Fundamentals of Earth's Atmospheric Structure & Circulation

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2022
https://umd.instructure.com/courses/1327017

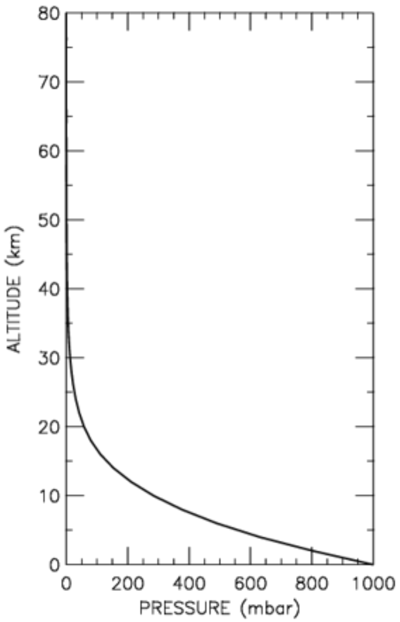
Goals:

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

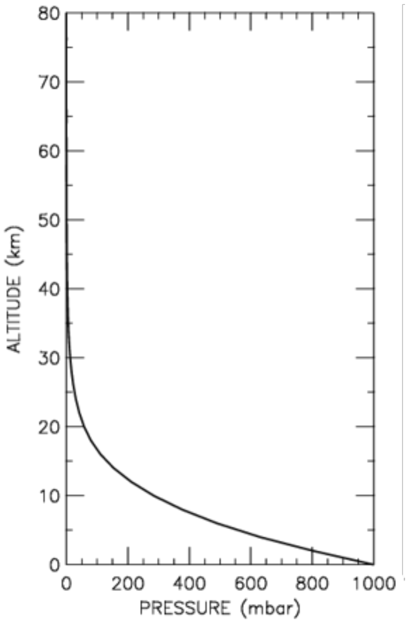
8 September 2022

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) $\times\ e^{-z/H}$

where H is called the "scale height"

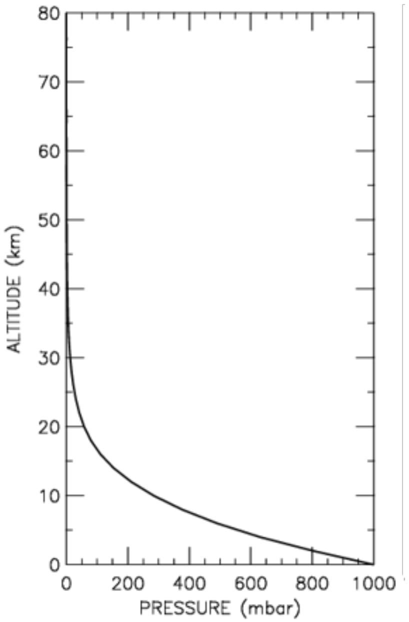
Can show H = R_{EARTH} T (z) / *grav* ,

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

***grav* = 981 cm sec^{-2} and T(lower trop) ≈ 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) $\times$ $e^{-z/H}$

where H is called the "scale height"

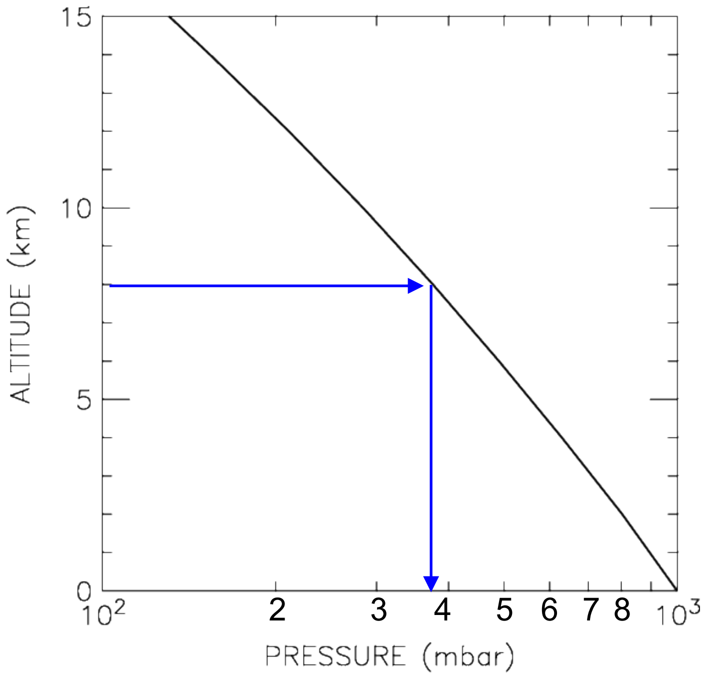
Can show H = R_{EARTH} T (z) / *grav* ,

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



p (z=0) = 1013.25 mbar

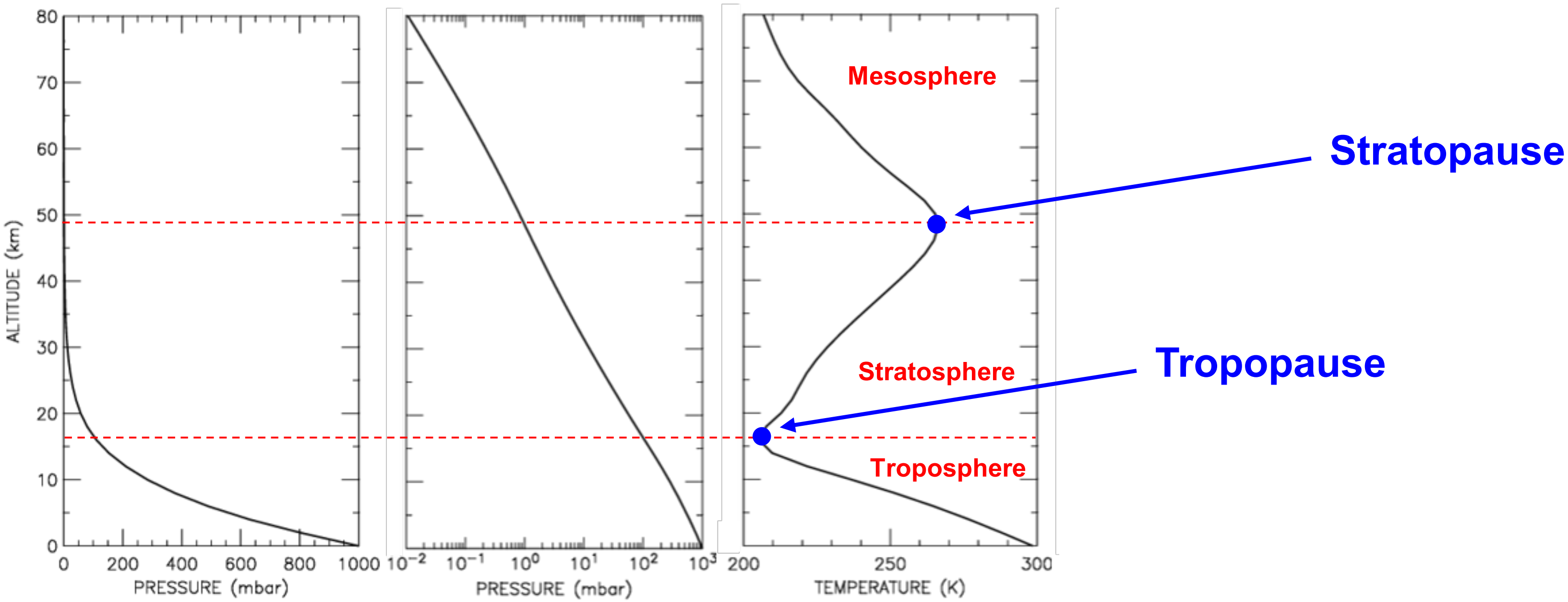
p (z=8 km) =

- **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

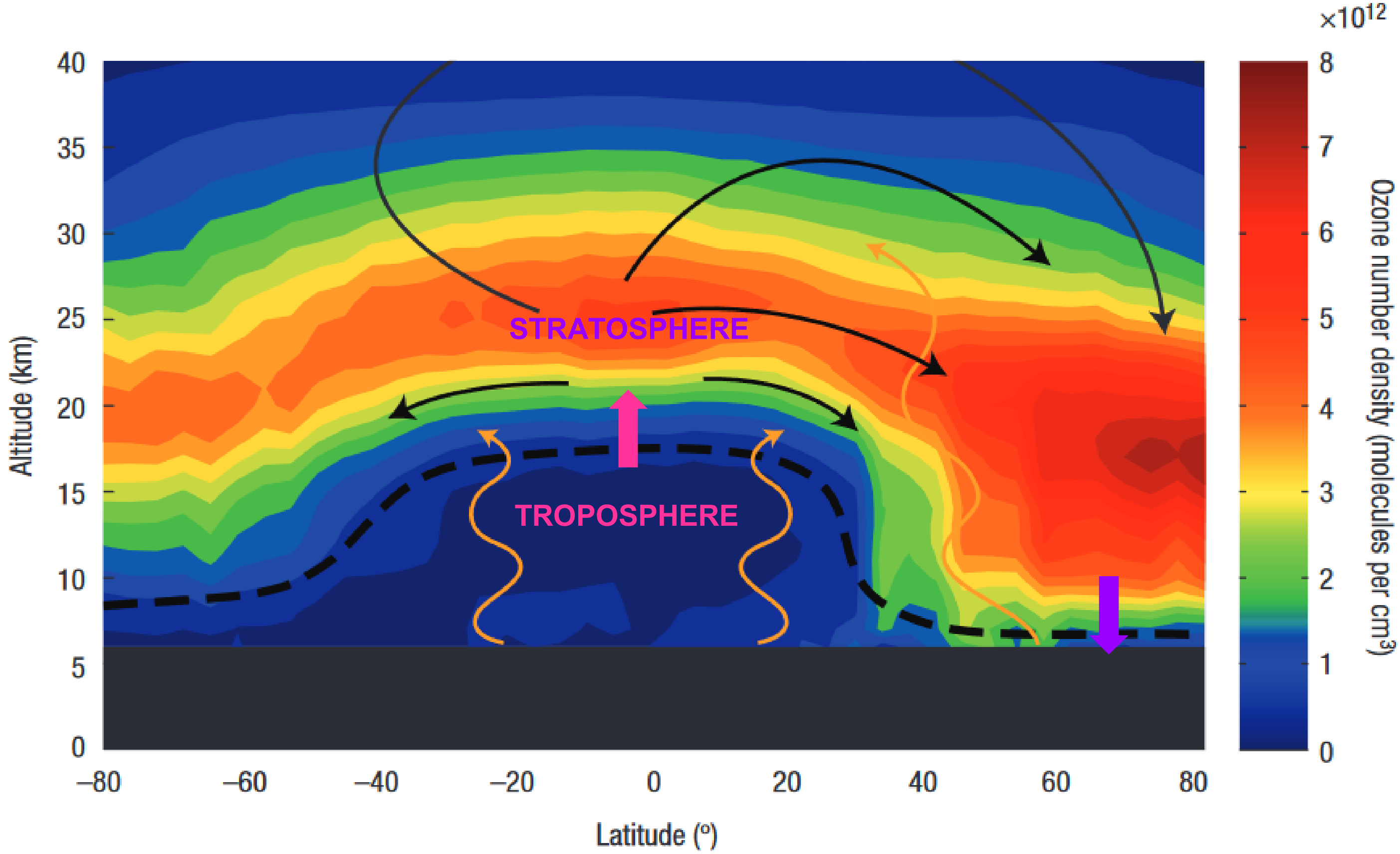
Temperature versus Altitude



- **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.



