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"A Review of Parameterization Schemes for Radiative Transfer"

(Transparencies)

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Please note: These are preliminary notes intended for internal distribution only.

A Review of Parameterization Schemes for Radiative Transfer

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Important Questions

Are climate models sensitive to radiation?

What radiation quantities need to be calculated?

How accurately do they need to be calculated?

How can one tell if a model is useful for a climate/NWP application?

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Climate Model Sensitivity to Radiation

Model climates are, in general, *very sensitive* to radiation

- The projected effects of a 1% change in the solar constant are the result of a change of about a 3.5 $W \cdot m^{-2}$ in the annually and globally-averaged energy incident on the earth's atmosphere.
- The projected effects doubling of CO2 concentration from 300 to 600 ppmv result from about a 4 $W \cdot m^{-2}$ change in the net flux at the tropopause.
- A systematic 10 $W \cdot m^{-2}$ error in the surface radiation budget will lead to about a 1°C change in sea level temperature if it persists for a year.

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Required Accuracy

Depends upon the application

Examples

Estimation of surface greenhouse effect

$$\Delta T_{sfc} = \beta \Delta F_{net}(\text{tropopause})$$

Uncertainty in the greenhouse effect

$$\delta(\Delta T_{sfc}) = \delta\beta \bullet \Delta F_{net} + \beta \bullet \delta(\Delta F_{net})$$

Uncertainty in the estimation of sea surface temperature

$$\delta T_{sfc} = \gamma\, \delta F_{net}$$

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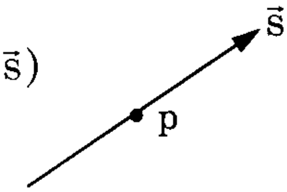
Radiative Transfer - General

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



- Basic equations governing the transfer of radiation are generally well-known
- Mathematical solutions possible for many useful problems
- Basic physics are generally well-understood
- Computational resources are now available to work on almost any problem

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Interaction of Radiation and Matter

F_o - Incident Flux ⇓

$\varepsilon\sigma T^4$ - Emitted ⇑

$F_o R$ - Reflected ⇑

Layer of Matter

$F_o A$ - Absorbed

⇓ **$\varepsilon\sigma T^4$ - Emitted**

⇓ **$F_o T$ - Transmitted**

$R + T + A = 1$

T - Transmissivity

R - Reflectivity

A - Absorptivity

ε - Emissivity

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Radiative Transfer - Practical

- Basic equations apply to monochromatic radiation, whereas we are interested in frequency averaged or integrated radiation. Monochromatic formalism is not transferable.
- Major obstacle for practical application is the spectral detail of gaseous absorption.
- Details concerning line shapes are not well known, particularly for water vapor.
- Radiative properties of clouds, even simple ones, are not well known or are difficult to model (particularly ice clouds)

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Calculation of Fluxes and Heating Rates

Most models make the approximation

$$F = (1 - N^*) F_{clear} + N^* F_{cloudy}$$

where N^* is the "effective" cloud fraction, and F_{clear} and F_{cloudy} are homogeneous (plane-parallel) clear- and cloudy- sky fluxes, respectively. Clear-skies are generally assumed to include the effects of absorption, scattering and thermal emission by the atmospheric gases and non-cloud aerosols. Parameterizations must be developed for each term.

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Basic Techniques for Calculating Radiation

2 Major Types

- **Line-by-Line radiation codes**
- **Band Models (Narrow and Broad)**

Line-by-line Models

- May include all of the detailed physics including multiple scattering

  All of the numerics performed with high accuracy

- Useful for checking less detailed models
- Extremely computer time consuming

  Impractical for use in climate simulations because the calculations must be performed at a spectral resolution of ~ 10^{-4} cm^{-1}

Band Models

Purpose

Rapid, but accurate, evaluation of the integral over detailed gas absorption spectra.

