Fundamentals of Earth's Atmosphere

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2017

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 Cell (mean circulation Earth's atmosphere ⇨ climate regimes)

Lecture 3

2 February 2017

Ozone Depletion and Halocarbons

Table Q7-1. Atmospheric Lifetimes and Ozone Depletion Potentials of some halogen source & HFC substitute gases.

Gas	Atmospheric Lifetime (years)	Ozone Depletion Potential (ODP) [c]
Halogen source gases		
Chlorine gases		
CFC-11	45	1
CFC-12	100	0.82
CFC-113	85	0.85
Carbon tetrachloride (CCl_4)	26	0.82
HCFCs	1–17	0.01–0.12
Methyl chloroform (CH_3CCl_3)	5	0.16
Methyl chloride (CH_3Cl)	1	0.02
Bromine gases		
Halon-1301	65	15.9
Halon-1211	16	7.9
Methyl bromide (CH_3Br)	0.8	0.66
Hydrofluorocarbons (HFCs)		
HFC-134a	13.4	0
HFC-23	222	0

continuous

$$\text{ODP (species "}i\text{")} = \frac{\text{global loss of O}_3 \text{ due to unit mass emission of "}i\text{"}}{\text{global loss of O}_3 \text{ due to unit mass emission of CFC-11}}$$

$$\approx \frac{(\alpha\, n_{\mathrm{Br}} + n_{\mathrm{Cl}})}{3} \; \frac{\tau_i}{\tau_{\text{CFC-11}}} \; \frac{MW_{\text{CFC-11}}}{MW_i}$$

continuous

where :

τ is the global atmospheric lifetime

MW is the molecular weight

n is the number of chlorine or bromine atoms

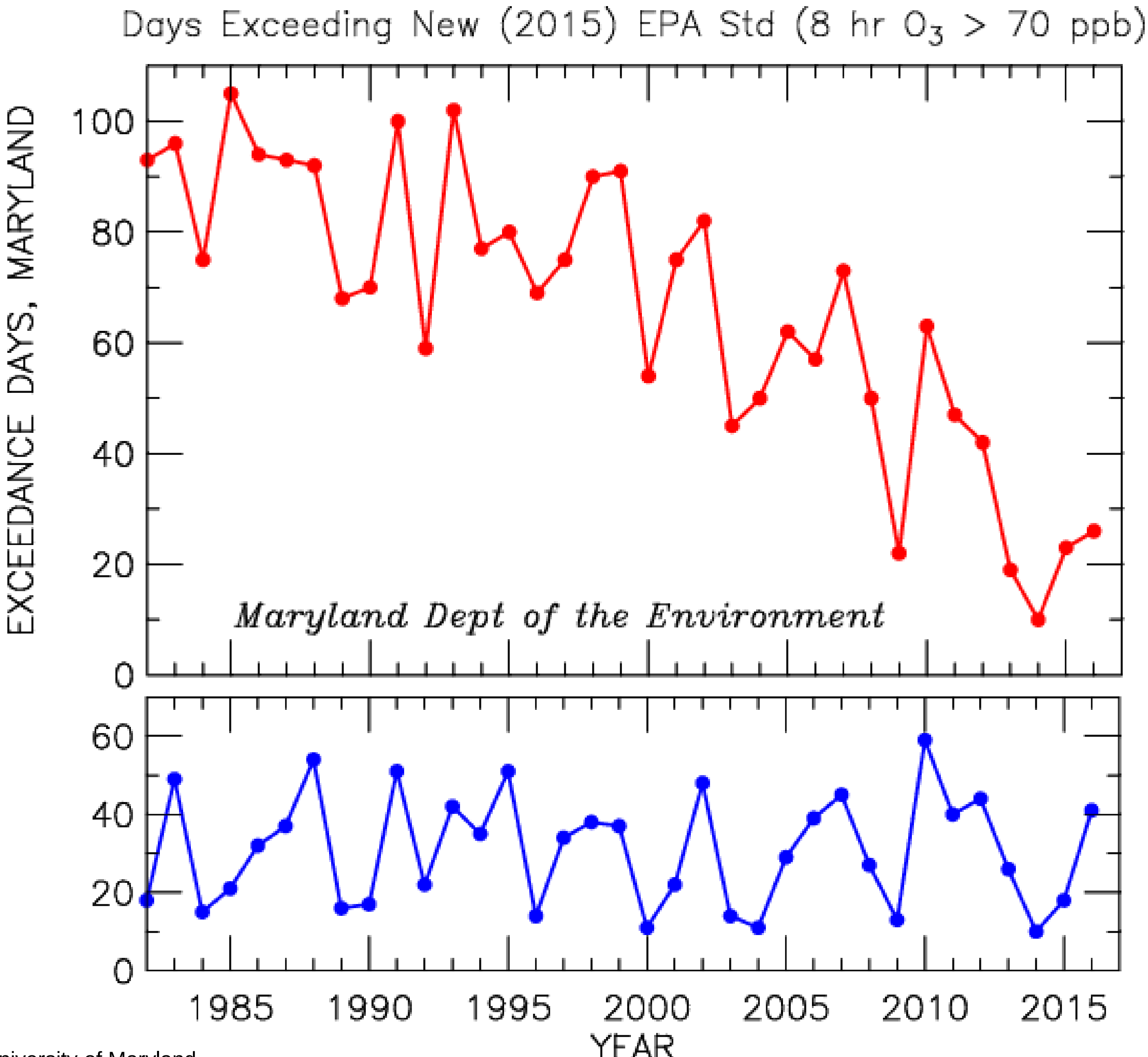
α is the effectiveness of ozone loss by bromine relative to ozone loss by chlorine

$\alpha = 60$

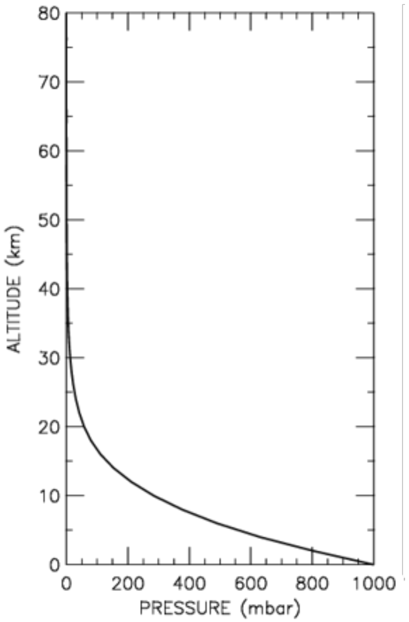
Halons (anthropogenic halocarbons containing bromine) much worse for ozone than CFCs (anthropogenic halocarbons containing chlorine)

HFCs (anthropogenic halocarbons containing only fluorine, carbon, and hydrogen) and thus pose no threat to the ozone layer

Significant Improvements in *Local* Air Quality since early 1980s

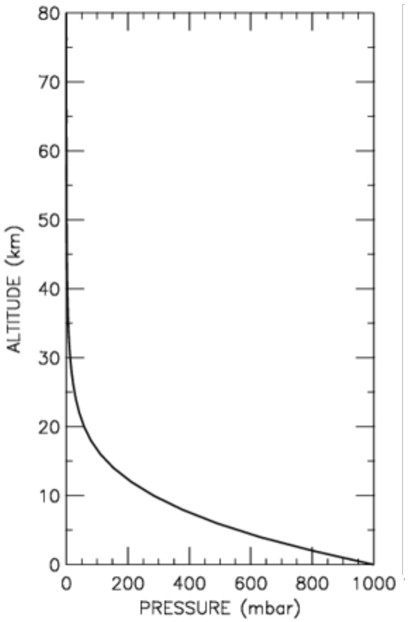


Pressure versus Altitude



- **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



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

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

where H is called the "scale height"

