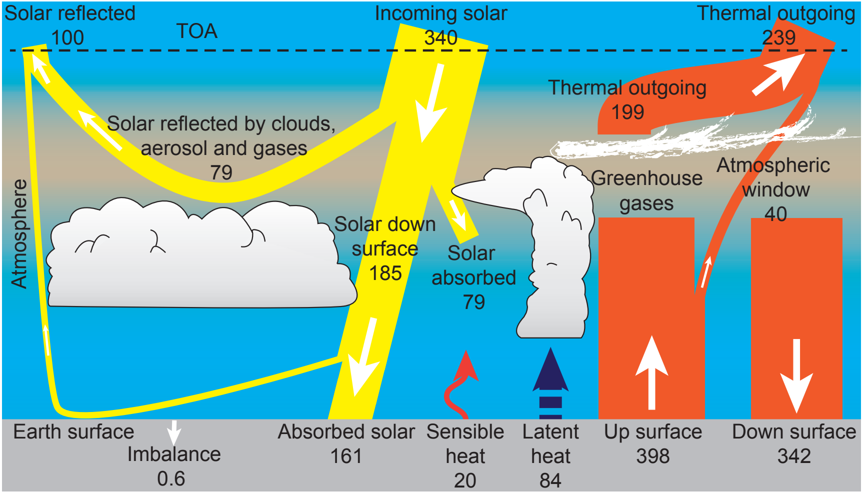
Parameterization of radiative transfer



Script Atmospheric Physics

Parameterization of atmospheric radiation

- GCMs require the net (upward $F^{\uparrow}$ and downward $F^{\downarrow}$) radiative fluxes at the top-of-the-atmosphere (TOA), the surface, and internal atmospheric heating rates.
- Parameterize the net effect of photons being either absorbed or scattered as they propagate through the atmosphere.
- The net radiative heating $Q_{rad} = Q_{SW} + Q_{LW}$ as obtained from the divergence of the net radiative flux is needed in the prognostic equation for temperature (or dry static energy)
- Obtain Q_{SW}, Q_{LW} from the first law of thermodynamics with $dp = 0$:

$$Q_{rad} = \rho c_p \frac{dT}{dt} = -\nabla \vec{F} \approx -\frac{d}{dz}(F^{\uparrow} - F^{\downarrow}) \tag{1}$$

Radiative transfer equation (RTE)

- RTE is a conservation equation for radiant energy:

$$\cos\Theta \frac{dI}{d\tau} = I - J \tag{2}$$

I = intensity at an angle Θ from the upward normal $\vec{k}$

- τ = optical depth with k = mass absorption coefficient:

$$\tau = \int_z^\infty \rho k dz \tag{3}$$

τ is 0 at TOA and increases downward

- J = blackbody source function

$$J = \frac{1}{\pi} B(T) \tag{4}$$

with $B(T) = \sigma T^4$

Two-stream method

- Obtain closed form solutions to the original RTE by dividing the radiation into a upward and downward stream of radiant energy (2-stream method) assuming horizontally isotropic radiation:

$$\begin{aligned} \frac{dF^{\uparrow}}{d\tau} &= F^{\uparrow} - B(T) && (5) \\ -\frac{dF^{\downarrow}}{d\tau} &= F^{\downarrow} - B(T) && (6) \end{aligned}$$

- where

$$F^{\uparrow,\downarrow} = \int_{2\pi} \vec{I} \cdot \vec{k} d\Omega^{\uparrow,\downarrow} \tag{7}$$

- Need multiple layers for the entire atmosphere to obtain fluxes and heating rates.