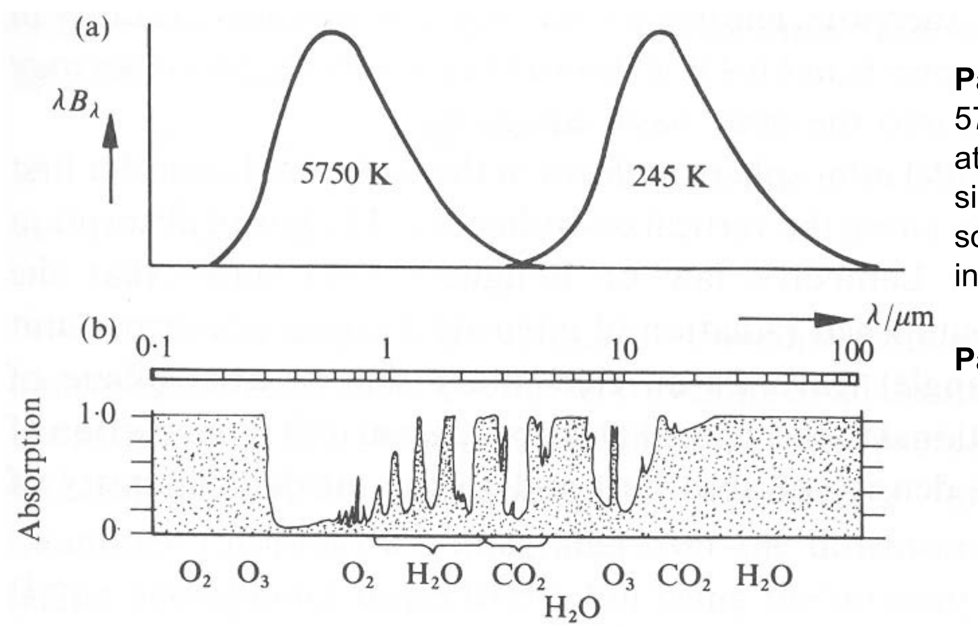
Brewer–Dobson circulation (arrows), ozone (colors), and tropopause (black dashed line).

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)

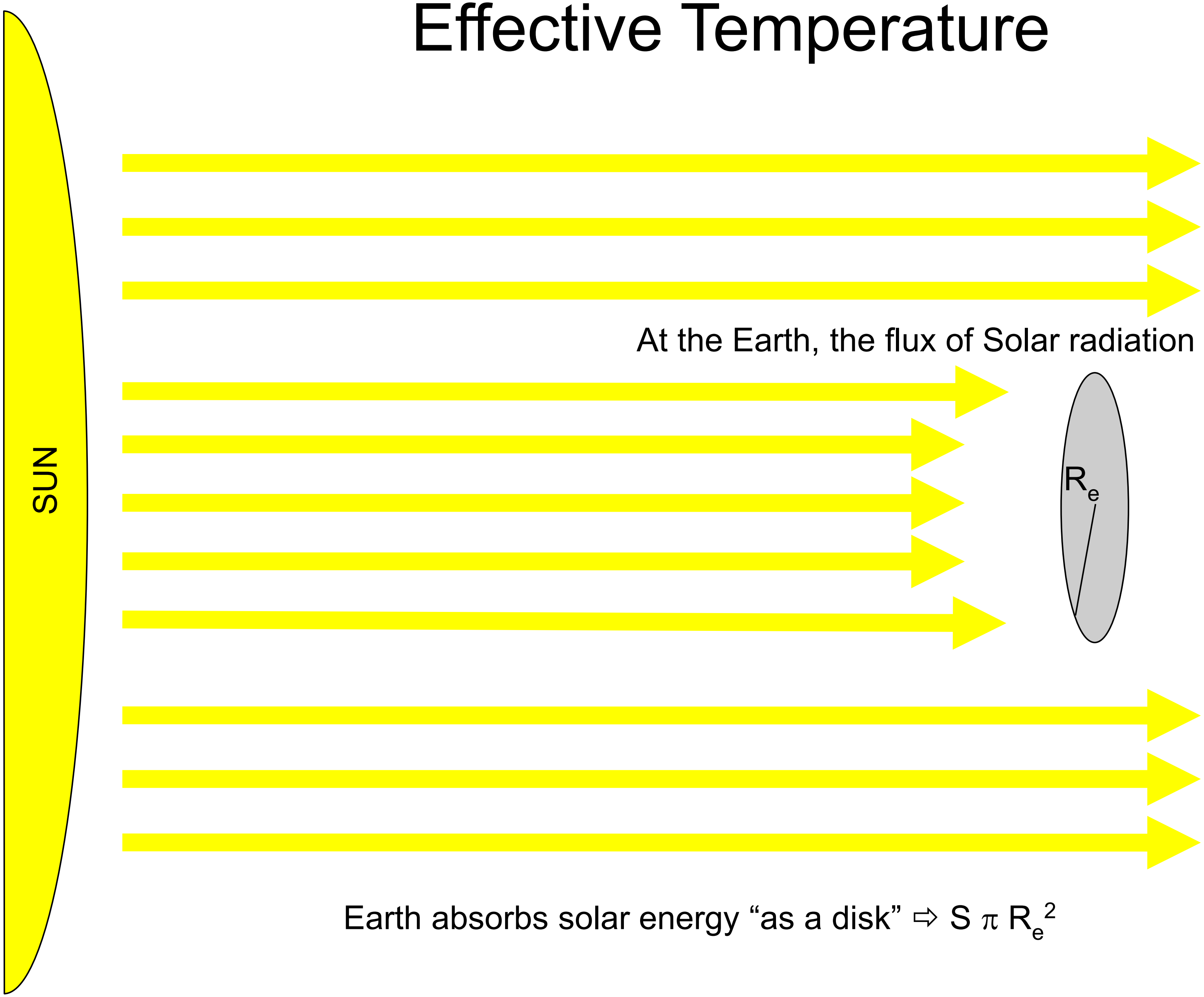


Panel (a): Black-body energy versus wavelength for 5750 K (Sun's approx T) and 245 K (Earth's mean atmospheric T). Curves are drawn with equal area since integrated over entire Earth, at top atmosphere, solar downwelling and terrestrial upwelling fluxes are in close balance.

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

From Houghton, *Physics of Atmospheres*, 1991

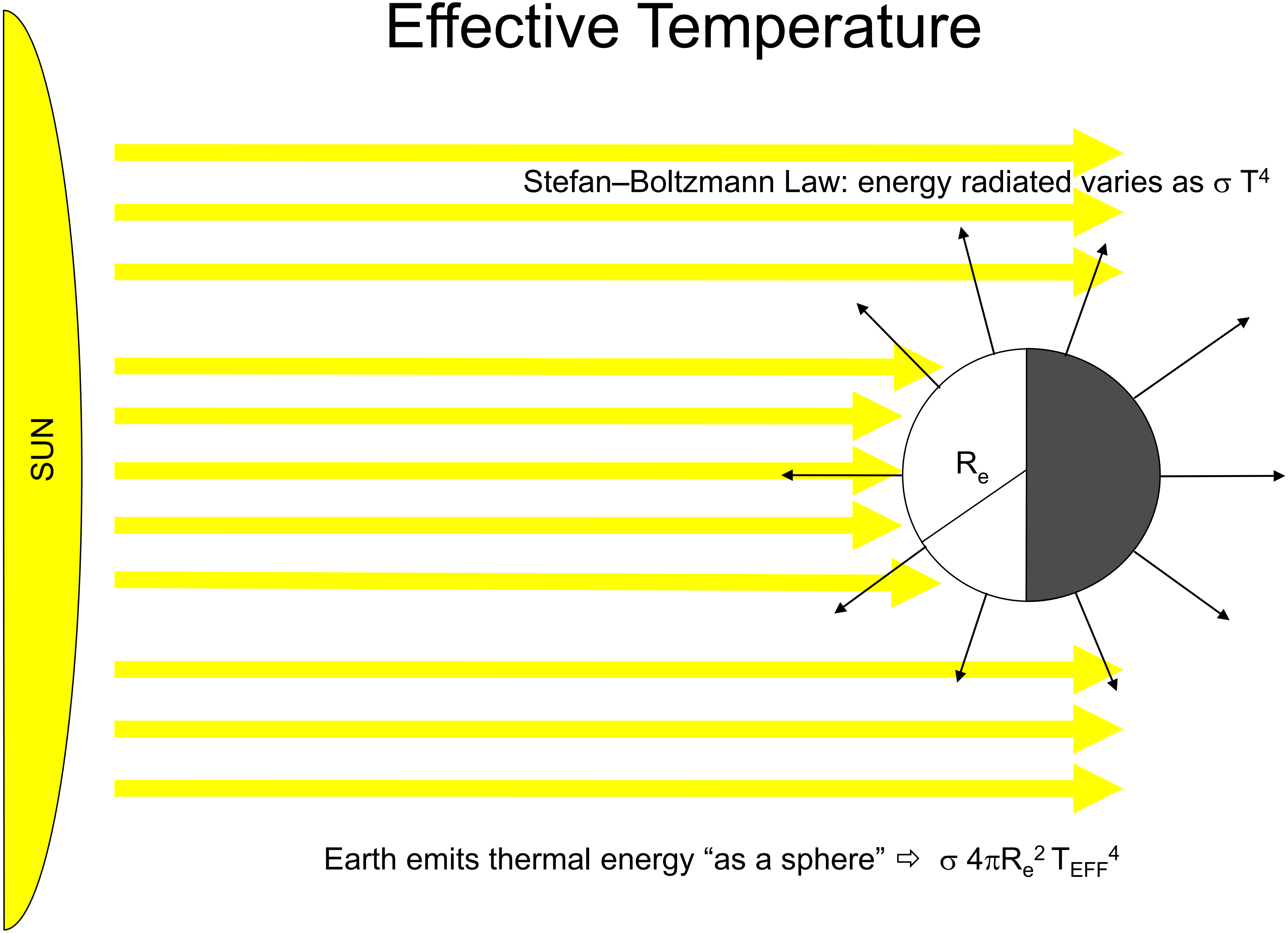
Effective Temperature



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



Stefan–Boltzmann Law: energy radiated varies as $\sigma\ T^4$

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" ⇨ $\sigma\,4\pi R_e^2\,T_{EFF}^4$

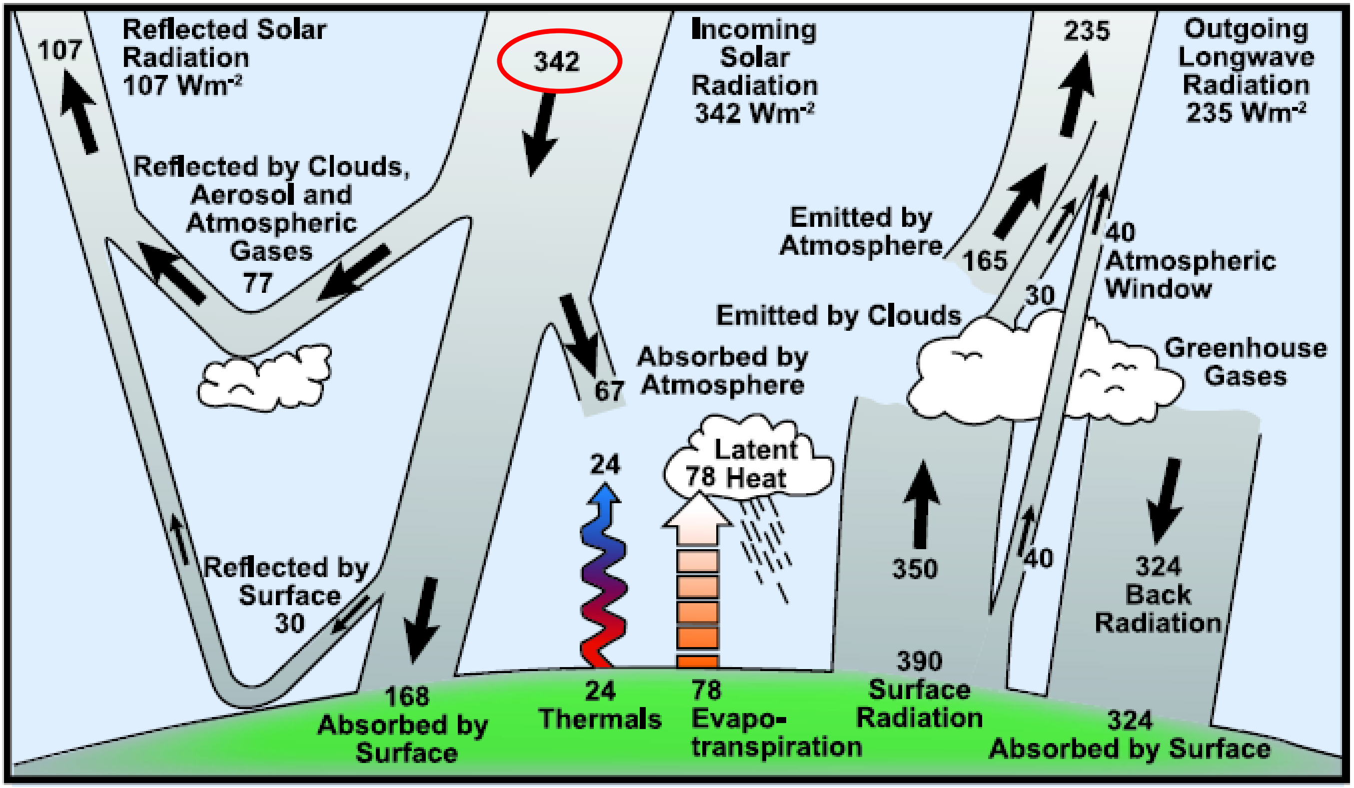
$$(1-\text{Albedo}) \times S = 4\,\sigma\,T_{EFF}^4$$

