GFDL Summer School [2012]

Radiation Transfer

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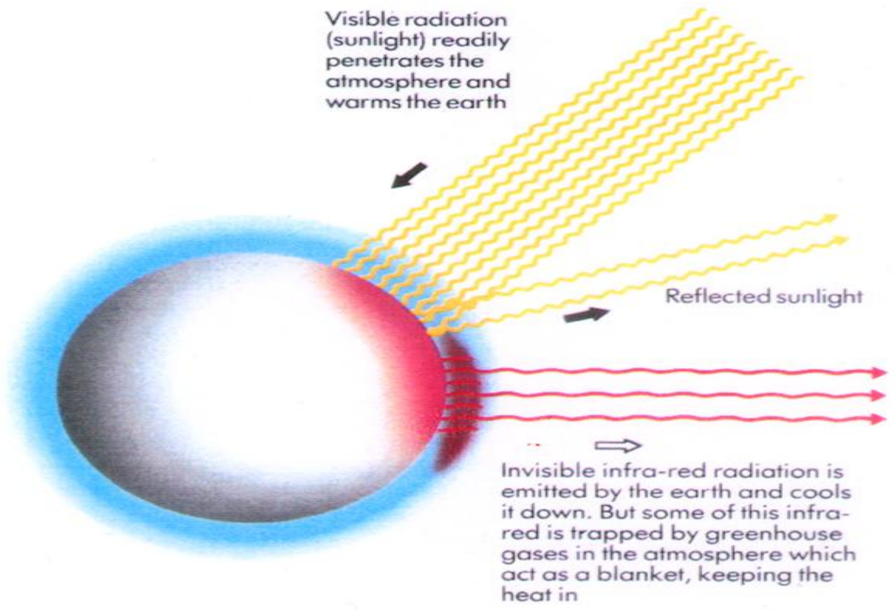
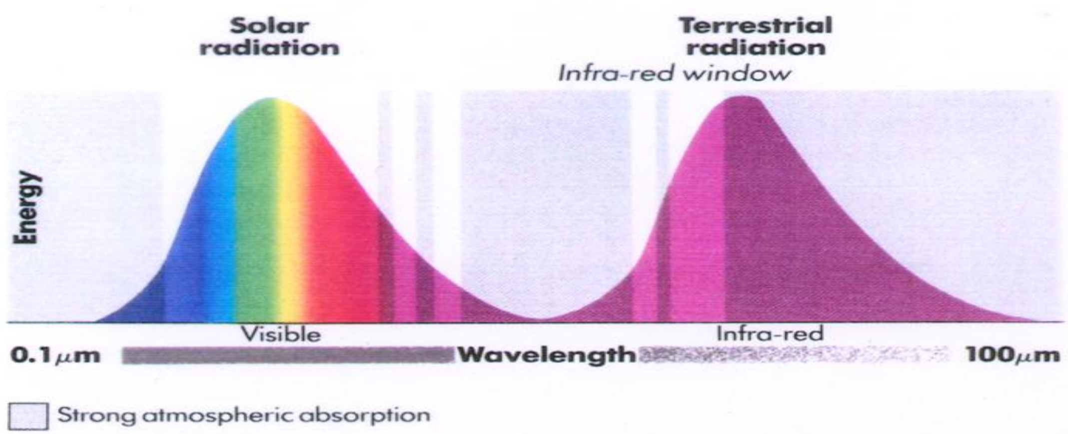
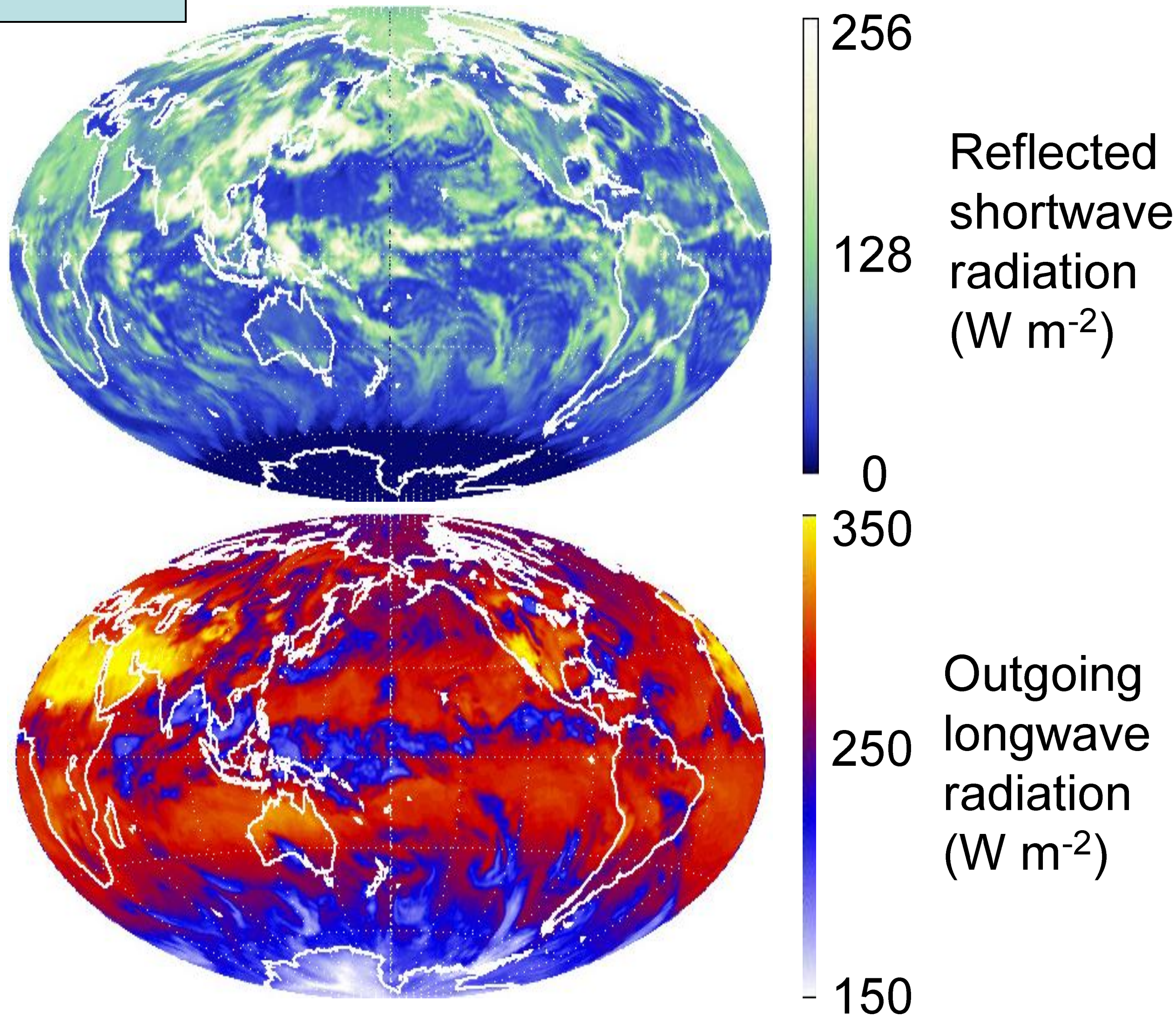
July 16, 2012

