Climate Modeling

*Discussion (available as Lecture 9 on web site)*

# Radiative-Convective Models

*Manabe and Strickler (1964)*

# Radiative Properties of Atmospheric Gases

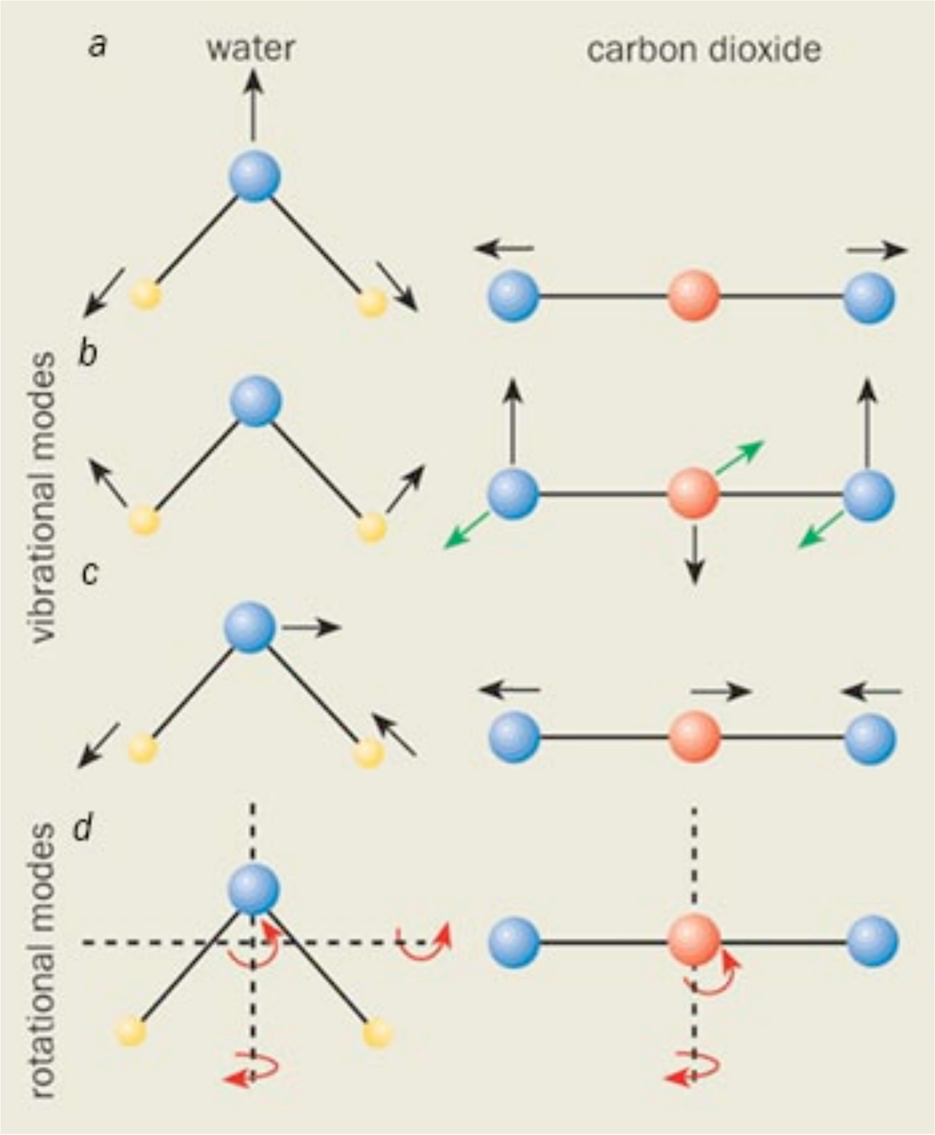
- Transmission
- Scattering (change in direction):
  - e.g. water droplets in clouds
- Absorption (photon is absorbed raising the internal energy of a molecule)
  - e.g. $H_2O$, $CO_2$
- Emission (photon is emitted lowering the internal energy of a molecule)

# Absorption and Emission of Atmospheric Gases

- Absorption and emission of photons can only occur at those discrete frequencies that correspond to the quantized energy levels of a molecule => atmospheric gases are not blackbodies
- Rotational Energy (dipole needed)
- Vibrational Energy

# $CO_2$

No Permanent Dipole Moment
but
**Vibrational Modes**
(b) and (c) below can induce temporary dipole leading to vibration-rotation absorption bands



Hartmann, 1994

No Dipole Moment

Dipole Moment: 15 um (important because near peak of terrestrial emission spectrum)

Dipole Moment: 4.3 um

Broadening of sharp spectral lines due to

- natural broadening (finite time of absorption = energy uncertainty)
- pressure broadening (due to collisions with other molecules during absorption/ emission)
- doppler broadening (due to movement of molecule relative to photon)

- Lifetime of high energy states are long ($10^{-1}$ - $10^{-3}$ s) compared to time between collisions ($10^{-7}$ s)
- Energy is redistributed increasing temperature