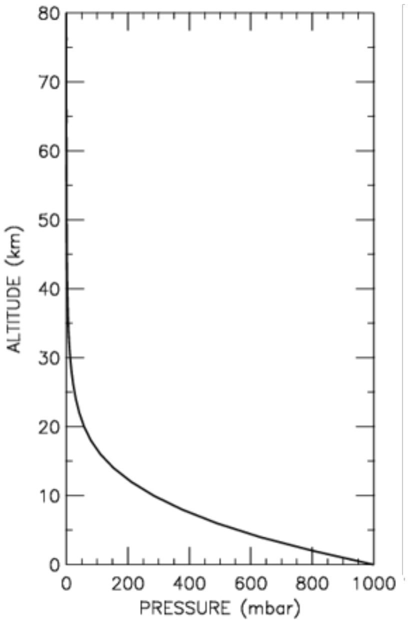
Can show H = R_{EARTH} T (z) / *grav* ,

where R_{EARTH} = $R_{UNIVERSAL}$ / $MW_{EARTH\ ATMOS}$

= 8.3143 $\times$ 10^7 ergs / K mole / (28.8 gm / mole)

= 2.88 $\times$ 10^6 ergs / K gm

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 ($8.3143 \times 10^{7} \; \frac{\text{ergs}}{\text{K mole}}$), and T is temperature.

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

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

where H is called the "scale height"

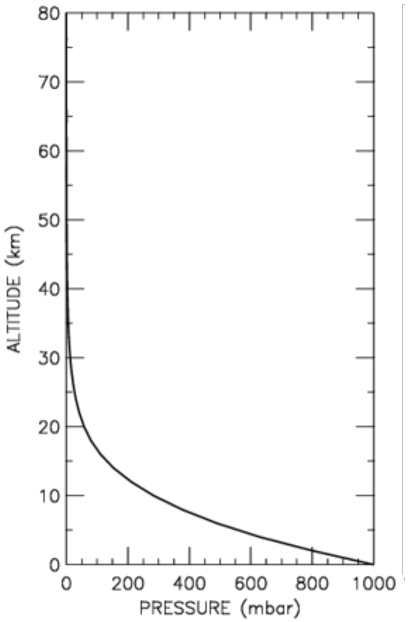
Can show H = R_{EARTH} T (z) / *grav* ,

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

***grav* = 981 cm sec^{-2} and T(lower trop) $\approx$ 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 $1.38 \times 10^{-19}\ \frac{\text{mbar cm}^3}{\text{K molecules}}$

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

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

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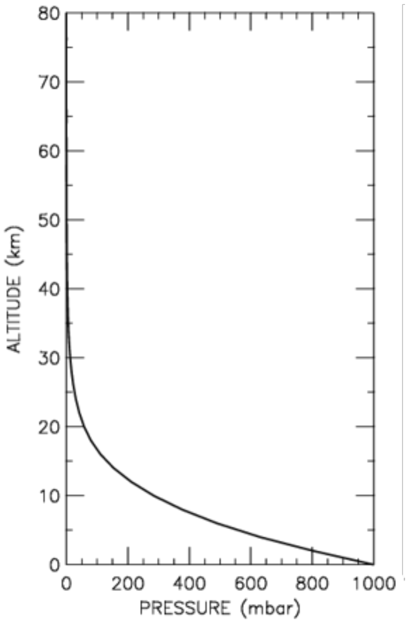
Pressure versus Altitude

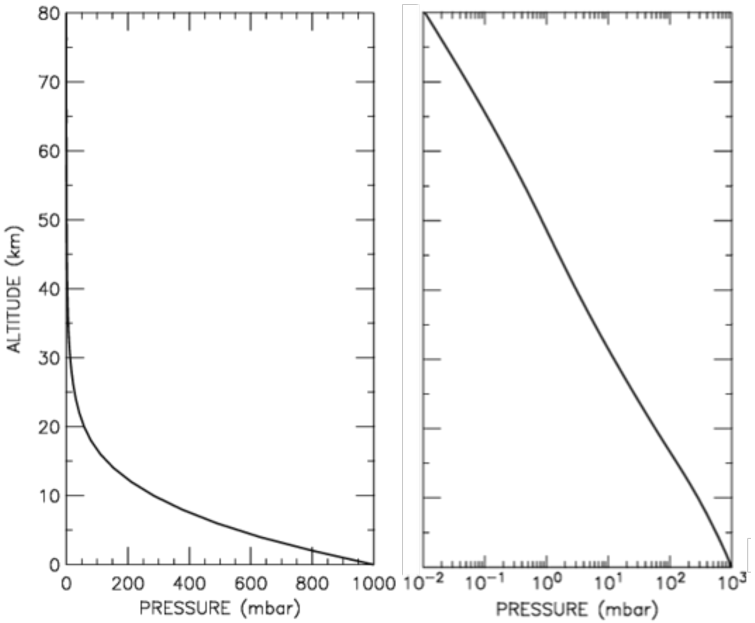


- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

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

What is a "more natural" way to display pressure as a function of altitude?

Pressure versus Altitude

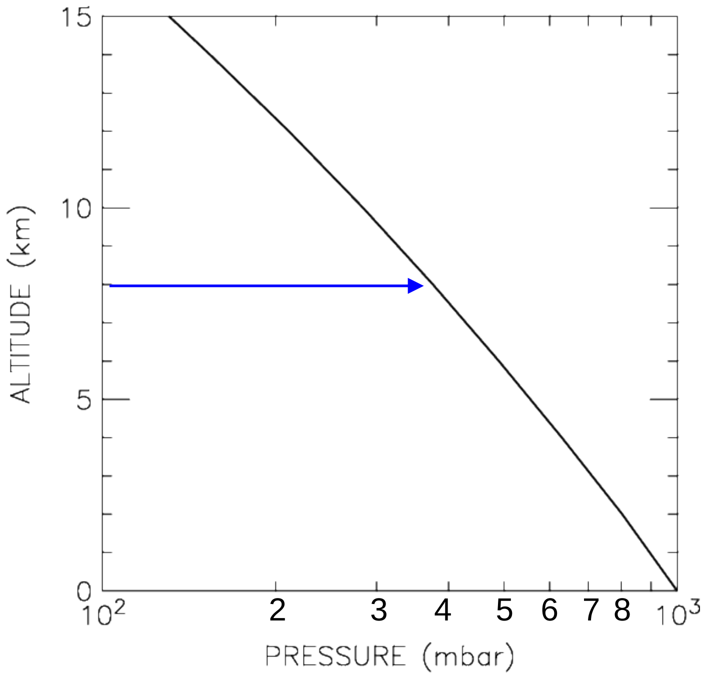


- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

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

Two plots convey the same information !

