An Introduction to Atmospheric Sciences

Lecture Notes for First Year Course

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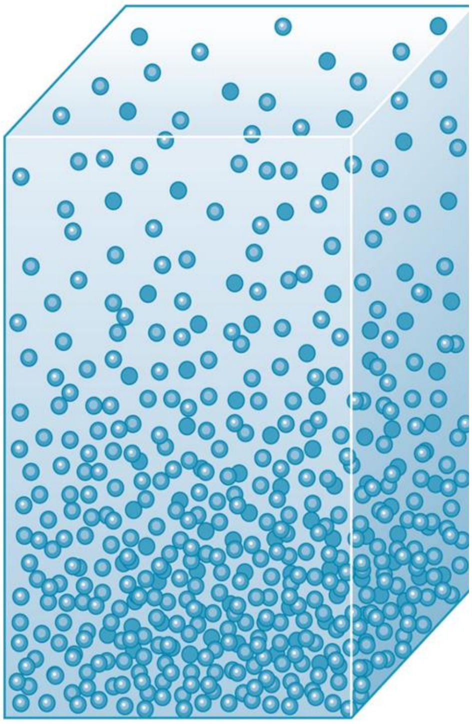
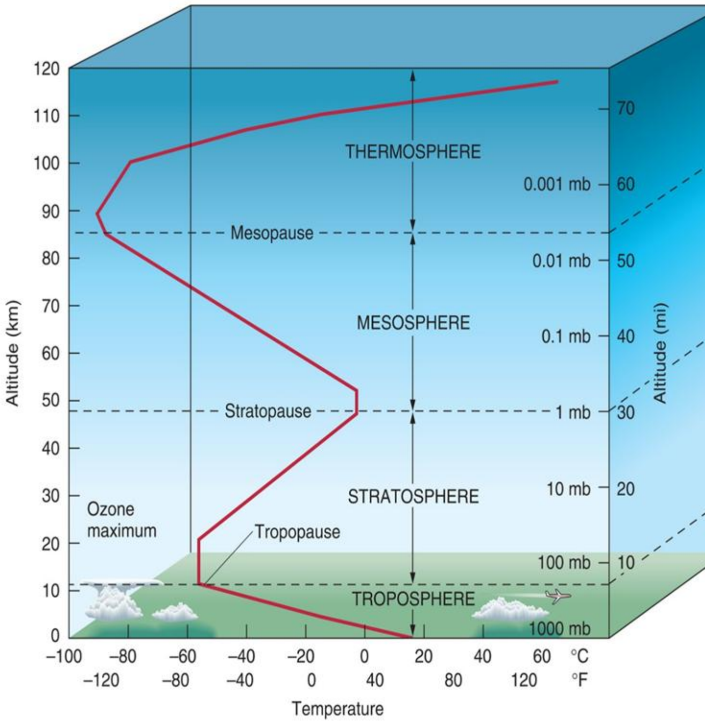
Chapter 1

The Composition and Structure of the Atmosphere





Chapter One
The Composition and Structure of the Atmosphere

Terms and Definitions

Atmosphere – The mixture of gases, water droplets, and solid particles above the earth's surface
Weather – Short-term atmospheric phenomena lasting from hours up to about a week (e.g. thunderstorms, hurricanes, periods of high winds, drizzle)
Climate – Long-term atmospheric conditions lasting from weeks to years (e.g. average yearly Baghdad precipitation, global warming)
Meteorology – The study of weather
Climatology – The study of climate

Thickness of the Atmosphere

How high is the atmosphere?

- No defined top
- 99.99997% of atmosphere is below 100 km (60 mi)
- Weather occurs in lowest 11 km (7 mi)
- Atmospheric depth is very thin relative to earth's horizontal distances

The Evolution of the Atmosphere

Earth's early atmosphere contained mostly hydrogen and helium

- Two hypotheses exist that explain the dispersion of this early atmosphere
    1. The gases escaped to space by overcoming gravity with large enough escape velocities
    2. Collisions between earth and other large bodies launched the early atmosphere to space

- A modern atmosphere began to form through outgassing by volcanic eruptions, and possibly through collisions of comets with earth (Both supplying mostly carbon dioxide and water vapor)
- Water vapor condensed and precipitated to form oceans
- Carbon dioxide lost to oceans
- Oxygen released first through primitive oceanic bacteria, later through plants (protected by ozone layer)
- Plants further reduced carbon dioxide
- Nitrogen slowly increased over long periods of time through outgassing

Composition of the Modern Atmosphere

The atmosphere today contains:

- Gases (permanent and variable)
- Water droplets (clouds and precipitation)
- Microscopic solid particles (aerosols)

The Permanent Gases

Permanent gases form a constant proportion of the atmosphere, and have long residence times (thousands to millions of years)

TABLE 1–2 Permanent Gases of the Atmosphere

Constituent	Formula	Percent by Volume	Molecular Weight
Nitrogen	N_2	78.08	28.01
Oxygen	O_2	20.95	32.00
Argon	Ar	0.93	39.95
Neon	Ne	0.002	20.18
Helium	He	0.0005	4.00
Krypton	Kr	0.0001	83.8
Xenon	Xe	0.00009	131.3
Hydrogen	H_2	0.00005	2.02

The Variable Gases

Variable gases vary in atmospheric concentration in both time and space

TABLE 1–3 Variable Gases of the Atmosphere

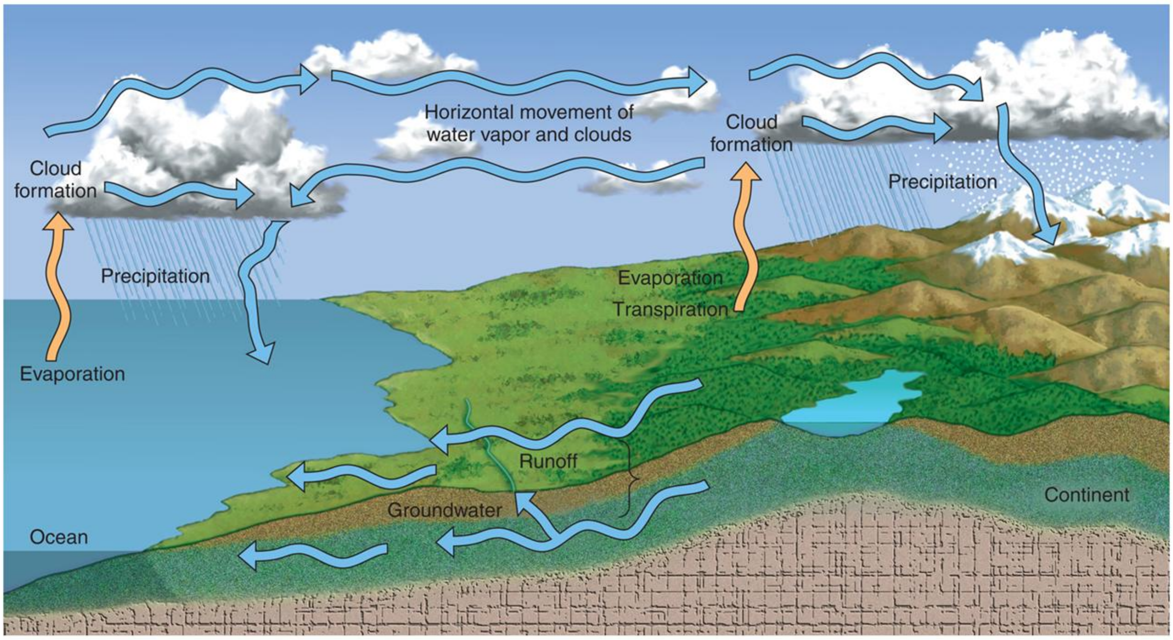
Constituent	Formula	Percent by Volume	Molecular Weight
Water Vapor	H_2O	0.25	18.01
Carbon Dioxide	CO_2	0.038	44.01
Ozone	O_3	0.01	48.00

