Tropical Meteorology

Kerry Emanuel

Course Outline

- **Radiative-Convective Equilibrium**
  - General principles of radiative transfer
  - Simple models without phase change
  - General principles of moist convection
  - Simple models with phase change
  - Quantitative assessments of the equilibrium state - comparisons to observations
- **The Zonally-Averaged Circulation**
  - The observed climatology
  - Breakdown of the radiative-convective equilibrium state
  - Dry theory
  - Moist theory
  - Regulation of intensity

- **Asymmetric Steady Circulations**
  - Monsoons
    - Development and onset of the Asian monsoon
    - Monsoon breaks
    - Nonlinear, asymmetric theory
  - The Walker Circulation
    - Observations
    - Theory
- **Interannual Fluctuations of the Walker Circulation – ENSO**
  - Observed behavior
  - Theory and modeling of ENSO

- **Intraseasonal Oscillations**
  - Observations
  - GCM simulations
  - Theory of equatorial waves
    - Dry
    - Moist
  - WISHE
  - Cloud-radiation interactions and ISOs
- **Higher Frequency Disturbances**
  - Monsoon depressions
  - Equatorial waves
  - Easterly waves

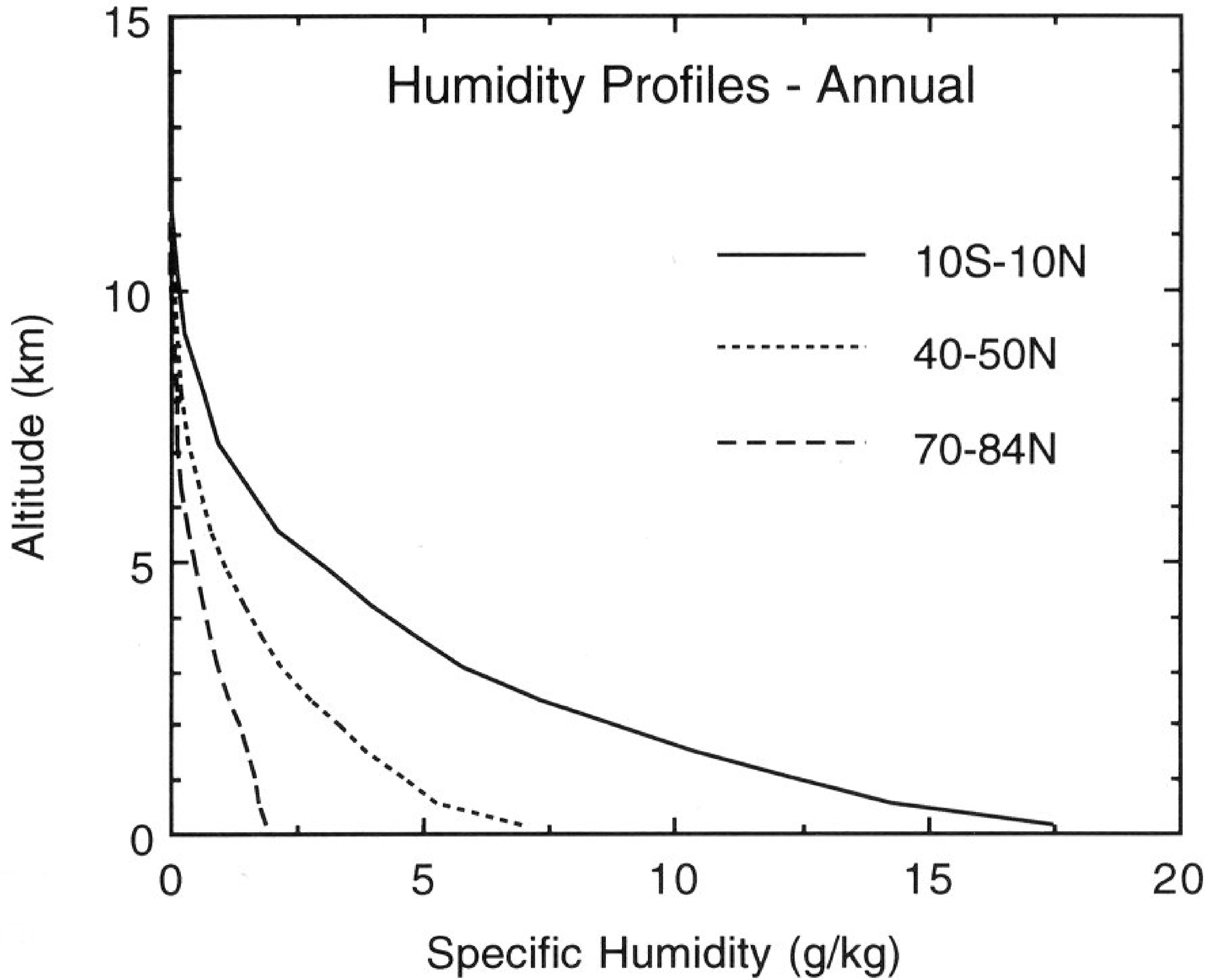
- **Tropical Cyclones**
  - Structure and climatology
  - Steady-state physics
  - Genesis
  - Ocean interaction

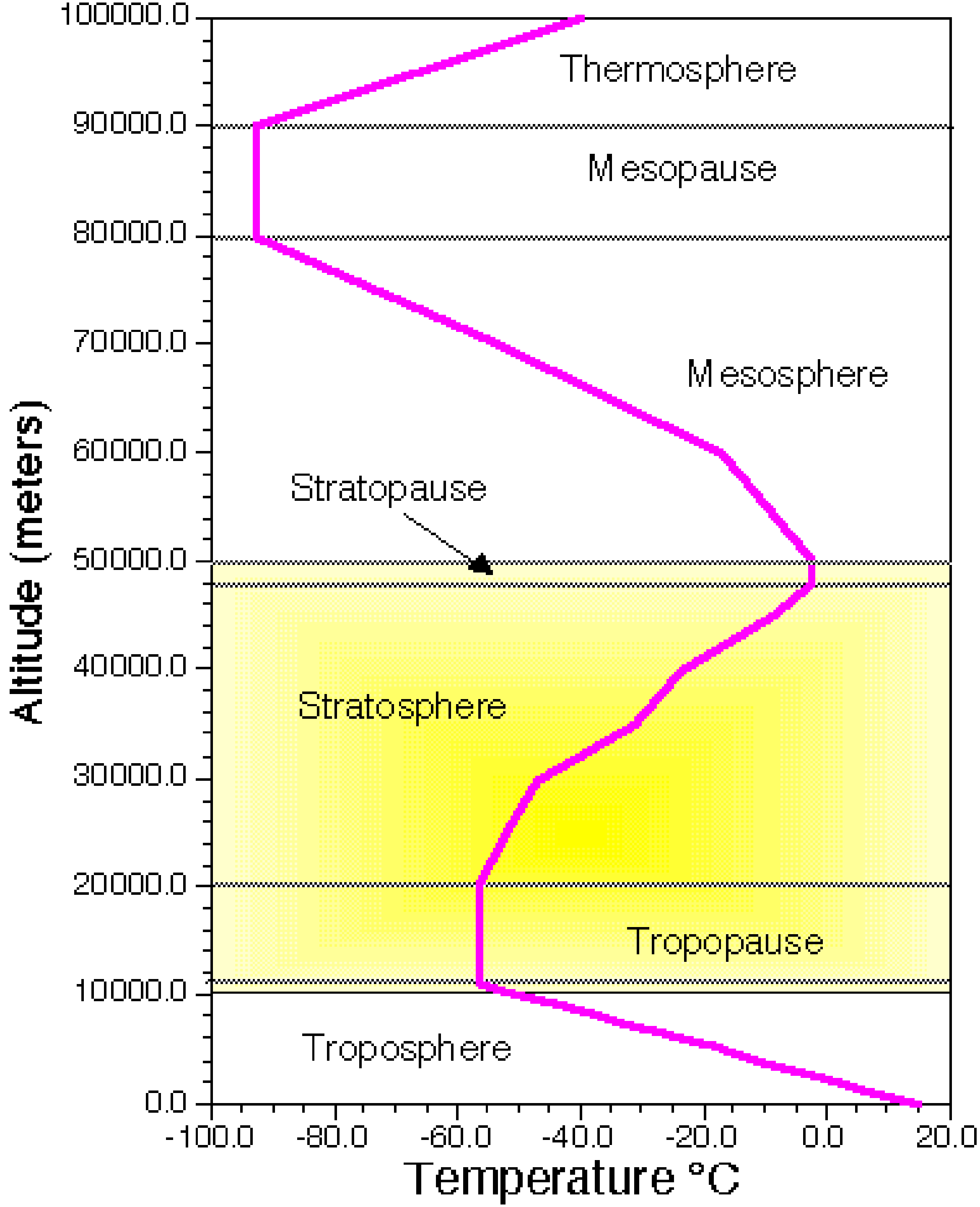
Brief Overview of the Global Atmosphere

Atmospheric Composition

Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
*Water	H_2O	0 to 4%
Argon	Ar	0.93%
*Carbon Dioxide	CO_2	0.0360%
Neon	Ne	0.0018%
Helium	He	0.0005%
*Methane	CH_4	0.00017%
Hydrogen	H_2	0.00005%
*Nitrous Oxide	N_2O	0.00003%
*Ozone	O_3	0.000004%

*** variable gases**


Humidity Profiles - Annual
10S-10N
40-50N
70-84N
Altitude (km)
Specific Humidity (g/kg)
0
5
10
15
20



Altitude (meters)
100000.0
90000.0
80000.0
70000.0
60000.0
50000.0
40000.0
30000.0
20000.0
10000.0
0.0
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
Temperature °C

