



# Composition of the Atmosphere



Pages 6 – 22 of UWC

Chapter 1 of MSE

Sections 1.2, 1.3, 1.5, and 1.6 of AS



# Topics In This Section

- Composition of the atmosphere
- Past Atmospheres
- Hydrosphere and atmospheric oxygen
- Distribution of atmospheric constituents and mass
  - Hydrostatic equation
  - Changes in pressure and density with height
- Temperature and stratification
- Layers of the atmosphere

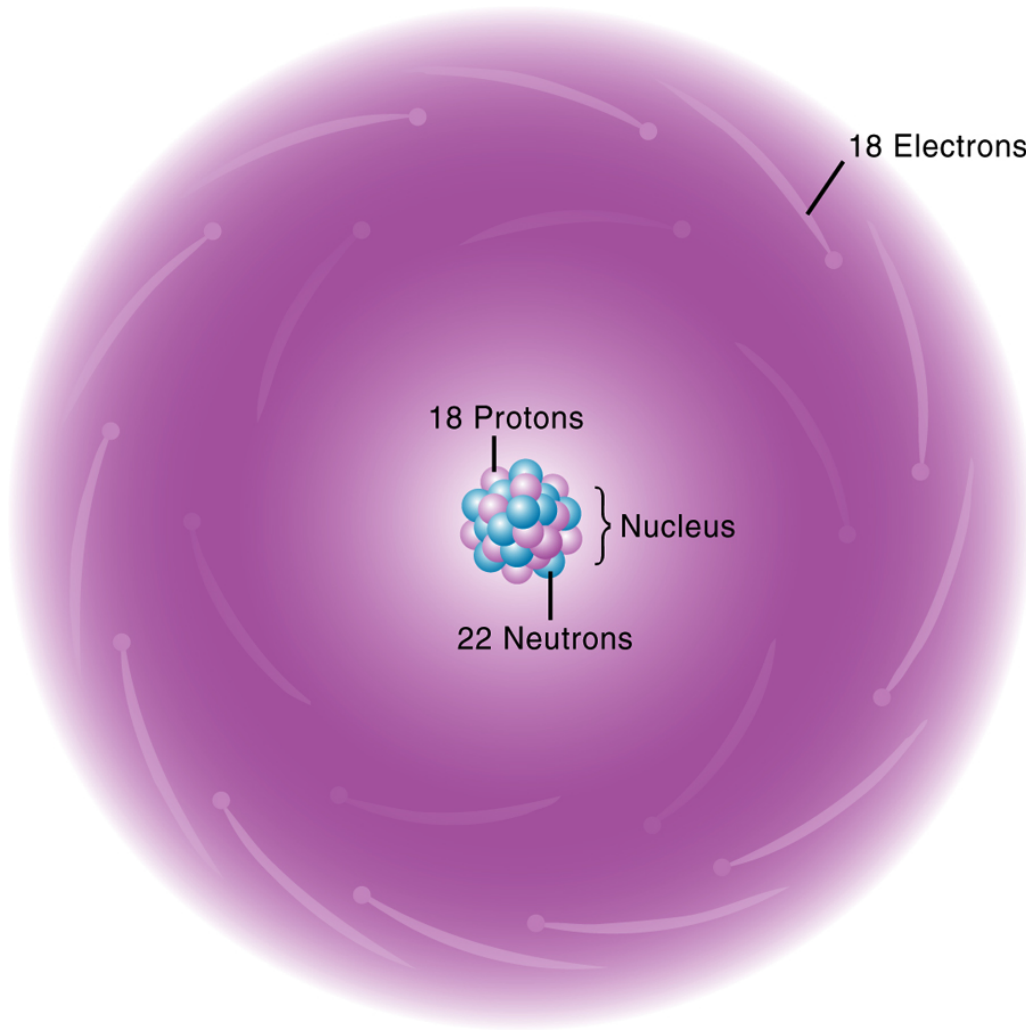


# Properties of Matter

- Key properties can be divided into large-scale and small (atomic) scale properties.
  - Small scale feature are related to atomic structure.
    - Elements
    - Molecules, and
    - Mixtures
  - Large scale properties are
    - Volume
    - Mass
    - Number of molecules
    - Density (mass per unit volume)
    - Pressure (force per unit area)
    - Temperature



# An Argon Atom



- Atoms are made up of protons, neutrons, and electrons.
- For a neutrally charged atom, the number of protons (charge +1 each) equals the number of electrons (charge of -1 each)
- The number of neutrons is equal to or greater than the number of protons.
- The nucleus is made up of protons and neutrons.
- Electrons move rapidly around the nucleus

Graphic from *Meteorology* by Danielson, Levin and Abrams



# Molecules

- Molecules are groups of atoms that are bonded together

- Examples are  $O_2$  (molecular oxygen),  $O_3$  (ozone)

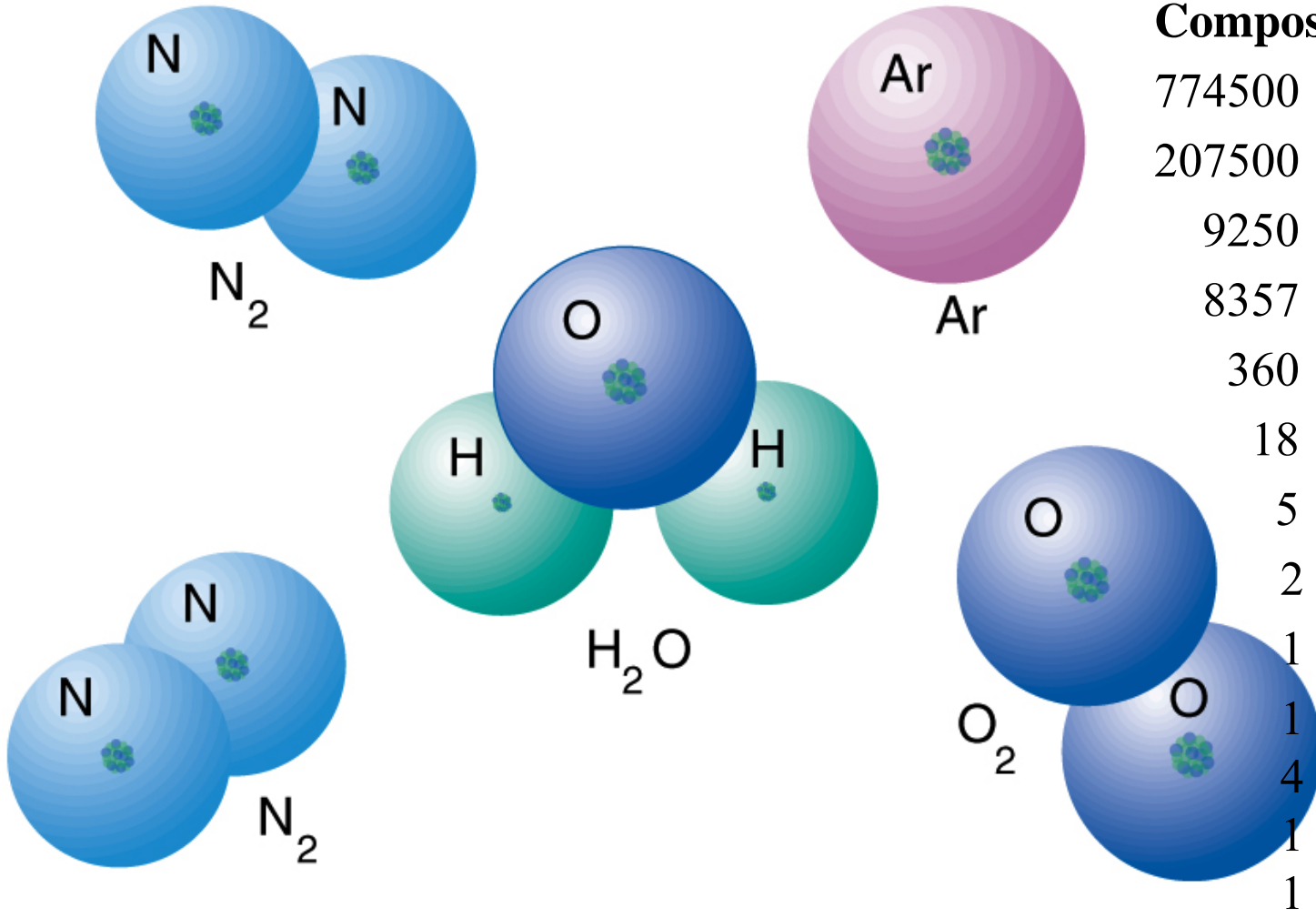
Symbol for element      number of atoms

$CO_2$  (carbon dioxide),  $NH_3$  (Ammonia),  $H_2O$  (water)

- A substance formed from a single type of molecule is called a compound.
- A mixture is a collection of different atoms or molecules.



# Typical Molecules in the Air



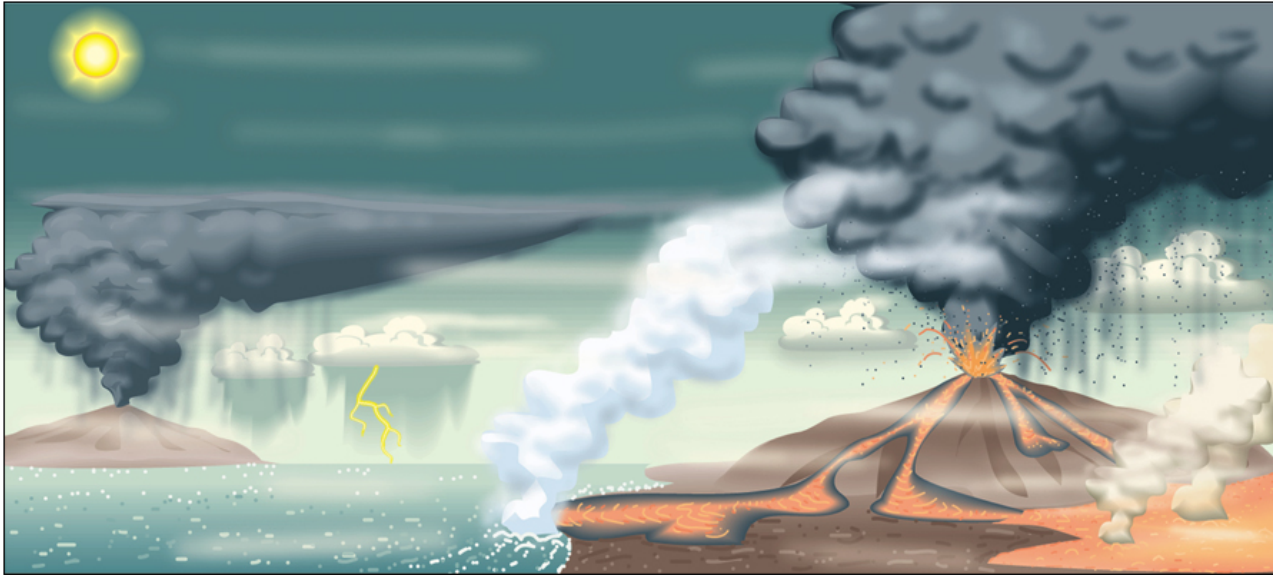
## Composition of Air (ppm)

774500	Nitrogen
207500	Oxygen
9250	Argon
8357	Water vapor
360	Carbon Dioxide
18	Neon
5	Helium
2	Methane
1	Krypton
1	Hydrogen
4	Dust particles
1	Water droplet
1	Pollen grain

Graphic from *Meteorology* by Danielson, Levin and Abrams



# Past Atmospheres of Earth



- The earliest atmosphere of the earth probably contained far more hydrogen and helium than the current atmosphere.
  - These light gasses were lost soon after the planet formed.
- New atmosphere believed to have originated from outgassing from volcanoes and steam vents

# Past Atmospheres of Earth

- Typical concentrations in volcanic gas:
  - Water vapor (85%), carbon dioxide (10%), a few percent nitrogen, sulfur and sulfur compounds
  - Note there is negligible oxygen
- Constant outgassing provided a supply of water vapor for cloud development and rain leading to the formation of bodies of surface water
- Oxygen likely came from the reaction of ultraviolet radiation with water (photodissociation)
  - Splits the water into hydrogen and oxygen
- Photosynthesis further increased the atmospheric oxygen content
  - Takes in carbon dioxide and gives off oxygen



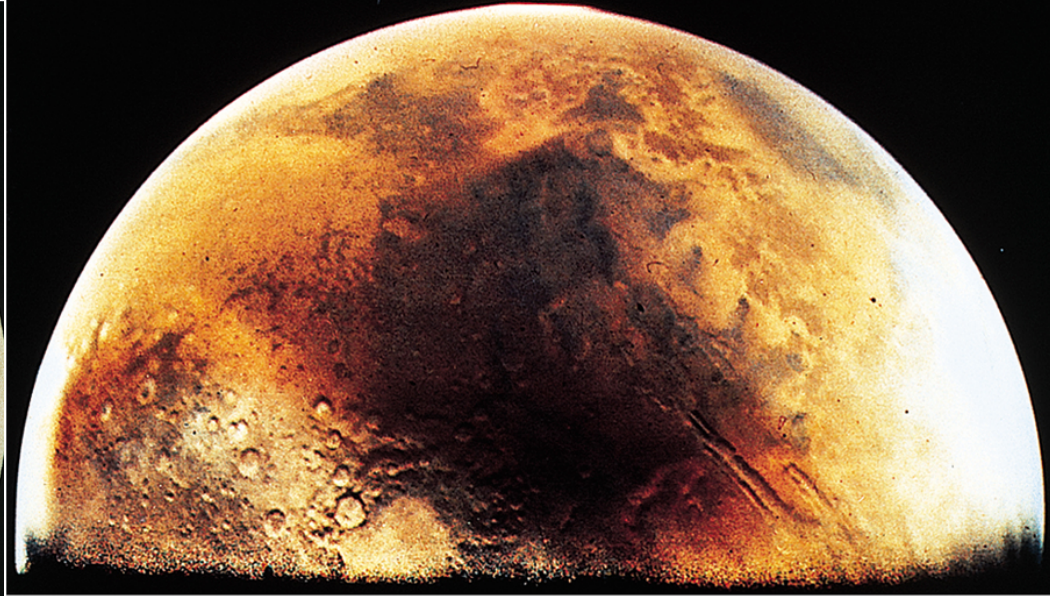
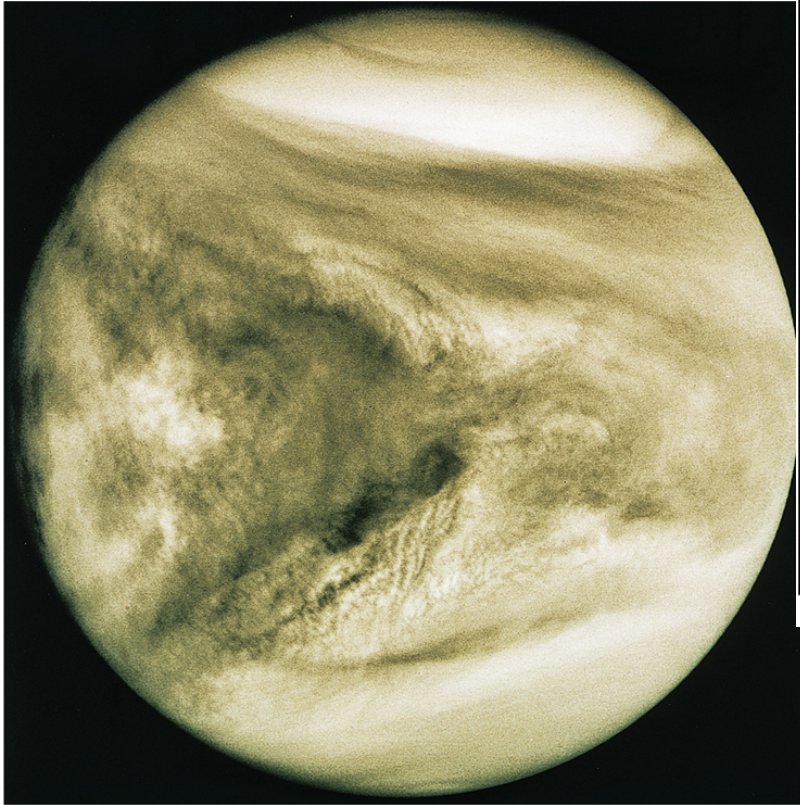


# Where is the Water Now?

- The following breakdown of water sources comes from a 1972 study by H. H. Lamb.
  - 97% Oceans
  - 2.4% Ice
  - 0.6% Fresh water below ground
  - 0.02% Fresh water in lakes and rivers
  - 0.001% Atmospheric water (rain droplets and water vapor)
- These number are currently known in much more detail due to attempts to explain observations of sea level rise (~1.8mm/yr).
  - In the long run (how long?) we would like to know if this observed rate of sea level change is likely to continue.



# Venus and Mars



B

Graphics from *Meteorology* by Danielson, Levin and Abrams

- Venus and Mars have atmospheres that are mostly (>95%) CO<sub>2</sub>.
  - The surface conditions of Venus are 470°C and 90,000mb.
  - The surface conditions on Mars are -60°C and 7mb.
- Note that Venus's surface gravity is 0.894g, while Mar's 0.379g.



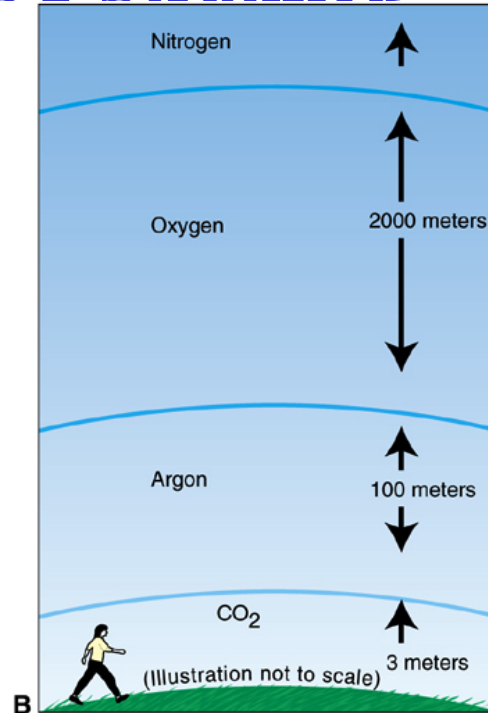
# Sources of Atmospheric Oxygen

- There are two suggested processes for converting Oxygen in water (H<sub>2</sub>O) to Oxygen gas (O<sub>2</sub>).
  - Dissociation due to the absorption of energetic light
    - $2 \text{H}_2\text{O} + \text{UV light} \rightarrow 2\text{H}_2 + \text{O}_2$
    - Rate of production of oxygen depends upon rate that hydrogen escapes to space
    - If escape rate is much slower than production rate then most of the oxygen will recombine with hydrogen to form water
  - Photosynthesis
    - $\text{H}_2\text{O} + \text{CO}_2 \rightarrow \{\text{CH}_2\text{O}\} + \text{O}_2$
    - Where {} indicates a product of the atoms indicated in the brackets.
    - This process is linked to living organisms.





# The Atmospheric Constituents are NOT Stratified



- If there is little mixing of a liquid, the most dense material will sink to the bottom.
- Does this happen in a mixture of gasses such as our atmosphere?

- **Mixing due to fluid motions** in lower atmosphere (below ~ 100 km) causes principle gases (Ar, O<sub>2</sub>, and N<sub>2</sub>) to be independent of height
- Above ~ 100 km **molecular diffusion** dominates causing lighter molecules to found at higher altitudes

Graphics from *Meteorology* by Danielson, Levin and Abrams

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# Properties of Matter

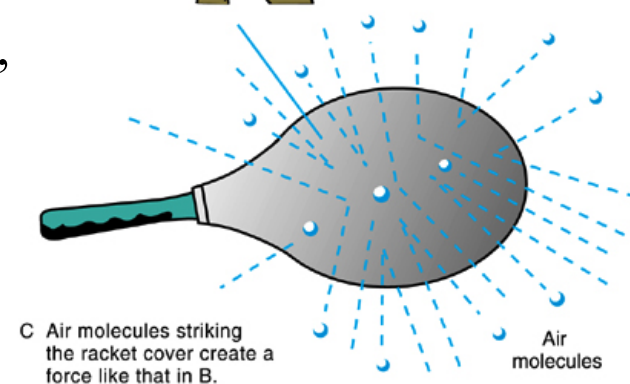
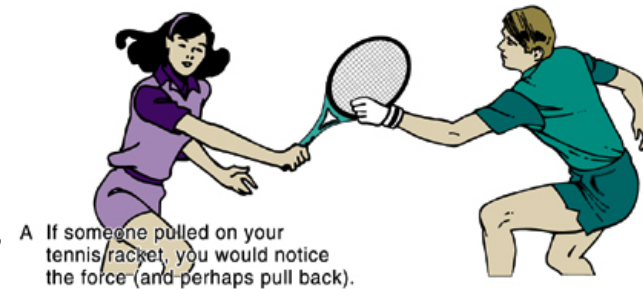
Key properties can be divided into large-scale and small (atomic) scale properties.

