Fundamentals of Earth's Atmospheric Structure & Circulation

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/spr2022
https://myelms.umd.edu/courses/137772

Goals:

1) Tie up loose ends from last lecture
2) Barometric law (pressure vs height)
3) Thermal structure (temperature vs height)
4) Geostrophy (balance of pressure force & Coriolis Force ⇨ storms)
5) Ferrel circulation (mean circulation Earth's atmosphere ⇨ climate regimes)

Lecture 3

3 February 2022

Tropospheric Ozone Production

$$OH + \mathbf{CO} \rightarrow \mathbf{CO_2} + H$$

$$H + \mathbf{O_2} + M \rightarrow HO_2 + M$$

$$HO_2 + NO \rightarrow OH + NO_2$$

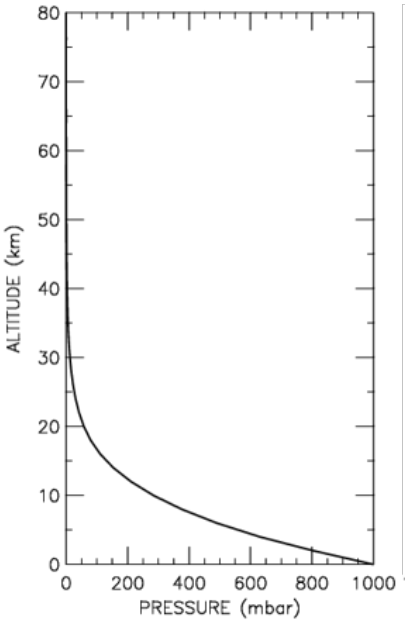
$$NO_2 + h\nu \rightarrow NO + O$$

$$O + \mathbf{O_2} + M \rightarrow \mathbf{O_3} + M$$

$$\text{Net:} \quad \mathbf{CO + 2\,O_2 \rightarrow CO_2 + O_3}$$

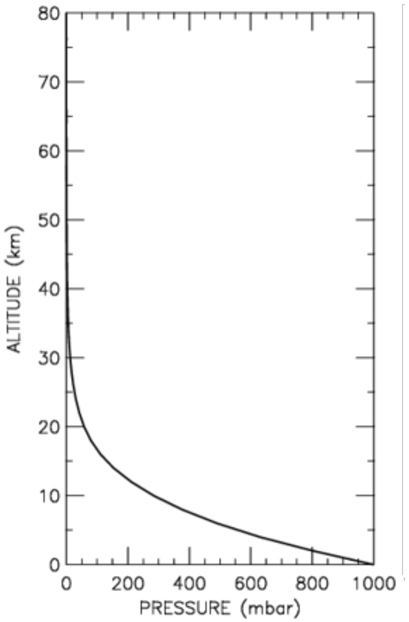
Oxidation of CO in the presence of elevated NO_x ($NO + NO_2$) leads to ***production*** of tropospheric ozone

Pressure versus Altitude



- **Pressure = Force per unit area**
- **Graph shows how "force" of atmosphere varies as a function of altitude**
- **Pressure shown in units of mbar : 1 mbar = 10^3 dynes/cm^2**
- **1 dyne = gm cm / sec^2; therefore 1 mbar = 10^3 gm / cm sec^2**
- **Also:**
  - **European community prefers to write hPa; 1 hPa is exactly equal to 1 mbar**
  - **1 atmosphere = $p/p_{STANDARD}$, where $p_{STANDARD}$ = 1013.25 mbar (or 1013.25 hPa)**

Pressure versus Altitude



Derivation of the Barometric Law involves use of the Ideal Gas Law:

$$p\ Vol = n\ R\ \mathrm{T}$$

where p is pressure, Vol is volume, n is the number of moles of a gas,

R is the gas constant ($8.3143\times10^{7}\ \frac{\text{ergs}}{\text{K mole}}$), and T is temperature

as shown on Extra Slide 1 at end of Class Notes (you will not be tested on this!)

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

Pressure (z) = Pressure (surface) × $e^{-z/H}$

where H is called the "scale height"

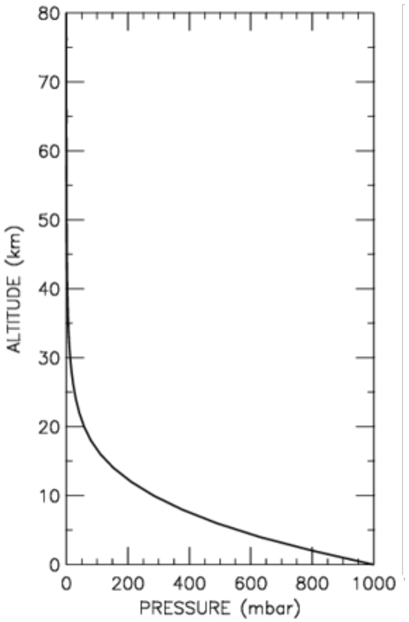
Can show H = R_{EARTH} T (z) / *grav* ,

Since R_{EARTH} = 2.88×10^{6} ergs / K gm

***grav* = 981 cm sec^{-2} and T(lower trop) ≈ 272 K**

then H (z=0) = 8.0×10^{5} cm = 8 km

Pressure versus Altitude



In modern atmospheric sciences, the most handy version of the Ideal Gas Law is:

$$p = M\ k\ \mathrm{T}$$

where p is pressure (force per unit area), M is number density (molecules/volume), k is Boltzmann's constant (1.38×10^{-16} ergs/K), and T is temperature.

If p is given in units of mbar (or hPa), M is in units of $\frac{\text{molecules}}{\text{cm}^3}$, and T is in K,

then can show k must be $1.38\times10^{-19}\ \frac{\text{mbar cm}^3}{\text{K molecules}}$

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

Pressure (z) = Pressure (surface) $\times\ \mathbf{e}^{-z/H}$

where H is called the "scale height"

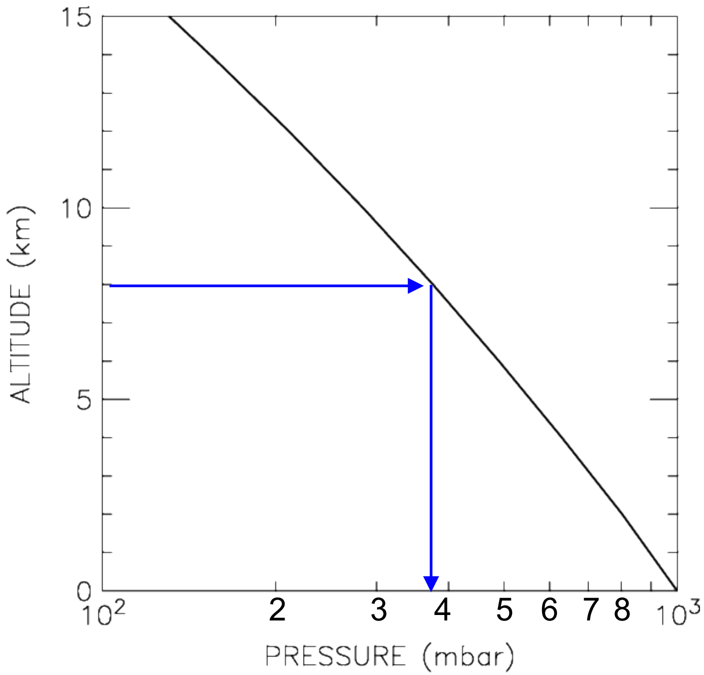
Can show H = R_{EARTH} **T (z) /** ***grav*** **,**