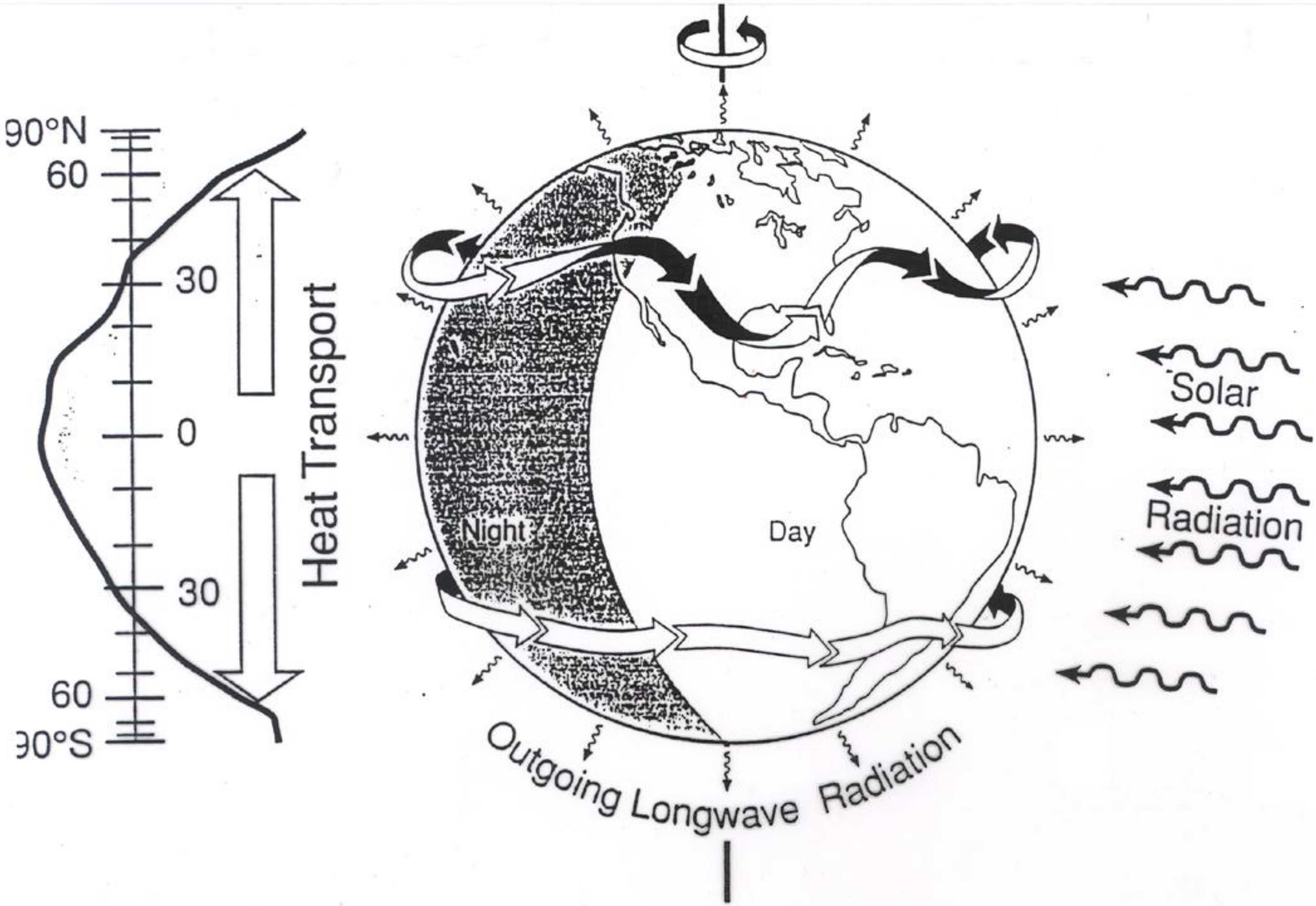

Visible radiation (sunlight) readily penetrates the atmosphere and warms the earth
Reflected sunlight
Invisible infra-red radiation is emitted by the earth and cools it down. But some of this infra-red is trapped by greenhouse gases in the atmosphere which act as a blanket, keeping the heat in


Solar radiation
Terrestrial radiation
Infra-red window
Energy
Visible
Infra-red
0.1μm
Wavelength
100μm
Strong atmospheric absorption

Aqua CERES Measurement



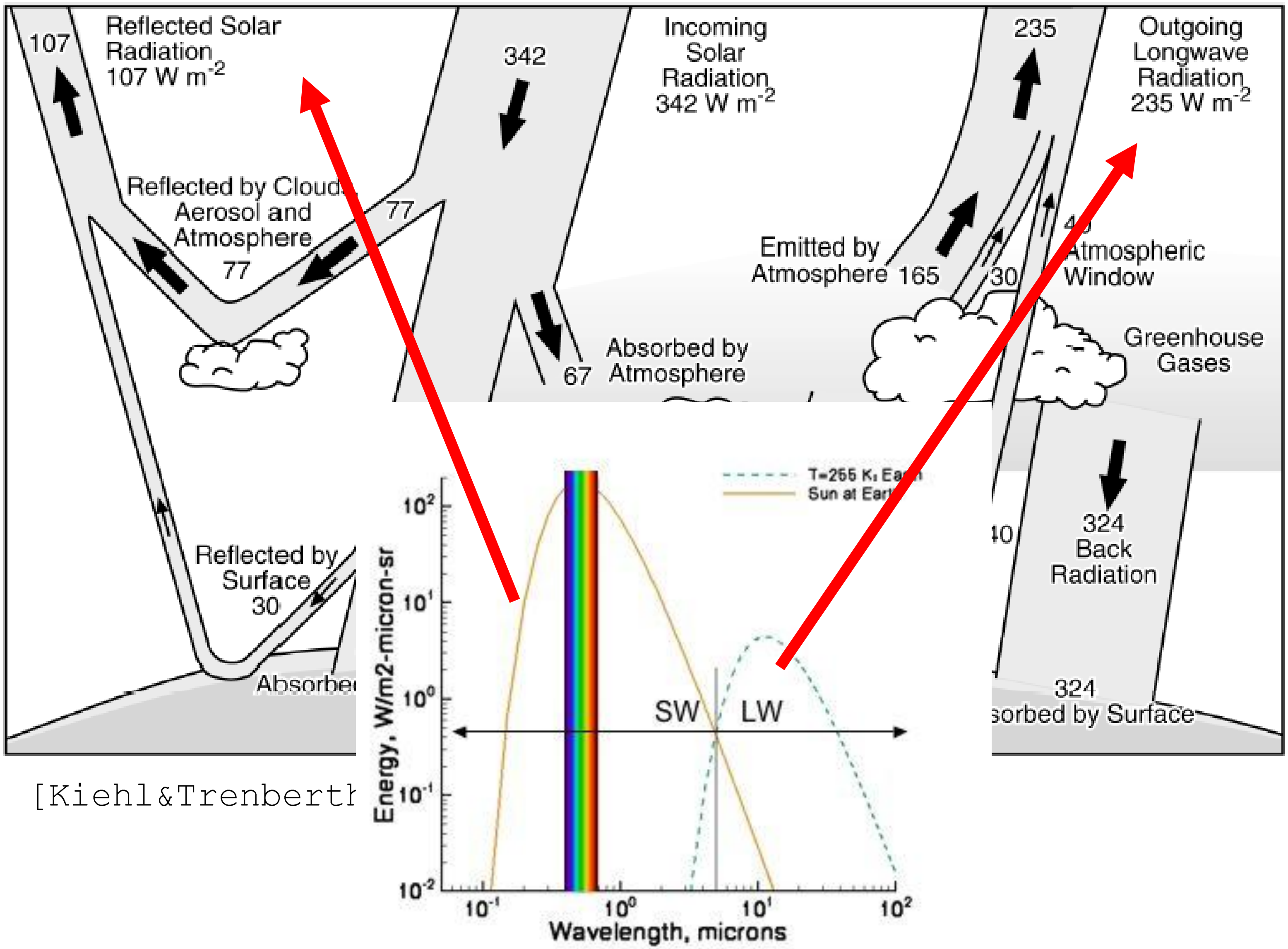
Global, annual-mean
Net SW = Net LW ~ 235 W/m^2