- Large scale properties can be further divided into
  - properties that do change when the material is subdivided:
    - Volume
    - Mass
    - Number of molecules
  - those that don't change when the material is subdivided:
    - Density
    - Pressure
    - Temperature
- Small scale features are related to atomic structure.



# Pressure Applied By A Gas

- Pressure is a force per unit area.
  - Why is the example of someone pulling on a tennis racket a good example of force but not pressure?
- Pressure is uniform over the area to which it is applied – in the absence of external forces.
- Given sufficient time, the distribution of molecules striking the tennis racket will be well approximated as uniform.
- More energetic molecules move faster, and consequently hit the surface more often.



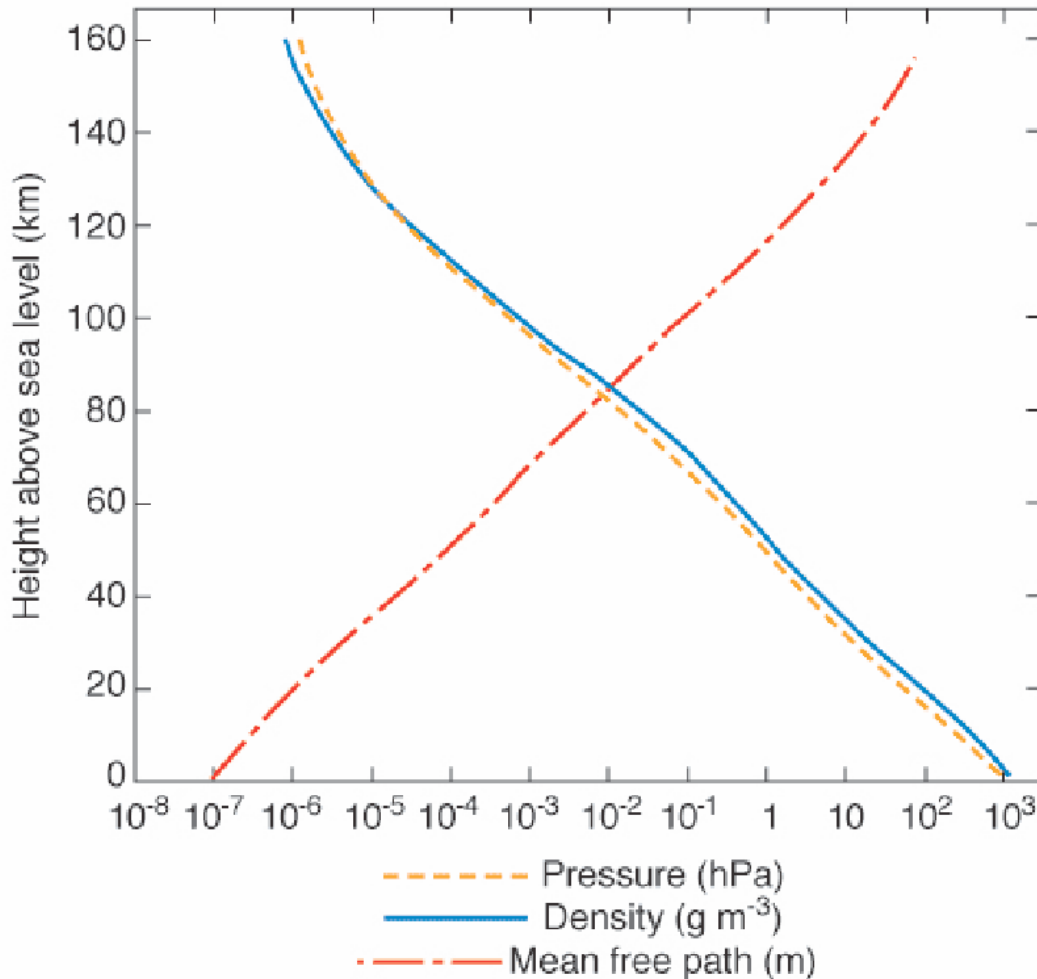
Graphic from *Meteorology* by Danielson, Levin and Abrams  
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# Changes in Pressure with Altitude: Hydrostatic Equation

- One of the key equations in Meteorology is the **hydrostatic equation**.
  - It describes the change in pressure ( $P$ ) with changes in height ( $z$ ).
  - Strictly speaking, it is accurate only when vertical motion can be ignored (when the pressure force balances the gravitational force).
- The hydrostatic equation is
$$\partial P / \partial z = -\rho g$$
, where  $\rho$  (rho) is density, and  $g$  is gravitational accel.
  - For those of you uncomfortable with calculus, you can think of this as  $\Delta P / \Delta z = [P(z_2) - P(z_1)] / [z_2 - z_1] = -\rho g$ , where the density and gravitational attraction are similar at the two heights.
  - The negative sign indicates that pressure decreases as altitude increases
- Pressure has units of *force* (N) per unit *area* ( $m^2$ )
  - In this case, *force* is equal to the *mass* at greater altitude times *gravitational attraction*
- Is  $\partial P / \partial z$  different below the ocean's surface?



# Changes in Value with Height

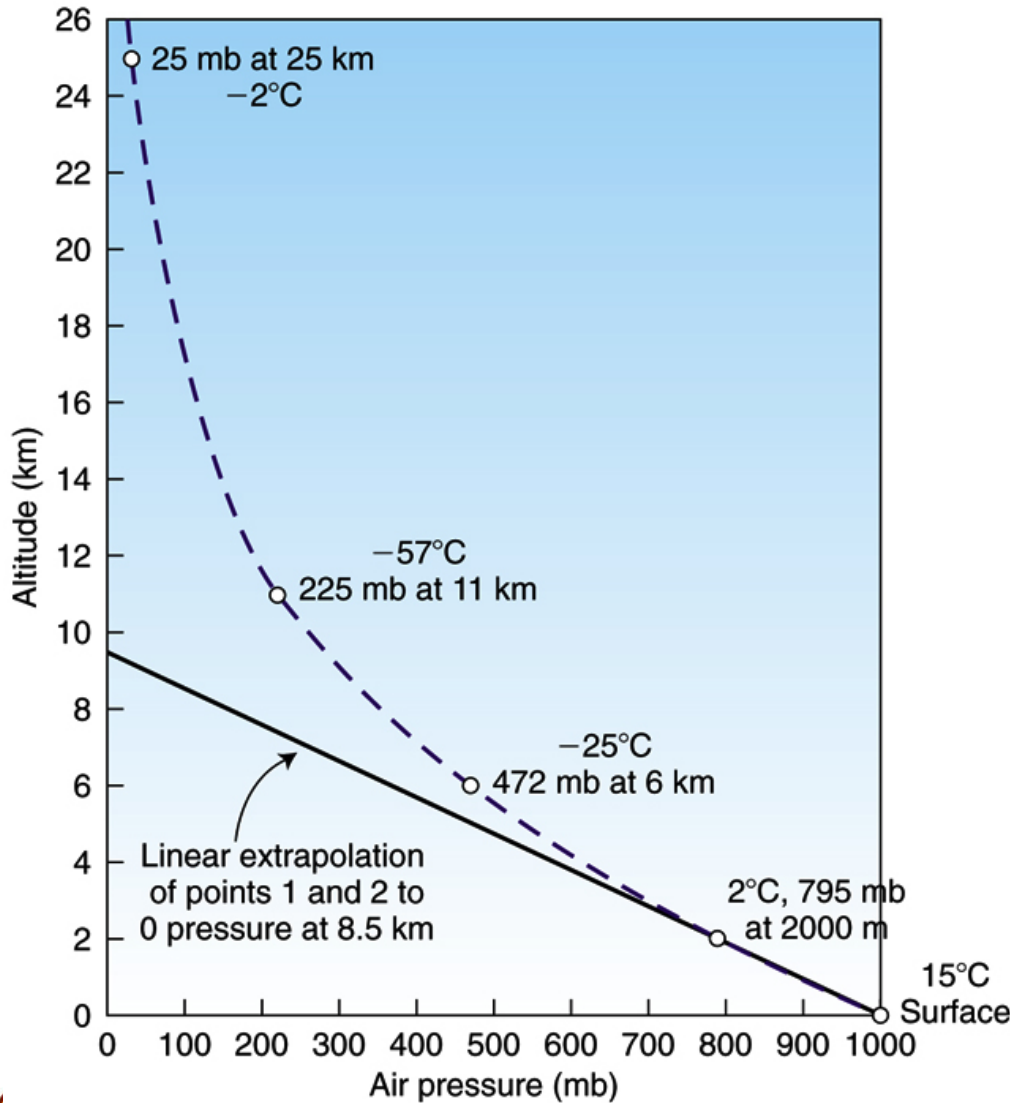


- In the lower atmosphere, the pressure, density, and the mean free path change approximately linearly with height.
- The mean free path is the average distance a particle travels before colliding with another particle.





# Changes with Altitude

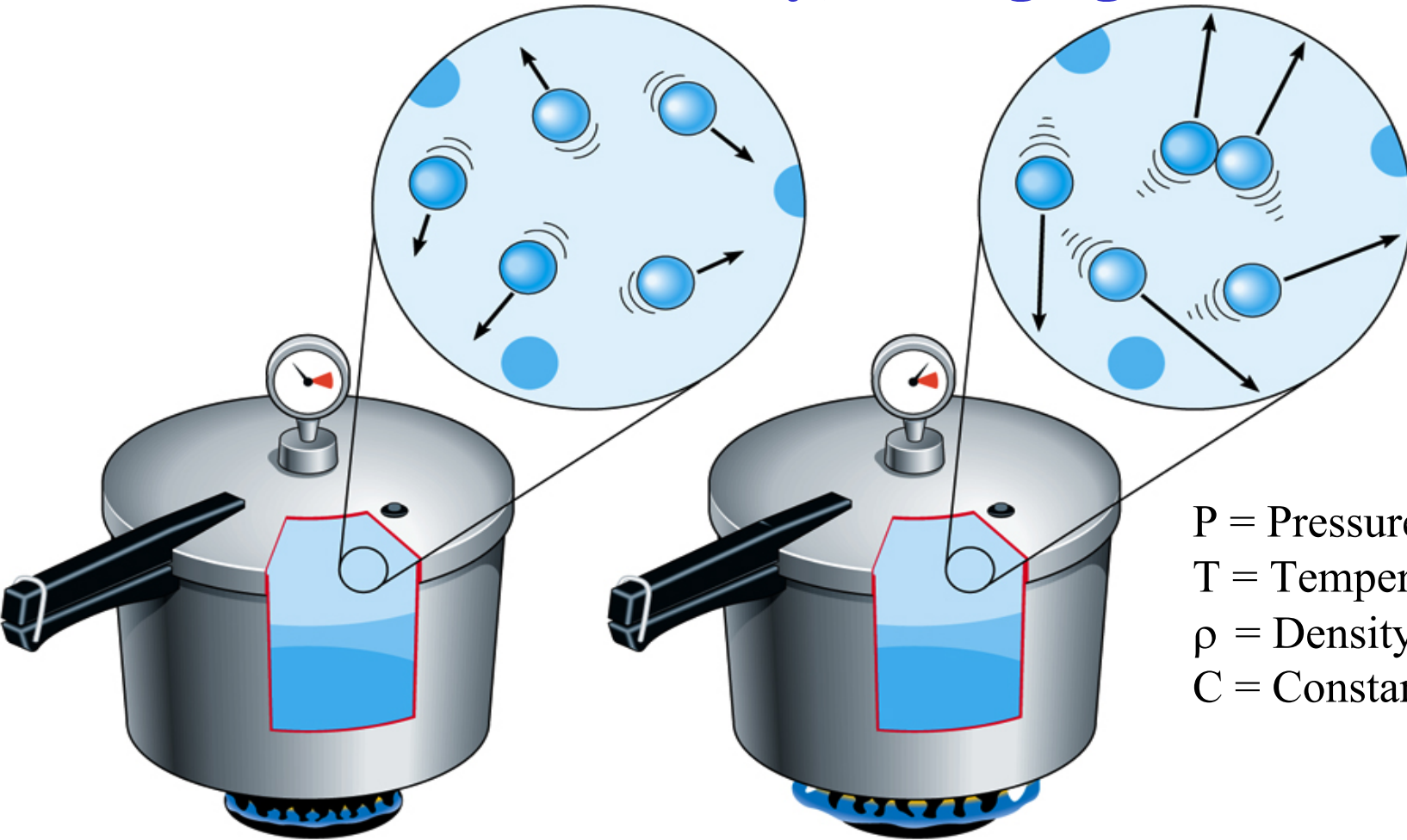


- The mean surface pressure is 1013 mb
- See that  $\Delta P / \Delta z = [P(z_2) - P(z_1)] / [z_2 - z_1]$  decreases as the pressure decreases.
  - Why?
  - How does density change with height ( $\rho = \text{mass}/V$ )?
- If we assumed a constant density, then the thickness of the atmosphere would be <10 km

Graphic from *Meteorology* by Danielson, Levin and Abrams



# Pressure Cooker Example: Constant density; Changing T & P



P = Pressure  
T = Temperature  
 $\rho$  = Density  
C = Constant

$$P = C \cdot \rho \cdot T$$

$$P = C \cdot \rho \cdot T$$

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# Change In Temperature With Height (The Lapse Rate)

- In meteorology jargon, the rate at which the air temperature decreases with height is called the temperature lapse rate ( $-dT/dz$ )
  - Average (or standard) lapse rate:  $\sim 6.5^{\circ}\text{C km}^{-1}$ 
    - Variable in time and space
  - Dry adiabatic lapse rate:  $\sim 10^{\circ}\text{C km}^{-1}$ 
    - Change in temperature due to a parcel rising (expanding & cooling) or sinking (compress & warm) with no interchange of heat with its surroundings
    - Air in parcel is unsaturated (no heat added via condensation)
  - Moist adiabatic lapse rate: less than dry adiabatic lapse rate
    - Rate at which rising or sinking saturated air changes temperature

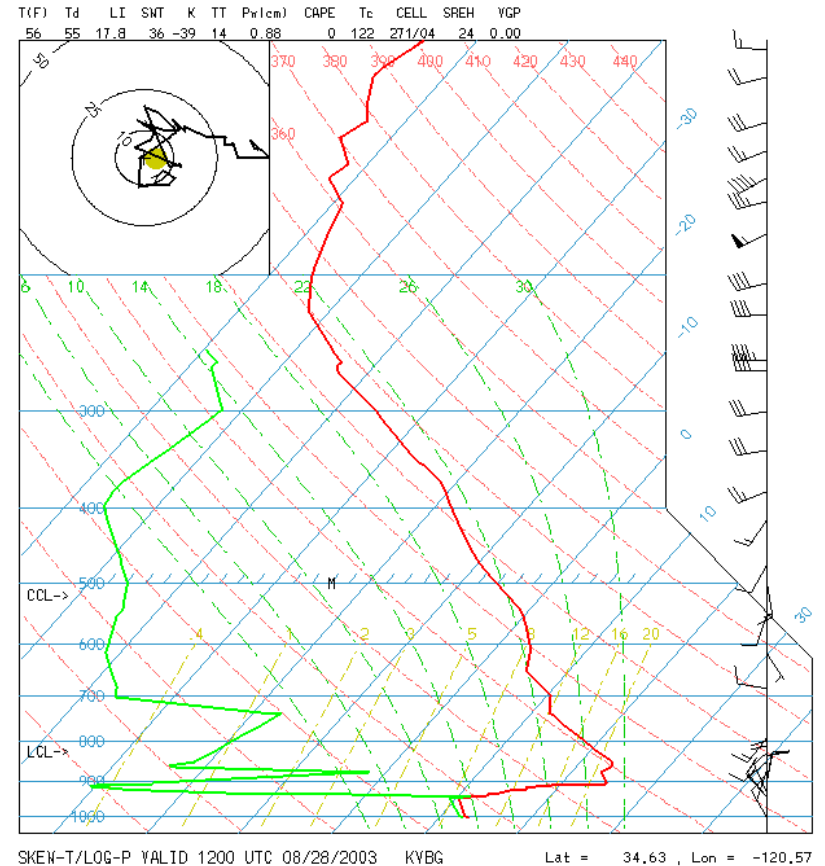
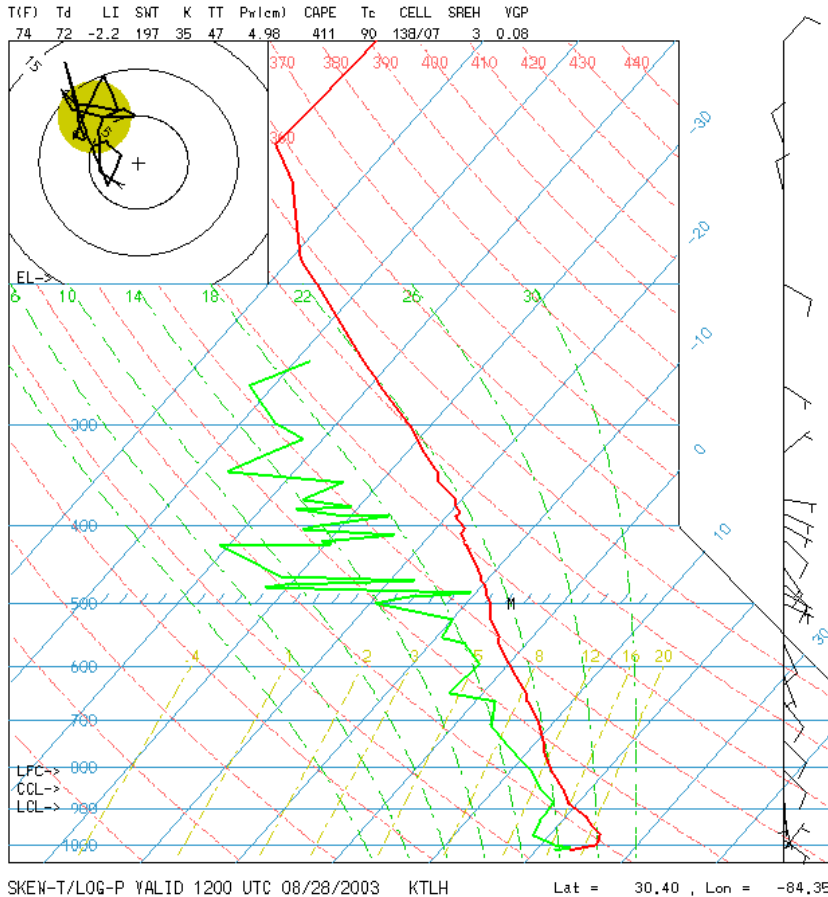


# Atmospheric Stratification

- We have already said that the lower atmosphere is chemically well mixed: the distribution of atmospheric constituents is homogeneous.
- The parts of the atmosphere are stratified.
  - Stable stratification occurs when more energetic air (less dense air) is above less energetic (more dense) air.
    - Stable layers inhibit vertical mixing, and can be maintained.
    - For example, radiation and subsidence inversions
  - Unstable stratification occurs when less energetic air (more dense air) is above more energetic (less dense) air.
    - Unstable layers increase vertical mixing, and will not be maintained without external forcing.
  - Neutral stratification is neither stable nor unstable.
- The above concepts work well for small changes in location. Why to they fail for larger changes?