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}



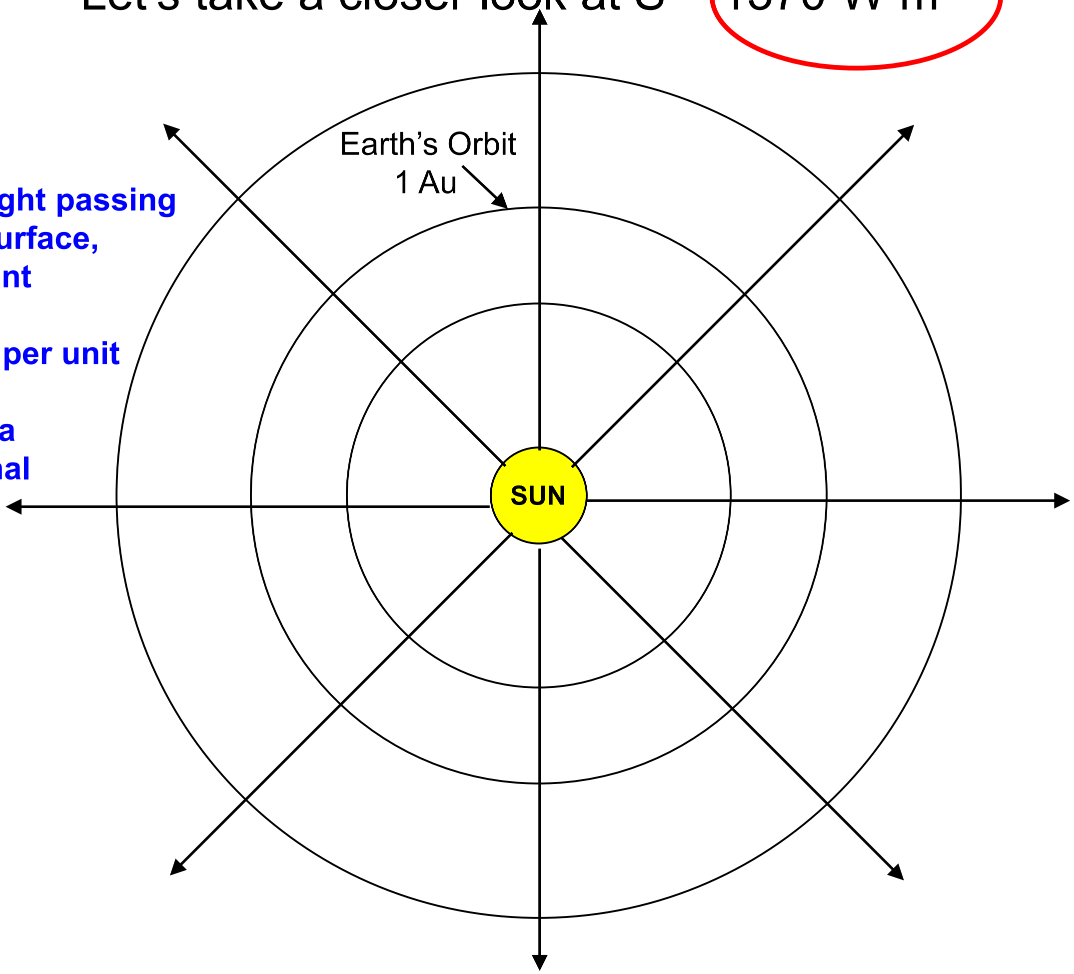
FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming 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.

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

Shaun and Jahyron: 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

Akarsh, Natalia, and Maddie: 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

Yixin, Rachel and Alisha: 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

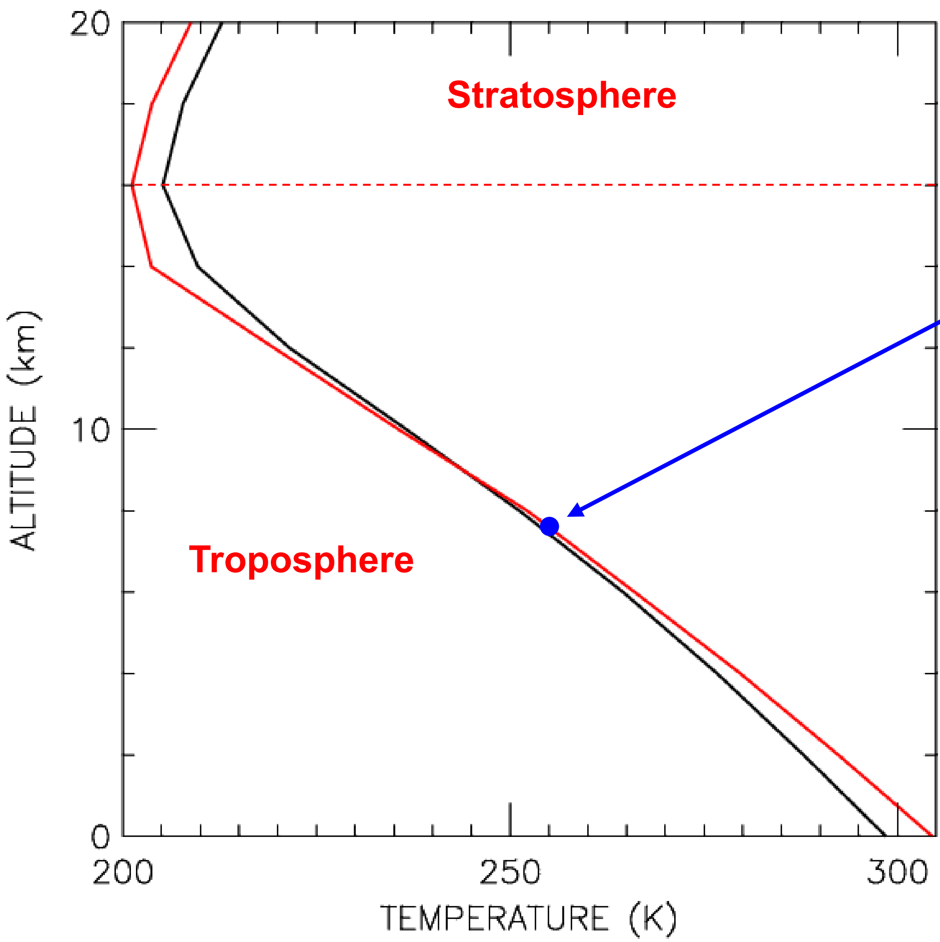
$T_{EFFECTIVE} \approx$???

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

Temperature versus Altitude

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



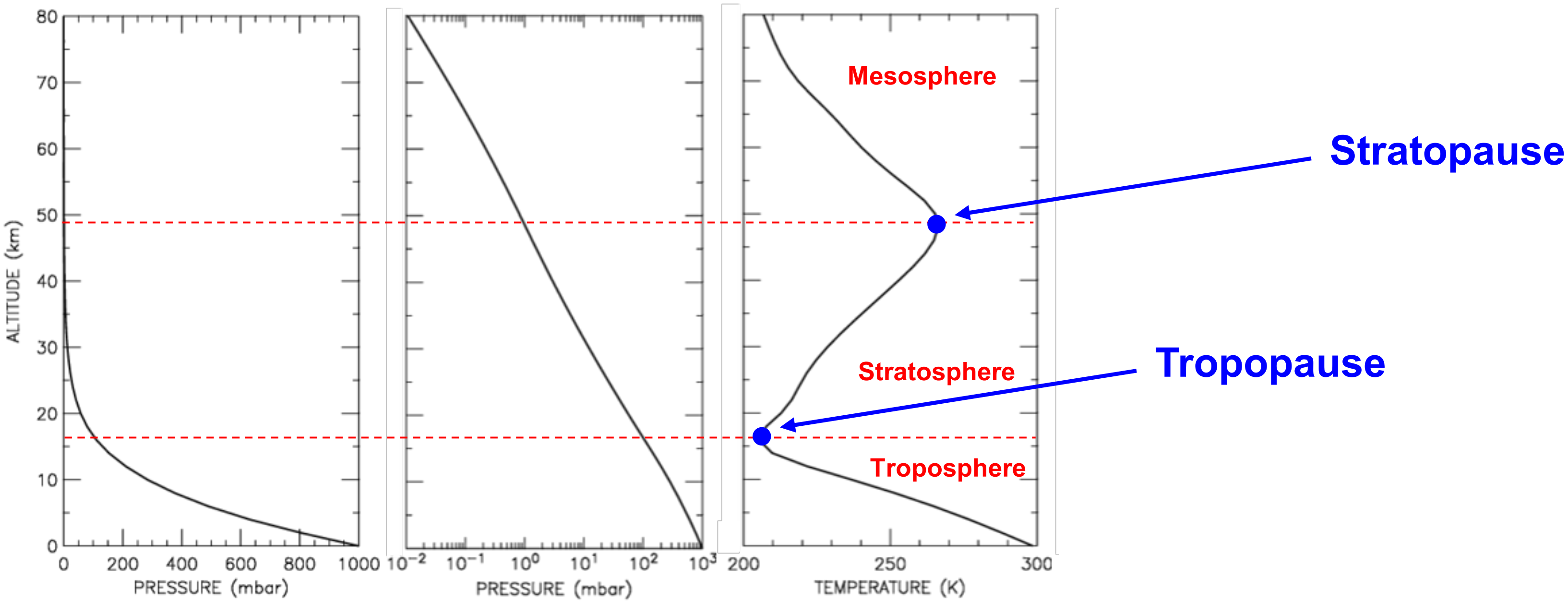
Altitude in troposphere where T = 255 K

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

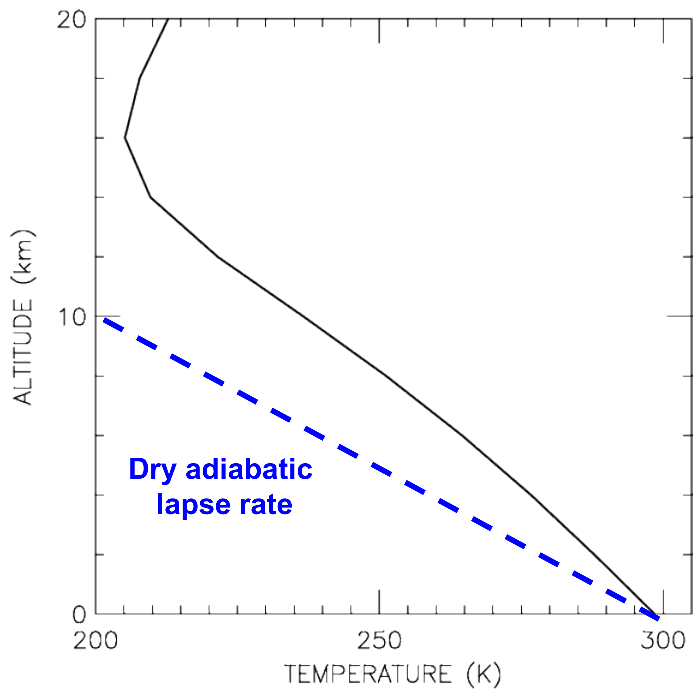
where c_p is specific heat of air at constant pressure = 1 × 10^7 erg gm^{-1} K^{-1}

