A REVIEW OF PARAMETERIZATION SCHEMES FOR RADIATIVE TRANSFER

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1. INTRODUCTION

Radiative transfer plays an important role in the dynamics of the atmosphere at a variety of time and spatial scales. As such, its effects must be included in models that attempt to portray the evolution of weather and climate systems. The inclusion of such effects in models is compounded by the details of the physics that govern the transfer of electromagnetic radiation, particularly the monochromatic nature of the transfer. Given enough computer time, most details concerning the radiative transfer could, in theory, be accommodated, although at questionable accuracy for some physical problems. If all such details were included, however, we might yet be waiting for our first climate simulation.

Interest in obtaining climate simulations in a practical amount of time has led to the development of more simplified radiative transfer models that include the major effects of atmospheric media on the heating and cooling of the atmosphere by radiation. A rather large body of literature has been compiled on these less detailed or parameterized models over the past 50 years, and any attempt at to review any portion of this field in detail would be faced with a monumental task. Therefore, I have decided to give a rather cursory review of the elements that I find to be most important and that summarize the current state of the important aspects of this area. Nevertheless, the reader is encouraged to consult the literature for the requisite details. Recent texts by Liou (1992) and Stephens (1994) offer excellent starting points, and Stephens (1984) presents an excellent summary of parameterization of radiation for climate studies.

2. RADIATIVE TRANSFER

The basic physics governing the transfer of electromagnetic radiation are generally well-understood. Following Goody (1964), the basic equation governing the transfer of radiation may be written as

$$dI_\nu(p,\vec{s}) = -e_\nu \rho_a ds\, I_\nu(p,\vec{s}) + e_\nu \rho_a ds\, J_\nu(p,\vec{s}) \qquad (1)$$

where I_ν is the specific intensity of radiation at frequency ν in direction s, e_ν is the extinction coefficient (sum of the scattering absorption coefficients), ρ_a is the density of the radiatively active material which influence the transfer in direction s, and J_ν is the source function for radiation (thermal emission as well as scattering into s). The detailed physics of the problem are associated with e_ν and J_ν. It must be remembered that (1) applies to monochromatic radiation (i.e., radiation within a wavenumber (inverse of wavelength) interval the order of 10^{-4} cm^{-1})

Mathematical solutions to (1) are relatively straightforward for many useful problems given information concerning the geometry of the problem and the radiative properties of the boundaries. Furthermore, computational resources are now available to obtain numerical solutions if the radiative properties can be specified.

Climate modelers are generally interested in the spectrally integrated fluxes and heating rates. Unfortunately, the mathematical formalism developed with the monochromatic solutions is not transferable to frequency averaged radiation. Furthermore, modelers are generally interested in effects of quantities over large spatial domains. The challenge of developing models for climate applications is to find solutions to (1) that adequately account for frequency variations as well as the spatial variations of the radiative fields.

The major obstacle for frequency integration of (1) is the spectral detail of gaseous absorption. Absorption features are quantized, although the features are broadened due to collisions and/or thermal motions of the molecules. Nevertheless, the discontinuous nature of gaseous absorption features prohibit analytical solutions without approximations. Furthermore, the details concerning line shapes are not well known, particularly for water vapor.

Cloud particles and other aerosols tend to have relatively slowly varying spectral absorption features. Outside of homogeneous spherical particles, however, our knowledge of cloud and aerosol radiative properties is in its infancy, particularly as regards suspended ice particles. Furthermore, the horizontal and vertical distributions of clouds fall into an seemingly infinite range of possibilities, thereby precluding easy solutions.

Generally, however, most climate models tend to determine fluxes and cooling rates by taking the cloud amount(s) weighted average of values that are calculated assuming clear and overcast conditions separately. For example, the flux of radiation F at a given level is often calculated as

$$F = (1-N^*)\, F_c + N^*\, F_o \qquad (2)$$

where F_c and F_o are the fluxes calculated assuming homogeneous clear and overcast conditions respectively, and N^* is the effective cloud fraction. N^* can be used to include all those effects not included in F_o and F_c. Clear-skies are generally assumed to include the effects of absorption, scattering and thermal emission by the atmospheric gases and non-cloud aerosols.

