AOSC 621

Lesson 15

Radiative Heating/Cooling

Effect of radiation on clouds: fog

Clear-sky cooling/heating rate: longwave

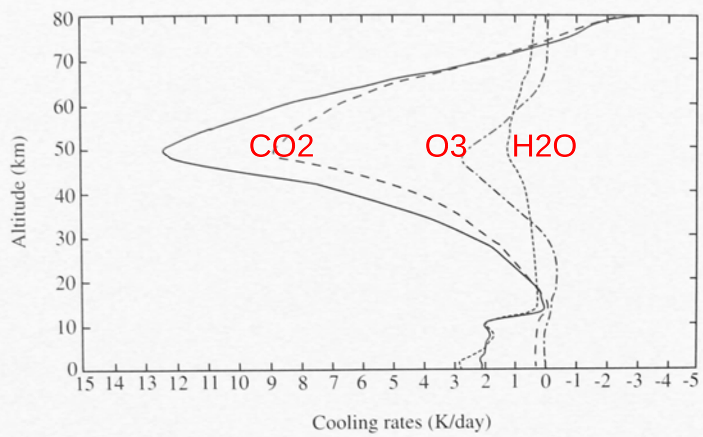
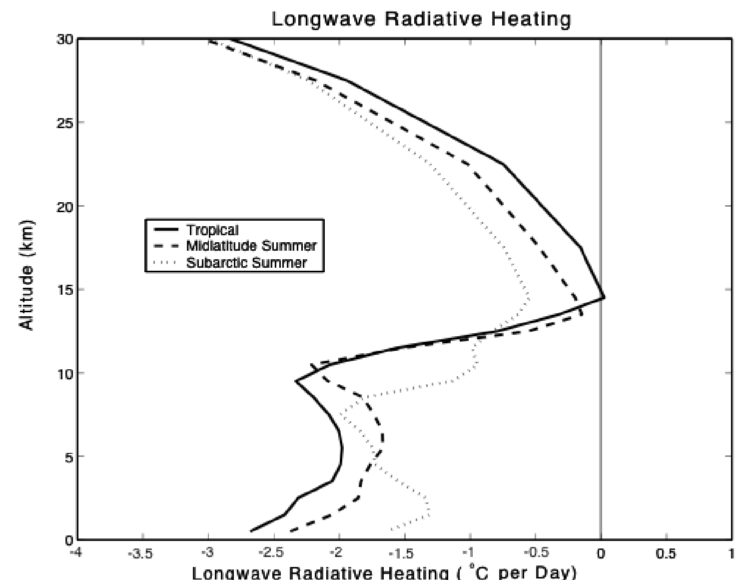
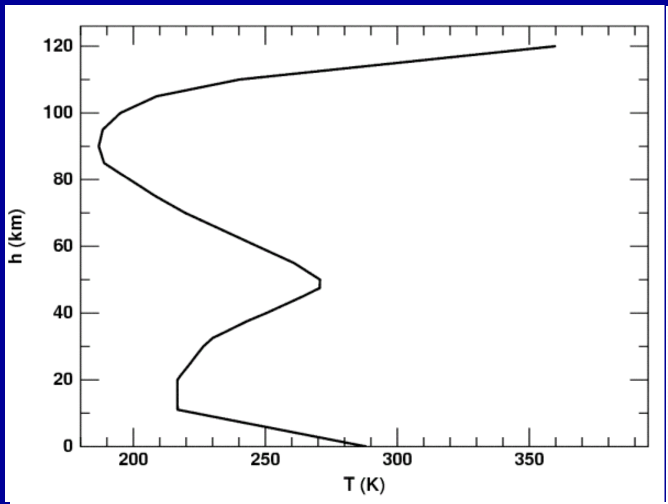
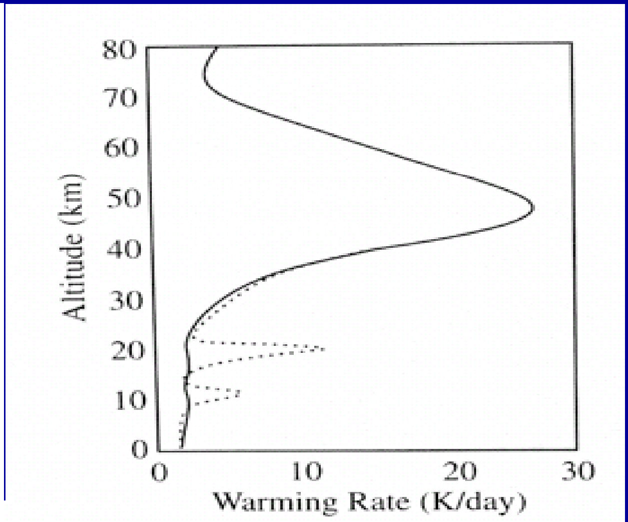