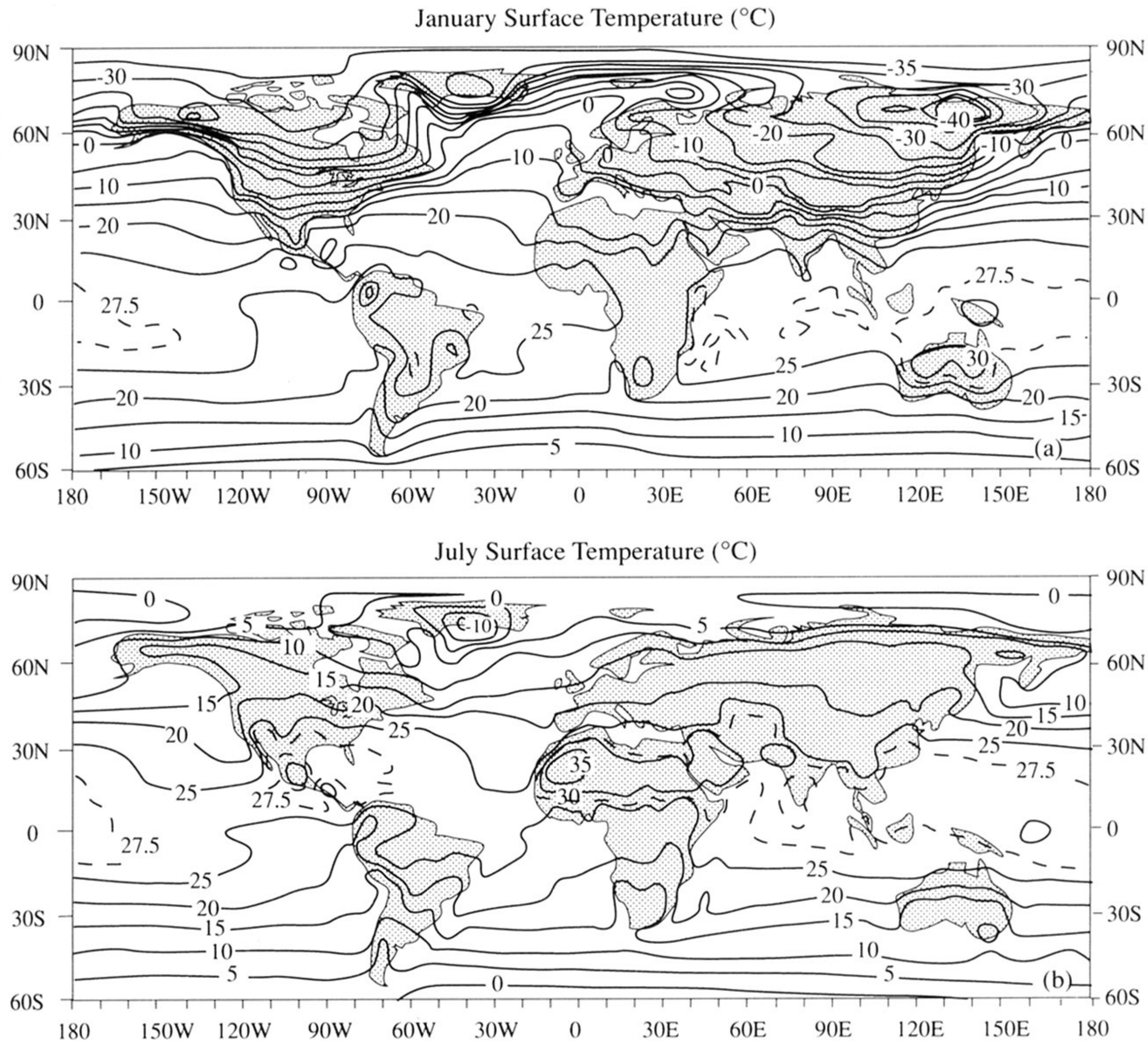
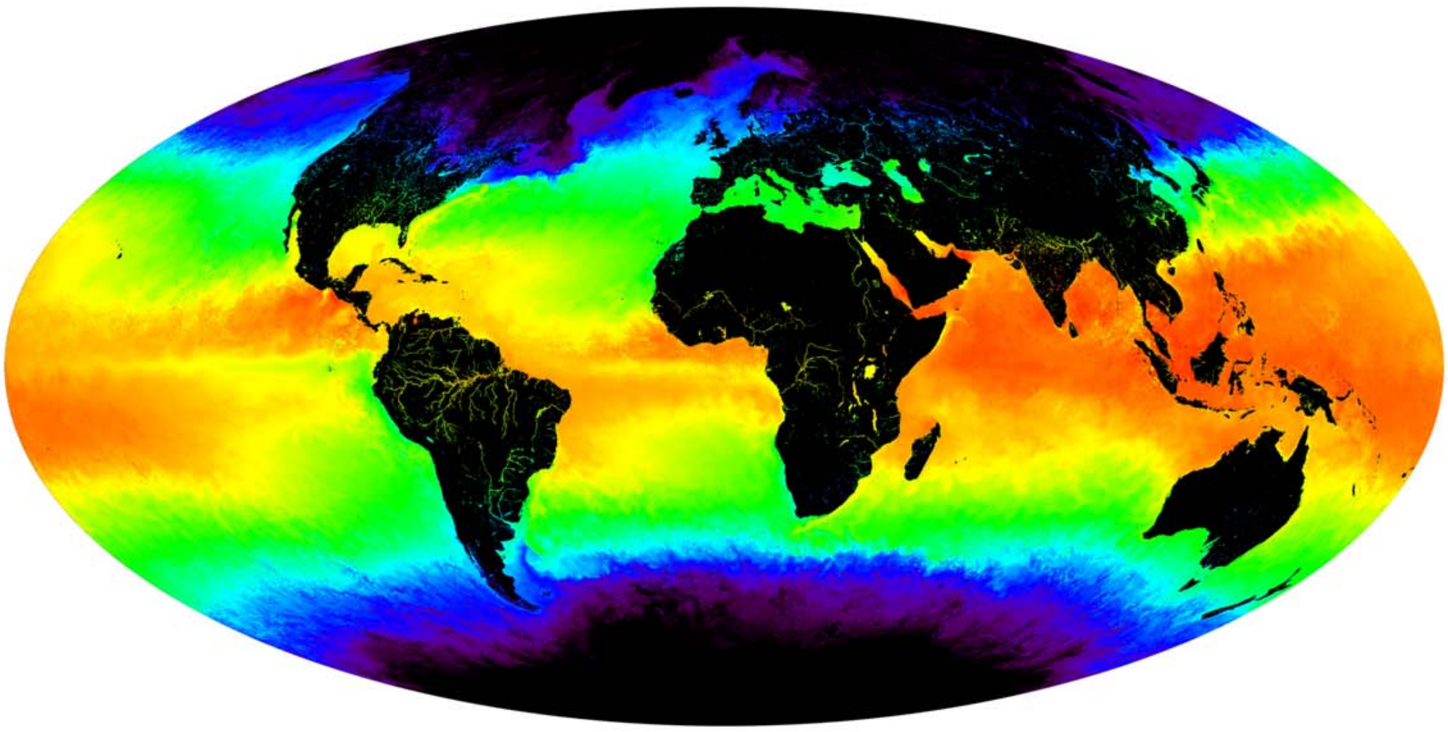


Fig. 1.6 Global map of the (a) January and (b) July surface temperature. [From Shea (1986). Reproduced with permission from the National Center for Atmospheric Research.]

