Tropical Meteorology

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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

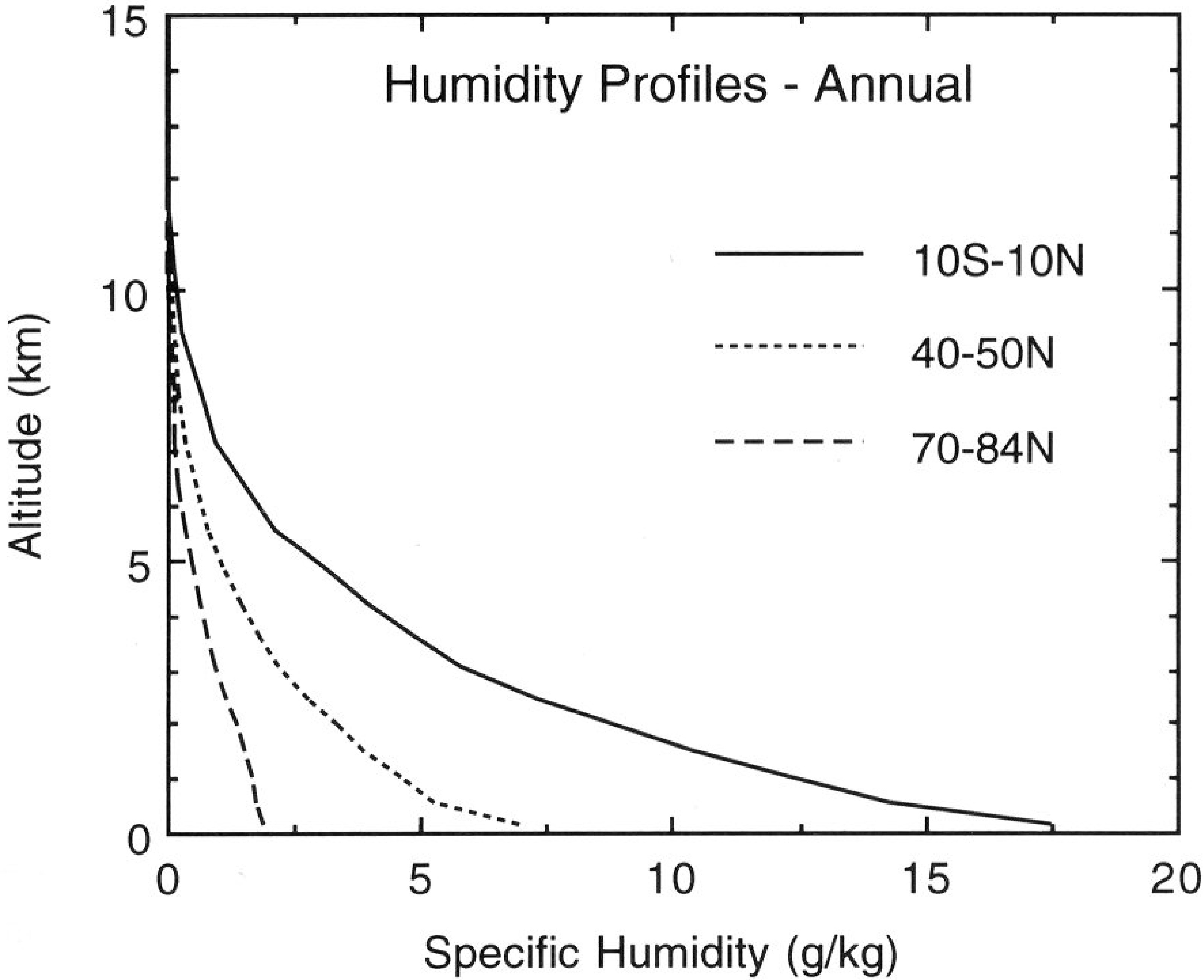
- **Tropical Cyclones**
  - Structure and climatology
  - Steady-state physics
  - Genesis
  - Ocean interaction

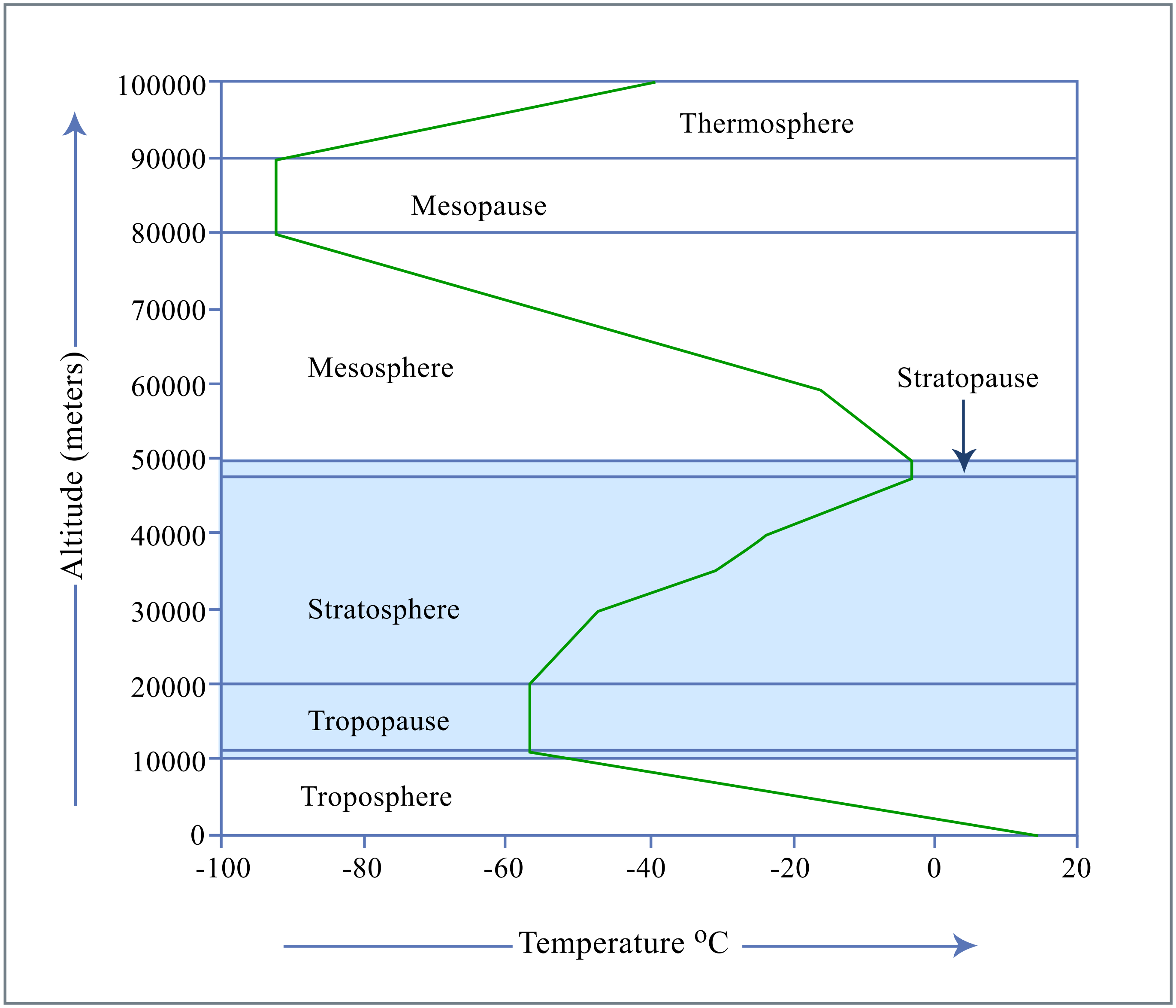
Brief Overview of the Global Atmosphere

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


100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Altitude (meters)
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
-100
-80
-60
-40
-20
0
20
Temperature °C

