J),2)-COEFF(KW(I,J),KU(I,J),2))
     1 *FW(I,J)+(COEFF(KW(I,J),KU(I,J)+1,2)-COEFF(KW(I,J),KU(I,J),2))
     2 *FU(I,J)
      WDEL(I,J)=(GL(KW(I,J)+1,KU(I,J))-GL(KW(I,J),KU(I,J)))*FW(I,J)+
     1          (GL(KW(I,J),KU(I,J)+1)-GL(KW(I,J),KU(I,J)))*FU(I,J)
      WW(I,J)=GL(KW(I,J),KU(I,J))+WDEL(I,J)
      WW(I,J)=AMAX1(WW(I,J),0.0)
      YW(I,J)=0.1*(COEFF(KW(I,J),KU(I,J),1)+ADEL(I,J))
      ZW(I,J)=0.001*(COEFF(KW(I,J),KU(I,J),2)+BDEL(I,J))
   10 CONTINUE
      RETURN
```

```
   0041         END


UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ---------------------------
LINE 0010               LINE 0038  RHS ARRAY MUST BE REAL, INTEGER, LOGICAL,
                                   HALF PRECISION, OR COMPLEX
LINE 0009               LINE 0010  NONVECTORIZABLE LOOP NESTED WITHIN LOOP

NUMBER OF LOOPS IN ROUTINE   = 0002

NUMBER OF VECTORIZABLE LOOPS = 0000

NUMBER OF STACKLIBED LOOPS   = 0000
```

```
   0001         SUBROUTINE GFUNC(N,A,B,C,WV,YV,ZV,WW,YW,ZW)
          C
          C
   0002         DIMENSION A(72,20),B(72,20),C(72,20),WV(72,20),YV(72,20),
               1  ZV(72,20),WW(72,20),YW(72,20),ZW(72,20)
   0003         DIMENSION A1(72,20),A2(72,20),A3(72,20),B1(72,20),B2(72,20),
               1  B3(72,20),B4(72,20),C1(72,20),C2(72,20),C3(72,20),C4(72,20)
   0004         DO 20 J=1,N
   0005         DO 20 I=1,72
   0006         A1(I,J)=(1.0+32.2095*A(I,J))/(1.0+52.85*A(I,J))
   0007         A2(I,J)=(0.534874+199.0*A(I,J)-1990.63*A(I,J)*A(I,J))/(1.0+
               1         333.244*A(I,J))
   0008         A3(I,J)=(1.0+74.144*A(I,J))/(0.43368+24.7442*A(I,J))
   0009      20 CONTINUE
   0010         DO 30 J=1,N
   0011         DO 30 I=1,72
   0012         WW(I,J)=(A1(I,J)+A2(I,J)*SQRT(C(I,J)))
               1        /(1.0+A3(I,J)*SQRT(C(I,J)))
   0013         WW(I,J)=AMAX1(WW(I,J),0.0)
   0014         WV(I,J)=1.0/(1.0+9.22411*SQRT(B(I,J))+33.1236*B(I,J)+176.396
               1        *B(I,J)*B(I,J))
   0015         WV(I,J)=AMAX1(WV(I,J),0.0)
   0016      30 CONTINUE
   0017         DO 40 J=1,N
   0018         DO 40 I=1,72
   0019         A(I,J)=AMIN1(A(I,J),0.06)
   0020         B(I,J)=AMIN1(B(I,J),2.0)
   0021         C(I,J)=AMIN1(C(I,J),8.0)
   0022      40 CONTINUE
   0023         DO 50 J=1,N
   0024         DO 50 I=1,72
   0025         YV(I,J)=0.1*(0.0851069*SQRT(B(I,J))+0.323105*B(I,J)-0.187096
               1        *B(I,J)*SQRT(B(I,J)))
   0026         ZV(I,J)=0.001*(0.239186*B(I,J)-0.0922289*B(I,J)*SQRT(B(I,J))-
               1         0.0167413*B(I,J)*B(I,J))
   0027      50 CONTINUE
   0028         DO 60 J=1,N
   0029         DO 60 I=1,72
   0030         B1(I,J)=(5.6383E-4+1.05173*A(I,J)-39.0722*A(I,J)*A(I,J))
               1        /(1.0+202.357*A(I,J))
   0031         B2(I,J)=(0.0779555+4.40720*A(I,J)+3.15851*A(I,J)*A(I,J))
                1       /(1.0+40.2298*A(I,J))
```

