Fundamentals of Earth's Atmosphere

AOSC / CHEM 433 & AOSC 633

Ross Salawitch & Walt Tribett

Class Web Site:
http://www.atmos.umd.edu/~rjs/class/spr2019
Email:
Ross: rsalawit@umd.edu or rjs@atmos.umd.edu
Walt: wtribett@umd.edu

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

7 February 2019

In class, I had shown a version of the figure from a National Academies of Sciences report entitled *Surface Temperature Reconstructions for the Last 2000 Years*, published in 2006.

The original source of this figure is Chapter 2 of the 2001 IPCC report:

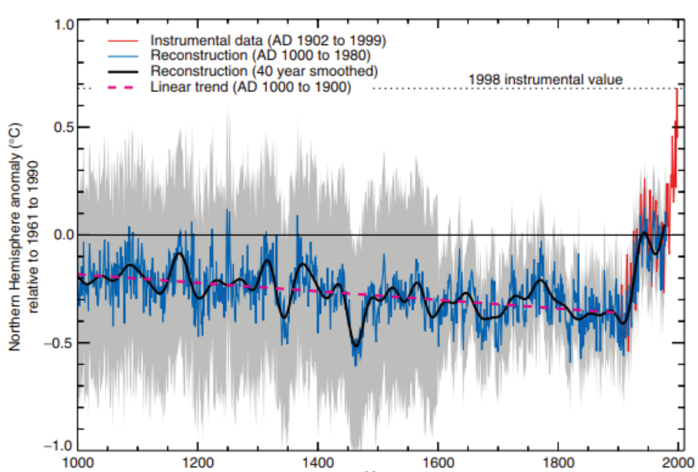
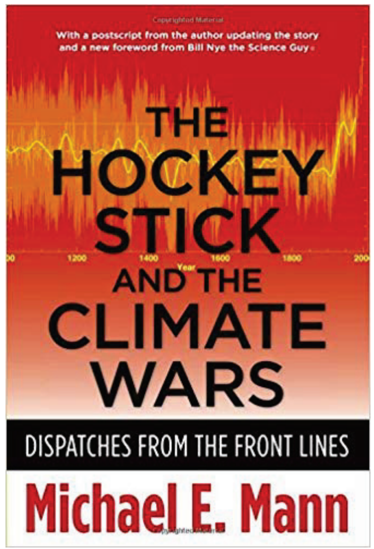


Figure 2.20: Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann *et al.* (1999). Smoother version of NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown.

https://archive.ipcc.ch/ipccreports/tar/wg1/pdf/TAR-02.PDF
Mann *et al.*, *GRL*, 1999: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/1999GL900070

Lots more info in:



https://www.amazon.com/Hockey-Stick-Climate-Wars-Dispatches/dp/0231152558

This is a great book to get an understanding of the political war being waged over the climate change issue today, as well as a bit about how science works. It is not intended to explain climate science, although it does cover some of the techniques used in putting together an estimate of earth's surface temperature over the past 1000 years (the so-called "hockey stick"). But that is not the major part of either the book or climate science. The hockey stick is important not for scientific reasons but because it has become an icon, conveying visually that the stable climate that fostered the creation of human civilization supporting 7 billion people has undergone a radical change in the last 100 years. And there is no end in sight.   First paragraph of top Amazon review by **Wendy Fehlauer**

Book published in 2012 so lacks salacious details of the recent political war being waged over climate change.

Tropospheric Pollutants (The Air We Breathe)

Table 1.2 U.S. National Ambient Air Quality Standards

Pollutant	Standard (ppm)	Approximate Equivalent Concentration (μg/m^3)
Carbon monoxide		
8-hr average	9	10,000
1-hr average	35	40,000
Nitrogen dioxide		
Annual average	0.053	100
Ozone		
8-hr average	0.075	147
1-hr average	0.12	235
*Particulates**		
PM_{10}, annual average	—	50
PM_{10}, 24-hr average	—	150
$PM_{2.5}$, annual average	—	15
$PM_{2.5}$, 24-hr average†	—	35
Sulfur dioxide		
Annual average	0.03	80
24-hr average	0.14	365
3-hr average	0.50	1,300

*PM_{10} refers to all airborne particles 10 μm in diameter or less. $PM_{2.5}$ refers to particles 2.5 μm in diameter or less.

—The unit of ppm is not applicable to particulates.

†$PM_{2.5}$ standards are likely to be revised after 2011.

Source: U.S. Environmental Protection Agency. Standards also exist for lead, but are not included here.

Chapter 1, Chemistry in Context

AT3, Q1:
What was the U.S. NAAQS for exposure to ozone over an 8 hr period of time in 2012, the time the 7th edition of *Chemistry in Context* was published, in units of parts per million?

0.075 ppm

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

(0.075 parts / 1 × 10^6) × (1 × 10^9) = 75 ppb

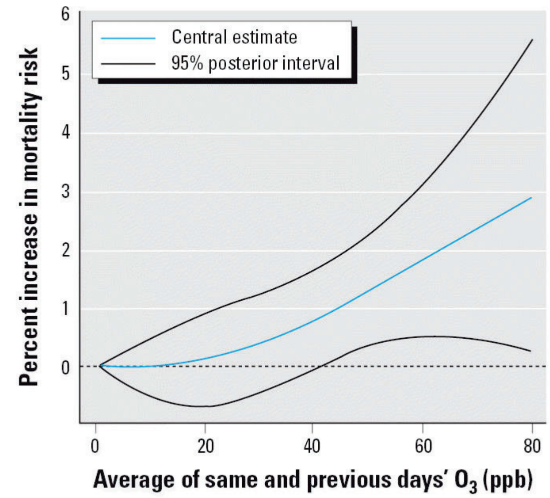
AT3, Q3:
Based on your own internet research, what is the current U.S. NAAQS standard for ozone?