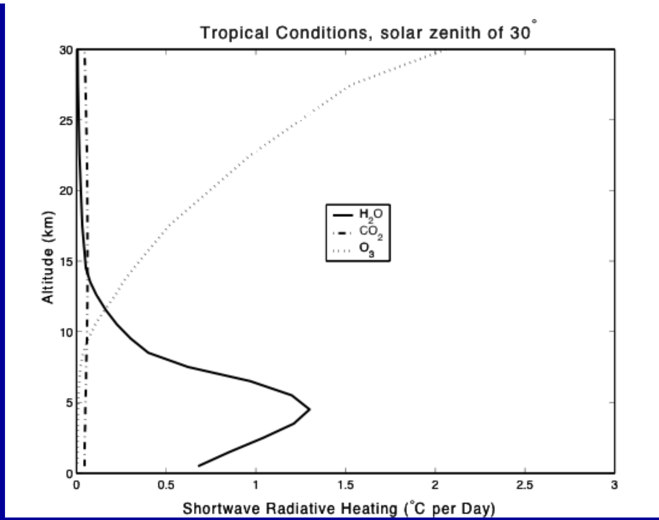
Figure 11.4 Clear-sky cooling rates based on line-by-line computations for H_2O (dotted line), CO_2 (dashed line), and O_3 (dashed-dotted line). The solid line gives the total cooling rate.

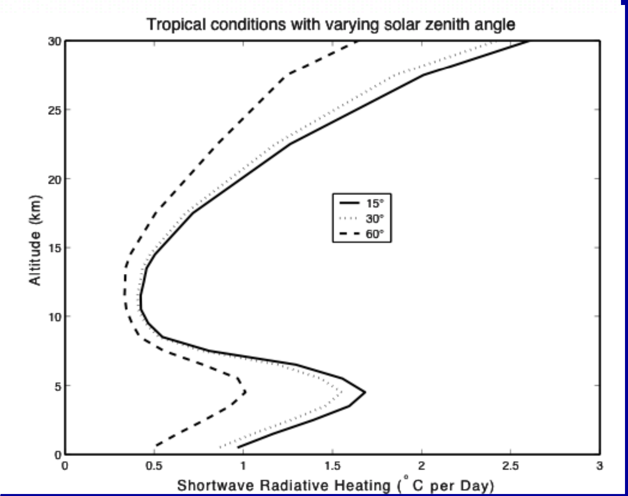


Clear-sky heating rate: shortwave



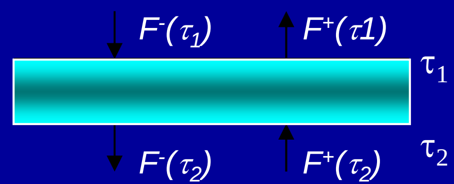






Net flux

Net flux: $F = F^{+} - F^{-}$



Net energy gain in a layer: $E = E_{in} - E_{out}$

For a unit volume in the layer: $E = \dfrac{F^{+}(\tau_2) + F^{-}(\tau_1) - \left(F^{-}(\tau_2) + F^{+}(\tau_1)\right)}{z_1 - z_2} = \dfrac{F(\tau_2) - F(\tau_1)}{z_1 - z_2}$ measured in $\dfrac{W}{m^3 \cdot \mu m}$

For very thin layer: $H_\lambda = -\dfrac{dF_\lambda}{dz}$

Heating rate (*H*)

$$H = \int_0^\infty H_\lambda \cdot d\lambda = \int_0^\infty -\frac{dF_\lambda}{dz} \cdot d\lambda$$

If $H < 0$: cooling
If $H > 0$: heating

How does temperature change? $H = \dfrac{dE}{dt}$

For a constant pressure: $dE = \rho \cdot c_p \cdot dT$

Therefore the time change is: $H = \dfrac{dE}{dt} = \rho \cdot c_p \cdot \dfrac{dT}{dt}$ This yields: $\dfrac{dT}{dt} = \dfrac{H}{\rho \cdot c_p}$ (usually measured in K/day)

Heating rates in the Atmosphere -LW

- Assume that the Earth's surface is a blackbody, and that the downward intensity at the top of the atmosphere is zero. Then we can write

$$F^+(z) = \pi B^* T_F(z,0) + \int_0^z \pi B(z') \frac{dT_F(z,z')}{dz'} dz' \qquad 1$$

$$F^-(z) = -\int_z^{z_t} \pi B(z') \frac{dT_F(z,z')}{dz'} dz' \qquad 2$$

- If we examine equation 1, the integrand can be viewed as *u.dv* in the relation *d(uv)=vdu+udv* and Eq 1 can be replaced by

$$\int_0^z \frac{\mathrm{d}\left[\pi \mathrm{B}(z')\mathrm{T_F}(z,z')\right]}{dz'} \mathrm{dz'} - \int_0^z \frac{d\left[\pi B(z')\right]}{dz'} T_F(z,z') dz'$$