Pierrehumbert (2011) Physics Today

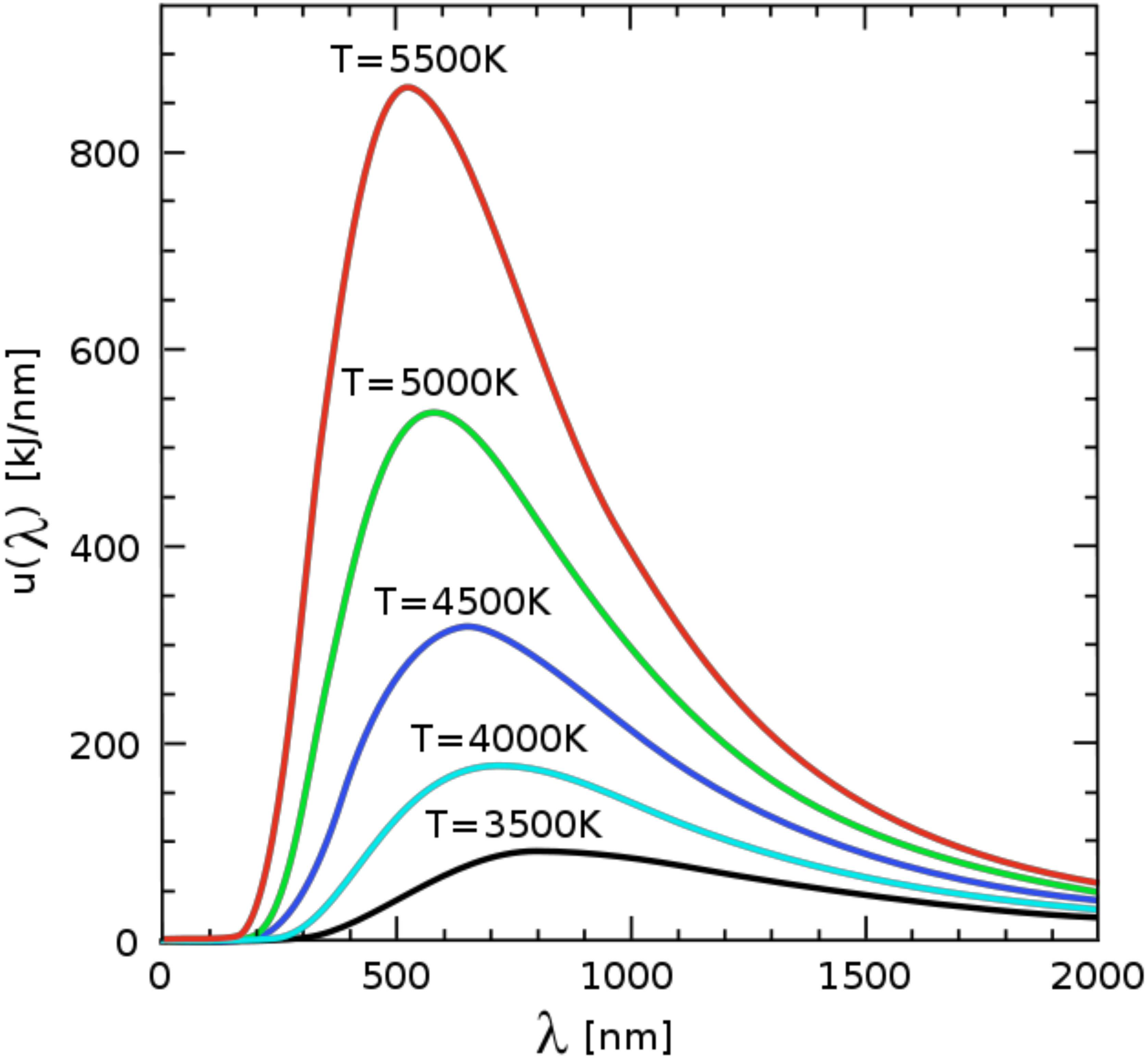
# Planck’s Law

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$

frequency

$$I'(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}.$$

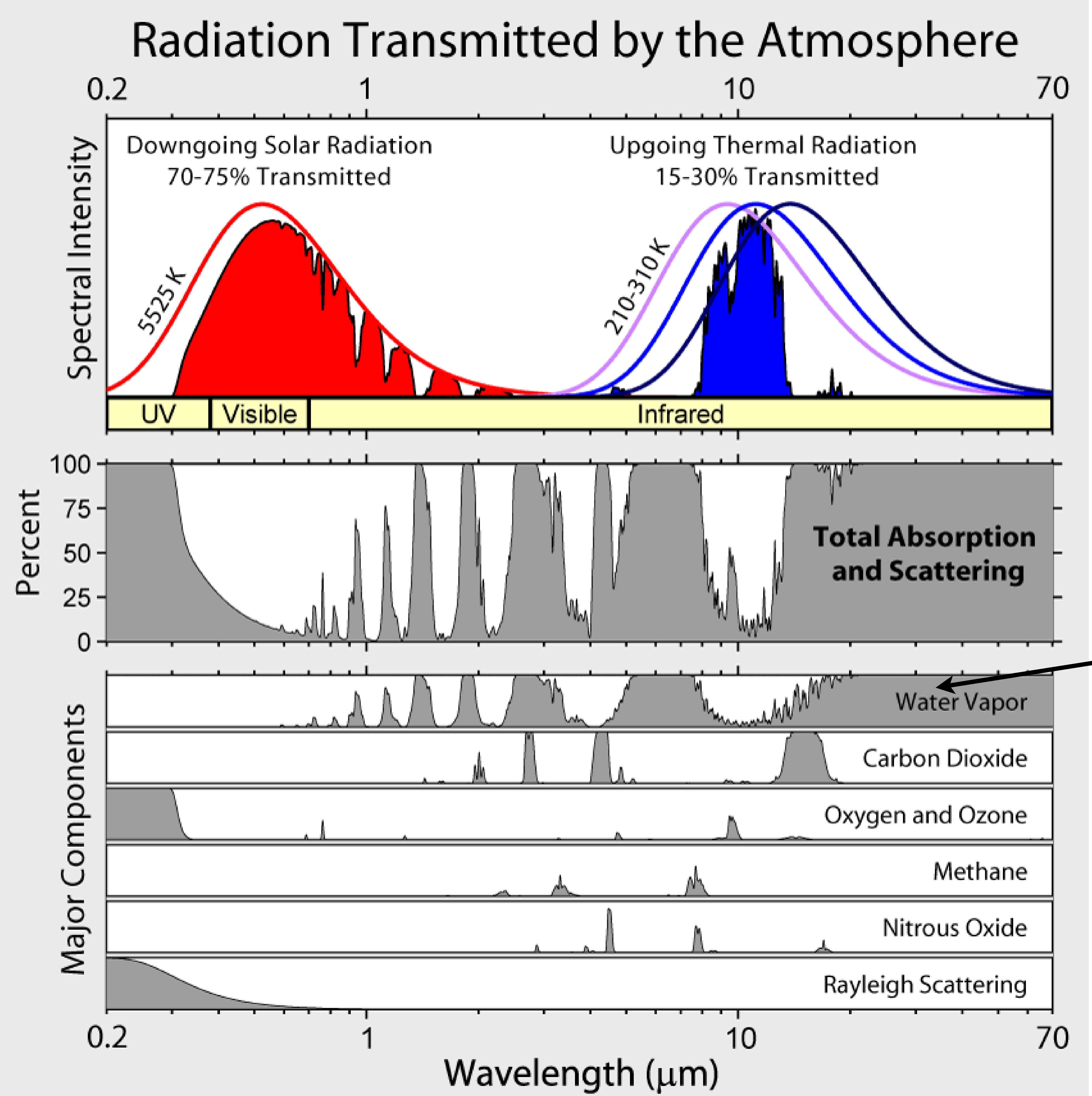
wavelength



**Black body spectrum** (spectral energy density **inside** a blackbody cavity). Indicated units are correctly kJ/m$^4$, or nJ/cm$^3$/µm. Scale by c/4π to achieve $I'(\lambda,T)$.