2015 EPA NAAQS Standard for O_3 is 0.070 ppm or 70 ppb

Air Quality Standards and Why We Care

Year	Averaging Period	EPA Surface Ozone Standard
1979	1 hr	125 ppb
1997	8 hr	85 ppb
2008	8 hr	75 ppb
2015#	8 hr *	70 ppb

* The 8 hr standard is met when the 3-yr average of the annual 4th highest daily maximum 8 hr O_3 is less than 70 ppb



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

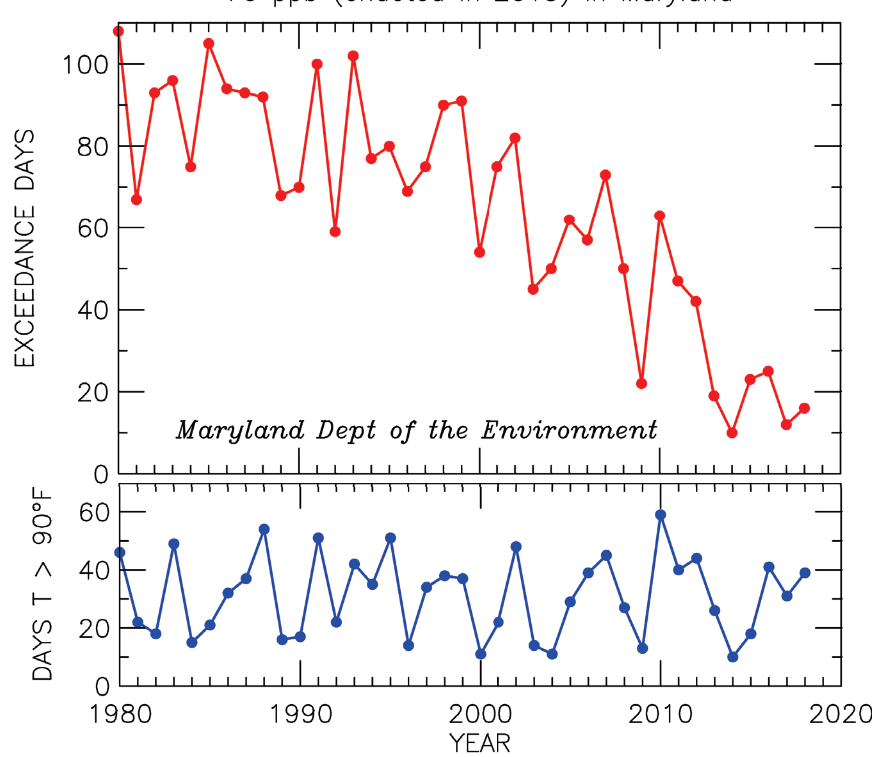
Bell *et al*., *Envir. Health Perspect*., 2006

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

\# On October 1, 2015 the EPA lowered the NAAQS for ground-level ozone 70 ppb, based on extensive scientific evidence about the harmful effects of tropospheric ozone

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

Days Exceeding New EPA Standard for 8 hr Ozone of 70 ppb (enacted in 2015) in Maryland



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

Tropospheric Ozone Production

Shown in Lecture 2

$$CO + OH \rightarrow CO_2 + H$$
$$H + O_2 + M \rightarrow HO_2 + M$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

Net: $CO + 2\,O_2 \rightarrow CO_2 + O_3$

More complicated tropospheric O_3 production pathway

$$RH + OH \rightarrow R + H_2O$$
$$R + O_2 + M \rightarrow RO_2 + M$$
$$RO_2 + NO \rightarrow RO + NO_2$$
$$RO + O_2 \rightarrow HO_2 + R'CHO$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$2 \times \quad NO_2 + h\nu \rightarrow NO + O$$
$$2 \times \quad O + O_2 + M \rightarrow O_3 + M$$

Net: $RH + 4O_2 \rightarrow R'CHO + H_2O + 2\,O_3$

Note: Chemists use the symbol R to represent molecules based upon CH_3
Examples of RH and R'CHO : CH_4 (methane) $\rightarrow$ CH_2O (formaldehyde)
: C_2H_6 (ethane) $\rightarrow$ CH_3CHO (acetaledhyde)
: C_3H_8 (propane) $\rightarrow$ CH_3COCH_3 (acetone)
Section 1.8 of CC provides a description of the vocabulary of chemistry relevant for this class

AT1, Q2: Nitrogen oxides, carbon monoxide, and hydrocarbons emitted by combustion of fossil fuels (mainly coal and gasoline) lead to production of tropospheric O_3

Sunlight is required for production of O_3 because [OH] & [HO_2] are very small at night

Trees and plants emit hydrocarbons such as isoprene (C_5H_8) or pinene ($C_{10}H_{16}$) that can also lead to production of tropospheric O_3 in the presence of elevated [NO_x]

Methane (CH_4), the primary component of natural gas, burns *much more cleanly* than either coal or gasoline and as such is touted as the "cleanest" fossil fuel.

What is one potential problem of switching from coal to natural gas?

Speaking of Chemical Nomenclature

Nitrogen Dioxide: NO_2
Radical involved with numerous aspects of tropospheric and stratospheric chemistry

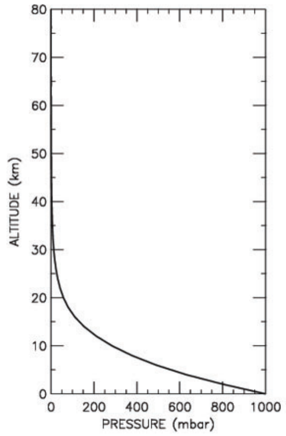
https://www.youtube.com/watch?v=0XTkO8KypUY

Nitrous Oxide aka Dinitrogen monoxide: N_2O
Very long-lived, nearly inert, well mixed greenhouse gas.
Rising abundance linked mainly to human use of fertilizer.
Causes global warming.
Decomposes in the stratosphere, leading to production of NO_2

https://www.youtube.com/watch?v=ZlHIQhJlWNs

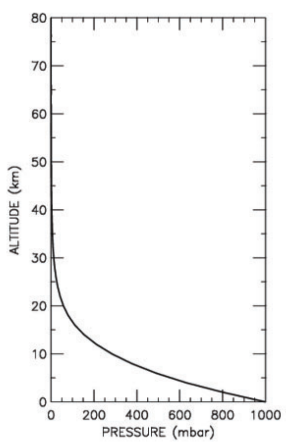
Nitrous: "Relating to or containing nitrogen"
https://www.yourdictionary.com/nitrous

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 ($8.3143 \times 10^7 \ \frac{\text{ergs}}{\text{K mole}}$), 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"

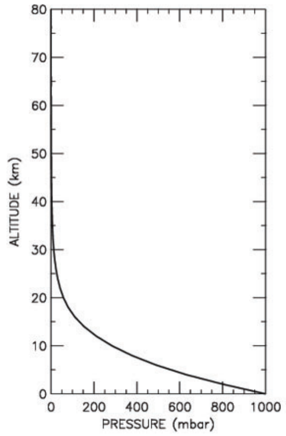
Can show H = R_{EARTH} T (z) / *grav* ,

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 $1.38 \times 10^{-19} \frac{\text{mbar cm}^3}{\text{K molecules}}$