Water Vapor

Water vapor (H2O) – Extremely important variable gas with short residence time (~10 days)

- Water vapor is the invisible gaseous phase of water (you can only see liquid water droplets!)
- Atmospheric concentration highest near ocean surface in tropics (~4%)
- Atmospheric concentration lowest in deserts and at high altitudes (near 0%)

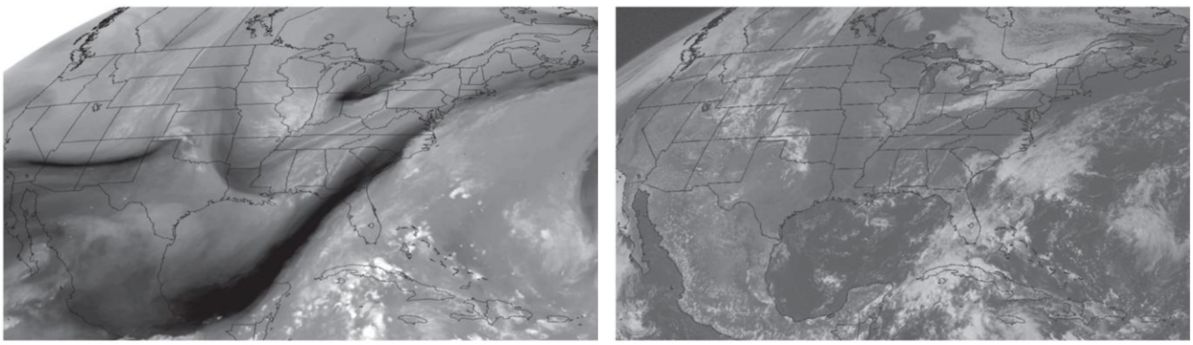
The Hydrologic Cycle



Water Vapor Satellite Imagery

- Satellite imagery reveals variable nature of water vapor concentration
- Water vapor satellite imagery also reveals moist and dry regions of the atmosphere (visible imagery does not)

Water vapor imagery | Visible imagery



(a) (b)

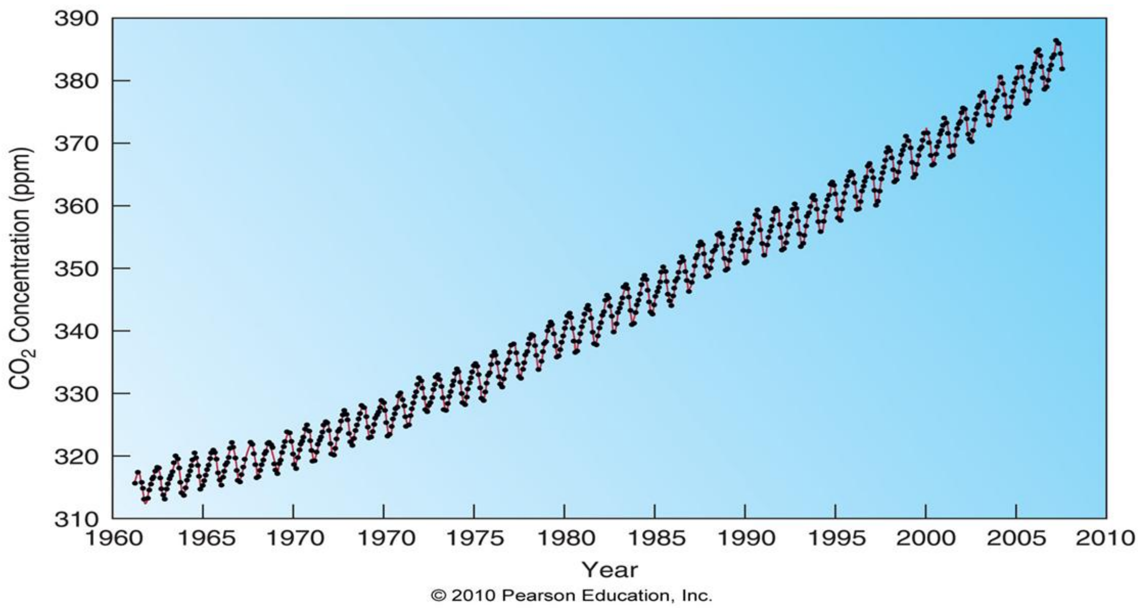
Carbon Dioxide

- **Carbon dioxide (CO_2)** – An important greenhouse gas with concentration 0.0386% (386 ppm) and residence time of 150 years

  - Sources - 1) Plant and animal respiration
    2) Volcanoes
    3) Organic decay
    4) Combustion

  - Sinks - 1) Photosynthesis (plants)
    2) The oceans

- Seasonal oscillation in concentration
- Long term increase in concentration (due to anthropogenic combustion and deforestation)



Mauna Loa Observatory (~11,000 ft. in Hawaii)

Ozone

Ozone (O_3) – A beneficial and harmful variable gas

- O_3 concentrations in the stratosphere (~15-50 km above sea level) are relatively high (15 ppm), occurs from natural chemical reactions

  → Absorbs UV radiation!!

- O_3 concentration near earth's surface is usually near zero, but can increase to 0.15 ppm through chemical reactions in polluted air

→ Irritant!!

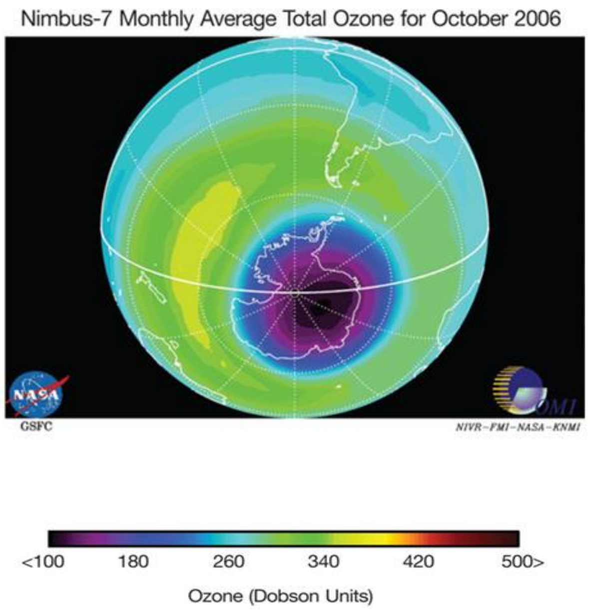
Stratospheric Ozone Creation and Destruction