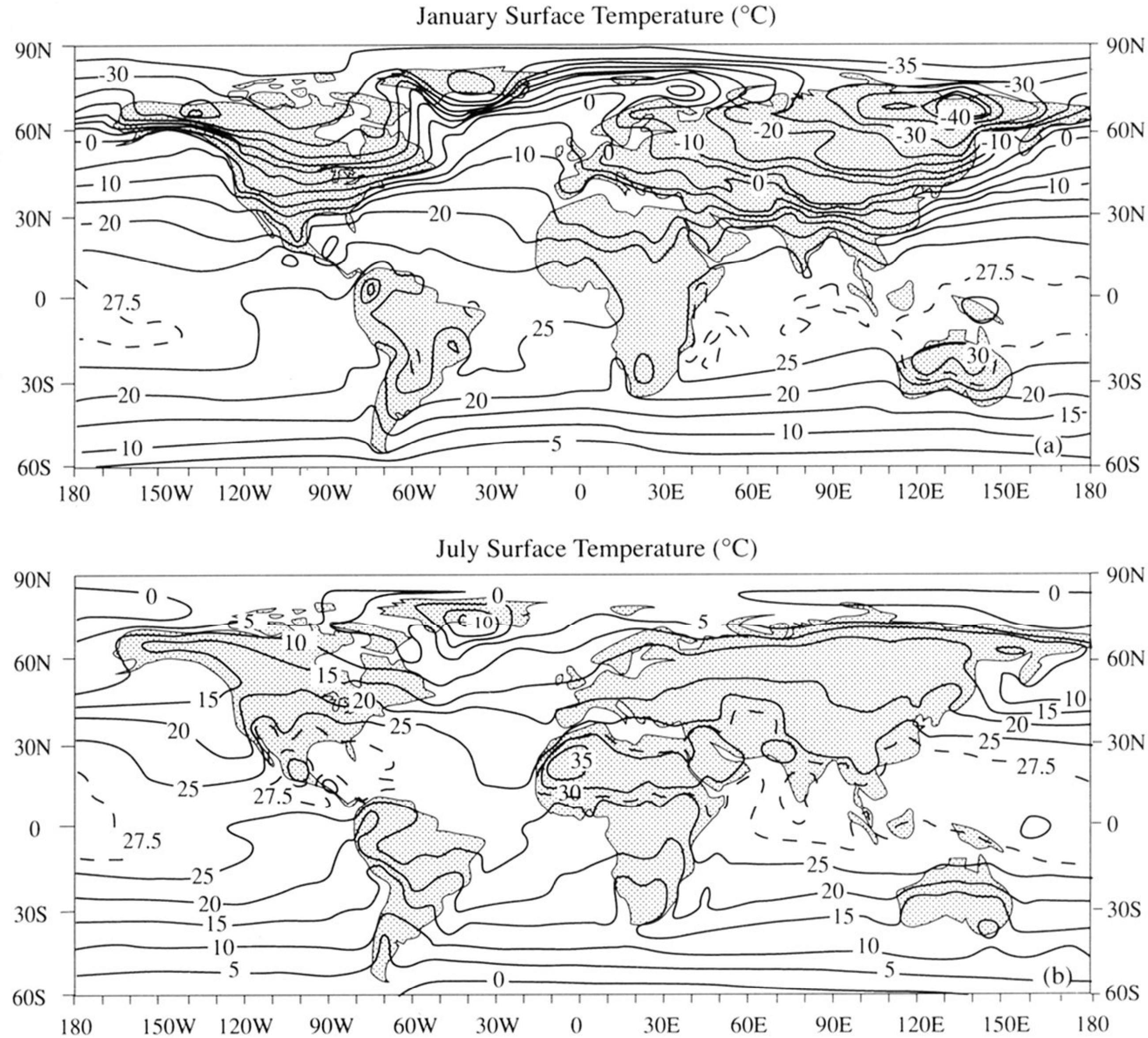


Fig. 1.6 Global map of the (a) January and (b) July surface temperature. [From Shea (1986). Reproduced with permission from the National Center for Atmospheric Research.]