Common Approach

Perform the integral over wavelength for a homogeneous path. Scale to the atmosphere using results from radiative transfer theory (e.g., Curtis-Godson Approximation).

$$A(a,p,T) = \int_{\Delta\nu} (1 - e^{-k_\nu a}) d\nu = f(a,p,T)$$

$$A(\text{atmospheric path}) = \int_{\Delta\nu} (1 - e^{-\int k_\nu \rho_a dz}) d\nu = f(\bar{a},\bar{p},\bar{T})$$

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Popular Band Model Approaches

- Analytic equations fit to spectral line data or LBL calculations (e.g., Malkmus model)
- Empirical formulae fit to LBL/NBM calculations or laboratory observations
- Tabular values from LBL/NBM model calculations
- Transformation of the integral over frequency to that over absorption coefficient followed by a fit to NBM/LBL calculations
(i.e., the k-distribution technique)

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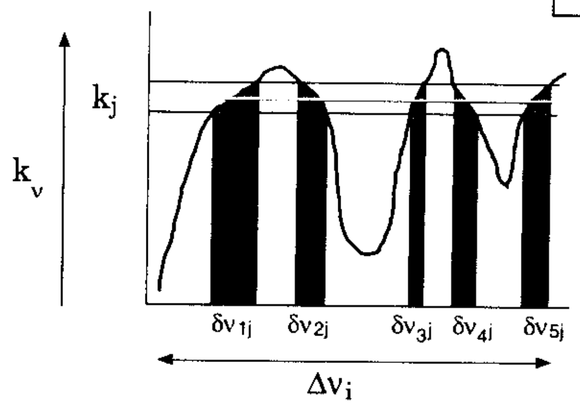
k-Distribution Approach

$$I_i \equiv \frac{1}{\Delta\nu_i}\int I_\nu d\nu$$

Since the Planck function or the solar constant is about constant within an interval, I_ν is the same when k_ν is the same.



$$a_j = \sum_k \frac{\delta\nu_{kj}}{\Delta\nu}$$

Fraction of $\Delta\nu_i$ for which $k_\nu \sim k_j$

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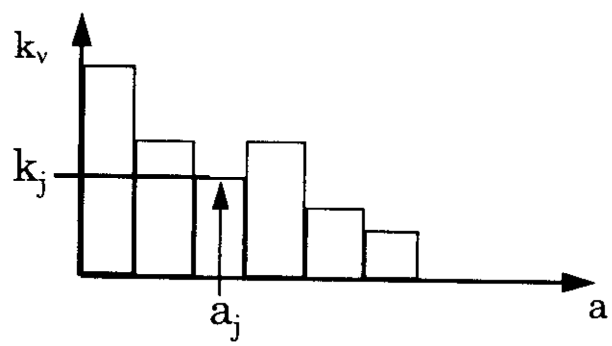
k-Distribution Approach - cont.

Rearrange k_ν as a probability histogram



Now we need only solve M monochromatic problems

$$I_i = \sum_{j=1}^{M} a_j I(k_\nu = k_j)$$

The appropriate histograms may be obtained from LBL or band model calculations.

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Band Model Problems

- The absolute accuracy of such models are 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

Band Model Problems - cont.

- Application of scaling approximations are inaccurate in some situations
- Difficult to to use in problems involving multiple scattering (with the exception of k-distribution)
- Difficult to develop *one* model that is adequate for the entire range of atmospheric variability or which can accommodate all radiative processes

Results from ICRCCM

See the following publications for a complete description of ICRCCM

Luther, F. M., et al., 1988: Intercomparison of radiation codes in climate models (ICRCCM): Longwave clear-sky results. *Bull. Amer. Meteor. Soc.*, **69**, 40-48.

Special edition of *J. Geophysical Research - Atmospheres*, May 20, 1991, 8921-9157. (16 papers)

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Results from ICRCCM - LW

- Different line-by-line (LBL) model results tend to agree to within 1%. LBL modelers 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.

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Results from ICRCCM - SW

- 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.
- More definitive recommendations will emerge only from comparisons of high resolution calculations with high precision observations.