Since R_{EARTH} **=** 2.88×10^{6} **ergs / K gm**

grav **= 981 cm** sec^{-2} **and T(lower trop) ≈ 272 K**

then H (z=0) = 8.0×10^{5} **cm = 8 km**

Pressure versus Altitude



p (z=0) = 1013.25 mbar

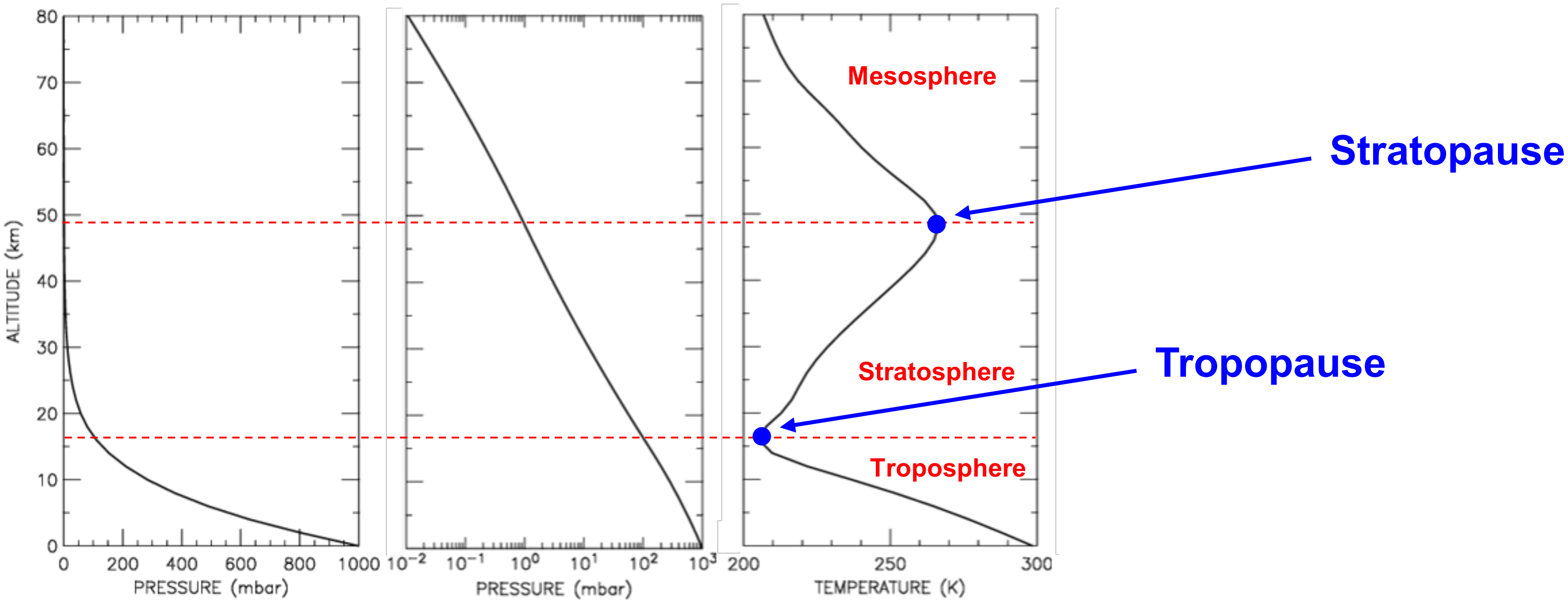
p (z=8 km) =

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

Pressure (z) = Pressure (surface) × $e^{-z/H}$

Let's take a closer look at log pressure versus altitude, in the troposphere

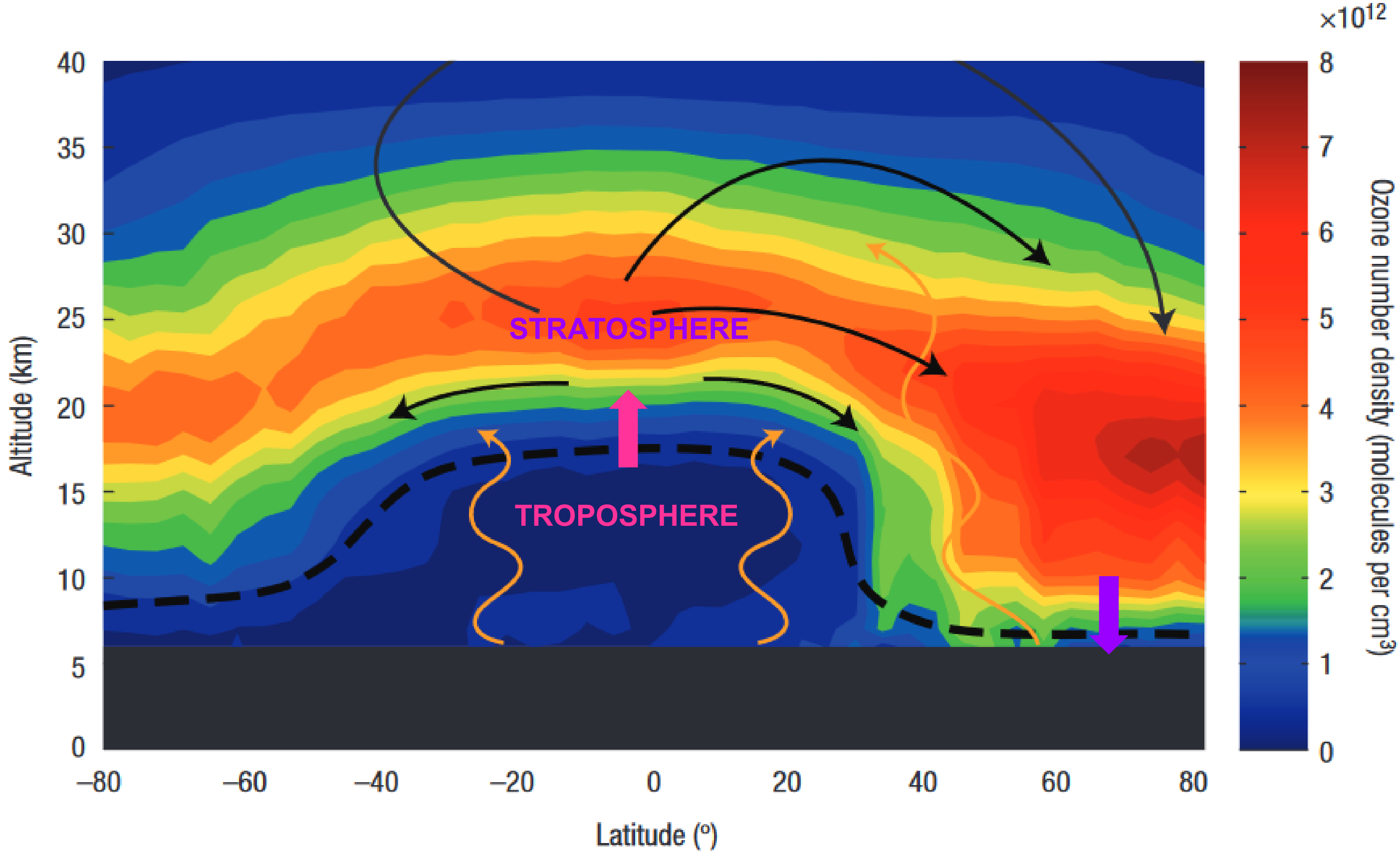
Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

Tropopause versus Latitude

Page 29 of *Chemistry in Context* states depth of tropopause varies from about 12 miles (20 km) at mid-latitudes to about 5 miles (8 km) at the poles; in reality, the tropopause is closer to 17 to 18 km in the tropics, and much lower at mid-latitudes.



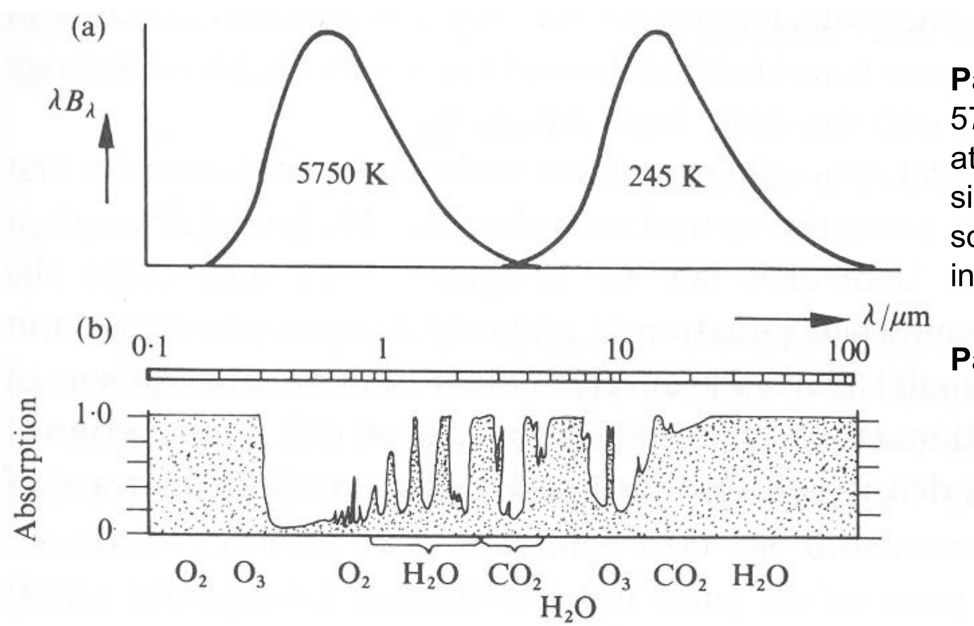
Brewer–Dobson circulation (arrows), ozone (colors), and tropopause (black dashed line).

The ozone distribution as measured by the OSIRIS satellite instrument in March 2004. The circulation is forced by waves propagating up from the troposphere (orange arrows), especially in the winter hemisphere. Generally, air enters the stratosphere in tropics (slow leak it) and exits at high latitudes, in the winter hemisphere (slow leak out), as noted by the pink & purple block arrows, respectively.

Shaw and Shepherd, Nature Geoscience, 2008.

Atmospheric Radiation

- Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)
- Thermal irradiance (upwelling) at top of the atmosphere occurs at wavelengths between ~5 and 50 μm (~245 K "black body" temperature)