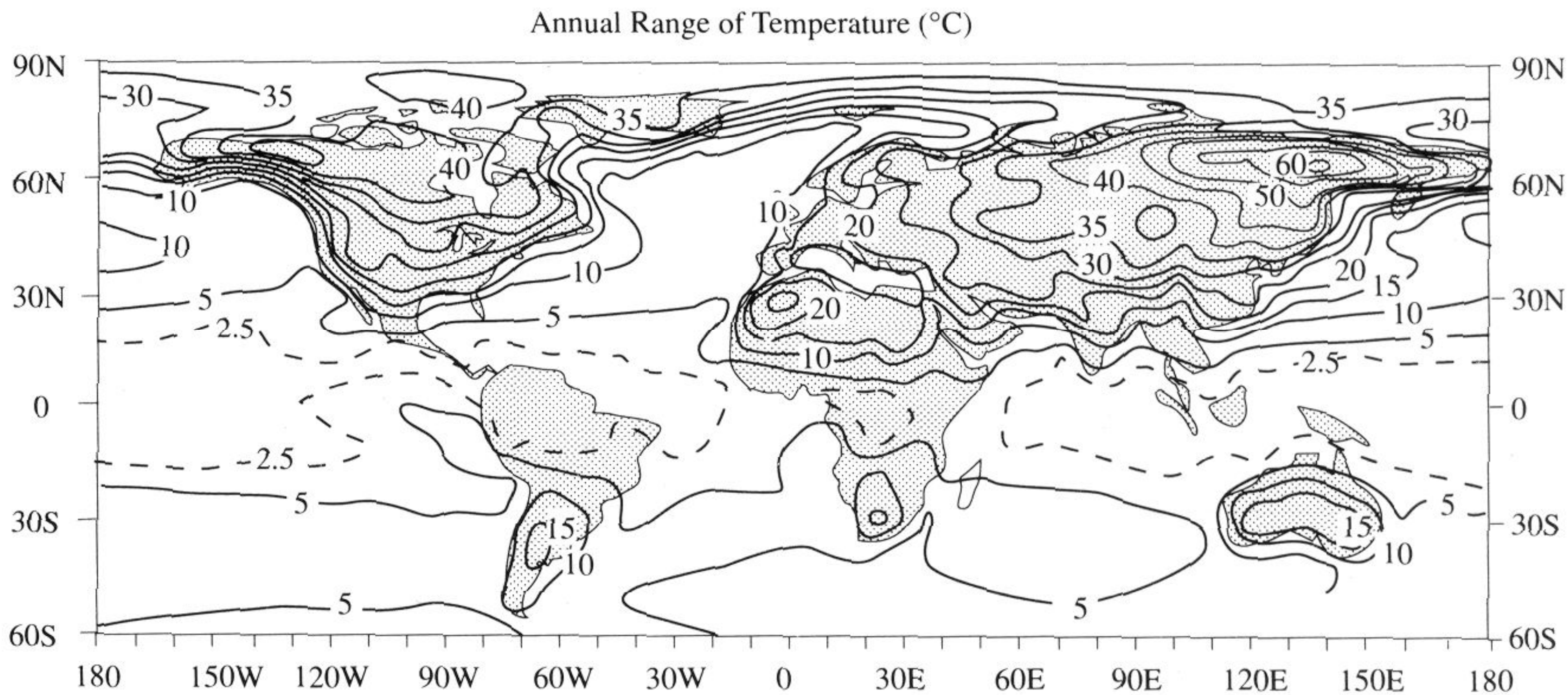
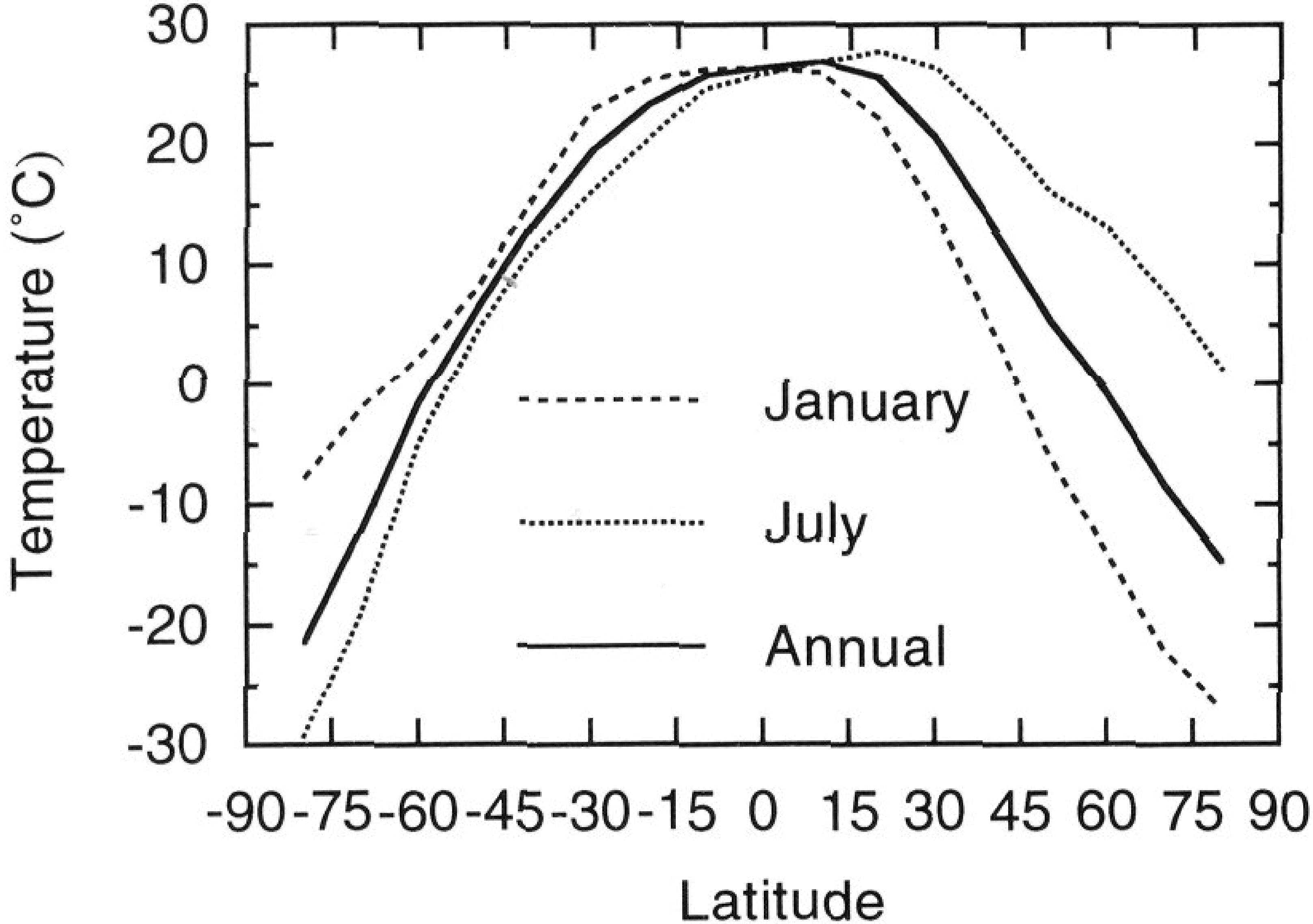
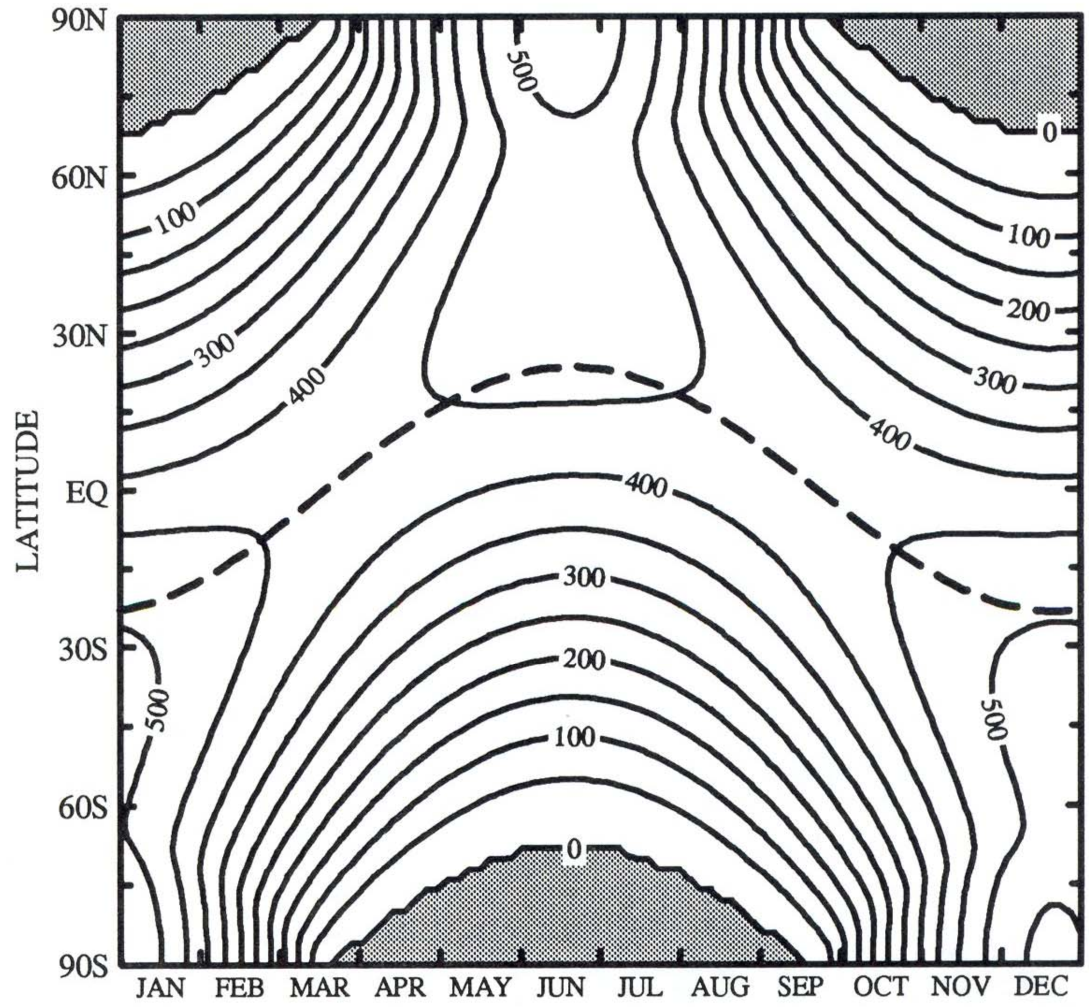
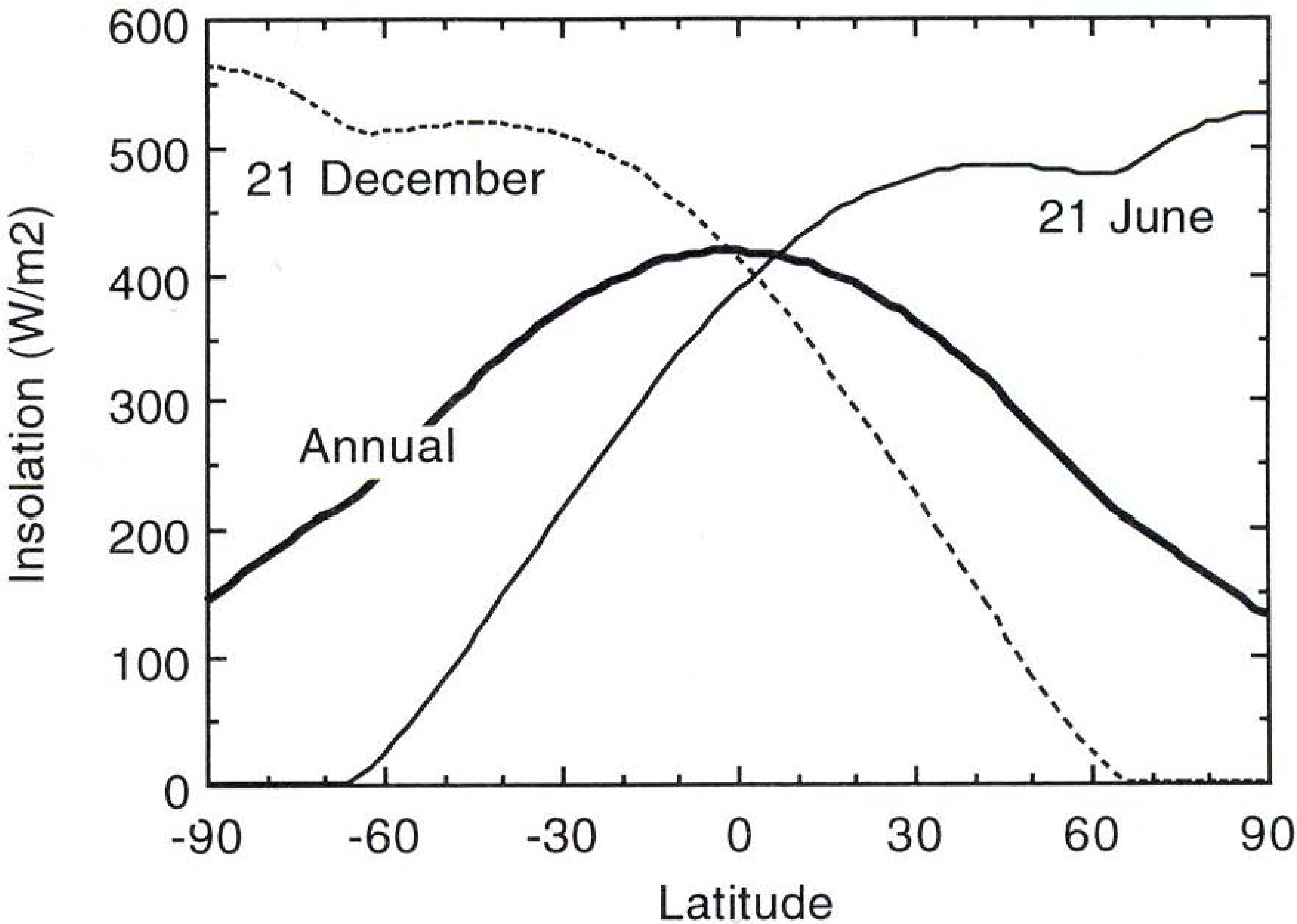


Fig. 1.7 Map of the amplitude of the annual cycle of surface temperature. [From Shea (1986). Reproduced with permission from the National Center for Atmospheric Research.]