Pressure versus Altitude



p (z=0) = 1013.25 mbar

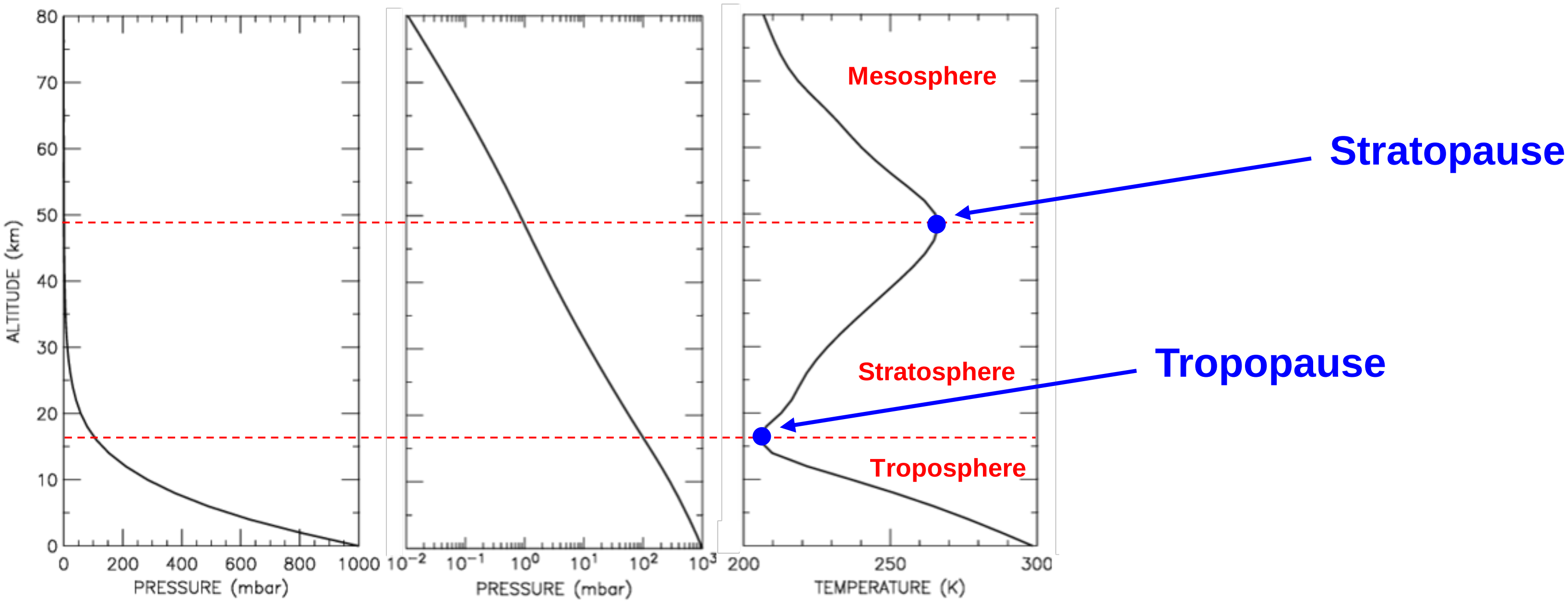
p (z=8 km) =

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

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

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

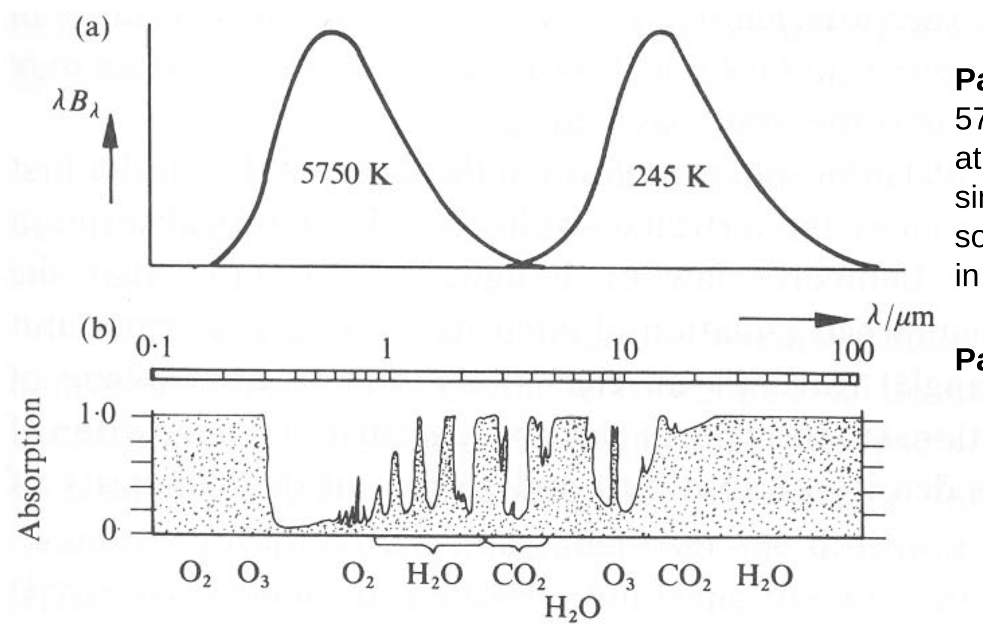
Temperature versus Altitude



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

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

My Favorite Planets

Venus:
$T_{SURFACE} \approx 753$ K

$T_{EFFECTIVE} \approx$???

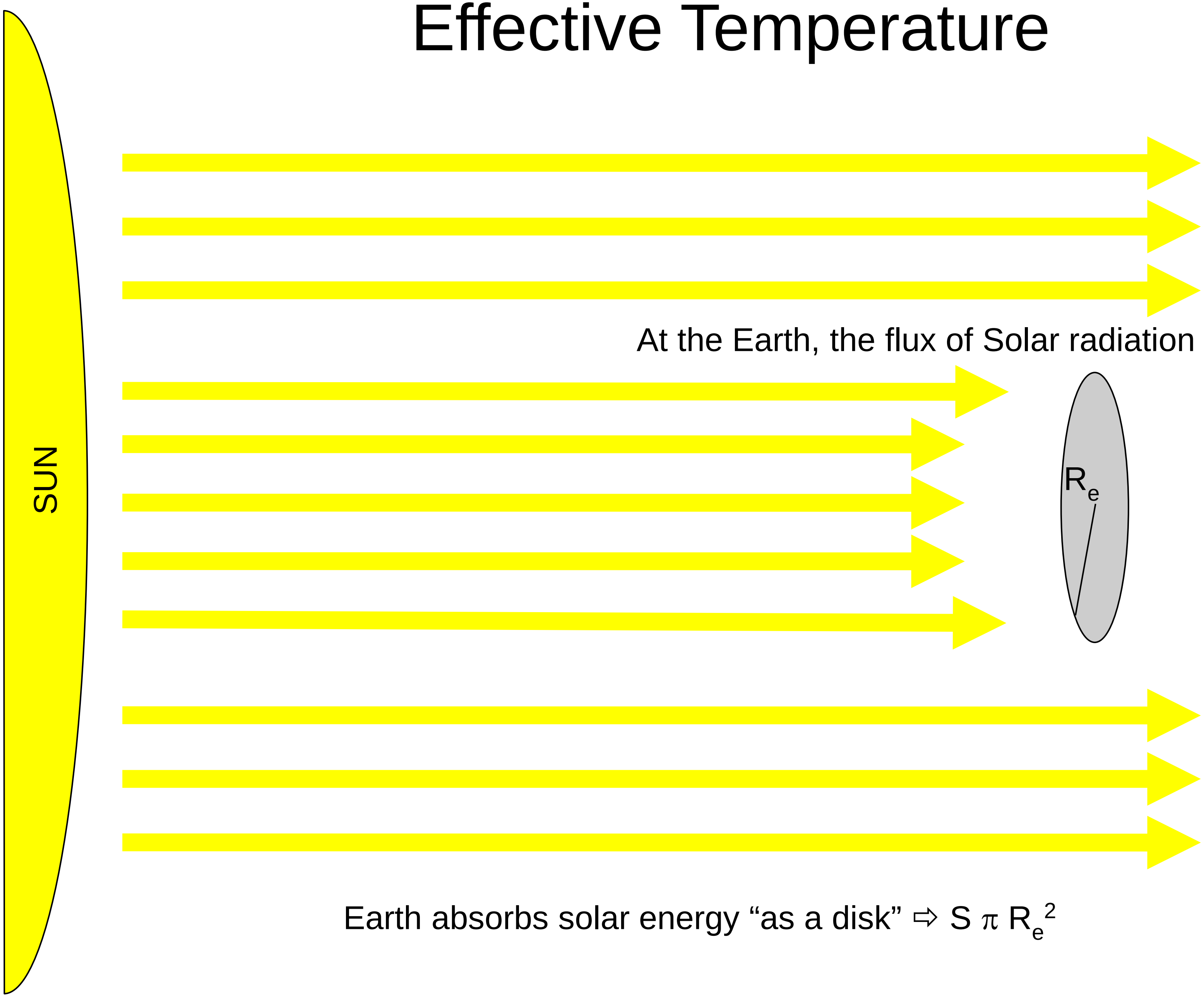
Earth:
$T_{SURFACE} \approx 288$ K

$T_{EFFECTIVE} \approx$???