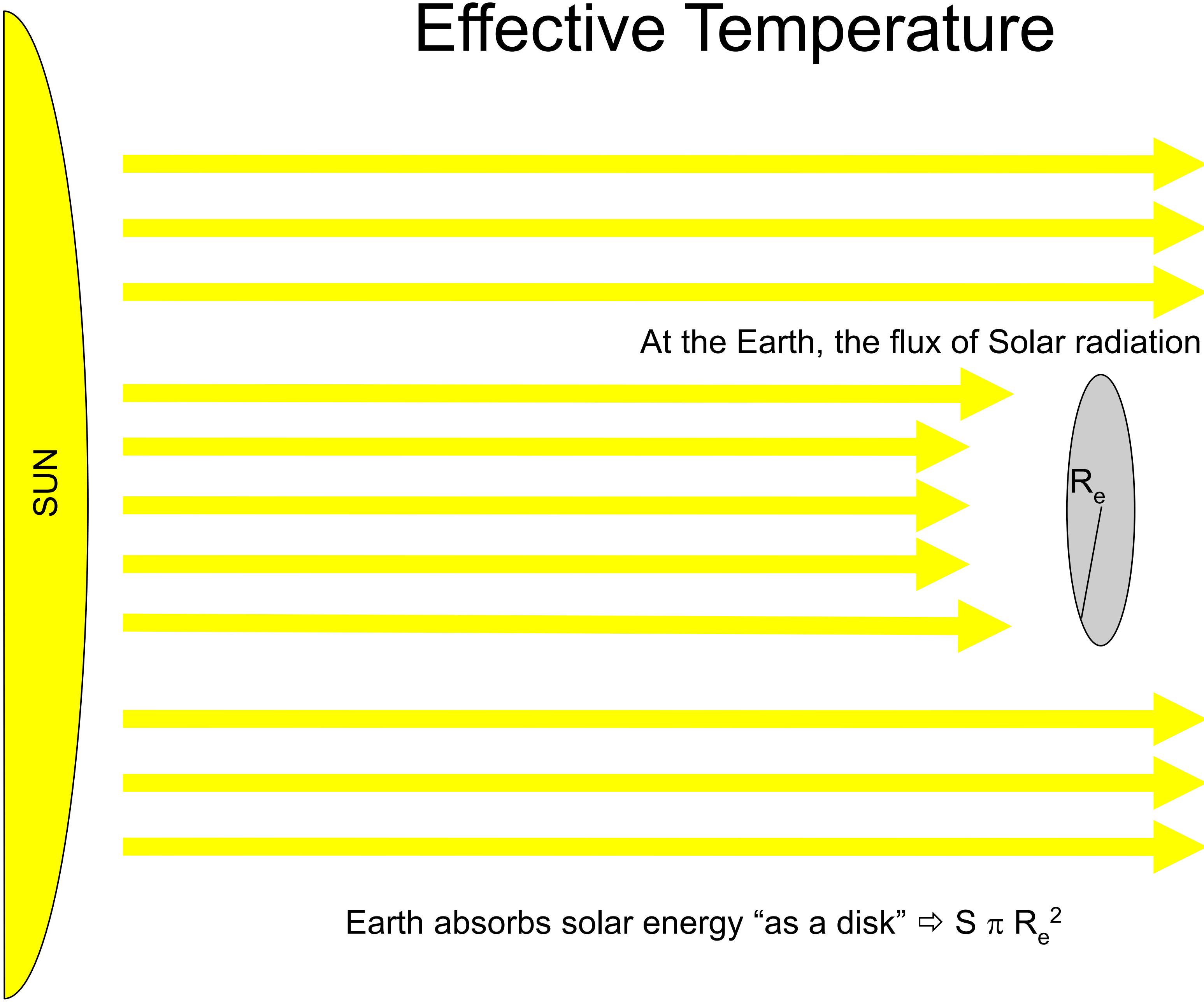


Panel (a): Black-body energy versus wavelength for 5750 K (Sun's approx T) and 245 K (Earth's mean atmospheric T). Curves are drawn with equal area since integrated over entire Earth, at top atmosphere, solar downwelling and terrestrial upwelling fluxes are in close balance.

Panel (b): absorption by atmospheric gases: 1.0 represents complete absorption.

From Houghton, *Physics of Atmospheres*, 1991

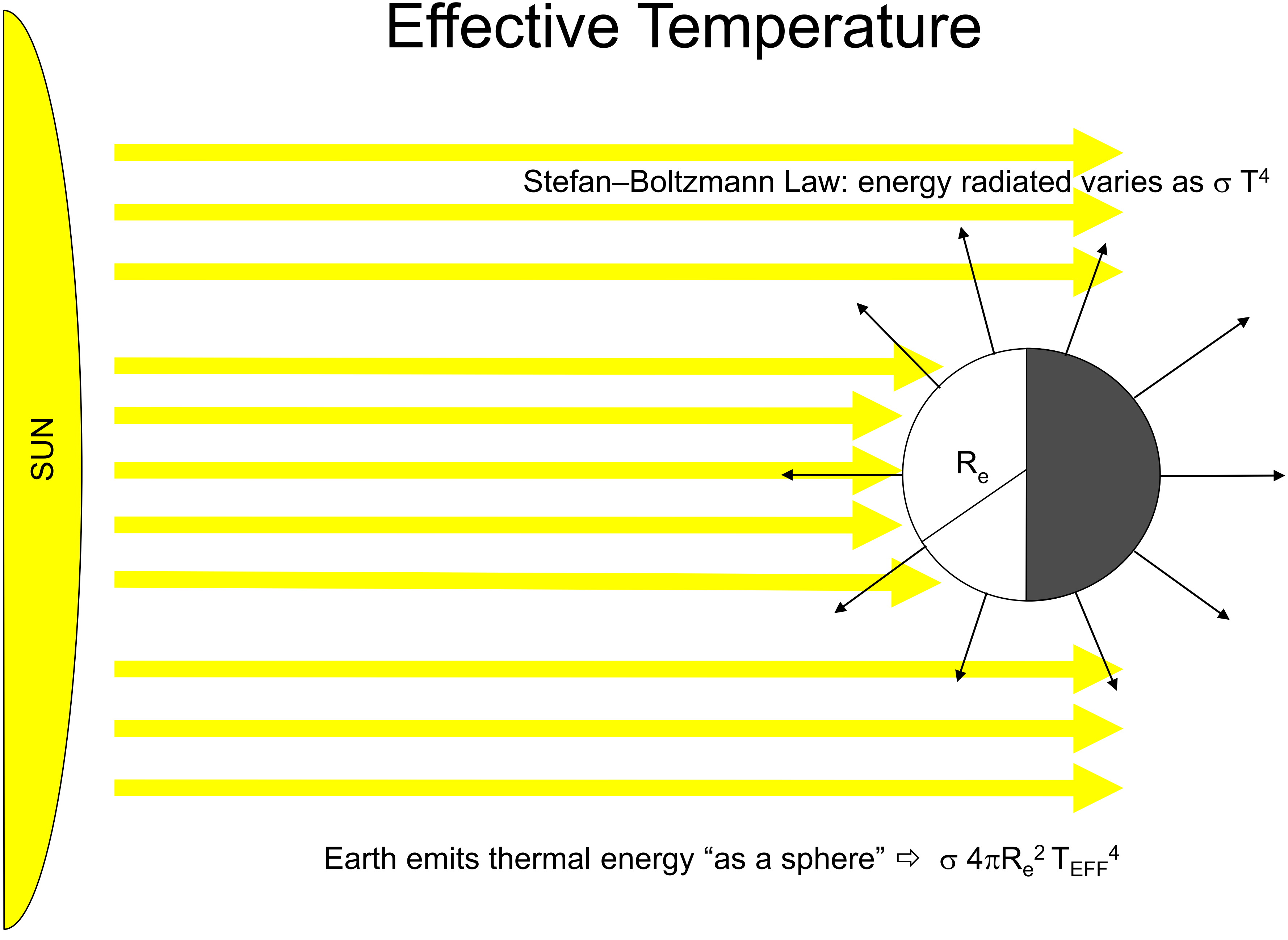
Effective Temperature



At the Earth, the flux of Solar radiation S = **1370 W m^{-2}**

Earth absorbs solar energy “as a disk” ⇨ $S\ \pi\ R_e^2$

Effective Temperature



Earth emits thermal energy "as a sphere" ⇨ $\sigma\, 4\pi R_e^2\, T_{EFF}^4$

Effective Temperature

Earth absorbs solar energy "as a disk" ⇨ $(1 - \text{Albedo}) \times S \pi R_e^2$

Earth emits thermal energy "as a sphere" ⇨ $\sigma 4\pi R_e^2 T_{EFF}^4$

$$(1-\text{Albedo}) \times S = 4 \sigma T_{EFF}^4$$

or

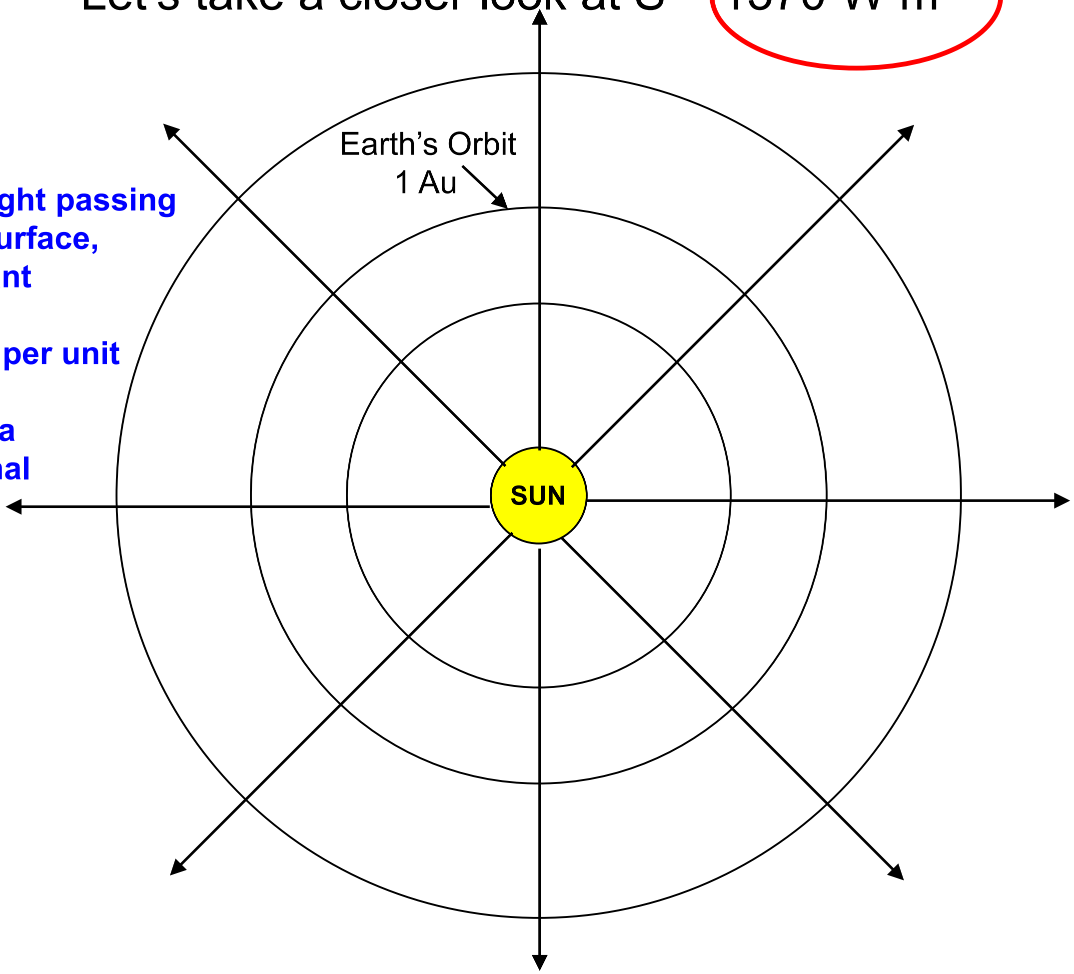
$$T_{EFF} = \{ (1 - \text{Albedo}) \times S / 4 \sigma \}^{1/4}$$