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
Insolation (W/m2)
21 December
21 June
Annual
-90
-60
-30
0
30
60
90
Latitude

A One-Dimensional Description of the Tropical Atmosphere

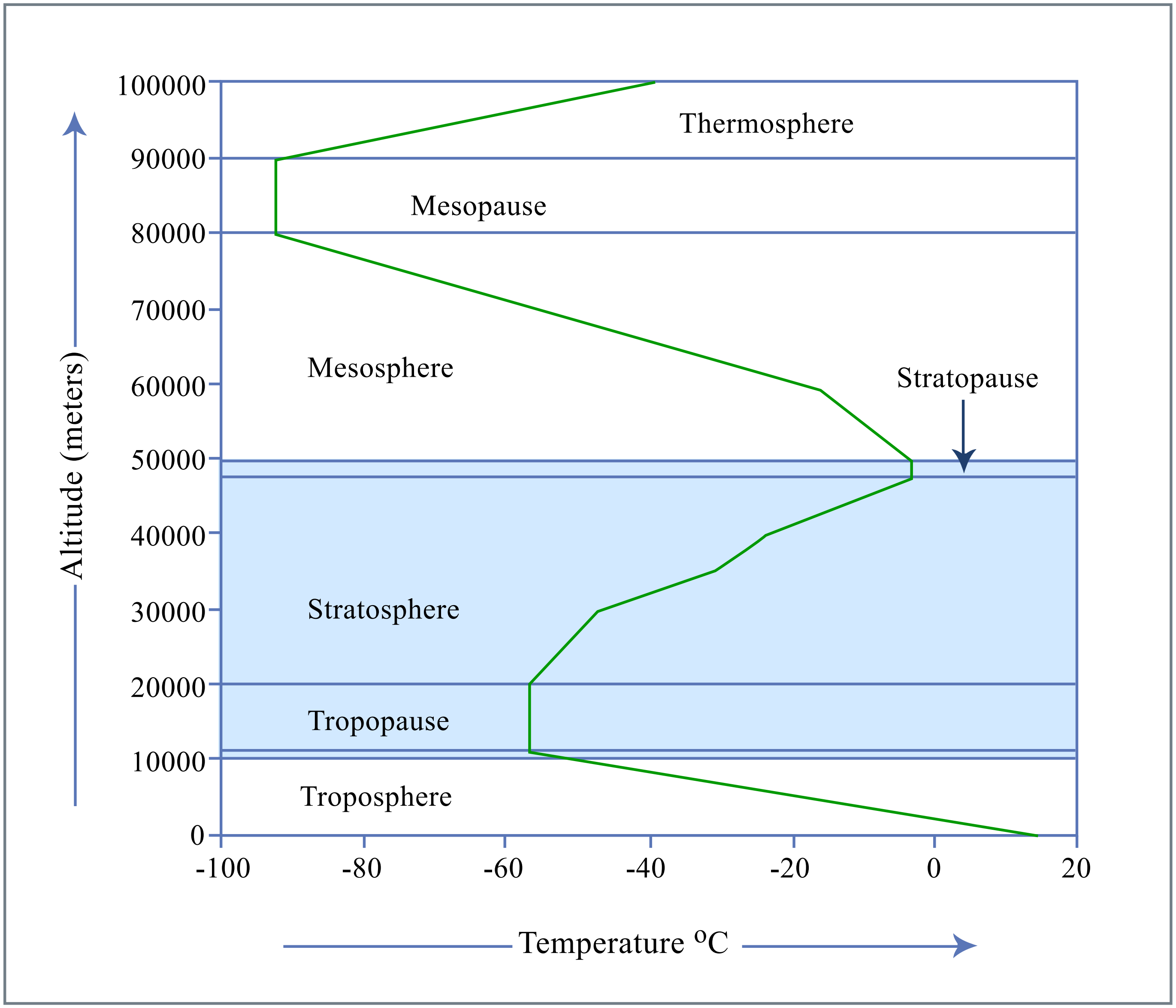


Image by MIT OpenCourseWare.

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:

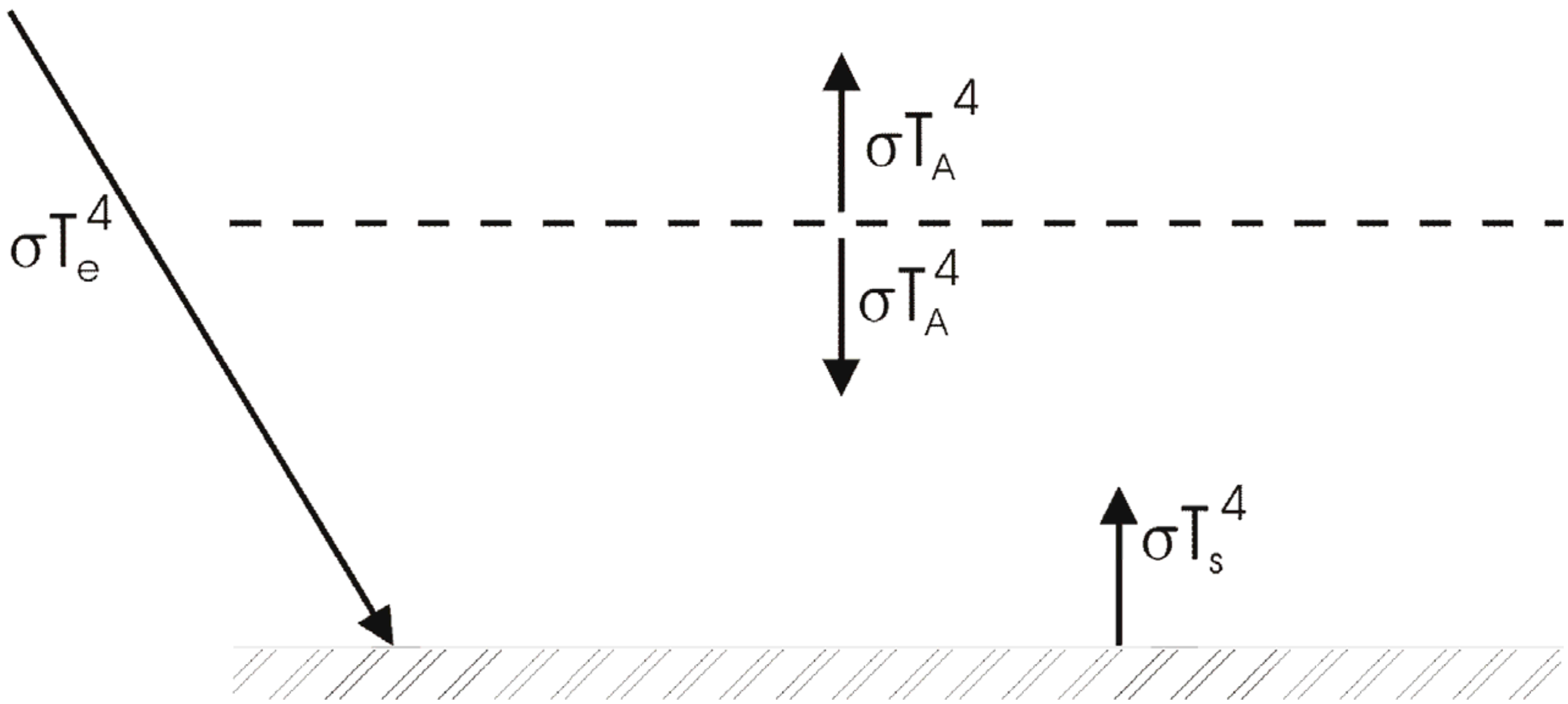
$$\sigma T_e^4 \equiv \frac{S_0}{4}\left(1 - a_p\right)$$