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Progress Since ICRCCM I

SPECTRE

The Spectral Radiance Experiment (Nov.-Dec.'91)

FIRE

The First ISCCP Regional Experiment

ARM

The Atmospheric Radiation Measurements Program (1 Nov. 1990 - present)

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Current ICRCCM Initiative

Compare Model Calculations with *Clear-Sky* Radiance Observations from *SPECTRE*

- Participants furnished with four soundings, but only one detailed observed spectrum
- Remaining observations integrated to model resolution* distributed after calculations received
- Data exchange via ftp

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Progress to Date

- 23 participants with 30 sets of calculations
  - 10 line-by-line
  - 13 narrow band
  - 7 Broad-band (6 climate model types)
- Line-by-line and narrow-band results integrated to a common spectral grid
- Spectral and spectrally integrated results compared for LBL and NB models
- Workshop to discuss results - 24 - 26 May 1995

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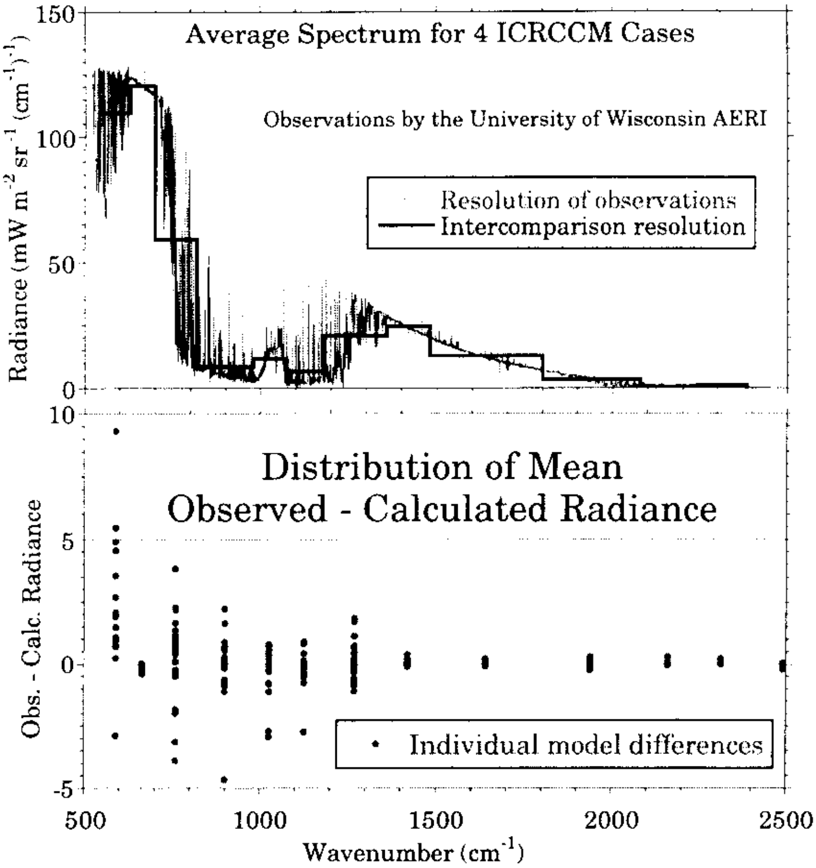
Average Spectrum for 4 ICRCCM Cases
Observations by the University of Wisconsin AERI
Resolution of observations
Intercomparison resolution
Radiance (mW m-2 sr-1 (cm-1)-1)
150
100
50
0
Distribution of Mean
Observed - Calculated Radiance
Obs. - Calc. Radiance
10
5
0
-5
Individual model differences
500
1000
1500
2000
2500
Wavenumber (cm-1)