Objectives of radiation parameterizations

- Calculate F_{SW}^{net} and F_{LW}^{net} for clear and/or cloudy conditions at each gridpoint of the model domain.
- The processes that need to be parameterized are of molecular scale for gaseous absorption and micrometer scale for scattering on aerosol particles and clouds
- Since the source of radiation is quite different for SW and LW radiation, these processes are considered separately:
  - F_{SW} = transmission, absorption, scattering
  - F_{LW} = absorption and emission

Shortwave (SW) and longwave (LW) radiation

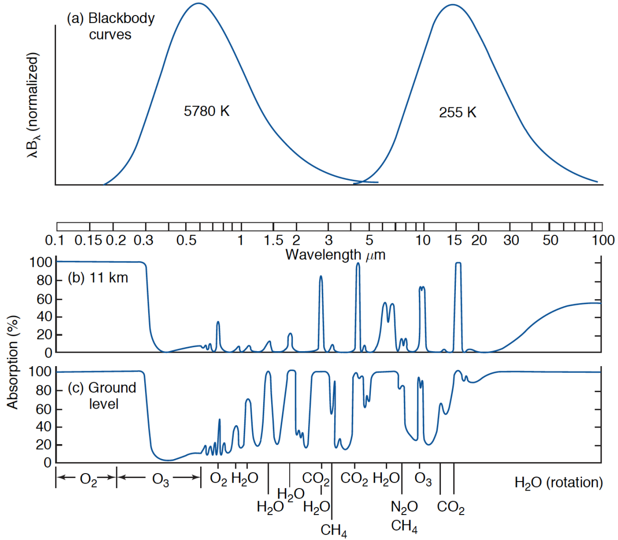
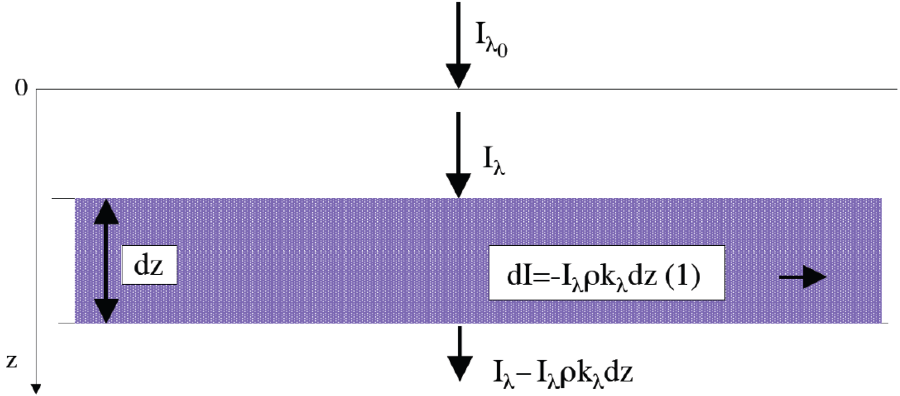


Fig. 4.7, Wallace&Hobbs, 2006

Beer's law

Atmospheric attenuation of solar radiation by absorbers and scatters



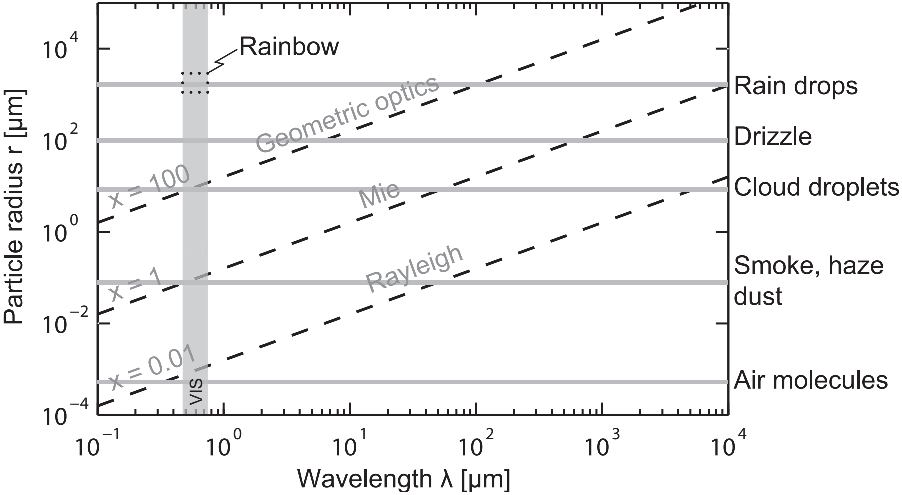
where ρk_λ = extinction coefficient (absorption and scattering per unit mass), $I_{\lambda 0}$= insolation at TOA, I_λ = shortwave flux at height z