Heating rates in the Atmosphere

which equals

$$\pi B(z) - \pi B(0) T_F(z,0) - \int_0^z \frac{d\left[\pi B(z')\right]}{dz'} T_F(z,z')\,dz'$$

and equation 1 becomes

$$F^+(z) = \pi B(z) + \left(\pi B^* - \pi B(0)\right) T_F(z,0) - \int_0^z \frac{d\left[\pi B(z')\right]}{dz'} T_F(z,z')\,dz'$$

If we apply the same procedure to Equation 2 we get

$$\begin{aligned} F^-(z) &= -\int_z^{z_t} \frac{\mathrm{d}\left[\pi B(z') T_F(z,z')\right]}{dz'}\,\mathrm{d}z' + \int_z^{z_t} \frac{d\left[\pi B(z')\right]}{dz'} T_F(z,z')\,dz' \\ &= \pi B(z) + \pi B(z_t) T_F(z,z_t) + \int_z^{z_t} \frac{d\left[\pi B(z')\right]}{dz'} T_F(z,z')\,dz' \end{aligned}$$

Heating rates in the Atmosphere

The net flux $F_{net} = F^+ - F^-$ will consist of four terms

$$F_{net} = -\int_0^z T_F(z,z')\frac{d\left[\pi B(z')\right]}{dz'}dz' - \int_z^{z_t} T_F(z,z')\frac{d\left[\pi B(z')\right]}{dz'}dz'$$

$$+\pi B(z_t)T_F(z,z_t) + \left(\pi B^* - \pi B(0)\right)T_F(z,0)$$

Heating rates in the Atmosphere

- The heating rate at z is defined as follows:

$$H(z) = -\frac{dF_{net}(z)}{dz}$$

and will consist of four terms

$$H(z) = +\int_0^z \frac{dT_F(z,z')}{dz}\frac{d\left[\pi B(z')\right]}{dz'}dz' \qquad \text{A.}$$

Exchange from below

$$+\int_z^{z_t} \frac{dT_F(z,z')}{dz}\frac{d\left[\pi B(z')\right]}{dz'}dz' \qquad \text{B.}$$

Exchange with above

$$-\pi B(z_t)\frac{dT_F(z,z_t)}{dz} \qquad \text{C.}$$

Exchange with space

$$-\left[\pi B^* - \pi B(0)\right]\frac{dT_F(z,0)}{dz} \qquad \text{D.}$$

Exchange with surface

Meaning of the Terms

- A: Exchange from below
- B: Exchange from above
- C: Cooling to space
- D: Exchange from surface

Heating rates in the Atmosphere

Let's now examine the contribution that each term makes to the heating and cooling of the atmosphere.

But first we must examine the sign of the term $\frac{dT_F}{dz}$

This term can be defined as follows:

$$\frac{dT_F}{dz} = \text{limit as } \Delta z \rightarrow 0 \ \ \frac{T_F(z+\Delta z, z') - T_F(z.z')}{\Delta z}$$

for any z' greater than z, $T_F(z+\Delta z, z') > T_F(z, z')$

and $\frac{dT_F}{dz}$ will be positive because the distance from

$(z+\Delta z)$ to z' is less than from z to z'. Hence T is greater.

Heating rates in the Atmosphere

- By similar arguments it can be shown that for z' less than *z*, *dT/dz* will be negative
- Now we will examine the four terms for three classes of atmosphere.
- Isothermal
- One with a nominal lapse rate
- One with a temperature inversion

Isothermal Atmosphere

- For an isothermal atmosphere dB/dz will be zero. Hence the terms A and B are zero
- In an isothermal atmosphere the temperature at the surface is equal to the temperature of the atmosphere directly above the surface, hence term D is zero
- Term C is the only term that survives. dT/dz is positive (z’>z) and B is positive. The sign in front of the term is negative, hence the overall term is negative – cooling.
- Term dB/dz’ dT/dz overall

Term	dB/dz’	dT/dz	overall
A	0	-	0
B	0	+	0
C		+	-
D		-	0

Heating rates in Isothermal Atmosphere

- The heating rate at z is defined as follows:

$$H(z) = -\frac{dF_{net}(z)}{dz}$$

and will consist of four terms

$$H(z) = +\int_0^z \frac{dT_F(z,z')}{dz} \frac{d\left[\pi B(z')\right]}{dz'} dz' \qquad \text{A.}$$

$$+\int_z^{z_t} \frac{dT_F(z,z')}{dz} \frac{d\left[\pi B(z')\right]}{dz'} dz' \qquad \text{B.}$$

$$-\pi B(z_t) \frac{dT_F(z,z_t)}{dz} \qquad \text{C.}$$

$$-\left[\pi B^* - \pi B(0)\right] \frac{dT_F(z,0)}{dz} \qquad \text{D.}$$

A. Exchange from below
Nil

B. Exchange with above
Nil

C. Exchange with space
Cooling

D. Exchange with surface
Nil

Nominal lapse rate

- The temperature of the atmosphere decreases with *z*, hence *dB/dz'* is negative.
- The term dT_F/dz is negative for A, positive for B and positive for D. The signs can be summarized as follows:

Term	dB/dz'	dT/dz	overall sign
A	-	-	+ (heating)
B	-	+	- (cooling)
C		+	- (cooling)
D		-	+ (heating)

Heating rates in the nominal atmosphere

- The heating rate at z is defined as follows:

$$H(z) = -\frac{dF_{net}(z)}{dz}$$

and will consist of four terms

$$H(z) = +\int_0^z \frac{dT_F(z,z')}{dz} \frac{d[\pi B(z')]}{dz'} dz'$$

A. Exchange with below warming

$$+\int_z^{z_t} \frac{dT_F(z,z')}{dz} \frac{d[\pi B(z')]}{dz'} dz'$$

B. Exchange with above Cooling

$$-\pi B(z_t) \frac{dT_F(z,z_t)}{dz}$$

C. Exchange with space Cooling

$$-\left[\pi B^* - \pi B(0)\right] \frac{dT_F(z,0)}{dz}$$

D. Exchange with surface Warming

Temperature inversion

- Assume that *z* is at the inversion. *dB/dz'* changes sign at *z*:

Term	db/dz'	dT/dz	Overall sign
A	+	-	- (cooling)
B	-	+	+ (heating)
C		+	- (cooling)
D		-	+ (warming)

- Note that term A shows cooling, whereas for a nominal lapse rate it gave heating. The tendency of the atmosphere is to remove the inversion.

Heating rates in atmosphere of temperature inversion

- Temperature goes down with height

$$H(z) = -\frac{dF_{net}(z)}{dz}$$

and will consist of four terms

$$H(z) = +\int_0^z \frac{dT_F(z,z')}{dz} \frac{d\left[\pi B(z')\right]}{dz'} dz'$$