Sea Surface Temperature



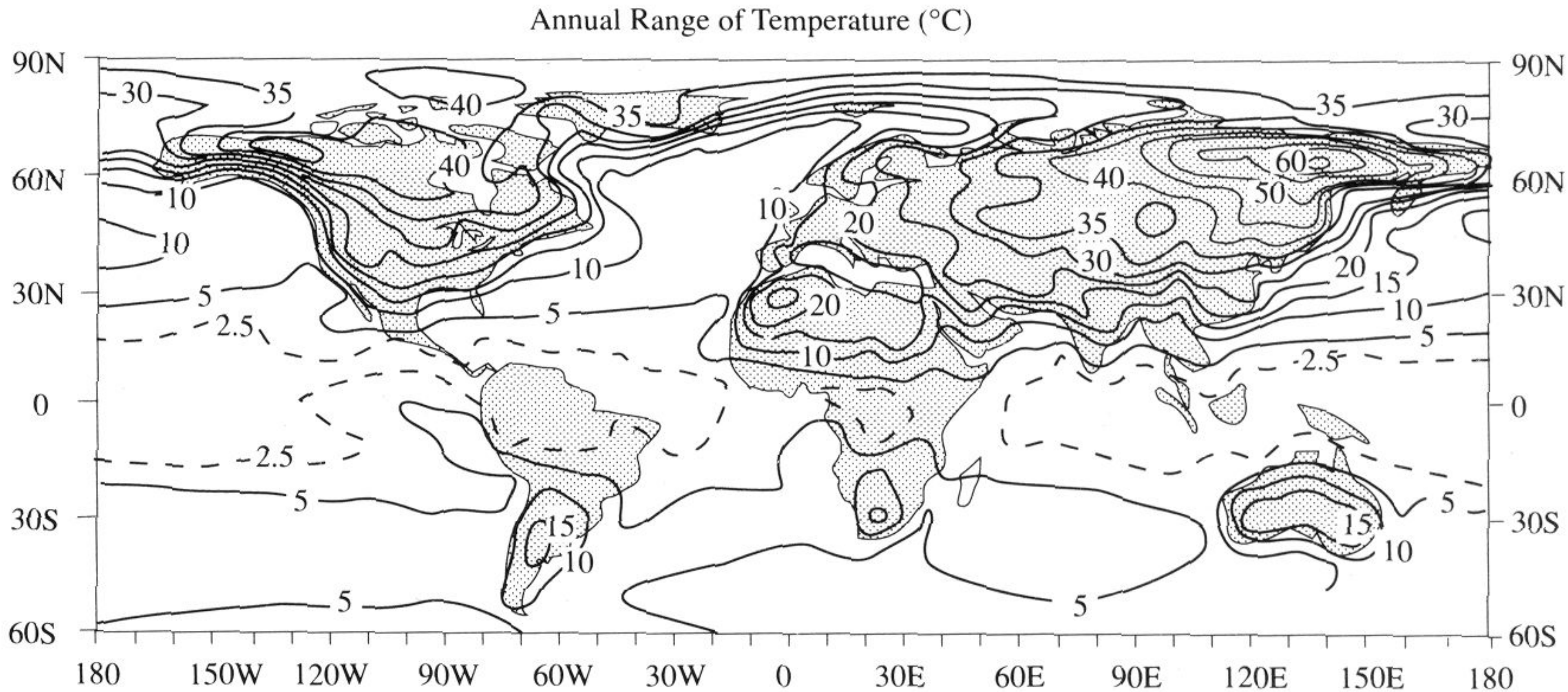
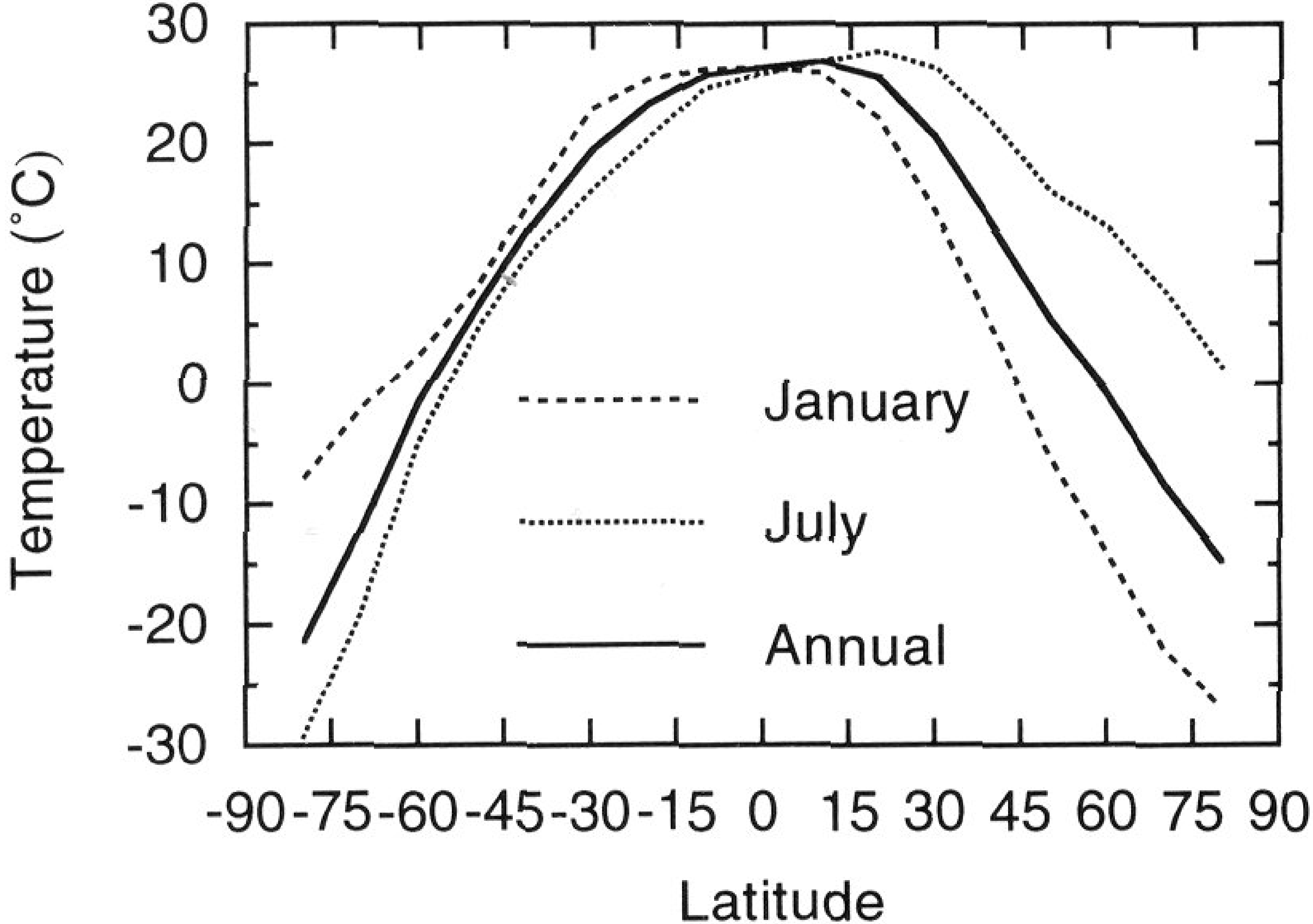
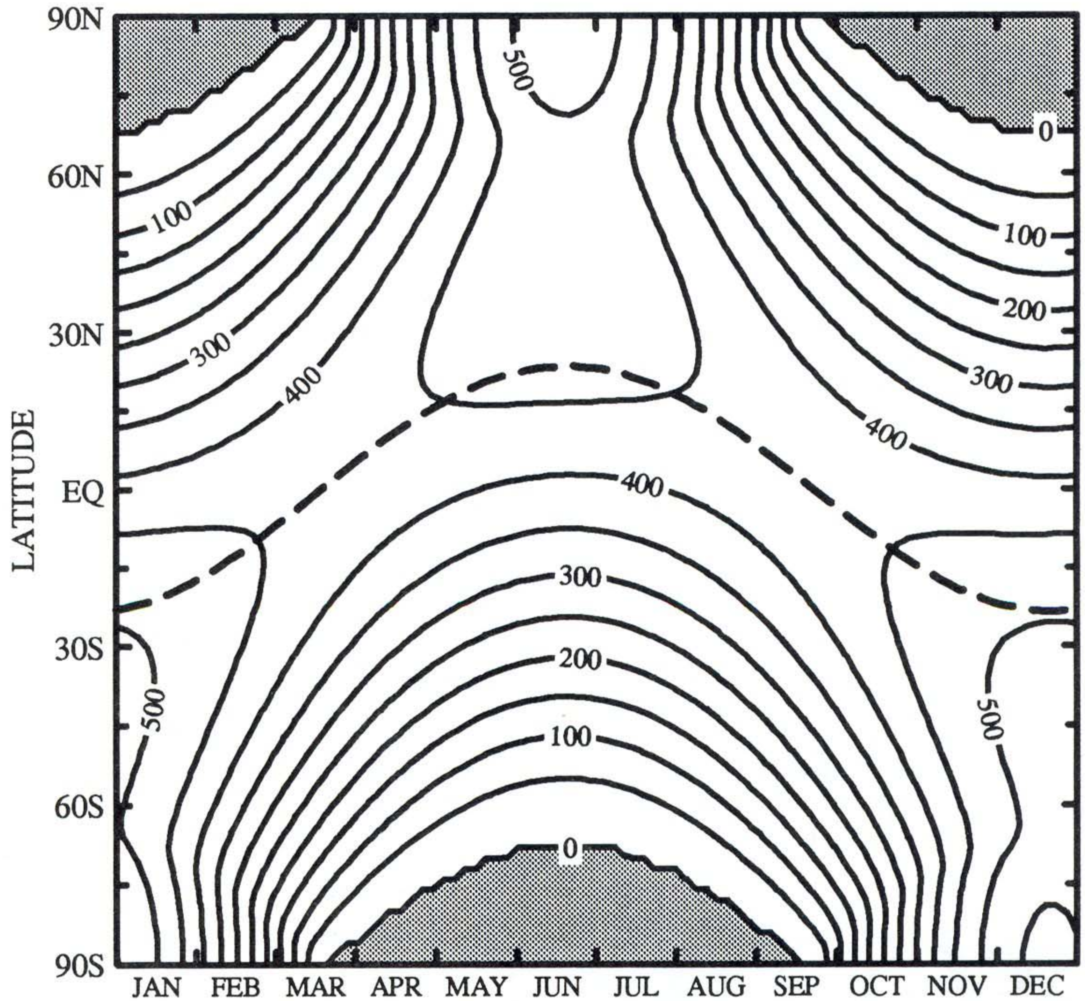
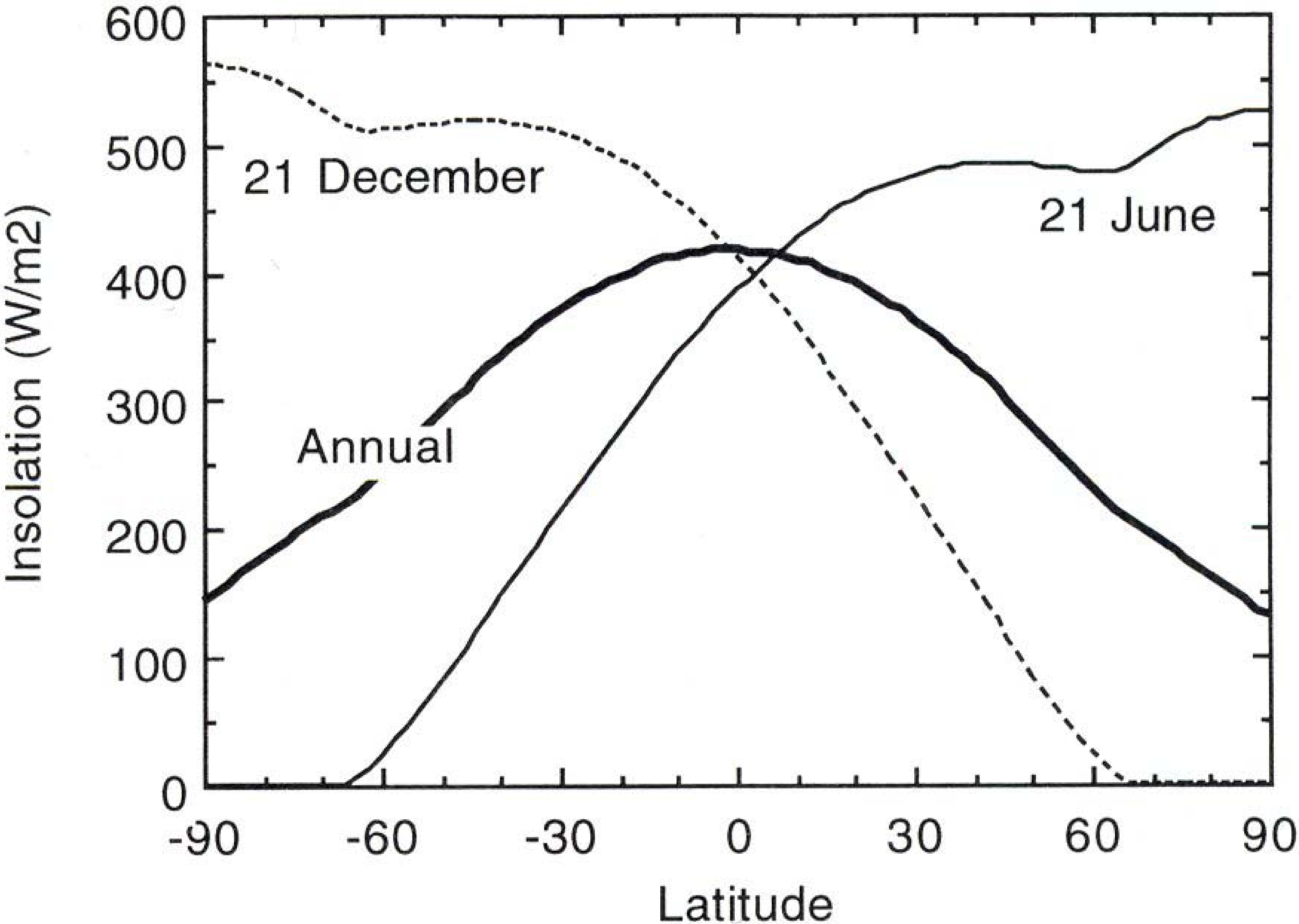


Fig. 1.7 Map of the amplitude of the annual cycle of surface temperature. [From Shea (1986). Reproduced with permission from the National Center for Atmospheric Research.]