# Temperature and Moisture Profiles



Tallahassee (TLH)  
August 29. 2003

Vandenberg AFB (central CA)  
Example from [www.rap.ucar.edu/weather](http://www.rap.ucar.edu/weather)



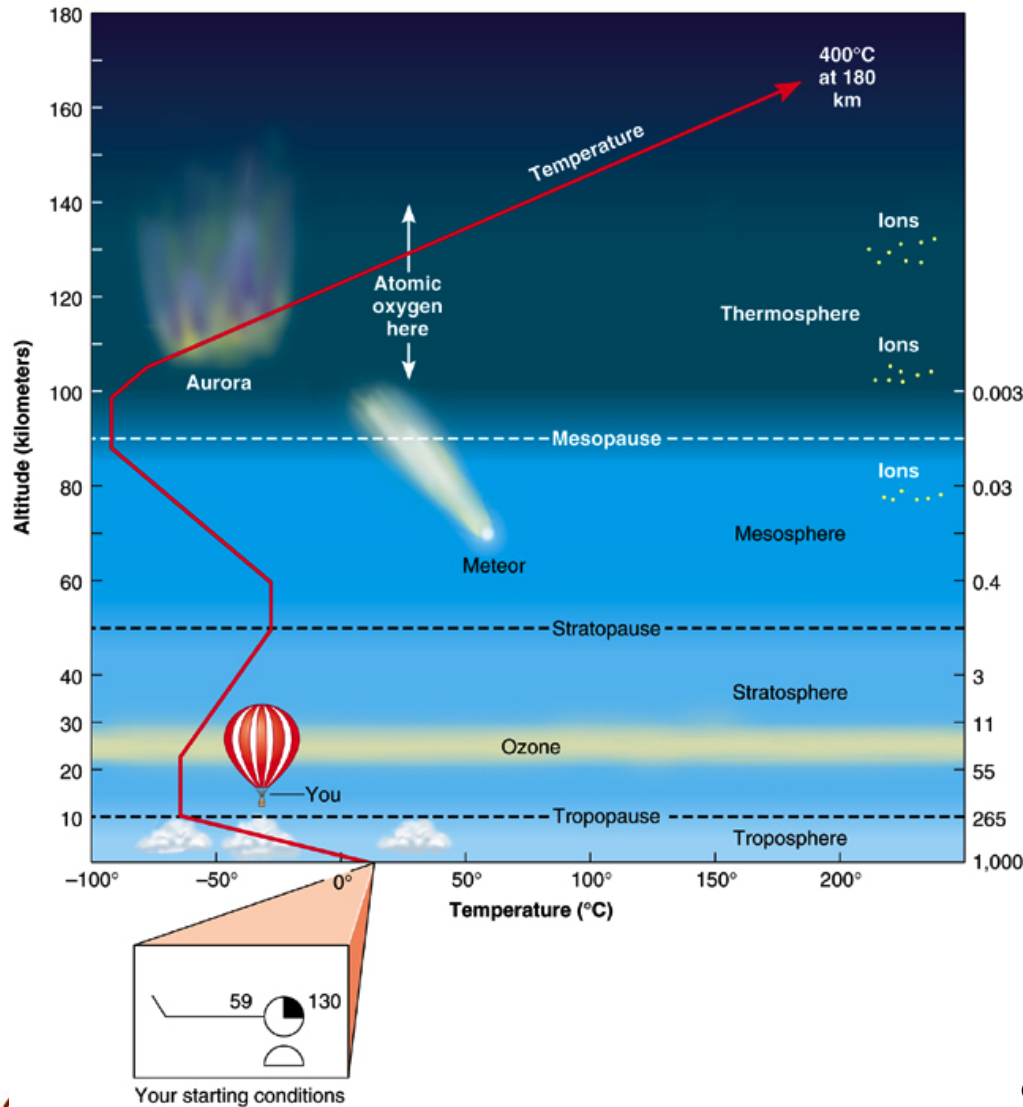
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# Layers of the Atmosphere



- Layers & boundaries

- Thermosphere

- Mesopause

- Mesosphere

- Stratopause

- Stratosphere

- Tropopause

- Troposphere

- The ‘**pause**’ layers are relatively thin boundaries between the larger layers

- The rate of temperature change with altitude changes sign in these boundary layers

Graphic from *Meteorology* by Danielson, Levin and Abrams

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# Troposphere

- This is the layer of the atmosphere that people live in.
  - There is considerable variability in all layers.
  - When we speak of weather, we are usually discussing variability in the troposphere.
  - The troposphere is capped by a stable layer called the tropopause.
    - Almost all clouds are within the troposphere.
    - A few storms with extremely strong updrafts can pierce the tropopause; others can change the height of the tropopause.
- The temperature (an average) decreases with height within the troposphere.
- The thickness of the troposphere changes with latitude. It is about 16 km at the equator, and about 11 km at mid-latitudes.



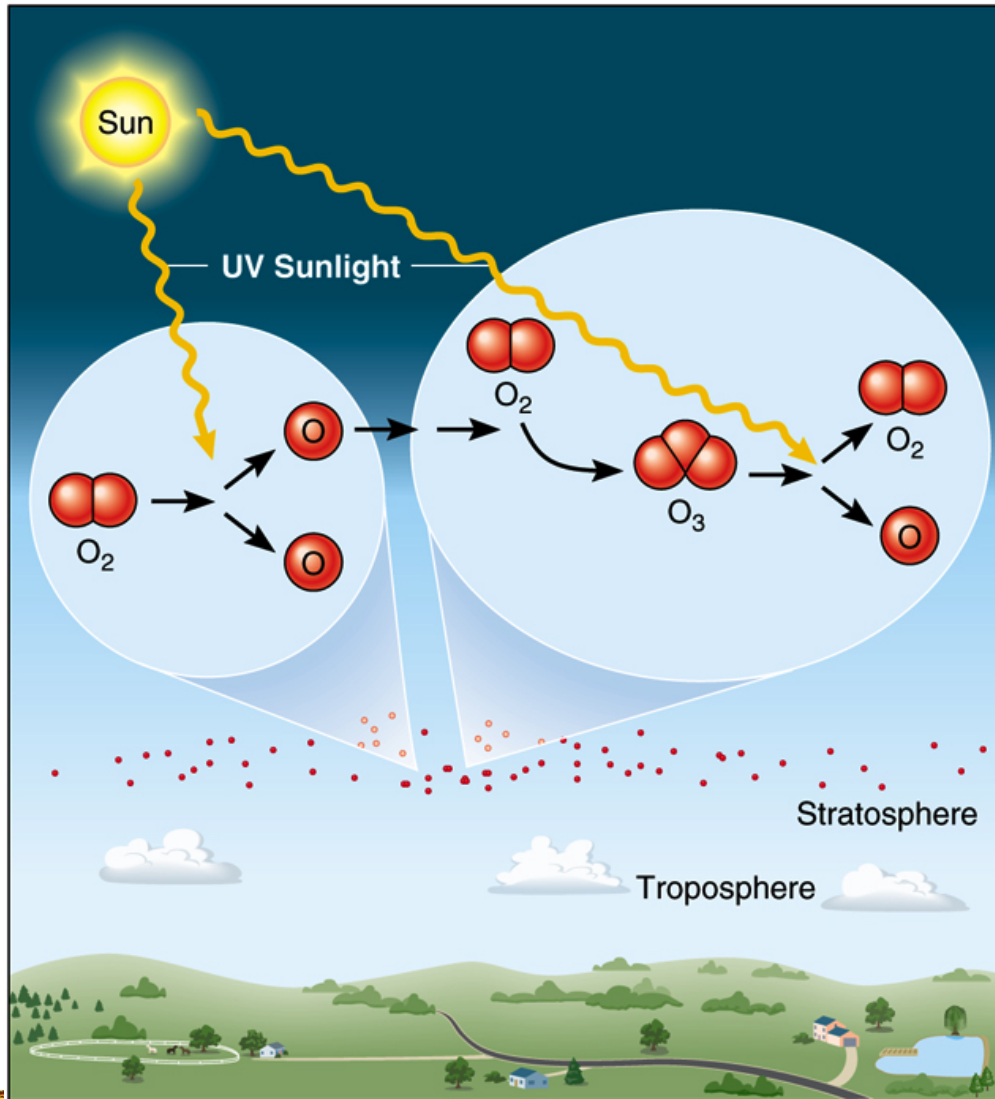
# Stratosphere

- The layer above the troposphere.
- One of the key features of this layer is relatively large concentrations of ozone.
- Ozone absorbs relatively larger quantities of ultraviolet light from the sun.
  - This absorption heats the lower stratosphere, resulting in the tropopause.
  - Without this ozone, much more ultraviolet light would reach the surface of the earth, presumably resulting in different characteristics of plants and animals.
- Much of the other radiation is absorbed in the thermosphere.
- What does this suggest about man-made habitats on airless planets or moons?





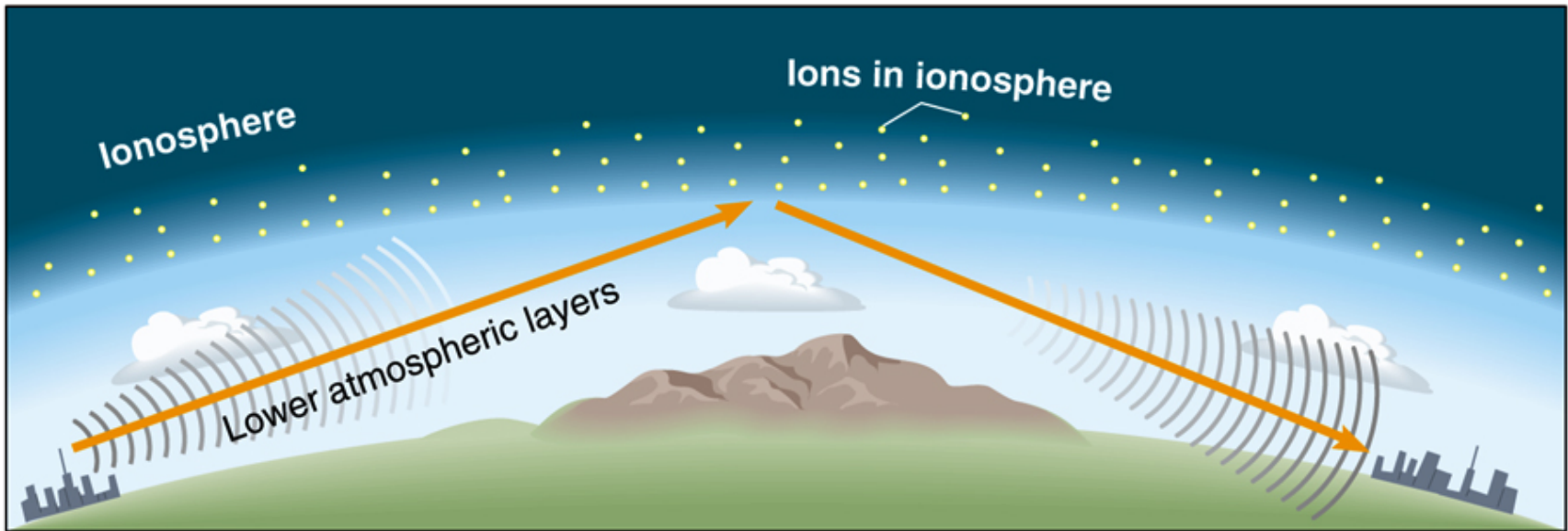
# Absorption of Solar Radiation



- Both Oxygen (O<sub>2</sub>) and Ozone (O<sub>3</sub>) absorb ultraviolet (UV) light.
- UV radiation is absorbed in both the creation and the breakdown of Ozone.  
$$O_2 + UV = 2O$$
$$O_2 + O = O_3$$
$$O_3 + UV = O_2 + O$$
- Note that UV radiation has a critical role in creating Ozone – not just breaking it down.

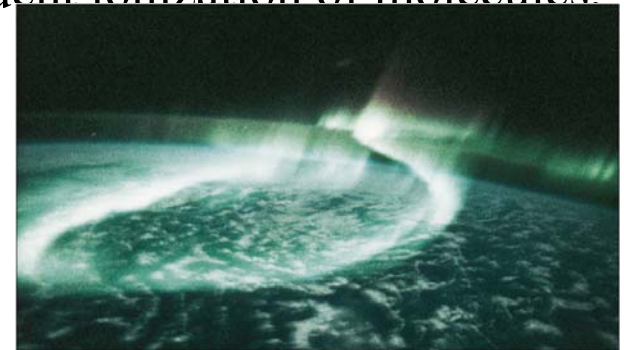
Graphic from *Meteorology* by Danielson, Levin and Abrams

# The Ionosphere



- The Ionosphere is apart of the upper mesosphere and the thermosphere.
- It is the region where there is relatively frequent ionization of molecules by solar radiation.
- It is also the region where light is emitted through the interactions of fast moving particles.

Graphics from *Meteorology* by Danielson, Levin and Abrams

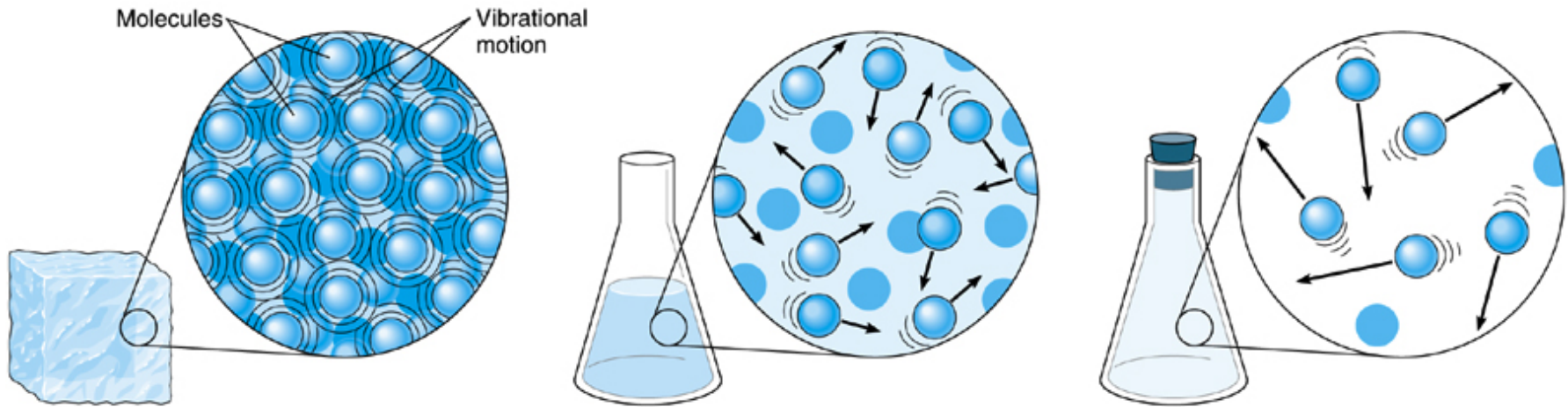


# Topics In This Section

- Properties of gasses.
  - Basic descriptions of matter (particularly gasses)
  - Energy associated with phase changes
  - Hydrostatic equation
  - Changes in pressure and density with height
  - Layers of the atmosphere
  - Atmosphere stratification & Temperature
  - Societal issues
    - Change in CO<sub>2</sub> and temperature
    - Ozone hole
    - Acid Rain
  - Large scale patterns in winds



# Phases of Matter

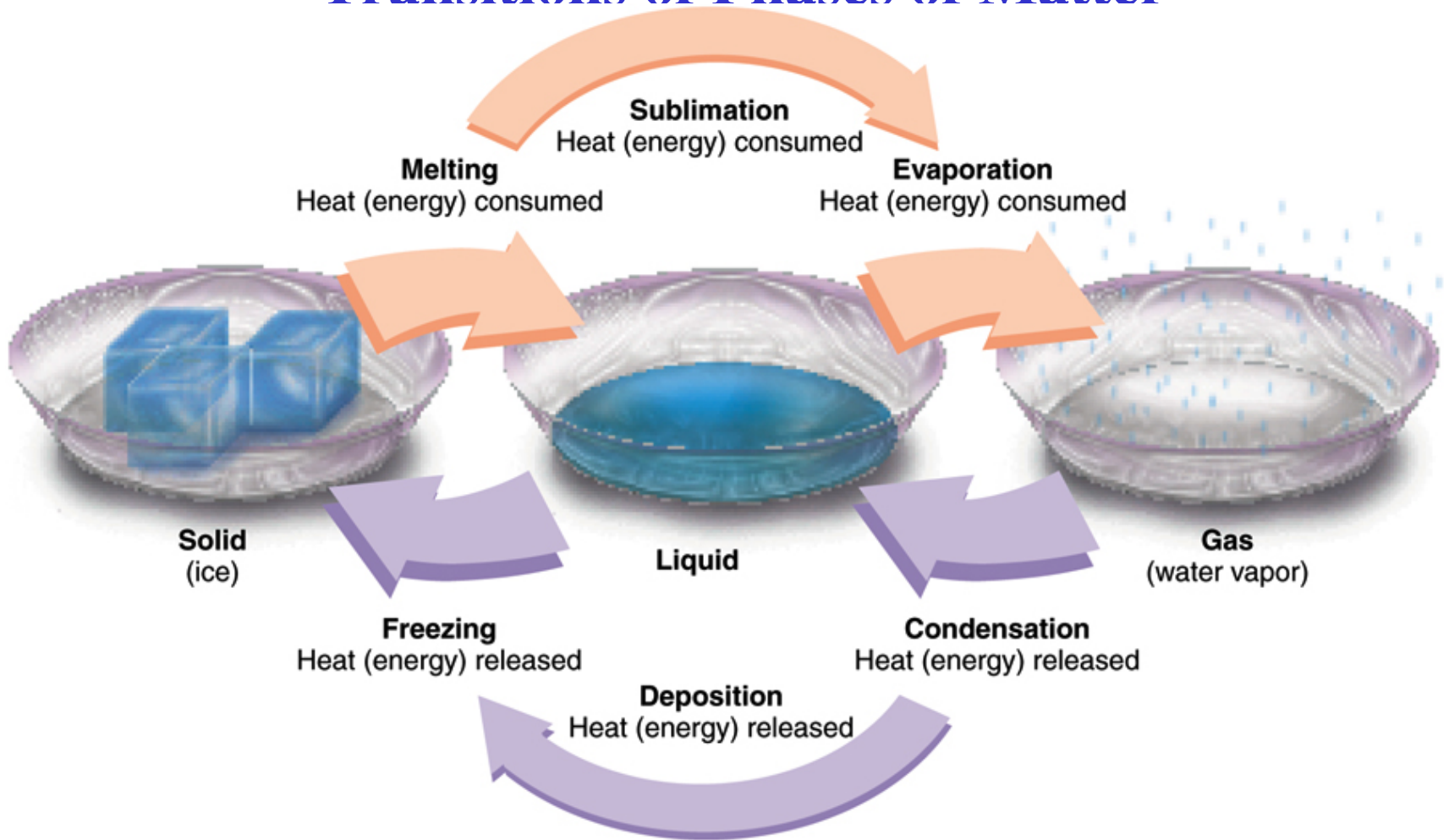


- In a solid phase, molecules vibrate in place, but cannot move freely.
- In a liquid phase, molecules are densely packed (as in solids), but they are free to move while remaining in close contact.
- In the gas phase, molecules move rapidly and freely, and expand to fill their container.
- Water is a particularly interesting example because the three phases can exist together for typical conditions on earth.

Graphic from *Meteorology* by Danielson, Levin and Abrams



# Phases of Matter and Transitions of Phases of Matter



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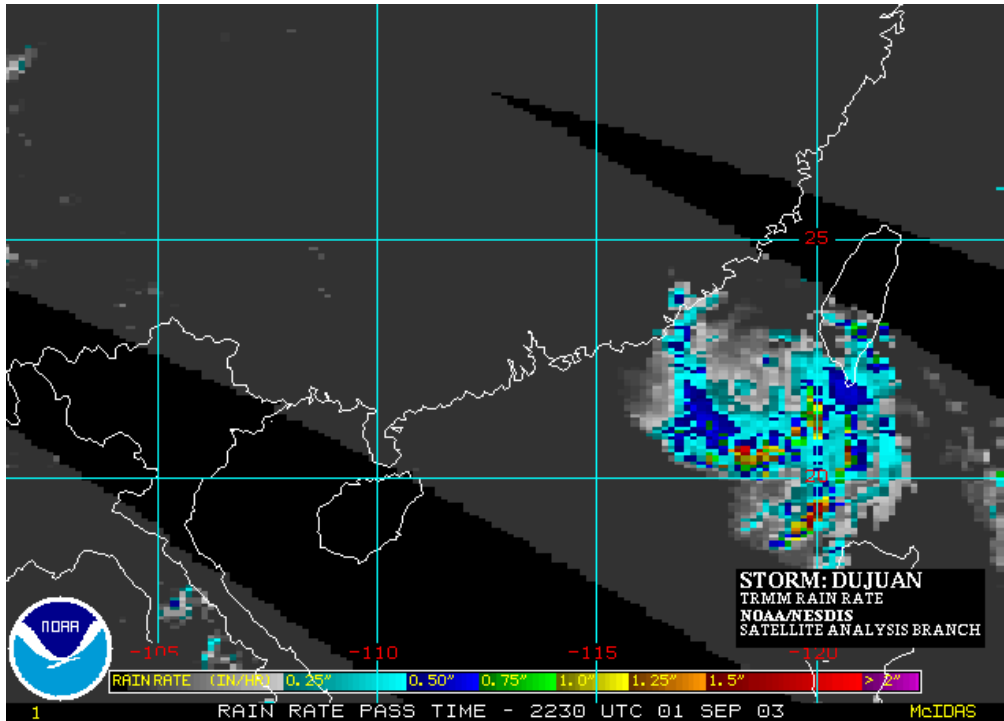


# Energy Associated with Phase Changes

- Changing phase requires either energy input (melting, sublimation, and evaporation), or releases energy (condensation, deposition, and freezing).
- H<sub>2</sub>O examples:
  - Latent heat of vaporization (evaporation):  $L_v \approx 2.258 \times 10^6 \text{ Jkg}^{-1}$
  - Latent heat of fusion:  $L_f \approx 3.34 \times 10^5 \text{ Jkg}^{-1}$
  - Ignoring other considerations, how much energy is required to change 1 gram of water to water vapor?  
$$1 \text{ g H}_2\text{O} \times \frac{1 \text{ kg}}{1000 \text{ g}} \times 2.258 \times 10^6 \text{ Jkg}^{-1} = 2.258 \times 10^3 \text{ J} = 2258 \text{ J}$$
  - How much energy is released when the 1g of water vapor condenses?