```
0032          B3(I,J)=(-0.0381305-3.63684*A(I,J)+7.98951*A(I,J)*A(I,J))
             1        /(1.0+62.5692*A(I,J))
0033          B4(I,J)=(0.00621039+0.710061*A(I,J)-2.85241*A(I,J)*A(I,J))
             1        /(1.0+70.2912*A(I,J))
0034          YW(I,J)=0.1*(B1(I,J)+B2(I,J)*SQRT(C(I,J))+B3(I,J)*C(I,J)
             1        +B4(I,J)*C(I,J)*SQRT(C(I,J)))
0035       60 CONTINUE
0036          DO 70 J=1,N
0037          DO 70 I=1,72
0038          C1(I,J)=(-2.99542E-4+0.238219*A(I,J)+0.519264*A(I,J)*A(I,J))
             1        /(1.0+10.7775*A(I,J))
0039          C2(I,J)=(-0.0291325-2.30007*A(I,J)+10.9460*A(I,J)*A(I,J))
             1        /(1.0+63.519*A(I,J))
0040          C3(I,J)=(0.0143812+1.80265*A(I,J)-10.1311*A(I,J)*A(I,J))
             1        /(1.0+98.4758*A(I,J))
0041          C4(I,J)=(-0.00239016-0.371427*A(I,J)+2.35443*A(I,J)*A(I,J))
             1        /(1.0+120.228*A(I,J))
0042          ZW(I,J)=0.001*(C1(I,J)+C2(I,J)*SQRT(C(I,J))+C3(I,J)*C(I,J)
             1        +C4(I,J)*C(I,J)*SQRT(C(I,J)))
0043       70 CONTINUE
0044          RETURN
0045          END
```

```
UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ----------------------------
LINE 0018               LINE 0021   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0017               LINE 0018   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0011               LINE 0015   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0010               LINE 0011   NONVECTORIZABLE LOOP NESTED WITHIN LOOP

NUMBER OF LOOPS IN ROUTINE    = 0012

NUMBER OF VECTORIZABLE LOOPS = 0008

NUMBER OF STACKLIBED LOOPS    = 0000
```

```
0001          SUBROUTINE TRC03(N,A,B,C,D,E,F,TAUF,TXUF)
        C
        C
0002          DIMENSION A(72,20),B(72,20),C(72,20),D(72,20),E(72,20),F(72,20)
0003          DIMENSION TAUF(72,20),TXUF(72,20)
0004          DIMENSION XV(72,20),XW(72,20),XZ(72,20),DX(72,20),DY(72,20)
0005          DO 10 J=1,N
0006          DO 10 I=1,72
0007          XV(I,J)=3.1*A(I,J)/(1.+15.1*A(I,J)**0.56)
0008          XW(I,J)=0.04*B(I,J)/(1.+0.9*B(I,J)**0.57)
0009          DX(I,J)=6.7*C(I,J)/(1.+16.*C(I,J)**0.6)
0010          DY(I,J)=27.*D(I,J)**0.83
0011          XV(I,J)=XV(I,J)+DX(I,J)+DY(I,J)
0012          XW(I,J)=XW(I,J)+DX(I,J)+DY(I,J)
0013          XV(I,J)=AMIN1(XV(I,J),30.)
0014          XW(I,J)=AMIN1(XW(I,J),30.)
0015          TAUF(I,J)=0.384615384*EXP(-XV(I,J))+0.615384615*EXP(-XW(I,J))
0016          DY(I,J)=9.79*D(I,J)
0017          DY(I,J)=AMIN1(DY(I,J),30.)
0018          F(I,J)=F(I,J)/(E(I,J)*1013.25)
```

```
 0019          XZ(I,J)=4.*345.28*E(I,J)/(0.8796*F(I,J))
 0020          XZ(I,J)=-4.398*F(I,J)*(SQRT(1.+XZ(I,J))-1.)
 0021          XZ(I,J)=1.0-81.21/120.0*(1.0-EXP(XZ(I,J)))
 0022          TXUF(I,J)=XZ(I,J)*EXP(-DY(I,J))
 0023      10  CONTINUE
 0024          RETURN
 0025          END

UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ----------------------------
LINE 0006               LINE 0017   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0005               LINE 0006   NONVECTORIZABLE LOOP NESTED WITHIN LOOP