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:

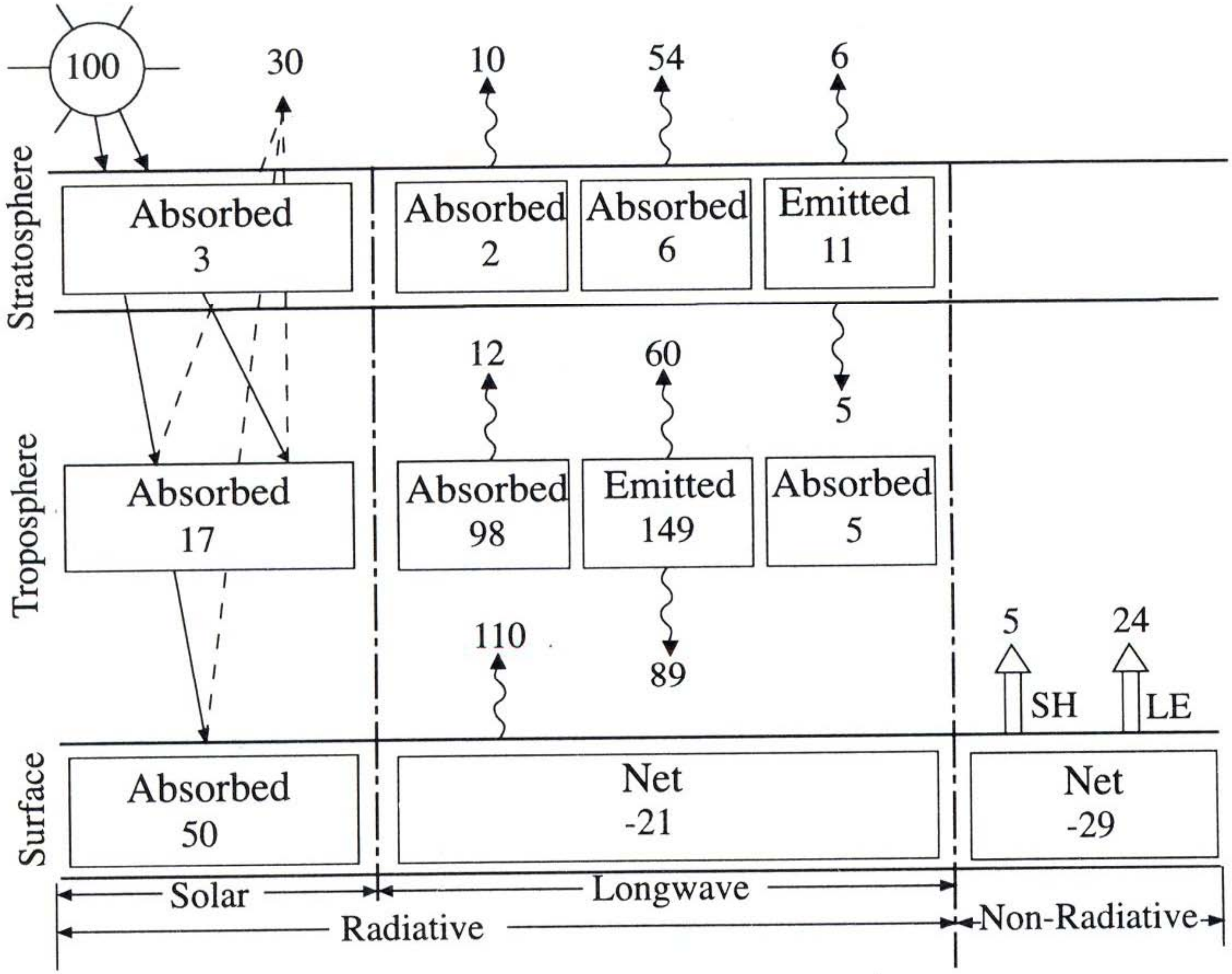
$$\sigma T_s^{\ 4} = \sigma T_A^{\ 4} + \frac{S_0}{4}\left(1 - a_p\right) = 2\sigma T_e^{\ 4}$$

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

Surface temperature too large because:

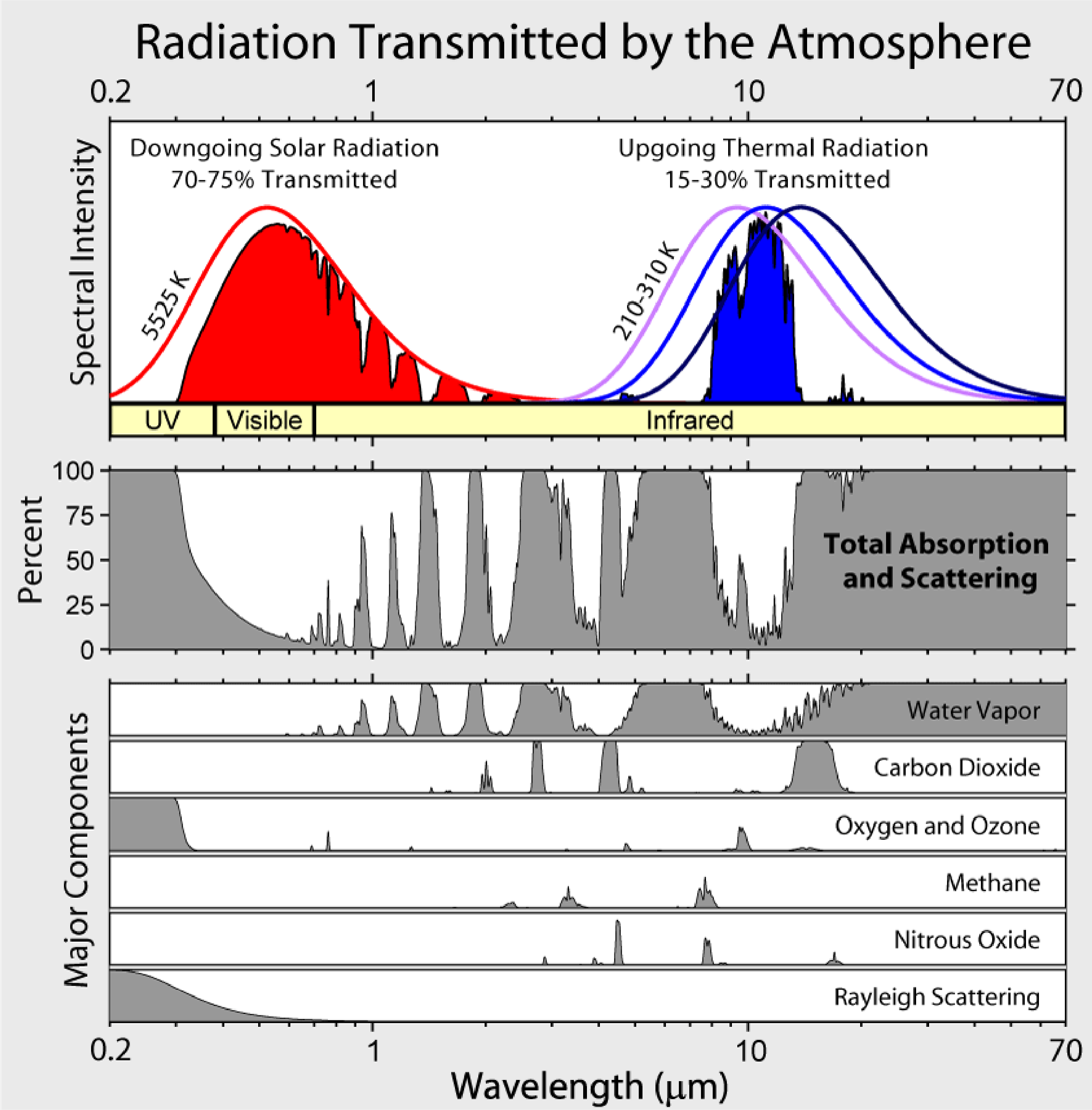
- Real atmosphere is not opaque
- Heat transported by convection as well as by radiation