# Examples Related to Rain



- Assume (incorrectly) that all rain came from local water vapor.
- Rate of energy release per unit area ( $E$ ) =  
rain rate \*  $L_v$  \*  $\rho_{\text{water}}$
- $L_v \approx 2.258 \times 10^6 \text{ J kg}^{-1}$
- $\rho_{\text{water}} \approx 1000 \text{ kg m}^{-3}$   
(density)

$$E [\text{Wm}^{-2}] = R [\text{in/hr}] * \frac{2.54 [\text{cm}]}{1 [\text{in}]} * \frac{1 [\text{m}]}{100 [\text{cm}]} * \frac{1 [\text{hr}]}{3600 [\text{s}]} * \rho [\text{kg m}^{-3}] * L_v [\text{J kg}^{-1}]$$

$$E [\text{Wm}^{-2}] = R [\text{in/hr}] * 15931 [\text{Wm}^{-2} \text{in}^{-1} \text{hr}]$$

$$E [\text{kWm}^{-2}] = R [\text{in/hr}] * 15.931 [\text{kW hr m}^{-2} \text{in}^{-1}]$$

# Thermal Energy

- The amount of energy required to heat an object depends on the mass of the object and the material.
  - The amount of energy required (or released) per unit mass is the heat capacity ( $C_p$ ).
  - Examples:
    - Water  $4217 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$
    - Copper  $386 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$
    - Oxygen (gas)  $919 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$
    - Nitrogen (gas)  $1045 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$
- The heat capacity of a mixture is a mass weighted average of the component molecules.

$C_p$  air = sum of “volume fraction \* molecular weight \*  $C_p$ ”, summed over each molecular constituent, and divided by the sum of “volume fraction \* molecular weight”.
- The heat capacity of air is
  - $C_p = 1004 \text{ J kg}^{-1} \text{ air}$





# More on Weighted Averages

- An unweighted average considers all elements of a set equally.

- Let a set of values  $\{x\} = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + \dots + x_N$

- The average value of  $x$  is

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \dots + x_N}{N}$$

- This can also be written with a summation  $\sum_i^N x_i = x_1 + x_2 + x_3 + \dots + x_N$

$$\bar{x} = \frac{\sum_i^N x_i}{N}$$

- A weighted average allows some values to be more influential than others. Let  $w$  be weights for the set  $\{x\}$

$$\bar{x} = \frac{w_1 * x_1 + w_2 * x_2 + w_3 * x_3 + \dots + w_N * x_N}{w_1 + w_2 + w_3 + \dots + w_N} = \frac{\sum_i^N (w_i * x_i)}{\sum_i^N w_i}$$



# Putting It Together (Example)

- Example of the energy required to convert 2 kg of ice at  $0^{\circ}\text{C}$  to water vapor at  $150^{\circ}\text{C}$ .
- Processes:
  - Convert ice to water
  - Heat water to  $100^{\circ}\text{C}$
  - Convert water to water vapor
  - Heat water vapor to  $150^{\circ}\text{C}$



## Putting It Together (Example)

Example of the energy required to convert 2 kg of ice at  $-20^{\circ}\text{C}$  to water vapor at  $150^{\circ}\text{C}$ .

Processes:

- Heat ice to  $0^{\circ}\text{C}$   $M * \Delta T * C_p = 2 \text{ kg} * 20^{\circ}\text{C} * 4217 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$
- Convert ice to water:  $M * L_f = 2 \text{ kg} * 3.34 * 10^5 \text{ J kg}^{-1}$
- Heat water to  $100^{\circ}\text{C}$   $M * \Delta T * C_p = 2 \text{ kg} * 100^{\circ}\text{C} * 4217 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$
- Convert water to water vapor  $M * L_v = 2 \text{ kg} * 2.258 * 10^6 \text{ J kg}^{-1}$
- Heat water vapor to  $150^{\circ}\text{C}$   $M * \Delta T * C_p = 2 \text{ kg} * 50^{\circ}\text{C} * 4217 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$

where

$M$  = mass

$L_f$  = latent heat of fusion

$L_v$  = latent heat of vaporization

$C_p$  = heat capacity

$\Delta T$  = change in temperature



# Putting It Together (Example)

Example of the energy required to convert 2 kg of ice at -20°C to water vapor at 150°C.

Processes:

- Heat ice to 0°C  $M * \Delta T * C_p = 2 \text{ kg} * 20^\circ\text{C} * 4217 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$   
 $= 168,680 \text{ J}$
- Convert ice to water:  $M * L_f = 2 \text{ kg} * 3.34 * 10^5 \text{ J kg}^{-1}$   
 $= 668,000 \text{ J}$
- Heat water to 100°C  $M * \Delta T * C_p = 2 \text{ kg} * 100^\circ\text{C} * 4217 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$   
 $= 843,400 \text{ J}$
- Convert water to water vapor  $M * L_v = 2 \text{ kg} * 2.258 * 10^6 \text{ J kg}^{-1} =$   
 $= 4,660,000 \text{ J}$
- Heat water vapor to 150°C  $M * \Delta T * C_p = 2 \text{ kg} * 50^\circ\text{C} * 4217$   
 $= 421,700 \text{ J}$
- For a total of 6,593,100 J

where

$M$  = mass

$L_f$  = latent heat of fusion

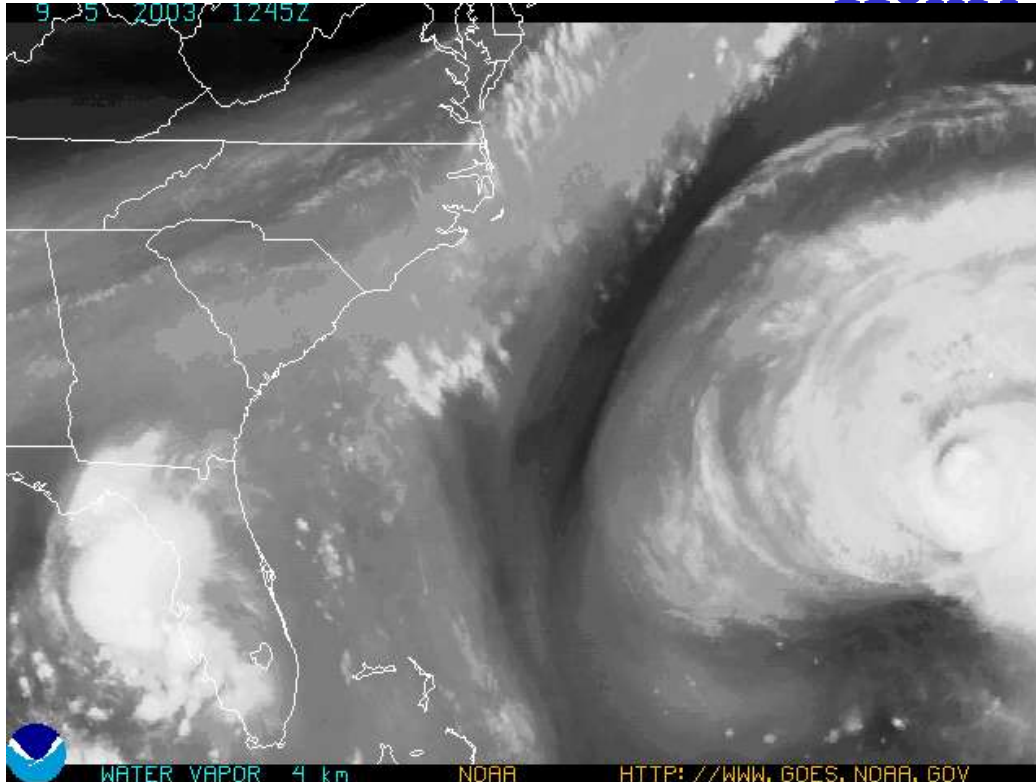
$L_v$  = latent heat of vaporization

$C_p$  = heat capacity

$\Delta T$  = change in temperature



# Water Vapor Images of Hurricane Fabian and TS Henri



- Lighter shades indicate tropical more water vapor, and dark areas indicate little water vapor.
- Much of the water vapor will be converted to water, releasing much of the energy needed to power these massive systems.



# Kinetic Theory

- Kinetic means “pertaining to motion”
  - The previous example indicates that temperature influences motion.
    - The speed at which a molecule moves, and
    - The number of collisions per unit time.
- Moving objects or changing phases of matter requires energy
- **Kinetic Energy ( $KE$ )** is one source of energy
  - $KE = 0.5 m v^2$ ,
    - where  $m$  is the mass of the object, and
    - $v$  is the speed of the object.



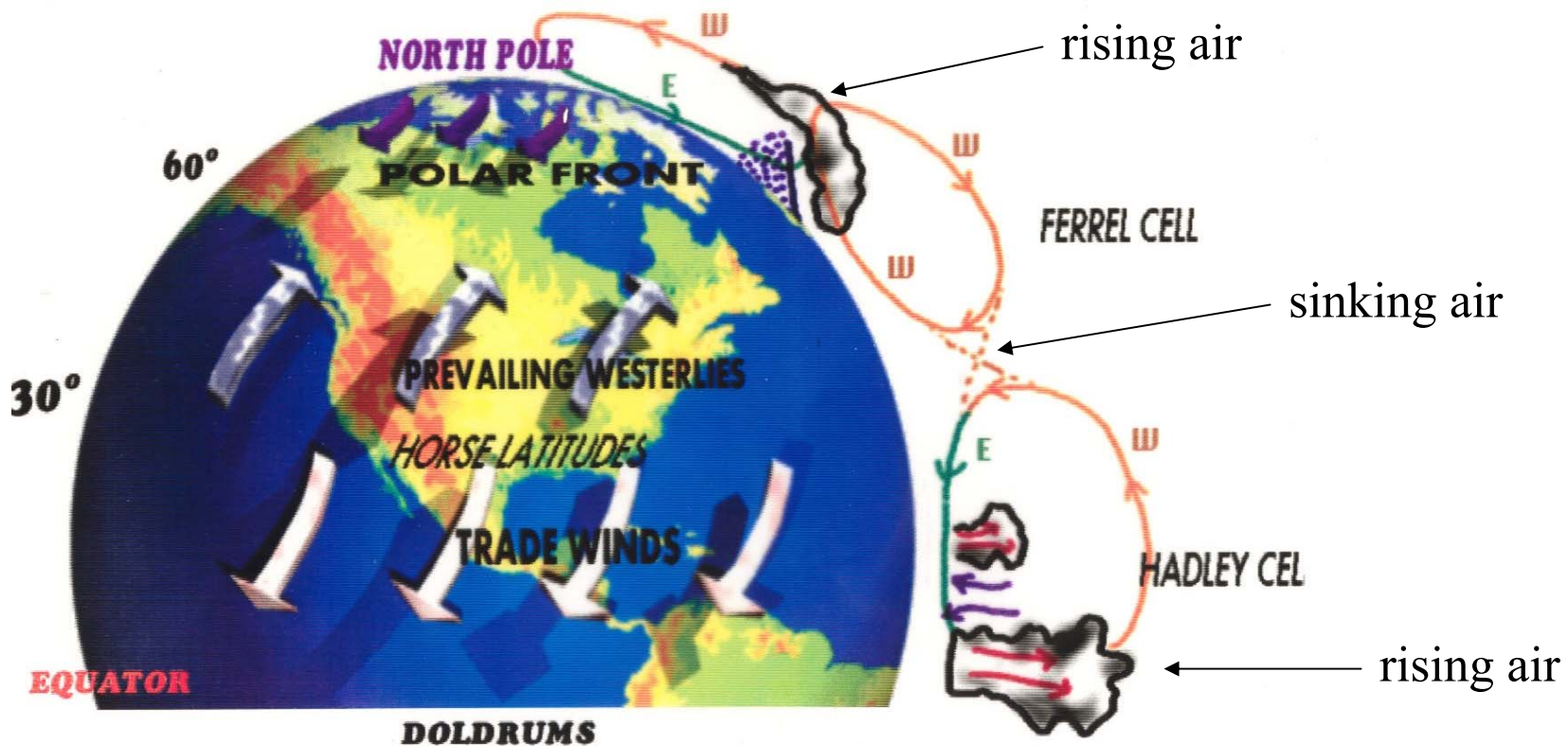
# Potential Energy

- It requires work (energy) to lift an object in a gravity field. The energy gained by such motion is potential energy.
  - Example: water wheels could be powered by a combination of kinetic and potential energy, whereas wind-wheels are powered by only kinetic energy.
  - Change in Potential Energy ( $PE$ ):  $\Delta PE = m g \Delta z$ ,
    - Where  $m$  is the mass that is moved,
    - $g$  is gravitational acceleration, and
    - $\Delta z$  is the change in height.
- Potential energy of air is an important type of energy for transferring energy from the equatorial oceans poleward (North and South).



# The Global Picture: Atmosphere

## Meridional Flow



- The energy from the sun is largely absorbed in the tropical oceans, transferred through several mechanisms to the air, which (we will soon discuss) causes the air to rise and gain potential energy.
- The potential energy rich air is then forced to move poleward.



# Escape Velocity and Planetary Atmospheres

Escape velocity ( $v_e$ ) is the minimum speed needed to escape a gravitational well.

- The kinetic energy ( $KE = 0.5 m_{\text{object}} v^2$ ) of the object must be greater than maximum potential energy.
- Gravitational acceleration is variable over this distance. The force ( $F$ ) of gravitational attraction between the object and the planet is

$$F = G m_{\text{planet}} m_{\text{object}} r^{-2}$$

- Where  $G$  is the gravitational constant ( $6.67 \times 10^{-11} \text{ m}^3 \text{ s}^{-2} \text{ kg}^{-1}$ ),  $m_{\text{planet}}$  is the mass of the planet,  $m_{\text{object}}$  is the mass of the object, and  $r$  is the distance between the centers of these masses.
- Potential energy is the integration of  $F$  from the position  $r_c$  of the object to infinity.

$$PE = 2 G m_{\text{planet}} m_{\text{object}} / r_c = KE = m_{\text{object}} v_e^2$$

- Solving this results in

$$v_e = [2 G m_{\text{planet}} / r_c]^{0.5} \quad (\text{assuming no interactions with the atmosphere})$$

- For earth,  $v_e = 10,732 \text{ m/s}$  for an object on the planet's surface.



# Distribution of Particle Speeds

- The distribution (probability distribution function) of speeds of particles is given by Boltzmann's distribution.
- This distribution indicates
  - The most likely speed ( $V_o$ )

$$V_o = \sqrt{\frac{2kT}{M m_H}}$$

- Where  $k=1.38 \times 10^{-23} \text{ JK}^{-1}$ ,  $T$  is the absolute temperature,  $M$  is the molecular weight of the particle, and  $m_H$  is the molecular weight of a Hydrogen atom.
- The dependence on  $M$  indicates that on average the speed of heavier particles will be less than the speed of lighter particles.
- The value of  $V_o$  for Hydrogen atoms is  $3000 \text{ ms}^{-1}$ , or about  $\frac{1}{4}$  of escape velocity.
- Boltzmann's distribution indicates that approximately one particle in  $10^6$  will have a speed greater than escape velocity.

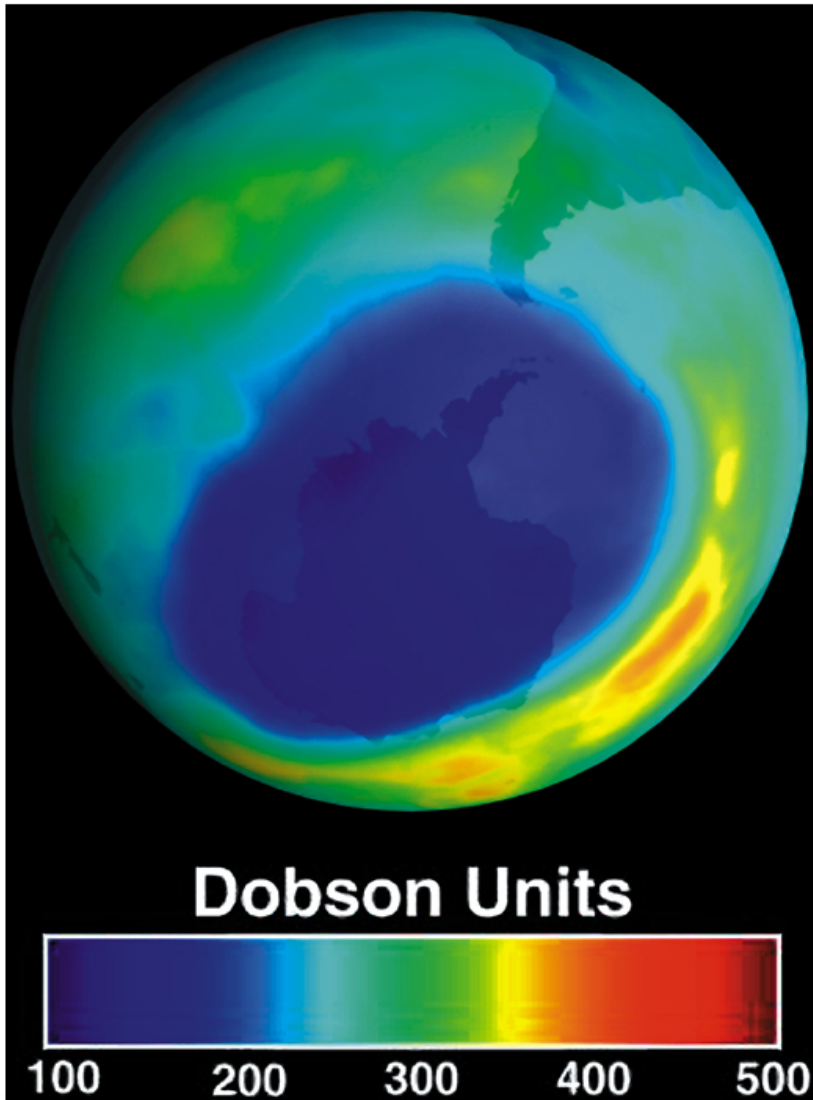


# Change In Temperature With Height (The Lapse Rate)

- In meteorology jargon, the rate of change of temperature, as height decreases ( $-dT/dz$ ), is called the lapse rate.
  - For air parcels without any changes in energy due to phase changes of water, or due to radiative heating or cooling, we call the rate of change the dry adiabatic lapse rate.
    - Dry means that no water vapor is converted to water.
    - Adiabatic means that there is no exchange of energy with items outside the air parcel.
  - $\Delta(\text{energy per unit mass}) / \Delta z = 0$
  - Energy per unit mass = thermal energy + potential energy =  $C_p T + gz$
  - For infinitely small  $\Delta z$  this ratio of differences becomes a derivative.
  - $d(C_p T + gz)/dz = 0$
  - $C_p dT / dz + g = 0$  (treat  $g$  and  $C_p$  as independent of  $z$ )
  - $-(dT / dz) = g / C_p \approx 10^\circ\text{C}/\text{km}$



# The Ozone Hole



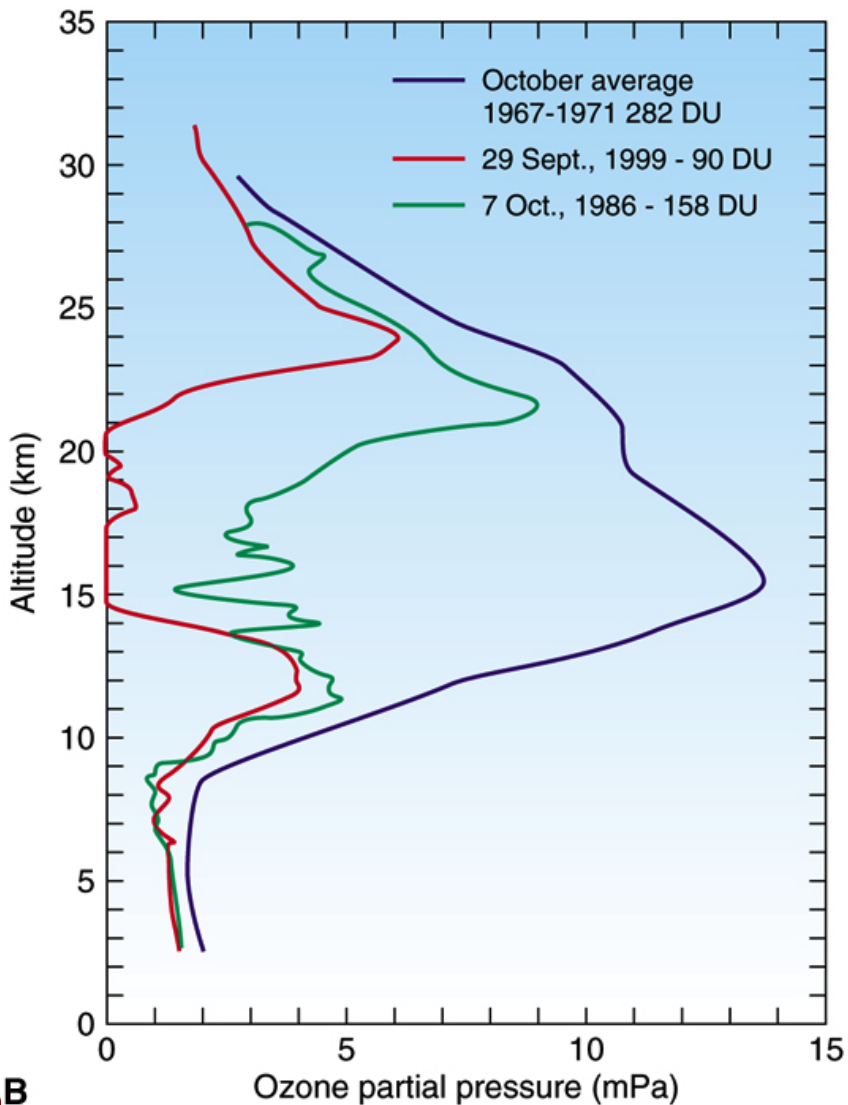
- The graphics shows a large area of relatively little ozone over Antarctica: The Ozone Hole.
  - This type of hole grows through winter, and sometimes passes over inhabited regions of Chile, Australia and New Zealand.
- A similar (but smaller and less severe) ozone hole occurs above the arctic during Winter.
- Dobson units [DU] correspond to 10  $\mu\text{m}$  of ozone in the atmospheric column, if that ozone was at a standard temperature ( $0^\circ\text{C}$ ) and pressure (101.325 kPa).