- Natural ozone cycle

$$O_2 + uv \dashrightarrow O + O$$
$$O_2 + O \dashrightarrow O_3$$
$$O_3 + uv \dashrightarrow O + O_2$$

- After introduction of CFCs

$$CFC + uv \dashrightarrow Cl + CFC^{byproduct}$$
$$Cl + O_3 \dashrightarrow ClO + O_2$$
$$O + ClO \dashrightarrow Cl + O_2$$

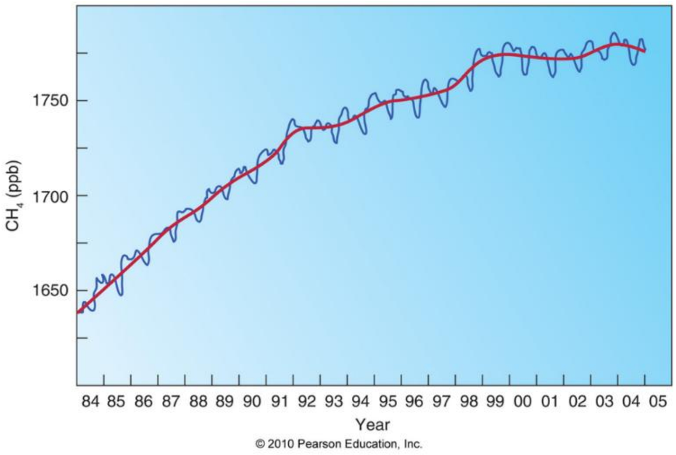


Methane

- **Methane** (CH_4) – A variable gas with residence time ~10 years that has high potential for greenhouse warming

  Sources - 1) Rice cultivation, wetlands
  2) Mining
  3) Biomass burning
  4) Fossil fuel extraction
  5) Animal digestion

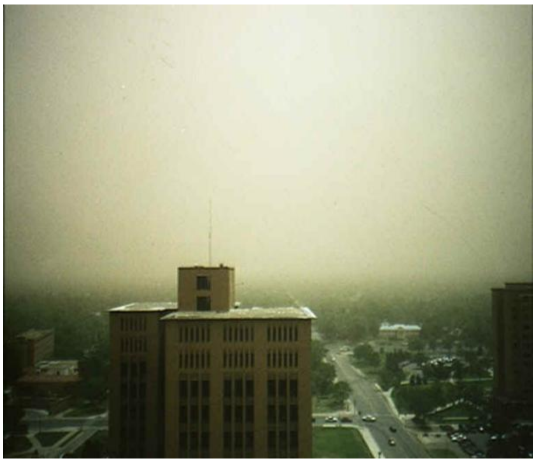
  Sinks - 1) Atmospheric chemical reactions



Aerosols

- **Aerosols –** Small solid particles (e.g. dust, smoke, sea spray, volcanic ash)

  Typical concentration = 1,000/cm^3
  Typical diameter = 10 microns (0.00001 meter)
  Typical life span = days to weeks
  Mostly from natural sources
  Primary sinks include dry and wet deposition
  Act as cloud condensation nuclei (without aerosols, there would never be clouds)

Lubbock, Texas Dust Storm

Haboob in Phoenix, AZ

Forest fire smoke in CA

Eruption of Mount St. Helens

Vertical Structure of the Atmosphere

There are various ways to characterize the vertical nature of the atmosphere

- Density profile
- Temperature profile (Most common)
- Chemical profile
- Electrical profile

The Chemical Profile

Homosphere – The atmosphere below 80km (~50miles)

- Permanent gases are in constant concentration
- Generally, “atmosphere” refers to the homosphere

Heterosphere – Above the homosphere

- Lighter gases dominate (helium, hydrogen)
- No permanent gases

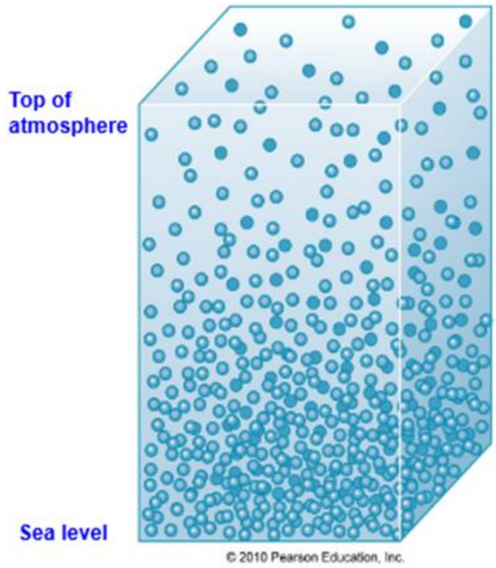
The Density Profile

Density is defined as the amount of mass per unit volume

Density of various materials

Water	1000 kg/m^3
Steel	7800 kg/m^3
Air (at sea level)	1.2 kg/m^3

- The atmosphere is compressible
- Density decreases with height



Atmospheric Pressure

How does pressure decrease with height in the atmosphere?

Pressure decreases with height fastest near the surface, less so aloft

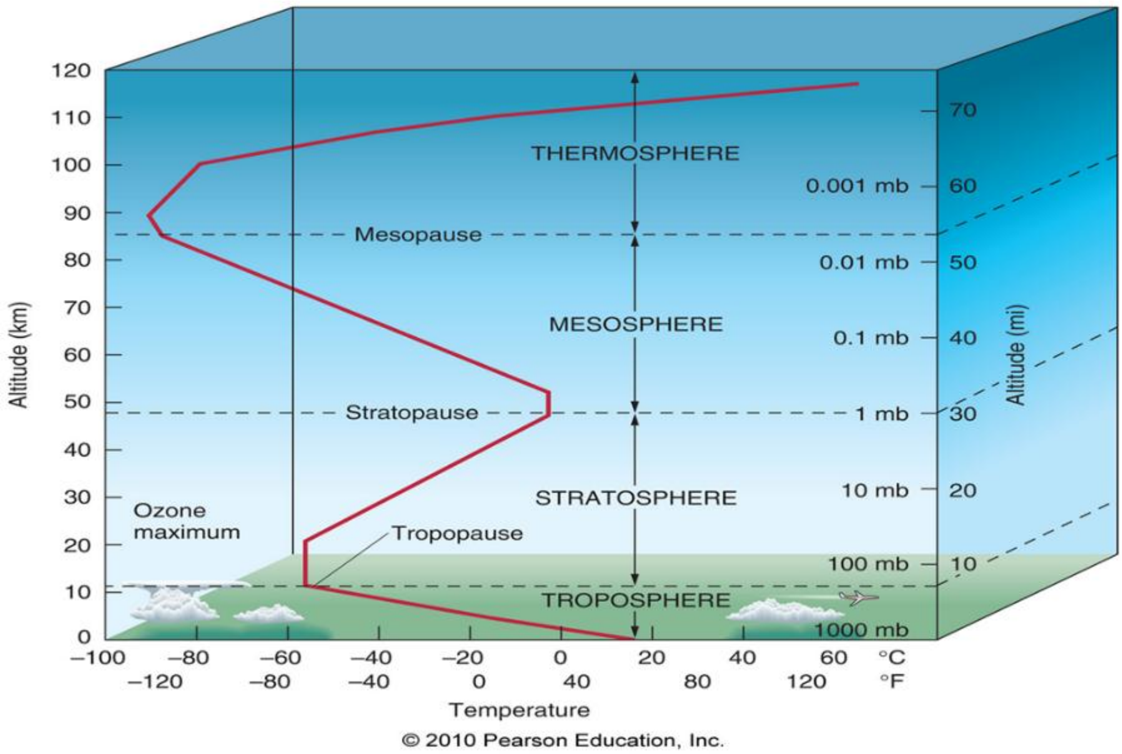
How much pressure (psi) is pushing on you right now?