Integration over all frequencies gives Stephan Boltzmann law ~T$^4$

http://en.wikipedia.org/wiki/Planck%27s_law



# Line-by-Line Model

Rotation

## 2.7 Radiative-Convective Models

The simple energy balance model of Figure (2.4) can be modified and extended to include more layers as shown in Figure (2.19). Now we assume the atmosphere is transparent to shortwave radiation and the atmospheric layers 1 and 2 are completely opaque for longwave radiation. Assuming also the atmospheric layers to be perfect black bodies the energy balance at the top of the atmosphere becomes

$$S(1-\alpha)=\sigma T_1^4 \quad . \qquad (2.47)$$

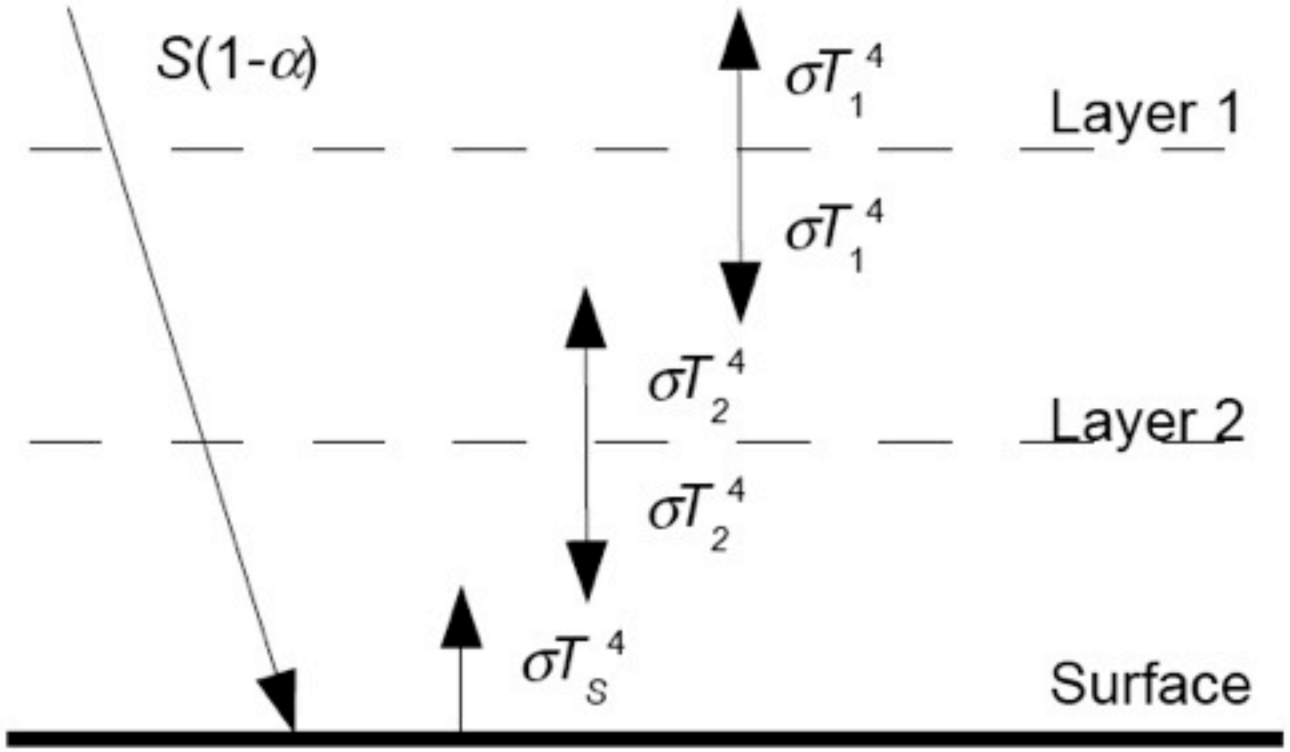


*Figure 2.19: Simple two-layer radiative equilibrium model.*

For layer 1 the energy balance is

$$\sigma T_2^4=2\sigma T_1^4=2S(1-\alpha) \quad , \qquad (2.48)$$

for layer 2 we have

$$\sigma T_1^4+\sigma T_s^4=2\sigma T_2^4=4S(1-\alpha) \quad ,$$