30
20
10
0
-10
-20
-30
Temperature (°C)
January
July
Annual
-90 -75 -60 -45 -30 -15 0 15 30 45 60 75 90
Latitude

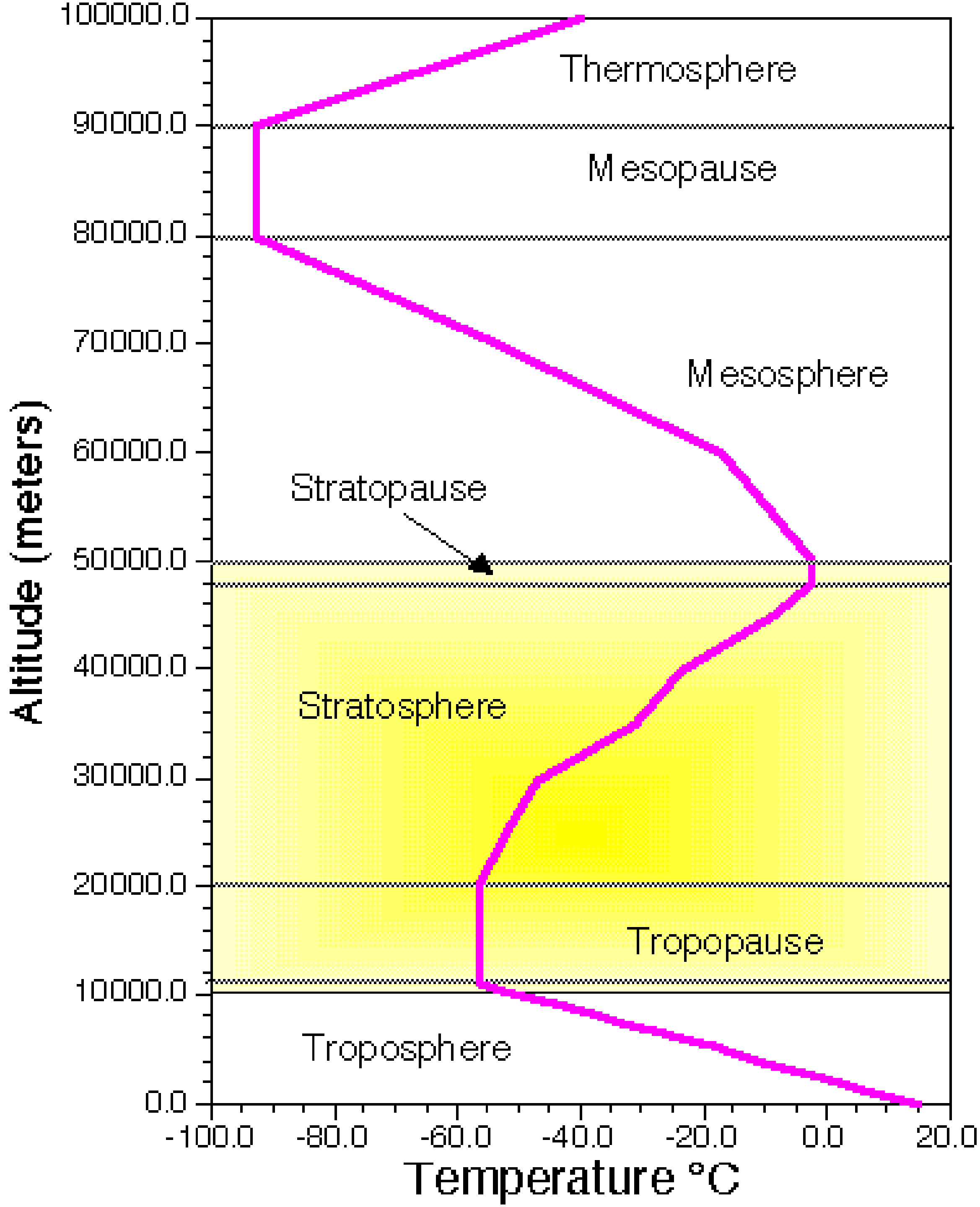
Seasonal variation of solar radiation





600
500
400
300
200
100
0
-90
-60
-30
0
30
60
90
Latitude
Insolation (W/m2)
21 December
21 June
Annual

A One-Dimensional Description of the Tropical Atmosphere



100000.0
90000.0
80000.0
70000.0
60000.0
50000.0
40000.0
30000.0
20000.0
10000.0
0.0
Altitude (meters)
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
Temperature °C

Elements of Thermal Balance: Solar Radiation

- Luminosity: 3.9×10^{26} J s^{-1} = 6.4×10^{7} Wm^{-2} at top of photosphere

- Mean distance from earth: 1.5×10^{11} m
- Flux density at mean radius of earth

$$S_0 \equiv \frac{L_0}{4\pi d^2} = 1370\, Wm^{-2}$$

Stefan-Boltzmann Equation: $F = \sigma T^4$

$\sigma = 5.67 \times 10^{-8}\ Wm^{-2} K^{-4}$

Sun: $\sigma T^4 = 6.4 \times 10^7\ Wm^{-2}$

$\rightarrow \quad T \simeq 6{,}000\, K$

Disposition of Solar Radiation:

$$\text{Total absorbed solar radiation} = S_0\left(1-a_p\right)\pi r_p^{\,2}$$

$$a_p \equiv \text{planetary albedo}\left(\simeq 30\%\right)$$

$$\text{Total surface area} = 4\pi r_p^{\,2}$$

$$\text{Absorption per unit area} = \frac{S_0}{4}\left(1-a_p\right)$$

Absorption by clouds, atmosphere, and surface

Terrestrial Radiation:

Effective emission temperature:

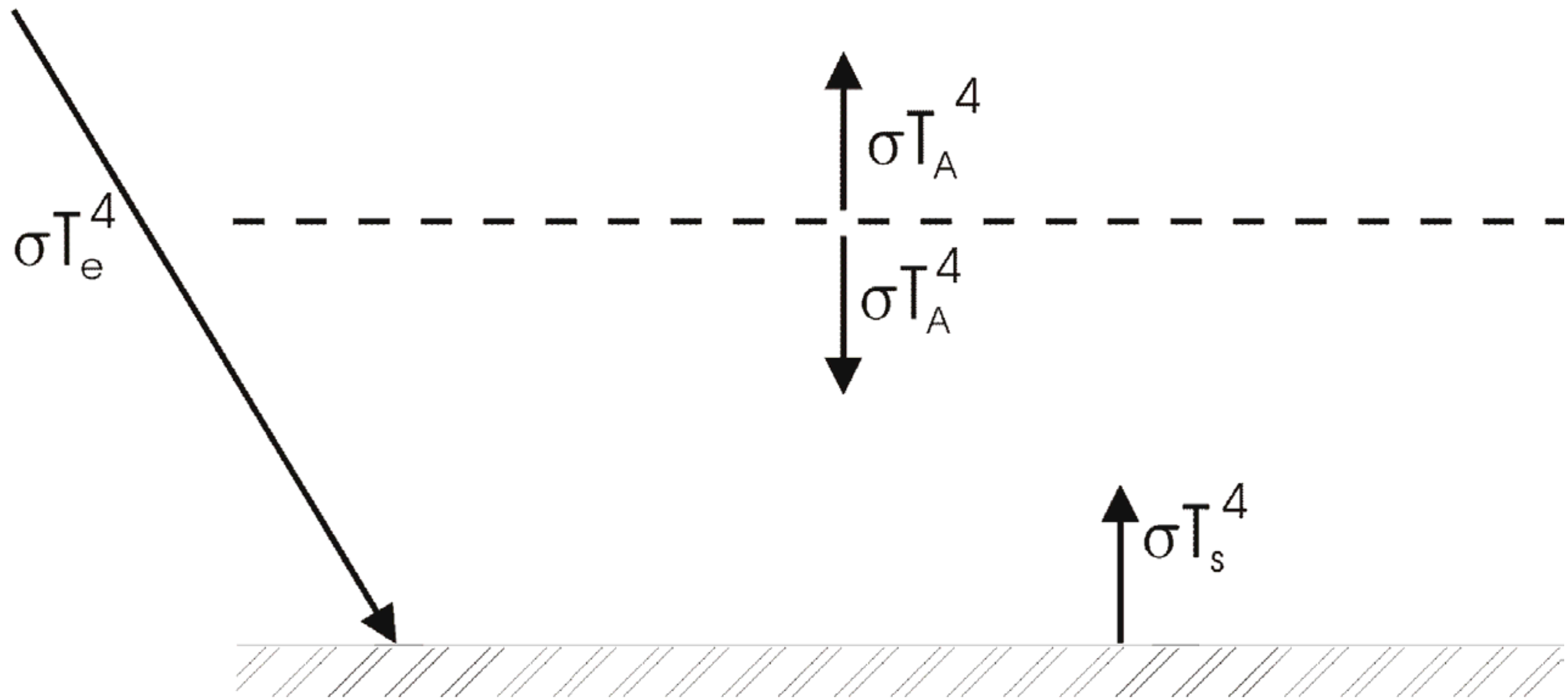
$$\sigma T_e^4 \equiv \frac{S_0}{4}\left(1 - a_p\right)$$

Earth: $T_e = 255K = -18°C$

Observed average surface temperature $= 288K = 15°C$

Highly Reduced Model

- Transparent to solar radiation
- Opaque to infrared radiation
- Blackbody emission from surface and each layer



Radiative Equilibrium:

Top of Atmosphere:

$$\sigma T_A^{\,4} = \frac{S_0}{4}\left(1 - a_p\right) = \sigma T_e^{\,4}$$

$$\rightarrow \quad \boxed{T_A = T_e}$$

Surface:

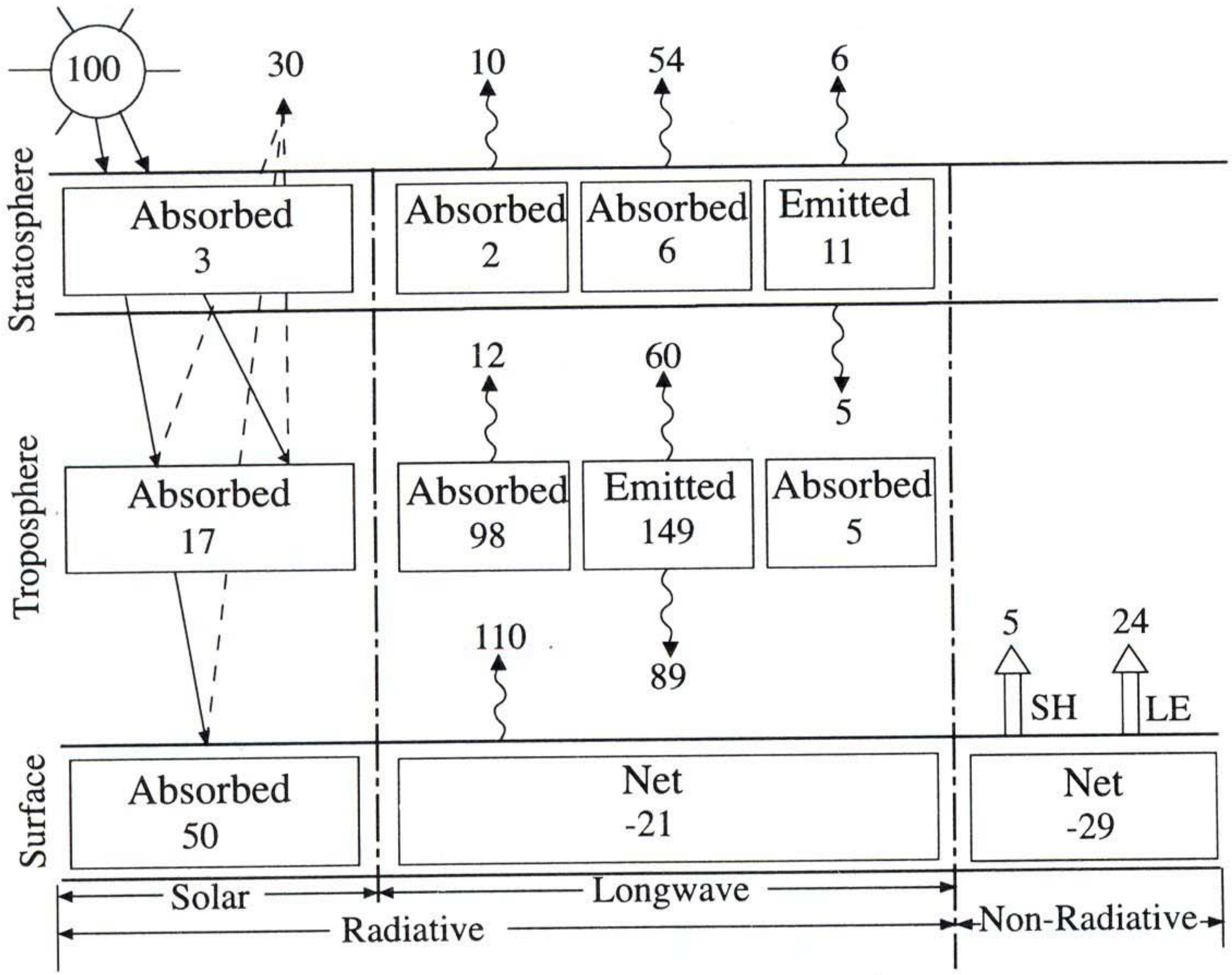
$$\sigma T_s^{\,4} = \sigma T_A^{\,4} + \frac{S_0}{4}\left(1 - a_p\right) = 2\sigma T_e^{\,4}$$

$$\rightarrow \boxed{T_s = 2^{1/4} T_e} = 303\ K$$

Surface temperature too large because:

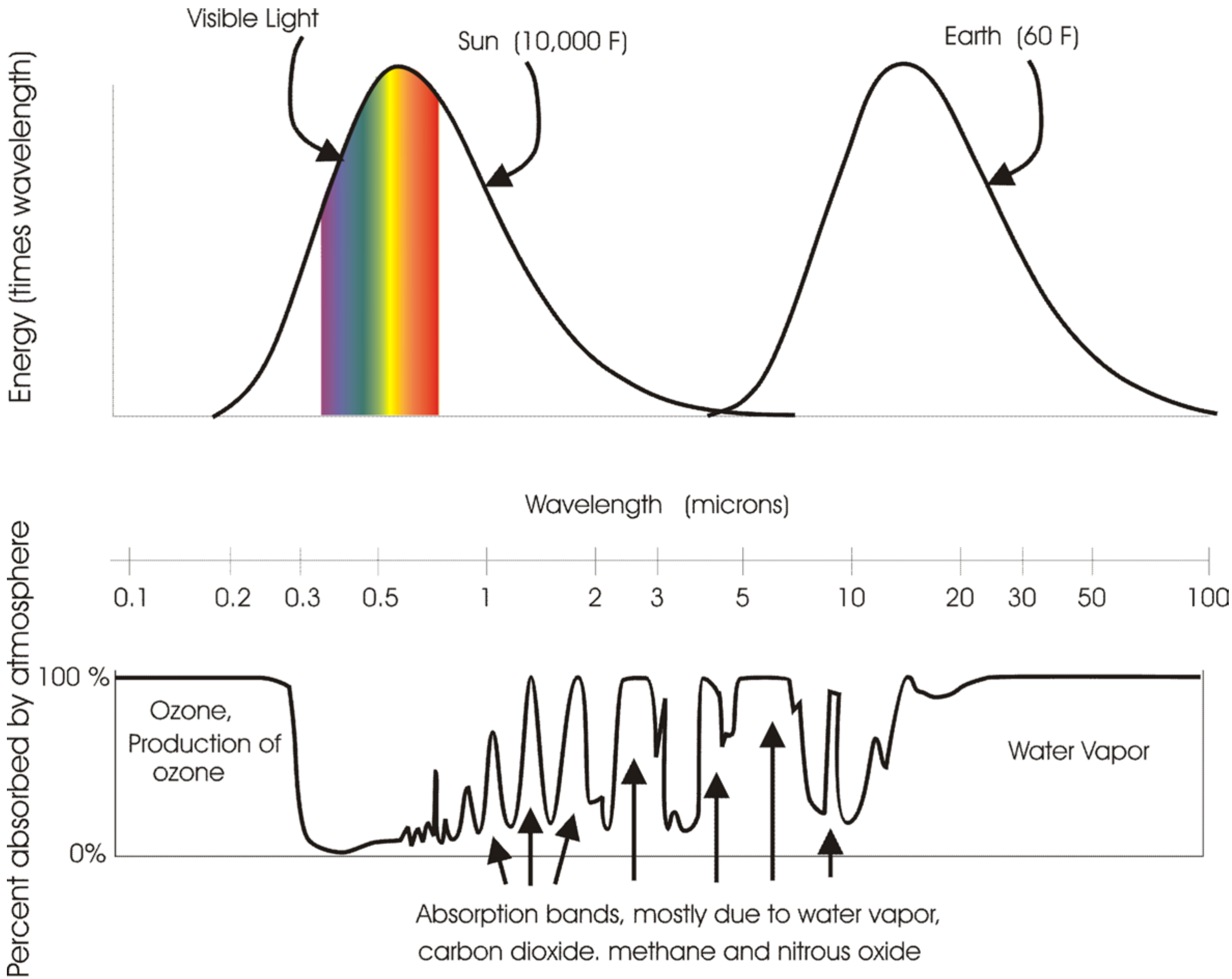
- Real atmosphere is not opaque
- Heat transported by convection as well as by radiation

Energy Balance



Principal Atmospheric Absorbers

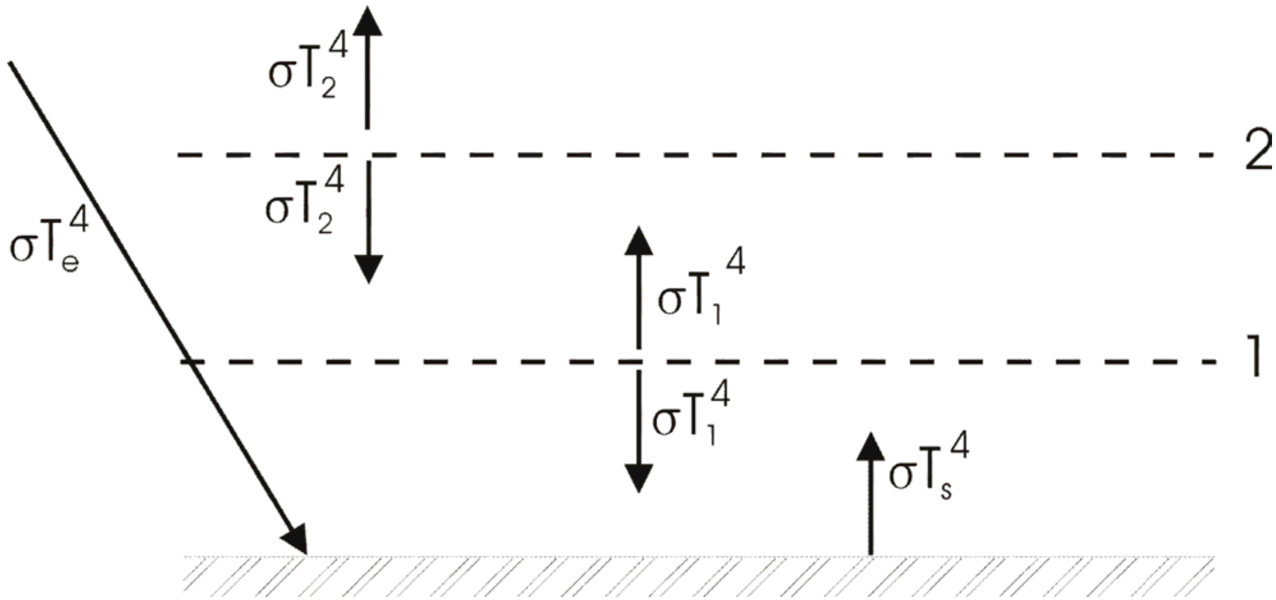
- H_2O: Bent triatomic, with permanent dipole moment and pure rotational bands as well as rotation-vibration transitions
- O_3: Like water, but also involved in photodissociation
- CO_2: No permanent dipole moment, so no pure rotational transitions, but temporary dipole during vibrational transitions
- Other gases: N_2O, CH_4


Visible Light
Sun (10,000 F)
Earth (60 F)
Energy (times wavelength)
Wavelength (microns)
0.1
0.2
0.3
0.5
1
2
3
5
10
20
30
50
100
Percent absorbed by atmosphere
100 %
0%
Ozone, Production of ozone
Water Vapor
Absorption bands, mostly due to water vapor, carbon dioxide. methane and nitrous oxide

Radiative Equilibrium

- Equilibrium state of atmosphere and surface in the absence of non-radiative enthalpy fluxes
- Radiative heating drives actual state toward state of radiative equilibrium