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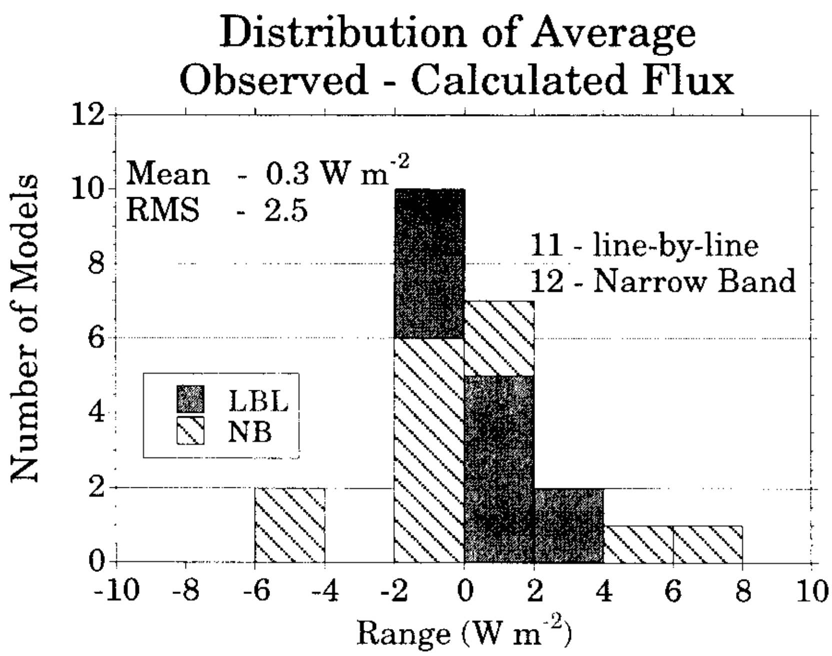
Distribution of Average
Observed - Calculated Flux
Number of Models
12
10
8
6
4
2
0
Mean - 0.3 W m-2
RMS - 2.5
11 - line-by-line
12 - Narrow Band
LBL
NB
-10
-8
-6
-4
-2
0
2
4
6
8
10
Range (W m-2)

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Status of the Clear-Sky Problem

Validation of models for calculating gaseous absorption in the atmosphere is close to being solved, at least for the thermal IR at the surface and for the major atmospheric absorbers. The same can not be said for the shortwave.

Observations of atmospheric heating rates are pretty sparse. Nevertheless, substantial progress should be made in this area during the next few years with UAV's.

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Calculation of Cloud Radiative Properties

Detailed radiation models require the scattering phase function, the amount of material, and the monochromatic absorption and scattering coefficients. These may be determined (approximated) given the:

chemical composition, shape(s), size(s) and number of each size particle size(s) in the cloud

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Parameterization of Cloud Radiative Properties

- Approximate solutions of RTE require

  cloud optical depth - τ

  asymmetry factor - g
  (measure of directionality of scattering)

  albedo of single scattering - ω
  (ratio of scattering to total optical depth)
- Parameterizations for solar and longwave must follow a consistent treatment of the radiative properties (particularly important for ice clouds)

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Parameterization of Liquid Water Clouds (visible)

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

LWP – Liquid water path = $\int w\,dz$

w – liquid water content

r_e – Effective droplet radius

k_v – Absorption coefficient

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Slingo* Parameterization

Using results based on a number size distributions, cloud radiative properties for four spectral bands are specified as

$$\tau_i = LWP(a_i + b_i / r_e)$$
$$\omega_i = c_i + d_i r_e$$
$$g_i = e_i + f_i r_e$$

This requires the LWP and r_e to be specified from the climate model.

* Slingo, A., 1989: *J. Atmos. Sci.*, **46**, 1419-1427.