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



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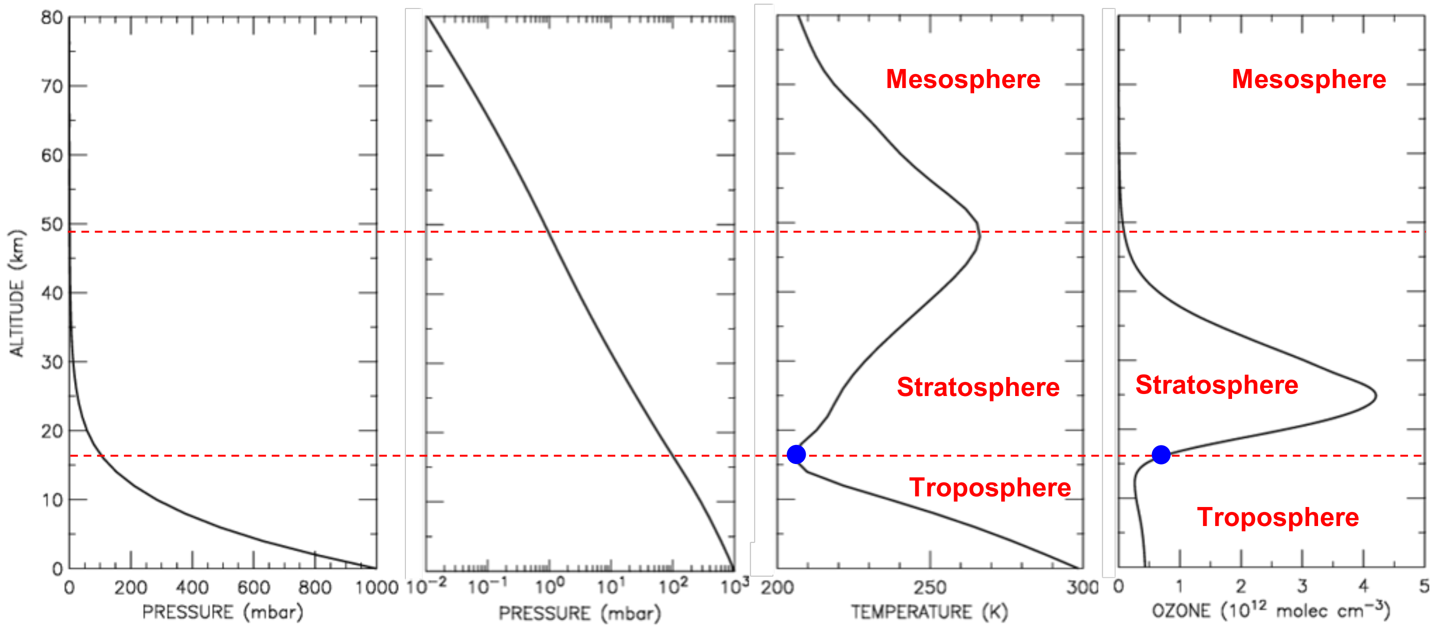
Temperature versus Altitude



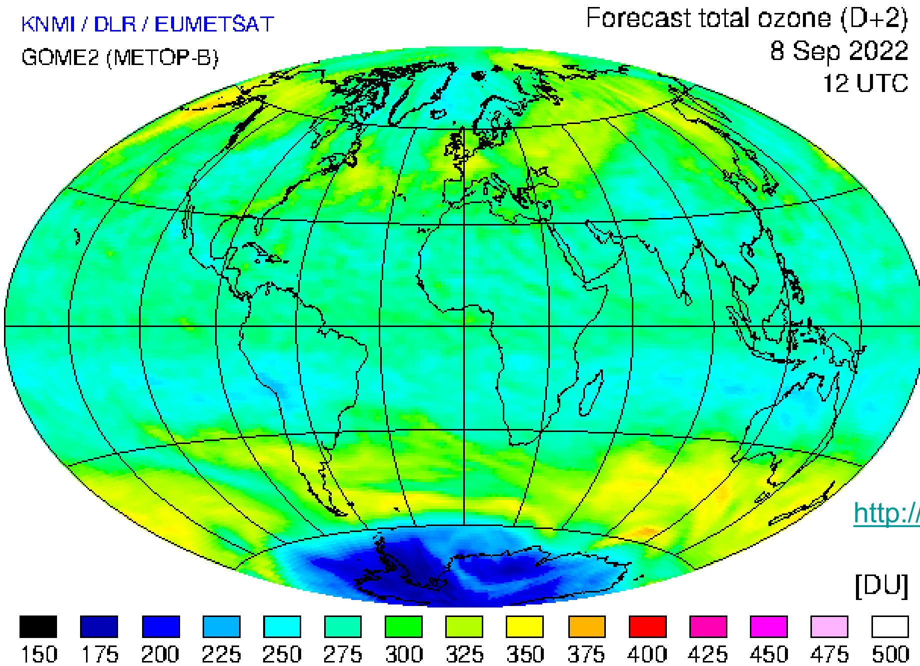
- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

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?

0.25 inch



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

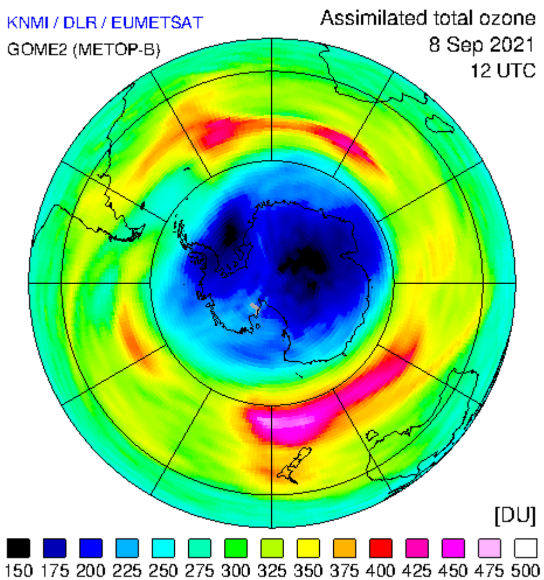
Mathematically:

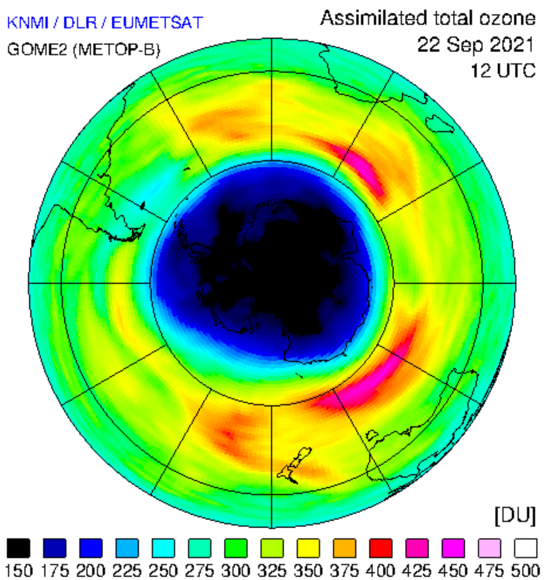
$$\text{Ozone Column} = \int_{\text{Ground}}^{\text{Top of Atmosphere}} [O_3(z)]\, dz$$

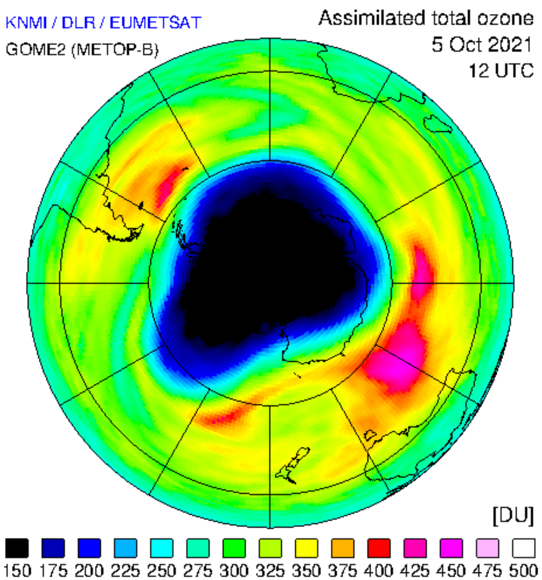
$$\text{Units}: [O_3(z)] \text{ in } {}^{\text{molecule}}\!/_{\text{cm}^3} \text{ and z in cm, leading to Ozone Column in } {}^{\text{molecule}}\!/_{\text{cm}^2}$$

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

Seasonal Evolution of Ozone Hole

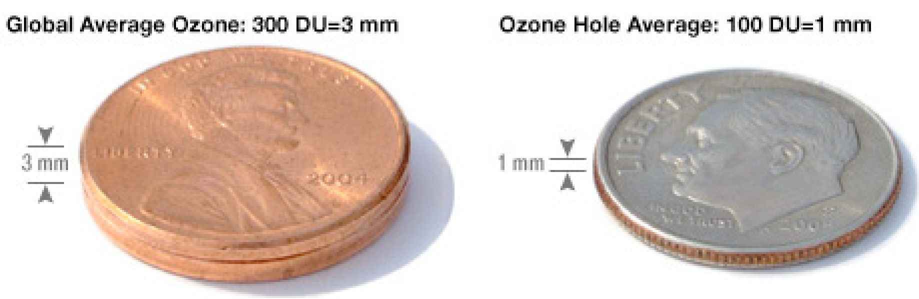






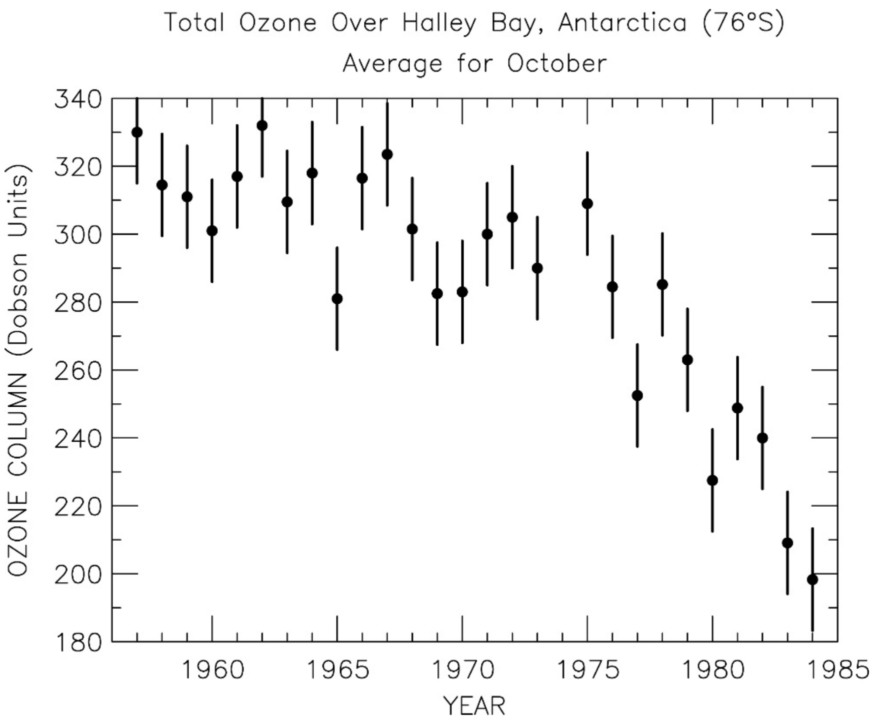
http://www.temis.nl/protocols/O3global.html

1 Dobson Unit is defined to be a 0.01 millimeter thickness of air, at "standard temperature and pressure"
Today we have about 325 Dobson Units (*CC*) = 325 × 0.01 millimeter = 3.25 millimeter or 0.325 cm = 0.128 inch of ozone, isolated and compressed to STP, between us and outer space.