Extended Layer Models



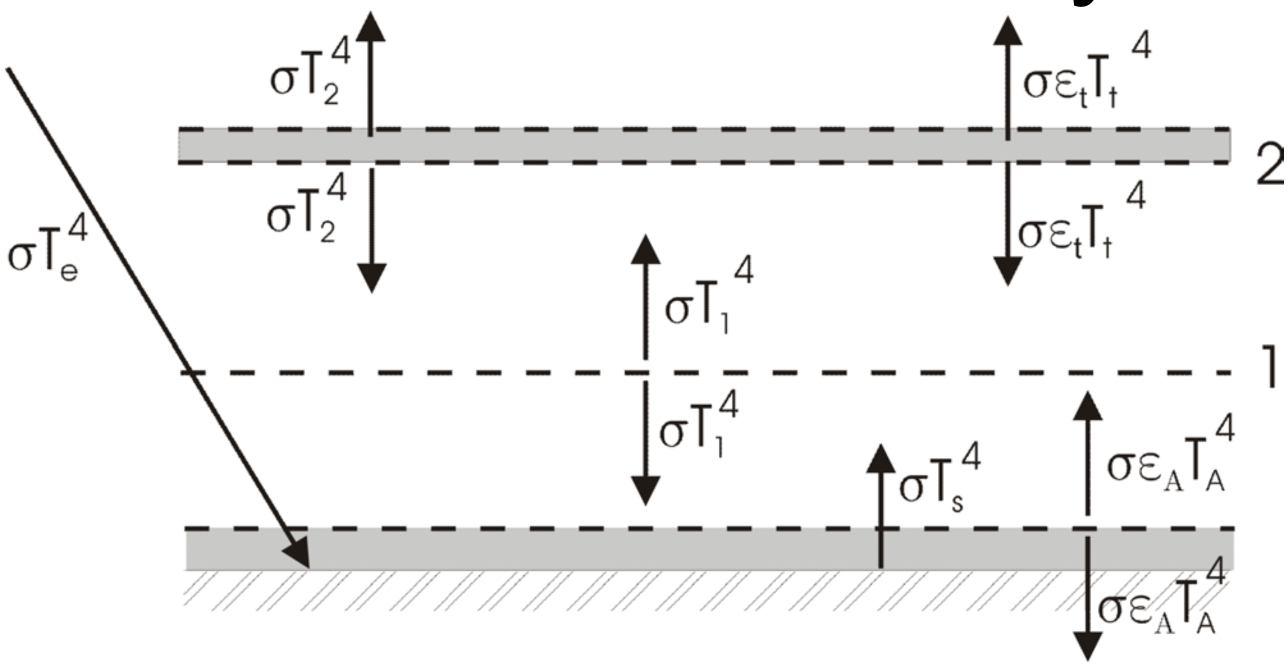
$$TOA: \quad \sigma T_2{}^4 = \sigma T_e{}^4 \rightarrow T_2 = T_e$$

$$Middle\ Layer: \quad 2\sigma T_1{}^4 = \sigma T_2{}^4 + \sigma T_s{}^4 = \sigma T_e{}^4 + \sigma T_s{}^4$$

$$Surface: \quad \sigma T_s{}^4 = \sigma T_e{}^4 + \sigma T_1^4$$

$$\rightarrow \quad T_s = 3^{1/4} T_e \qquad\qquad T_1 = 2^{1/4} T_e$$

Effects of emissivity<1



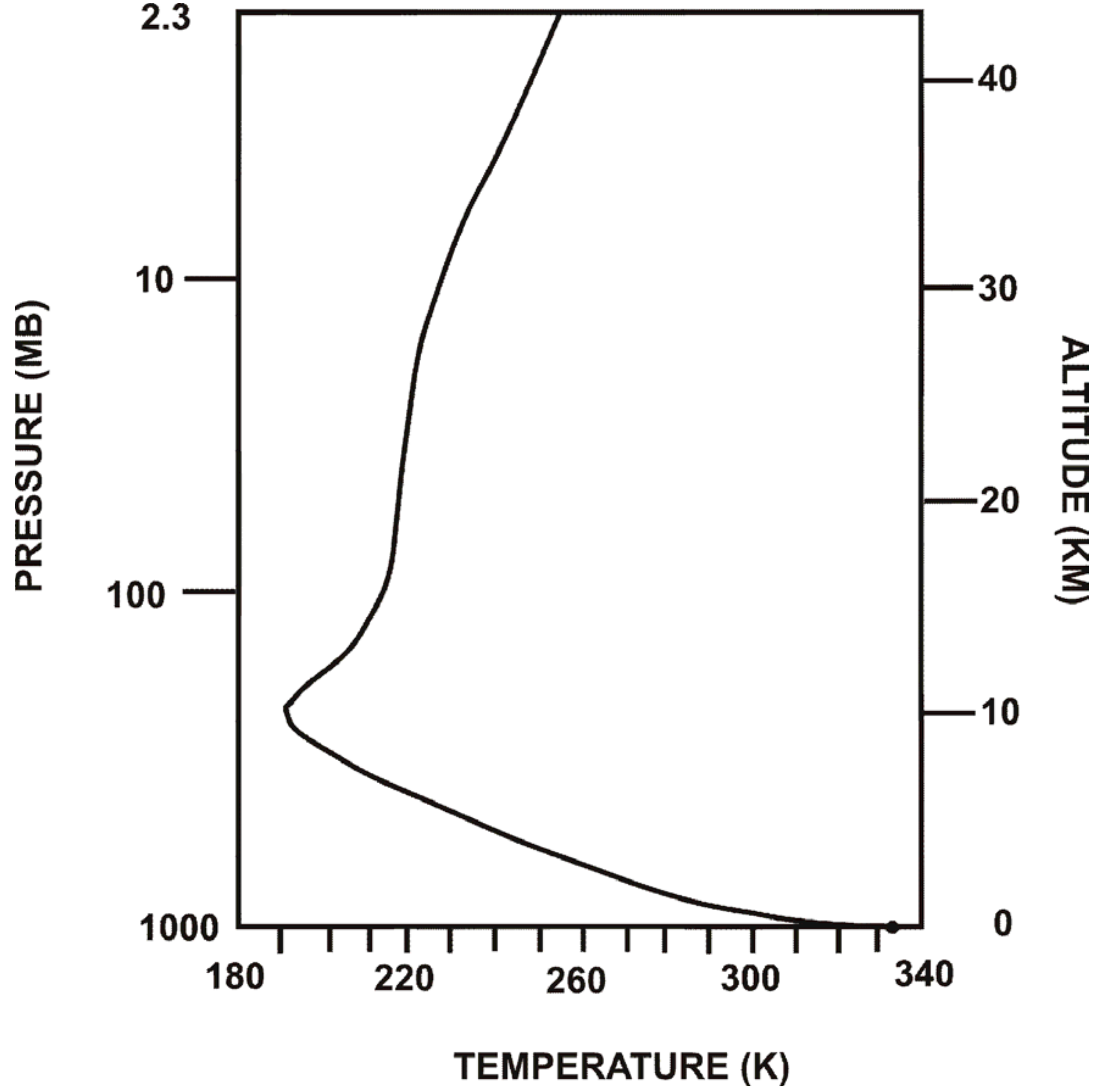
$$Surface: \quad 2\varepsilon_A \sigma T_A^{\ 4} = \varepsilon_A \sigma T_1^{\ 4} + \varepsilon_A \sigma T_s^{\ 4}$$

$$\rightarrow \quad T_A = \left(\tfrac{5}{2}\right)^{1/4} T_e \simeq 321K \quad < T_s$$

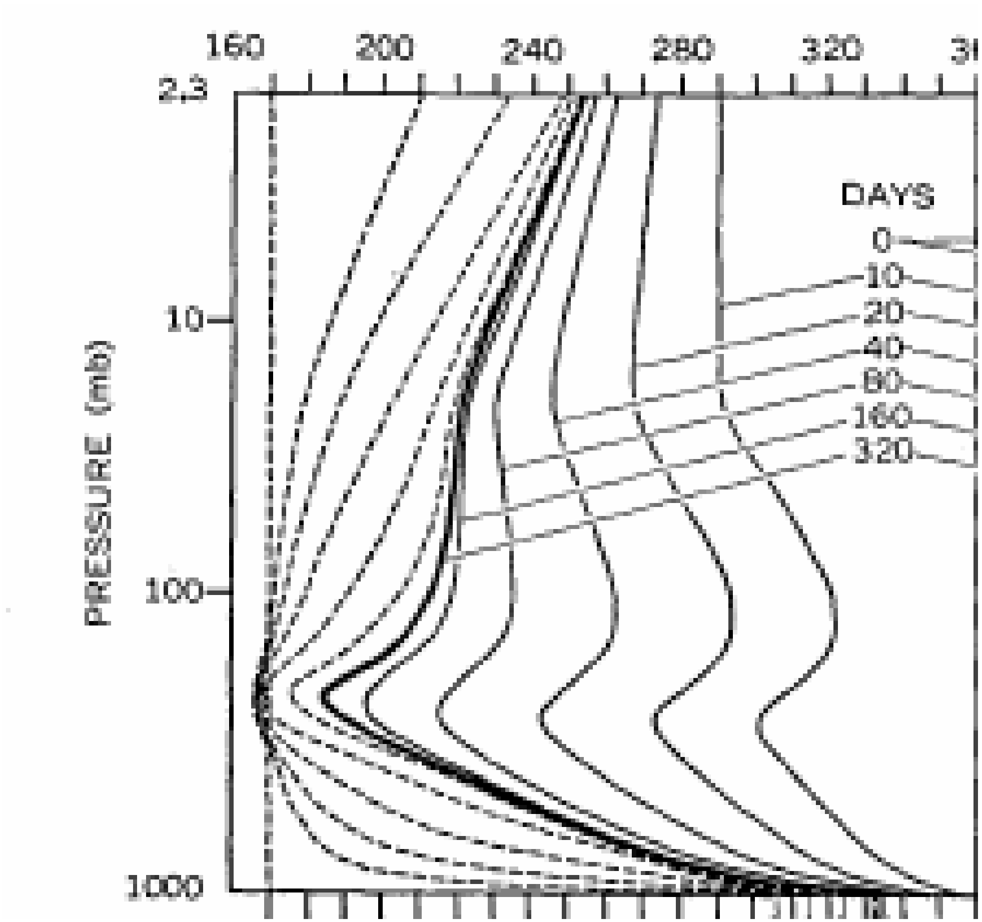
$$Stratosphere: \quad 2\varepsilon_t \sigma T_t^{\ 4} = \varepsilon_A \sigma T_2^{\ 4}$$

$$\rightarrow \quad T_t = \left(\tfrac{1}{2}\right)^{1/4} T_e \simeq 214K \quad < T_e$$