Graphic from *Meteorology* by Danielson, Levin and Abrams

General Meteorology

Atmos. Composition 44

# Changes in Ozone Concentration

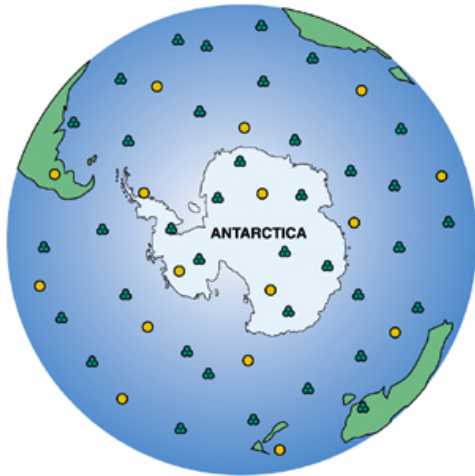


- The Ozone concentration above Antarctica decreased after the introduction of several man made compounds.
- Can we extrapolate a long term trend from three samples?

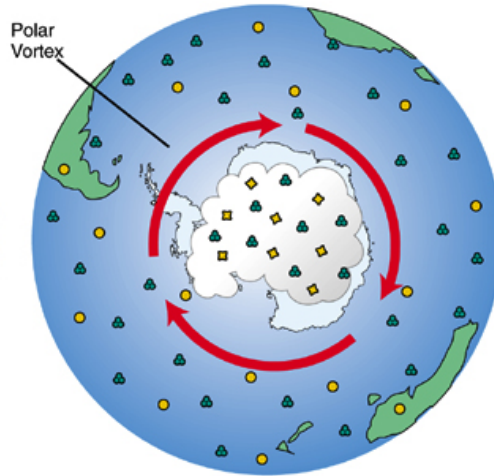
Graphic from *Meteorology* by Danielson, Levin and Abrams



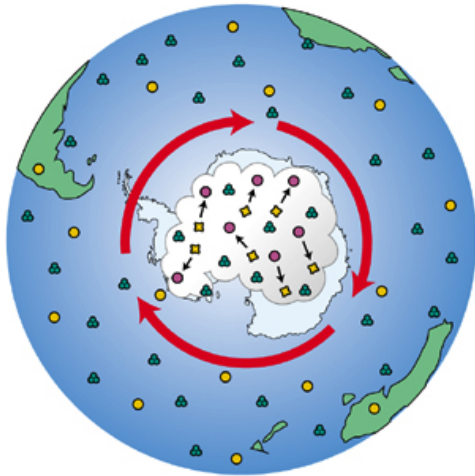
# Polar Vortex and CFCs



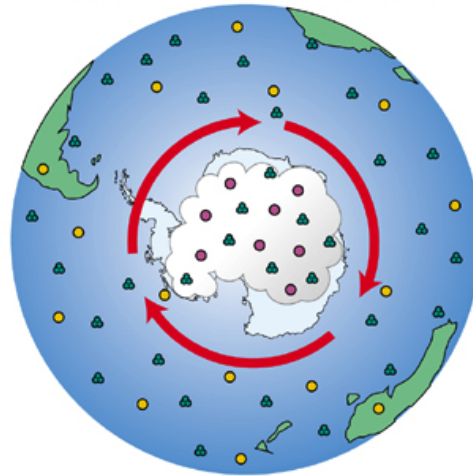
A CFCs (●) are distributed across the globe by the winds.  
 ▲ = ozone



B During polar winter,  
 1. Intense cold causes polar vortex to isolate Antarctic air.  
 2. Cold causes stratospheric clouds.  
 3. CFCs interact with clouds to become less stable (◀).



C Early spring sunlight breaks down CFCs, separating Cl (●) atoms.



D Cl atoms attack ozone:  $\text{Cl} + \text{O}_3 = \text{ClO} + \text{O}_2$

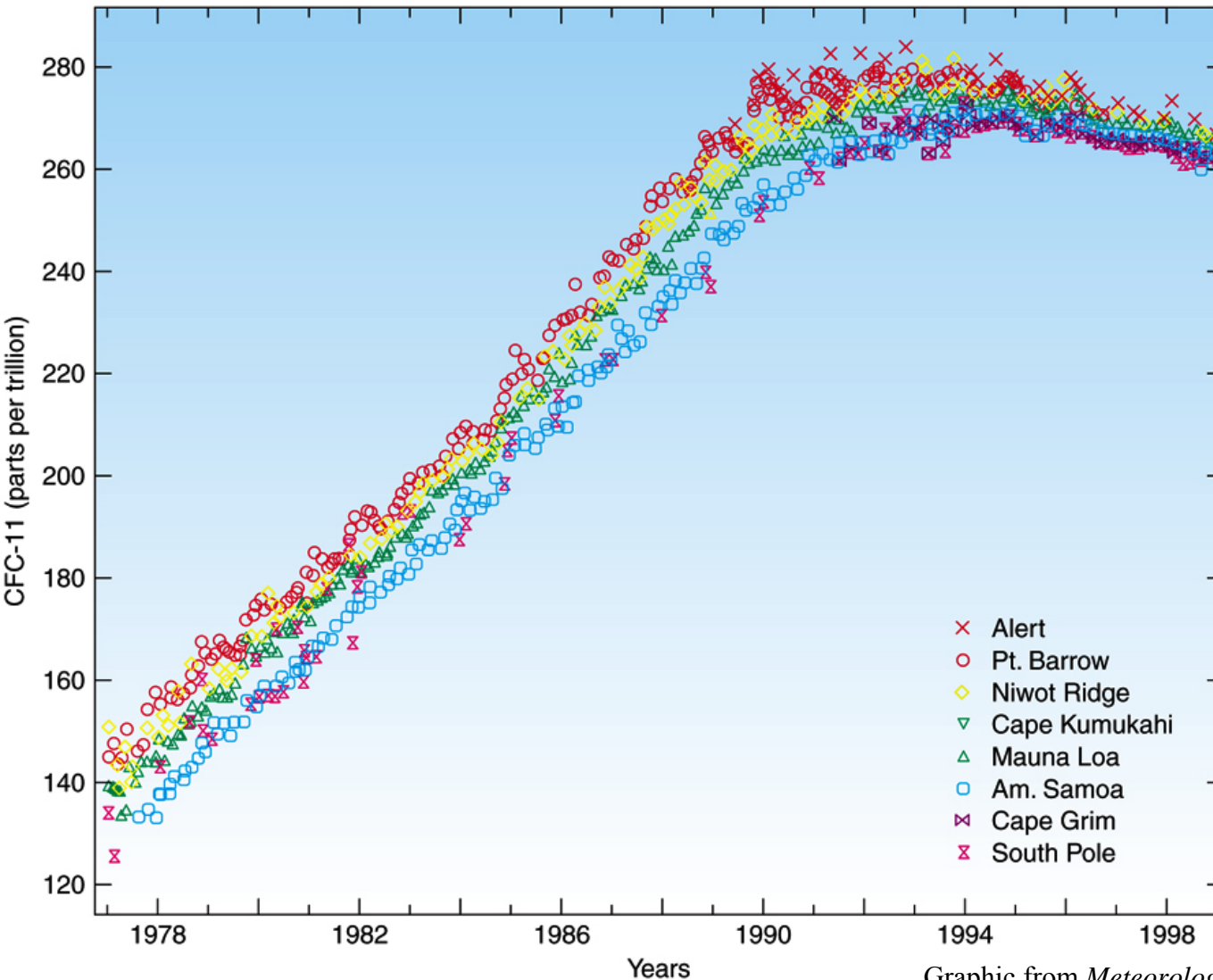
Graphic from *Meteorology* by Danielson, Levin and Abrams

- In the summer (Fig. A), Chlorofluorocarbons (CFCs) are scattered across the globe.
- As the Antarctic winter strengthens (Fig. B), the polar vortex strengthens, trapping the Antarctic air.
- The intense cold causes stratospheric clouds to form.
- Clouds interact with CFCs and weaken the Chlorine bounds.
- Early spring sunlight separates the Chlorine (Fig. C), which is a catalyst in the breakdown of ozone (Fig. D).





# Time Series of CFC Concentration



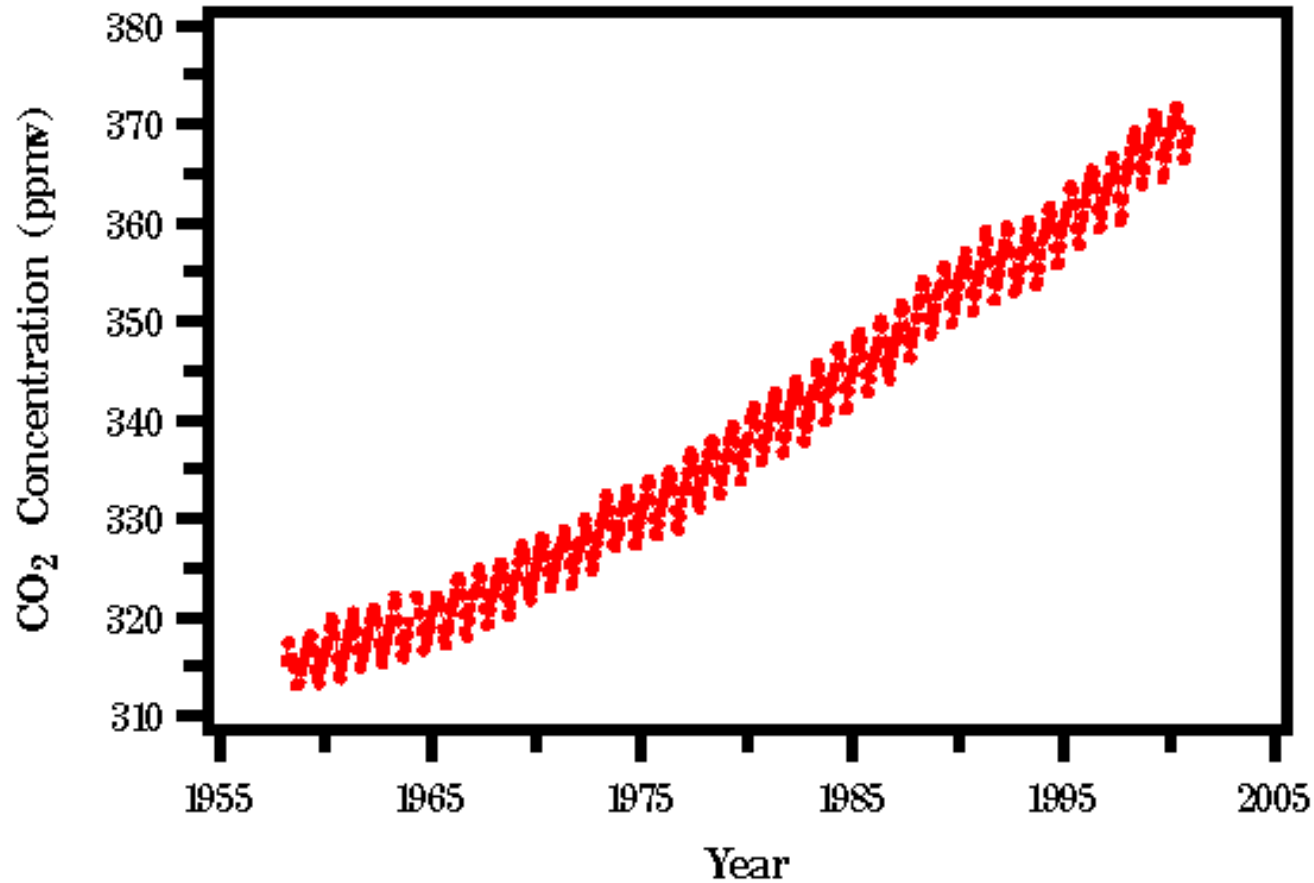
- CFC concentration has been decreasing since the early 1990s.
- Countries that have signed on to the Montreal protocol agreed cease production of CFCs by 2000, and many compounds with similar issues by 2010.
- There are plenty of CFCs that will be in use for another 10-20 years.

Graphic from *Meteorology* by Danielson, Levin and Abrams  
General Meteorology

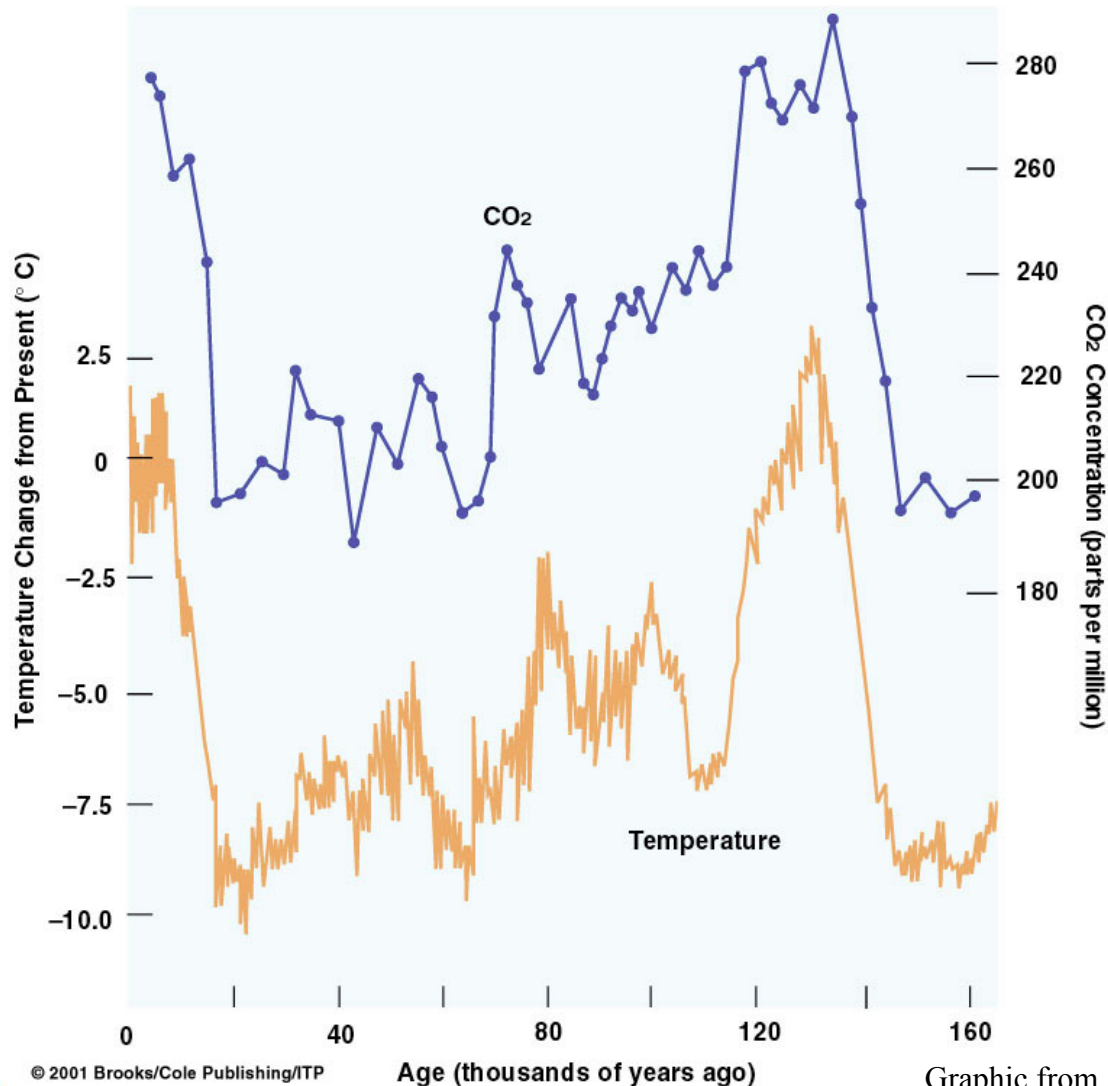


# Current Trends in CO<sub>2</sub>

- Pre-industrial amounts
  - 280 ppm
- 1960,
  - ~315 ppm
- 2000
  - ~370 ppm
- 2100?
  - ~500 ppm??
- The concentration of CO<sub>2</sub> in the lower atmosphere is clearly increasing with time.



# Effect of CO<sub>2</sub> on Recent History



- Strong correlation between global mean surface temperatures and the concentration of CO<sub>2</sub>
- Correlation DOES NOT imply cause and effect!

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Age (thousands of years ago)

Graphic from *Meteorology* by Danielson, Levin and Abrams

General Meteorology

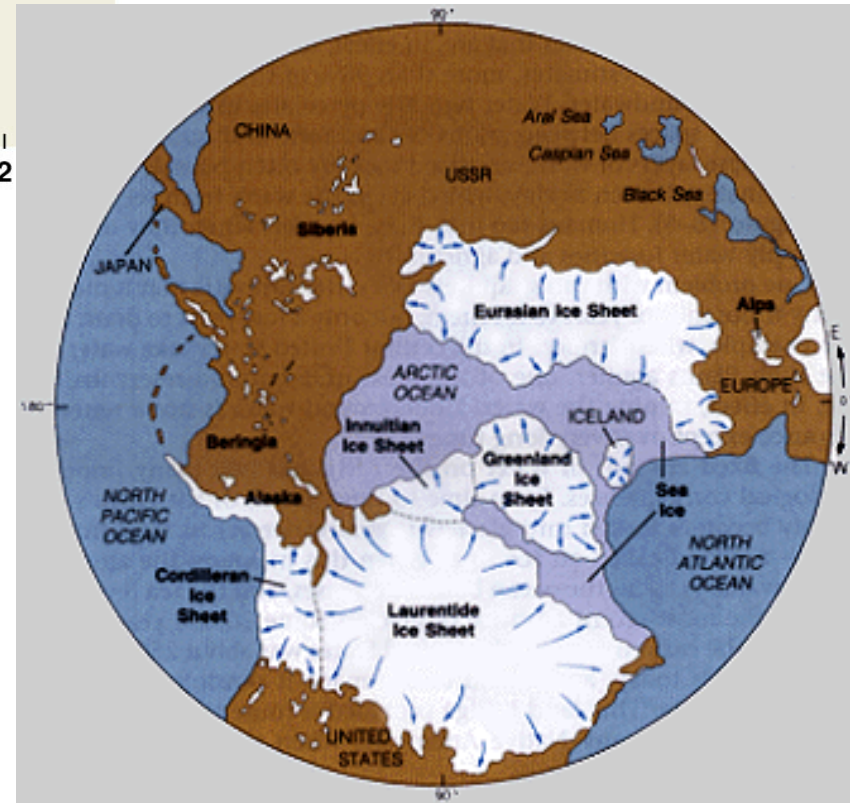
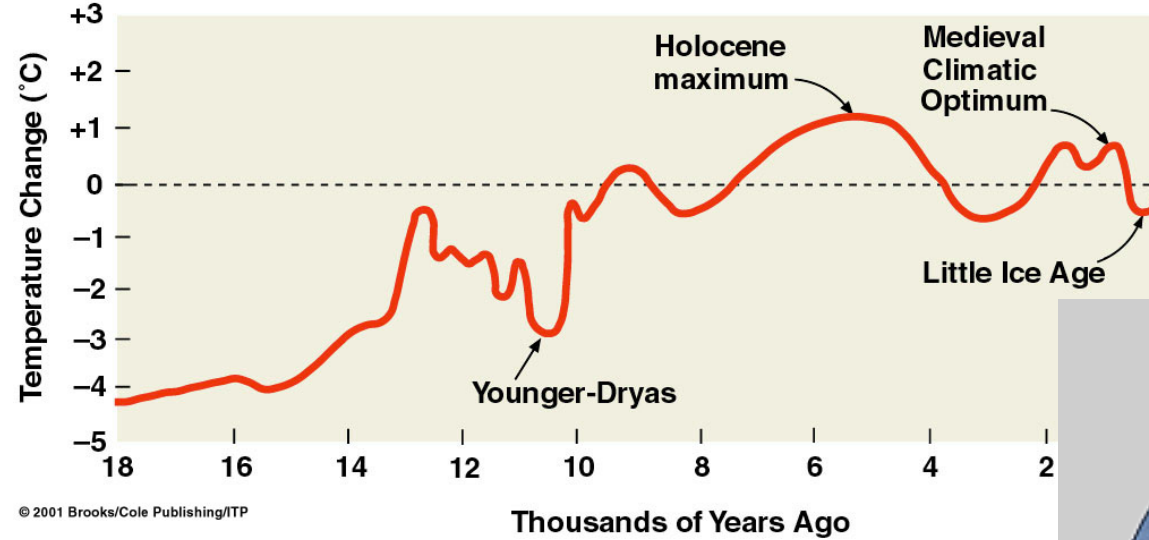
Atmos. Composition 49