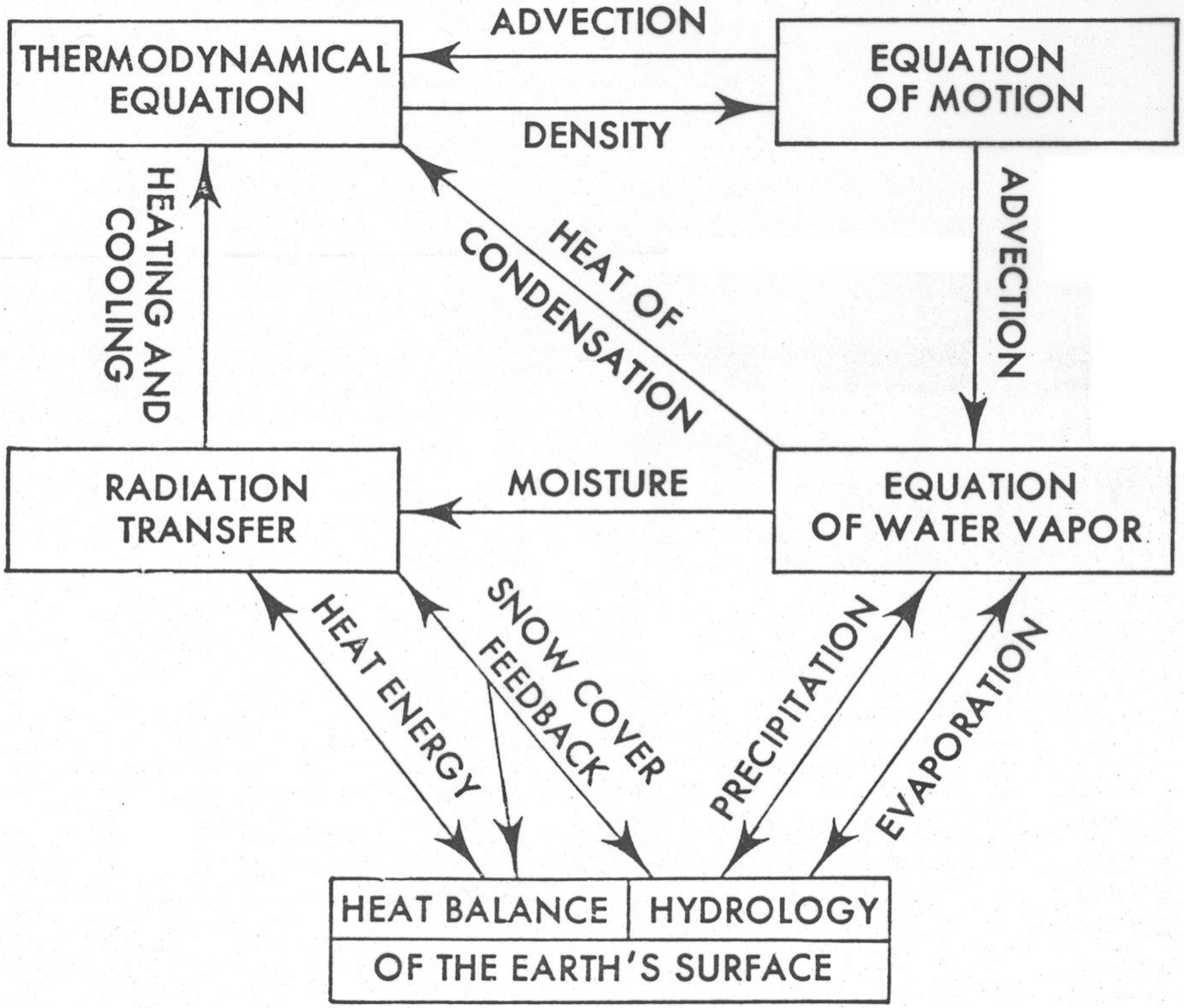
90°N
60
30
0
30
60
90°S
Heat Transport
Night
Day
Solar
Radiation
Outgoing Longwave Radiation

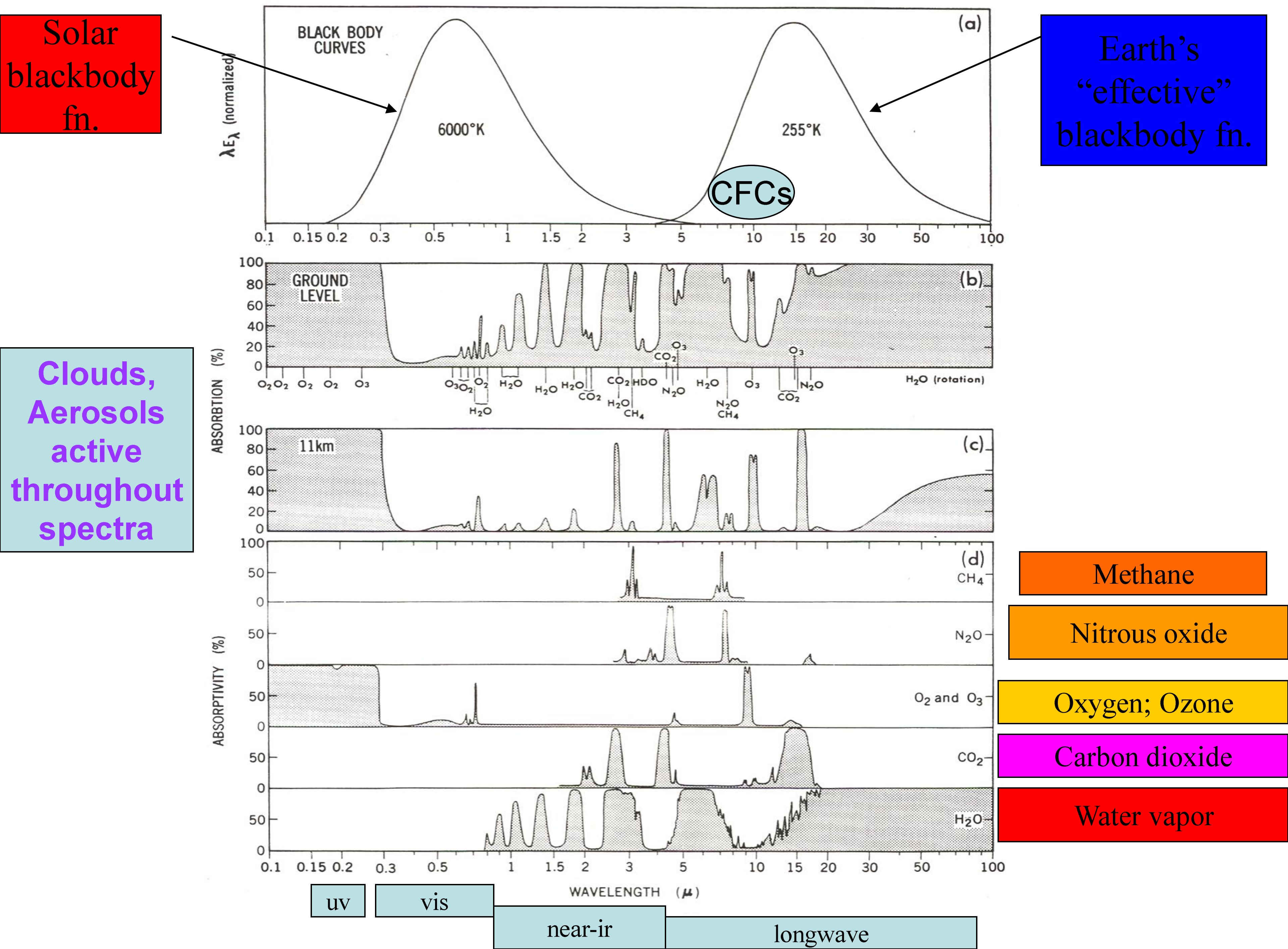
Introduction (1/3)

Global annual mean energy budget



[Kiehl&Trenbert


THERMODYNAMICAL EQUATION
ADVECTION
DENSITY
EQUATION OF MOTION
HEATING AND COOLING
HEAT OF CONDENSATION
ADVECTION
RADIATION TRANSFER
MOISTURE
EQUATION OF WATER VAPOR
HEAT ENERGY
SNOW COVER FEEDBACK
PRECIPITATION
EVAPORATION
HEAT BALANCE
HYDROLOGY
OF THE EARTH'S SURFACE



Solar blackbody fn.
Earth's "effective" blackbody fn.
BLACK BODY CURVES
(a)
6000°K
255°K
CFCs
λE_λ (normalized)
GROUND LEVEL
(b)
11km
(c)
ABSORBTION (%)
H2O (rotation)
(d)
CH4
N2O
O2 and O3
CO2
H2O
ABSORPTIVITY (%)
WAVELENGTH (μ)
Clouds, Aerosols active throughout spectra
Methane
Nitrous oxide
Oxygen; Ozone
Carbon dioxide
Water vapor
uv
vis
near-ir
longwave