Average sea-level pressure = 14.7 psi
= 1013.25 mb
= 101325 Pa
= 29.92 in Hg
= 1 atmosphere

Record high sea-level pressure = 1083.8 mb (Siberia, 1968)
Record low sea-level pressure = 870 mb (Typhoon Tip near Guam, 1979)

Layering the Atmosphere Based on Temperature

4 layers identified by similar temperature rates of change with height



A Quick Note on Temperature…

Temperature is expressed in Fahrenheit (°F), Celsius (°C), or Kelvin (K)

<u>Conversions</u>

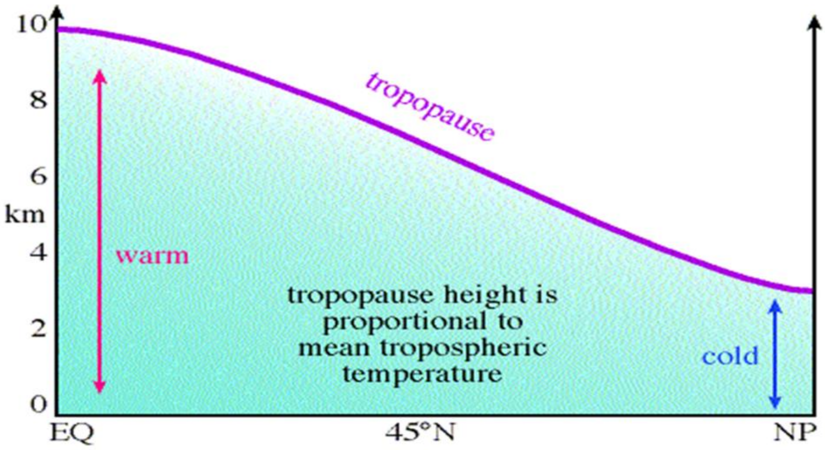
$$K = {}^{o}C + 273.16$$

$${}^{o}F = (9/5) * {}^{o}C + 32$$

Troposphere

Troposphere – Lowest atmospheric layer

- Located at about 0-11km (0-7.0 mi)
- Practically all weather occurs in the troposphere
- Temperature generally decreases with height (environmental lapse rate, typical value = 6.5 °C/km) – Why??
- Top of troposphere is called the **tropopause**
- Contains 80% of atmospheric mass
- Depth varies with latitude and season



Stratosphere

Stratosphere – The atmospheric layer above the troposphere (2nd layer up)

- Only weather in stratosphere are overshooting thunderstorm tops

- Ozone layer is located in stratosphere
- Temperature increases with height (inversion) – due to O3 absorbtion of UV
- Located from about 11-50 km
- Top of stratosphere is called the **stratopause**
- Contains about 19.9% of atmospheric mass

Mesosphere and Thermosphere

The **mesosphere** (3rd layer up) and the **thermosphere** (4th layer up) contain only 0.1% of atmospheric mass

- Mesosphere located from about 50-80km
- Temperature decreases with height in the mesosphere
- Thermosphere located above 80km
- Temperature increases with height in the thermosphere

Characterizing the Atmosphere Based on Electrical Properties

The **ionosphere** is an atmospheric layer located from the upper mesosphere into the thermosphere

- The ionosphere contains electrically charged particles called ions due to UV radiation
- The ionosphere affects AM radio waves, absorbing them in the day and reflecting them at night
- The ionosphere creates the northern lights (**aurora borealis**) and the southern lights (**aurora australis**) through interactions between the sun's rays and earth's magnetic field

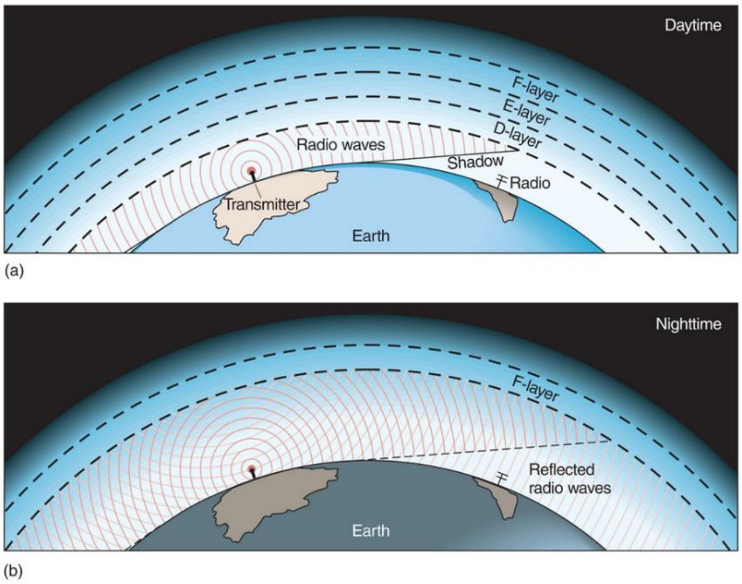
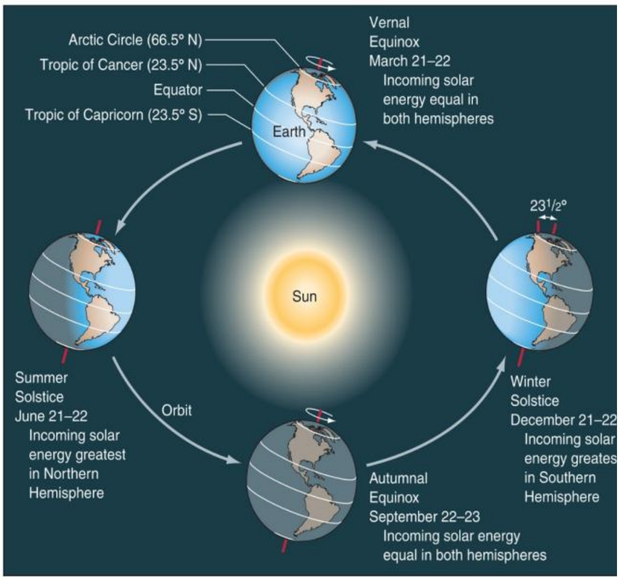