and at the surface

$$S(1-\alpha)+\sigma T_2^4=\sigma T_s^4 \quad . \qquad (2.49)$$

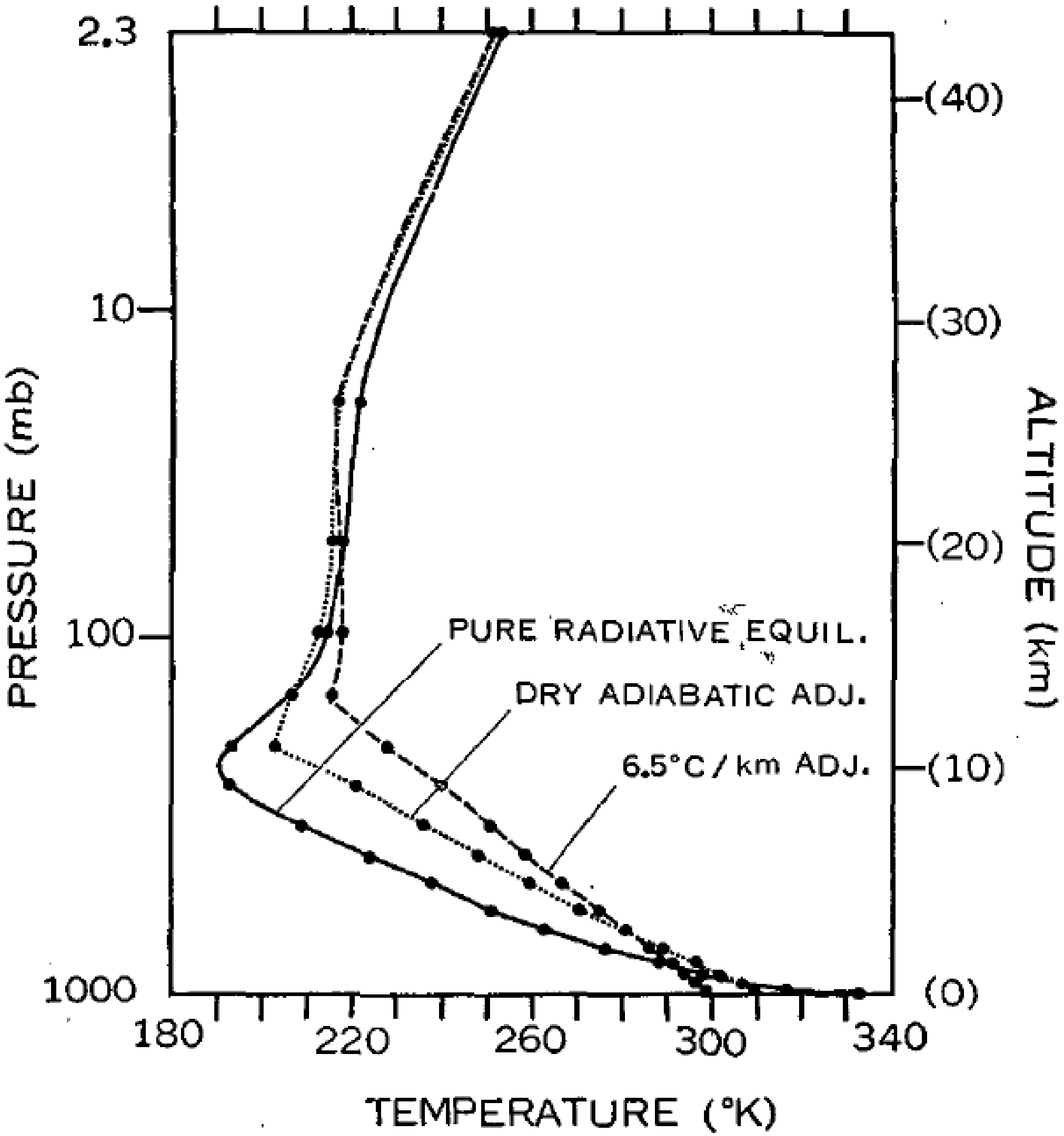
We notice that the temperatures increase downward. Solving these equations for the surface temperature we get

$$T_s^4=3\mathrm{S}\frac{1-\alpha}{\sigma}=3T_1^4 \quad . \qquad (2.50)$$

Extending the model to *n* layers we see that the surface temperature is equilibrium will be always be larger than the temperature of the upper layer.

$$T_s=\sqrt[4]{n+1}\,T_1 \quad . \qquad (2.51)$$

For 2 layers the surface temperature is $T_s$ = 335 K and the atmospheric temperatures are $T_2$ = 303 K and $T_1$ = 255 K. We see that the surface temperature is much too warm compared to the observed



Radiative transfer models resolve frequency bands.

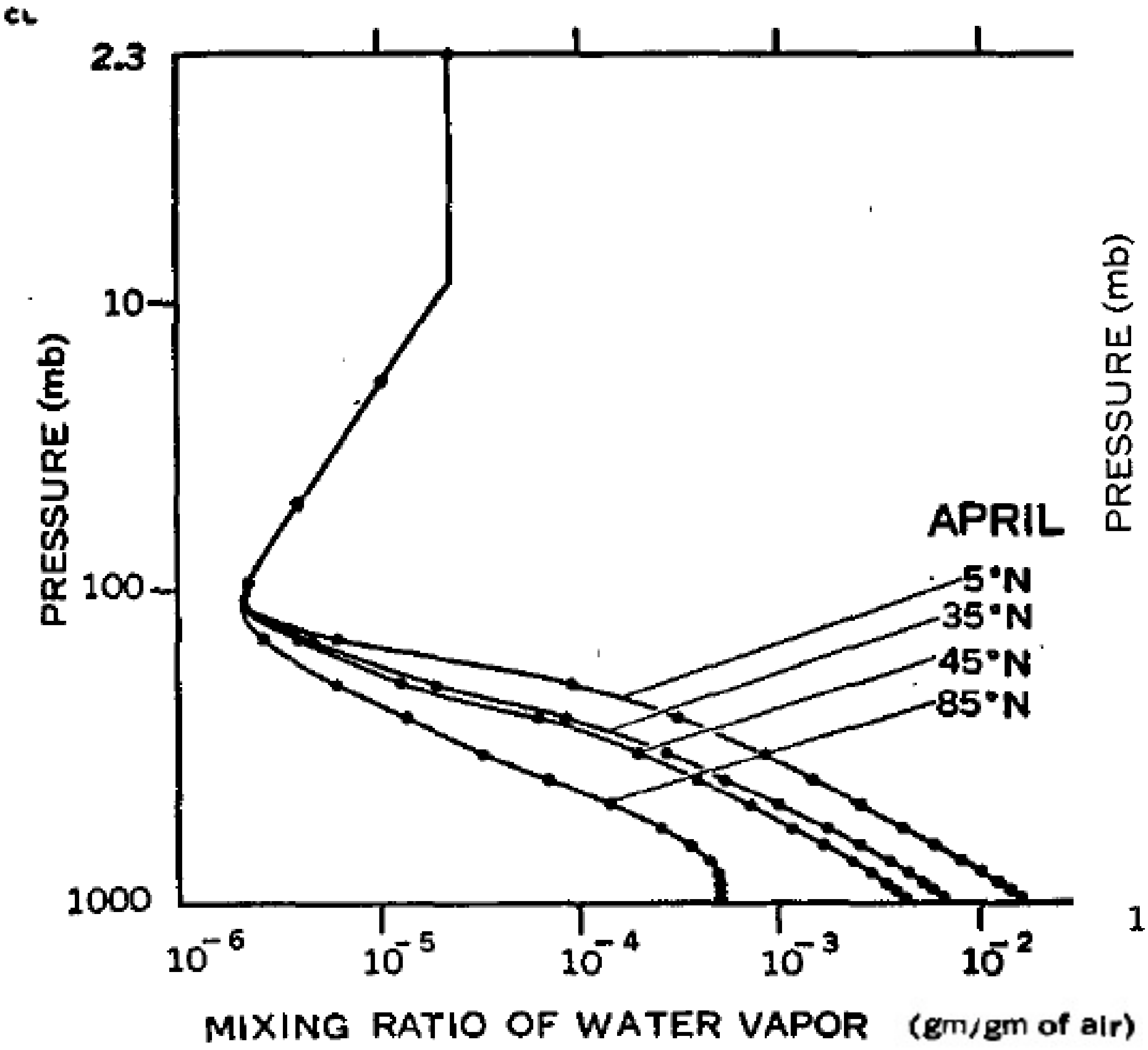
Radiative fluxes only (pure radiative equil.) gives very high surface temps.