bourassa@met.fsu.edu

The Florida State University



# A closer look

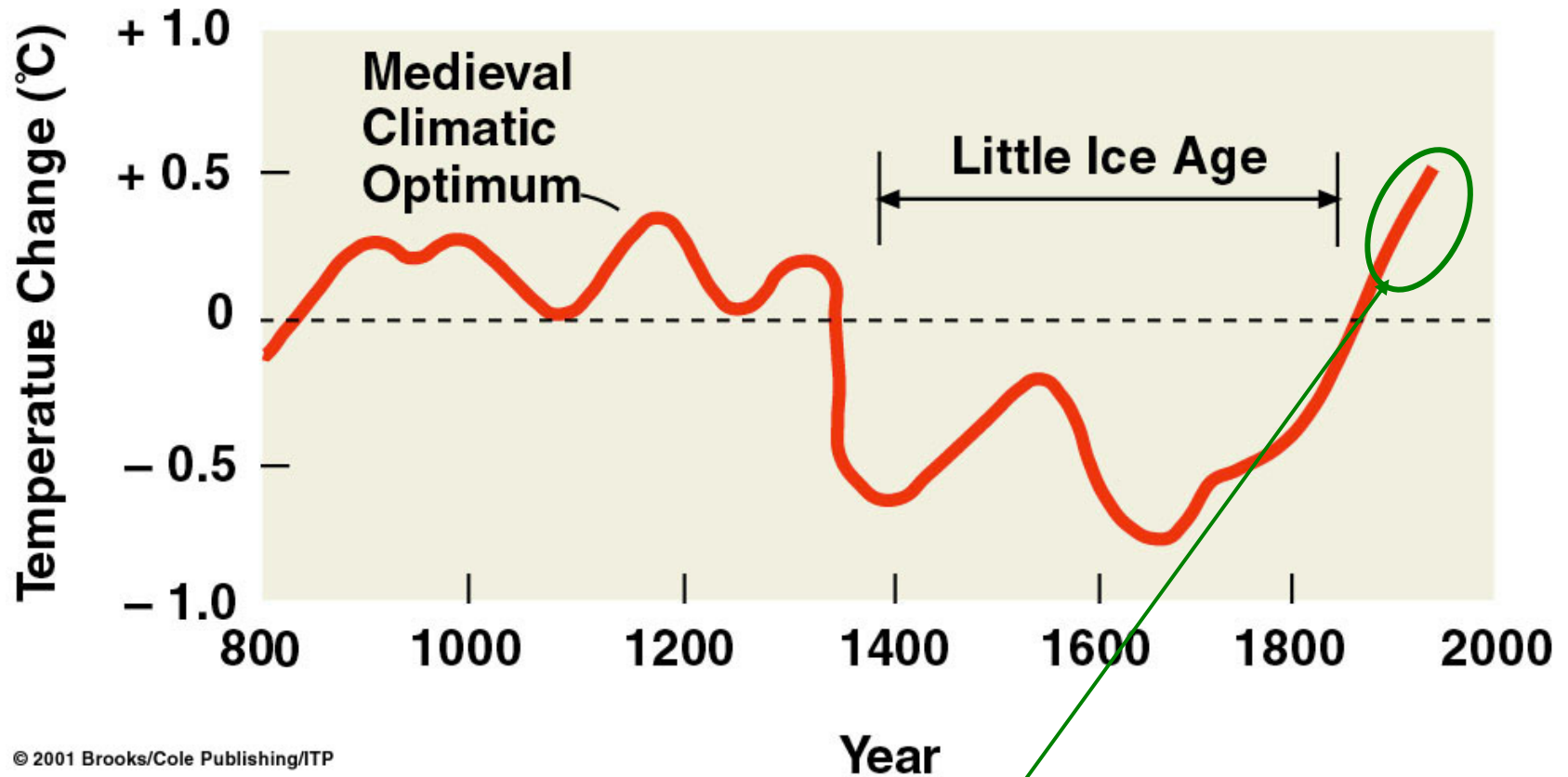


- Even relatively recent times have been warmer than now
- During colder periods, lots of current water channels were land (or ice)
- Medieval times were warm in higher latitudes...expansion of territories

Graphics from *Meteorology* by Danielson, Levin and Abrams



# More recent climate change



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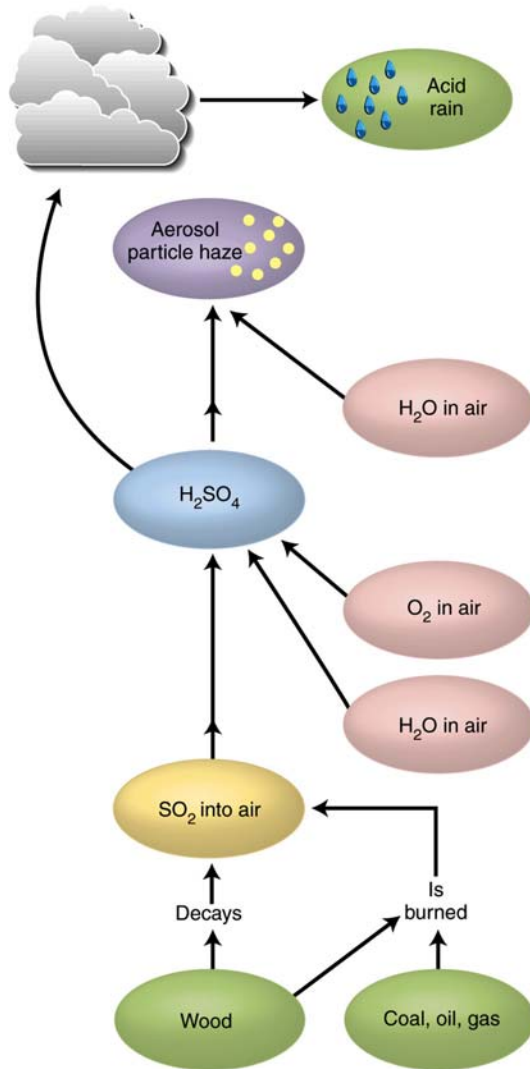
- Bitter cold winters during Revolutionary War and during wars in Eastern Europe
- Warning: The circled temperatures don't match a reasonable sampling of the observations!

Graphic from *Meteorology* by Danielson, Levin and Abrams

General Meteorology  
Atmos. Composition 51



# Sulfur-Based Air Pollution



- Approximately 1% of plant mass is Sulfur.
- When a plant decay or is burnt, the Sulfur reacts with Oxygen to form Sulfur Dioxide (SO<sub>2</sub>)
- Fossil fuels, particularly coal, also contain Sulfur.
  - Burning coal accounts for about 50% of the anthropogenic contribution to atmospheric Sulfur.
- Sulfur Dioxide (SO<sub>2</sub>) interacts with atmospheric water (H<sub>2</sub>O) and oxygen (O<sub>2</sub>) to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>).
- In extreme cases, sulfuric acid in the atmosphere can cause haze and is dangerous to humans.
- In the last 200 years, atmospheric Sulfur concentrations have quadrupled.

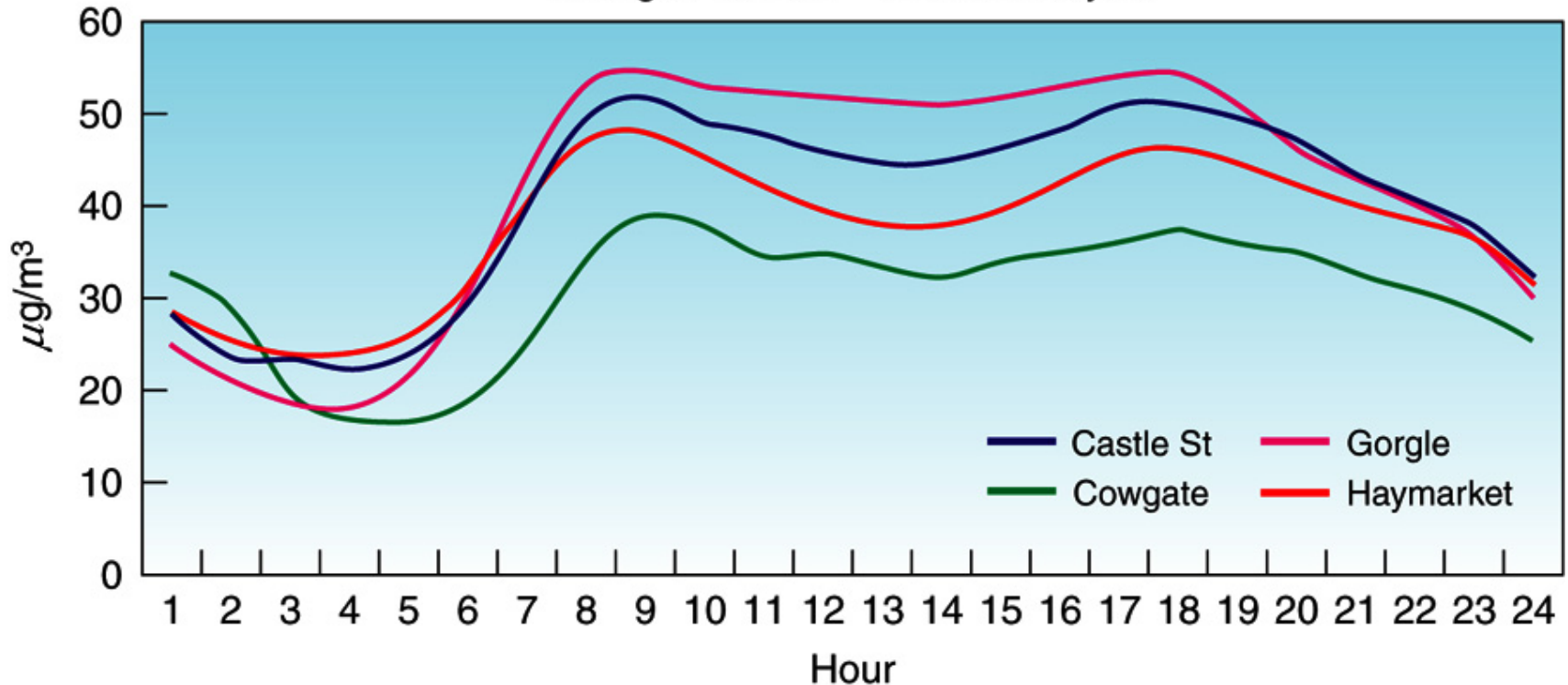
Graphic from *Meteorology* by Danielson, Levin and Abrams





# Nitrogen-Based Air Pollution

## Nitrogen dioxide—diurnal analysis

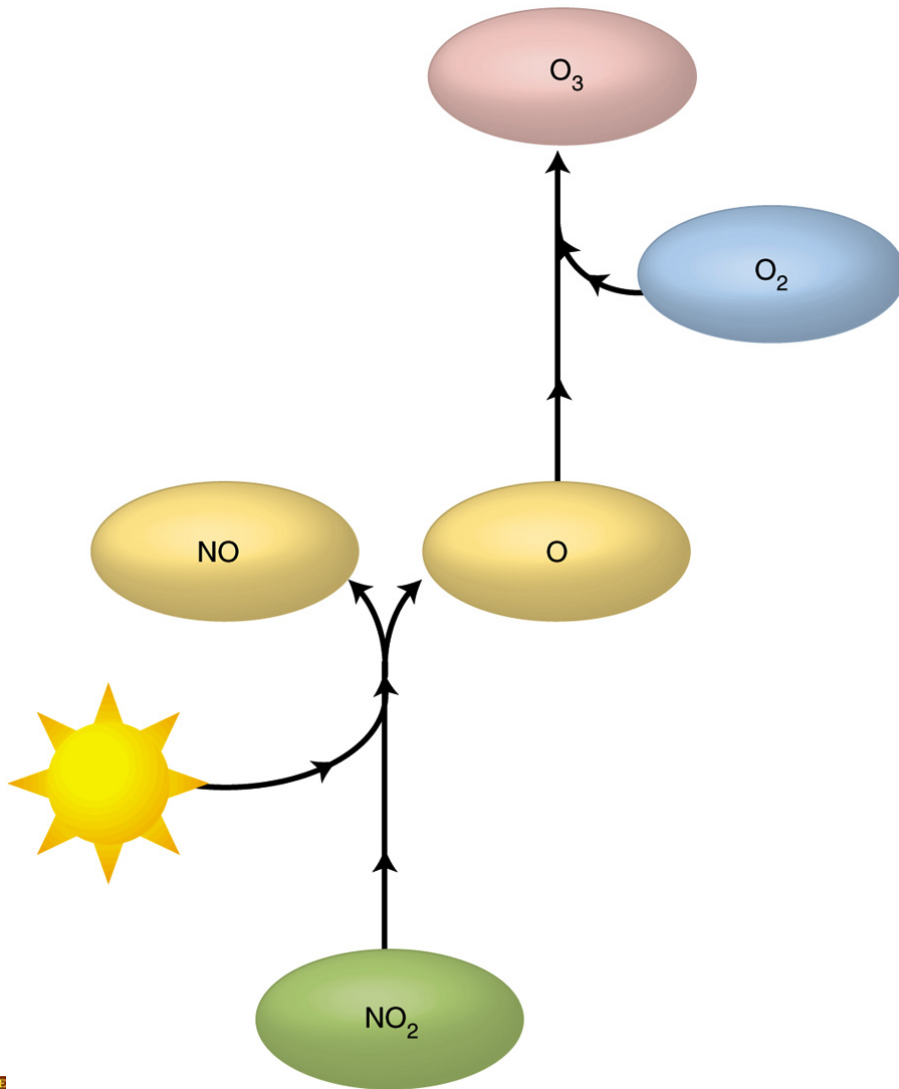


- $N_2 + O_2 + \text{heat} = 2NO$  (nitric oxide, mildly toxic)
  - Main source: automobiles. Greatest concentrations in population centers.
- $2NO + O_2 = NO_2$  (nitrogen dioxide, highly toxic)
- $4NO_2 + O_2 + 2H_2O = 4HNO_3$  (nitric acid)
  - causes problems similar sulfuric acid

Graphic from *Meteorology* by Danielson, Levin and Abrams  
General Meteorology  
Atmos. Composition 53



# Ozone-Related Air Pollution



- Ozone is highly corrosive and highly toxic.
  - That's OK in the stratosphere,
  - Bad in the lower troposphere!
- Clean air concentrations are typically 0.1 to 0.2 ppm.
- Concentrations  $>0.1$  ppm are considered unhealthy
- In extreme prolonged cases, the concentration can reach 0.6 ppm.

Graphic from *Meteorology* by Danielson, Levin and Abrams



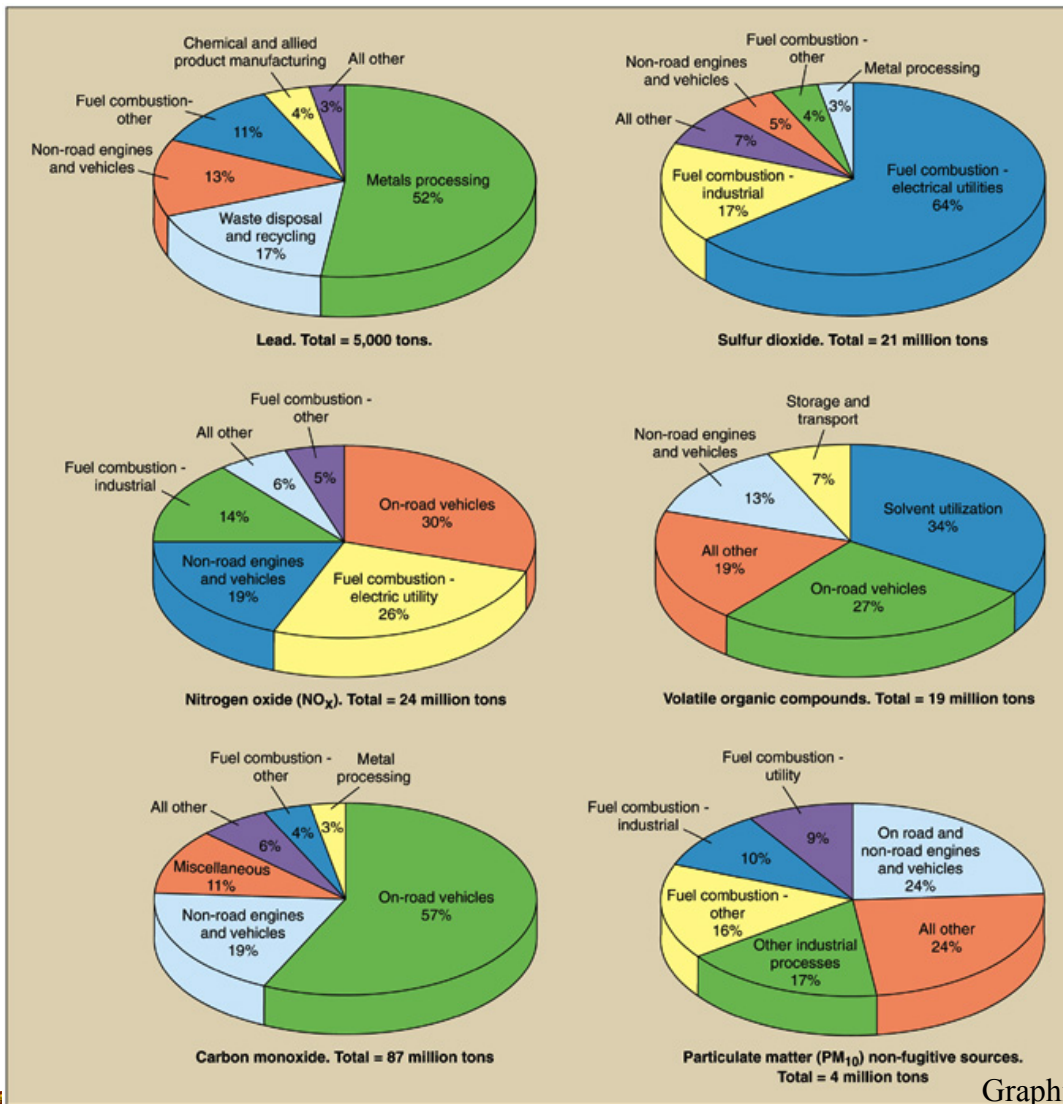
# Other Pollutants

- Methane (marsh gas)
  - A Volatile Organic Compound (VOC)
  - A greenhouse gas
  - Produced by plant decomposition, cattle and pigs, production of natural gas, and termites.
- Carbon Monoxide (CO)
  - Highly toxic
  - Short lived, so global levels are not increasing
- Heavy Metals
  - Examples are Lead and Mercury
  - Lead levels in the US dropped dramatically in the 1980s
  - A source of atmospheric lead in the US is the Sahara
- Particulate Matter
  - Ash, pollen, in some cases sand.



# Sources of Various Pollutants in the USA

- Vehicles and power plants are key sources of many pollutants!