Clear-sky attenuation of SW radiation

- with $\tau = \int_{z'=0}^{z'=z} \rho k_\lambda dz' =$ optical depth
- $q_\lambda = \frac{I_\lambda}{I_{\lambda 0}} =$ transmission
- $q = 0.7$ (Sun perpendicular, no clouds); $q < 0.65$ (clouds are present)
- Under cloud-free conditions: extinction coefficient $k = k_G + k_R + +k_A + k_M$, where
- $k_G =$ gas absorption (H_2O, CO_2, O_3, O_2,....)
- $k_R \sim \lambda^{-4} =$ molecular (Rayleigh) scattering, $r < 0.1\lambda$
- $k_M \sim \lambda^{-1.3} =$ aerosol (Mie) scattering, $r = (0.1 - 25) \cdot \lambda$
- $k_A \sim \lambda^{-1} =$ aerosol (black carbon) absorption
- Clear sky transmittance q_0:

$$
\begin{aligned}
q_0 = e^{-\tau} &= e^{-\int_{z'=0}^{z'=z} \rho k_G dz'} e^{-\int_{z'=0}^{z'=z} \rho k_R dz'} e^{-\int_{z'=0}^{z'=z} \rho k_M dz'} e^{-\int_{z'=0}^{z'=z} \rho k_A dz'} \\
&= q_G q_R q_M q_A \qquad (8)
\end{aligned}
$$

Scattering regimes



Atmospheric Physics script

Solar radiation in a cloudy atmosphere

- Ray tracing method: assumes that solar radiation can be represented by beams propagating through the atmosphere
- Conceptually easy but cumbersome for multiple cloud layer cases.
- Consider the case of a single cloud layer in a non-absorbing clear-sky atmosphere with α_c: cloud albedo, t_c: transmissivity of the cloud, α_s: surface albedo
- Follow the beam can be followed through a number of reflections and transmissions

Shortwave radiation in a cloudy atmosphere

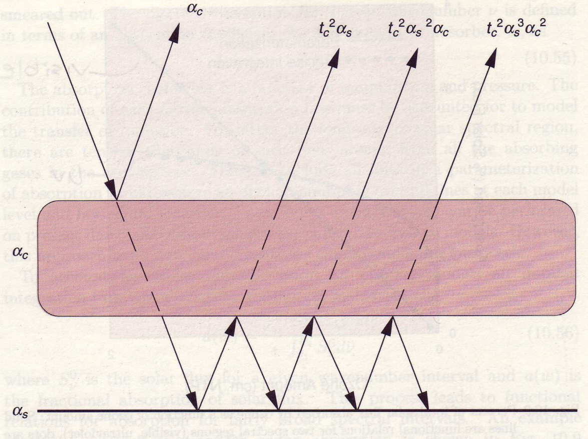


Fig. 10.10 Diagram of a solar beam reflecting from a system composed of a single cloud layer and surface.

Figure 10.10, Trenberth, 1992

Ray tracing for solar radiation

- This then yields the planetary albedo:

$$\alpha_p = \alpha_c + t_c^2\alpha_s + t_c^2\alpha_s^2\alpha_c + t_c^2\alpha_s^3\alpha_c^2 + t_c^2\alpha_s^4\alpha_c^3 + ... \tag{9}$$

which can be factored as:

$$\alpha_p = \alpha_c + t_c^2\alpha_s(1 + \alpha_s\alpha_c + (\alpha_s\alpha_c)^2 + (\alpha_s\alpha_c)^3 + ...) \tag{10}$$

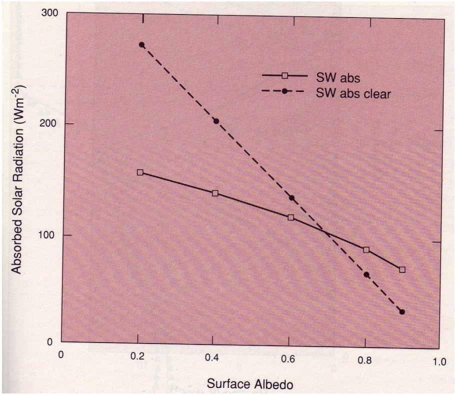
or

$$\boxed{\alpha_p = \alpha_c + \frac{t_c^2\alpha_s}{1-\alpha_s\alpha_c}} \tag{11}$$