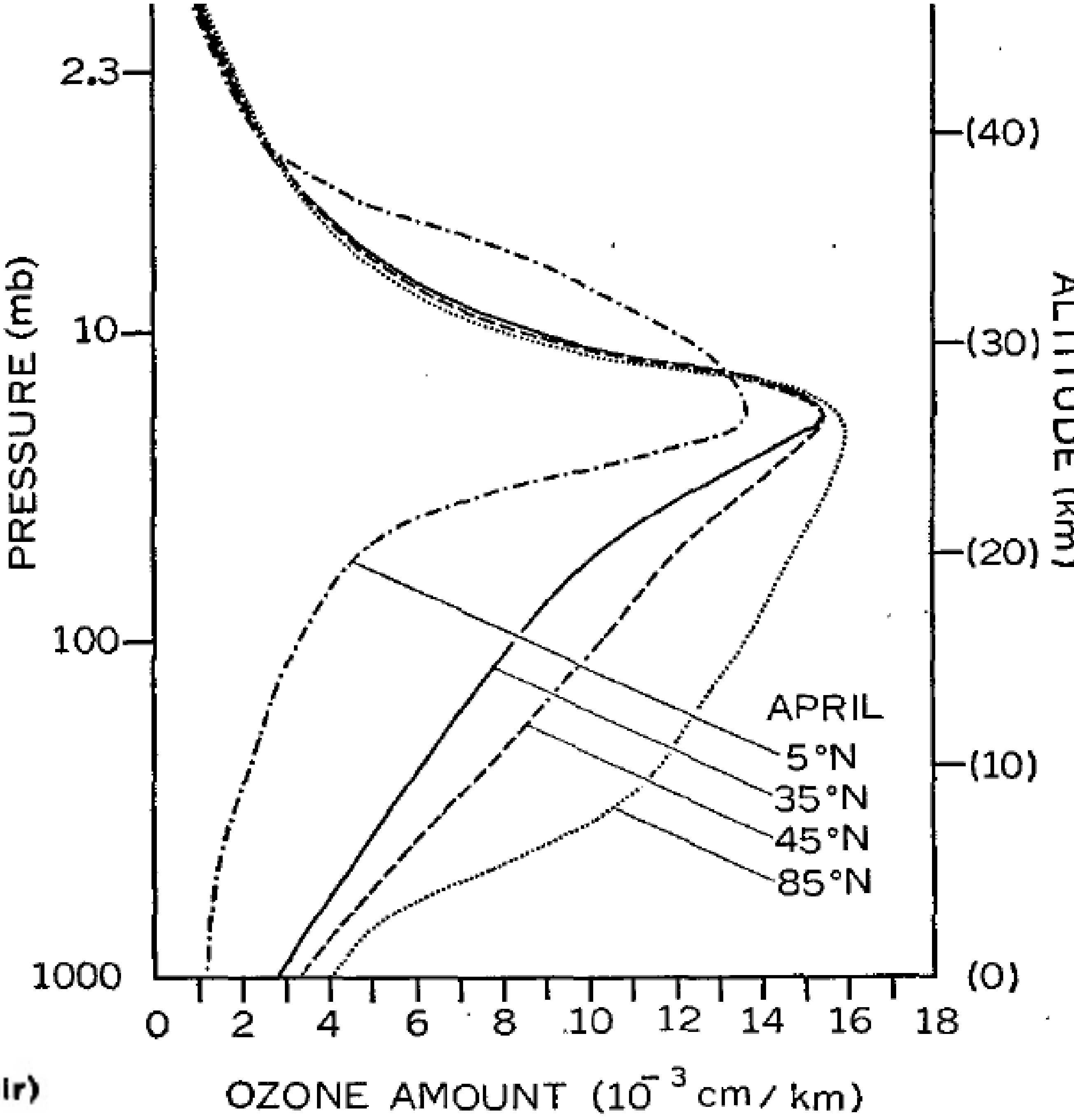
This leads to low densities and instability, which will cause convection.

Convective overturning, in the presence of liquid water at the surface (ocean), will lead to moist adiabatic lapse rate.

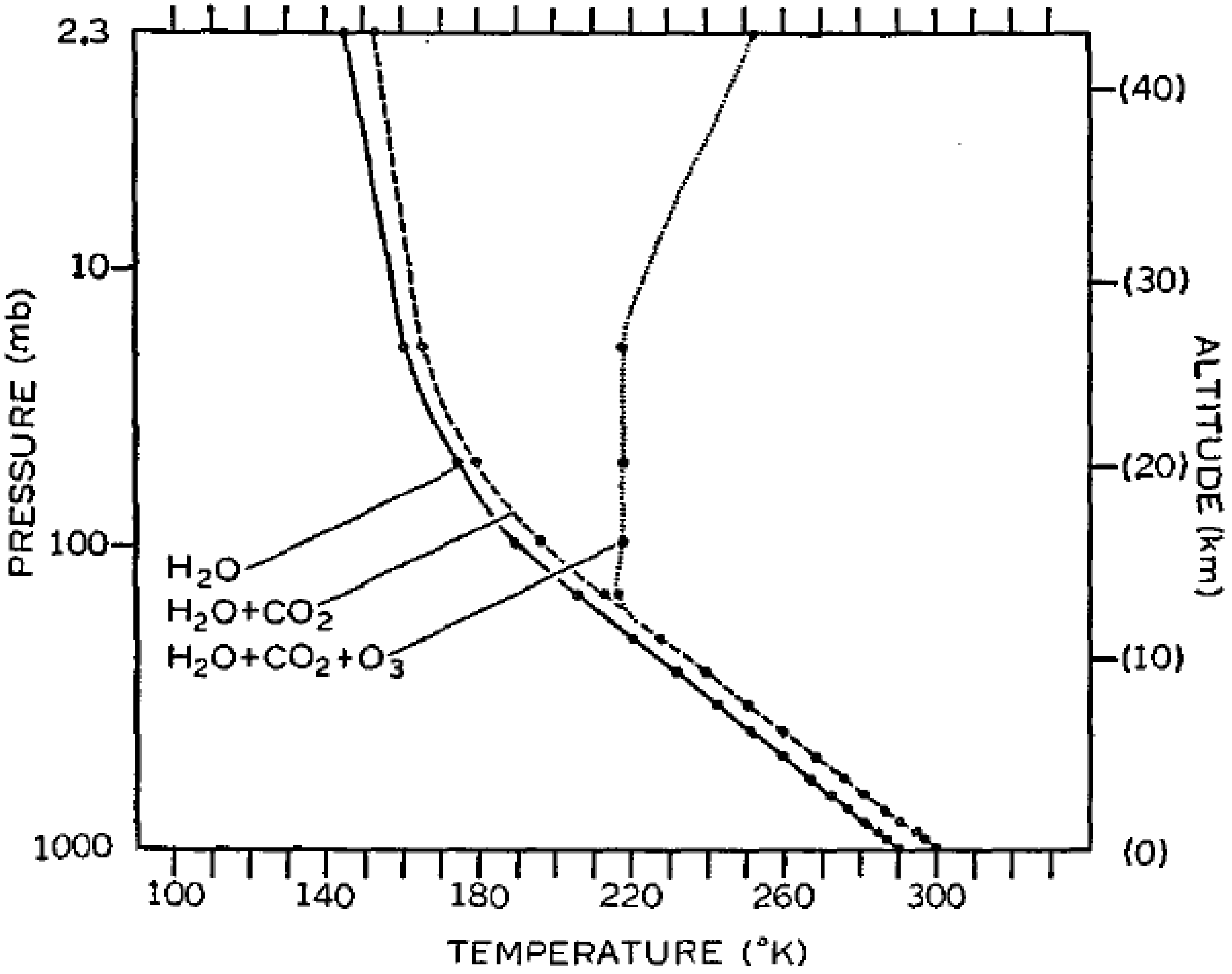
Manabe and Strickler (1964)