Effective Temperature

Let's take a closer look at S = 1370 W m^{-2}

The total amount of sunlight passing through each spherical surface, of various radii, is constant

Therefore the energy (W) per unit area (m^{-2}) decreases wrt distance from the Sun in a manner that is proportional to: ______________



Notes: 1) Au, or Astronomical Unit, is a measure of the distance of a planet from the Sun, normalized by the mean distance of Earth from the Sun. So by definition, **Earth's orbit is 1 Au from the Sun**

2) The diagram above represents orbits as perfect spheres, which is suitable for our study of effective temperatures. In reality, of course, planets orbit the Sun in an elliptical manner.

$$T_{EFF} = \{ (1 - \text{Albedo}) \times S \ / \ 4\,\sigma \}^{1/4}$$

633 students: find T_{EFF} for Earth, using:

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

S = 1370 W m^{-2}

Albedo = 0.3

433 student whose last name begins with letters A-M:

Find T_{EFF} for **Mars** using:

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

S = 1370 W m^{-2}

Albedo = 0.17

Distance from Sun = 1.5 AU

433 student whose last name begins with letters N-Z:

Find T_{EFF} for **Venus** using:

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

S = 1370 W m^{-2}

Albedo = 0.75

Distance from Sun = 0.72 AU

Effective Temperature

My Favorite Planets

Venus:

$T_{SURFACE} \approx 753$ K

$T_{EFFECTIVE} \approx$???

Earth:

$T_{SURFACE} \approx 288$ K

$T_{EFFECTIVE} \approx$???

Mars

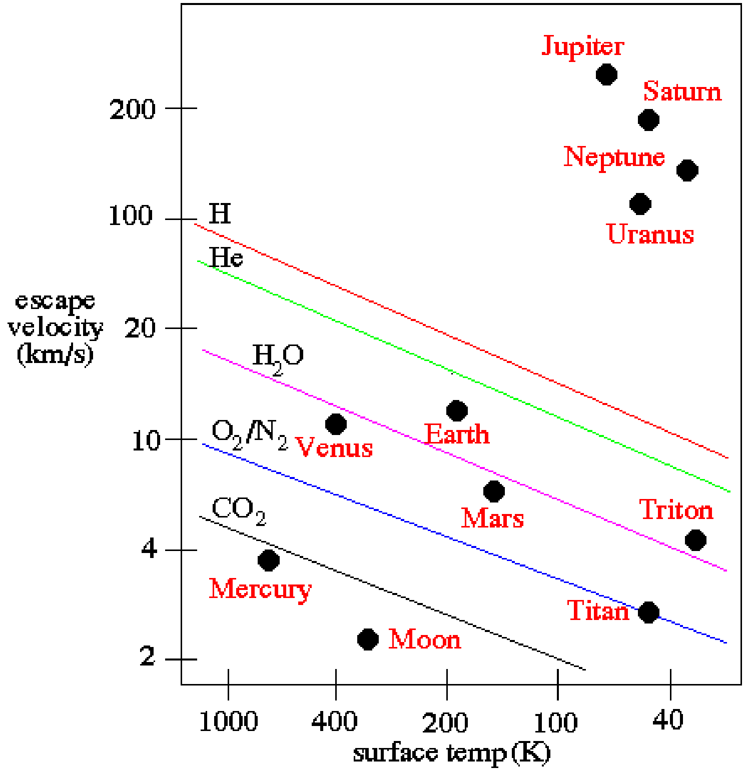
$T_{SURFACE} \approx 217$ K

$T_{EFFECTIVE} \approx$???

Geological Evolution of Earth's Atmosphere:
Earth, Mars, and Venus

	Earth	Venus	Mars
Radius (km)	6400	6100	3400
Mass (10^{24} kg)	6.0	4.9	0.6
Albedo	0.3	0.8	0.22
Distance from Sun (A.U.)	1	0.72	1.52
Surface Pressure (atm)	**1**	**91**	**0.007**
Surface Temperature (K)	~15 °C	~ 460 °C	–140 °C to 20 °C
N_2 (mol/mol)	0.78	3.4×10^{-2}	2.7×10^{-2}
O_2 (mol/mol)	0.21	6.9×10^{-5}	1.3×10^{-3}
CO_2 (mol/mol)	3.7×10^{-4}	**0.96**	0.95
H_2O (mol/mol)	1×10^{-2}	3×10^{-3}	3×10^{-4}
SO_2 (mol/mol)	1×10^{-9}	1.5×10^{-4}	Nil
Cloud Composition	H_2O	H_2SO_4	Mineral Dust

Geological Evolution of Earth's Atmosphere:
Earth. Mars. and Venus



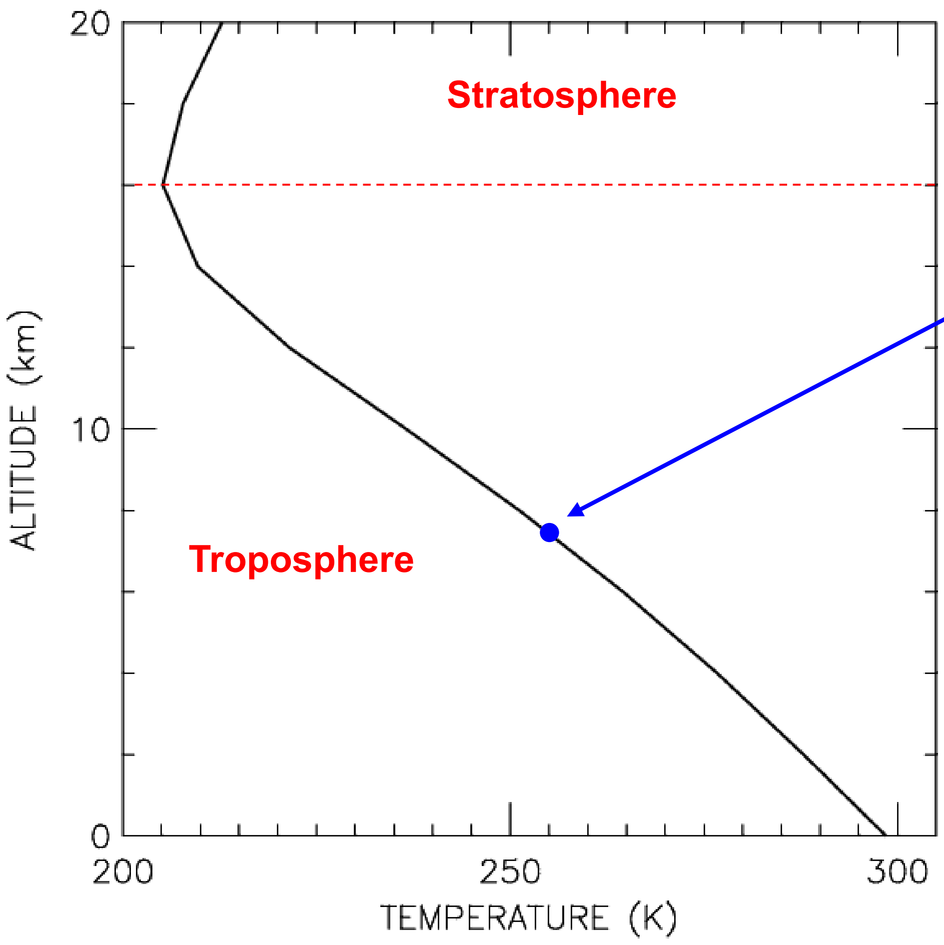
http://abyss.uoregon.edu/~js/ast121/lectures/lec14.html

Billions of years ago Venus had water. Most of this would have been in the form of vapor, since Venus is closer to the Sun. Water vapor is a greenhouse gas so heat from the Sun would have been trapped, temperature would have risen, and CO_2 would have been "baked" out of carbonate rocks. These circumstances likely led to increasing temperature in an strongly positive, upward spiraling fashion, leading to a "hot house" planet that persists today. https://www.sciencefocus.com/space/why-are-venus-and-mars-so-different-to-earth