Photo from climate.gi.alaska.edu/Curtis

The Northern Lights

Chapter 2

Solar Radiation and the Seasons



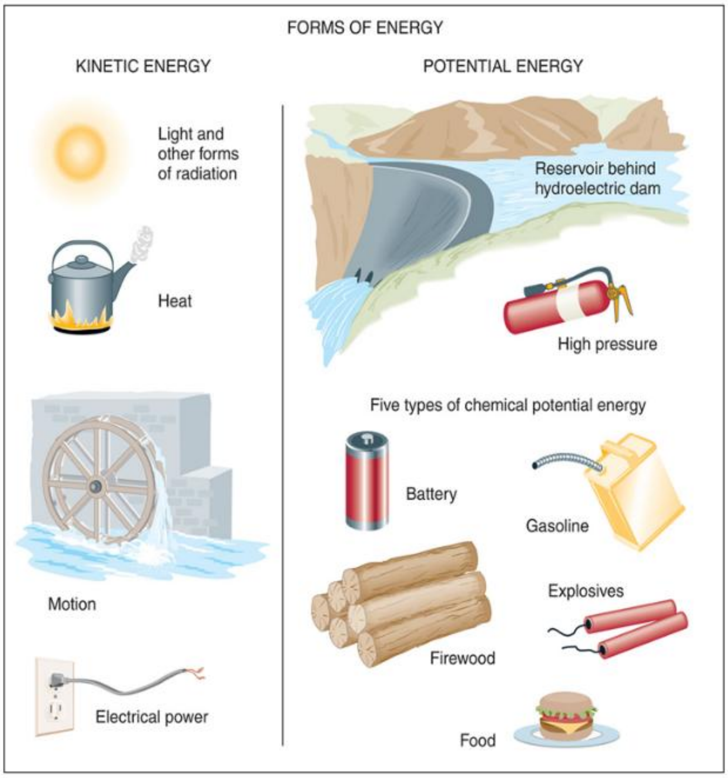
Chapter Two

Solar Radiation and the Seasons

Energy

- **Energy** is defined as the ability to do work
  - ➢ **Kinetic energy** – the energy of motion
  - ➢ **Potential energy** – energy that can be used

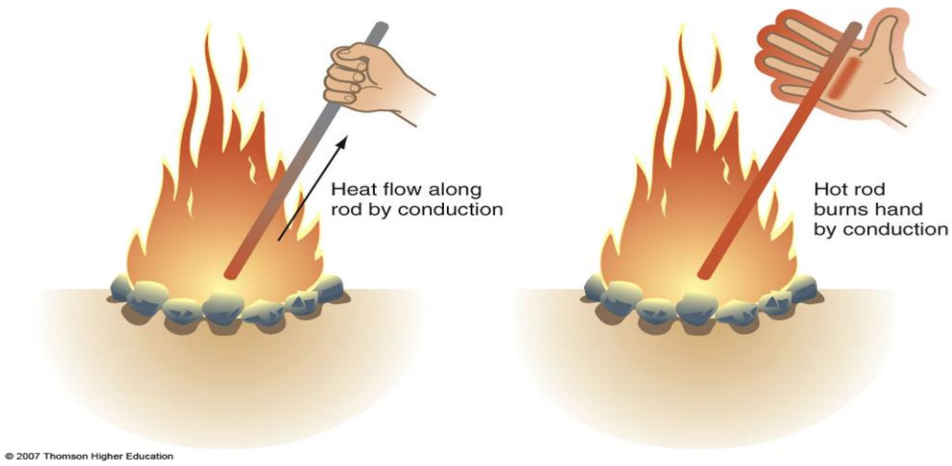
- Energy is conserved!
  (1st law of thermodynamics)



Energy Transfer

Although energy is conserved, it can move through the following mechanisms:

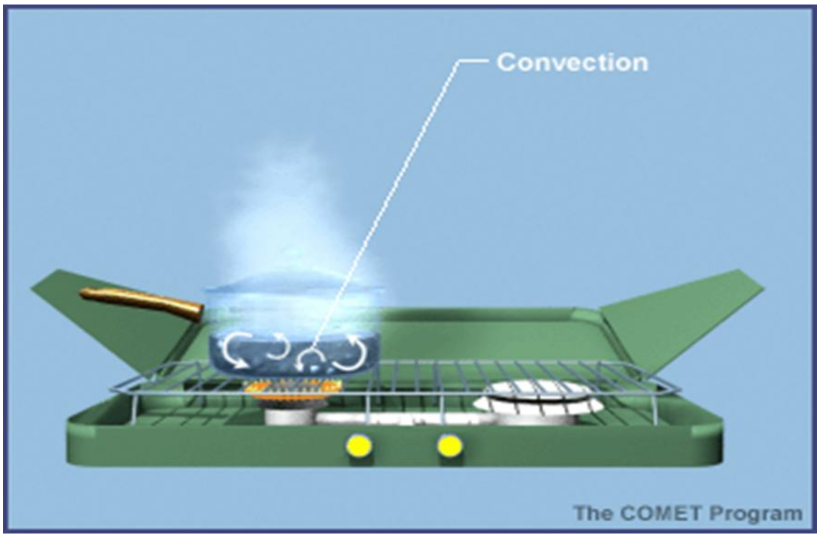
1) **Conduction** – heat transfer by physical contact, from higher to lower temperature



- Occurs at the atmosphere/surface interface

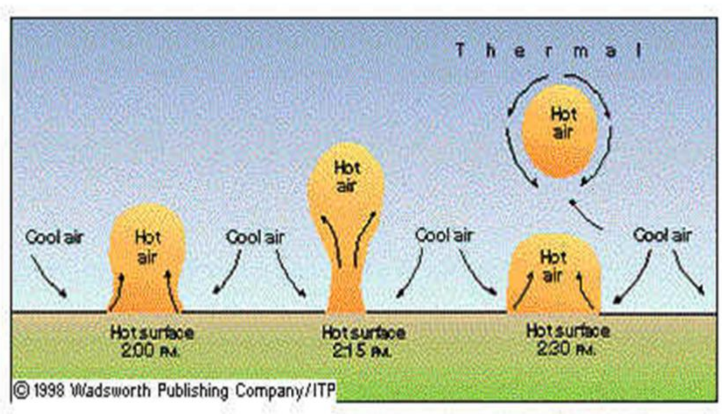
  Partly responsible for daytime heating/nighttime cooling! (The diurnal cycle)