Mars
$T_{SURFACE} \approx 217$ K

$T_{EFFECTIVE} \approx$???

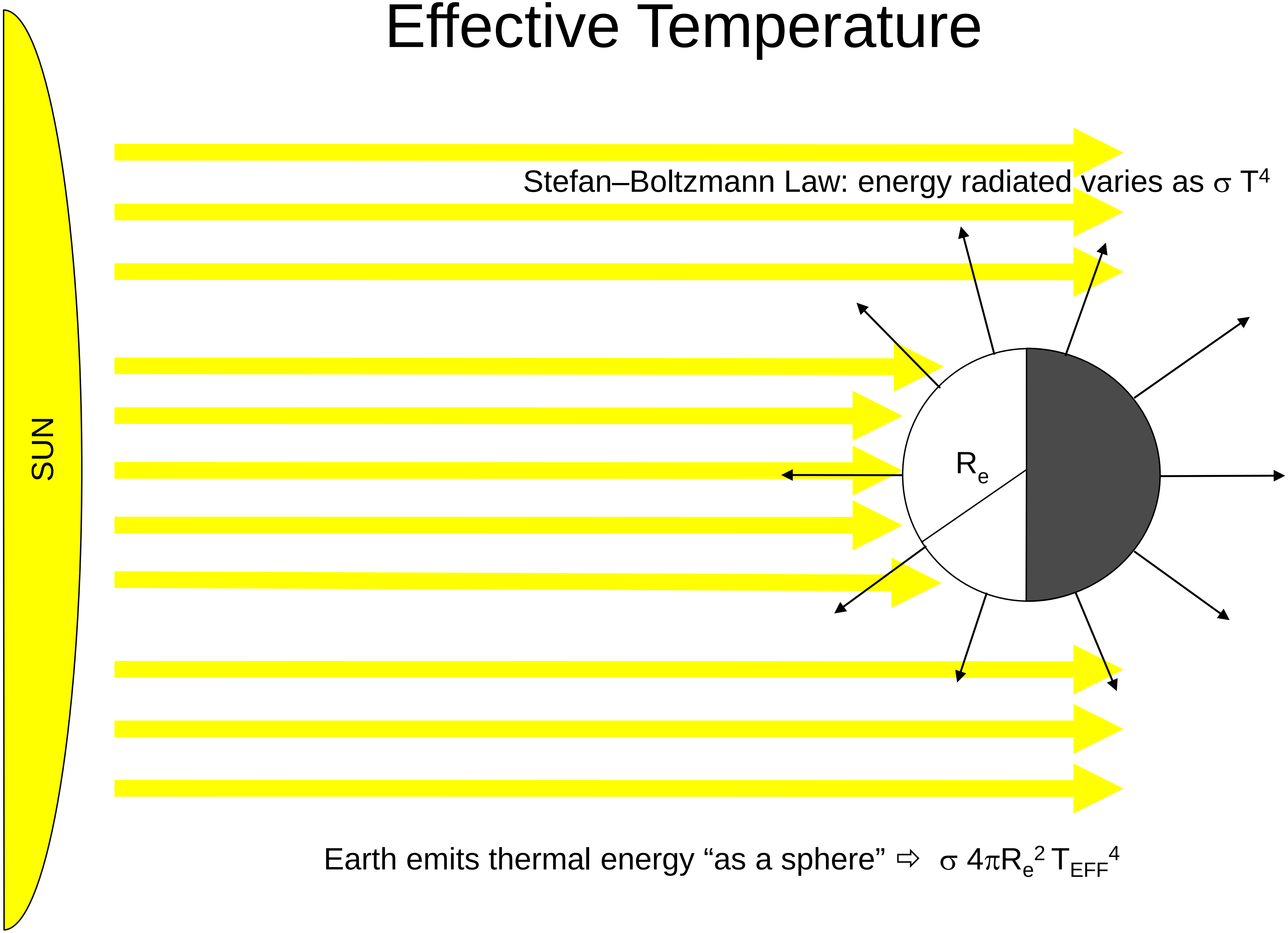
Effective Temperature



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" ⇨ $S \pi R_e^2$

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

$$S \pi R_e^2 = \sigma 4\pi R_e^2 T_{EFF}^4$$

or

$$S = 4 \sigma T_{EFF}^4$$

What have we left out of the formula for T_{EFF} ?

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" ⇨ $\sigma\ 4\pi R_e^2\ T_{EFF}^4$

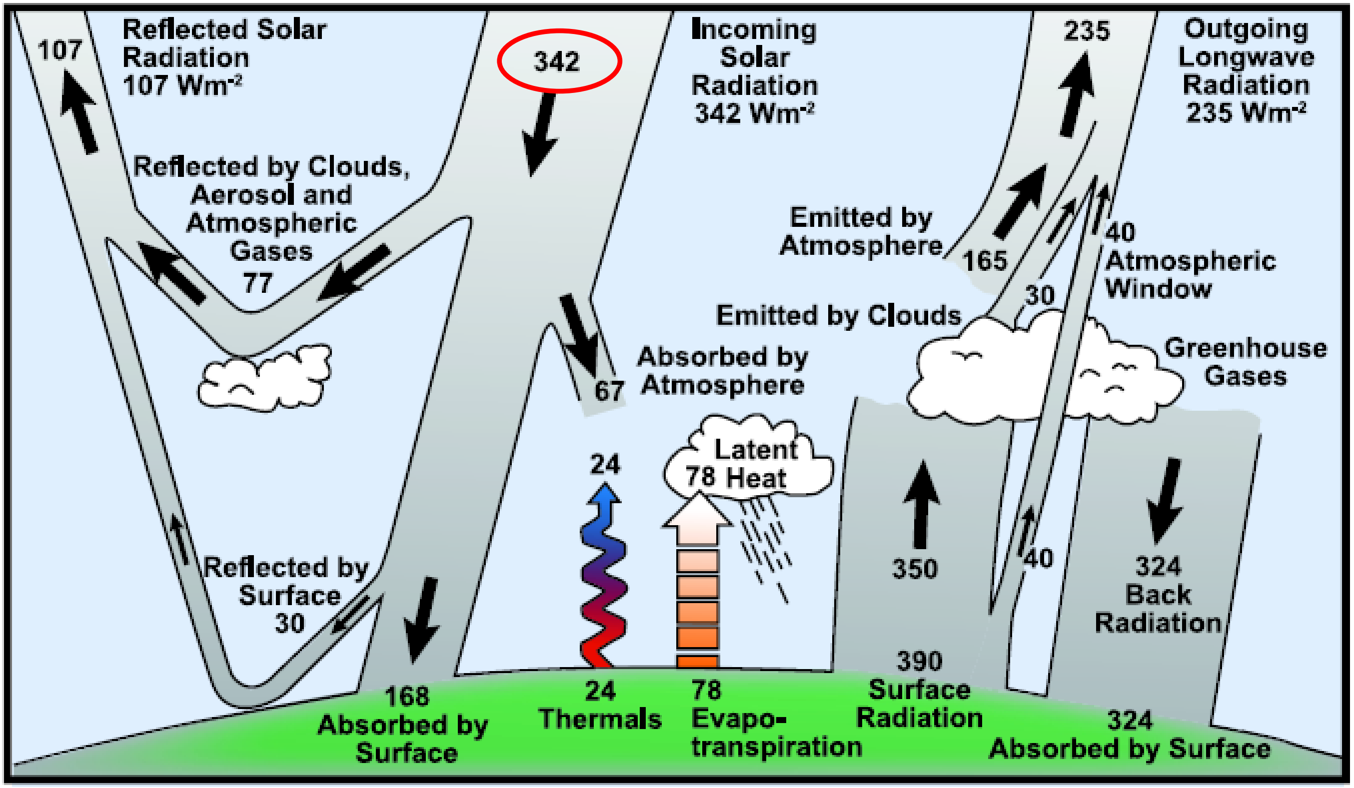
$$(1 - \text{Albedo}) \times S = 4\ \sigma\ T_{EFF}^4$$