It is common to distinguish between radiation from the sun, or solar radiation, and that thermally emitted by the earth-and atmosphere, or terrestrial radiation. About 99% of the radiation received from the sun is contained at wavelengths less than 4 μm, whereas about 99% of the terrestrial radiation is at wavelengths greater than 4 μm (2500 cm^{-1}). Solar and terrestrial radiation are commonly referred to as shortwave and longwave, respectively. Since the physical processes that dominate the transfer above and below about 4 μm are largely different (scattering and absorption by gases, clouds and aerosols below and thermal emission and absorption by gases and clouds above), modeling has often been done by different communities.

One should not be misled by the simplicity of the form of (2) into thinking that the parameterization problem is simple, because the details associated with the parameterization of each of the terms are substantial. The material below provides but a thumbnail sketch of some aspects of each of the terms. Nevertheless, the discussion does not include parameterization of scattering by atmospheric gases or non-cloud aerosols, details of which can be easily found in the aforementioned literature.

3. TECHNIQUES FOR CALCULATING RADIATIVE TRANSFER - GASES

Techniques for calculating radiative transfer are most easily classified according to the techniques employed to perform the spectral integration of the gaseous absorption features, namely line-by-line (LBL) models and Band Models. Calculations in LBLs are performed monochromatically, and they often include all of the detailed physics including multiple scattering. Descriptions of such techniques are given by Scott and Chedin (1981), Edwards (1988), Ridgeway et al. (1991), Feigelson et al. (1991), and Clough et al. (1992). Generally, these techniques offer the possibility to perform all of the numerics with high accuracy. They are particularly useful for checking the approximations made in less detailed models.

Nevertheless, LBLs require substantial computing resources. For example, the thermal infrared portion of the spectrum from may require the order of 10^7 intervals for monochromatic computations. Such computations were prohibitively expensive until the advent of supercomputers, but they are now relatively easy to do on desktop workstations. Furthermore, it is now possible to perform such calculations for a wide variety of atmospheric gases because of the wide distribution of tabular values of the line strengths and half-widths important for line absorption (e.g., Rothman et. al., 1987). However, these models are too time consuming to be used in climate models.

Climate modelers are interested in obtaining the distribution of radiative fluxes for the entire spectrum, and models of the spectrally integrated nature of gaseous absorption (i.e., band models) offer the possibility of rapid, but accurate, evaluation of the integral over detailed gas absorption spectra. The common approach used in band models is to make assumptions concerning the spectral distribution of absorption features for a homogeneous path that allow a solution in terms of analytical functions with a few adjustable parameters. The values of the adjustable parameters are specified either through fitting to more detailed model calculations or to asymptotic limits expressed in terms of line strengths and half-widths. Such models are applied to the inhomogeneous atmospheric path through a variety of scaling approximations developed from asymptotic solutions or linear expansions (e.g., the Curtis-Godson approximation). Excellent discussion of such techniques may be found in Goody (1964) and Liou (1992).

The analytical models take on a variety of forms and spectral resolution. Typically, those with spectral resolution less than about 50 cm^{-1} are called narrow band models, and those for larger intervals being labeled as wide band models. There has been a general assumption that the smaller the spectral interval, the more accurate the result. The results of the Intercomparison of Radiation Codes Used in Climate Models (ICRCCM; Ellingson and Fouquart, 1991), discussed below, do not substantiate that position, however.

In an attempt to surmount the problem of arbitrary assumptions concerning the properties of analytic models, there have been several attempts to develop tabular values from LBL calculations (e.g., Chou and Arking, 1980; Fels and Schwartzkopf, 1981; Harshvardhan et al., 1987). Such approaches increase numerical accuracy and speed at the expense of storage allocation, now a relatively minor problem.

Band models of the type discussed above have a serious limitation when applied to problems involving multiple scattering, because the multiplication property of transmittances applicable to monochromatic radiation no longer hold for frequency averaged radiation. To avoid this problem, modelers have developed what is commonly called the k-distribution technique, a good discussion of which is given by Lacis and Oinas (1991). This technique makes a transformation of the integral over frequency to one over absorption coefficient, since in a narrow spectral interval the intensity is the same when the absorption coefficient is the same. Thus, the frequency integration problem reduces to a sum of monochromatic problems. This approach requires the probability or cumulative probability distribution of absorption coefficients that may be determined numerically from LBL calculations or analytically from some band models.

The k-distribution technique is not without limitations, however, because approximations must be made for application to the inhomogeneous atmosphere, and one may be required to keep large numbers of k's for applications at low pressures (i.e., above about 20 km).