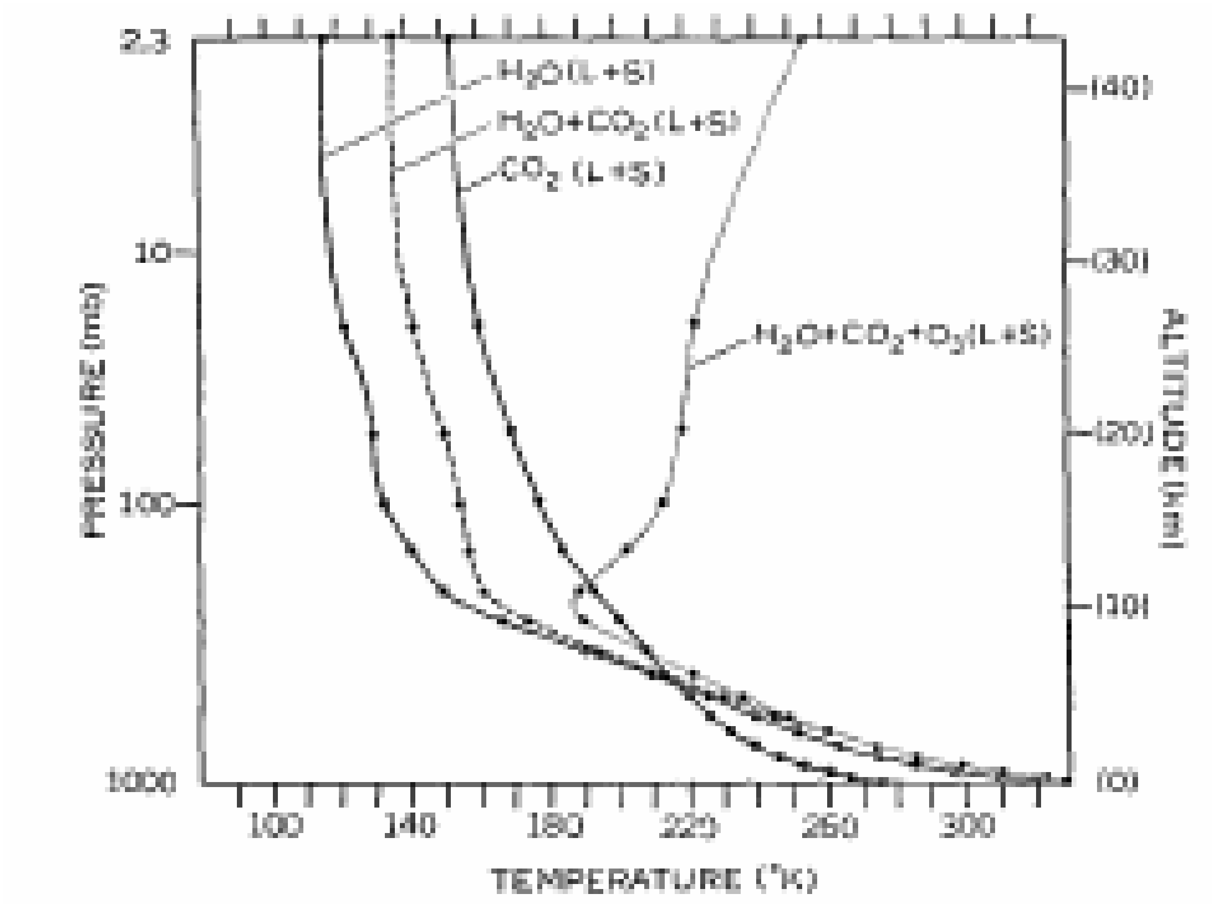
Full calculation of radiative equilibrium:



Time scale of approach to equilibrium:



Contributions of various absorbers:



Problems with radiative equilibrium solution:

- Too hot at and near surface
- Too cold at a near tropopause
- Lapse rate of temperature too large in the troposphere
- (But stratosphere temperature close to observed)

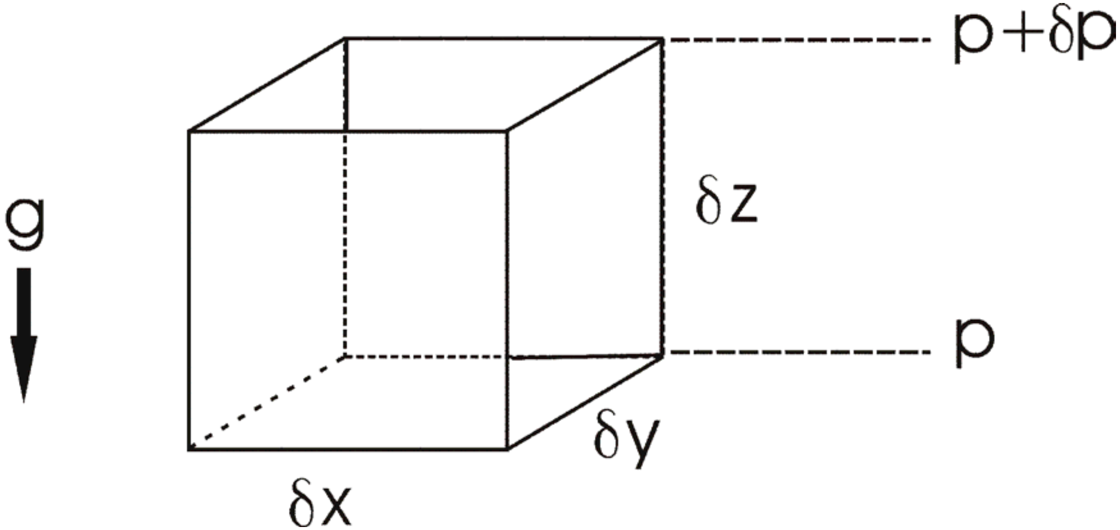
Missing ingredient: Convection

- As important as radiation in transporting enthalpy in the vertical
- Also controls distribution of water vapor and clouds, the two most important constituents in radiative transfer

When is a fluid unstable to convection?

- Pressure and hydrostatic equilibrium
- Buoyancy
- Stability

Hydrostatic equilibrium:



$$Weight: \quad -g\rho\delta x\delta y\delta z$$

$$Pressure: \quad p\delta x\delta y-\left(p+\delta p\right)\delta x\delta y$$

$$F=MA: \quad \rho\delta x\delta y\delta z\frac{dw}{dt}=-g\rho\delta x\delta y\delta z-\delta p\delta x\delta y$$

$$\frac{dw}{dt}=-g-\alpha\frac{\partial p}{\partial z}, \qquad \alpha = {}^{1}\!/_{\rho} = specific\ volume$$

Pressure distribution in atmosphere at rest:

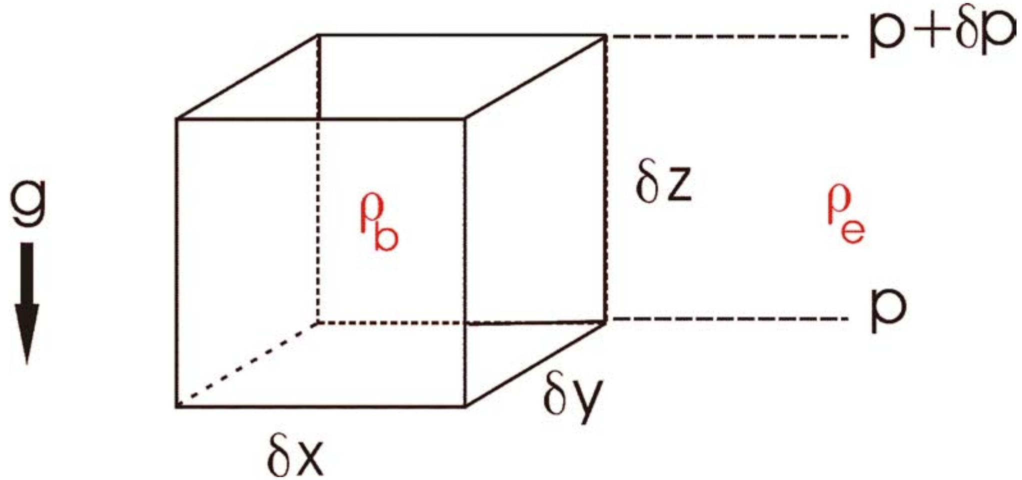
$$Ideal\ gas: \quad \alpha = \frac{RT}{p}, \qquad R \equiv \frac{R^*}{\bar{m}}$$

$$Hydrostatic: \quad \frac{1}{p}\frac{\partial p}{\partial z} = \frac{\partial \ln(p)}{\partial z} = -\frac{g}{RT}$$

$$Isothermal\ case: \quad p = p_0 e^{-z/H}, \qquad H \equiv \frac{RT}{g} = \text{"}scale\ height\text{"}$$

Earth: H~ 8 Km

Buoyancy:



$$Weight: \quad -g\rho_b \delta x \delta y \delta z$$

$$Pressure: \quad p\delta x \delta y - \left(p + \delta p\right)\delta x \delta y$$

$$F = MA: \quad \rho_b \delta x \delta y \delta z \frac{dw}{dt} = -g\rho_b \delta x \delta y \delta z - \delta p \delta x \delta y$$

$$\frac{dw}{dt} = -g - \alpha_b \frac{\partial p}{\partial z} \qquad but \quad \frac{\partial p}{\partial z} = -g/\alpha_e$$

$$\rightarrow \quad \frac{dw}{dt} = g\frac{\alpha_b - \alpha_e}{\alpha_e} \equiv B$$

Buoyancy and Entropy

Specific Volume: $\alpha = {}^{1}\!/_{\rho}$

Specific Entropy: s

$$Maxwell: \left(\frac{\partial \alpha}{\partial s}\right)_p = \left(\frac{\partial T}{\partial p}\right)_s$$

$$\alpha = \alpha(p, s)$$

$$\left(\delta\alpha\right)_p = \left(\frac{\partial \alpha}{\partial s}\right)_p \delta s = \left(\frac{\partial T}{\partial p}\right)_s \delta s$$

$$B = g\frac{\left(\delta\alpha\right)_p}{\alpha} = \frac{g}{\alpha}\left(\frac{\partial T}{\partial p}\right)_s \delta s = -\left(\frac{\partial T}{\partial z}\right)_s \delta s \equiv \Gamma\,\delta s$$