NUMBER OF LOOPS IN ROUTINE   = 0002

NUMBER OF VECTORIZABLE LOOPS = 0000

NUMBER OF STACKLIBED LOOPS   = 0000
```

```
 0001          SUBROUTINE CLOUDS
         C
         C
 0002          COMMON/CSC/CSS(72,20),CCU(72,20),CH(72,20),CC(72,20)
              1,           CS(72,20,20)
 0003          COMMON/INIT/NP,NPP1,NPM1
 0004          DIMENSION CT(72,20),CU(72,20),CR(72,20,20)
 0005          DO 10 IP=1,NP
 0006          DO 10 IL=1,72
 0007          CH(IL,IP)=1.0
 0008          CC(IL,IP)=1.0
 0009          CT(IL,IP)=1.0
 0010          CU(IL,IP)=1.0
 0011      10  CONTINUE
 0012          DO 15 IP=1,NP
 0013          DO 15 IX=1,NP
 0014          DO 15 IL=1,72
 0015          CS(IL,IX,IP)=1.0
 0016          CR(IL,IX,IP)=1.0
 0017      15  CONTINUE
 0018          DO 20 IP=2,NP
 0019          DO 20 IL=1,72
 0020          CT(IL,IP)=1.-CCU(IL,IP-1)
 0021          CT(IL,IP)=AMIN1(CT(IL,IP-1),CT(IL,IP))
 0022          CH(IL,IP)=CH(IL,IP-1)*(1.-CSS(IL,IP-1))
 0023      20  CONTINUE
 0024          DO 30 IP=2,NP
 0025          DO 30 IL=1,72
 0026          CH(IL,IP)=CH(IL,IP)*CT(IL,IP)
 0027      30  CONTINUE
 0028          DO 40 I=1,NPM1
 0029          IP=NP-I
 0030          DO 40 IL=1,72
 0031          CU(IL,IP)=1.-CCU(IL,IP)
 0032          CU(IL,IP)=AMIN1(CU(IL,IP+1),CU(IL,IP))
 0033          CC(IL,IP)=CC(JL,IP+1)*(1.-CSS(IL,IP))
 0034      40  CONTINUE
```

```
0035          DO 50 I=1,NPM1
0036          IP=NP-I
0037          DO 50 IL=1,72
0038          CC(IL,IP)=CC(IL,IP)*CU(IL,IP)
0039      50  CONTINUE
0040          DO 60 IP=2,NP
0041          IPM1=IP-1
0042          DO 60 IX=1,IPM1
0043          DO 60 IL=1,72
0044          CR(IL,IX,IP)=1.-CCU(IL,IP-1)
0045          CR(IL,IX,IP)=AMIN1(CR(IL,IX,IP-1),CR(IL,IX,IP))
0046          CS(IL,IX,IP)=CS(IL,IX,IP-1)*(1.-CSS(IL,IP-1))
0047      60  CONTINUE
0048          DO 70 IP=2,NP
0049          IPM1=IP-1
0050          DO 70 IX=1,IPM1
0051          DO 70 IL=1,72
0052          CS(IL,IX,IP)=CS(IL,IX,IP)*CR(IL,IX,IP)
0053      70  CONTINUE
0054          DO 80 I=1,NPM1
0055          IP=NP-I
0056          IPP1=IP+1
0057          DO 80 IX=IPP1,NP
0058          DO 80 IL=1,72
0059          CR(IL,IX,IP)=1.-CCU(IL,IP)
0060          CR(IL,IX,IP)=AMIN1(CR(IL,IX,IP+1),CR(IL,IX,IP))
0061          CS(IL,IX,IP)=CS(IL,IX,IP+1)*(1.-CSS(IL,IP))
0062      80  CONTINUE
0063          DO 90 I=1,NPM1
0064          IP=NP-I
0065          IPP1=IP+1
0066          DO 90 IX=IPP1,NP
0067          DO 90 IL=1,72
0068          CS(IL,IX,IP)=CS(IL,IX,IP)*CR(IL,IX,IP)
0069      90  CONTINUE
0070          RETURN
0071          END
```

```
UNCOLLAPSIBLE LOOPS     REASON FOR NON-VECTORIZATION
-------------------     ----------------------------
LINE 0063               LINE 0066   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP
LINE 0054               LINE 0057   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP
LINE 0057               LINE 0061   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                    VECTORIZATION OF LOOP
LINE 0058               LINE 0060   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0048               LINE 0050   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP
LINE 0040               LINE 0042   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP
LINE 0043               LINE 0046   RHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
LINE 0042               LINE 0043   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0035               LINE 0038   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                    VECTORIZATION OF LOOP
LINE 0028               LINE 0033   PROPERTY OF EMBEDDED LOOP PROHIBITS
                                    VECTORIZATION OF LOOP
LINE 0030               LINE 0032   STATEMENT CONTAINS NONVECTORIZABLE FUNCTION
LINE 0019               LINE 0022   RHS ARRAY HAS POSSIBLY RECURSIVE PROPERTIES
```

```
LINE 0018               LINE 0019   NONVECTORIZABLE LOOP NESTED WITHIN LOOP
LINE 0012               LINE 0013   LOOP WITH VARIABLE INITIAL/TERMINAL VALUE
                                    NESTED WITHIN LOOP

NUMBER OF LOOPS IN ROUTINE   = 0025

NUMBER OF VECTORIZABLE LOOPS = 0011

NUMBER OF STACKLIBED LOOPS   = 0000
```