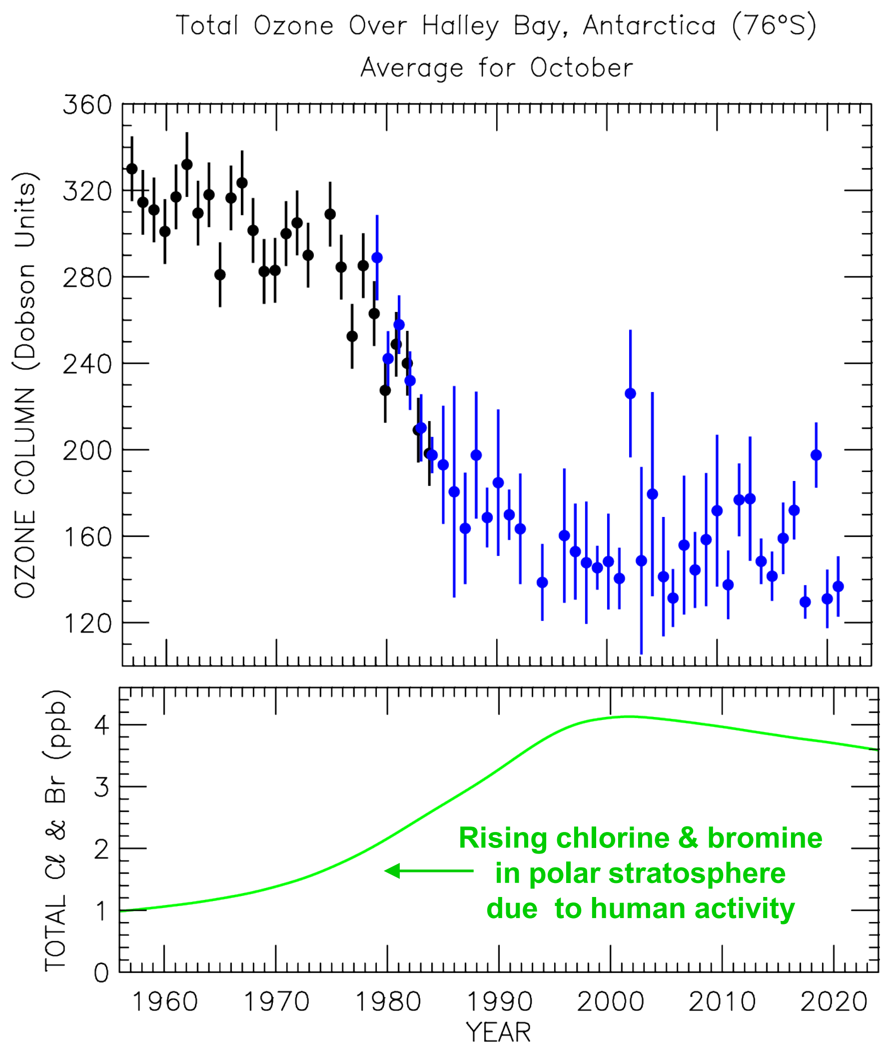
Long Term Evolution of Ozone Hole

Stratospheric Ozone – shields surface from solar UV radiation

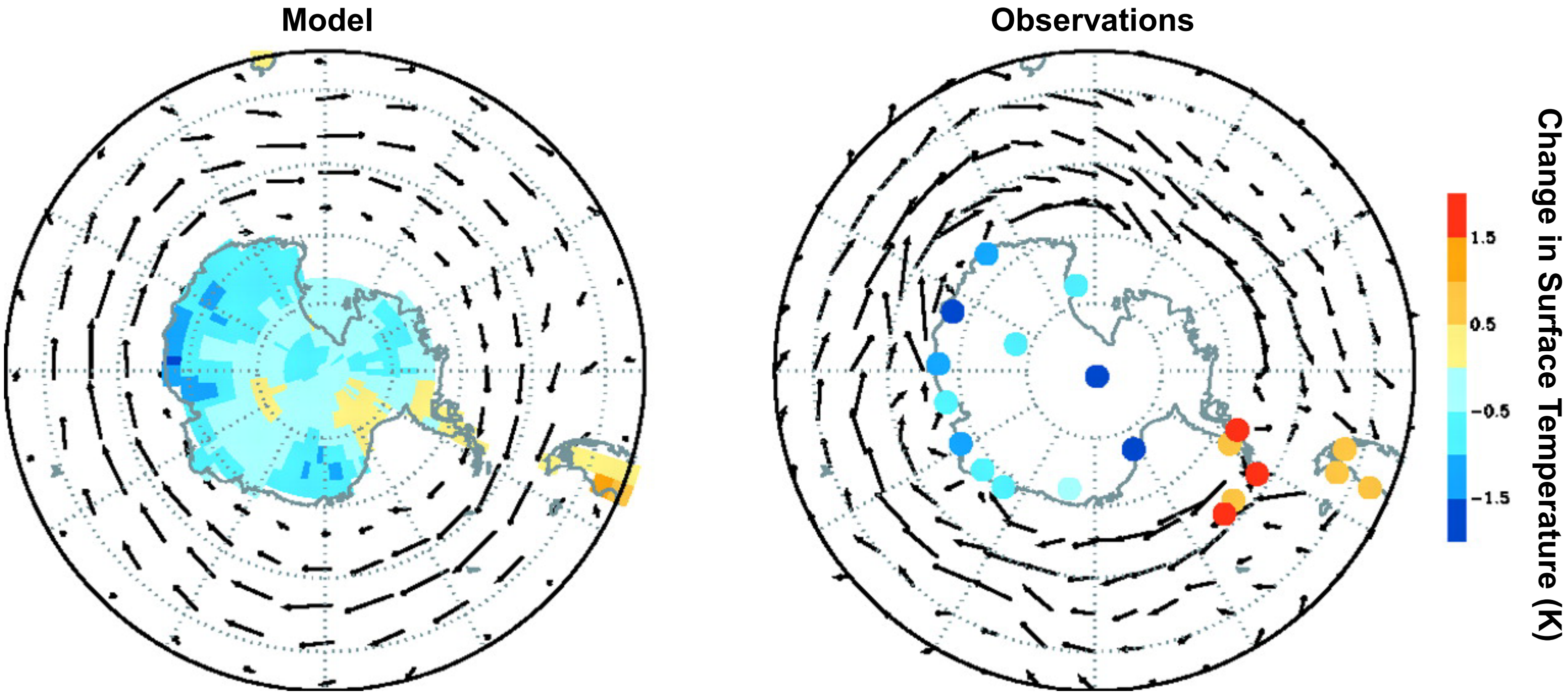


After Farman *et al*., Large losses of total ozone in Antarctica reveal Seasonal ClO_x/NO_x interaction, Nature, 315, 207, 1985.

Update



The Ozone Hole may have shielded the Antarctic surface from warming!



Simulated and observed changes in surface temperature (K) and wind speed,1969 to 2000, averaged over December to May. The longest wind vector corresponds to 4 m/s.

Gillett and Thompson, *Science*, 2003

As ozone depletion occurs:

The positive phase of the southern annular mode (SAM) increases, causing Antarctic surface westerlies to intensify, resulting in cooling of Antarctic continent

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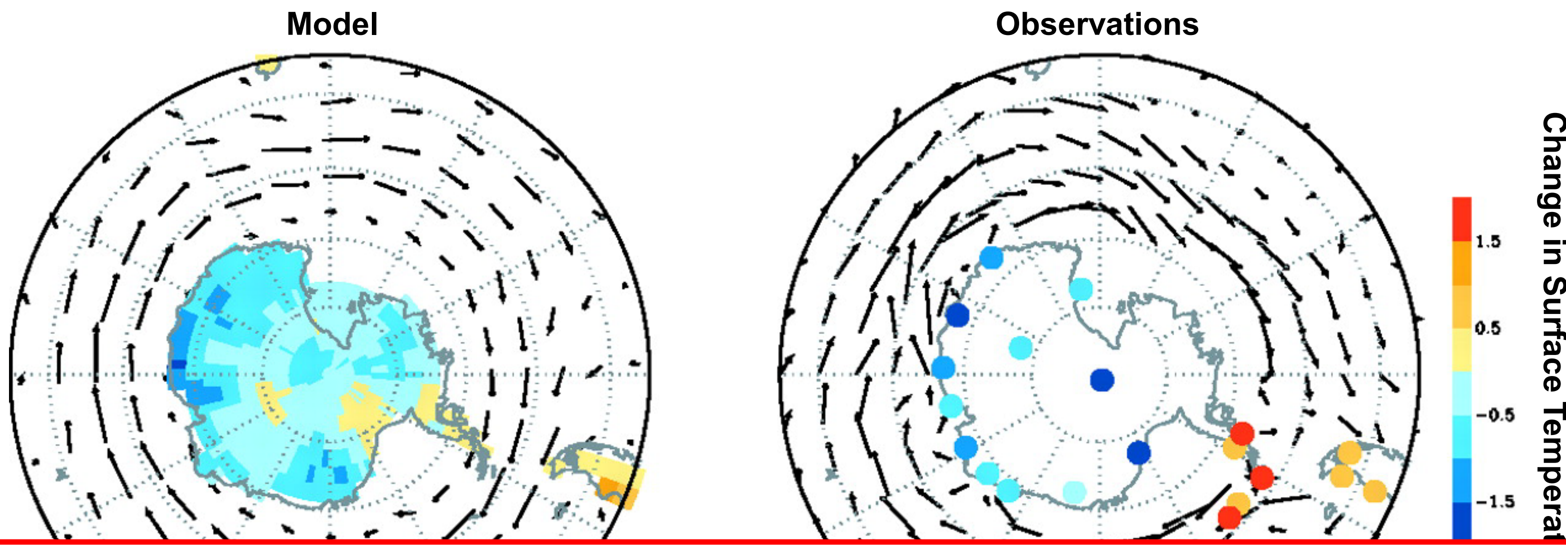

SAM: difference in zonal mean sea-level pressure between 40°S and 65°S. The pattern associated with SAM is a nearly annular pattern with a large low pressure anomaly centered on the South Pole and a ring of high pressure anomalies at mid-latitudes. The SAM effects storm tracks, precipitation patterns, etc.

http://www.climate.be/textbook/chapter5_node6.html

As ozone depletion occurs:

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Back to the ATs

AT3, Q1:
According to *Chemistry in Context*, what was the U.S. National Ambient Air Quality Standard for exposure to ozone over an 8 hour period of time (of course, at the time the 7th edition was published), in units of parts per million?

0.075 ppm

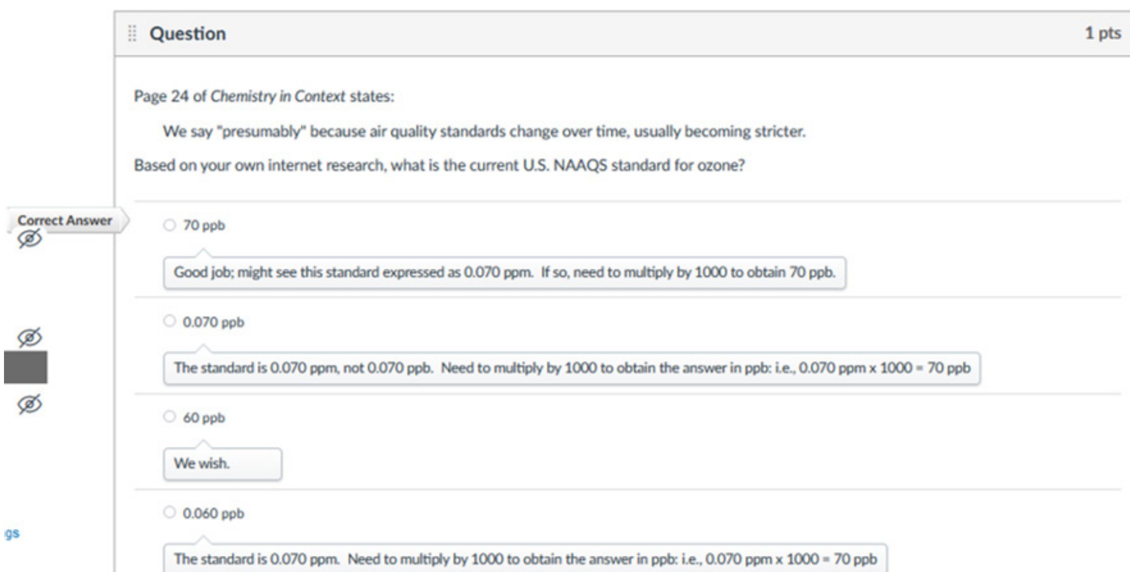
AT3, Q2:
Express the answer to Question 1 in units of parts per billion.