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

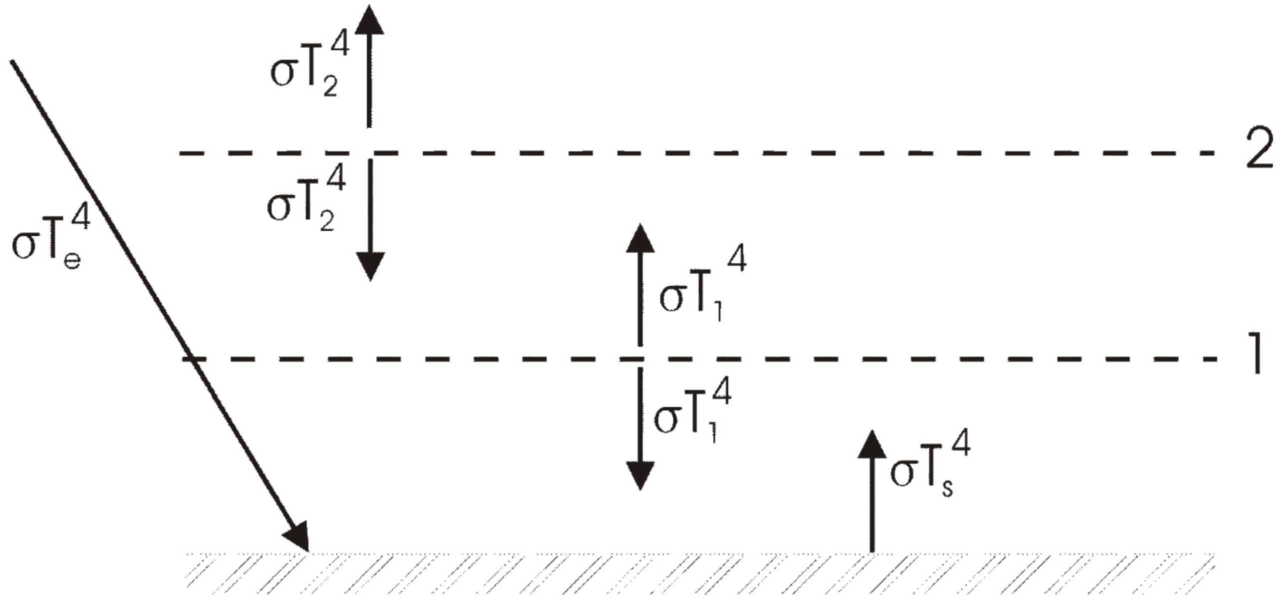


Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
0.2
1
10
70
Wavelength (μm)

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



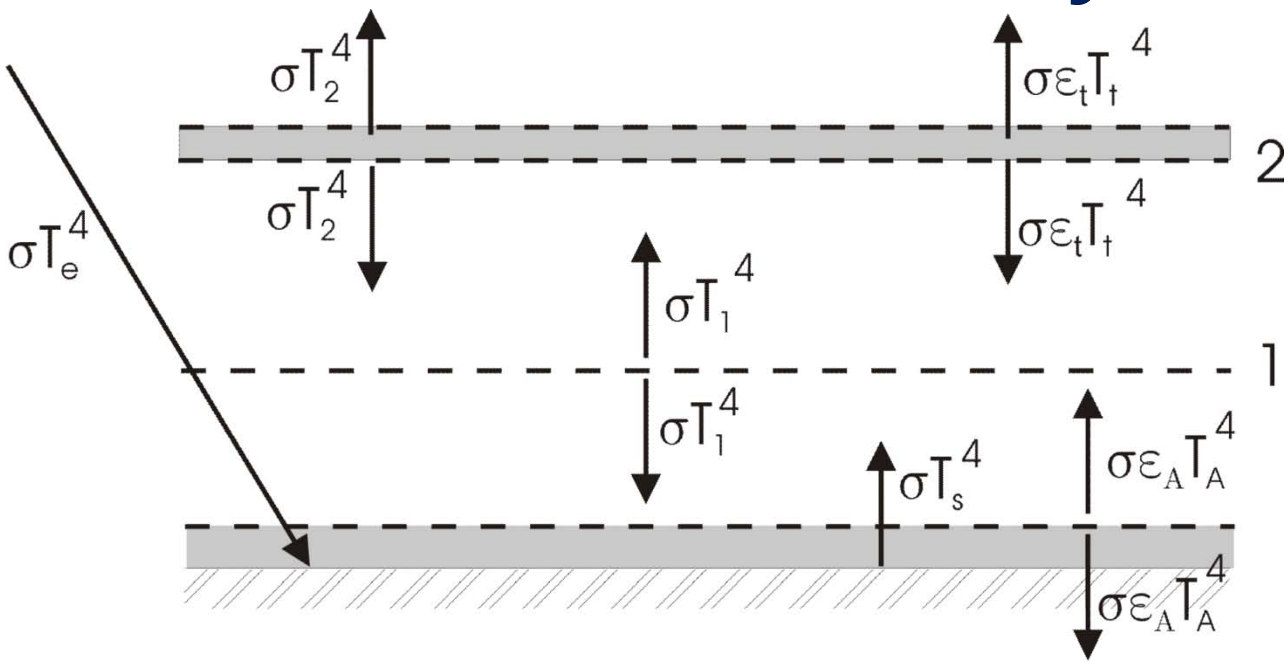
$$TOA: \quad \sigma T_2^{\ 4} = \sigma T_e^{\ 4} \rightarrow T_2 = T_e$$

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

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

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

Effects of emissivity<1



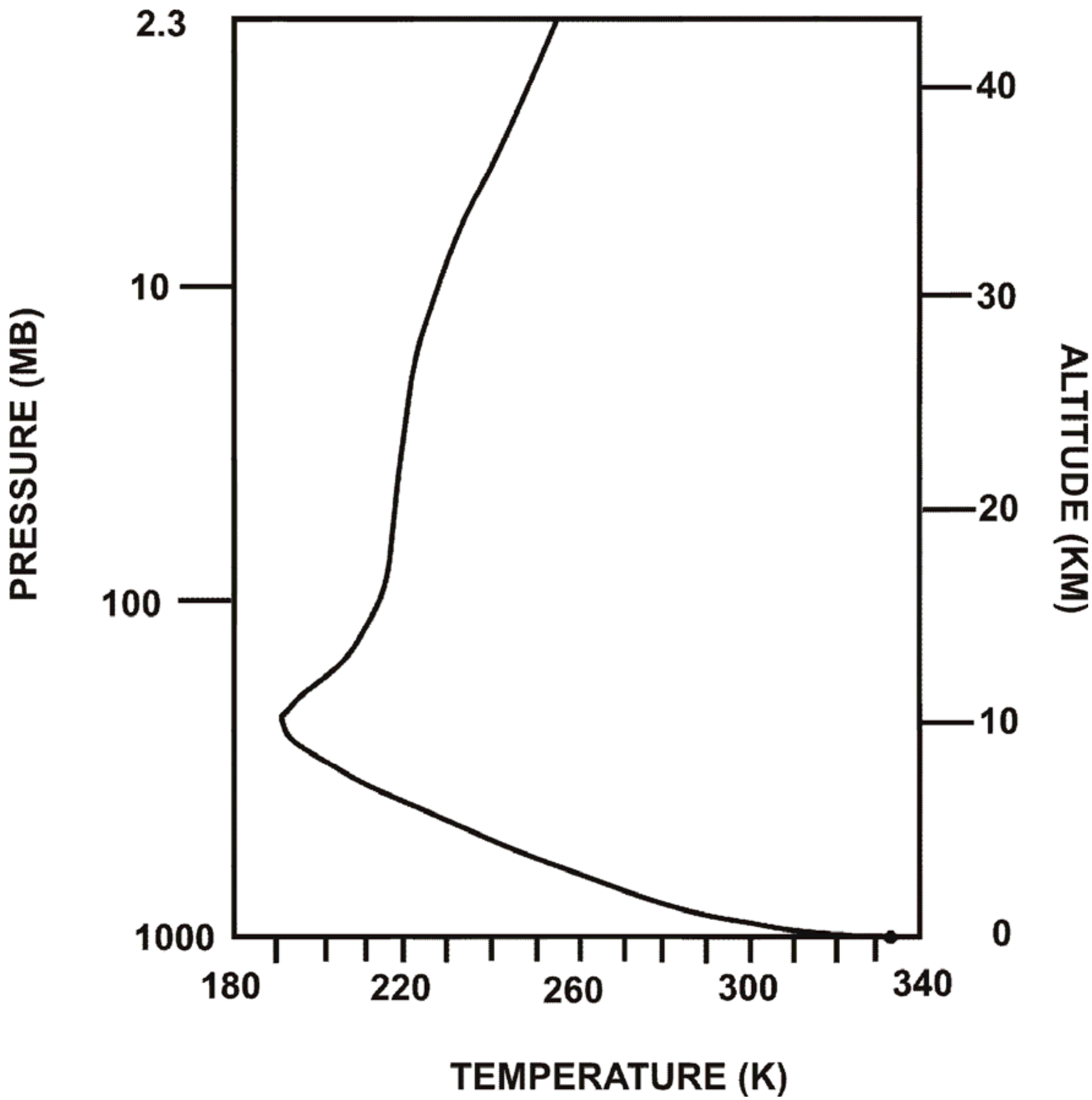
$$Surface: \quad 2\varepsilon_A \sigma T_A^{\ 4} = \varepsilon_A \sigma T_1^4 + \varepsilon_A \sigma T_s^{\ 4}$$