Scientists debate whether a runaway greenhouse effect could occur on Earth
https://en.wikipedia.org/wiki/Runaway_greenhouse_effect

Temperature versus Altitude

Let's take a closer look at T_{EFF} = 255 K

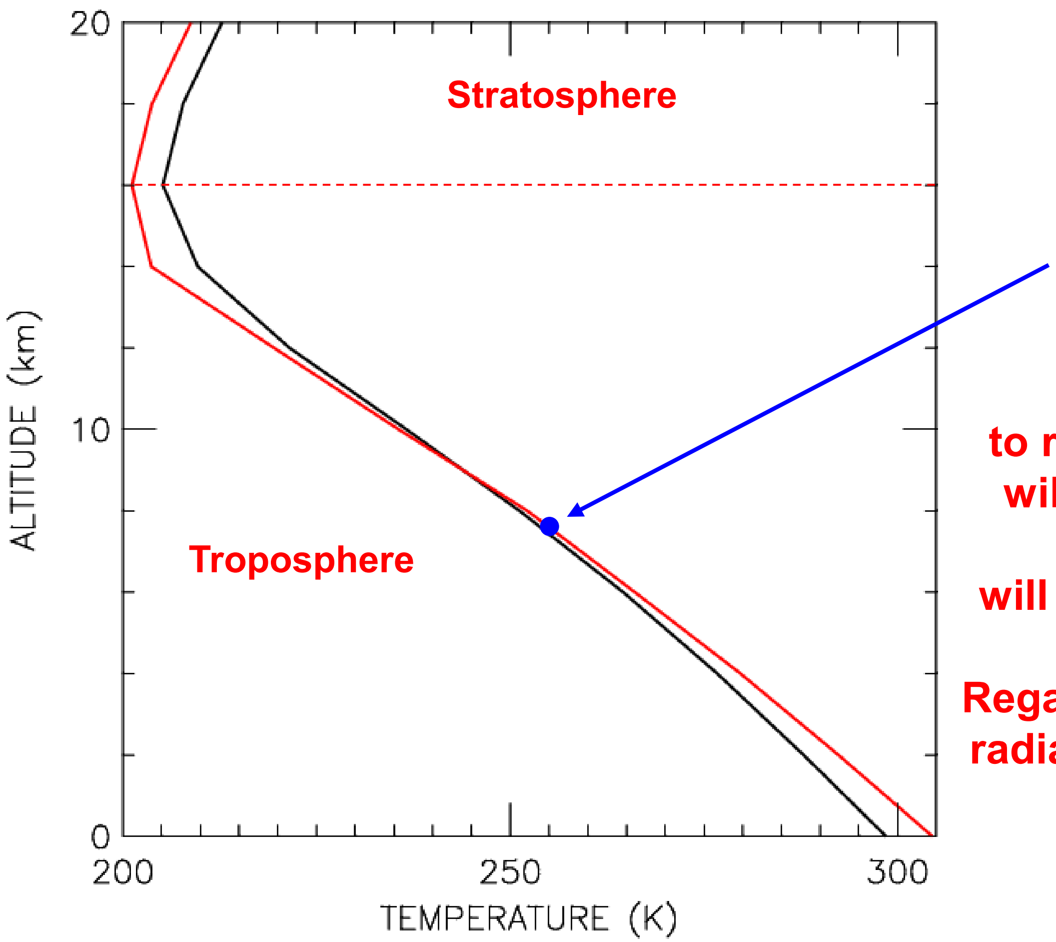


Altitude in troposphere where T = 255 K

Termed Earth's mean radiating altitude to space

Temperature versus Altitude

Let's take a closer look at T_{EFF} = 255 K



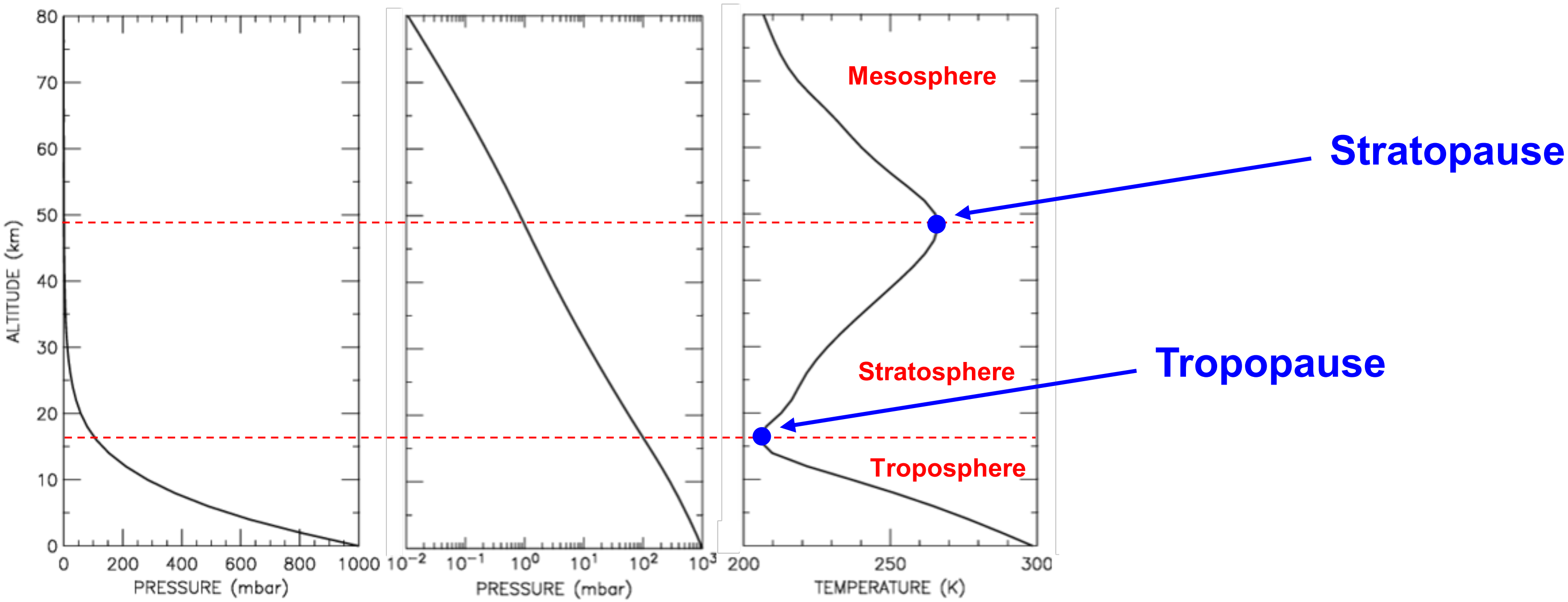
Altitude in troposphere where T = 255 K

Termed Earth's mean radiating altitude to space

As Earth warms in response to rising GHGs, the lower troposphere will warm, the stratosphere will cool, and the mean radiating level will likely rise slightly higher in altitude

Regardless, the temperature of the mean radiating altitude will not change unless

Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

If the troposphere is dry, dT/dz = – *grav* / c_p

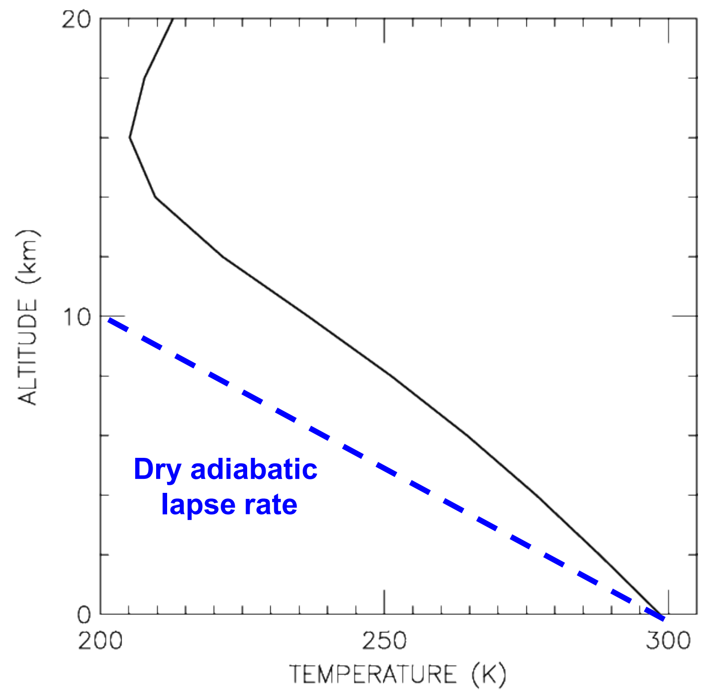
where c_p is specific heat of air at constant pressure = 1×10^7 erg gm^{-1} K^{-1}

Note: 1 erg = 1 dyne cm = gm cm^2 sec^{-2}

⇨ $dT/dz^{DRY} = -\ 981$ cm sec^{-2} / (10^7 cm^2 sec^{-2} K^{-1}) × 10^5 cm/km = 9.8 K / km