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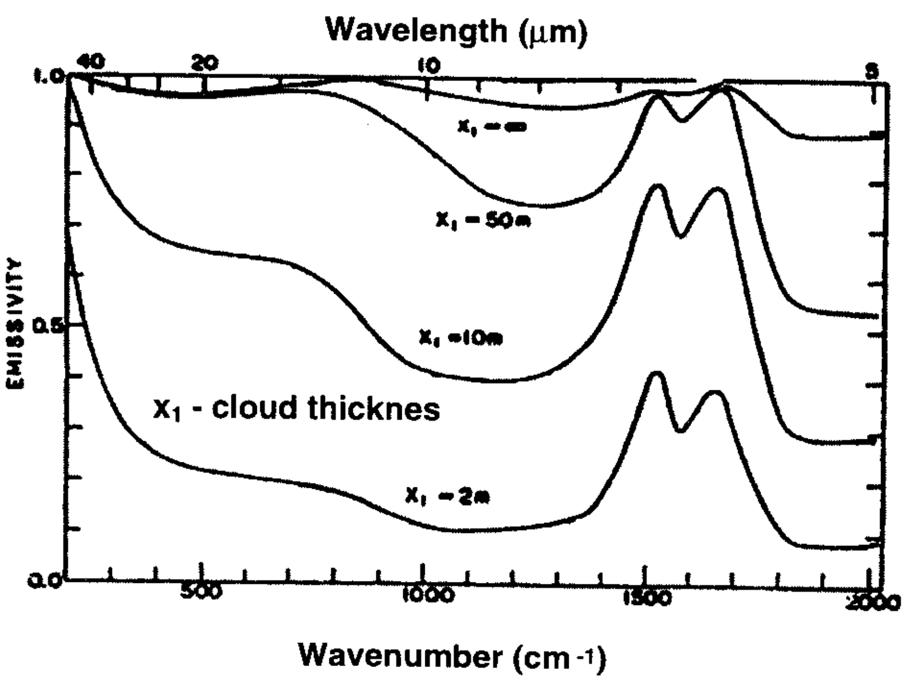
Longwave Properties of Liquid H2O Clouds



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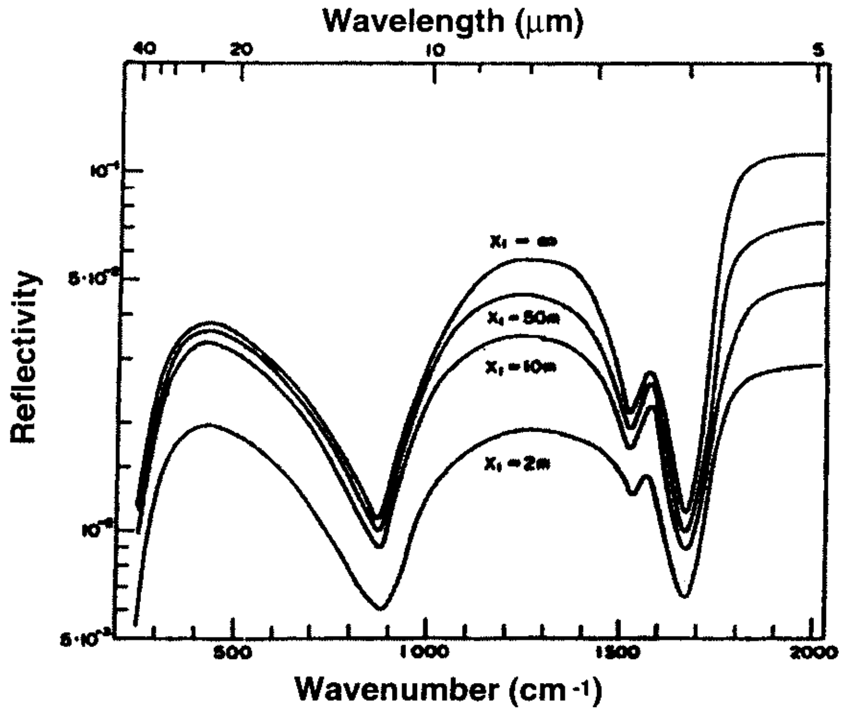
Longwave Properties of Liquid H2O Clouds



Parameterization of Liquid Water Clouds (IR)

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

$$k \sim 0.25 \quad m^2\, g^{-1} \quad \text{(for flux calculations)}$$

(ε - emissivity)

Note $\varepsilon \sim 1$ for a 300 m thick cloud with w = 0.15 g m^{-3}

Stephens, 1984: *Mon. Wea. Rev.*, **112**, 826-867.