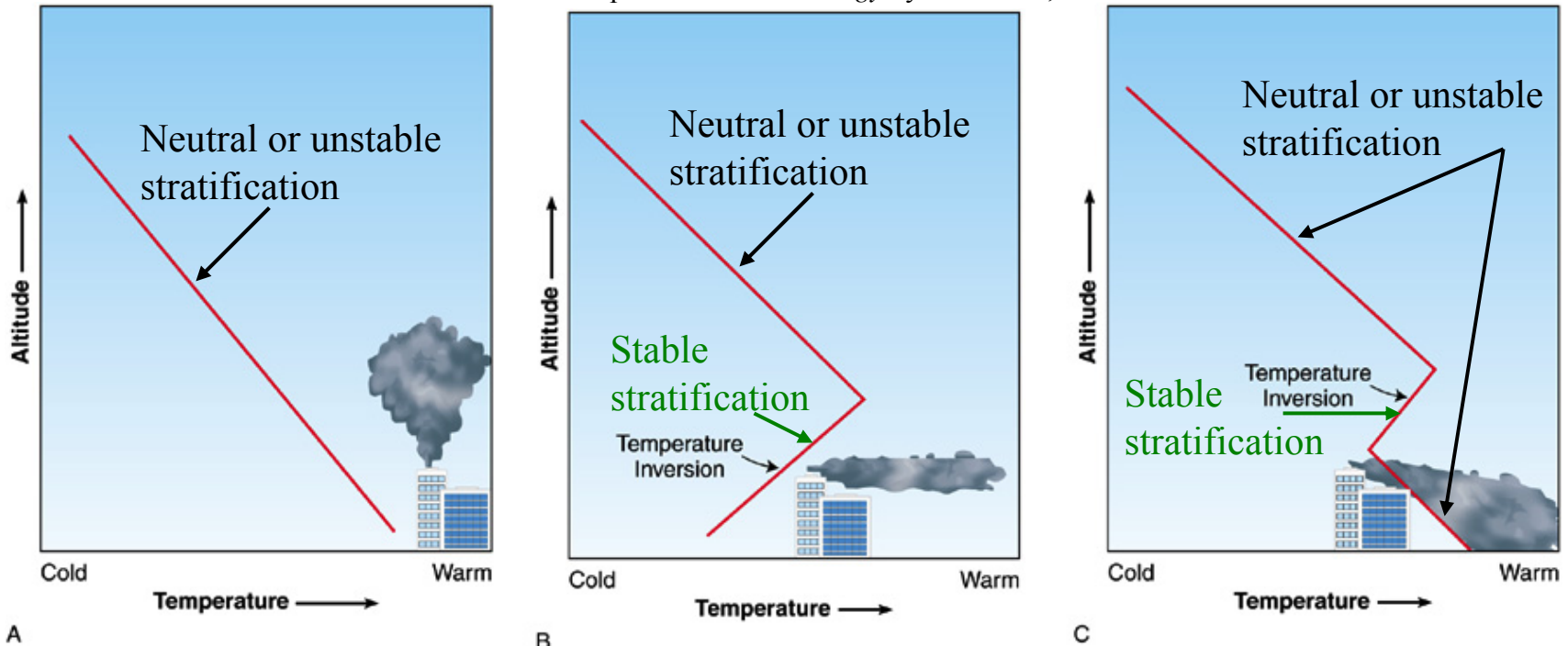


Graphic from *Meteorology* by Danielson, Levin and Abrams



# Atmospheric Stability and Pollution

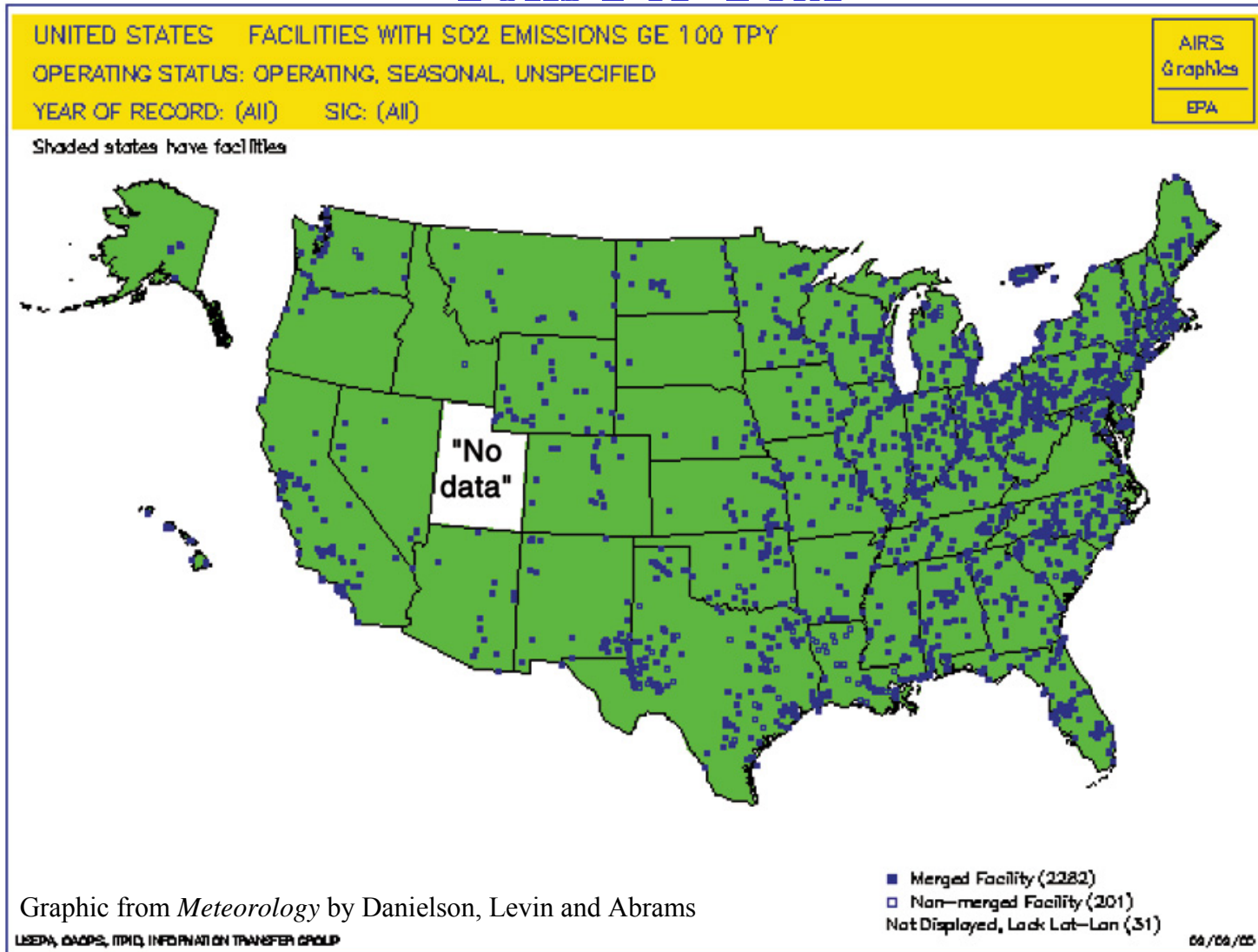
Graphic from *Meteorology* by Danielson, Levin and Abrams



- When hot pollutants are released into an atmosphere with neutral or unstable stratification (fig. A), they will rise and disperse.
- Temperature inversions are extremely stable layers.
  - They inhibit vertical motion and inhibit dispersion (fig. B).
- A capping inversion (fig. C) can trap pollutants below that layer.
  - Allows dispersion within the lowest layer (where people live).

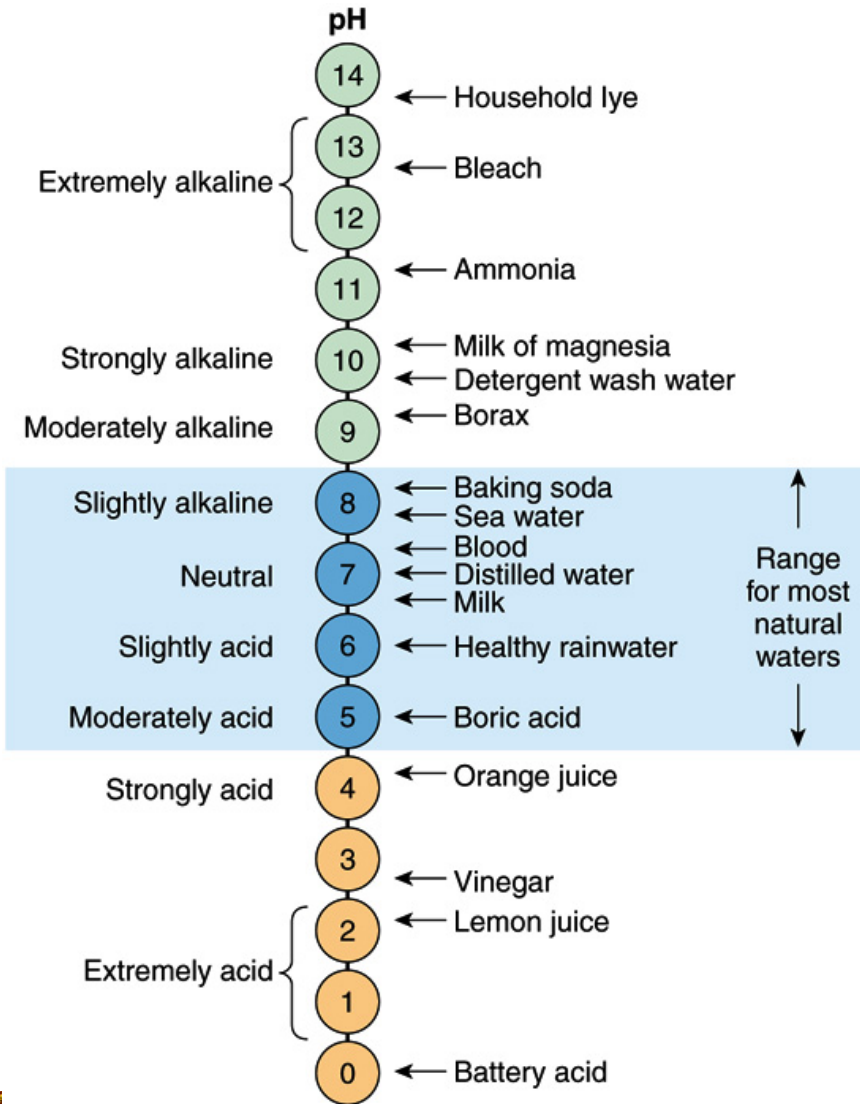


# Facilities Where Annual SO<sub>2</sub> emissions Exceeds 100 Tons Per Year





# Acid Rain



- Rain water and most lake water is slightly acidic.
- Some atmospheric pollutants (e.g., sulfur, nitric oxide, carbon dioxide) react with Oxygen and water to form acids.
  - These reduce the pH of rain water, and hence reduce the pH of lakes.
  - Too great a change in pH, particularly in a short time, is extremely harmful to organisms living in the lakes.
- In many regions within the USA, the pH of lakes is increasing towards normal values.

Graphic from *Meteorology* by Danielson, Levin and Abrams

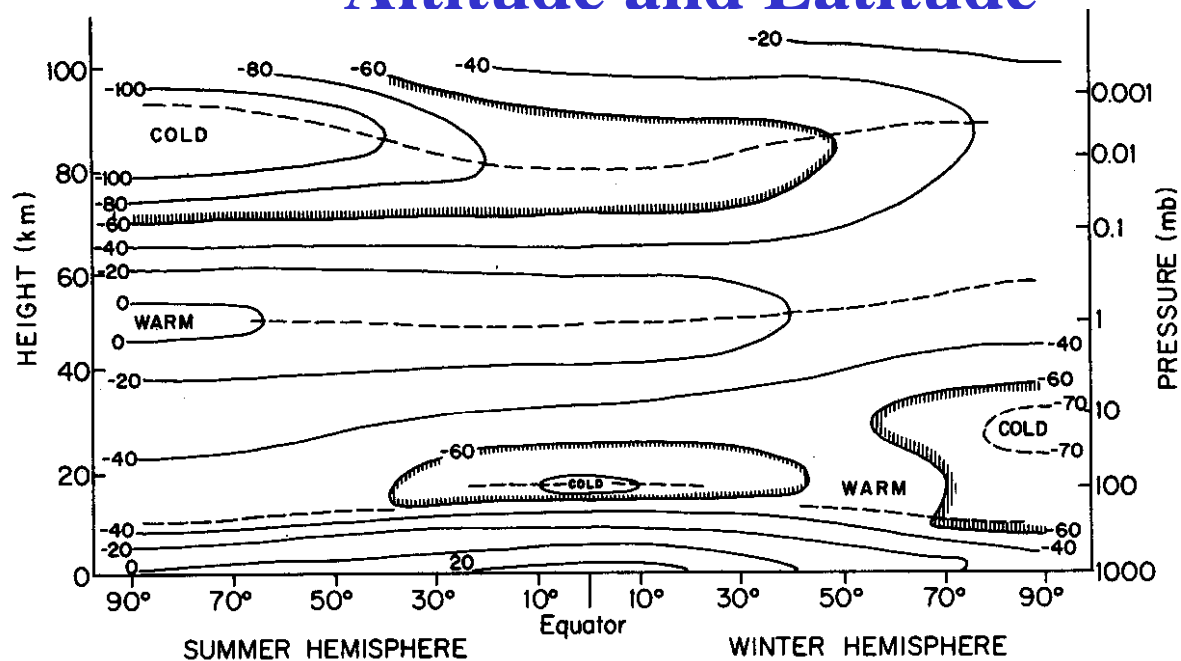


# General Wind Characteristics

- Seasonal to annual wind patterns are discussed.
- These wind patterns are usually considered to be more relevant to climate than to weather.
  - However, these processes that cause these wind patterns, and the associated weather/climate are the same processes that govern smaller scale weather.



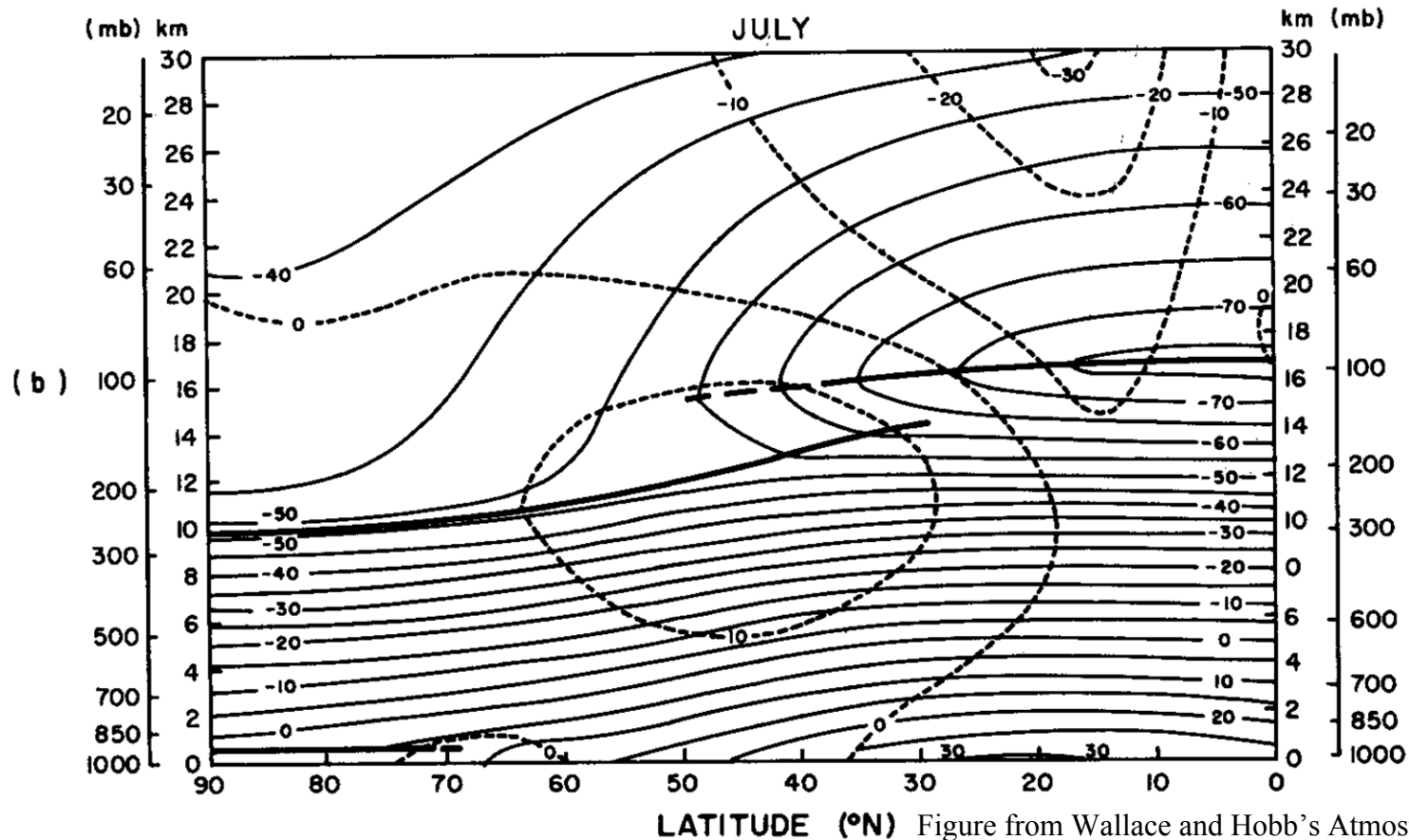
# Zonal Wind Dependence on Altitude and Latitude



**Fig. 1.10** Meridional cross section of longitudinally averaged temperature in degrees Celsius at the time of the solstices. Dashed lines indicate tropopause, stratopause, and mesopause. (Courtesy of R. J. Reed.)  
Figure from Wallace and Hobb's Atmospheric Science

- The minima in temperature at the tropopause indicates a layer of stable air, which acts as a barrier between 'air masses'.
- The air over the winter hemisphere pole is also relatively independent from surrounding air.

# Temperature Stratification and Winds



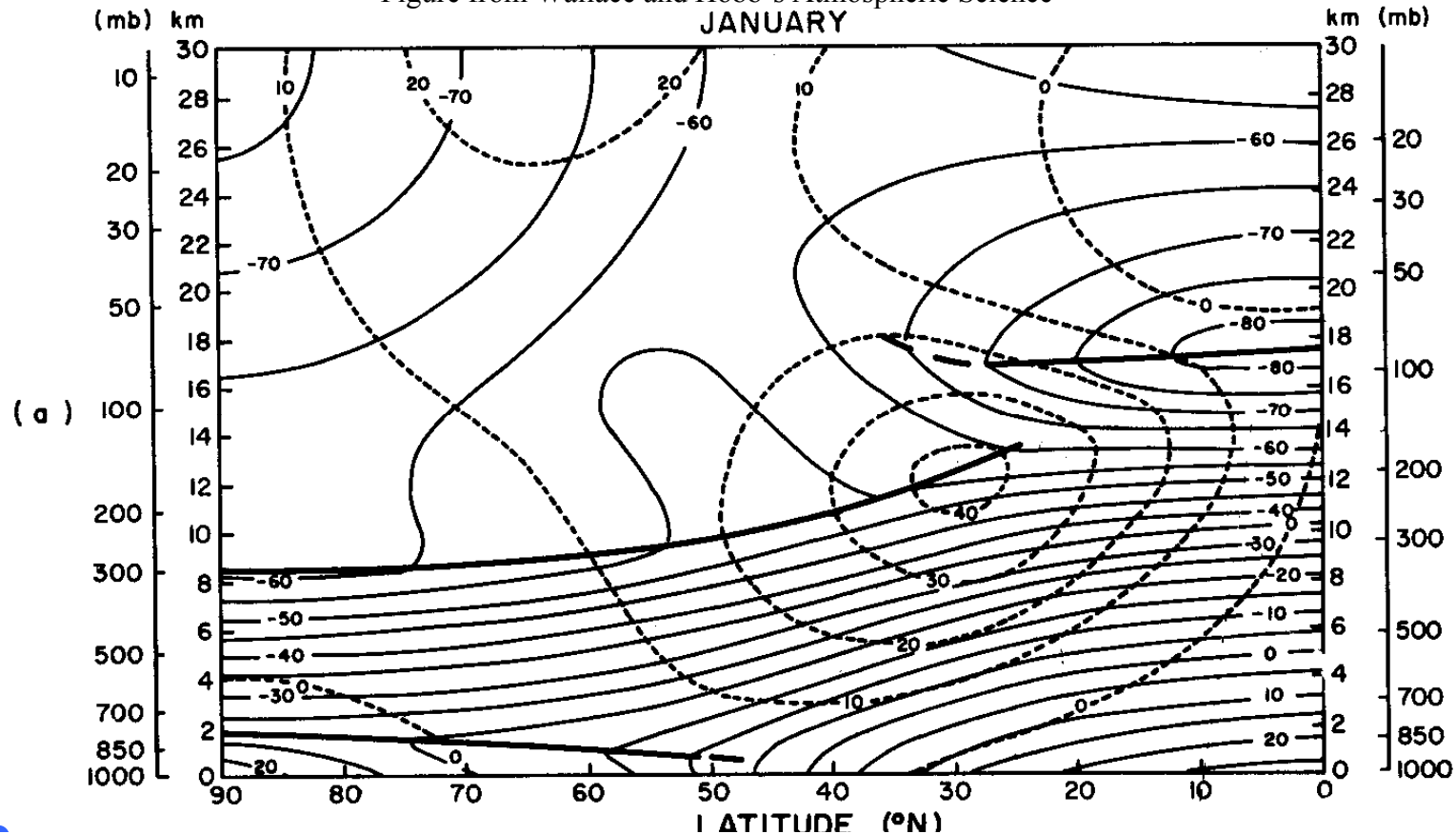
LATITUDE (°N) Figure from Wallace and Hobb's Atmospheric Science

**Fig. 1.11** Meridional cross sections of longitudinally averaged temperature in degrees Celsius (—) and zonal wind in meters per second (---) for the northern hemisphere in January (a) and July (b). Positive zonal winds indicate flow from west to east. Heavy lines denote the tropopause and the Arctic inversion. (After *Arctic Forecast Guide*, U.S. Navy Weather Research Facility, 1962.)