A. Exchange from below cooling

$$+\int_z^{z_t} \frac{dT_F(z,z')}{dz} \frac{d\left[\pi B(z')\right]}{dz'} dz'$$

B. Exchange with above warming

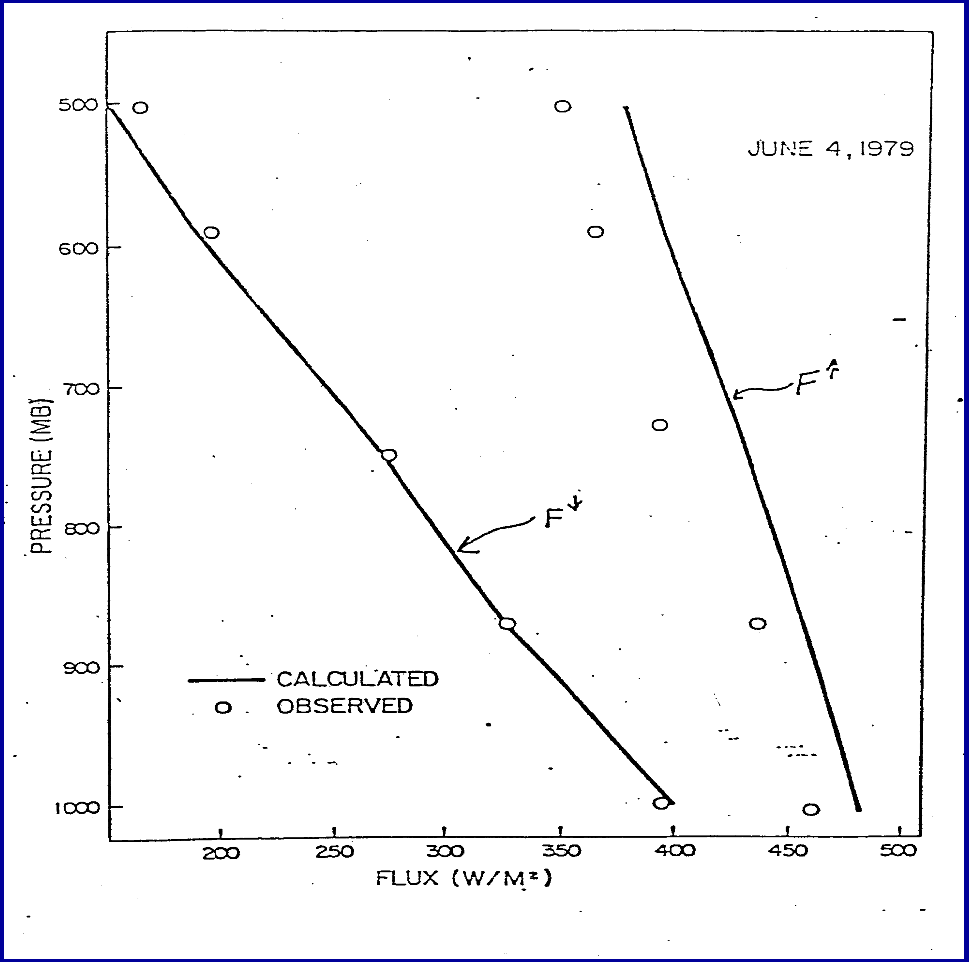
$$-\pi B(z_t) \frac{dT_F(z,z_t)}{dz}$$

C. Exchange with space cooling

$$-\left[\pi B^* - \pi B(0)\right] \frac{dT_F(z,0)}{dz}$$

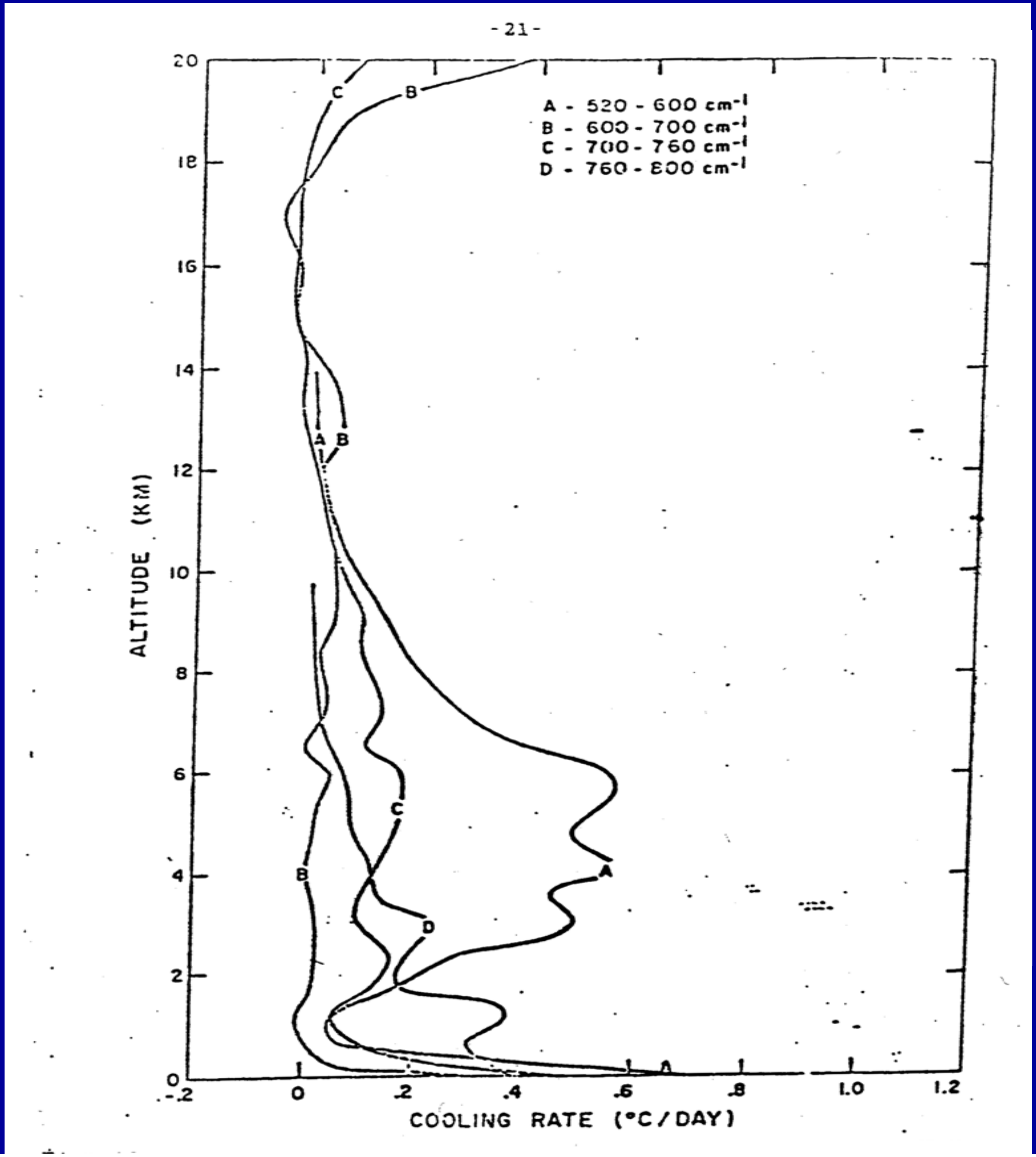
D. Exchange with surface warming

Profiles of clear sky upward and downward fluxes