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

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

where H is called the "scale height"

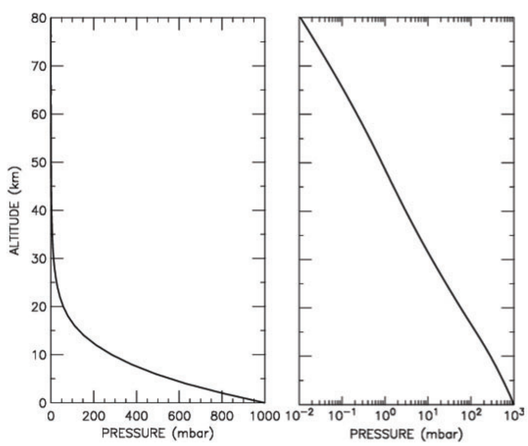
Can show H = R_{EARTH} T (z) / *grav* ,

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

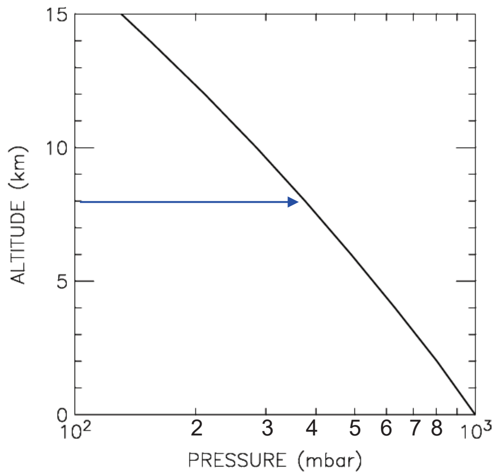


- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

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

Two plots convey the same information !

Pressure versus Altitude



p (z=0) = 1013.25 mbar

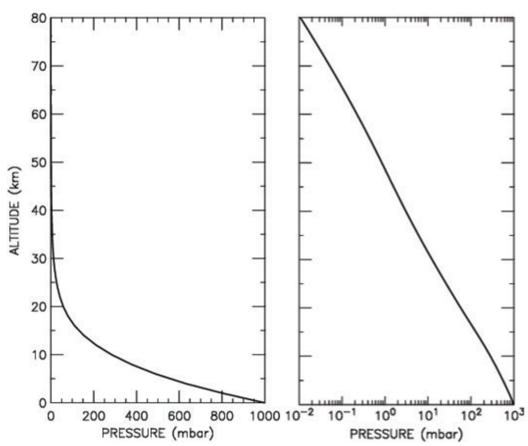
p (z=8 km) =

- **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

Pressure versus Altitude

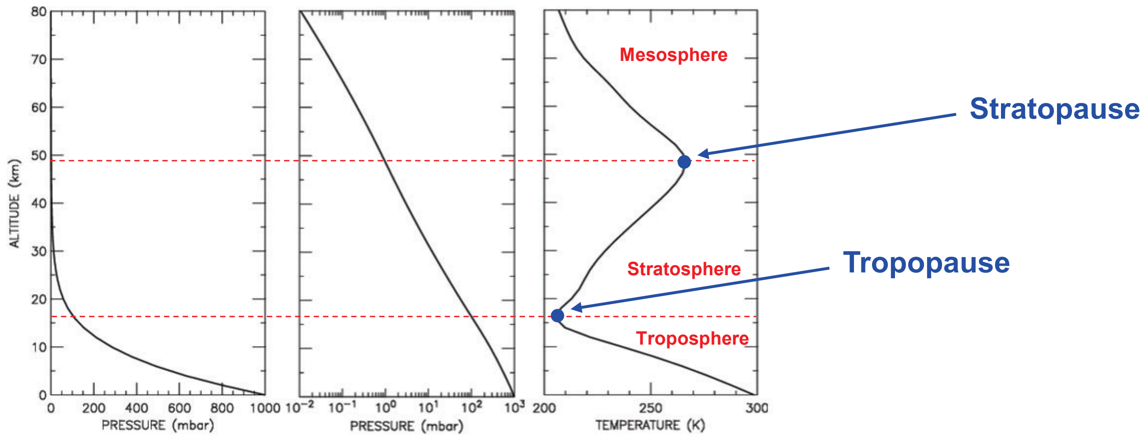


- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

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

How does pressure vary as a function of depth, in the ocean ?

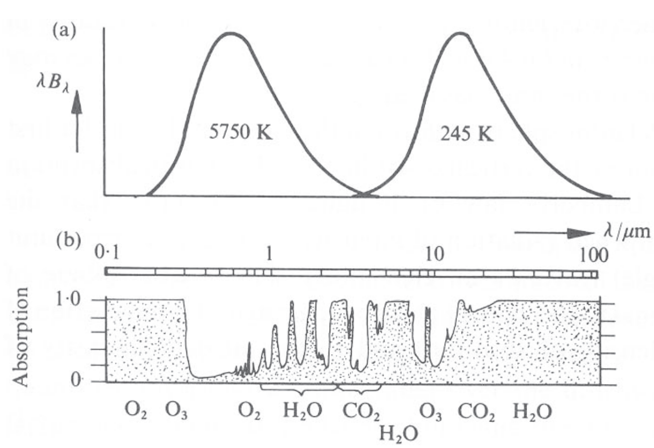
Temperature versus Altitude



- **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)