Parameterization of Ice Water Clouds (IR)

$$\varepsilon = 1 - \exp\left[-k(r_{eo})\frac{r_{eo}}{r_e}\,IWP\right]$$

$$IWP = \int w_i\,dz \qquad w_i \text{ - ice water content}$$

$$w_i = a\exp\{b(T+c)\}$$

ε - emissivity

Stephens et. al, 1990; *J. Atmos. Sci.*, **47**, 1742-1753

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Parameterization of Ice Water Clouds (Fu & Liou)

$$\tau = IWP \sum_{n=0}^{2} a_n / D_e^n \qquad \omega = \sum_{n=0}^{3} b_n D_e^n$$

$$g = \sum_{n=0}^{3} c_n D_e^n \quad (IR)$$

D_e – Effective width of an ice crystal

Randomly oriented hexagonal crystals

Effective sizes ranging from 24 to 124 μm

Fu, Q., and K. N. Liou, 1993: *J. Atmos. Sci.*, **50,** 2008-2025.

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Results from ICRCCM - Clouds

- For near-black clouds, the LW 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 spread of 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 SW, large differences occur which are attributed to the manner by which multiple scattering is taken into account in the low resolution codes.

Partial Cloud Cover

One cloud layer amount weighted average

$$F = (1 - N)\, F_{clear} + N\, F_{cloudy}$$

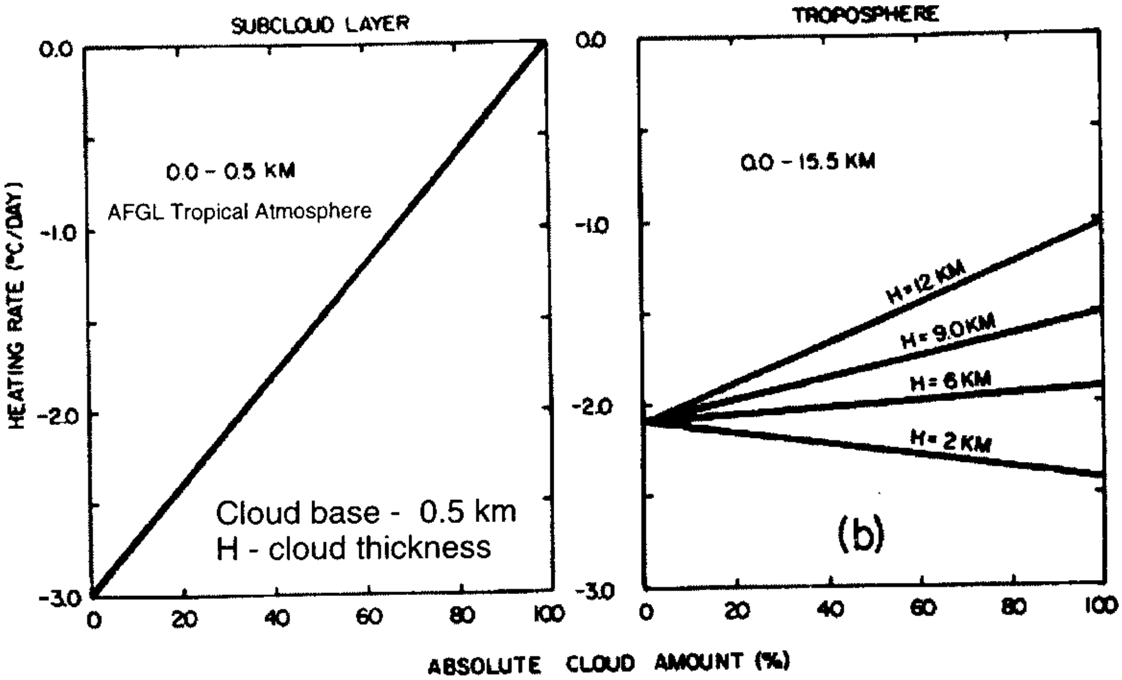
Thin Plates

N is the absolute cloud fraction

Vertically extended clouds

N is the effective cloud amount, N*, that is a function of the absolute cloud amount, geometry, height, width spatial distribution of the clouds, and ... (i.e., liquid water content, effective drop size, etc).