In summary, it must be remembered that band models are approximations and unwanted errors may occur unexpectedly. Some general statements concerning such models are:

- Their absolute accuracy is only as good as that of the more detailed models or data on which they are based;
- Fits based on asymptotic limits may be inaccurate for atmospheric calculations;
- Accounting for overlapping absorption by two or more gases may be difficult for large band areas;
- Application of scaling approximations are inaccurate in some situations; and
- They are difficult to use in problems involving multiple scattering.

4. CALCULATION OF CLOUD RADIATIVE PROPERTIES

Detailed calculations for horizontally homogeneous clouds require information concerning the scattering phase function, the amount of material, and the monochromatic absorption and scattering coefficients. These may be determined (approximately) given the chemical composition, shape(s), size(s) and number of each sized particle in the cloud (see Liou, 1992). Most parameterized models, however, use substantially less information.

Prior to about 1989, most climate model radiation parameterizations used fixed radiative properties and simplified models for clouds because the climate models were incapable of providing information on the cloud properties. In recent years there has been a concerted effort at developing unified treatments of short-and-long wave models that include the effects of multiple scattering (e.g., Slingo, 1989; Stephens et al., 1990; Fu and Liou, 1993). In general, such parametric models make use of approximate solutions of the radiative transfer equation that include multiple scattering through the use of two-stream type approximations. These solutions generally require information on cloud optical depth τ, the asymmetry factor g, (a measure of directionality of scattering) and the albedo of single scattering ω (the ratio of scattering to total optical depth).

As discussed by Liou (1992), asymptotic theory in the visible portion of the spectrum shows that the important parameters for liquid water clouds may be written as

$$\tau \approx \frac{3}{2}\frac{LWP}{r_e} \qquad 1-\omega = \frac{2}{3}k_v r_e \qquad g \approx 0.85 \tag{3}$$

where LWP is the integrated liquid water path through the cloud, r_e is the effective droplet radius and k_v is the droplet absorption coefficient.

Slingo (1989) used results based on a number of droplet size distributions to specify the cloud radiative properties in four shortwave spectral bands as

$$\tau_i = LWP\,(a_i + b_i / r_e) \qquad \omega_i = c_i + d_i r_e \qquad g_i = e_i + f_i r_e \tag{4}$$

where the subscript i denotes the i-th spectral interval and the quantities a-f are empirical coefficients. This type of parameterization requires the LWP and the values of r_e to be specified by the climate model in which it is used.

Liquid water cloud parameterizations in the longwave have generally followed the work of Stephens (1984) who introduced an effective cloud emissivity ε defined as

$$\varepsilon = 1 - \exp\left[-k\,LWP\right] \tag{5}$$

where $k \sim 0.25\ m^2\ g^{-1}$ for flux calculations. This parameterization is based on more detailed calculations for a variety of cloud drop distributions and includes effects of multiple scattering. One should be cautious when applying such parameterizations in a model that has different physics for the molecular absorption. Note that $\varepsilon \sim 1$ for a 300 m thick cloud with a liquid water content of $0.15\ g\ m^{-3}$. As a result, many modelers assume liquid water clouds to be black.

The parameterization of ice water clouds is much more complicated than that for liquid water because the quantities that play a major role in detailed solutions of the problem, the ice crystal shapes, orientation and number distributions, can not be modeled or specified precisely. Nevertheless, excellent descriptions of the formalism required to obtain approximate solutions are given by Stephens et al. (1990) for ice crystals approximated as spheres and by Fu and Liou (1993) for randomly oriented hexagonal ice crystals. The message common to both is that the parameterizations for solar and longwave problems must follow a consistent treatment of the cirrus radiative properties.

Both investigations show, as expected from asymptotic theory, that the optical depth depends inversely on a measure of the crystal size. Fu and Liou's parameterization is written as

$$\tau = IWP \sum_{n=0}^{2} a_n / D_e^n \qquad \omega = \sum_{n=0}^{3} b_n D_e^n \qquad g = \sum_{n=0}^{3} c_n D_e^n \quad (IR) \tag{6}$$

where D_e is the effective width of the crystals, IWP is the ice water path, the parameters a-c are empirical coefficients determined from fits to a wide range of crystal size distributions, and the parameterization for g holds only in the longwave. The shortwave scattering properties are much more complicated. Note that both investigations point out that there is a temperature dependence to the parameterizations because of the temperature dependence of the ice water content of cirroform clouds.

The different cloud parameterizations have been compared with data from field experiments with mixed results. Validation of such parameterizations is a major component of ongoing projects such as FIRE in the US and EUCREX in Europe, and we should expect to see substantial improvements in these areas over the coming years.