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}



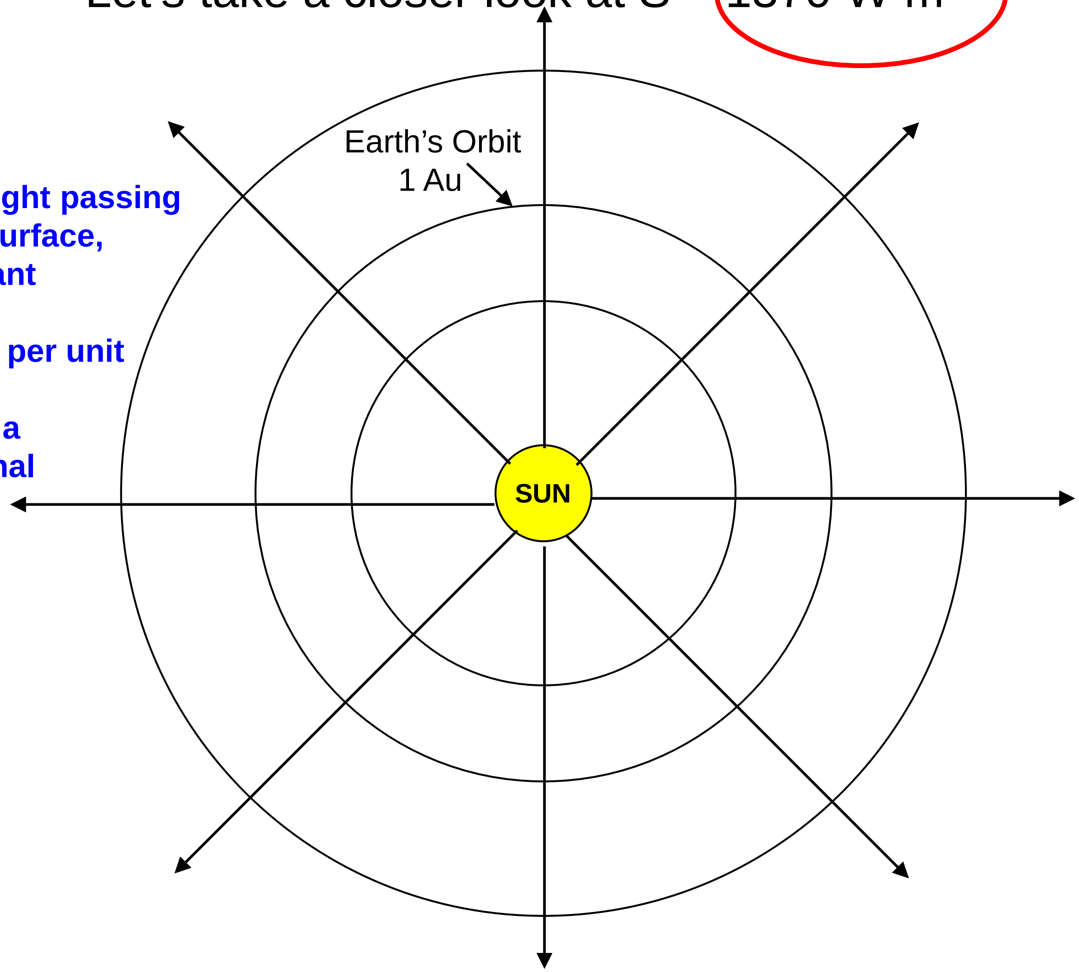
FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

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.