2) **Convection** – heat transfer by movement



Convection in the Atmosphere

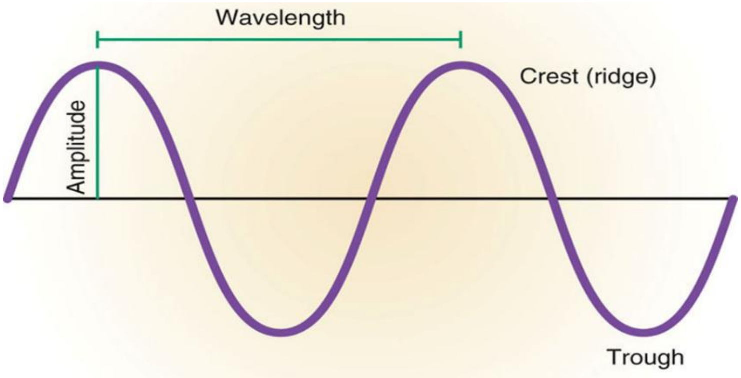
Vertical transport of heat



Horizontal transport of heat = **advection**

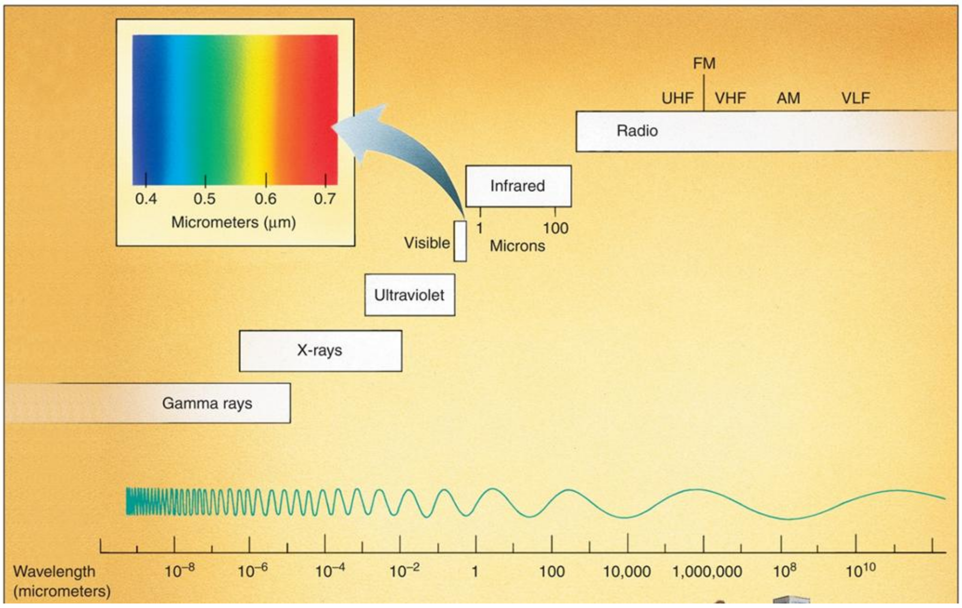
3) **Radiation** - transfer of energy by electromagnetic radiation (no medium required!)

Characteristics of radiation



1) **Wavelength** – the distance between wave crests
2) **Amplitude** – the height of the wave
3) **Wave speed** – constant! (speed of light Wave speed – constant! (speed of light - 2.998 x 10^8 m/s)

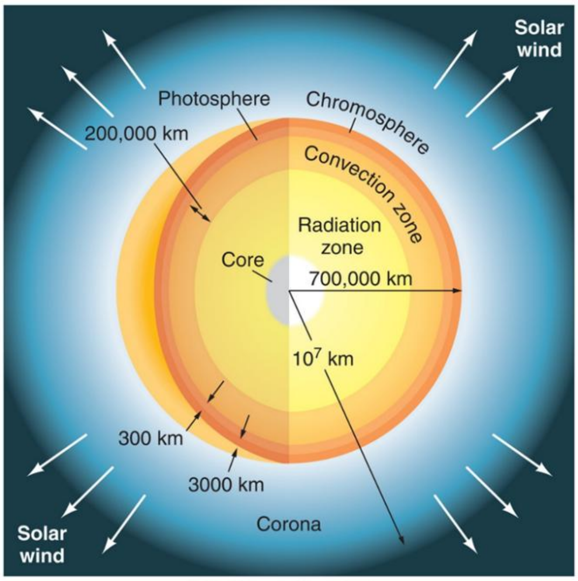
- The wavelength of radiation determines its type

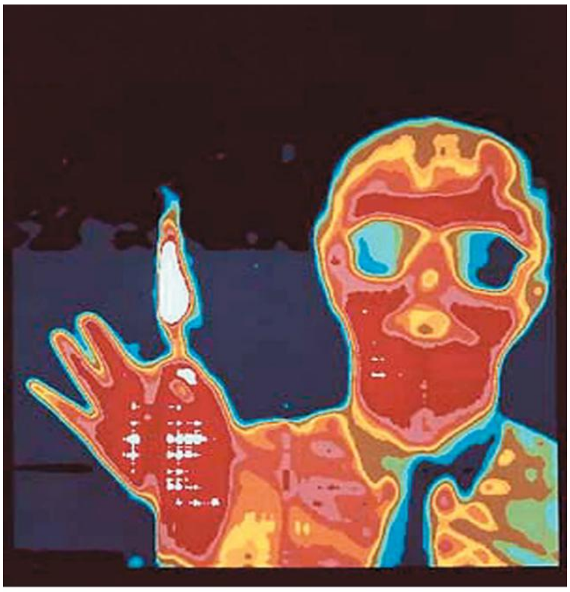


- The amplitude determines the intensity

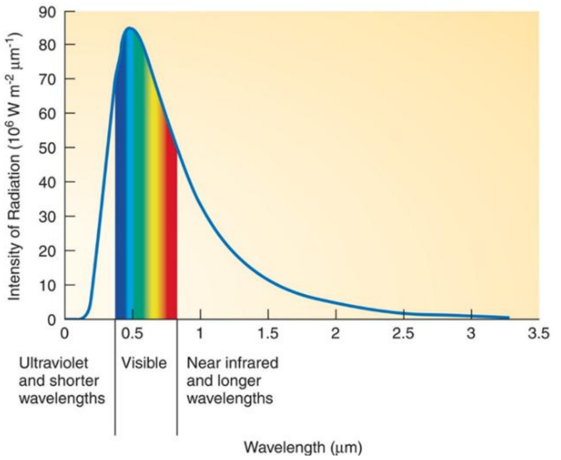
What emits radiation?

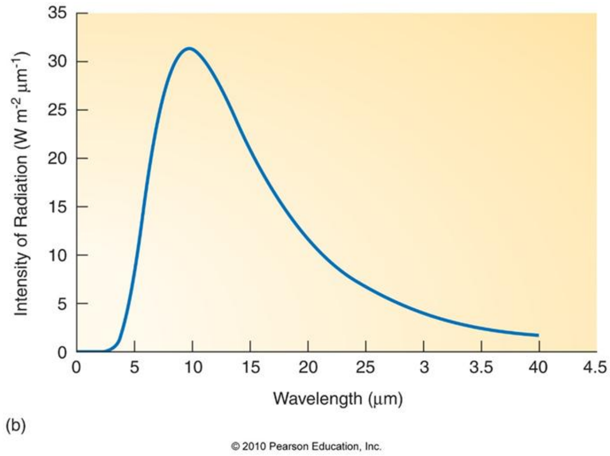
EVERYTHING





- The types (wavelengths) and intensity (amplitudes) of radiation depend on temperature





Sun is HOT (~5600 ^oC)
Shortwave radiation

Earth is NOT (~15 oC)
Longwave radiation

- **Blackbody** – an object that absorbs all radiation and emits the maximum amount of radiation at every wavelength (not realistic)
- **Graybody** – an object that emits a fraction (emissivity) of blackbody radiation (more realistic)