- Compare the amounts of absorbed SW radiation with and without clouds:

$$F_{SW}^{abs} = \frac{S_o}{4}(1-\alpha_p)\ ;\ F_{SW}^{abs,0} = \frac{S_o}{4}(1-\alpha_s) \tag{12}$$

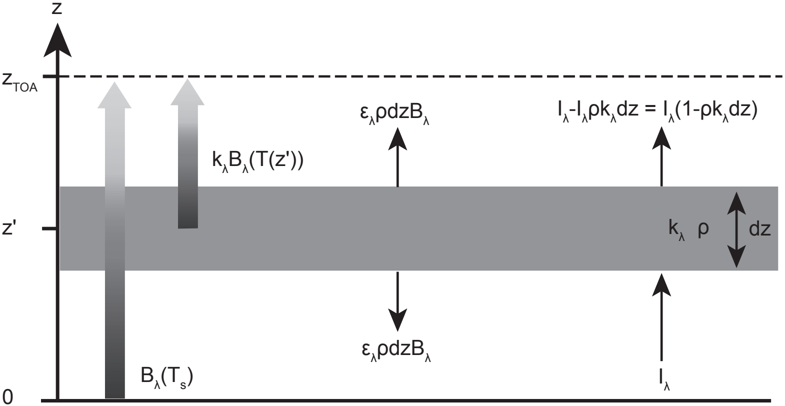
Shortwave radiation



→ For a highly reflecting surface the combined albedo of cloud and surface is lower than the clear-sky albedo, i.e. more solar radiation is absorbed in the Earth-atmosphere system

Figure 10.11, Trenberth, 1992

Schwarzschild's law for LW ($> 4\ \mu$m) radiation



- SW: only extinction, no emission: $\frac{dI_\lambda}{dz} = -\rho k_\lambda I_\lambda$
- LW: both emission and absorption: $\frac{dI_\lambda}{dz} = -\rho k_\lambda (I_\lambda - B_\lambda)$
- $B_\lambda(T)$ = blackbody emission of the material

Atmospheric Physics script

Longwave radiation

- The most important absorber of LW radiation in the Earth's atmosphere is water vapor followed by CO_2, which has dominant effects in the upper stratosphere, then followed by ozone.
- Methane, N_2O and CFCs (the other trace gases) are also radiatively significant and thus need to be included in GCMs
- As in the case of SW radiation, including the absorption of radiant energy by all of the above mentioned gases would require integration over 10,000s individual narrow absorption lines.
- For computational efficiency, implicit integration of these lines is provided by band models or the correlated$-k$ method.
- However, line-by-line models provide benchmark for all other models

Line-by-line models

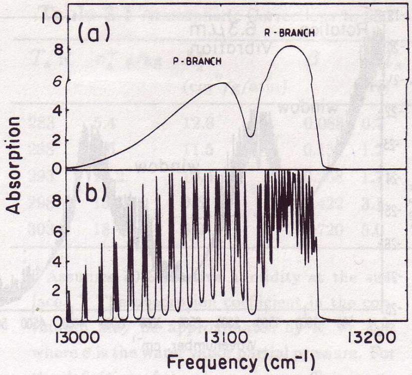
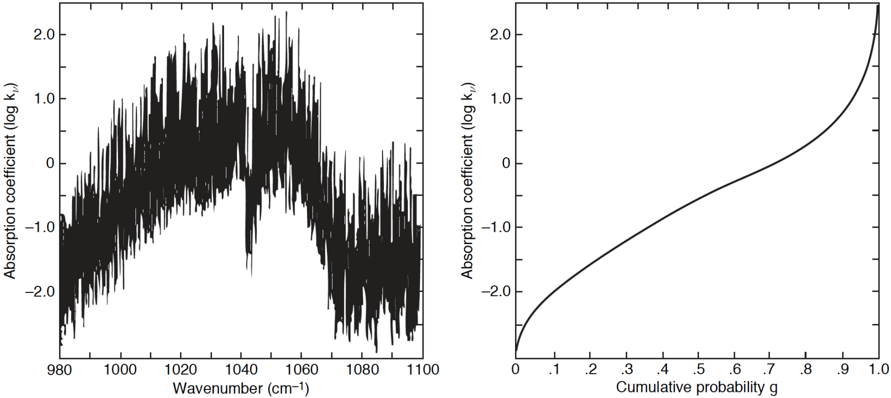