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

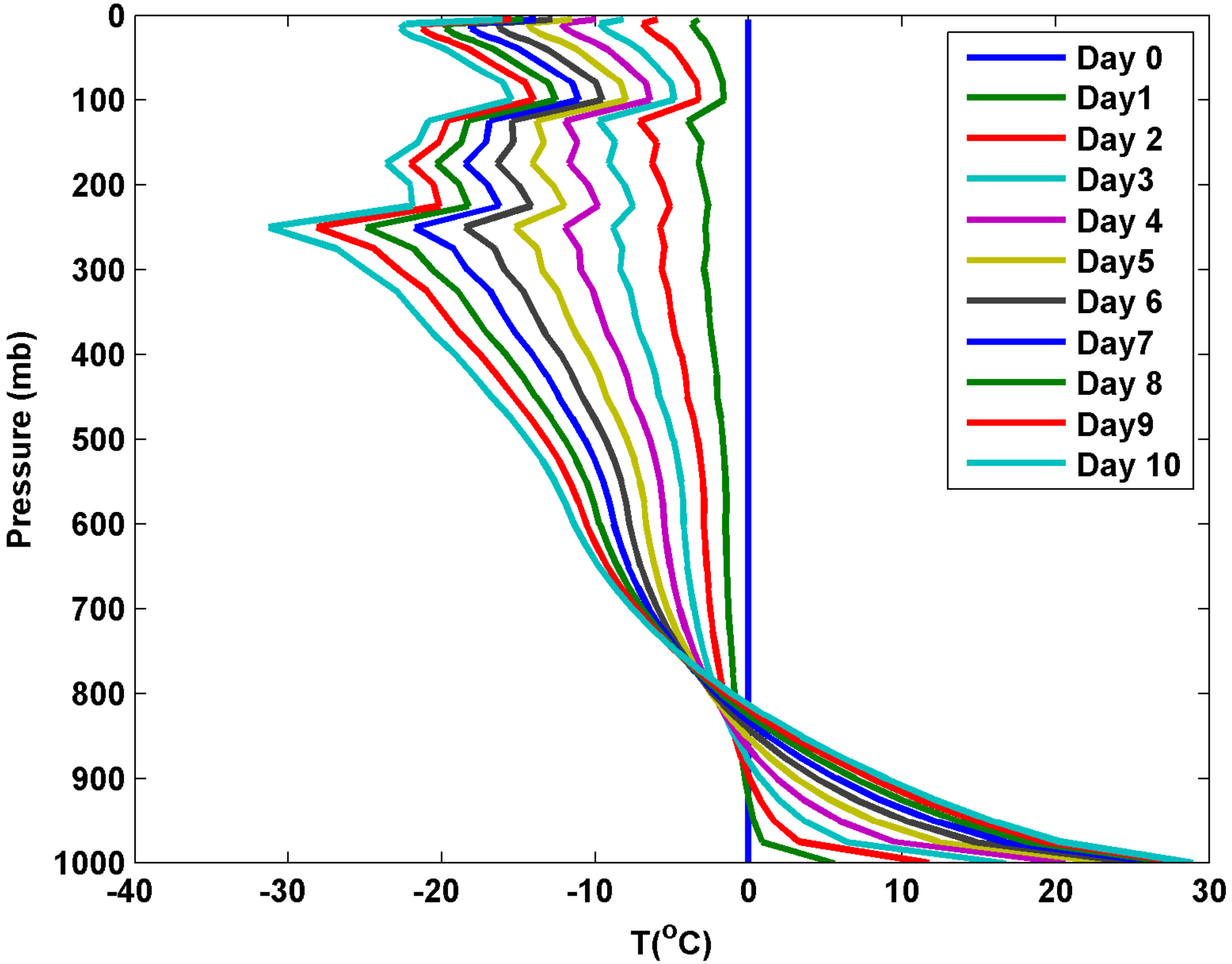
$$Stratosphere: \quad 2\varepsilon_t \sigma T_t^{\ 4} = \varepsilon_A \sigma T_2^{\ 4}$$

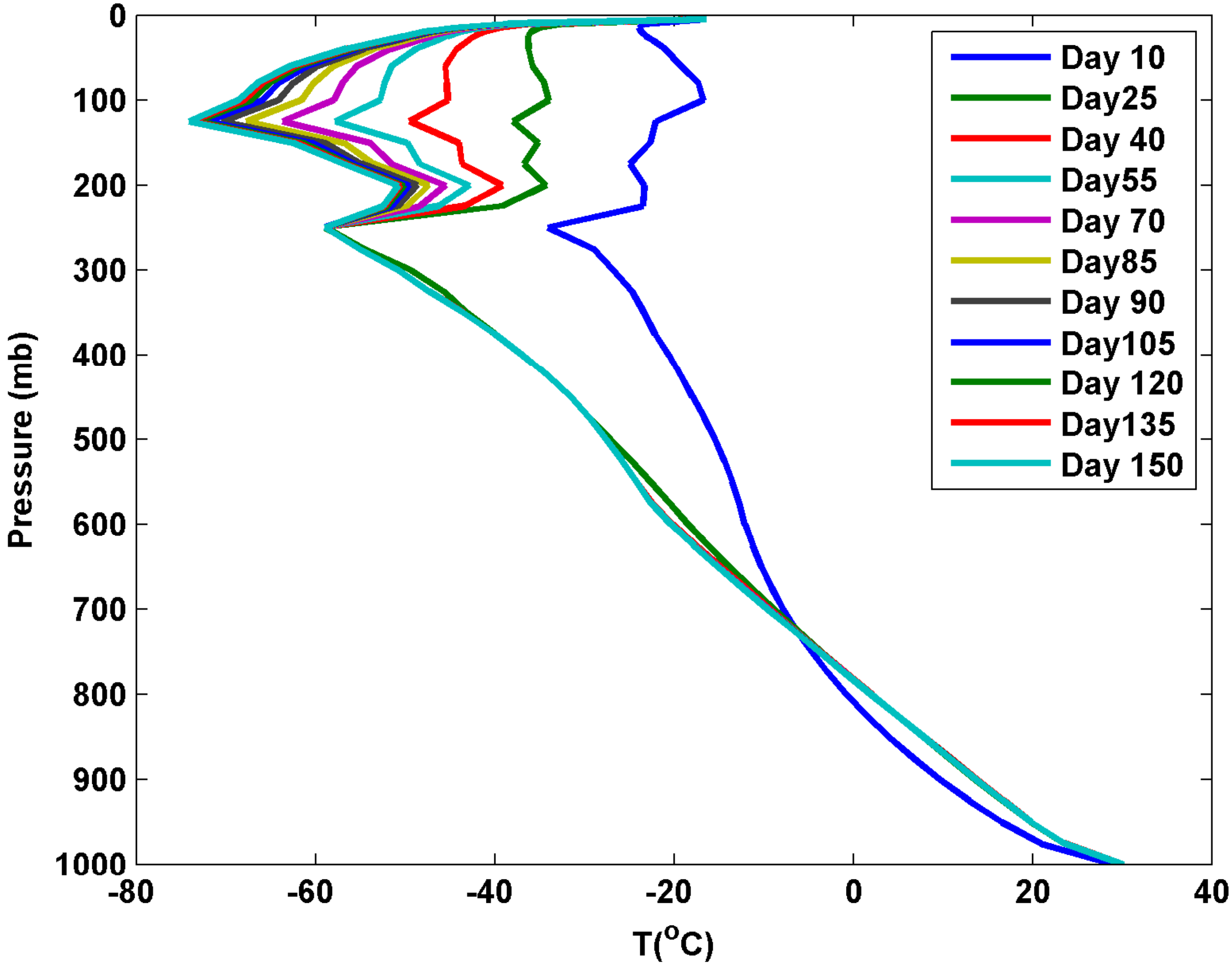
$$\rightarrow \quad T_t = \left(1/2\right)^{1/4} T_e \simeq 214K \quad < T_e$$