# January Temperature Stratification and winds

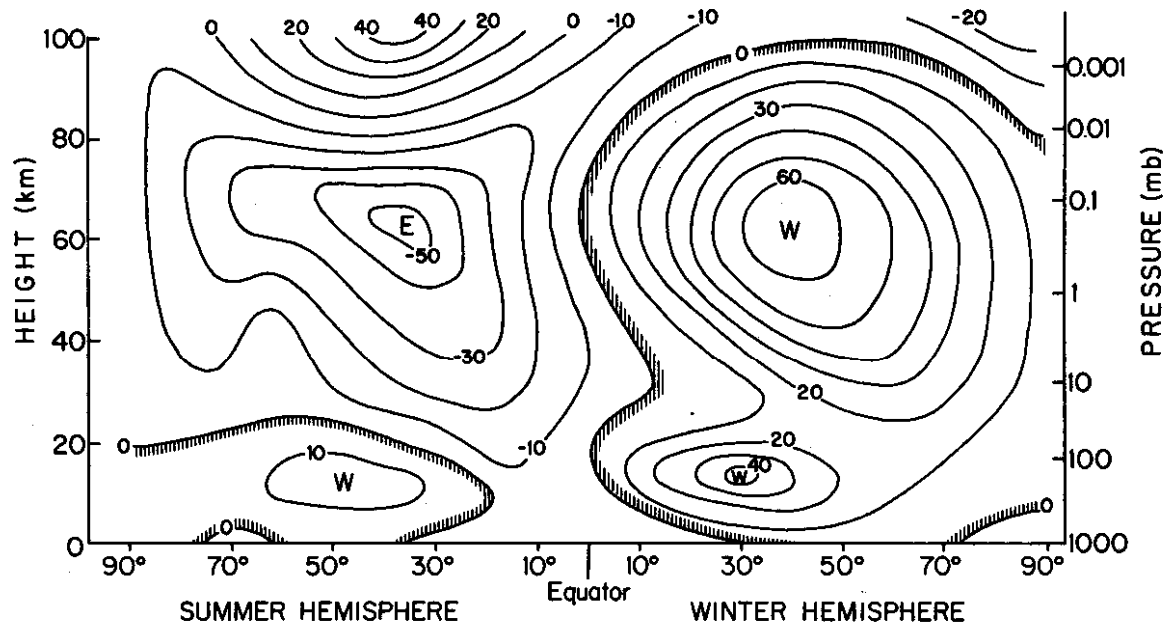
Figure from Wallace and Hobb's Atmospheric Science



**Fig. 1.11** Meridional cross sections of longitudinally averaged temperature in degrees Celsius (—) and zonal wind in meters per second (---) for the northern hemisphere in January (a) and July (b). Positive zonal winds indicate flow from west to east. Heavy lines denote the tropopause and the Arctic inversion. (After *Arctic Forecast Guide*, U.S. Navy Weather Research Facility, 1962.)



# Looking at Both Hemispheres



**Fig. 1.12** Meridional cross section of longitudinally averaged zonal wind in meters per second at the time of the solstices. Positive zonal winds denote flow from west to east. (Courtesy of R. J. Reed.)

Figure from Wallace and Hobb's Atmospheric Science

- The wind speeds in the summer hemisphere are much less than in the winter hemisphere.





# Mean Sea Level Pressure

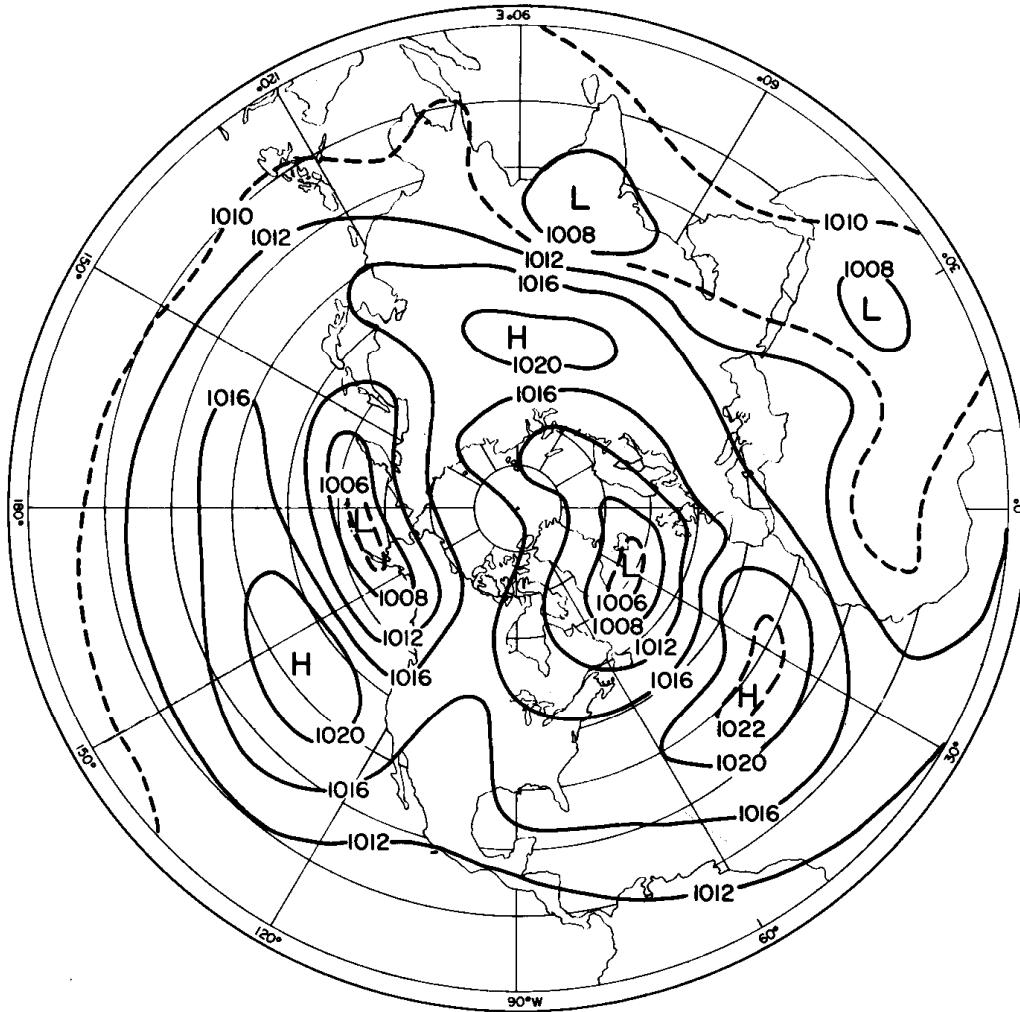
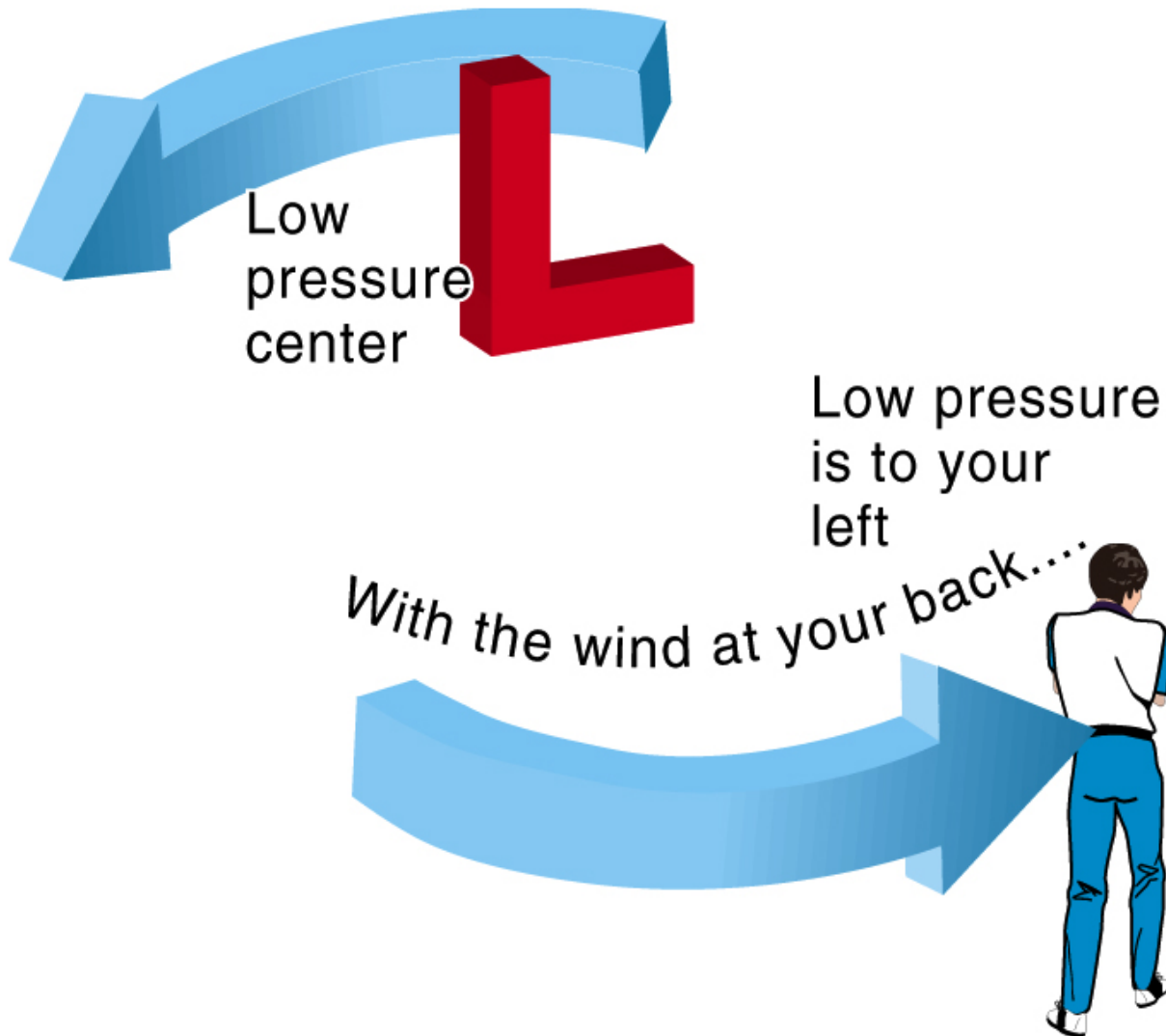


Fig. 1.15 Annual average sea level pressure in millibars. [From *Mon. Wea. Rev.*, 104(12) (1976).]  
Figure from Wallace and Hobb's *Atmospheric Science*

- The change in sea level pressure with the position on the surface is a very good indicator of the wind pattern.
- Away from the surface, wind motion is approximately parallel the lines of constant pressure (isobars).
- Close to the surface, the direction is 'tilted' towards lower pressure.



# Recall Buys Ballot's 'Law'



- This law applies to northern hemisphere winds, and is reversed in the southern hemisphere.
- In the northern hemisphere, air flow is counter-clockwise around a low pressure system, and clockwise around a high.

Graphic from *Meteorology* by Danielson, Levin and Abrams  
General Meteorology  
Atmos. Composition 66



# Apply Buys Ballot's Law to the Mean Annual Surface Pressures

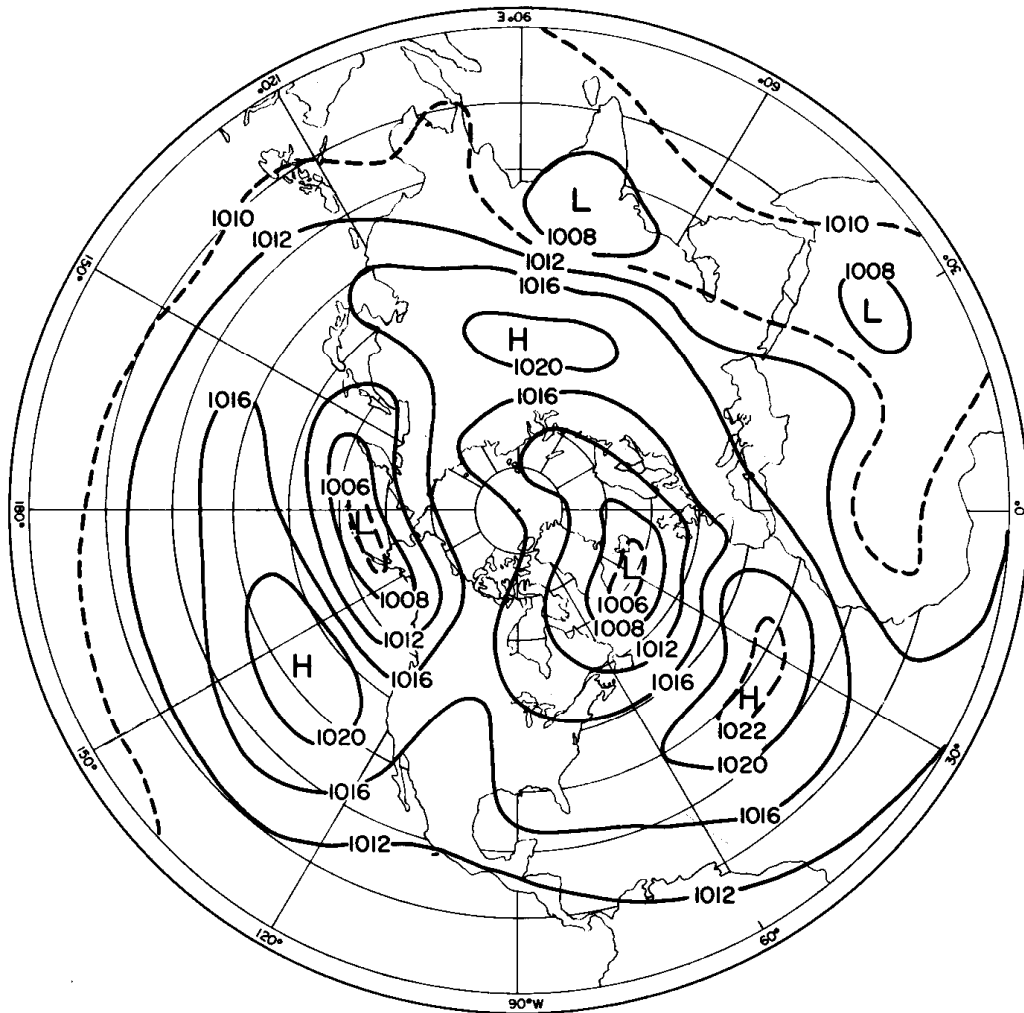
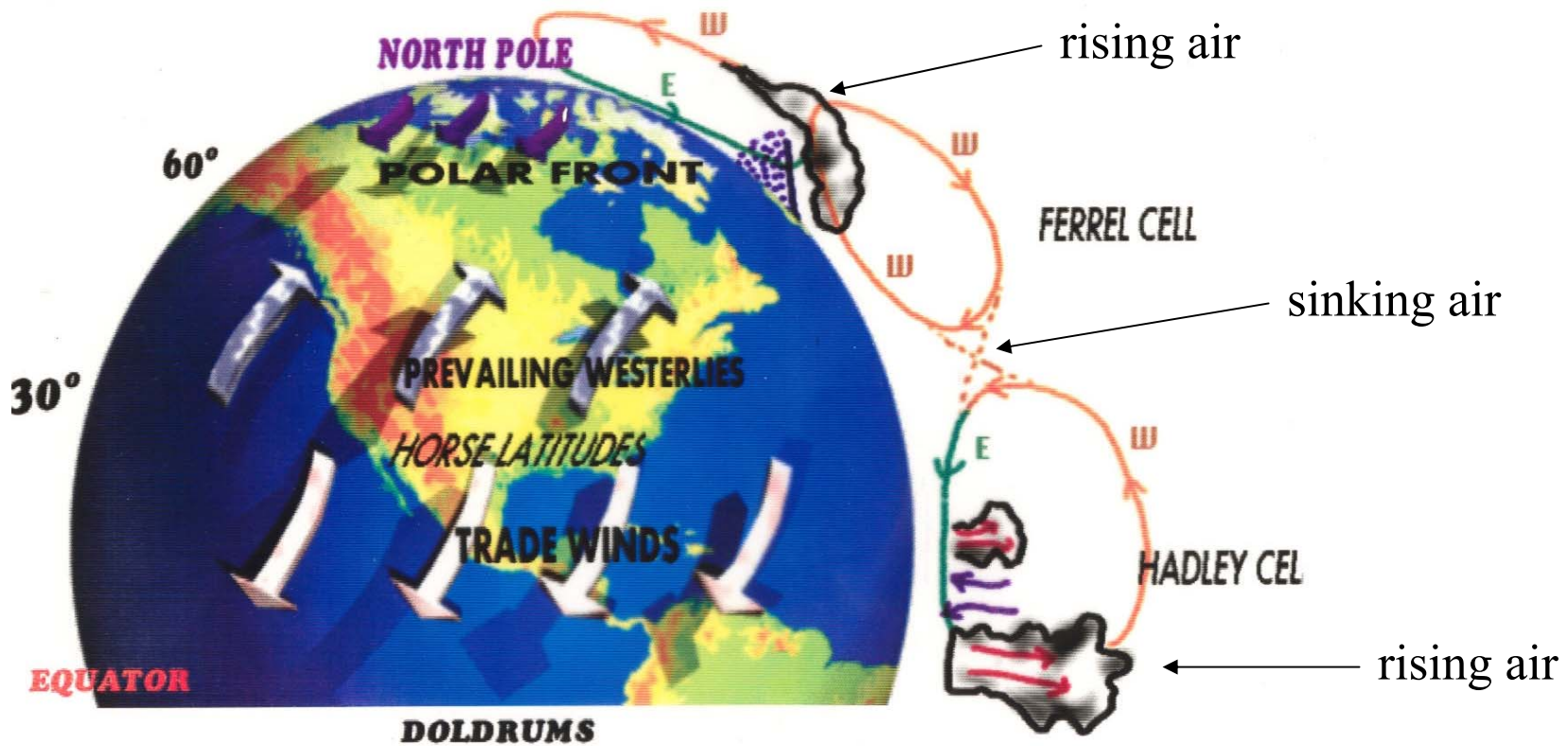


Fig. 1.15 Annual average sea level pressure in millibars. [From *Mon. Wea. Rev.*, **104**(12) (1976).]  
Figure from Wallace and Hobb's *Atmospheric Science*



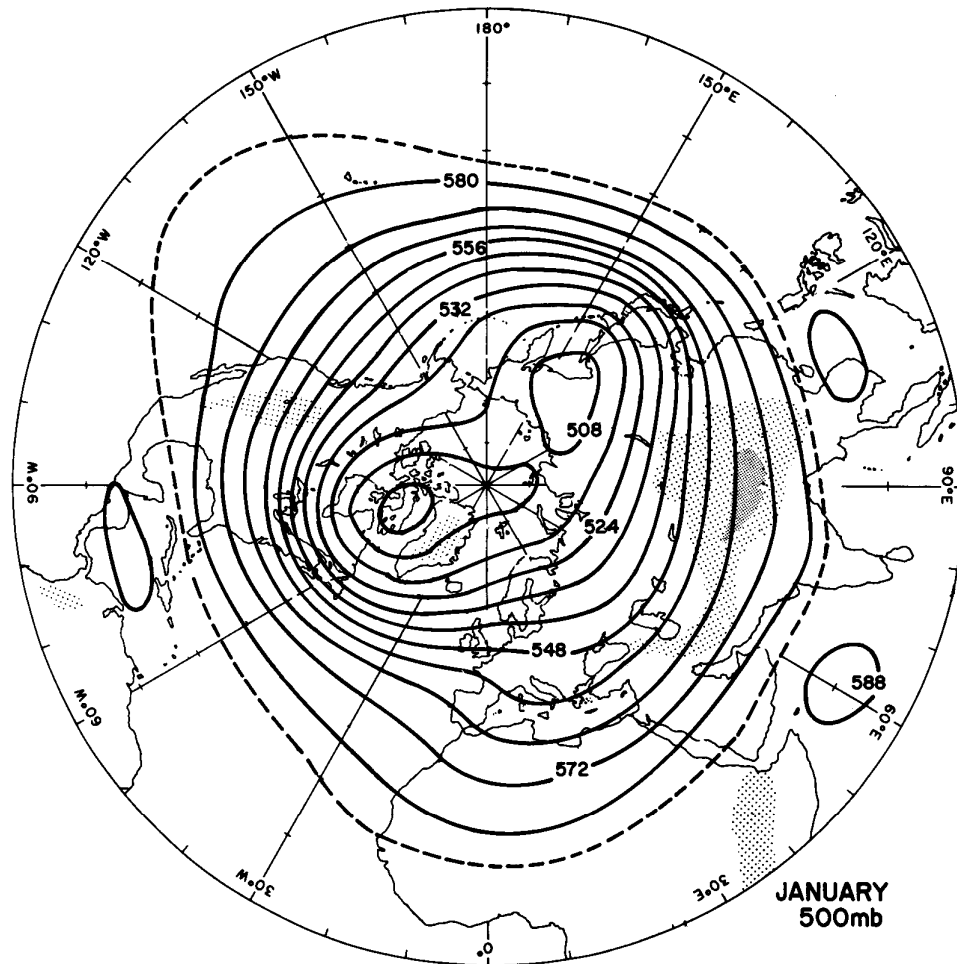
# Explain Features in The Global Picture



- The energy from the sun is largely absorbed in the tropical oceans, transferred through several mechanisms to the air, which causes the air to rise and gain potential energy. Phase changes also add energy.
- The potential energy rich air is then forced to move poleward.



# 500mb Heights & Air Temperature



**Fig. 1.14** The distribution of mean geopotential height (almost identical to geometric height above sea level) on the 500-mb surface for January. Contours are labeled in tens of meters. [Based on data in *Meteorol. Abhandl.*, 4(2), Part II, 32 (1958) as adapted by E. Palmén and C. W. Newton, "Atmospheric Circulation Systems," Academic Press, New York, 1969, p. 68.]

- The heights of a layer of constant pressure can be used as a proxy for the average temperature of air between the surface and the pressure level.
- Colder air has a greater density than warmer air.
- A constant pressure level implies that the same mass of air exists below each location on pressure level (if we ignore the height of land).
- Therefore, a lower height indicates a lower mean temperature below the pressure level.

Figure from Wallace and Hobb's Atmospheric Science  
General Meteorology  
Atmos. Composition 69