Radiative Transfer Equation (RTE): Photon Transport

At any frequency, the monocromatic RTE is

$$dI/\,d\tau = I - J$$

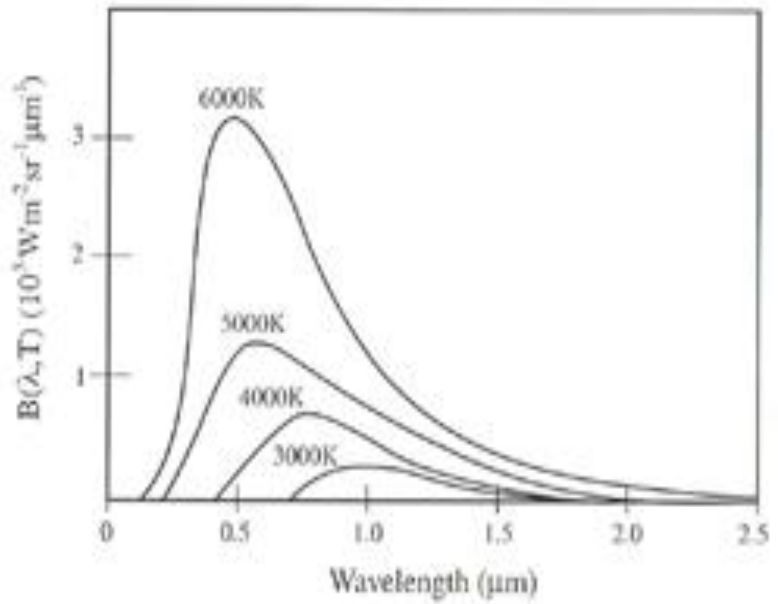
- **I = intensity, τ = extinction optical depth, J = source function.**
- **extinction = absorption + scattering.**
- **Source function from a volume is Planck emission in the longwave (LW), and photon scattering in shortwave (SW).**
- **If no scattering, equation reduces to Beer's Law of exponential attenuation {*also the case if there were no multiple scattering*}.**

Radiation laws

Kirchhoff's law: emissivity is absorptivity

$$\varepsilon(\lambda)=\alpha(\lambda)$$

for a blackbody =1
for a gray body <1



Planck's formula (emission intensity):

$$B(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{k\lambda T}\right)-1\right]^{-1}$$

in W m^{-2} sr^{-1} μm^{-1}

T is temperature (K)

k is Boltzmann constant (1.38×10^{-23} J K^{-1})

Integration of Planck function over all λ's

gives Stefan-Boltzmann law:

$$B(T) = \int_0^\infty B(\lambda,T)d\lambda = \frac{\sigma}{\pi}T^4$$

σ is S-B constant (5.67×10^{-8} W m^{-2} K^{-4})

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

is blackbody energy flux from one hemisphere

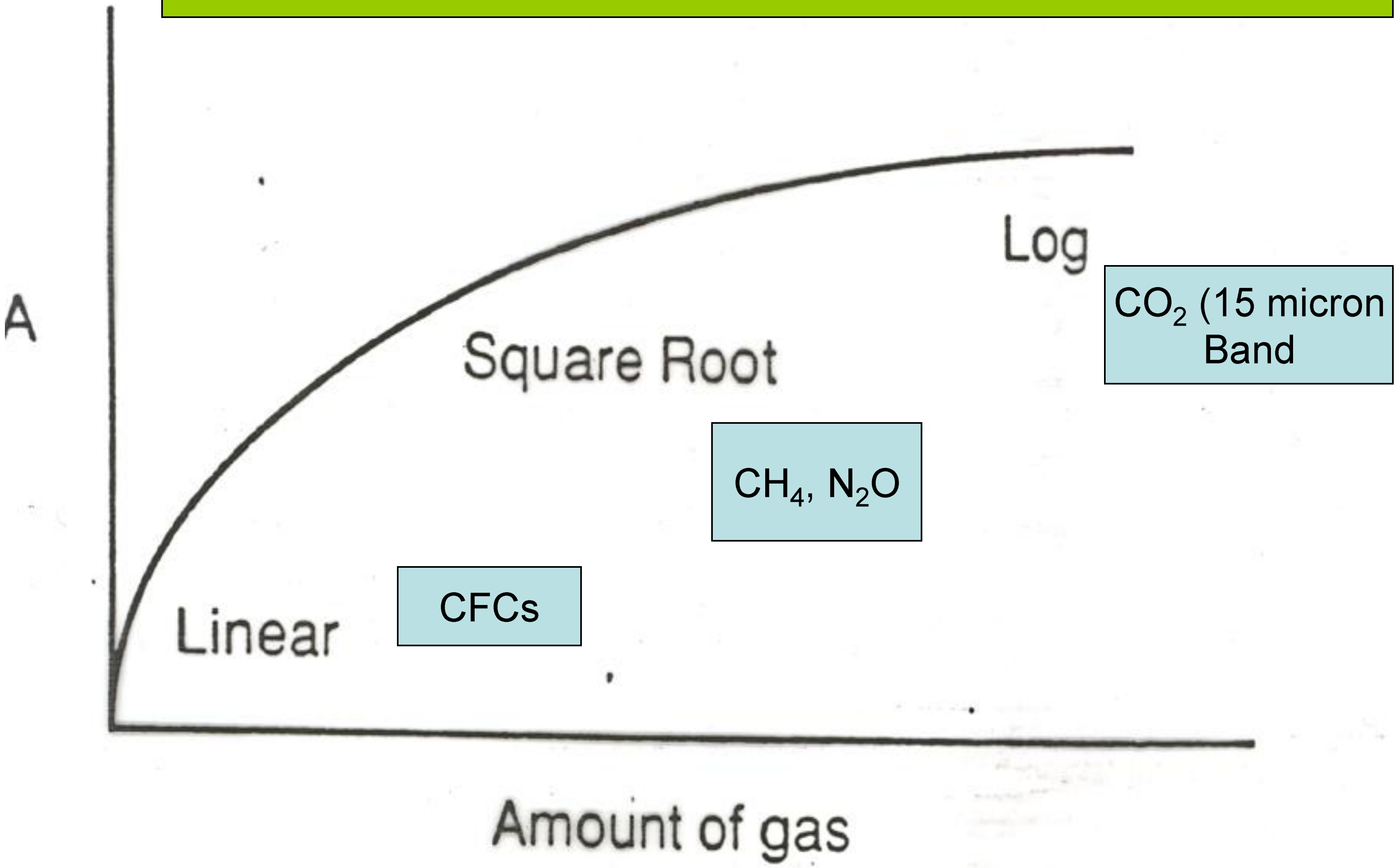
Every object with T > 0 K radiates!

Wien's law: integration Planck function and first derivative to zero

$$\lambda_{max} = \frac{hc}{4.965kT}$$

Note location of λ_{max} as a function of T!

Curve of growth of absorption by gases



Photon collides with scatterer

Photon encounters particulate matter (including molecules).

Then:

- can be scattered and absorbed
- relative amount of light scattered and absorbed can vary with frequency (or wavelength)
- Scattering by particulates can occur alongside gaseous absorption at the same wavelength

Scattering versus Absorption

- Molecules can scatter and absorb radiation
- Scattering is a more continuous phenomena with wavelength; no discreteness in wavelength as for molecular absorption
- Scatterers ▪ molecules; aerosols; water clouds; ice clouds; raindrops; snowflakes, hail
- Particles can also absorb radiation

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Solar Radiation Transfer

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Parameterizations of RTE

- **RTE can be solved exactly (line-by-line, doubling-adding method (e.g., Hunt and Grant, *J. Atmos. Sci*., 1969; Ramaswamy and Freidenreich, *JGR*, 1991)…*every molecular line, each species*.**
- **RTE is not solvable analytically for use in climate models.**
- **Approximations are used.**
- **For SOLAR, scattering-absorbing problem reduced to a pair of differential equations that can be solved analytically to yield photons absorbed and scattered out of a volume due to interactio of an incident light beam with matter.**
- **Most solar parameterizations in GCMs employ**
  - **2- (or 4-) stream approximation (e.g., Coakley-Chylek, *J. Atmos. Sci*., 1975)**
  - **Delta-Eddington approximation (Joseph et al., *J. Atmos. Sci*., 1976)**
  - **K-distribution strategy (e.g., Lacis and Oinas, *J. Atmos. Sci*., 1986)**

The particulate scattering-absorbing problem

Solving the EM equations, with the provision that the electric and magnetic fields have to be continuous across the air-particle discontinuity

MIE theory ▪ scattering by a sphere

Basically, most of the relevant particles are spherical in shape but important exceptions occur.