# $CO_2$=290 ppmv constant with height





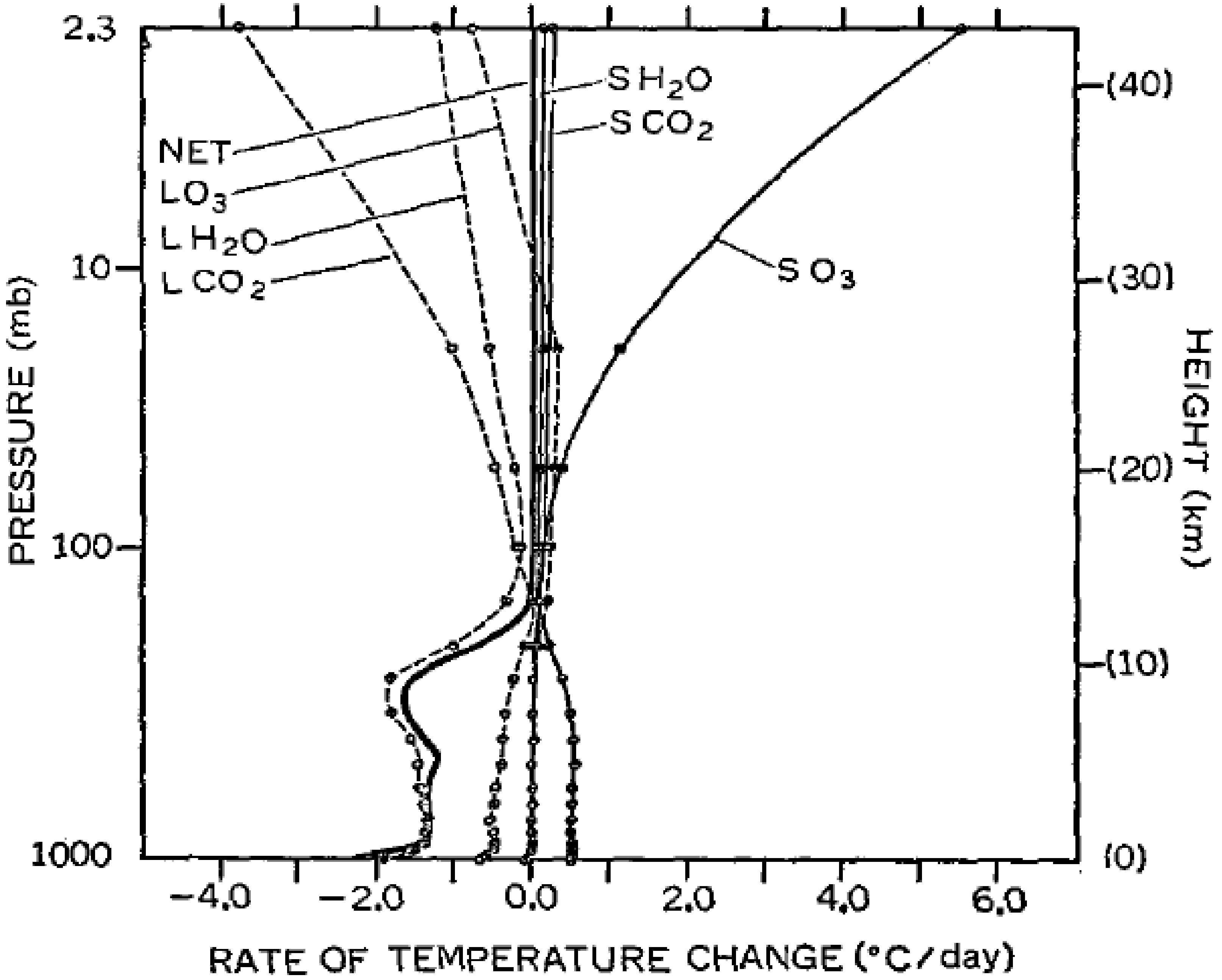
Manabe and Strickler (1964)



Ozone leads to warming in stratosphere, but not at surface.

$CO_2$ leads to surface warming of ~10 K.

Manabe and Strickler (1964)



Ozone absorbs sunlight in stratosphere, which leads to warming.