Full calculation of radiative equilibrium:



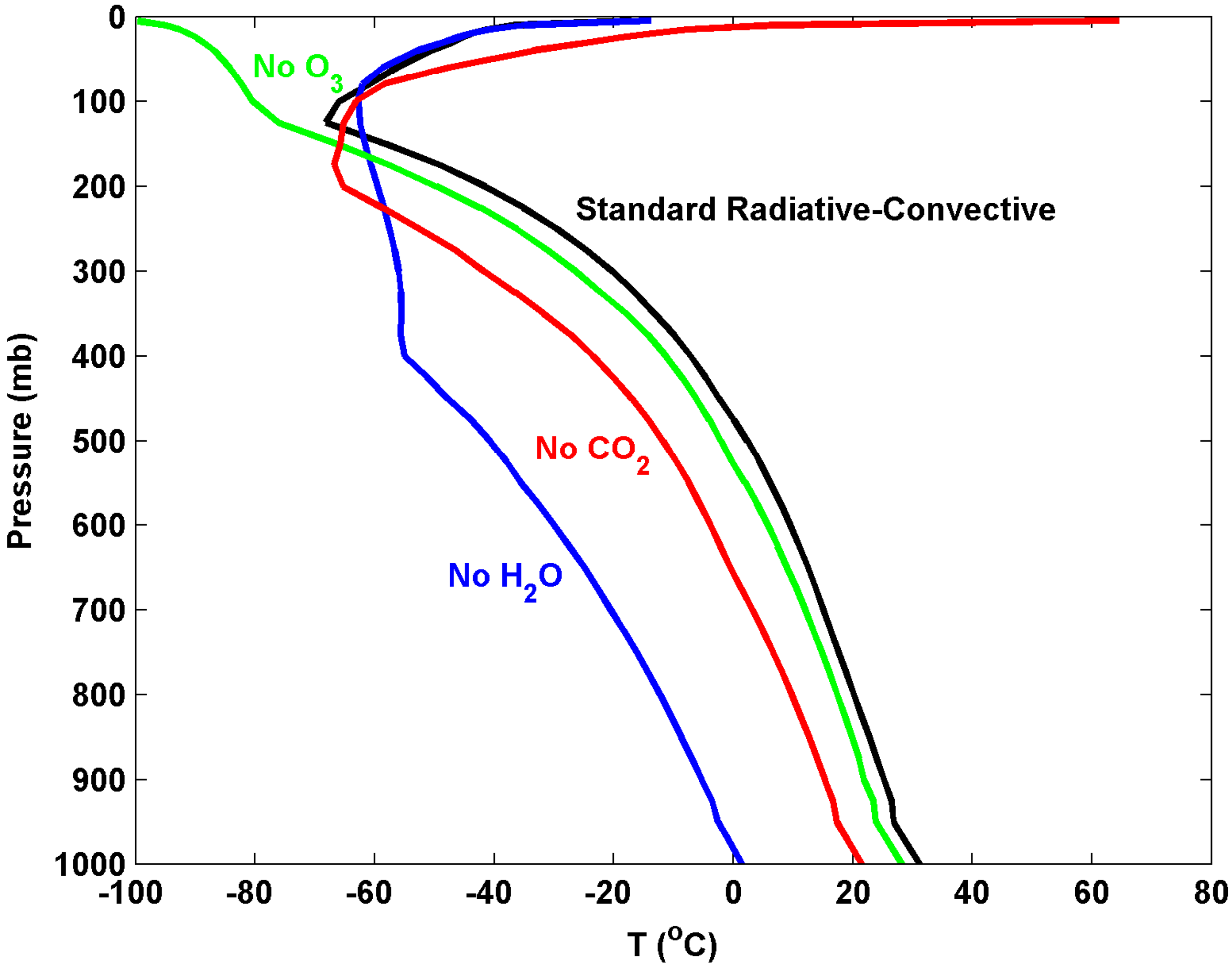
Time scale of approach to equilibrium



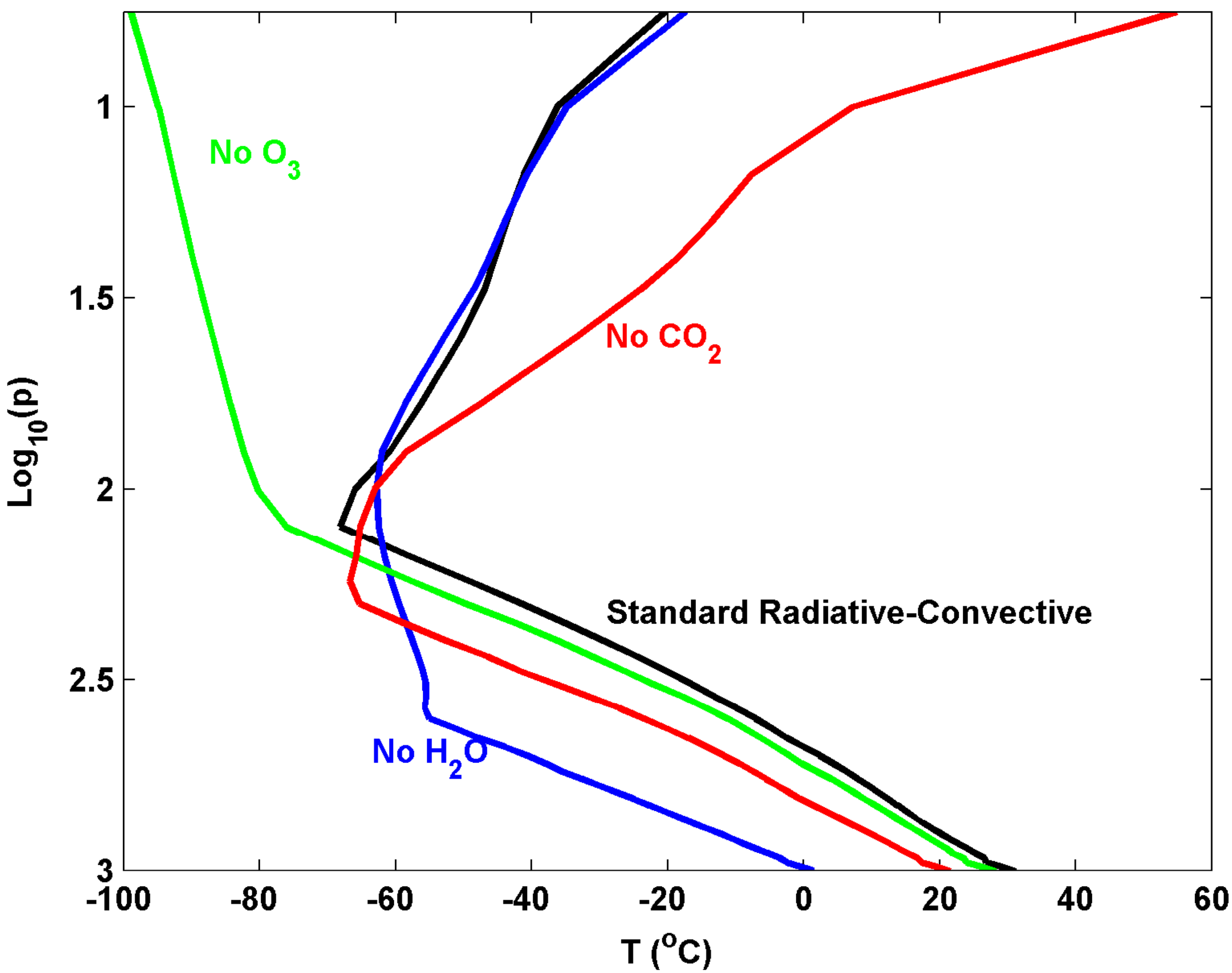


Day 10
Day25
Day 40
Day55
Day 70
Day85
Day 90
Day105
Day 120
Day135
Day 150
Pressure (mb)
T(°C)
0
100
200
300
400
500
600
700
800
900
1000
-80
-60
-40
-20
0
20
40

Contributions of various absorbers



Note: All simulations have variable clouds interacting with radiation


No O_3
No CO_2
Standard Radiative-Convective
No H_2O
$Log_{10}(p)$
1
1.5
2
2.5
3
-100
-80
-60
-40
-20
0
20
40
60
T (^oC)

12.811 Tropical Meteorology
Spring 2011