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

433 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

633 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

633 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}

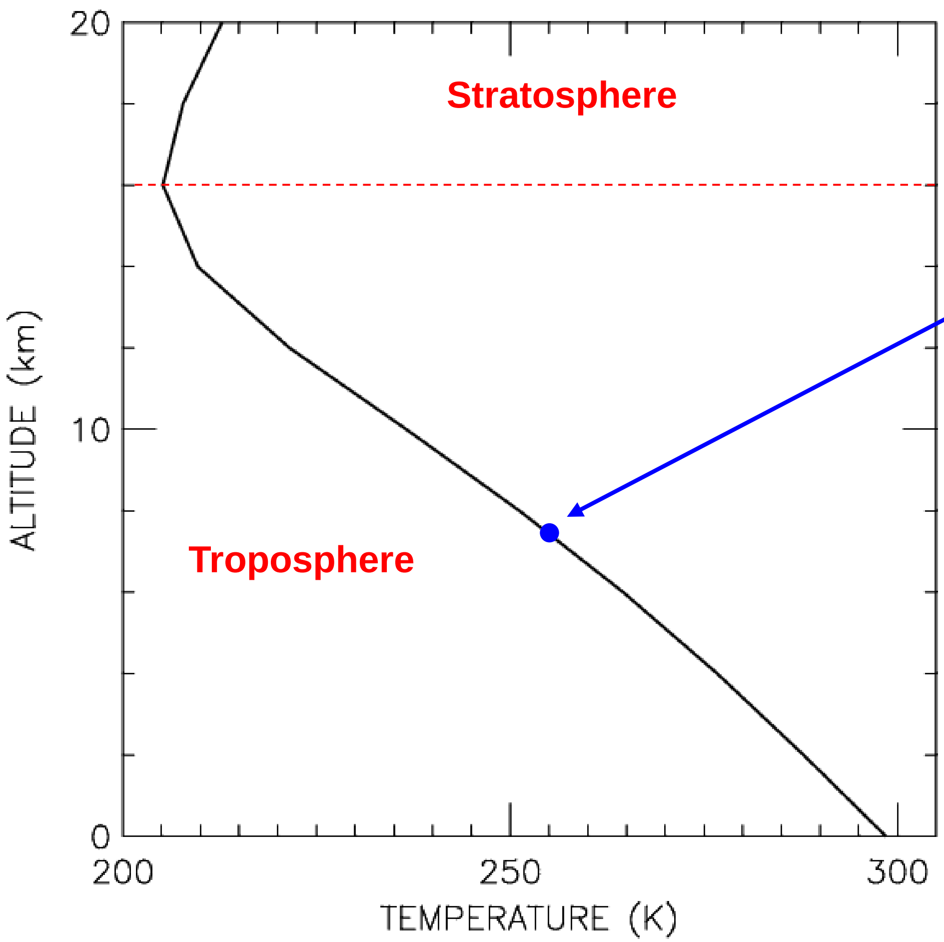
$S = 1370$ W m^{-2}

Albedo = 0.75

Distance from Sun = 0.72 AU

Temperature versus Altitude

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

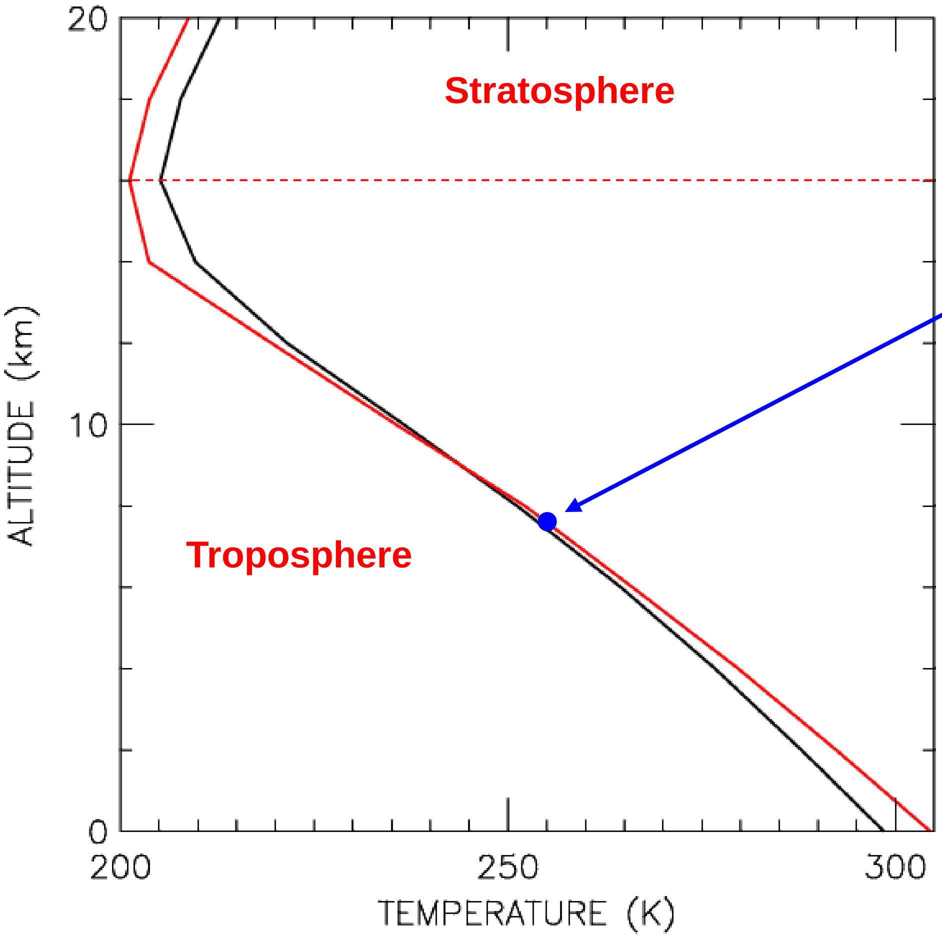


Altitude in troposphere where T = 255 K

Termed Earth's mean radiating altitude to space

Temperature versus Altitude

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



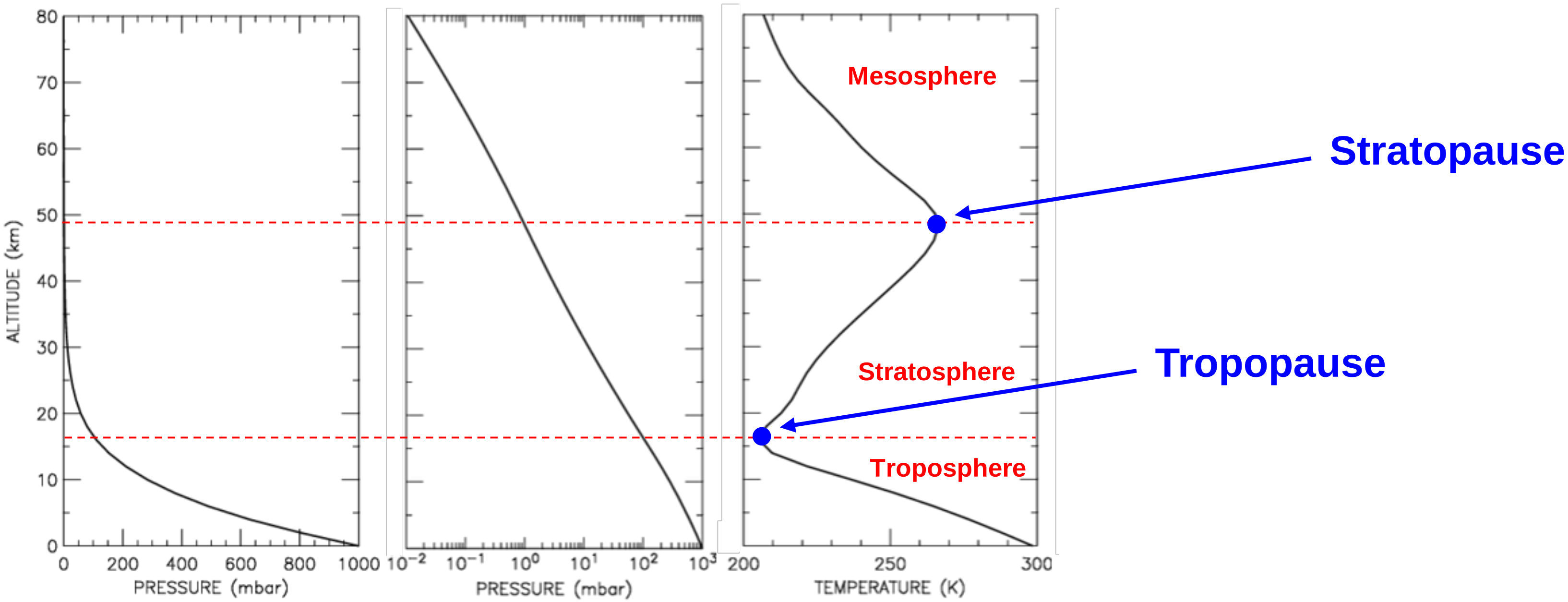
Altitude in troposphere where T = 255 K

Termed Earth's mean radiating altitude to space

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

Regardless, the T of the mean radiating altitude will not change

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

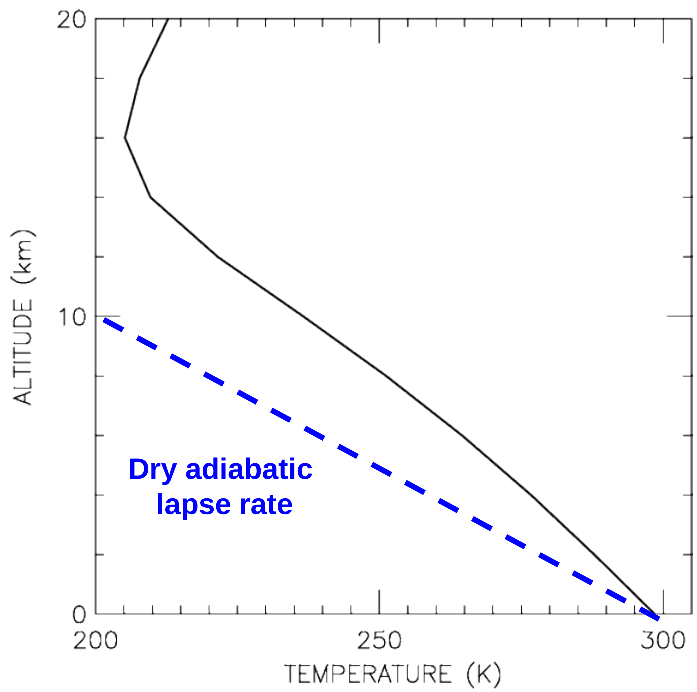
where c_p is specific heat of air at constant pressure = 1×10^7 erg gm^{-1} K^{-1}