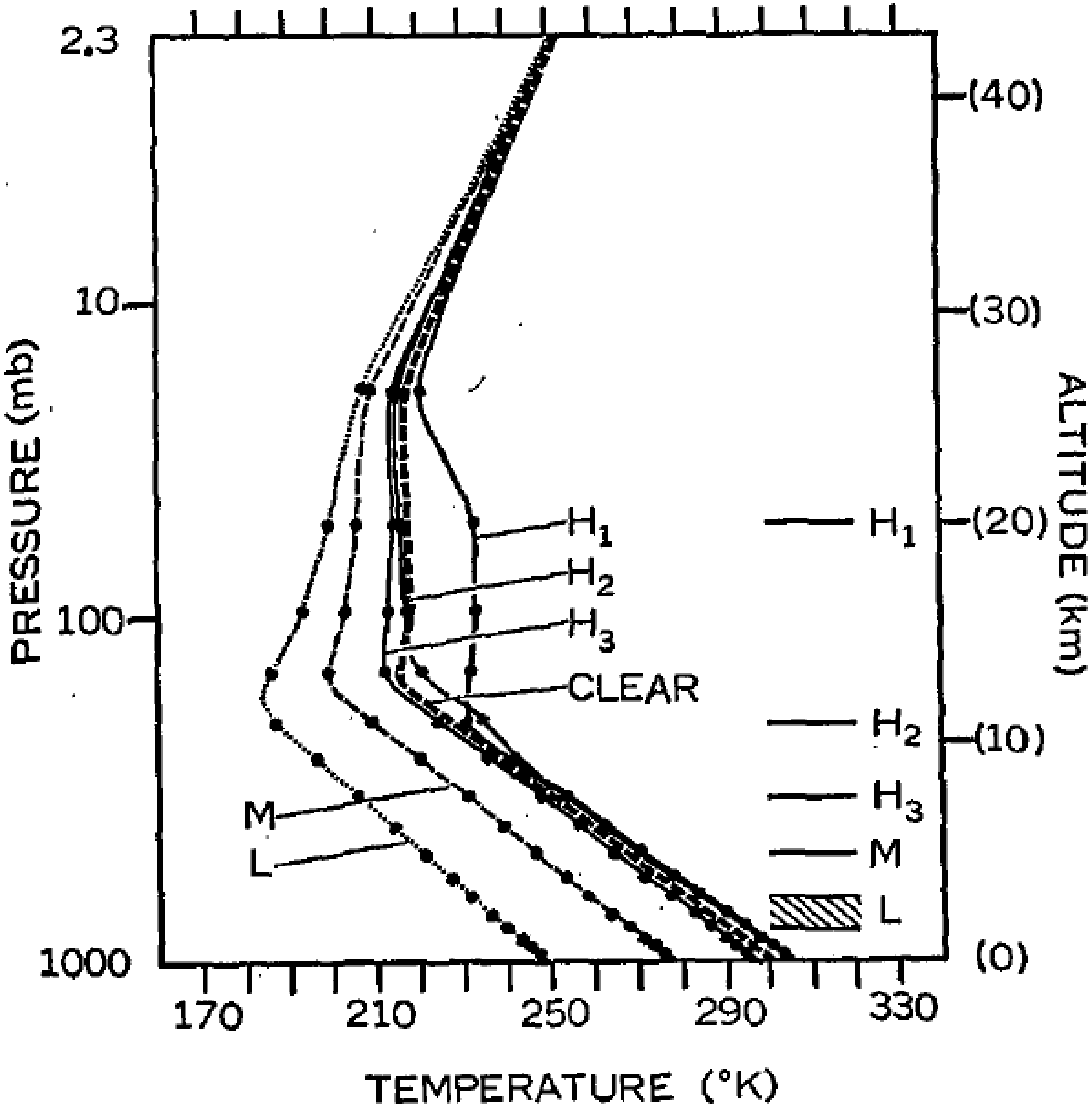
Stratosphere is cooled mainly by long wave radiation due to $CO_2$.

Long wave radiation by $H_2O$ and $CO_2$ cool the troposphere.

Convective fluxes heat the troposphere by transporting heat from the ground upwards.

Manabe and Strickler (1964)