5. FINITE SIZED CLOUDS

The parameter N* represents the effects of geometry and horizontal inhomogeneity that is not accounted for in the plane parallel assumptions. This is an active area of research by the international community, but I do not know of any climate model that includes such effects at the present time. Similarly, I know of no sensitivity tests of climate models to cloud geometry. Therefore, I have decided not to include this topic in the paper. This should not be construed to imply that this is an unimportant topic!

6. DISCUSSION

A logical question at this point is "How accurate are the various radiation models?" In 1983 the World Climate Research Program (WCRP) ordained a working group to examine this question under the acronym ICRCCM, the Intercomparison of Radiation Codes used in Climate Models. ICRCCM defined a set of clear and homogeneous cloud calculations that were to be done by the various climate modeling groups throughout the world. Workshops to discuss the results of the various calculations were carried out in 1984 and 1988, and formal publications describing the overall results appeared in the literature by Luther et al. (1988), Ellingson and Fouquart (1991), Ellingson et al. (1991) and Fouquart et al. (1991) (16 papers on ICRCCM related results appeared in a special 1991 edition of *J. Geophys. Res. Atmospheres*, pages 8921-9157). The reader is encouraged to consult those papers.

The results of the ICRCCM longwave clear-sky study may be stated as:

- Different line-by-line (LBL) model results tend to agree to within 1%. LBL modelers, however, do not believe that their results should be taken as an absolute reference.
- Medians of band model results agree within 1 to 2% with LBL results. However, there is a large variation among the models - 5 to 10% rms differences with LBL results.
- Band model calculations of absorption by individual gases show poorer agreement with LBL results than do fluxes.
- The H2O continuum masks many differences between model results. The continued absence of a widely accepted theory for it poses limitations for climate studies.

For the shortwave clear-sky study, Fouquart et al. (1991) summarize the conclusions as:

- Different parameterizations for H2O absorption may lead to significant differences between band model results.
- If the discrepancies attributable to various water vapor transmittances are removed, flux calculations at the surface generally agree to within 1%.
- Provided that the Rayleigh optical thickness is adequately parameterized, climate model codes appear to simulate clear-sky fluxes in reasonable correspondence with results from the high-resolution codes.

ICRCCM could not place an absolute accuracy on the various models because it could not identify a set of accurate observations with which to adequately test the models. This led to the recommendation of a second phase of ICRCCM which would attempt to formulate and carry out field experiments to obtain the necessary spectral observations to calibrate the more detailed models. An earlier paper in this volume by the author reports on three such projects.

It is the authors opinion that the results of SPECTRE and ARM indicate that the validity of longwave LBL models for calculating clear-sky fluxes in the atmosphere is close to being established at the 1% level for the major atmospheric absorbers - H2O, CO2 and O3. Observations of atmospheric heating rates are pretty sparse. Nevertheless, substantial progress should be made in this area during the next few years with UAVs. Similar statements can not be said for the shortwave, because there has not yet been a concerted effort to obtain accurate, detailed solar spectra concurrent with the measurement of the atmospheric radiative properties.

It must be emphasized, however, that none of the parameterized models used in climate studies yet include the water vapor continuum in a manner consistent with the Clough et al. (1989) continuum that is included in the LBL model compared with the SPECTRE observations. That is, both the water vapor spectral lines and the continuum must be treated together for the entire spectrum. Such new parameterizations should not be trusted until they have completed the ICRCCM test cases and compared calculations with the SPECTRE observations. A limited set of those data are available electronically from the author (bobe@atmos.umd.edu). The complete set of SPECTRE data will be available on CD-ROM early in 1995.

The situation for clouds is not as optimistic as that for clear-skies. ICRCCM concluded:

- For near-black clouds, the longwave calculations agree closely near the cloud boundaries. At distances away from the boundaries, the differences resemble those of the clear-sky calculations.
- There is a large spread of longwave fluxes (35 to 80 W m^{-2}) for optically thin clouds which appear to be attributable to the manner by which the clouds are treated in the models.

- For the shortwave, large differences between models occur which are attributed to the manner by which multiple scattering is taken into account in the low resolution codes.

It should be noted, however, that ICRCCM tested rather simple parameterizations of cloud effects and those did not include the more sophisticated treatments discussed herein. Such an intercomparison would serve a very useful purpose, and these in turn could perhaps have important input to the various cloud-radiation observation programmes.

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