0.075 ppm x (1000 ppb/ppm) = 75 ppb

AT3, Q3:
Page 24 of *Chemistry in Context* states:

> We say "presumably" because air quality standards change over time, usually becoming stricter.

Based on your own internet research, what is the current U.S. NAAQS standard for ozone?



Back to the ATs

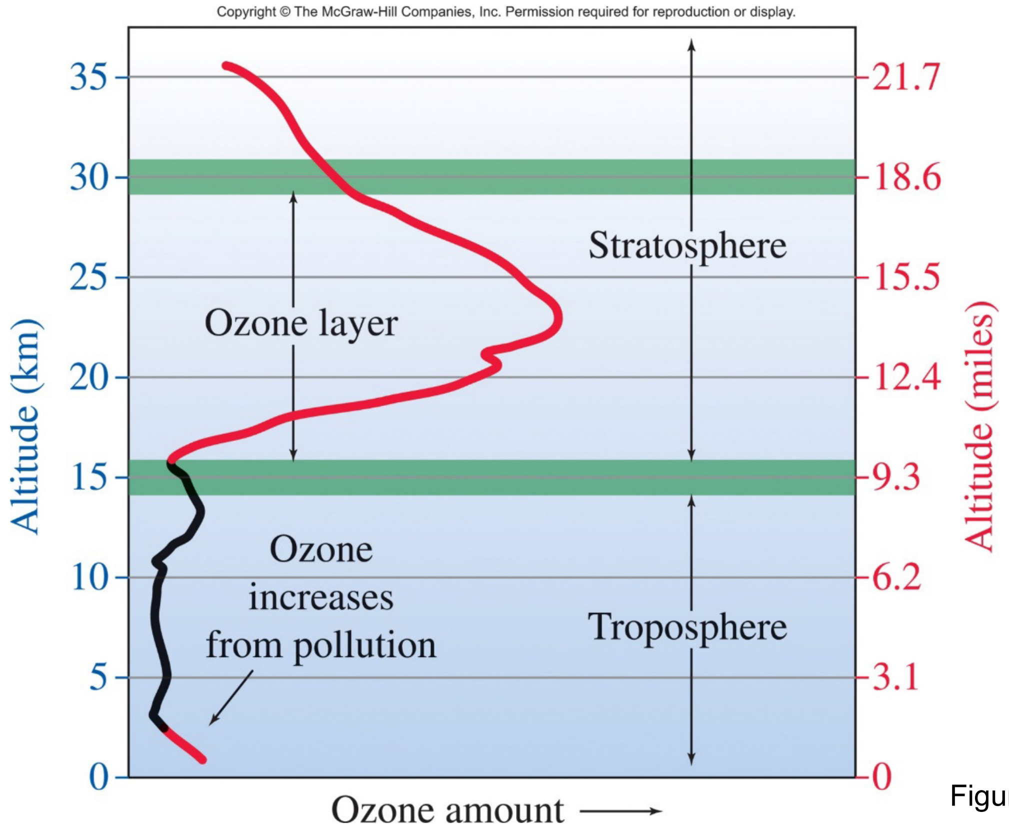


Figure 2.2, Chemistry in Context

Mean mixing ratio of stratospheric ozone is about 870 ppb

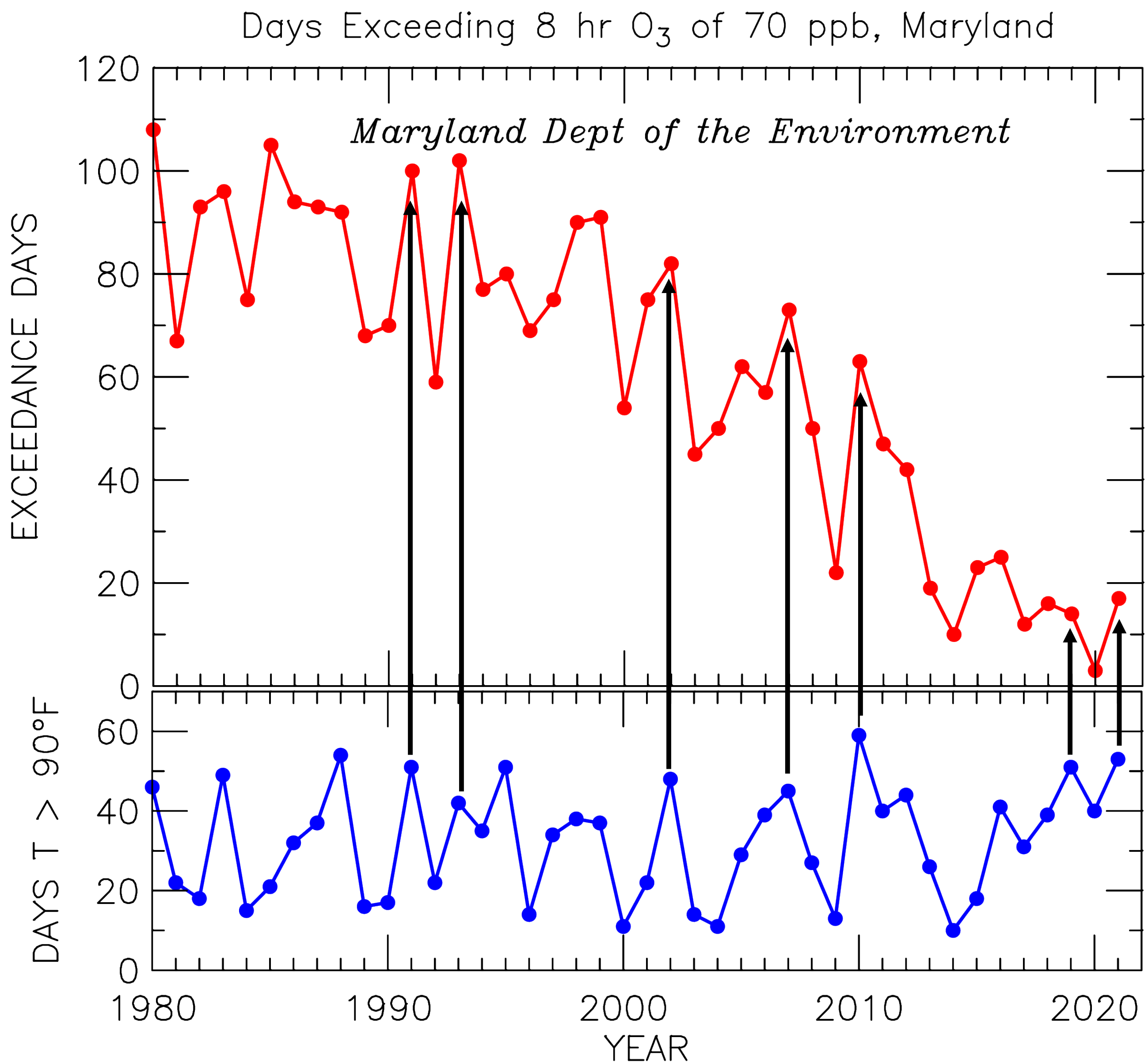
Old U.S. NAAQS was 75 ppb and the new standard is 70 ppb; hence, the mean mixing ratio of O_3 throughout Earth's atmosphere is more than a *factor of 10 larger* than the current air quality standard.

This circumstance is due to the fact much larger amounts of ozone exist in the stratosphere than the troposphere.

Air Quality Standards and Why We Care

For more information, have a look at:
https://www.weforum.org/agenda/2018/11/deadly-air-pollution-shortens-lives-by-nearly-2-years-researchers
https://aqli.epic.uchicago.edu/pollution-facts

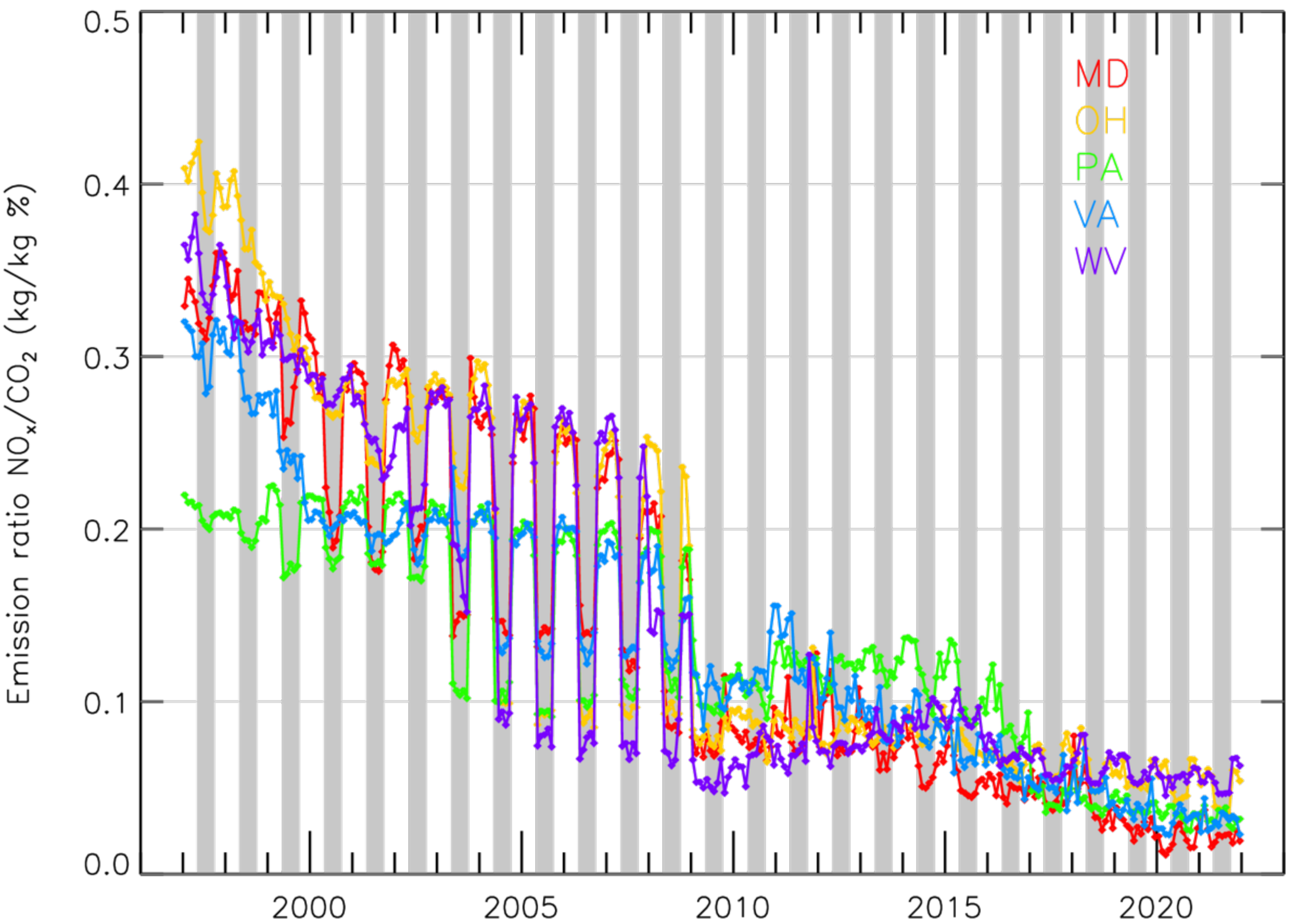
Significant Improvements in *Local* Air Quality since early 1980s



Number of days, each summer, for which T at BWI exceeded 90°F at some part of the day