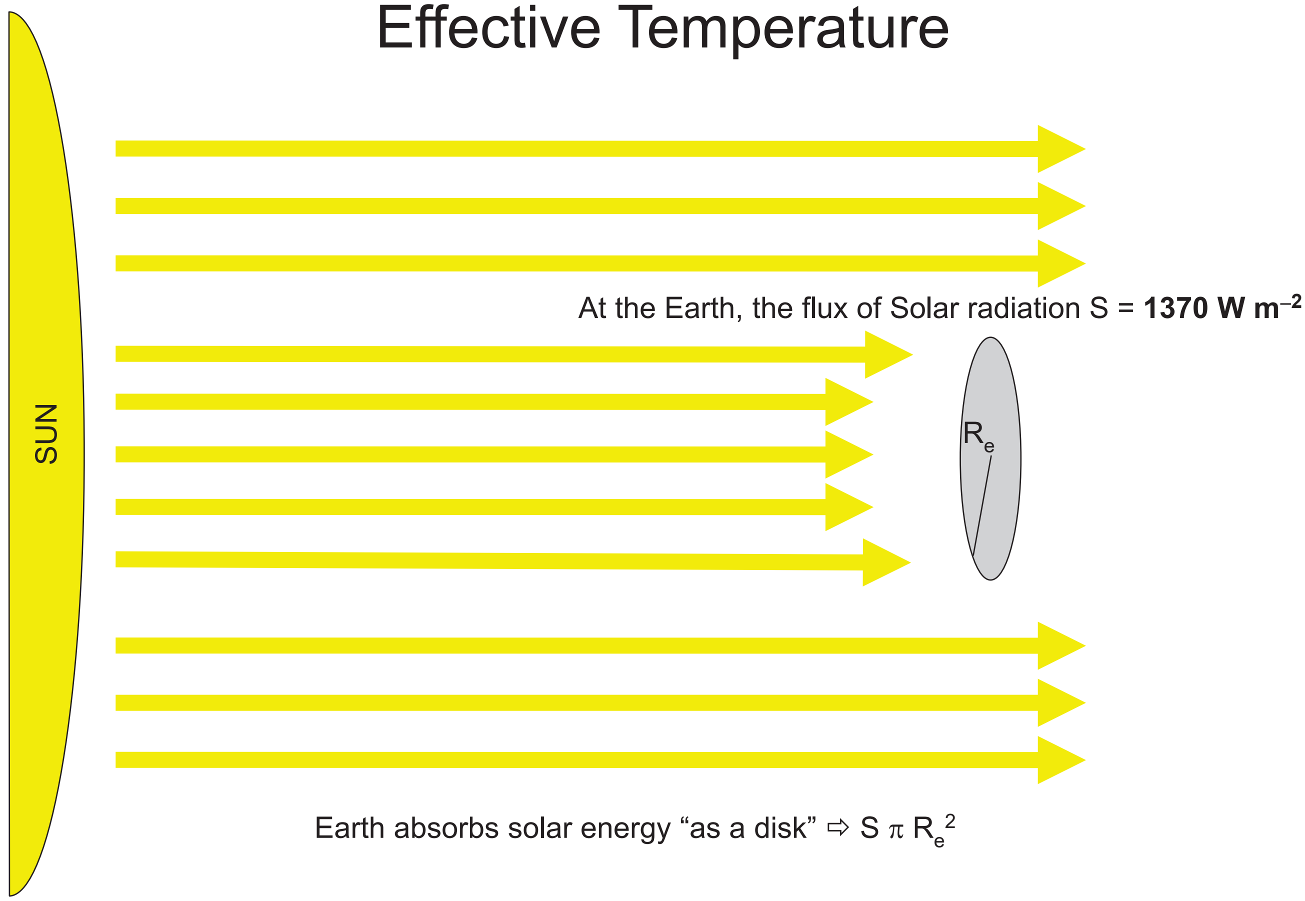


Panel (a): Black-body energy versus wavelength for 5750 K (Sun's approx T) and 245 K (Earth's mean atmospheric T). Curves are drawn with equal area since integrated over entire Earth, at top atmosphere, solar downwelling and terrestrial upwelling fluxes are in close balance.

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

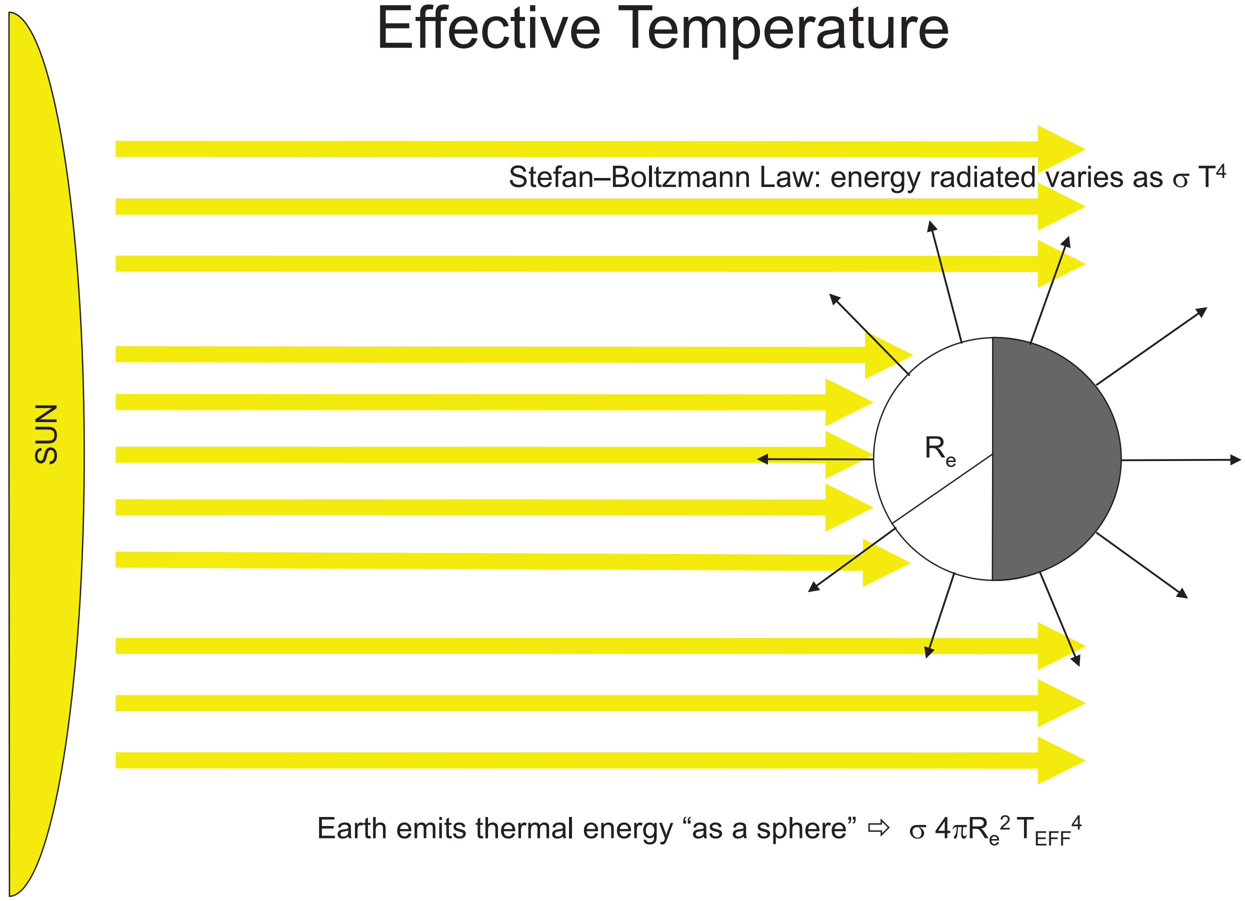
From Houghton, *Physics of Atmospheres*, 1991