Dry adiabatic lapse rate

Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

If the troposphere is dry, $dT/dz = -\,grav\,/\,c_p$

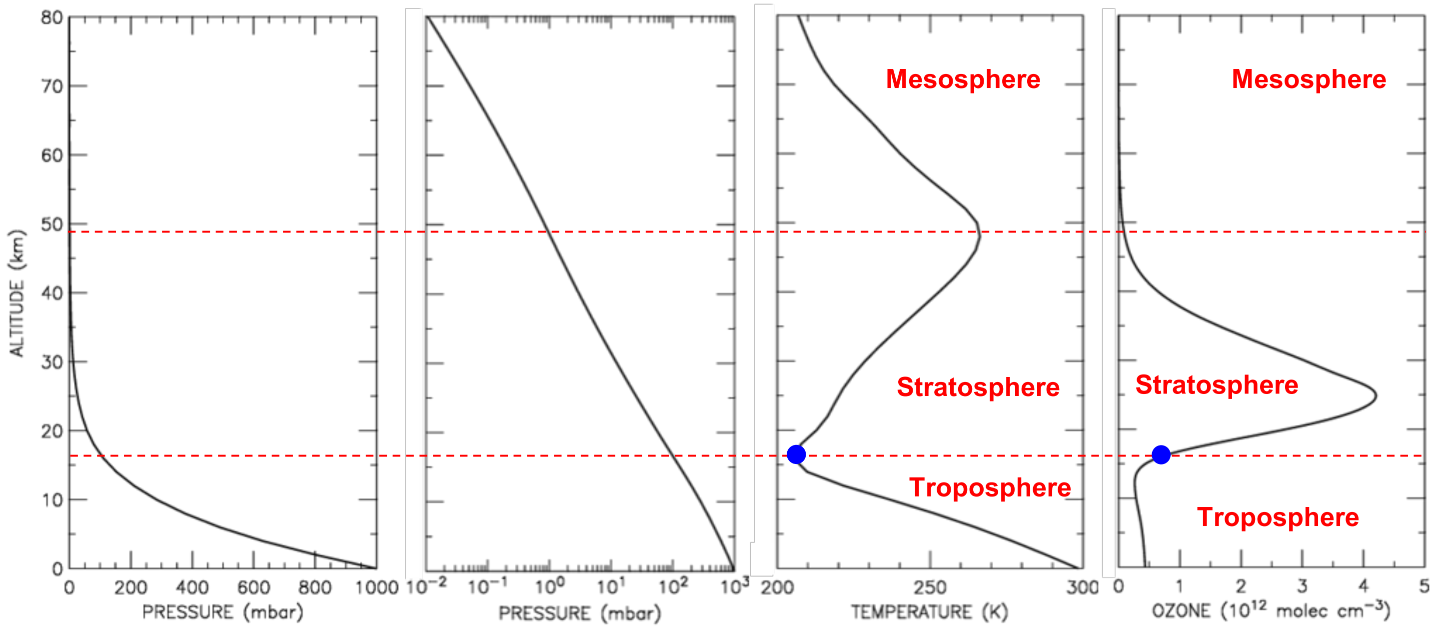
where c_p is specific heat of air at constant pressure = 1×10^7 erg gm^{-1} K^{-1}

Note: 1 erg = 1 dyne cm = gm cm^2 sec^{-2}

⇨ $dT/dz^{DRY} = -\,981\ cm\ sec^{-2} / (10^7\ cm^2\ sec^{-2}\ K^{-1}) \times 10^5\ cm/km = 9.8\ K / km$

Dry adiabatic lapse rate

Temperature versus Altitude

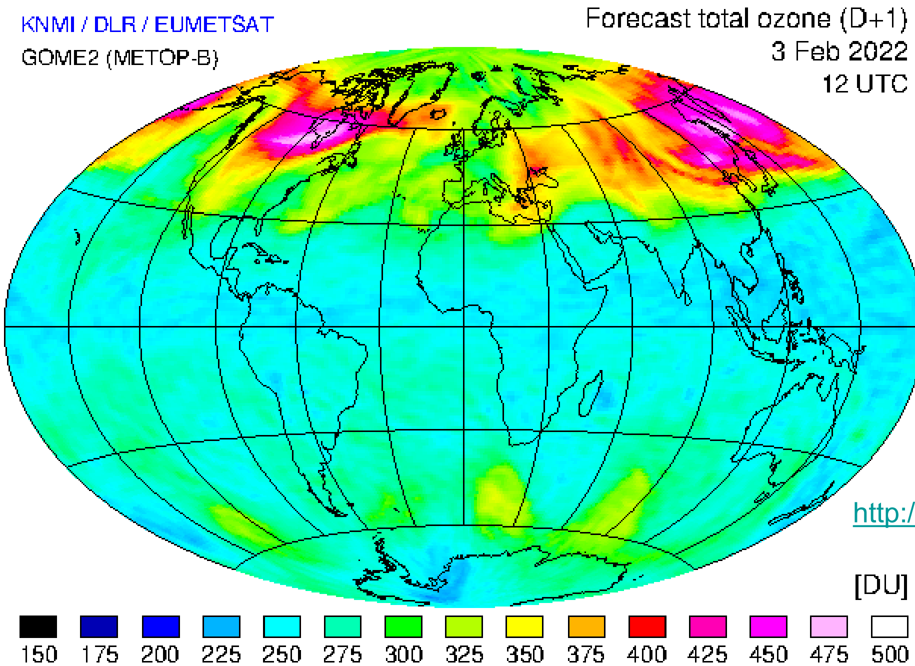


•T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude

Fourth chart expresses abundance of ozone concentration, or ozone density, or $[O_3]$, in units of molecules / cm^3

Back to the ATs

AT3, Q4:
According to *Chemistry in Context*, if all of the ozone in Earth's atmosphere could be isolated and brought to the surface at a pressure of 1 atmosphere and a temperature of 15°C), the resulting gas would have a thickness of how many inches?



http://www.temis.nl/protocols/O3global.html

Mathematically:

$$\text{Ozone Column} = \int_{\text{Ground}}^{\text{Top of Atmosphere}} [O_3(z)]\, dz$$

$$\text{Units}: [O_3(z)] \text{ in } \text{molecule}/\text{cm}^3 \text{ and z in cm, leading to Ozone Column in } \text{molecule}/\text{cm}^2$$

$$\text{Mathematically, } 1 \text{ DU} = 2.687 \times 10^{16} \text{ molecule}/\text{cm}^2$$

Back to the ATs

AT3, Q4:
According to *Chemistry in Context*, if all of the ozone in Earth's atmosphere could be isolated and brought to the surface at a pressure of 1 atmosphere and a temperature of 15^{o}C), the resulting gas would have a thickness of how many inches

AT3, Q5:
If all of the molecules in the entirety of Earth's atmosphere could be isolated and brought to the surface (at a pressure of 1 atmosphere and a temperature of 15^{o}C), the resulting gas would have a thickness of about 7.4 x 10^5 cm. This equals 7.4 km, about 4.6 miles, or 2.9 x 10^5 inches.

The mean mixing ratio of ozone throughout Earth's atmosphere can be found by dividing the answer to Q4 by the thickness of Earth's atmosphere given here, i.e. 2.9 x 10^5 inches.

Compute the mean mixing ratio of ozone throughout Earth's atmosphere (this is a simple ratio of two numbers), **express the answer in parts per billion** (need to understand the meaning of ppb, as explained in Chemistry and Context); then compare your answer to the NAAQS for O_3 given in your answer to either Q1 or Q3.

Specifically:

Is the mean mixing ratio of O_3 throughout Earth's atmosphere larger or smaller than the current U.S. NAAQS for O_3 and then, based on Figure 2.2 from Chemistry in Context, provide an "explanation" to the comparison of these two values for the mixing ratio of O_3?

Mean mixing ratio of ozone:

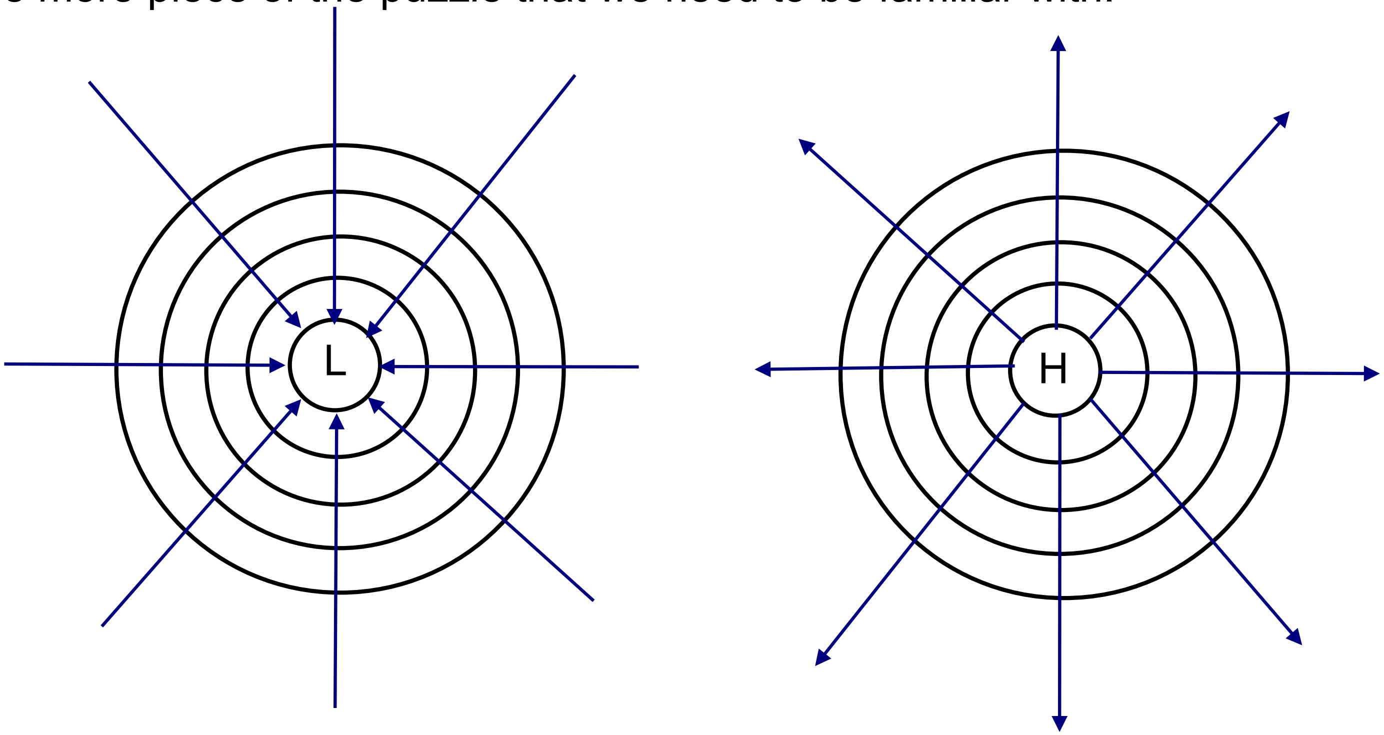
Note: mixing ratio has used throughout this class means number mixing ratio or: $\frac{\text{moles of a particular gas}}{\text{moles of all gases in the air sample}}$