Figure 3.19 Oxygen A–band absorption at the surface for an overhead sun. (a) spectral resolution of 5 cm^{-1} with a residual line structure smoothed out; (b) spectral resolution of 0.5 cm^{-1} (Barton and Scott,

Fig. 3.19, Stephens, 1994

Correlated$-k$ method



This method transforms individual absorption lines into a cumulative probability distribution in terms of absorption strength

Fig. 4.27, Wallace&Hobbs, 2006

Radiation in the cloudy atmosphere

- Include clouds in the radiative transfer equations by separating the total flux into a cloudy F_c and a clear-sky flux F_0:

$$F = F_0(1 - b) + F_c b \tag{13}$$

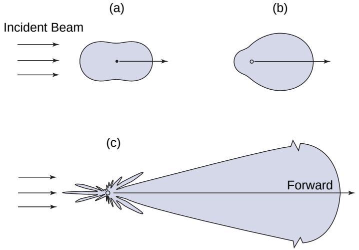
  where b = cloud cover
- Absorption of SW radiation tends to warm the upper layers of the clouds and cools the layers below cloud
- LW radiation tends to warm cloud base due to the net convergence of radiation from the warm surface into the cold cloud base
- LW processes cool cloud tops because the cloud top loses radiant energy to space
- LW heating depends on cloud altitude. Higher clouds display larger cloud top cooling and base warming

Cloud optical properties

Describe cloud optical properties in terms of τ, single scattering albedo ω_λ (ratio of scattering to extinction) and asymmetry factor g_λ:

$$g_\lambda = 0.5 \int_{-1}^{1} P(\cos\theta) \cos\theta d \cos\theta \qquad (14)$$

θ = angle between the incident and the scattered gradation;
$P(\cos\theta)$ = normalized angular distribution of scattered radiation (scattering phase function).



Cloud optical properties

- g_λ: 0 for isotropic radiation; > 0 for predominantly forward scattering
- $g_\lambda \sim 0.85$ for cloud droplets and 0.5-0.8 for ice crystals
- Mass absorption coefficient for liquid water clouds in ECHAM6:

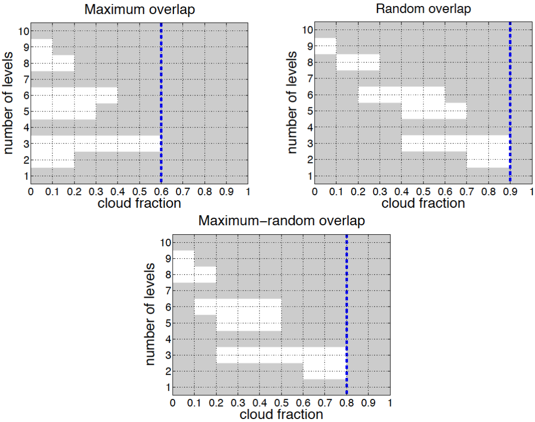
$$k = c + d_1 \exp(-d_2 r_{e,l}) \; ; \; r_{e,l} = \kappa \left(\rho \frac{q_l}{N_l} \right)^{1/3} \qquad (15)$$

- Mass absorption coefficient for ice clouds in ECHAM6:

$$k = a_\lambda + b_\lambda r_{e,i}^{-1} \; ; \; r_{e,i} = 83.8 q_i^{0.216} \qquad (16)$$

  where $r_{e,l}$, $r_{e,i}$ = effective radius of cloud droplets and ice crystals; a_λ, b_λ, c, $d_{1,2}$ and κ = constants
- Consider cloud inhomogeneities by reducing the homogeneous τ: $(\tau = \gamma \tau_{hom})$ with $\gamma < 1$

Cloud overlap



- Max. overlap:
  $b = \max(b_k, b_{k-1})$
- Random overlap:
  $b = b_k + b_{k-1} - b_k b_{k-1}$
- Max-random:

$$b = 1 - (1 - b_{k-1}) \cdot \frac{1 - \max(b_k, b_{k-1})}{1 - \min(b_{k-1}, 1 - \delta)}$$