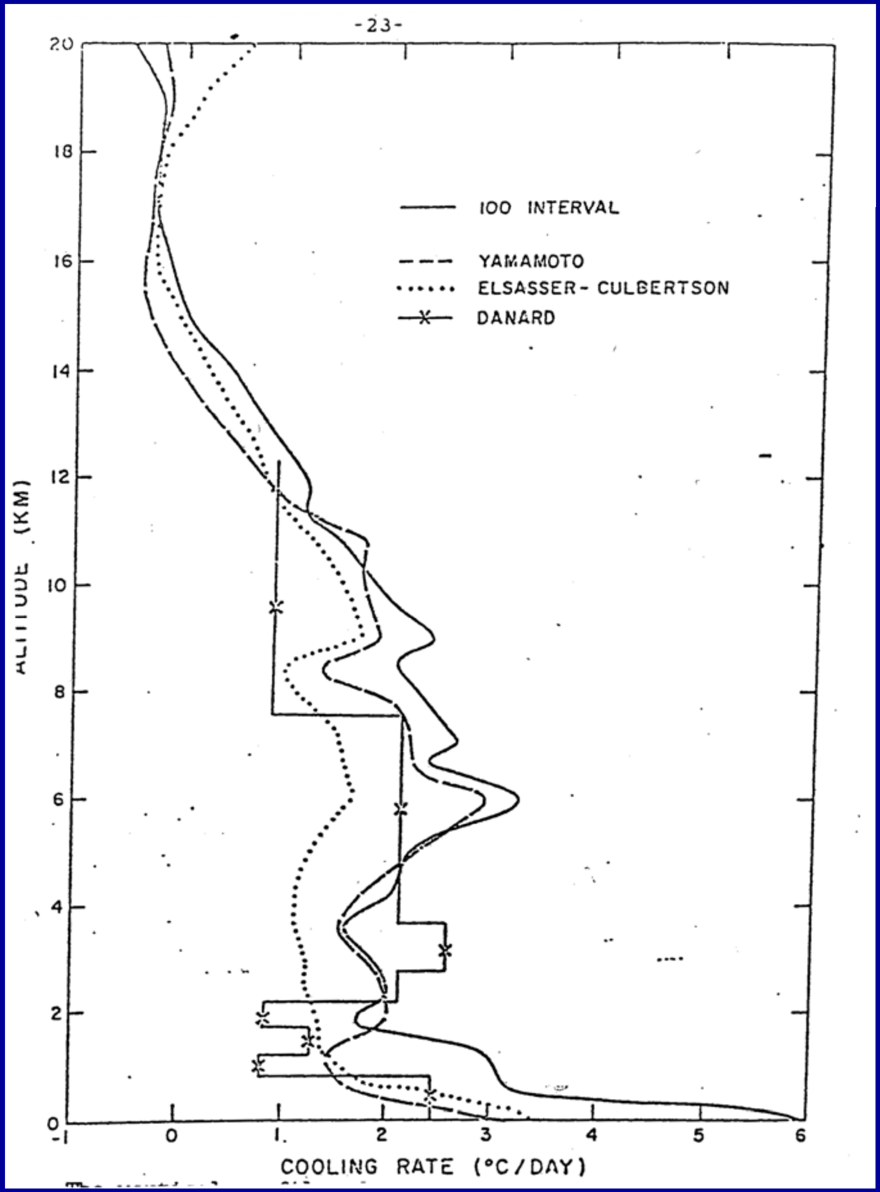


1. Note that both the upward and downward fluxes decrease with increasing, but at different rates.
2. The upward flux decrease because the principle source of heating is the radiation from the ground, and this is attenuated with height.
3. The downward radiation fluxes increase towards the surface because the increasingly opaque atmosphere is emitting at progressively warmer temperatures.