Effective Temperature



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" ⇨ $\sigma\, 4\pi R_e^2\, T_{EFF}^4$

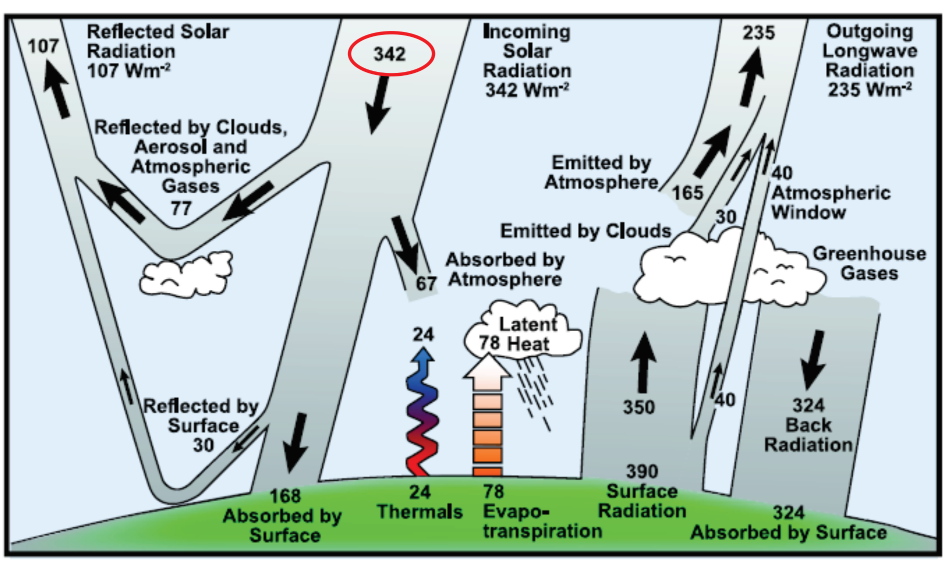
$$(1 - \text{Albedo}) \times S = 4\, \sigma\, T_{EFF}^4$$

or

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

Effective Temperature

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



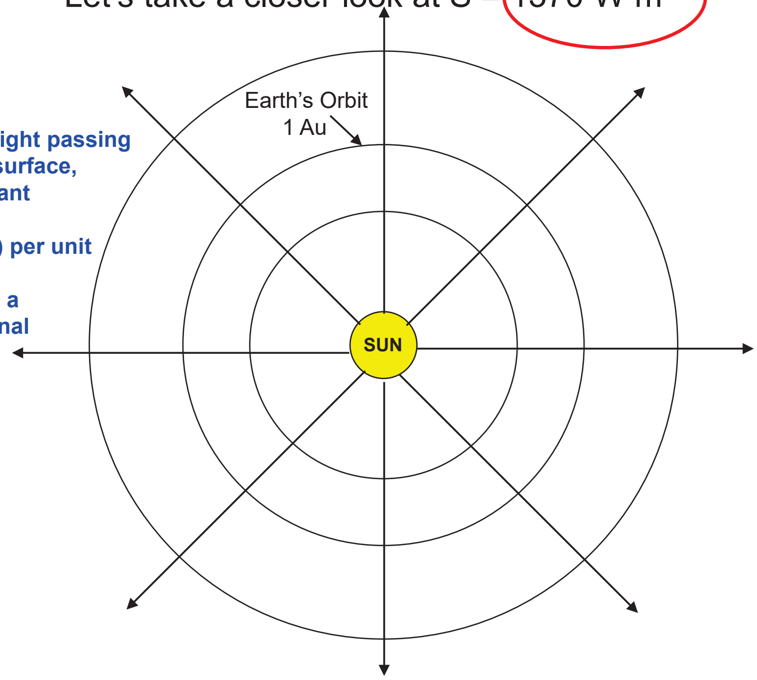
FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming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

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

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

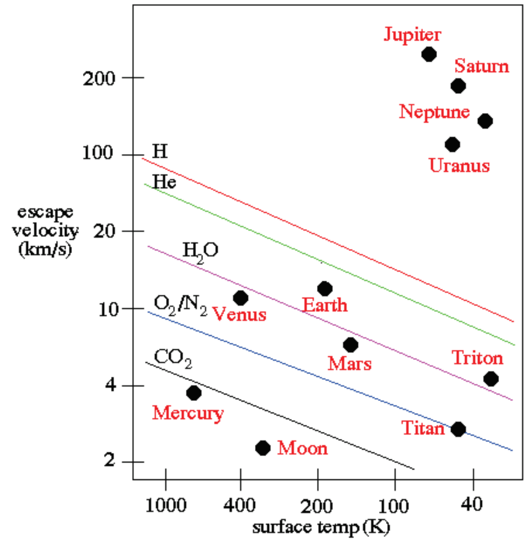
Venus:	Earth:	Mars
$T_{SURFACE} \approx 753$ K	$T_{SURFACE} \approx 288$ K	$T_{SURFACE} \approx 217$ K
$T_{EFFECTIVE} \approx$???	$T_{EFFECTIVE} \approx$???	$T_{EFFECTIVE} \approx$???

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



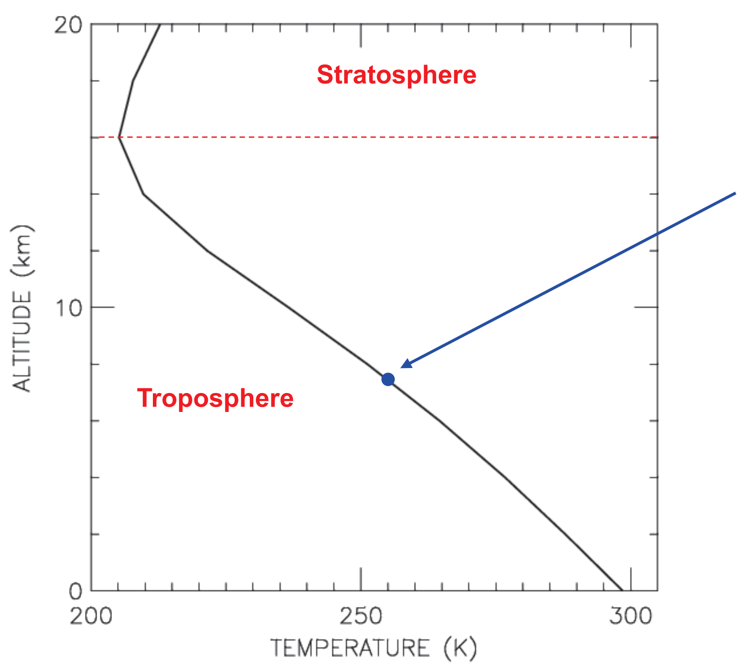
http://abyss.uoregon.edu/~js/ast121/lectures/lec14.html