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



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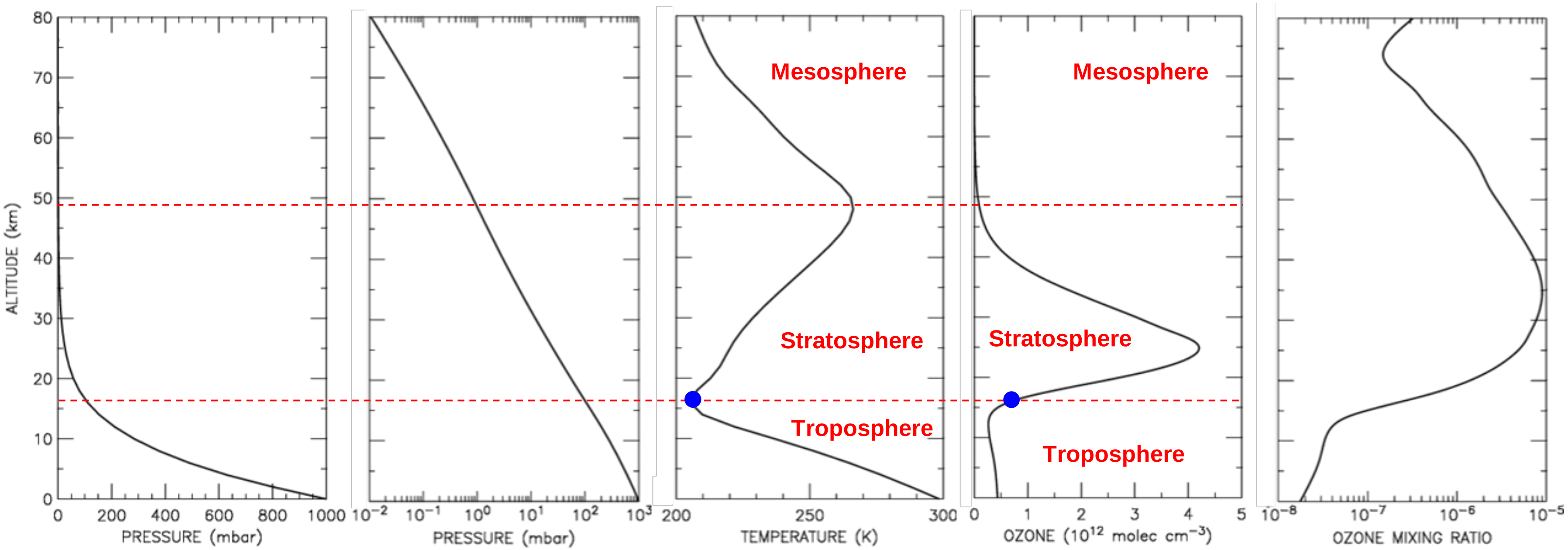
Dry adiabatic lapse rate

Temperature versus Altitude



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

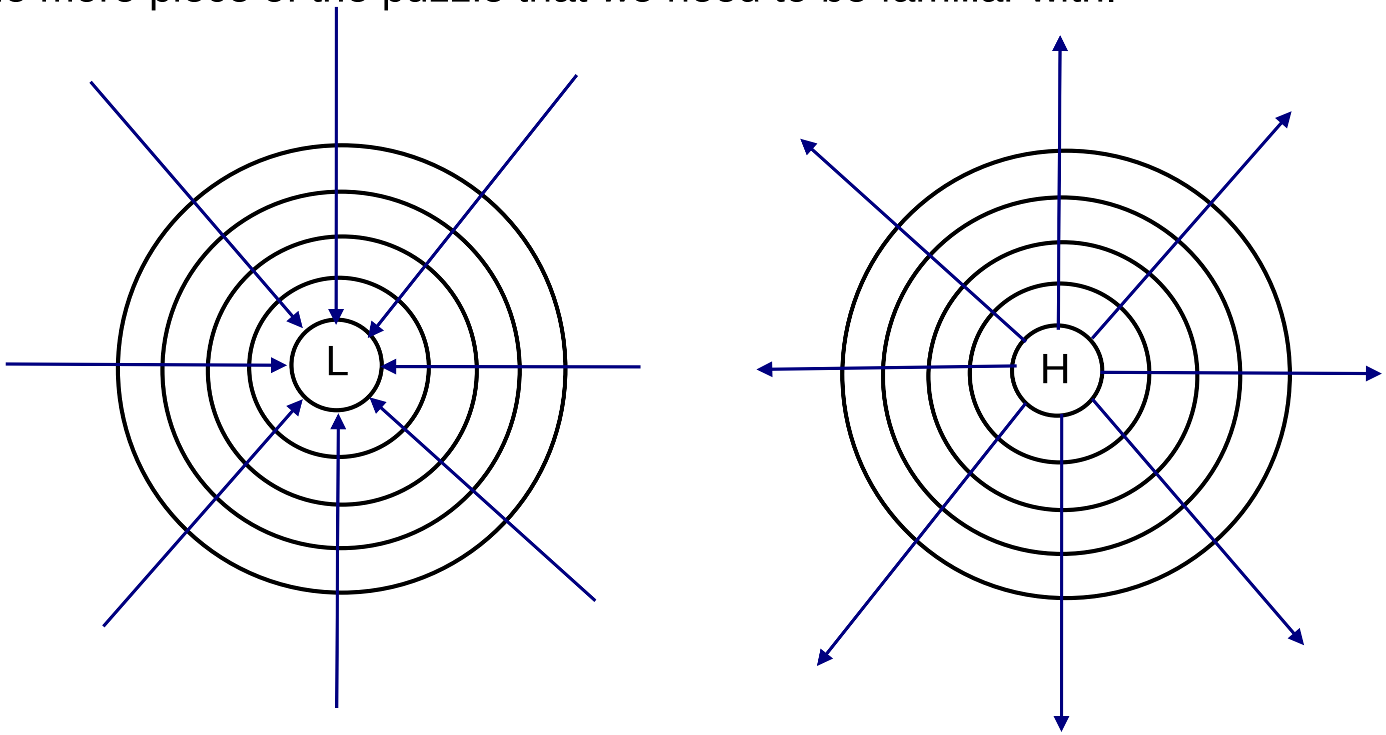
Fourth chart expresses abundance of ozone concentration, or ozone density, or $[O_3]$, in units of molecules / cm^3

Chart on far right expresses ozone mixing ratio, O_3 mr in dimensionless units, where O_3 mr = $[O_3]$ / [M] , where [M] is the concentration (or density) of air

Coriolis Force

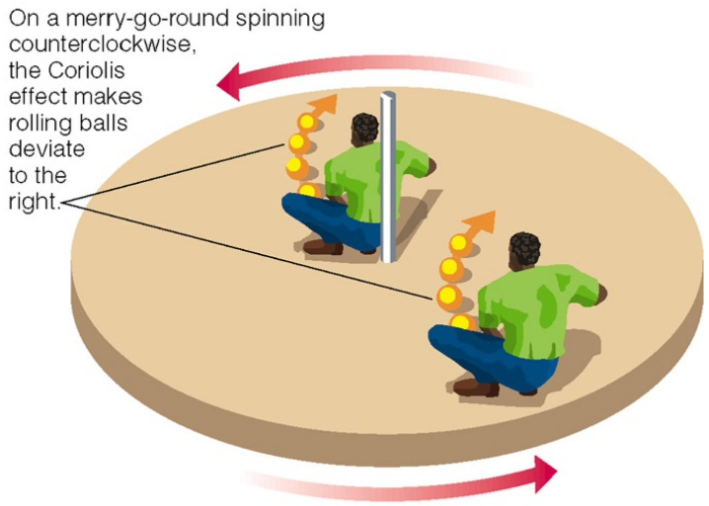
So far, we've reviewed temperature, pressure, and the balance between solar energy input to the atmosphere and terrestrial radiation leaving the atmosphere.