Radiation Laws

- **Stefan-Boltzmann Law** – the total amount of blackbody radiation emitted (I) is related to temperature:

$$I = \sigma T^4$$

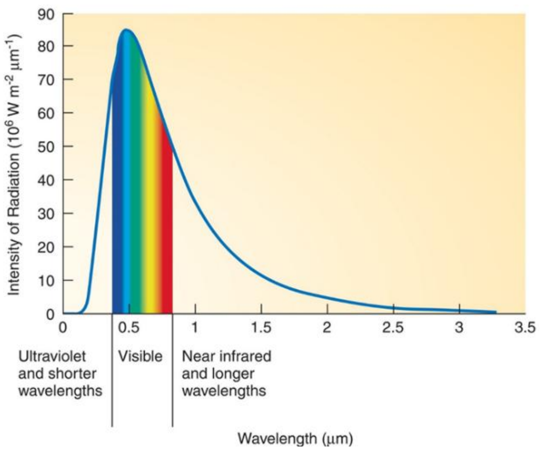
- For a graybody, this becomes:

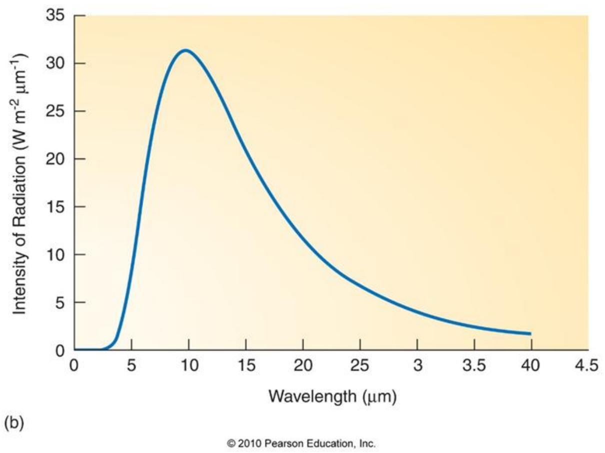
$$I = \varepsilon \sigma T^4$$

where ε is the emissivity

- **Wien's Law** – the wavelength of maximum blackbody emission is related to temperature:

$$\lambda_{\max} = 2900 / T$$



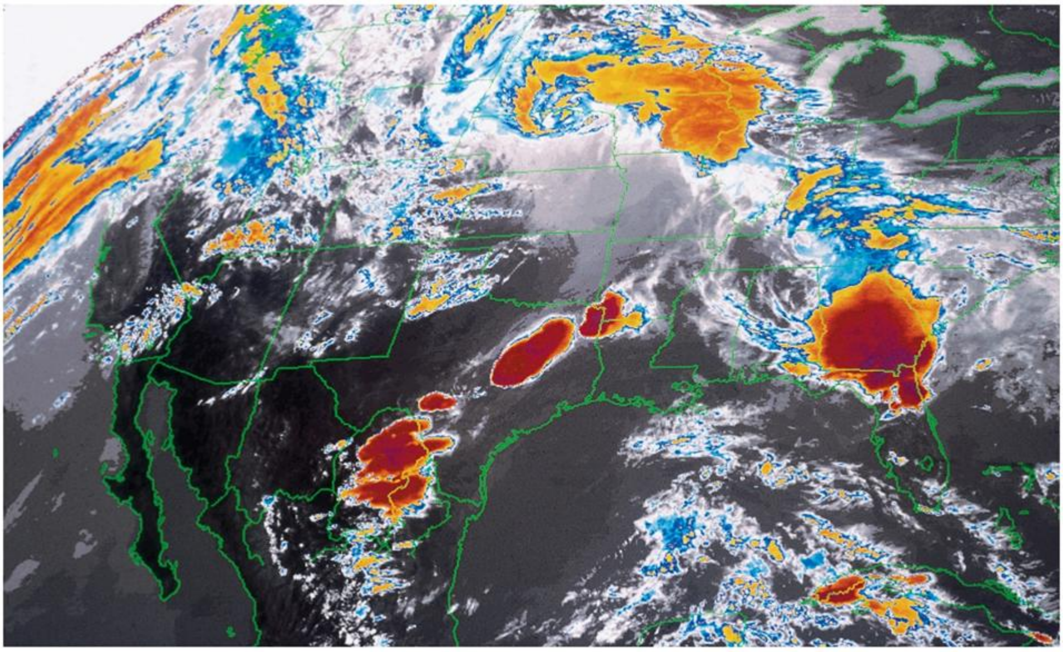


Sun is HOT (~5600 ^oC)
Shortwave radiation

Earth is NOT (~15 oC)
Longwave radiation

Practical use of Radiation Properties

- Visible satellite imagery doesn't work in the dark
- Infrared (longwave) radiation occurs always – use infrared satellite imagery!