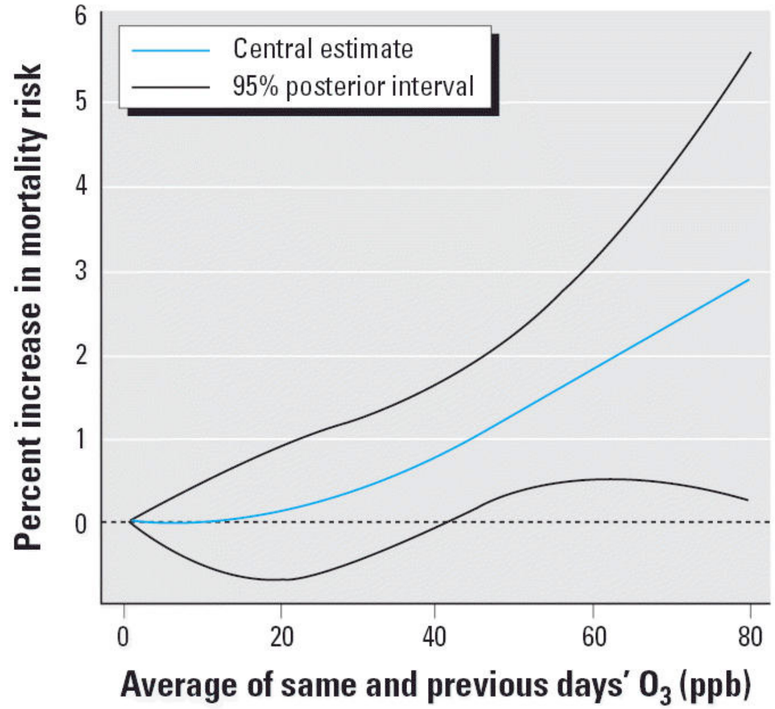
http://www.mde.state.md.us/programs/Air/AirQualityMonitoring/Pages/SeasonalReports.aspx

Trends in power plant emissions of NOx



Shading denotes "ozone season", April to Sept

Air Quality Standards and Why We Care



Increased risk of premature death (mortality) for all levels of surface O_3
Reductions in surface ozone will benefit public health, regardless of present conditions

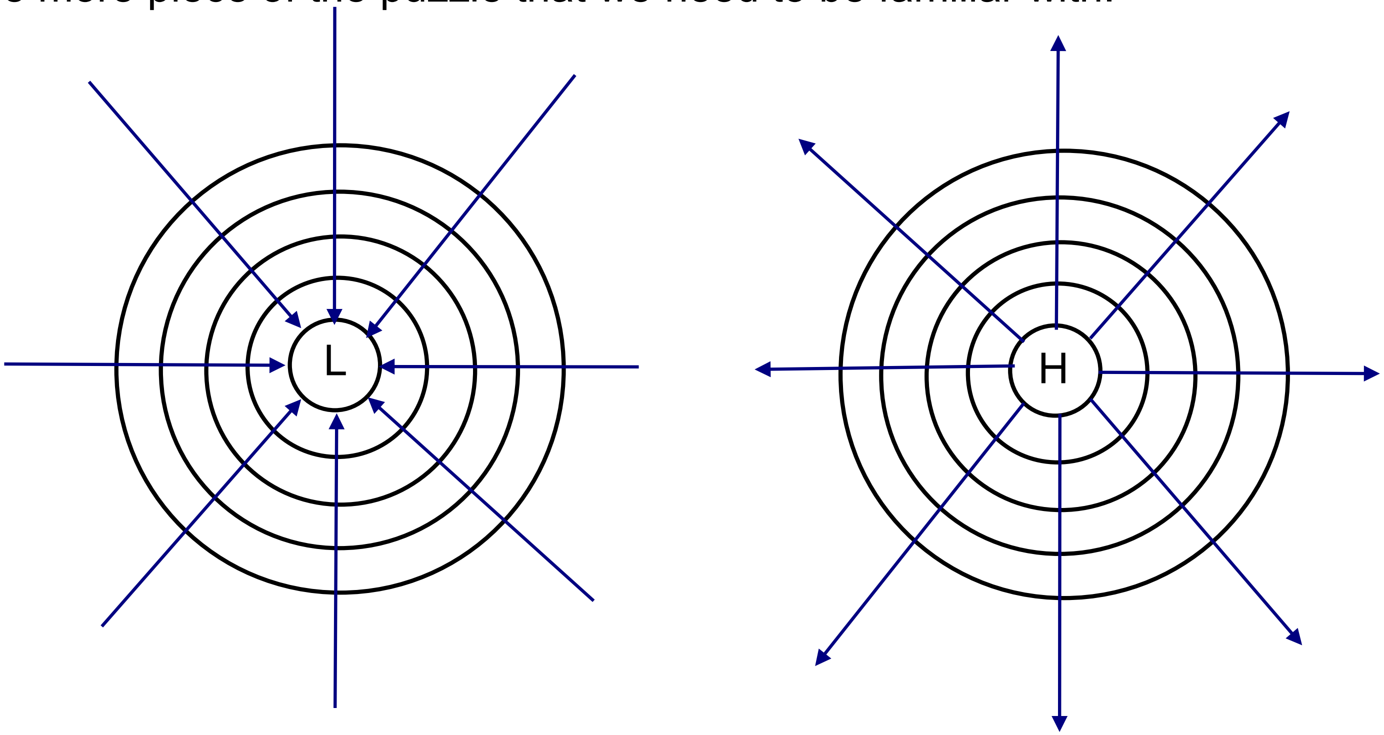
Bell et al., 2006

http://www.ncbi.nlm.nih.gov/sites/ppmc/articles/PMC1440776

Coriolis Force

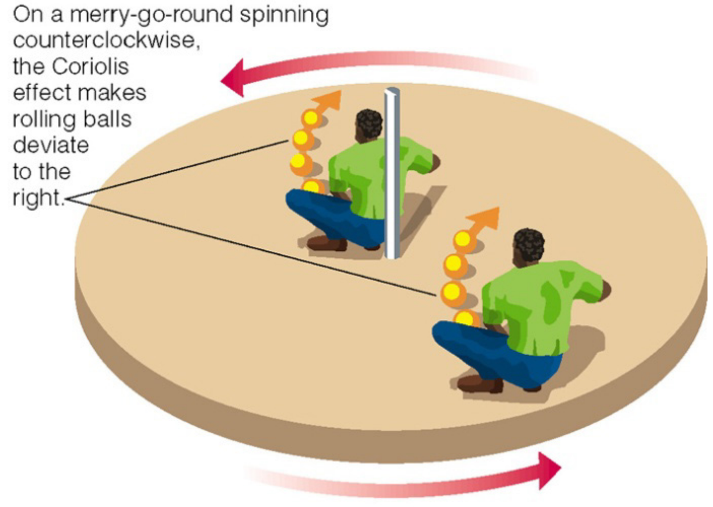
So far, we've reviewed temperature, pressure, and the balance between solar energy input to the atmosphere and terrestrial radiation leaving the atmosphere.

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

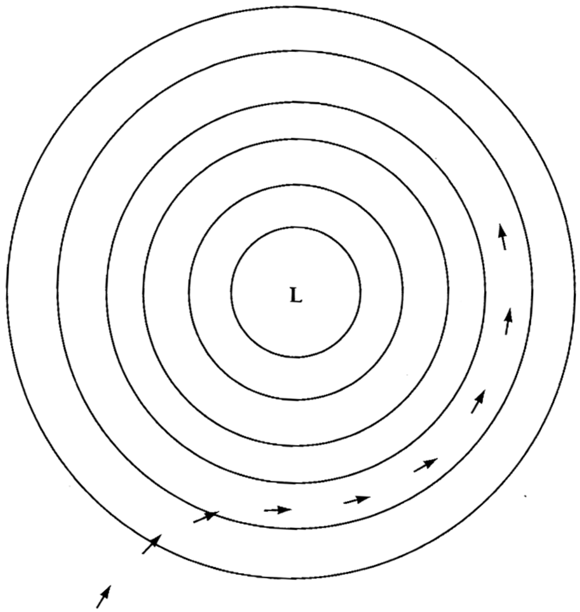


Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

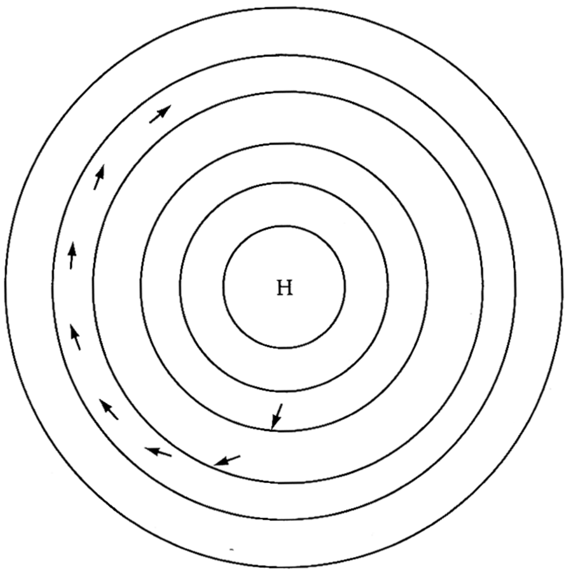


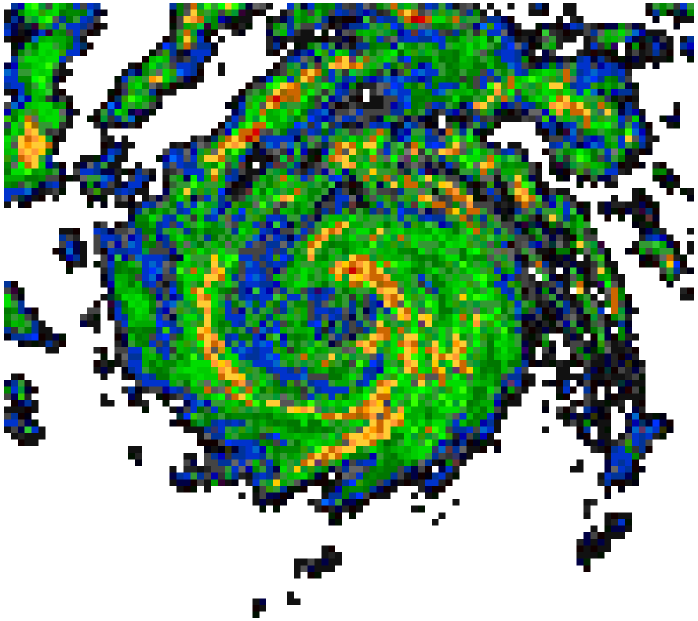
Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

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

Geostrophic balance: balance between Coriolis Force and pressure gradient

Geostrophy

NH Weather System:

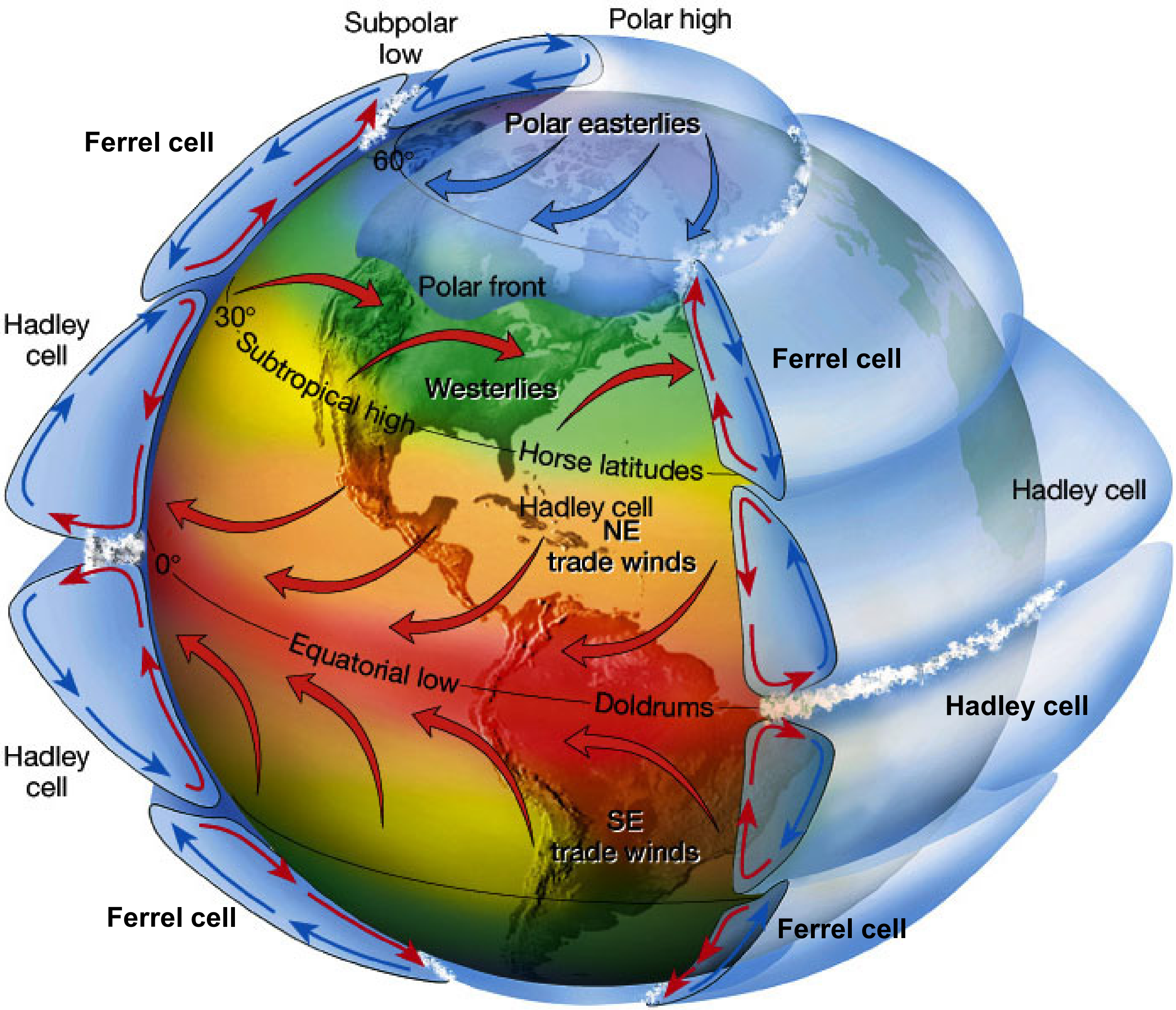


Cyclonic Flow: when the wind swirls
counter-clockwise in the NH

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

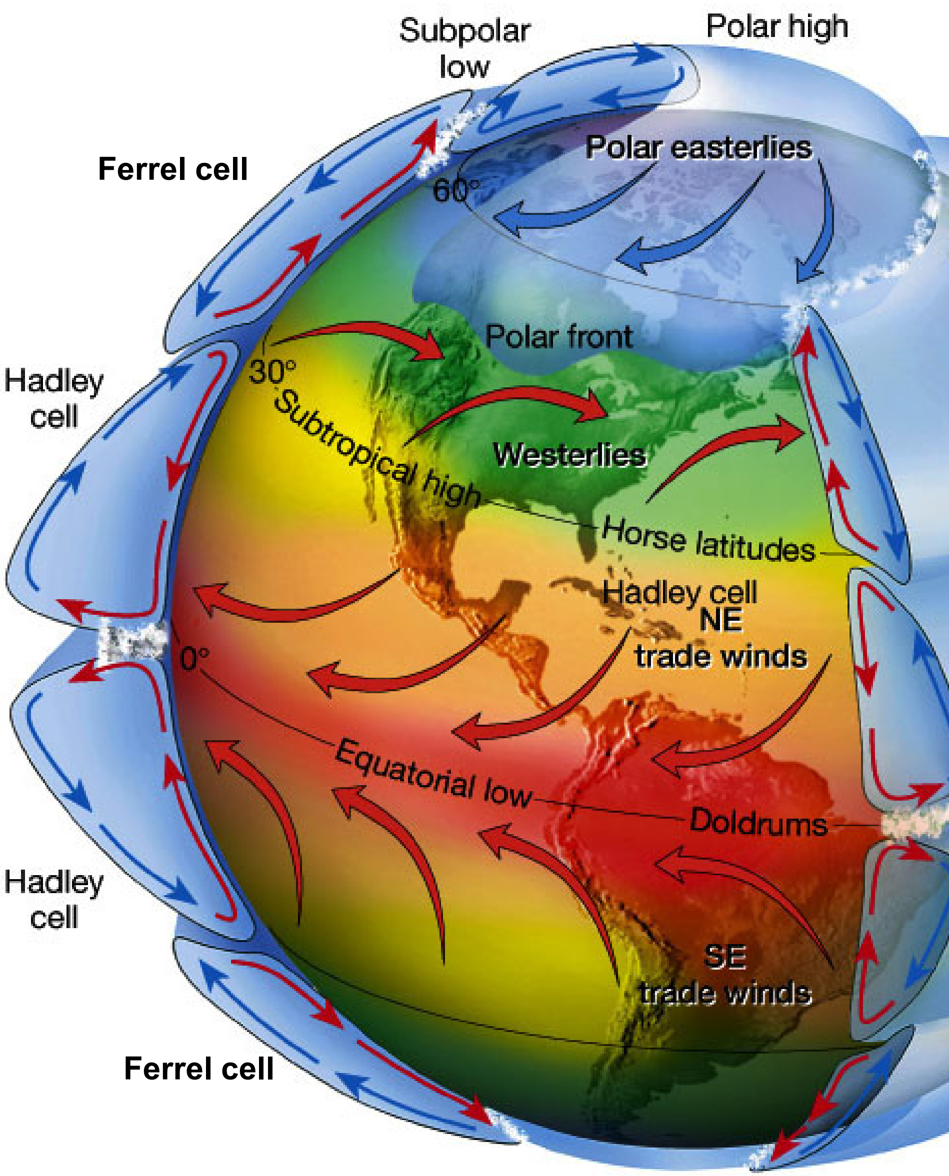
Typhoon: Cyclonic flow occurring in the NW Pacific Ocean, west of the dateline.
Cyclones: Cyclonic flow occurring in the South Pacific and Indian Ocean.

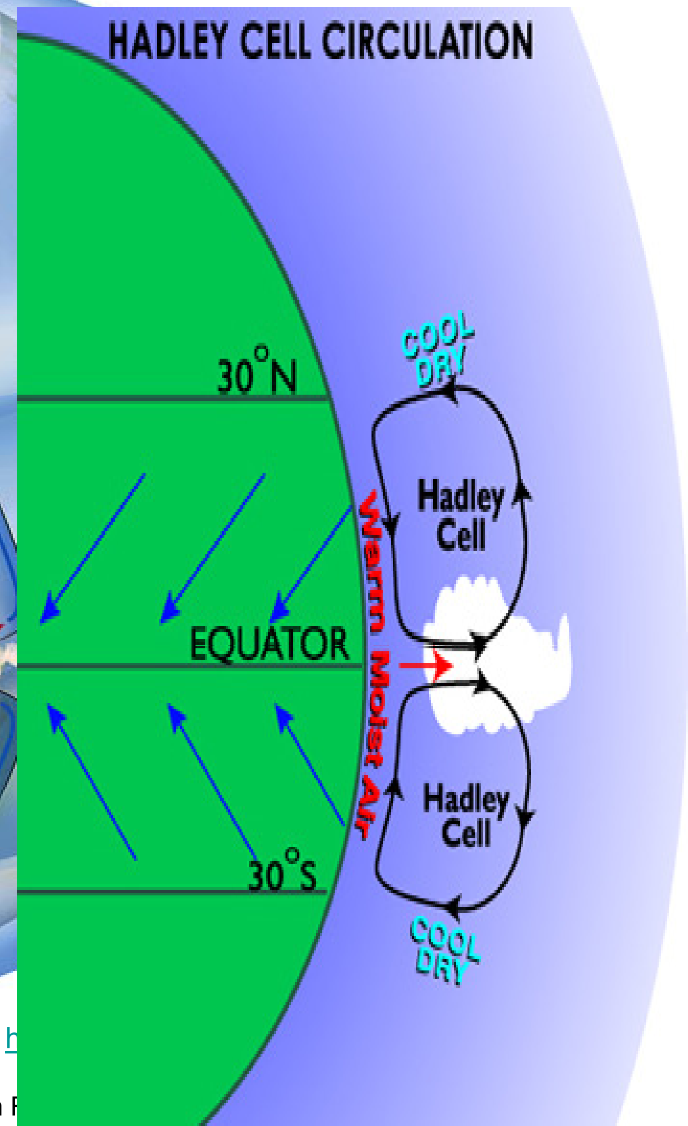
Ferrel Circulation (Modern View)



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

Ferrel Circulation (Modern View)





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As CO_2 and other GHGs rise:

- Hadley Cell becomes more energetic
- WWDD: Wet gets wetter, dry gets drier
- Deserts expand poleward

REVIEW ARTICLE
https://doi.org/10.1038/s41558-018-0246-2
nature climate change

Re-examining tropical expansion

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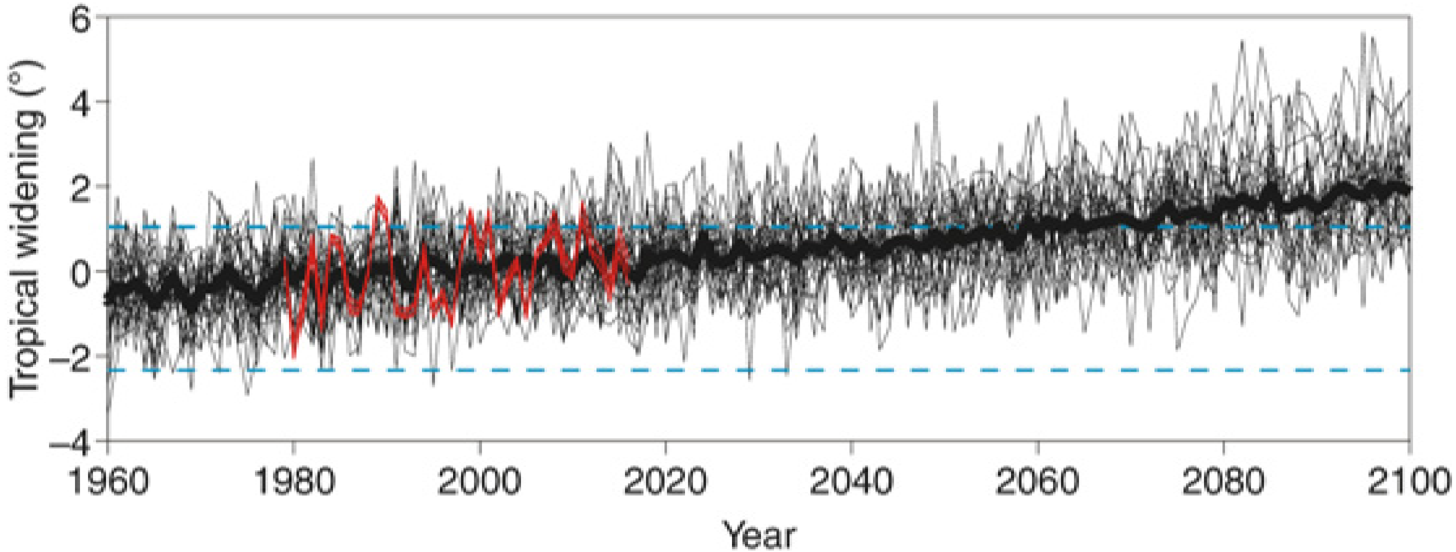

Change in the latitudinal width of the tropics relative to 1981-2010 mean from satellite observations (red) and climate models (thin black lines), along with the multi-model mean (thick black). The blue dashed lines show the 2σ range of the width of the tropics due to natural variability for pre-industrial levels of GHGs.

From Staten *et al.*, *Nature Climate Change*, 2018. https://www.nature.com/articles/s41558-018-0246-2

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*

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

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

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:

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