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



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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

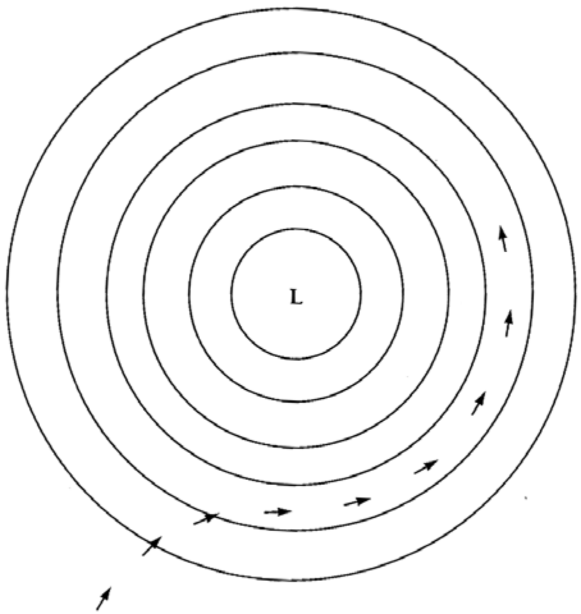


Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

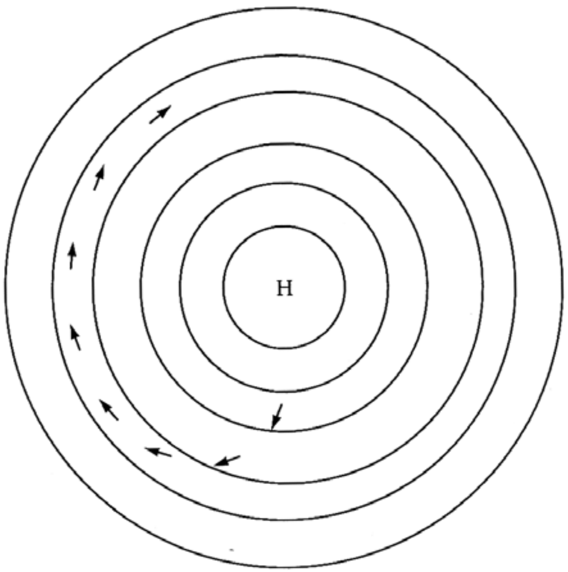


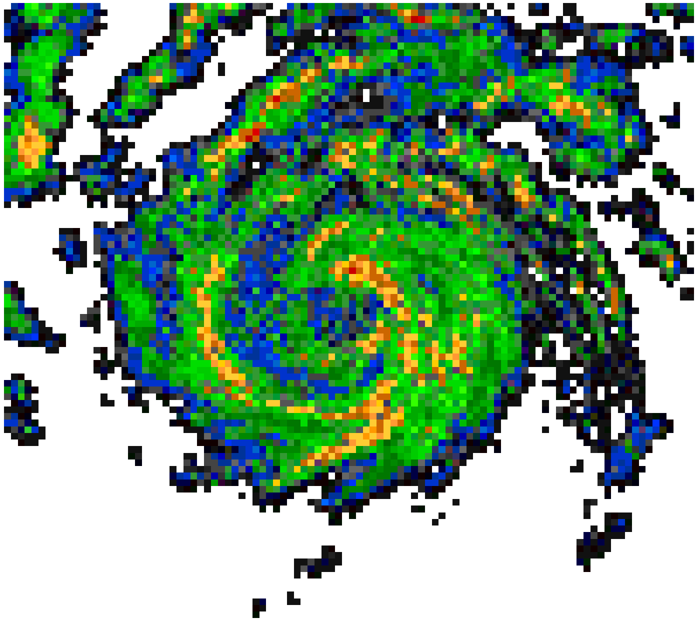
Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

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

Geostrophic balance: balance between Coriolis Force and pressure gradient

Geostrophy

NH Weather System:

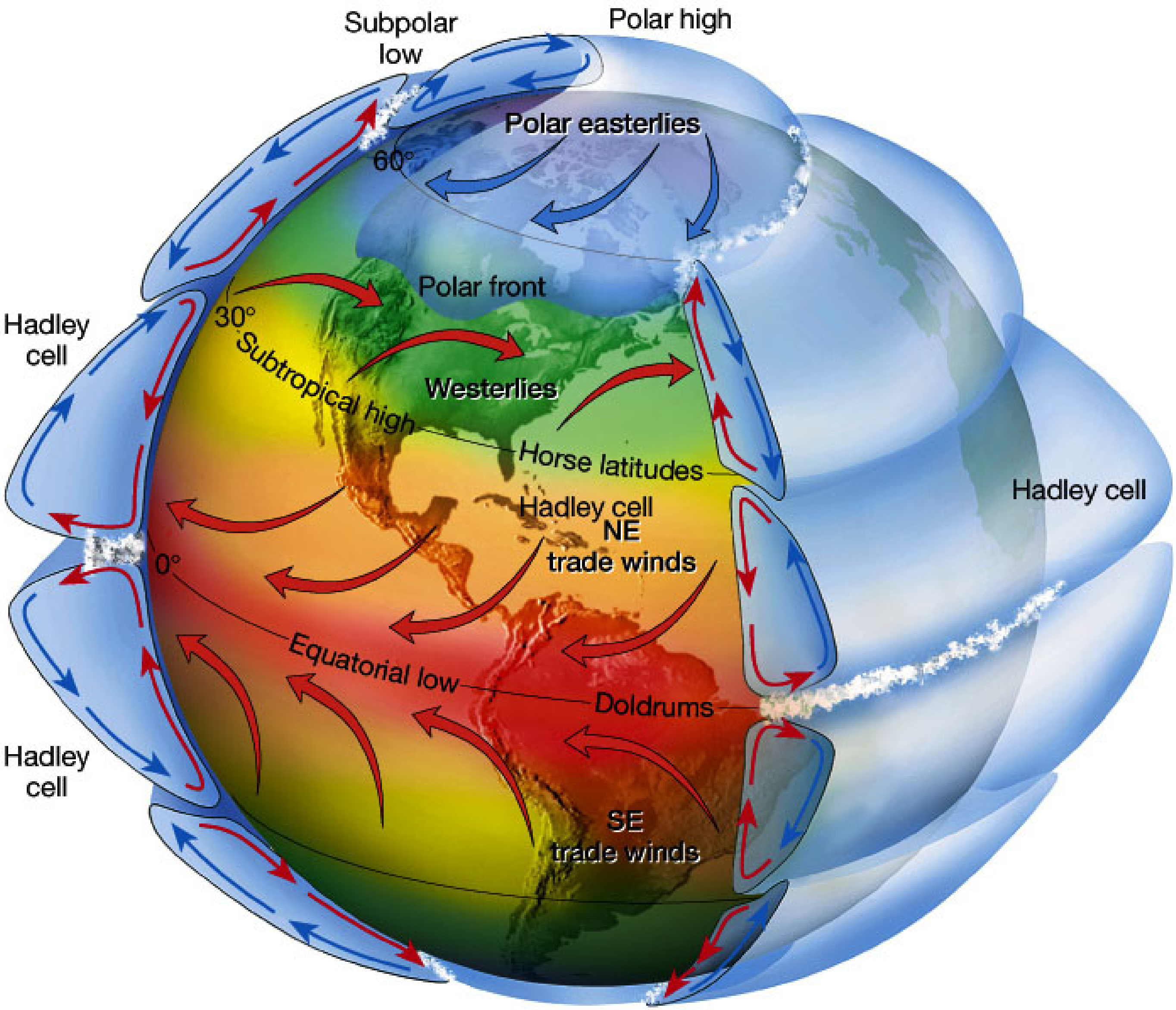


Cyclonic Flow: when the wind swirls
counter-clockwise in the NH

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

Typhoon: Cyclonic flow occurring over the NW Pacific Ocean, west of the dateline.

Ferrel Circulation (Modern View)



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

Next Lecture: Climates of the Past

Next Reading:

Chemistry in Context, Secs 2.2, 3.0, 3.1, 3.2 (~17 pgs)

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

Also, you are responsible for reading all of Chapter 1, *Paris Beacon of Hope* (minus Methods) prior to the first exam, which is penciled in for 28 Feb

Need to use css2416 to open psswrd protected files

Problem Set #1, due 14 Feb, is posted on the class website

The Barometric Law

Extra Slide #1

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 $p = R_{\mathrm{EARTH}} \; \rho \; \mathrm{T}$

$$\text{where } R_{\mathrm{EARTH}} = 8.3143 \times 10^7 \, \frac{\text{ergs}}{\text{K mole}} \; \times \frac{\text{mole}}{\text{28.8 gm}} \; = 2.87 \times 10^6 \, \text{ergs/ K gm}$$

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:

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