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

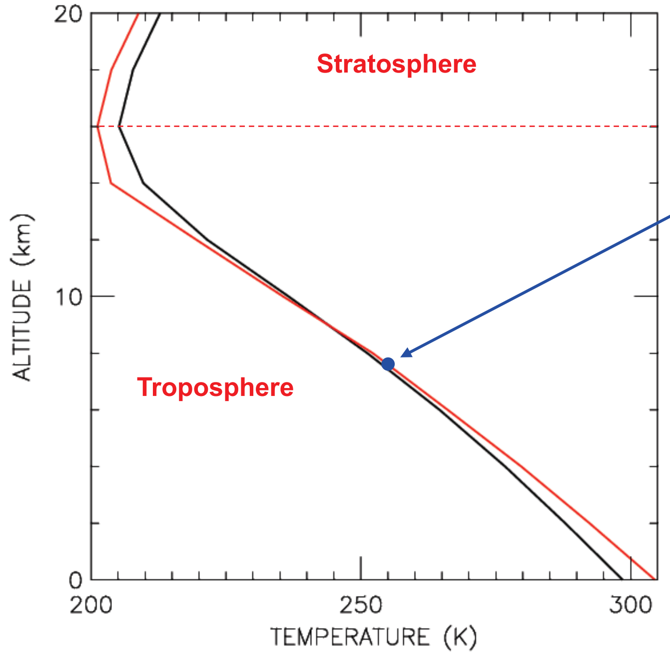


Altitude in troposphere where T = 255 K

Termed Earth’s mean radiating altitude to space

Temperature versus Altitude

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



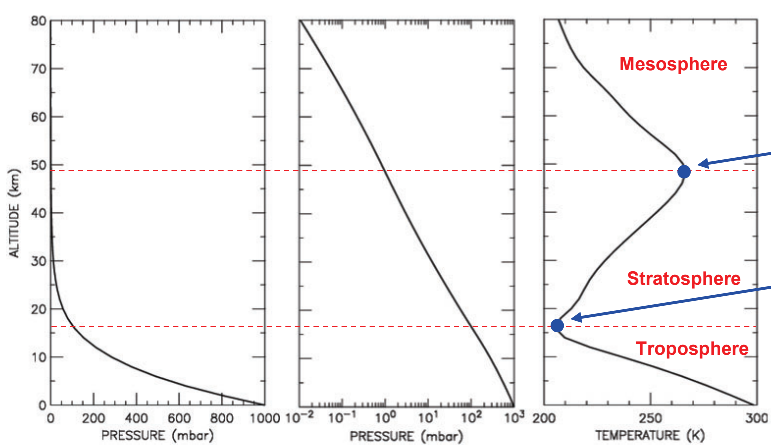
Altitude in troposphere where T = 255 K

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, $dT/dz = -\,grav / c_p$

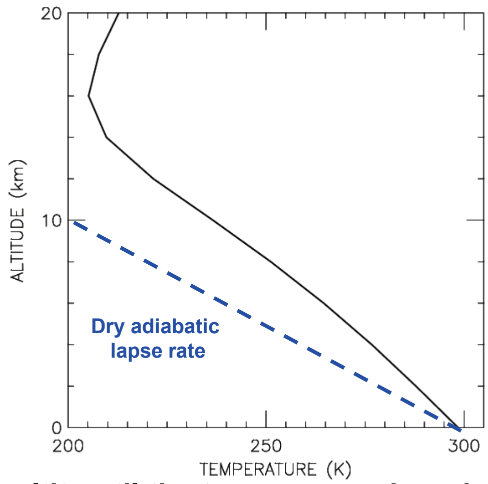
where c_p is specific heat of air at constant pressure = 1×10^7 erg gm^{-1} K^{-1}

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, $dT/dz = -\,grav\,/\,c_p$

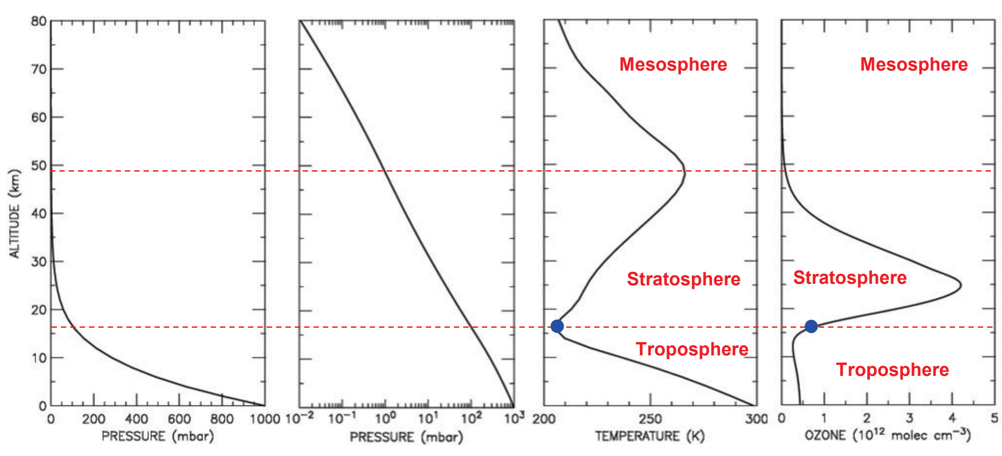
where c_p is specific heat of air at constant pressure = 1×10^7 erg $gm^{-1}\,K^{-1}$

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

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

Dry adiabatic lapse rate

Temperature versus Altitude

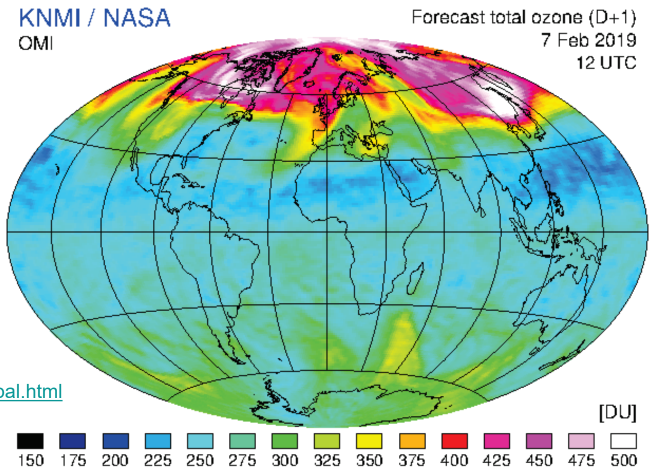


- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

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^{o}C), the resulting gas would have a thickness of how many centimeters?