To convert to ppb, need to realize 1 ppb corresponds to: $\frac{\text{1 moles of a particular gas}}{10^9 \text{ moles of all gases in the air sample}}$

Coriolis Force

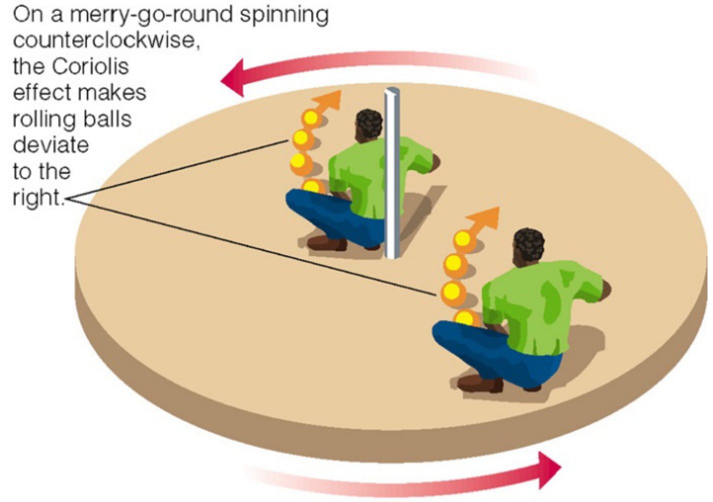
So far, we've reviewed temperature, pressure, and the balance between solar energy input to the atmosphere and terrestrial radiation leaving the atmosphere.

There's one more piece of the puzzle that we need to be familiar with.



In general, air moves from areas of high pressure to areas of low pressure. In the absence of external forces, air will move in a straight line, following pressure gradients

Coriolis Force



© 2005 Pearson Education, Inc., publishing as Addison Wesley

http://lasp.colorado.edu/~bagenal/3720/CLASS15/15EVM-Dyn1.html

Earth's rotation provides an apparent force that deflects air
to the right in the Northern Hemisphere,
to the left in the Southern Hemisphere.

Force is proportional to sin(latitude), so vanishes at the equator

Geostrophy

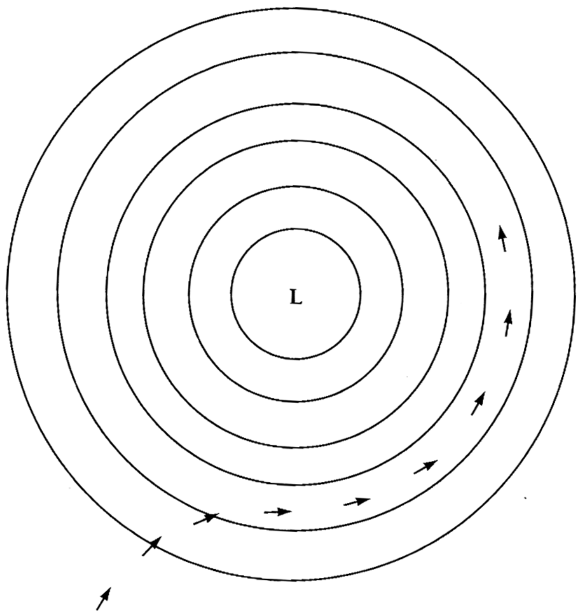


Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

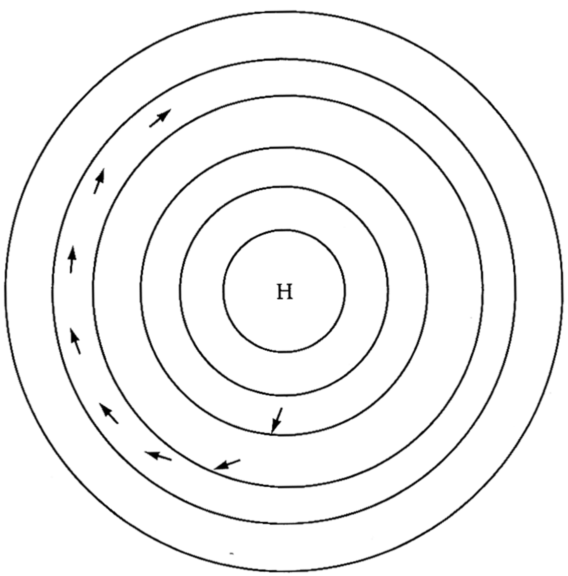


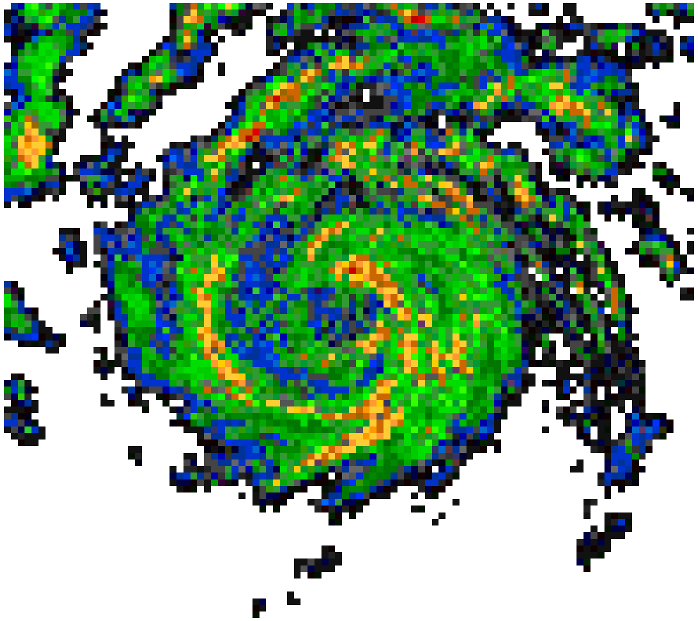
Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

From "The Atmospheric Environment", M. B. McElroy

Geostrophic balance: balance between Coriolis Force and pressure gradient

Geostrophy

NH Weather System:

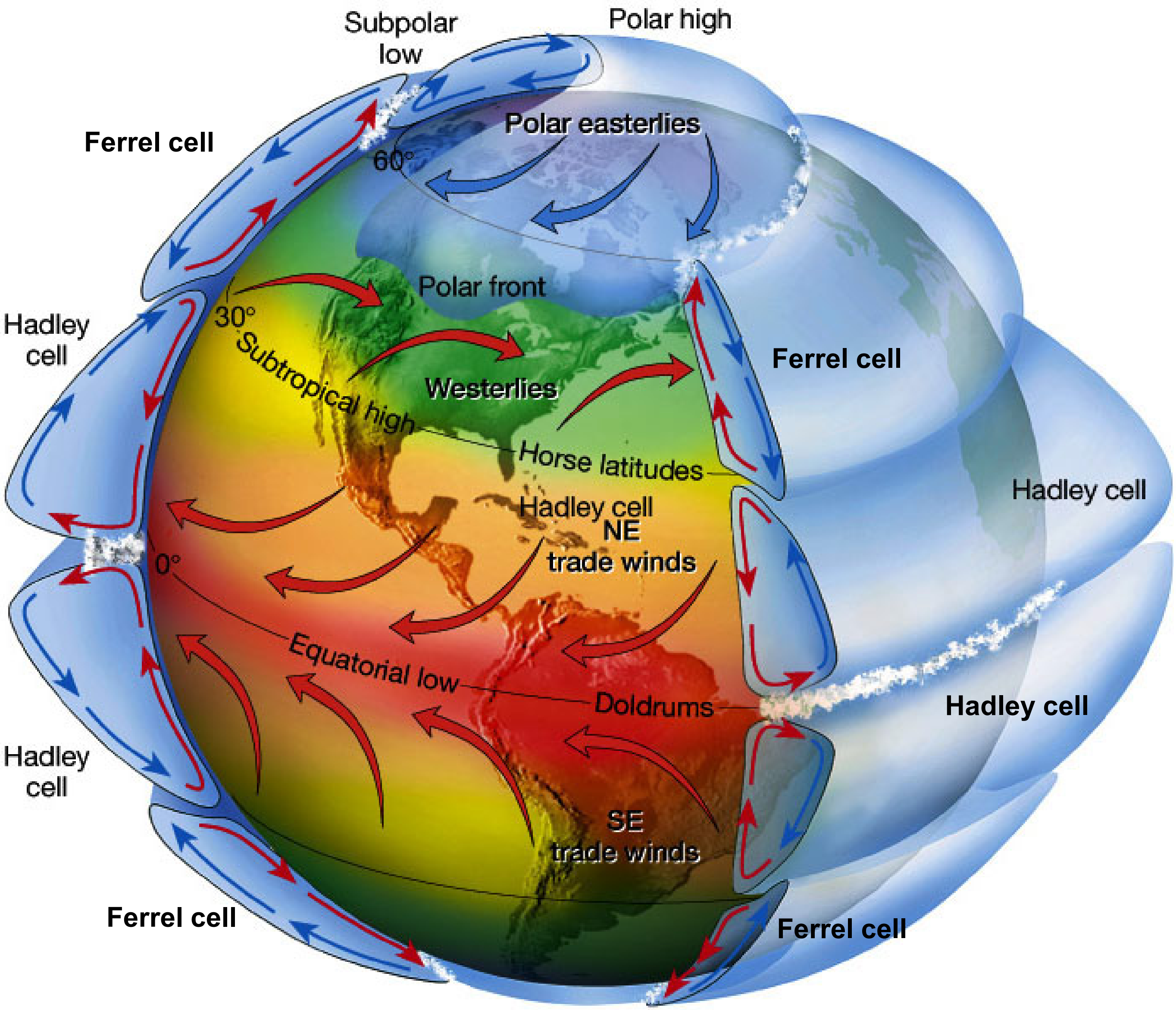


Cyclonic Flow: when the wind swirls
counter-clockwise in the NH

Hurricane: Cyclonic flow occurring in the N Atlantic or NE Pacific Ocean east of the dateline.

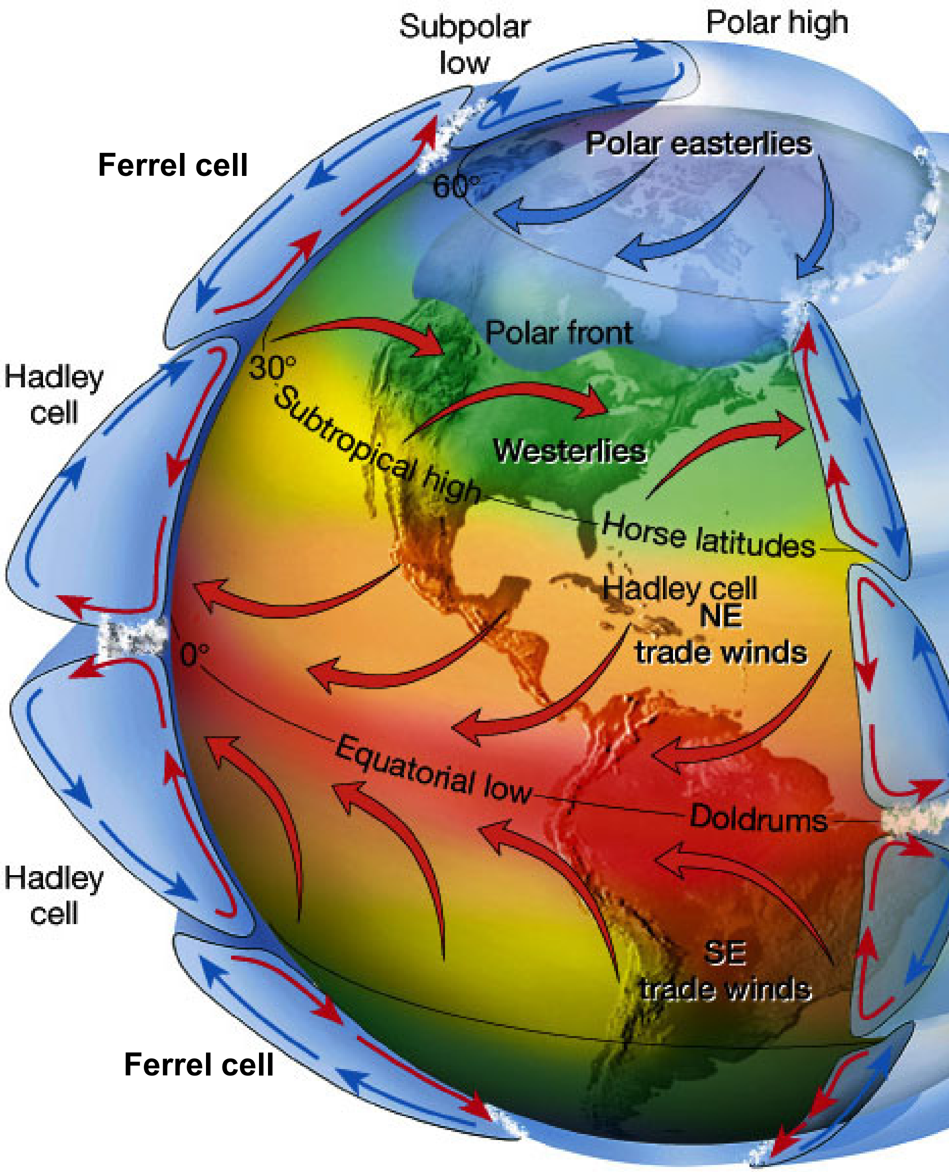
Typhoon: Cyclonic flow occurring in the NW Pacific Ocean, west of the dateline.
Cyclones: Cyclonic flow occurring in the South Pacific and Indian Ocean.

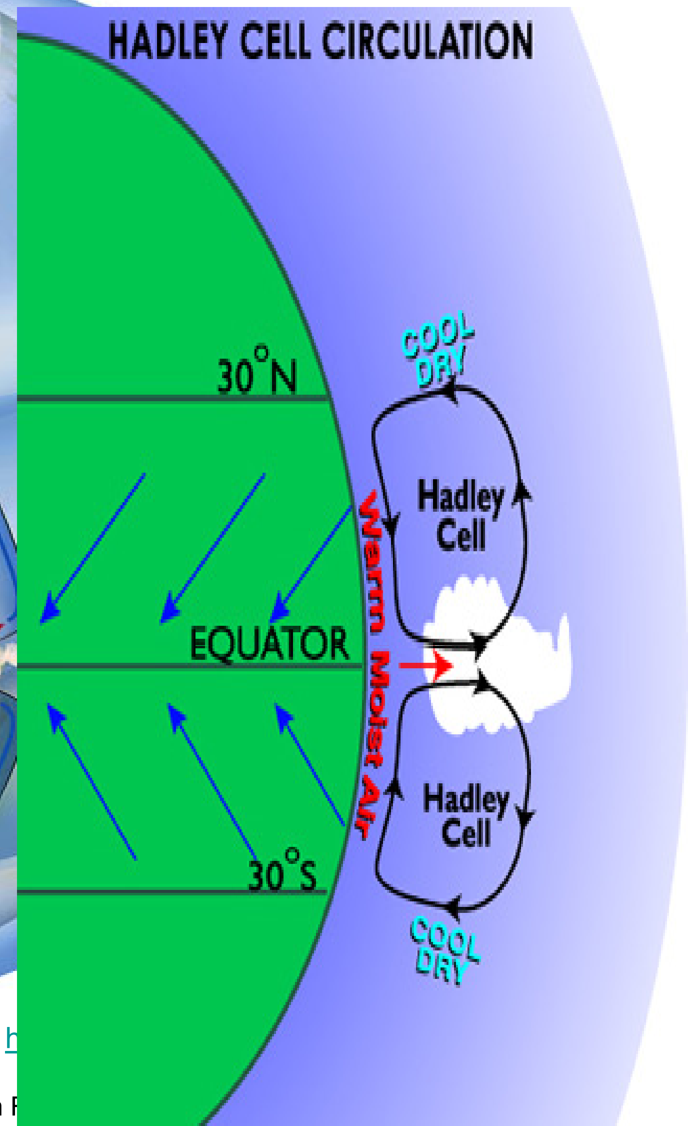
Ferrel Circulation (Modern View)



http://www.ux1.eiu.edu/~cfjps/1400/circulation.html

Ferrel Circulation (Modern View)





h

Next Lecture: Climates of the Past

Next Reading:

Chemistry in Context, Secs 2.2, 3.0, 3.1, 3.2 (~14 pgs)

as well as 8 pages from *Global Warming: The Complete Briefing* by Houghton
7 pages from *Paris Beacon of Hope*

Need to use **ATL2428** to open psswrd protected files

Derivation of the Barometric Law

Assume a sample volume is at rest with respect to vertical motion :

$$p(z) - p(z+\Delta z) = \rho \;\; grav \; \Delta z$$

in other words, the pressure difference between z and $z+\Delta z$

is equal to the weight of air contained in a volume of unit horiz area.

Using calculus:

$$\frac{dp}{dz} = -\rho(z) \; grav$$

Writing the gas law as $p = R_{\mathrm{EARTH}} \; \rho \; \mathrm{T}$

$$\text{where } R_{\mathrm{EARTH}} = 8.3143\times10^{7} \frac{\text{ergs}}{\text{K mole}} \times \frac{\text{mole}}{28.8 \text{ gm}} = 2.87\times10^{6} \text{ ergs/ K gm}$$

and substiting gives:

$$\frac{dp}{dz} = - \frac{p \; grav}{R_{\mathrm{EARTH}} \; \mathrm{T}}$$

Or

$$\frac{dp}{dp} = - \frac{dz}{H} \qquad \text{where } H = \frac{R_{\mathrm{EARTH}} \; \mathrm{T}}{grav}$$

The solution of this ODE is:

$$p(z) \; = \; p(z=0)e^{-z/H}$$