Spectral contributions to the cooling rate – tropical atmopshere



Vertical profile of total longwave cooling



Radiative Heating by Clouds

Spectral dependence of cloud absorption

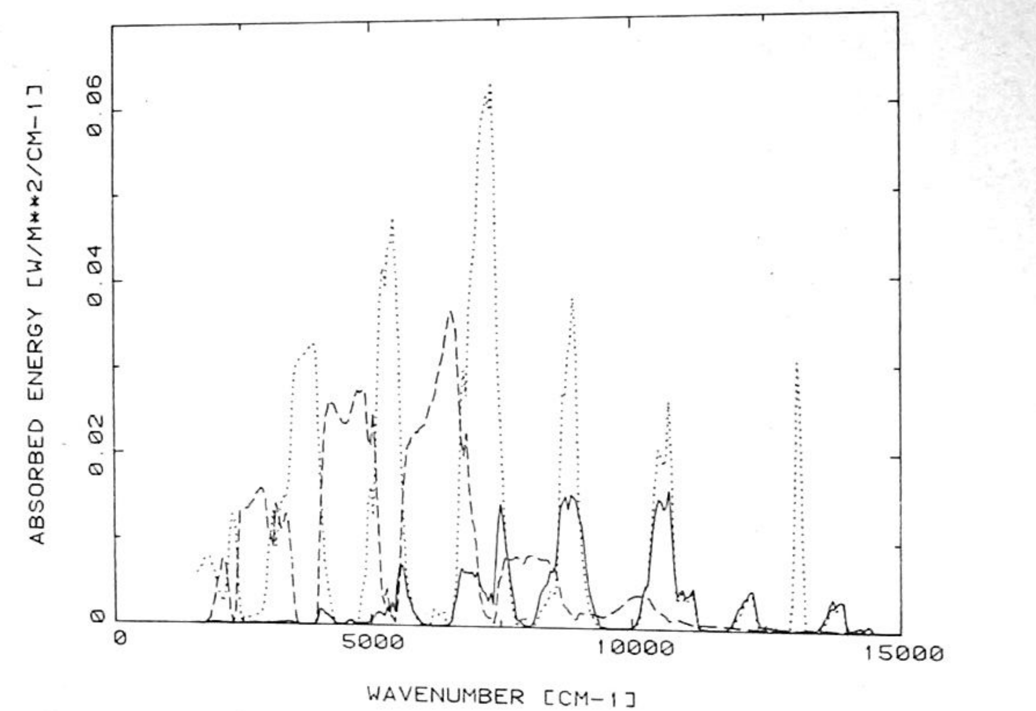
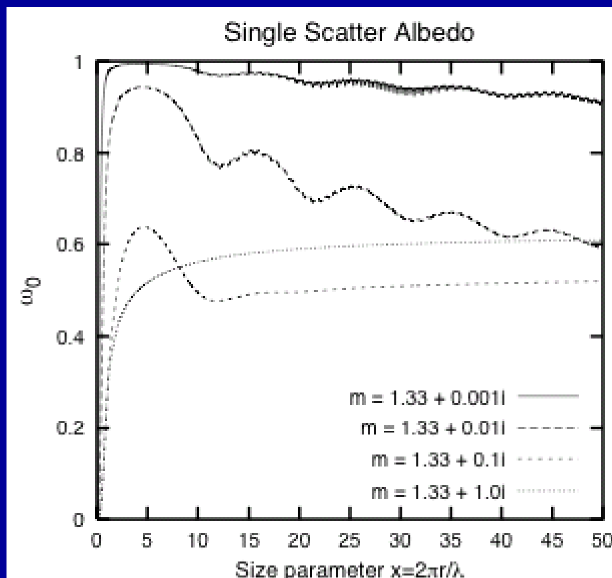


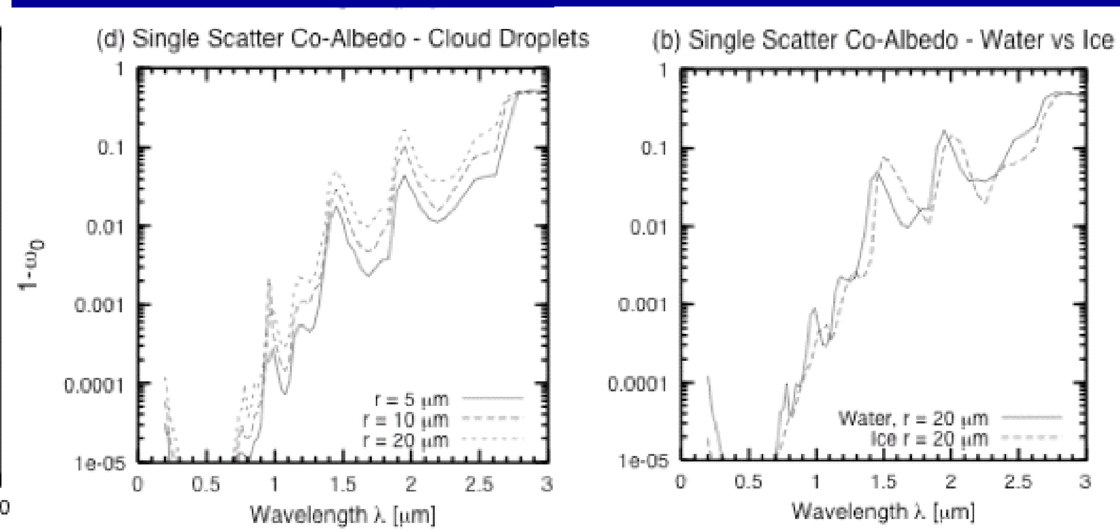
FIG. 4. Spectral absorption at 50 cm^{-1} resolution by cloud water vapor (solid), cloud droplets (dashed) and column vapor (dotted), typical of a 1 km thick stratus cloud with cloud top altitude of 2 km in a standard atmosphere with overhead sun.

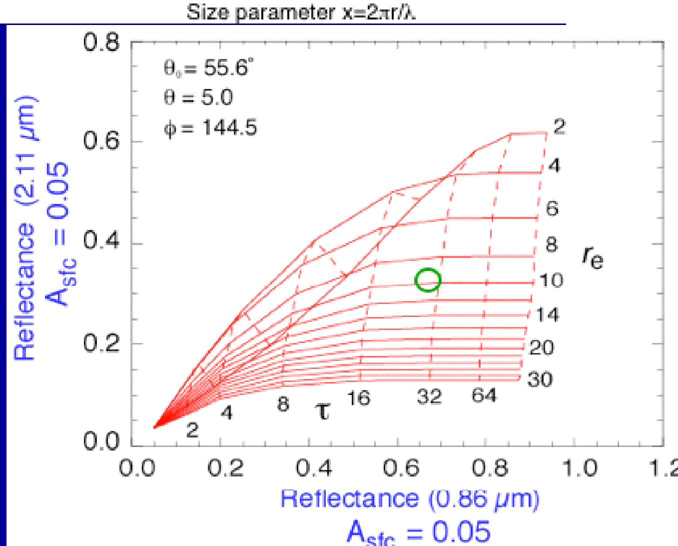
Factors increasing vapor absorption:

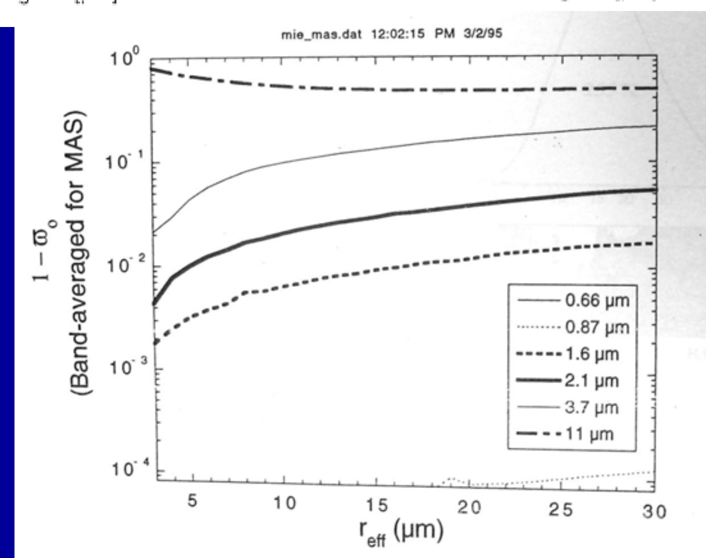
Influence of cloud altitude:

Cloud absorption: dependence on particle size



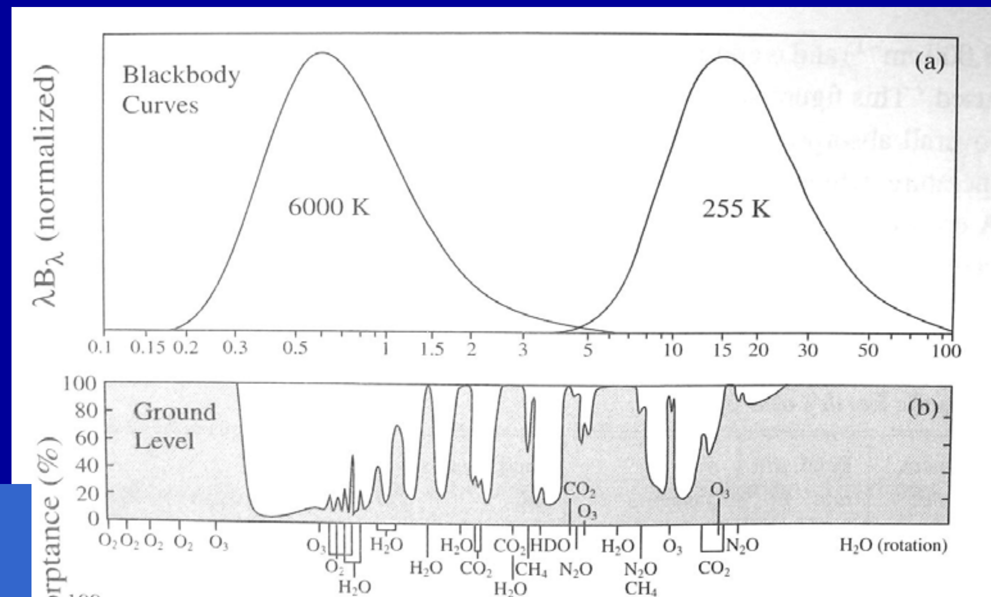






Longwave radiative cooling heating in clouds

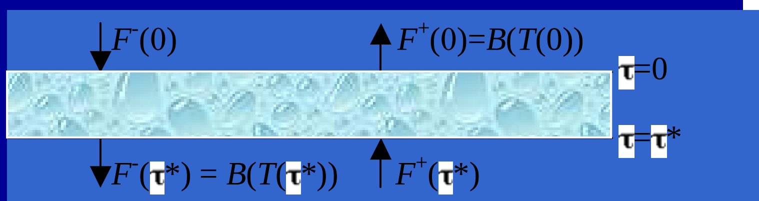
Longwave radiative effects of clouds strongest at which wavelengths?



Heating/cooling inside cloud:

Net energy gain in a layer: $E = E_{in} - E_{out}$

Overall heating rate of entire cloud:



$$H(\tau) \propto \left[\left(F^+(\tau^*) - B(T(\tau^*))\right)\cdot e^{-\frac{\tau^*-\tau}{\bar{\mu}}} + \left(F^-(0) - B(T(0))\right)\cdot e^{-\frac{\tau}{\bar{\mu}}} \right]$$

Draw graph of vertical profile:

- middle of cloud
- near top
- near bottom
- below cloud
- above cloud