Longwave Cooling and Cloud Fraction



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Multiple Cloud Layers

Random Minimum - Maximum	***overlap assumptions*** **result in simple algebaric solutions**

<u>Example</u> - 2 layers with random overlap

$$F\downarrow = (1 - N_1)(1 - N_2)\, F_o\downarrow + N_2\,(1 - N_1)\, F_2 + N_1 F_1\downarrow$$

$(1 - N_1)(1 - N_2)$ --> Effective clear-sky fraction

$N_2\,(1 - N_1)$ --> Portion of N_2 see from below

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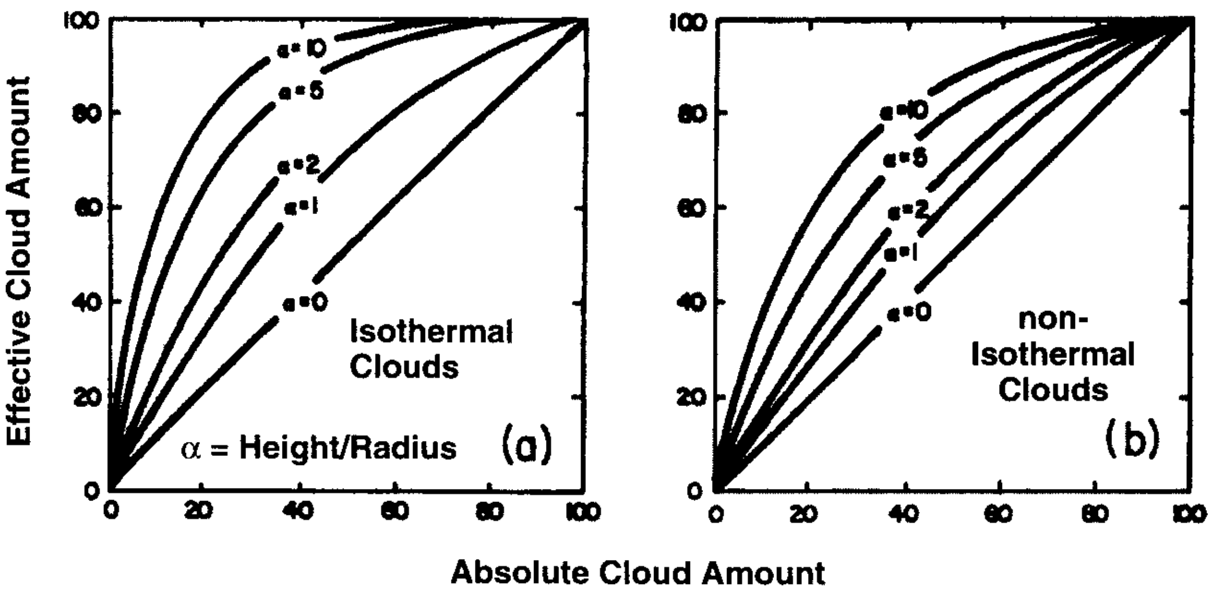
Clouds and Radiation

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 or 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.

Effective Cloud Amount for Black Cylindical Clouds



Ellingson, 1982: *J. Atmos. Sci.*, **39,** 886-896.
Killen and Ellingson, 1994: *J. Atmos. Sci.*, **51**, 2123-2136.

Frequent Inquiry

I Have a radiation model. Is it okay to use it for the ________ problem?

Has the model been tested in ICRCCM? If not, do those tests before you proceed.

If the model has been tested, and the agreement with LBL calculations is within your accuracy needs, proceed with the usual due caution .