Stephanie Jess, Ph.D. thesis, 2010

Radiative effect of clouds [W m^{-2}]

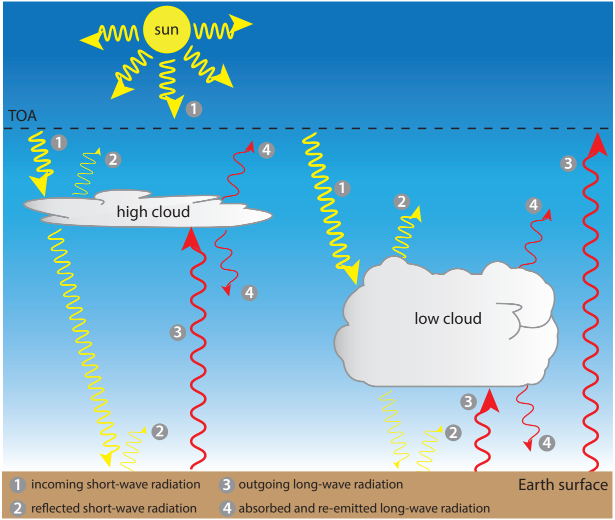
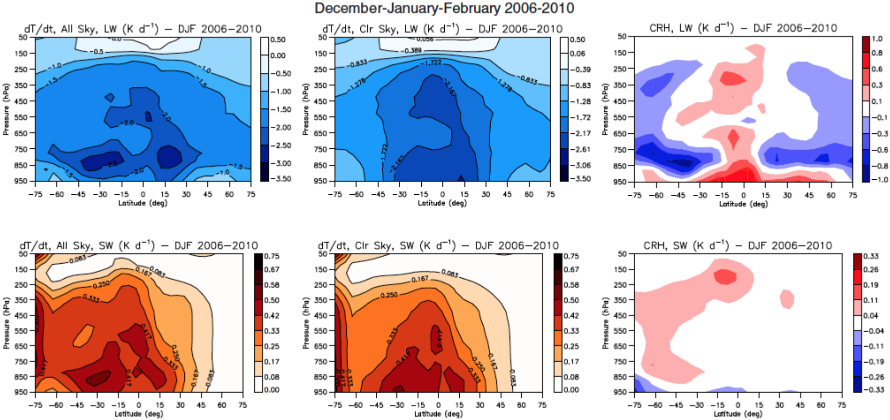


Figure: Atmospheric Physics script

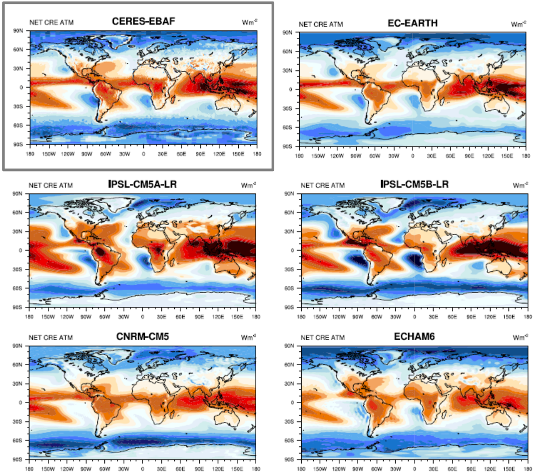
LW and SW heating rates from satellites



CRH = cloud radiative heating (Haynes et al., GRL, 2013)

Net cloud radiative effect in the atmosphere

CERES vs CMIP5 models



Courtesy Sandrine Bony

Take-home messages

- Radiative transfer is usually calculated using the two-stream approach (upward and downward irradiances)
- Radiative transfer remains the most expensive parameterization and because of this is not calculated every timestep (every 1-2 h in ECHAM depending on the horizontal resolution)
- Absorption is calculated over pseudowavelengths (g-points) called correlated$-k$ method where g is the cumulative distribution of absorption k within a band
- Cloud overlap is normally considered as maximum-random
- Cloud optical properties depend on wavelength and effective radii