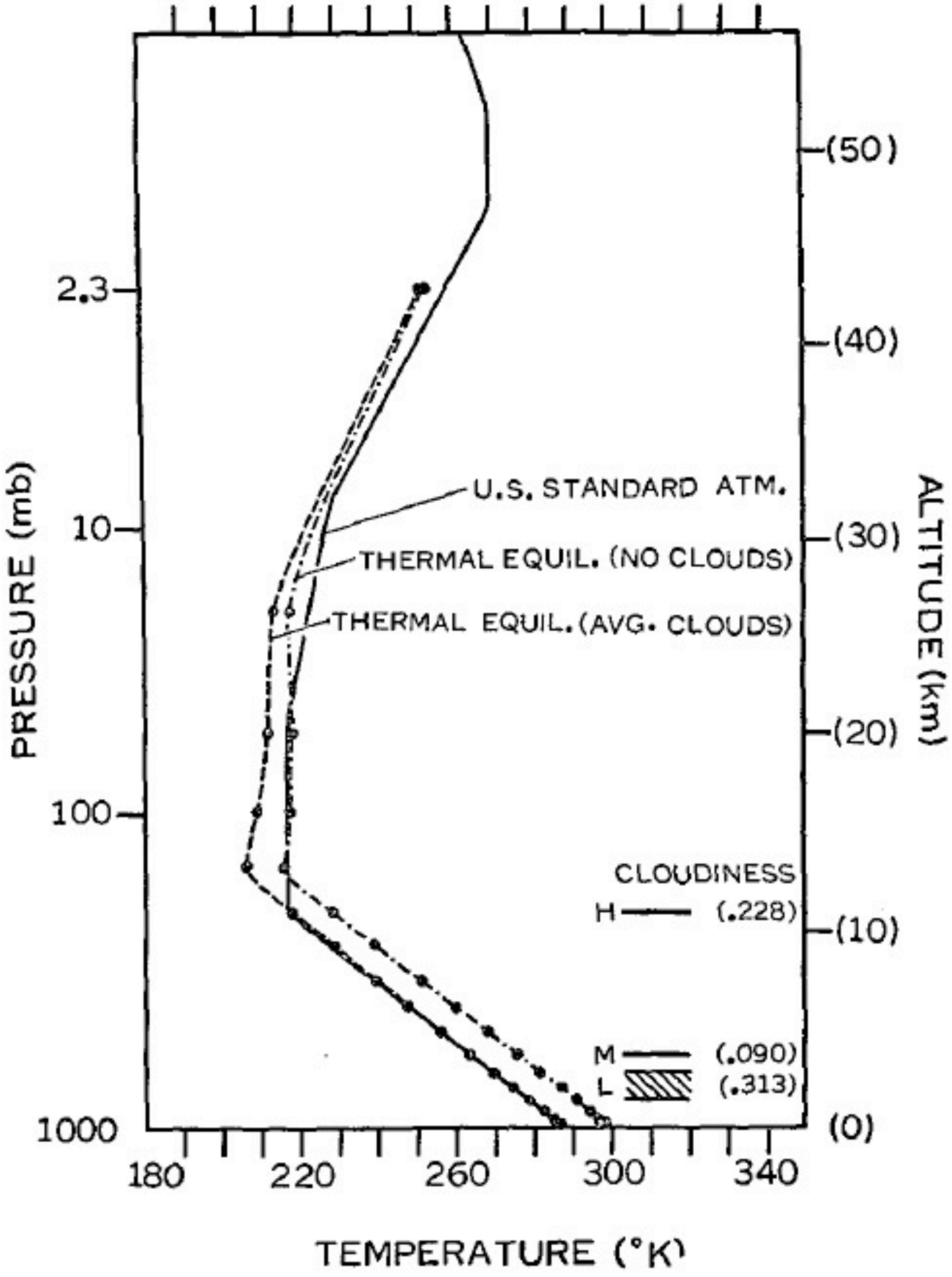
# Effect of Clouds



Low and mid level clouds cool the surface and troposphere.

High clouds can heat the surface.

Manabe and Strickler (1964)



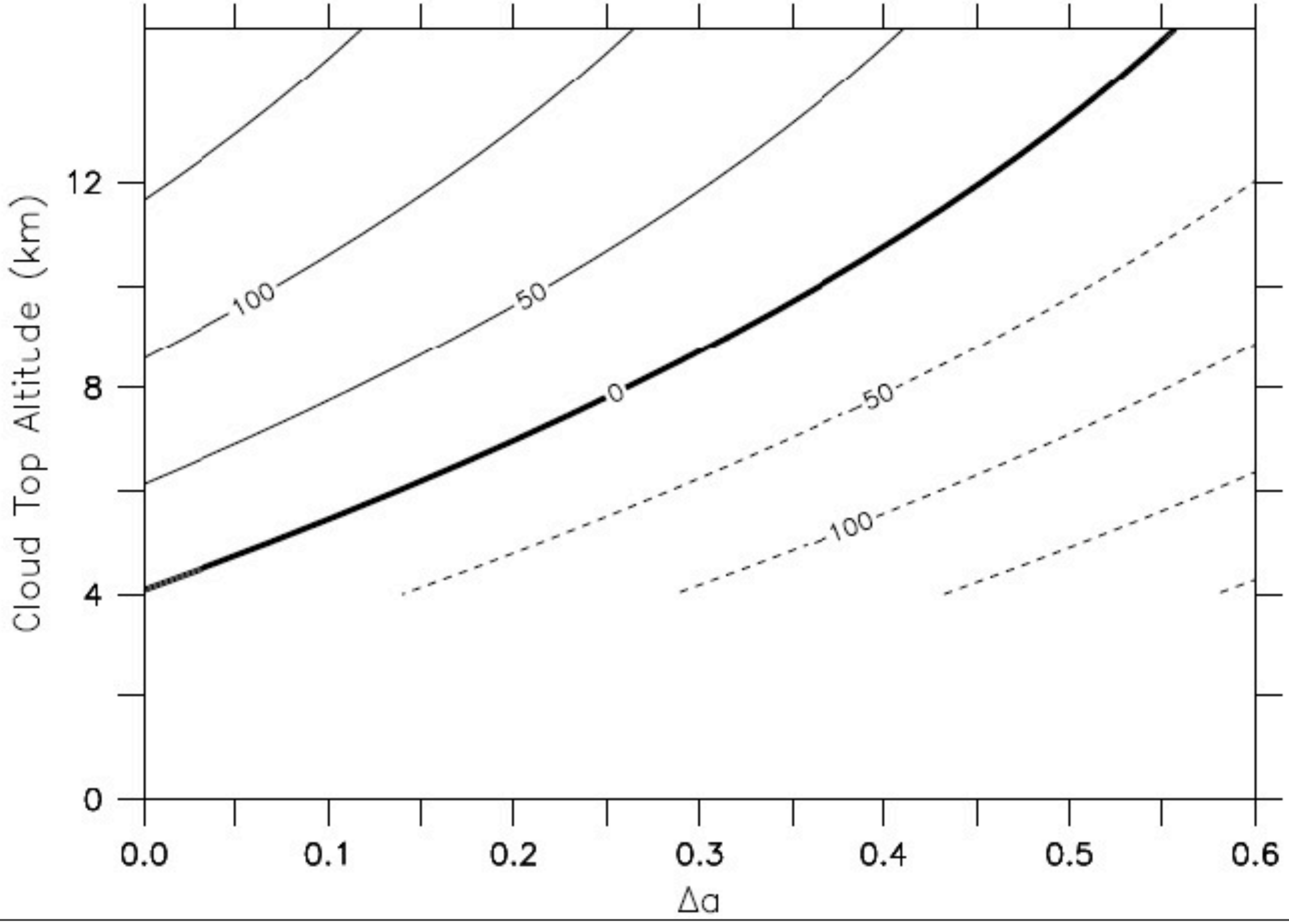
Average effect of clouds is to cool the surface and troposphere.

$$\Delta F_{SW} = S(1-a_{cloud}) - S(1-a_{clear}) = -S(a_{cloud} - a_{clear}) = -S\,\Delta a \leqslant 0$$

$$\Delta F_{LW} = \sigma T_{ct}^4 - F_{LWclear} \qquad F_{LW} = \sigma T_{ct}^4$$

$$\Delta R_{TOA} = \Delta F_{SW} - \Delta F_{LW} = -S\,\Delta\alpha + F_{LWclear} - \sigma T_{ct}^4$$

$$T_{ct} = T_s - \Gamma z_{ct}$$



Cloud radiative forcing $\Delta R_{TOA}$ as a function of change in albedo and cloud top altitude. Negative values are show as dashed lines. $S$ = 342 Wm$^{-2}$, $F_{LWclear}$ = 265 Wm$^{-2}$, $T_s$ = 288 K, $\Gamma$ = 6.5 K/km. From Hartmann (1994).

# Conclusions

- Radiative transfer heats the surface
- Convection leads to upward heat transport causing temperature in the troposphere to follow the moist adiabatic lapse rate
- Absorption of shortwave radiation by ozone in the upper atmosphere leads to the temperature increase in the stratosphere