Solution for the scattered field is represented by Bessel functions and Legendre polynomials which are functions of the **size parameter** (ratio of particle radius to wavelength) AND **Refractive Index** .(a function of wavelength and depending on the particle type).

Mie solution ▪ provides scattering and extinction (and thus absorption) coefficients; and the phase function (or how the scattered energy is distributed with angle).

Quantities needed to determine the radiation distribution, and that are obtained from the MIE solutions:

- Extinction cross-section (leading to extinction coefficient and extinction optical depth)

- Scattering cross-section (leading to scattering coefficient and scattering optical depth)

ω = scattering optical depth / extinction optical depth

$(1 - \omega)$ = fraction of light absorbed at each photon-particle encounter ("coalbedo")

If $\omega = 1$, no absorption and photons are merely redistributed

If $\omega < 1$, then absorption also occurs, leading to HEATING of the layer where the particles are located.

- Phase function describing the angular distribution of scattering [a simplified version of this is the 'asymmetry parameter', which describes the ratio of light scattered that is in the forward direction]

RTE: Photon Transport

- **Convolution of absorption and scattering. How to convolve the fine structure of molecular absorption with the broader spectral variation of scatterers?**
- **Represent by sum of exponentials, with each term having Beer's Law-like property**

$$T\,(gas) = \Sigma\,[a_i \exp(-k_i\, W)]$$

T = transmission of gas that represents the approximation

W = amount of gas absorber in path

i = pseudo-monochromatic intervals

a = numerical weights

K = coefficients

Wiscombe and Evans (*J. Comput. Phys.*, 1977); Freidenreich and Ramaswamy (*JGR*, 1999).

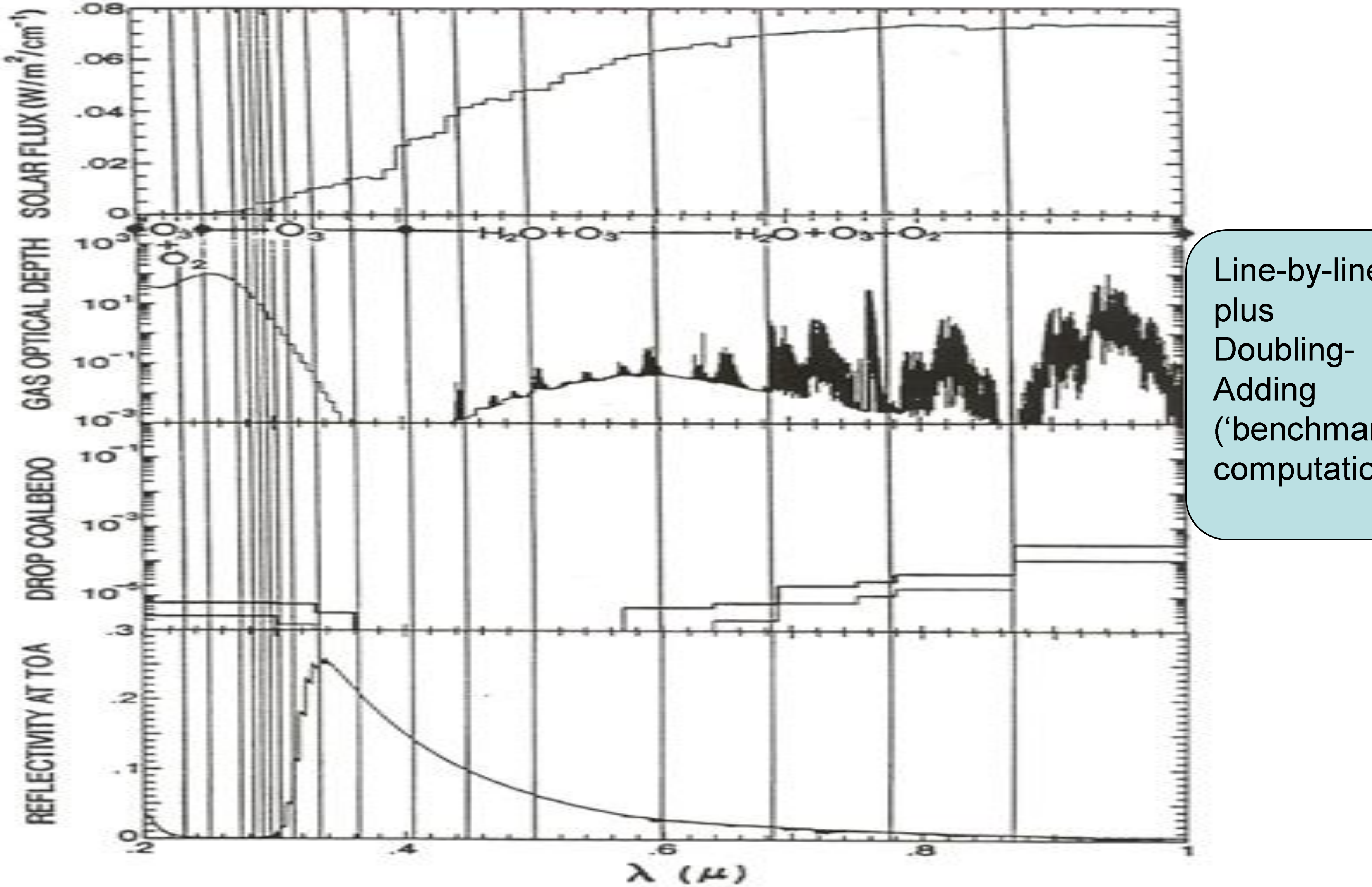
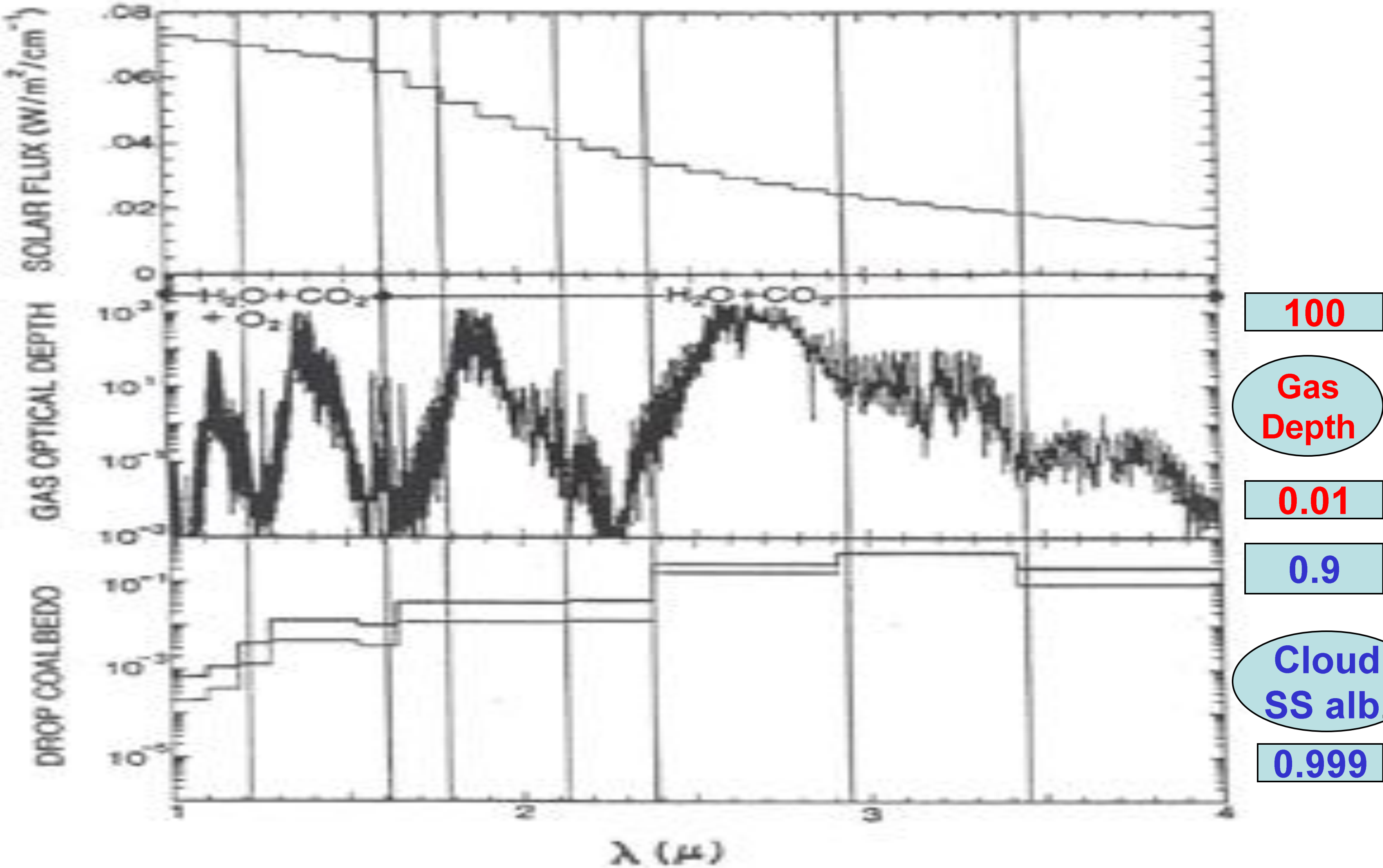