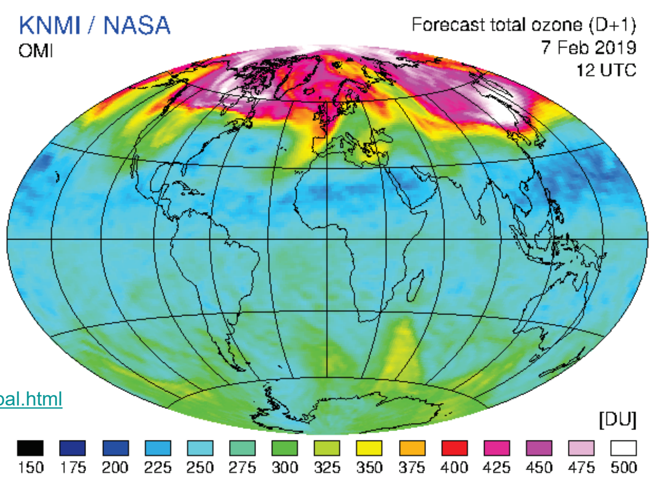


http://www.temis.nl/protocols/O3global.html

1 Dobson Unit is defined to be a 0.01 millimeter thickness of air, at "standard temperature and pressure"
Today we have about 300 Dobson Units (*CC*) = 300 × 0.01 millimeter = 3 millimeter or 0.3 cm of ozone, isolated and compressed to STP, between us and outer space.

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 centimeters?



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

Mathematically:

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

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

$$\text{It can be shown that 1 DU} = 2.687 \times 10^{16}\ \text{molecule}/\text{cm}^2$$

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 centimeters?

0.5 cm

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

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 million.***

Mean mixing ratio of ozone: 0.5 cm / 7.4 × 10^5 cm = 6.8 × 10^{-7} (no units!)

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 6.8 × 10^{-7} to ppm, need to realize 1 ppm corresponds to: $\frac{\text{1 moles of a particular gas}}{10^6 \text{ moles of all gases in the air sample}}$

Hence, 6.8 × 10^{-7} × 1 ppm / 10^6 = **0.68 ppm** ***OR*** **ppb**

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

What figure in the assigned material from *CC* provides the "explanation" to the comparison of these two values?

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 centimeters?

0.5 cm

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

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 million.***

Mean mixing ratio of ozone: 0.5 cm / 7.4 × 10^5 cm = ________(no units!)

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 6.8 × 10^{-7} to ppm, need to realize 1 ppm corresponds to: $\frac{\text{1 moles of a particular gas}}{10^6 \text{ moles of all gases in the air sample}}$

Hence, 6.8 × 10^{-7} × 1 ppm / 10^6 = **____ ppm** ***OR*** **____ ppb**

Compare your answer to the NAAQS for O_3 given in your answer to either Q1 or Q3.

Specifically:

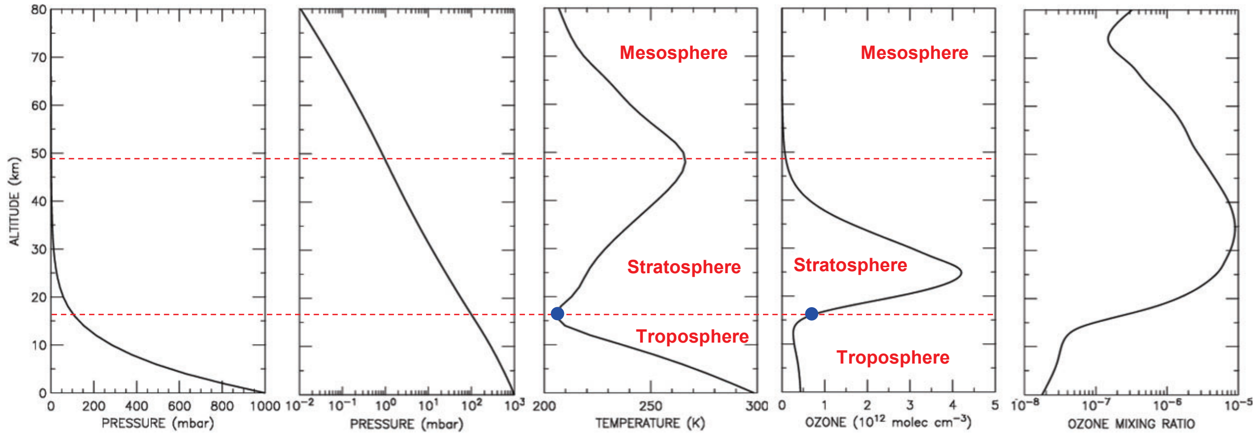
Is the mean mixing ratio of O_3 throughout Earth's atmosphere larger or smaller than the current U.S. NAAQS for O_3?

and

What figure in the assigned material from *CC* provides the "explanation" to the comparison of these two values?

Mean mixing ratio of O_3 in Earth's Atmosphere >> than U.S. NAAQS
Much higher mixing ratios of O_3 in the stratosphere than ever exists near the surface