The adiabatic lapse rate:

$$\textit{First Law of Thermodynamics}:$$

$$\dot{Q} = T\frac{ds_{rev}}{dt} = c_v\frac{dT}{dt} + p\frac{d\alpha}{dt}$$

$$= c_v\frac{dT}{dt} + \frac{d\left(\alpha p\right)}{dt} - \alpha\frac{dp}{dt}$$

$$= \left(c_v + R\right)\frac{dT}{dt} - \alpha\frac{dp}{dt}$$

$$= c_p\frac{dT}{dt} - \alpha\frac{dp}{dt}$$

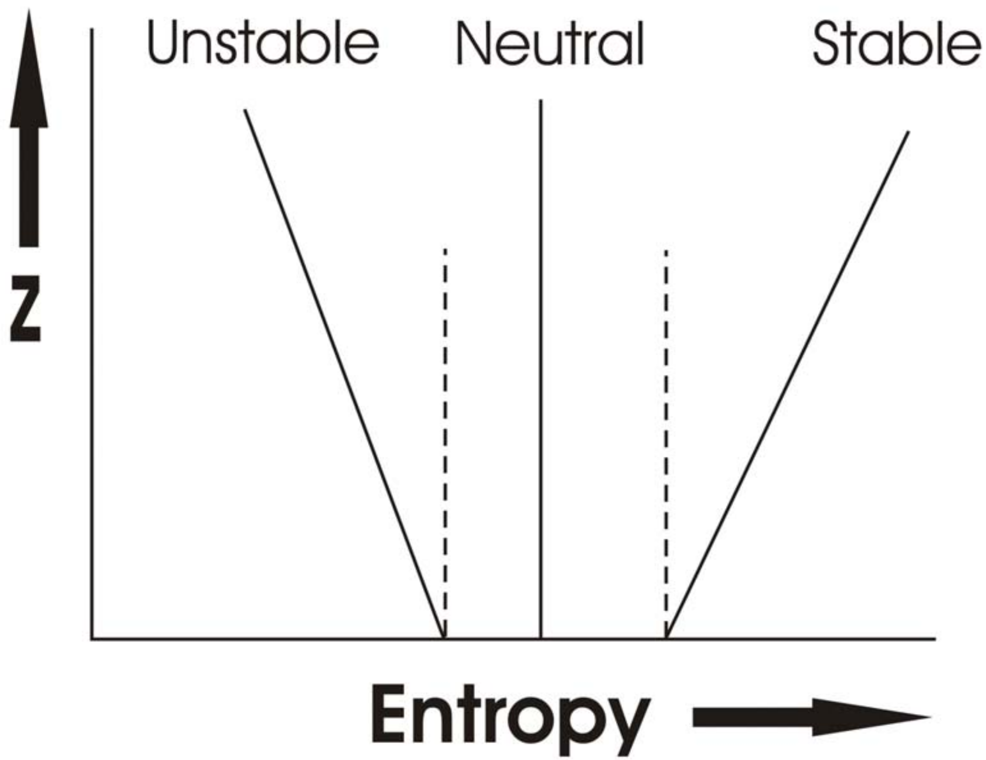
$$\textit{Adiabatic}: \quad c_p dT - \alpha dp = 0$$

$$\textit{Hydrostatic}: \quad c_p dT + g dz = 0$$

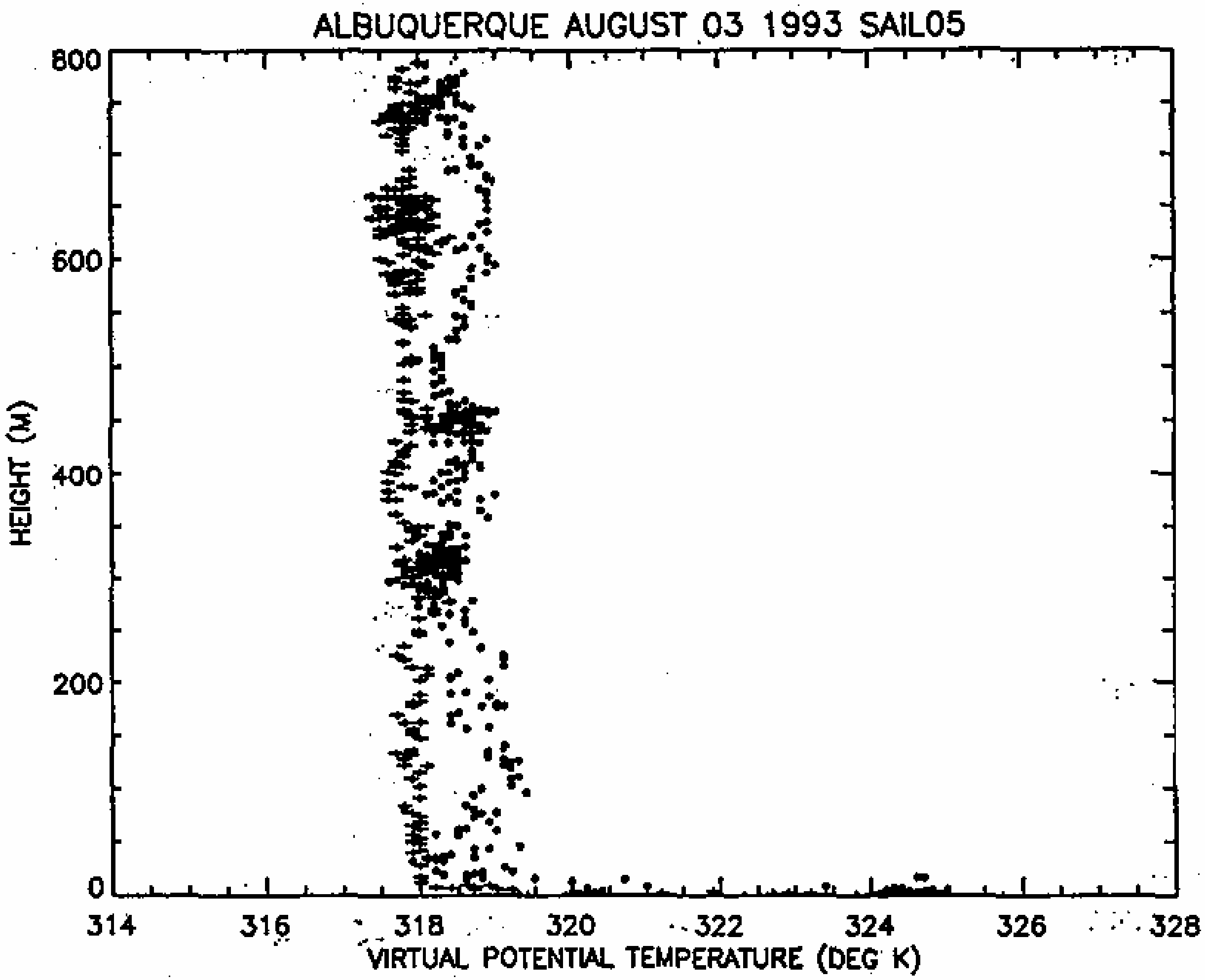
$$\rightarrow \quad \left({}^{dT}\!/_{dz}\right)_s = -{}^{g}\!/_{c_p} \equiv -\Gamma_d$$

$$\Gamma = g / c_p$$

Earth's atmosphere: $$\Gamma = 1\,K / 100\,m$$



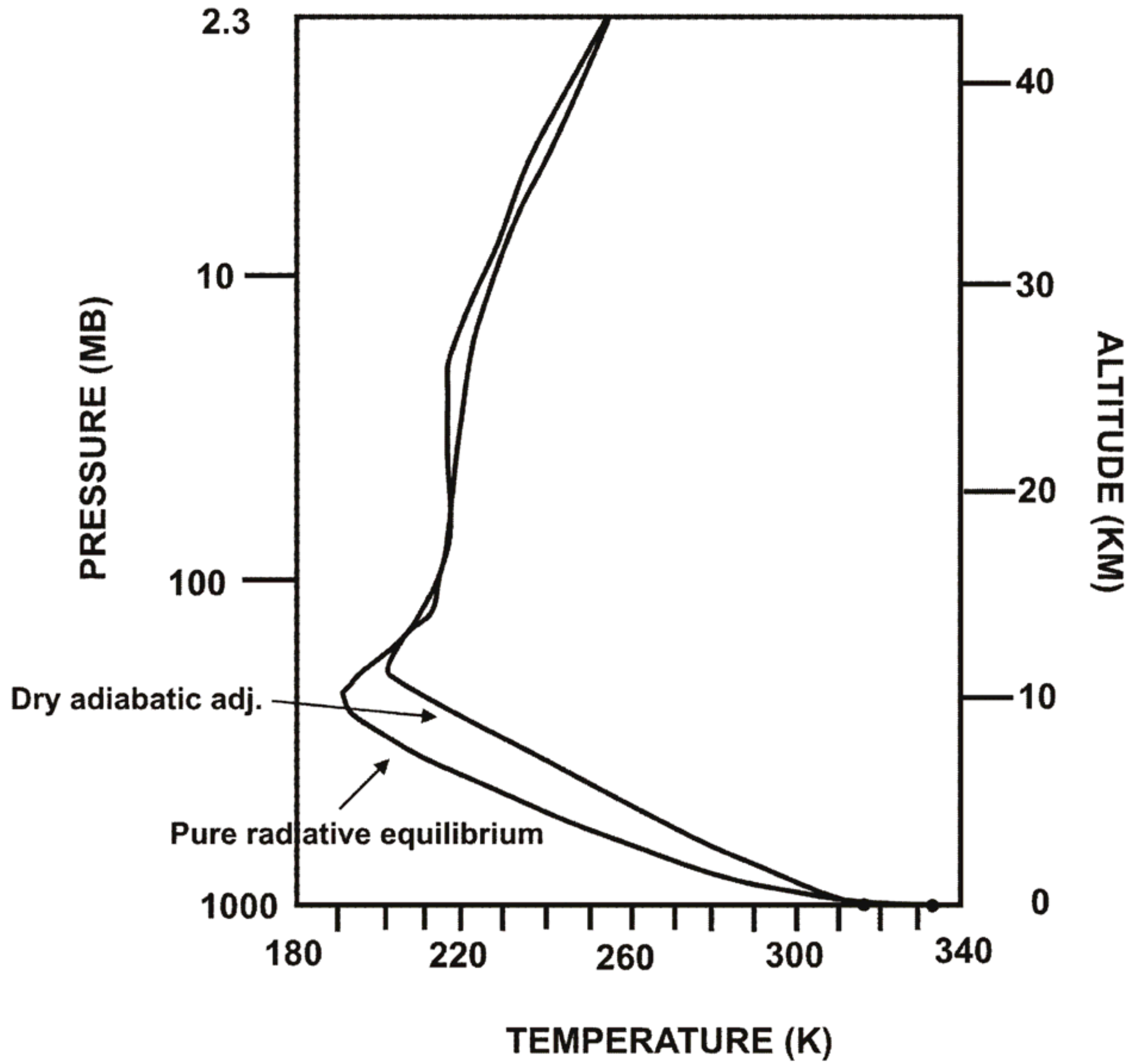
Model Aircraft Measurements (Renno and Williams, 1995)



Radiative equilibrium is unstable in the troposphere

Re-calculate equilibrium assuming that tropospheric stability is rendered neutral by convection:

Radiative-Convective Equilibrium



Better, but still too hot at surface, too cold at tropopause