Fig. 2.1a Spectral dependence ($W/m^2\ cm^{-1}$) of the incoming solar flux between 0.2 and 1 μm wavelength at the top-of-the-atmosphere (TOA), the gaseous optical depth, the drop coalbedo of a typical water cloud, and the clear-sky reflectivity. Also shown are the delineation of the band structure adopted to construct a new shortwave parameterization for GCMs. The gases contributing to the absorption in each band are also shown.



Line-by-line plus Doubling-Adding ('benchmark') computation

Fig. 2.1b Same as Fig. 2.1a, but for near-infrared wavelengths greater than 1 μm. Reflectivity at TOA in the near-infrared is negligible and hence is not shown.

GFDL	Hitran (2000) (solar) Doubling and Adding method	Molecular Transmission: Represent by Exponential sum fit	H_2O, O_3, CO_2, O_2 (solar) Absorption and scattering by molecules, aerosols, clouds	<u>BANDS</u> 18 *Monoch-romatic terms* 38	dEdd (solar) no scat (IR)

	Water cloud	Ice cld		Cloud overlap	Aerosols	Other features
GFDL	Improved Slingo (Freidenreich & Ramaswamy 99)	Fu & Liou (93)		max-rand	sulf, ss, bc, oc, dust: climatology; rh effect	variation in soil and vegetation; ocean with sza dependence; spectral dependence

Basic: Ramaswamy and Freidenreich (*JGR*, 1998). Freidenreich and Ramaswamy (*JGR*, 1999). Slingo (*J. Atmos. Sci.*, 1989). Fu and Liou (*J. Atmos. Sci.*, 1993).

AM2: GFDL GAMDT (*J. Clim.*, 2004).

AM3: Donner et al., (*J. Clim.*, 2011).

- Atmosphere contains particulate matter in the different homogeneous layers.
- Multiple scattering occurs when photons keep on encountering particles. This can happen within a single layer and gives rise to the net REFLECTION and TRANSMISSION of light by that layer
- Multiple scattering can also occur between different layers of the atmosphere, and between the atmosphere and surface

CLOUDS (Water)

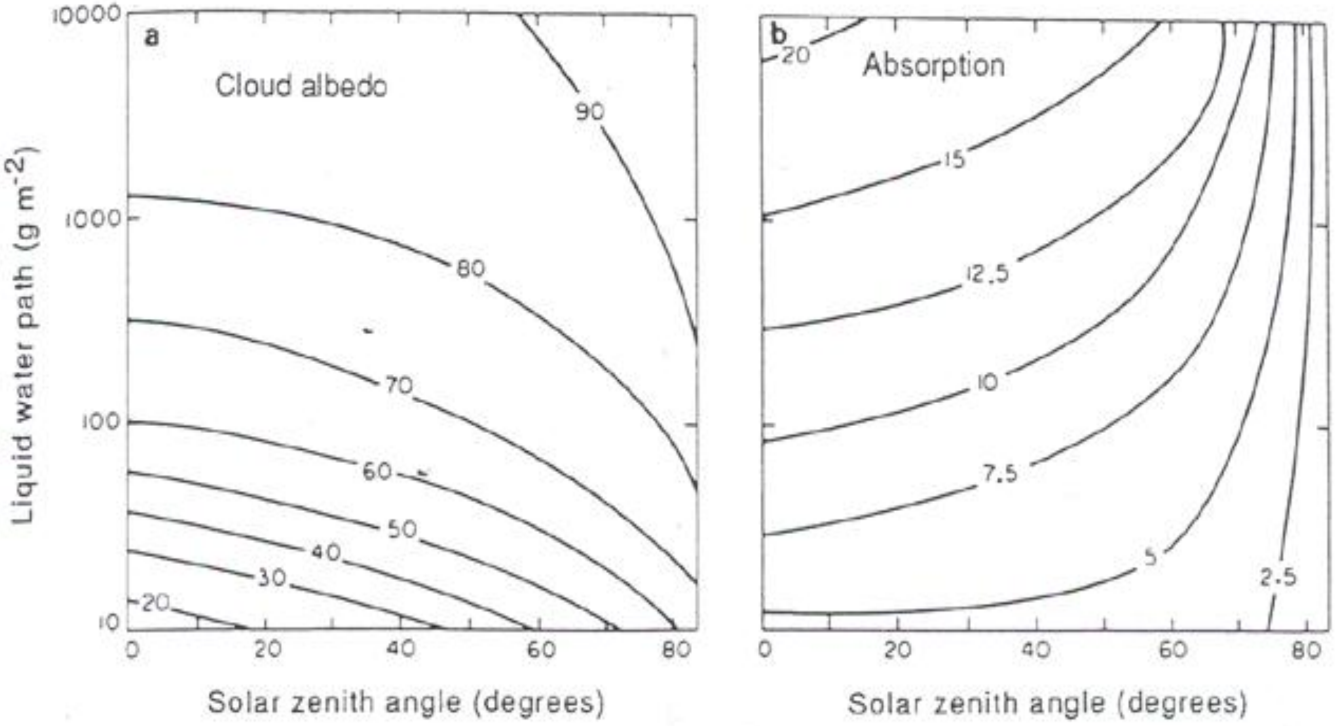


Fig. 3.13 The dependence of (a) cloud albedo and (b) cloud absorption on cloud liquid water path and solar zenith angle. Values are given in percent. [From Stephens (1978). Reprinted with permission from the American Meteorological Society.]