Temperature versus Altitude



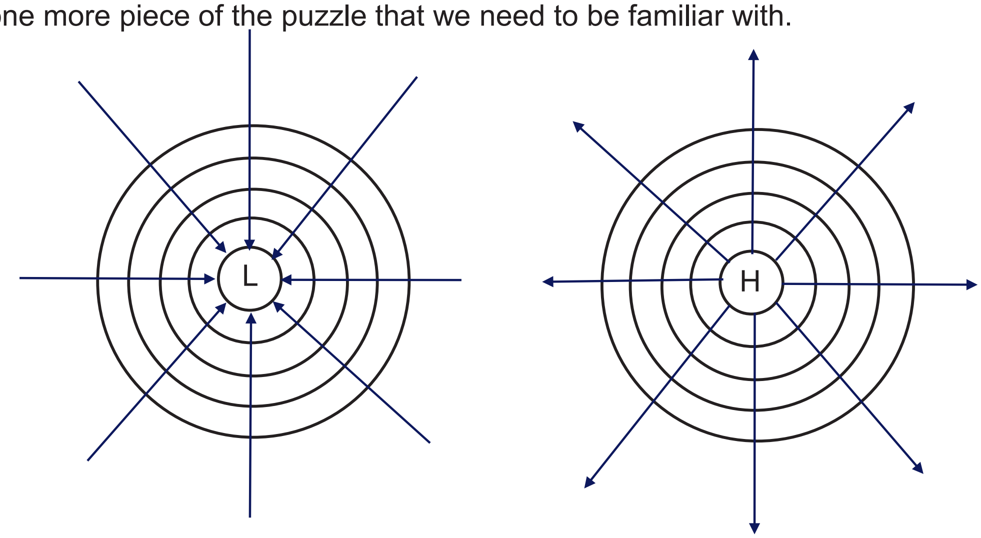
- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

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

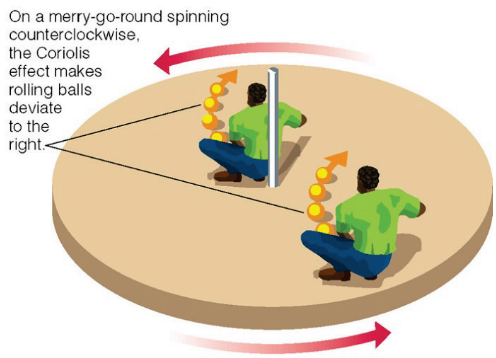
So far, we've reviewed temperature, pressure, and the balance between solar energy input to the atmosphere and terrestrial radiation leaving the atmosphere.

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



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

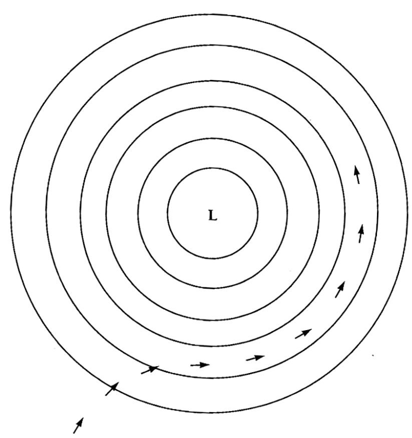


Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

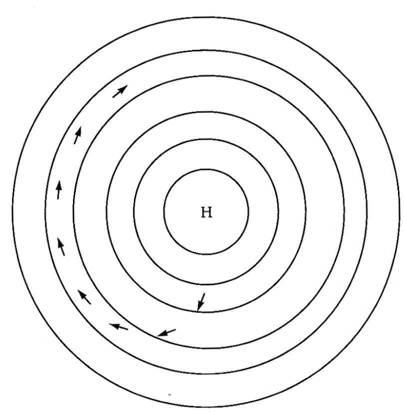


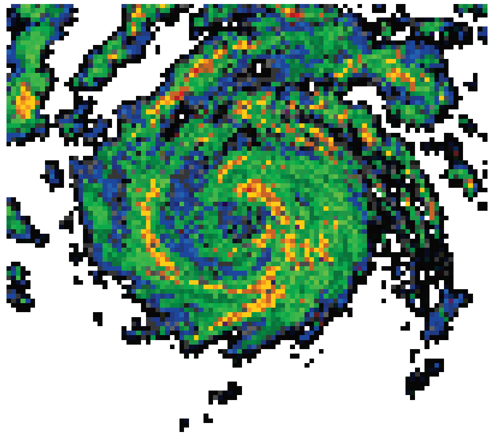
Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

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

Geostrophic balance: balance between Coriolis Force and pressure gradient

Geostrophy

NH Weather System:

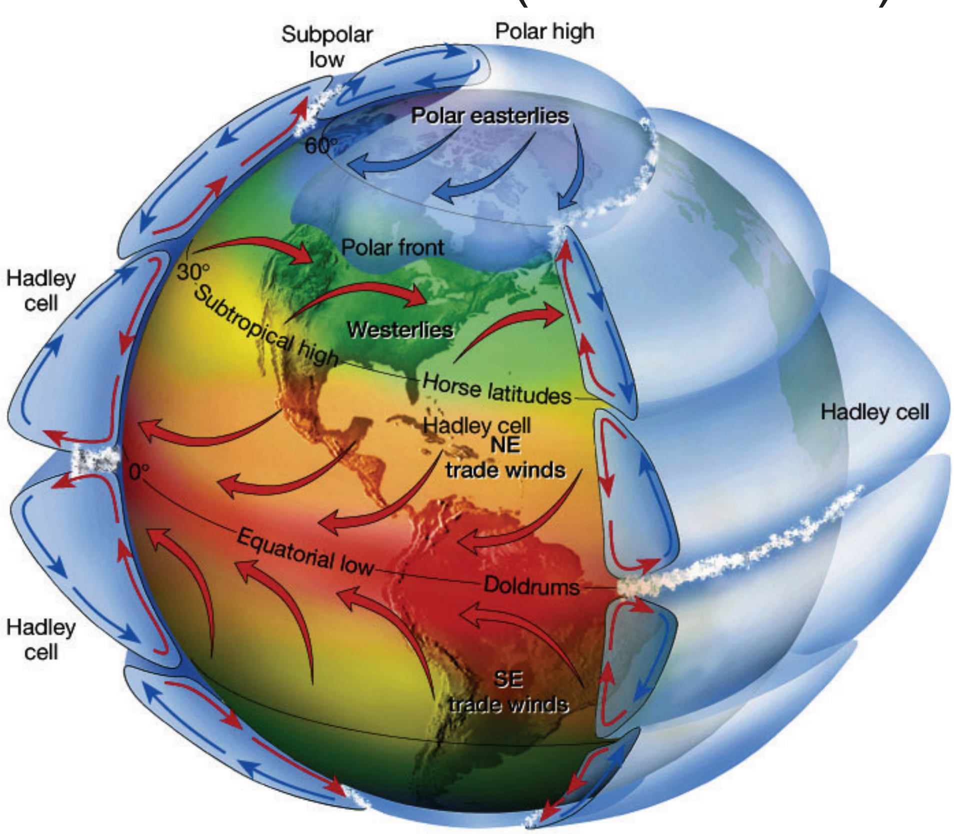


Cyclonic Flow: when the wind swirls
counter-clockwise in the NH

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 (~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 ATL2416 to open psswrd protected files