CLOUDS (Water vs. Ice)

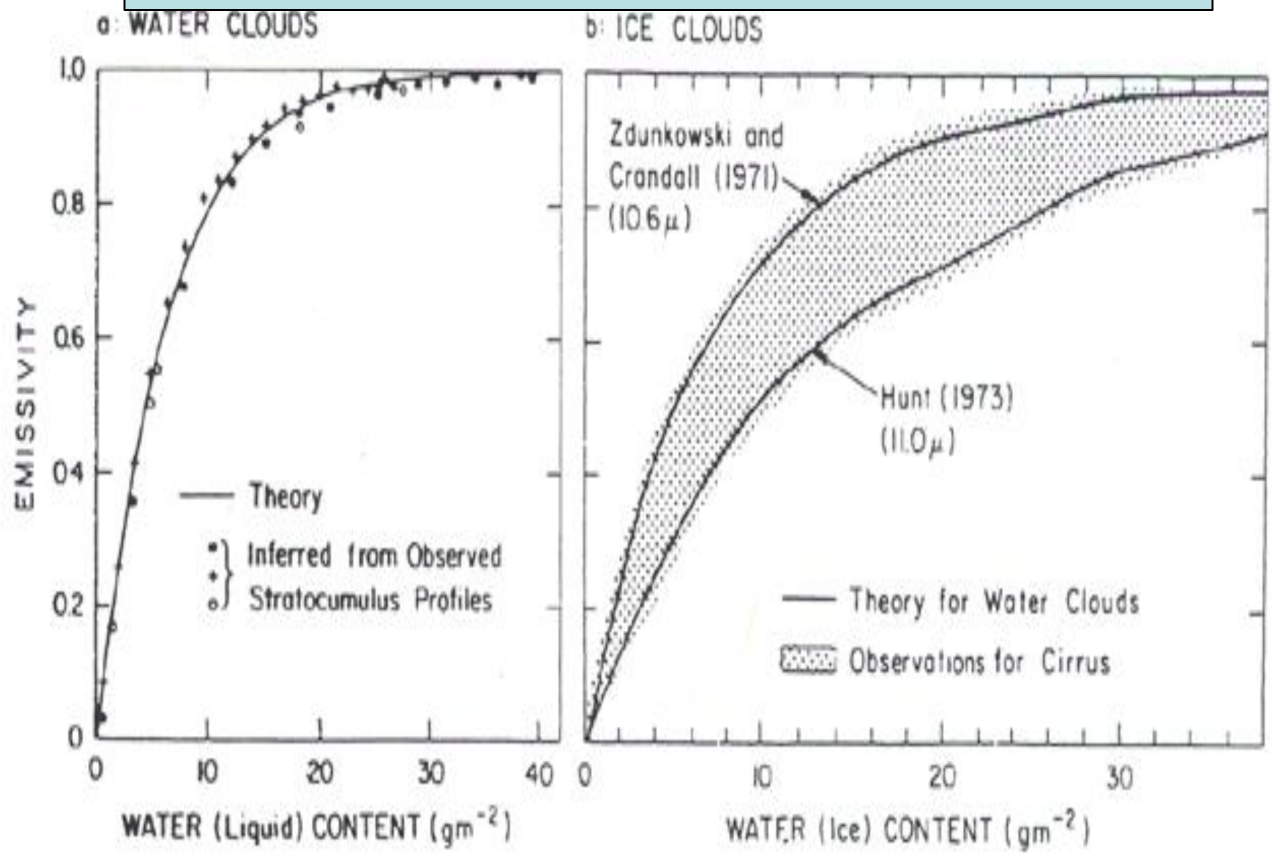
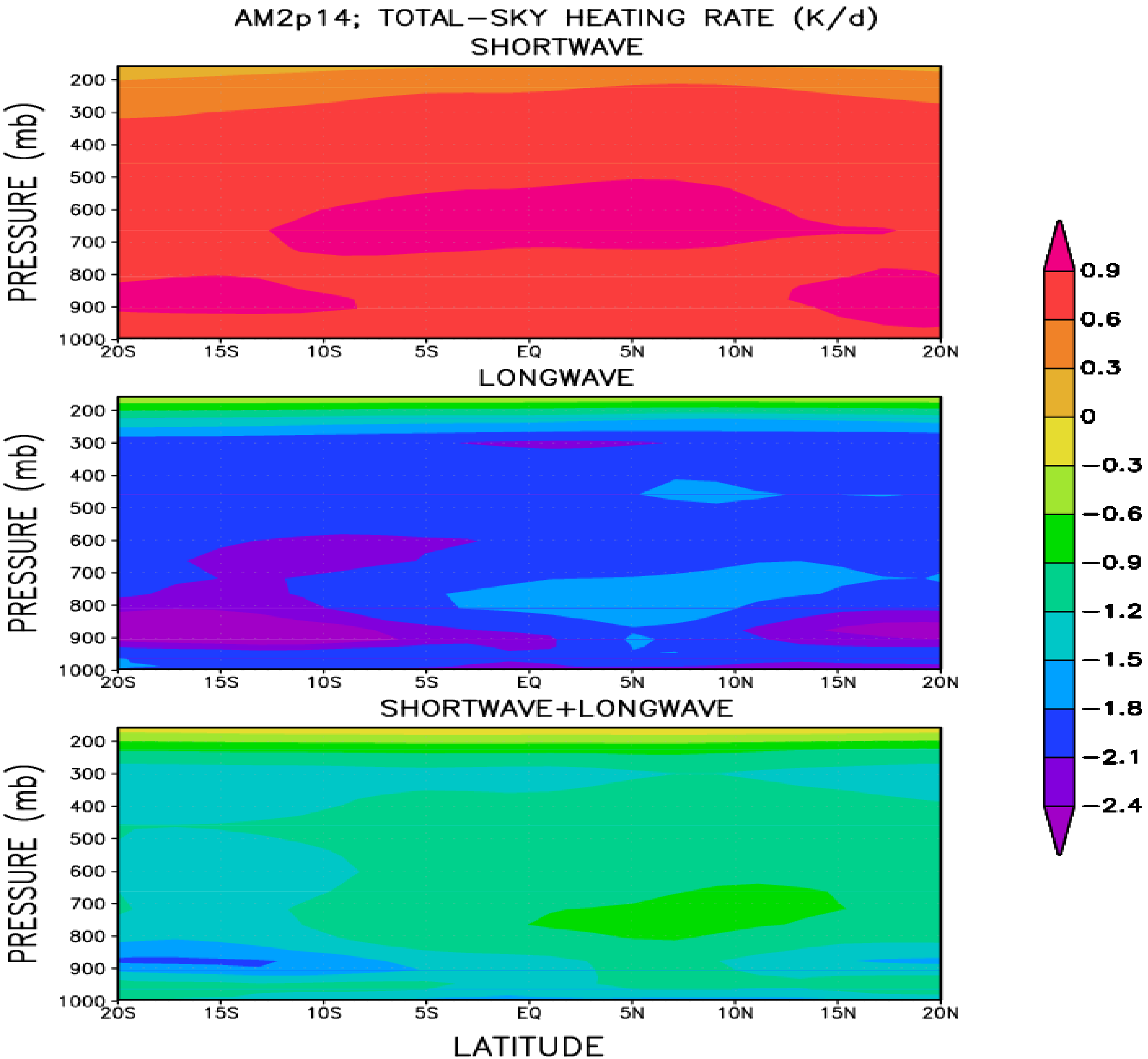


Fig. 3.15 The dependence of the longwave emissivity on (a) liquid water content [from Slingo *et al.* (1982); reprinted with permission from the Royal Meteorological Society] and (b) ice content [from Griffith *et al.* (1980); reprinted with permission from the American Meteorological Society].

Water clouds can usually be treated as "blackbody" radiative agents in the longwave, just like the surface.


AM2p14; TOTAL-SKY HEATING RATE (K/d)
SHORTWAVE
LONGWAVE
SHORTWAVE+LONGWAVE
PRESSURE (mb)
200
300
400
500
600
700
800
900
1000
20S
15S
10S
5S
EQ
5N
10N
15N
20N
LATITUDE
0.9
0.6
0.3
0
−0.3
−0.6
−0.9
−1.2
−1.5
−1.8
−2.1
−2.4

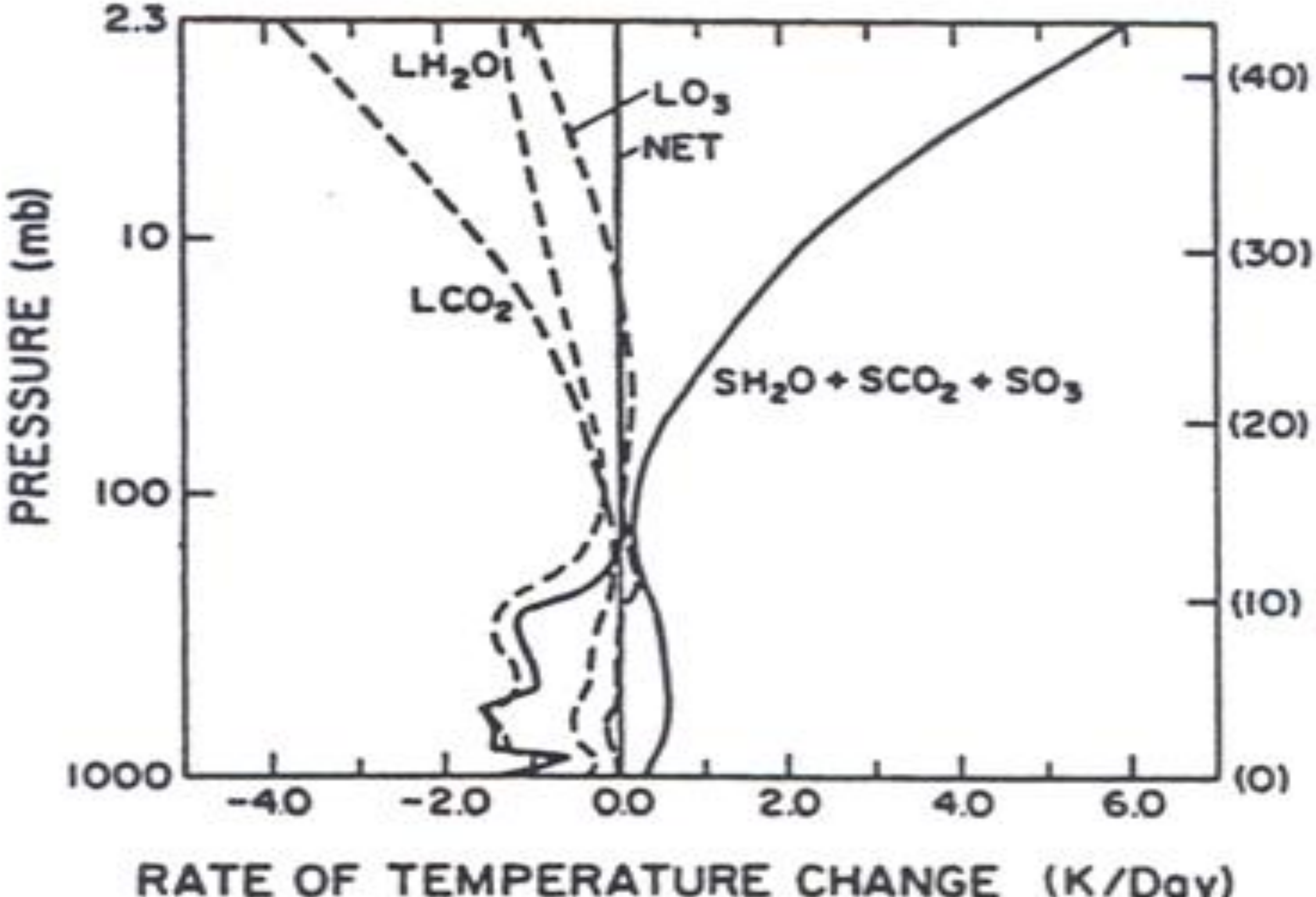


Fig. 4. Radiative-convective model results for the long-wave cooling and solar heating rates. The letters L and S denote long-wave and solar, respectively. The model results are taken from *Manabe and Strickler* [1964].

The END

For a THIN aerosol layer, with optical depth τ, backscatter fraction $\beta(\mu)$ and single-scattering albedo ω, irradiated by Sun at angle $\cos^{-1}(\mu)$,

Fraction of radiation Reflected and Transmitted is [see *Coakley and Chylek, J. Atmos. Sci., 1973; 2-stream approximation*]

$$\mathbf{R(\mu) = (U^2 - 1)\,[\exp(\alpha\tau / \mu) - \exp(-\alpha\tau / \mu)]\,/D}$$

$$\mathbf{T(\mu) = 4U / D}$$

where $U = [1 - \omega + 2\omega\beta(\mu)]^{1/2} / [1 - \omega]^{1/2}$

$\alpha = [1 - \omega + 2\omega\beta(\mu)]^{1/2}\ [1 - \omega]^{1/2}$

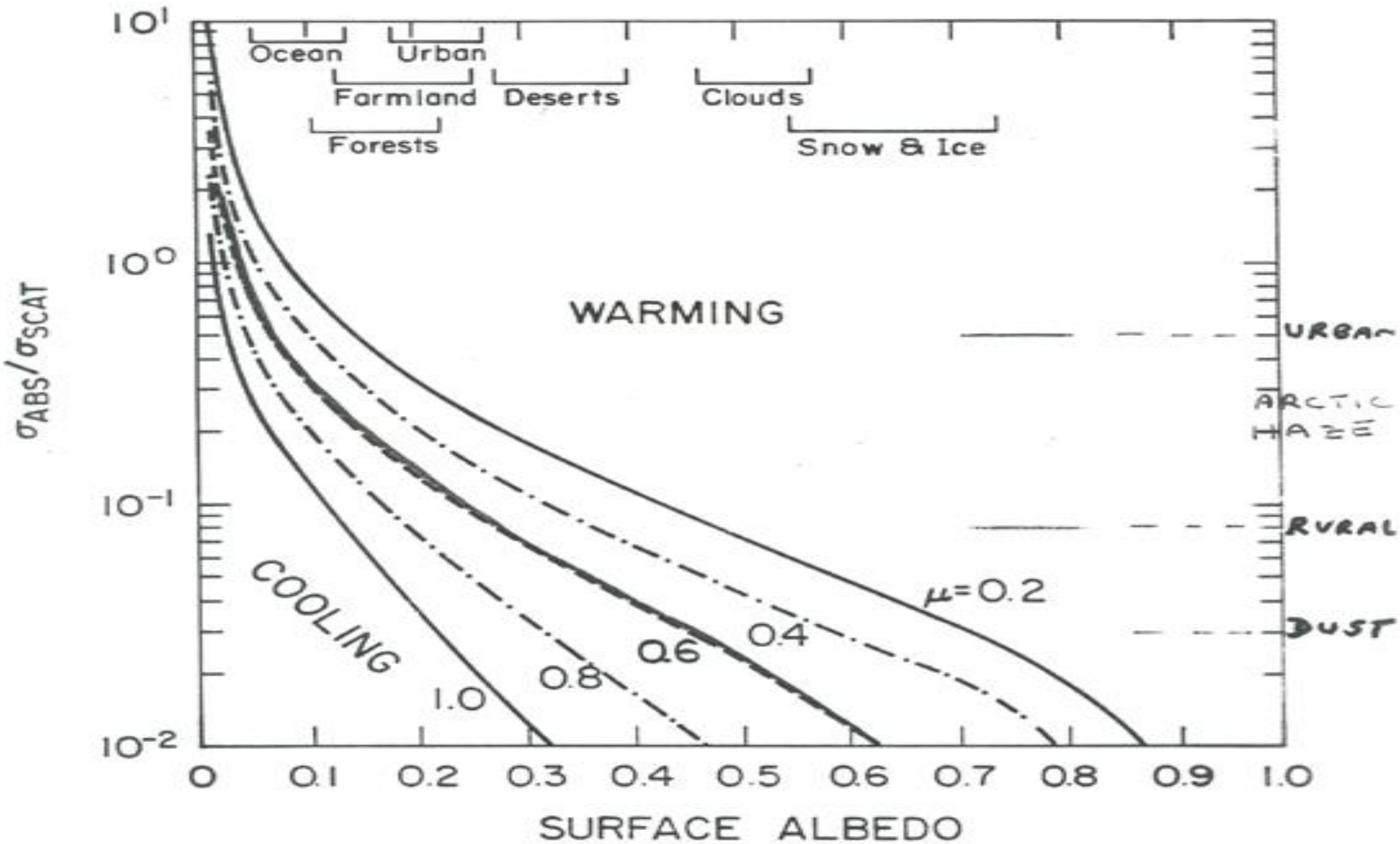
$D = \{(U + 1)^2 \exp(\alpha\tau / \mu)\} - \{(U - 1)^2 \exp(-\alpha\tau / \mu)\}$

If aerosol is over a surface with albedo A,

$$\mathbf{[\,R(\mu) - A\,]}$$

expresses whether aerosol causes a COOLING or HEATING radiative tendency for the climate system

Critical Aerosol Absorption-to-Backscatter Ratio as a function of Surface Albedo



Ramaswamy (1982)