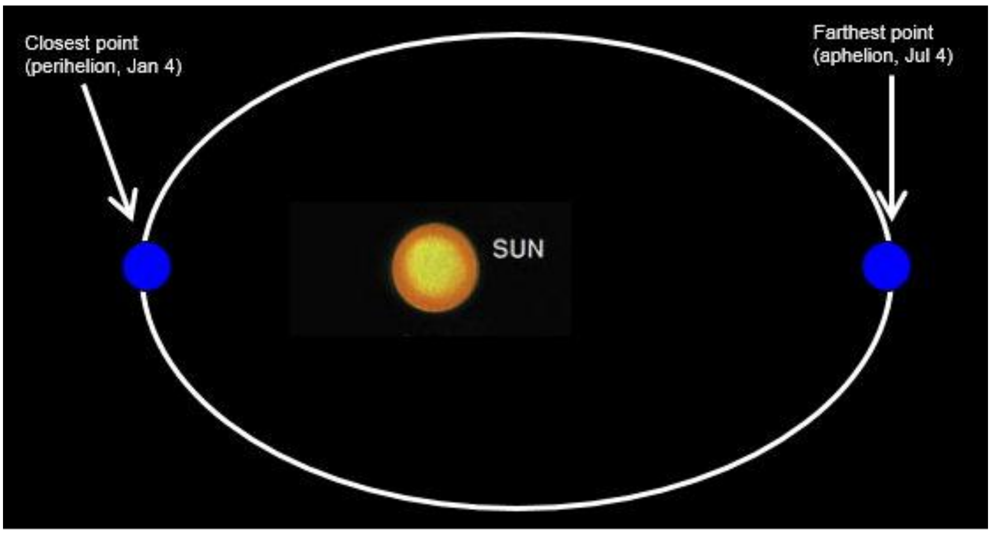
Solar Radiation and the Earth

- The solar constant – the amount of solar radiation hitting the earth

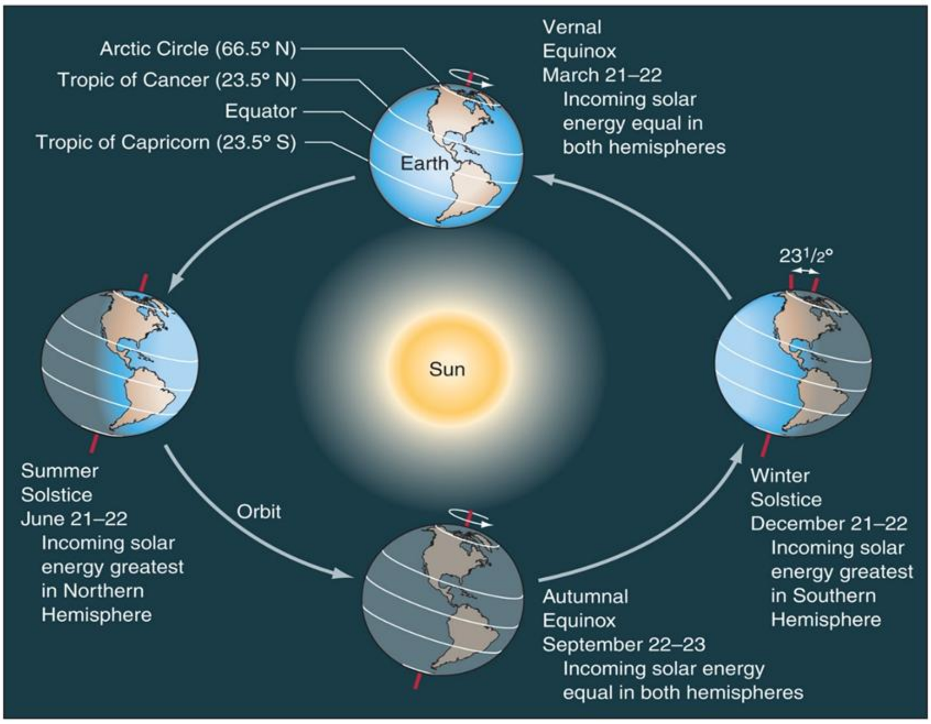
  Earth – 1367 W/m^2

  Mars – 445 W/m^2

- Earth orbits the sun elliptically (once per 365.25) days

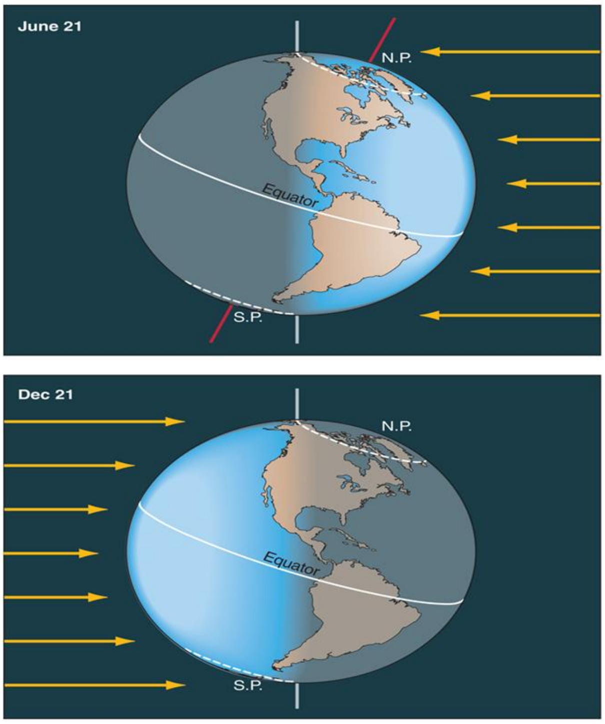


- Earth gets ~7% more radiation in winter (not enough to cause the seasons!) What does?
- Earth's tilt is the true cause of the seasons!
  Earth's axis is tilted 23.5°



Three factors contribute to the amount of incoming solar radiation **(insolation)**:

1) Period of daylight



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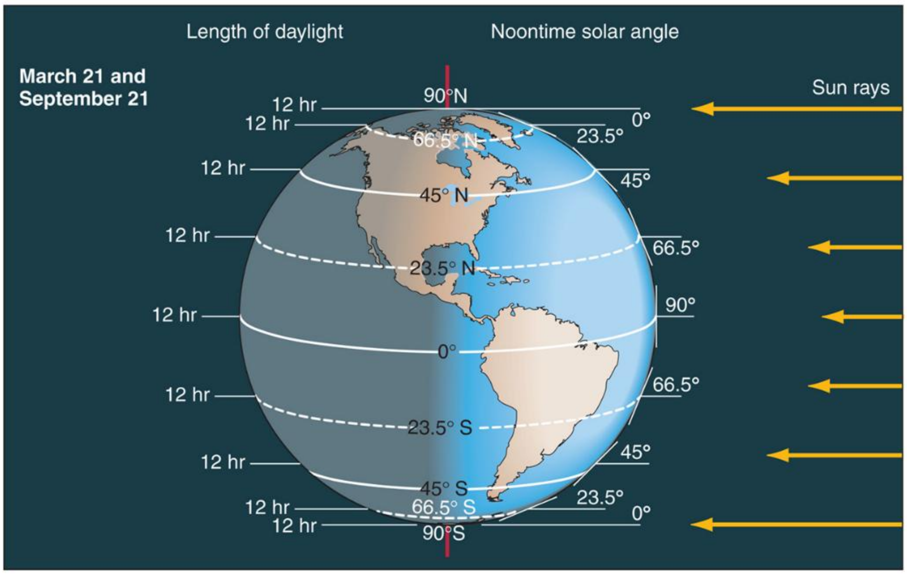
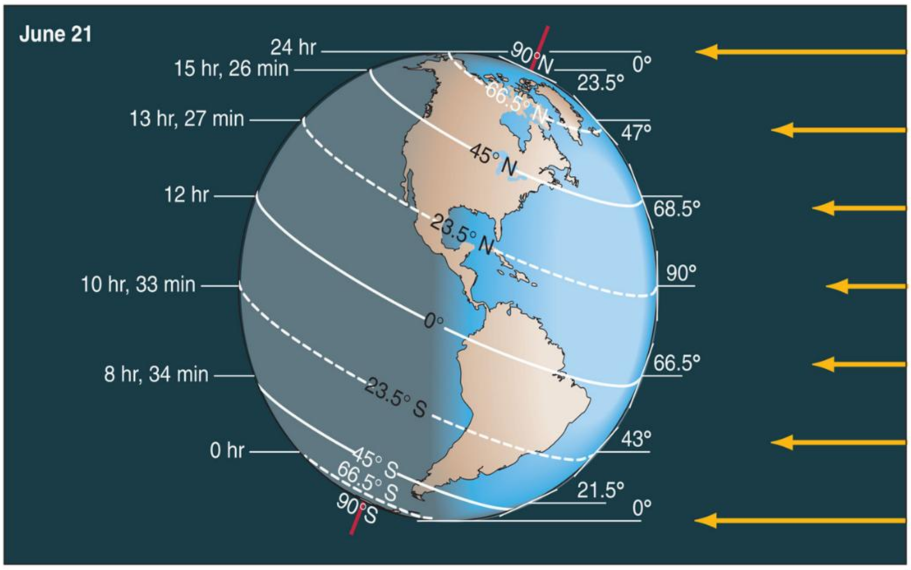
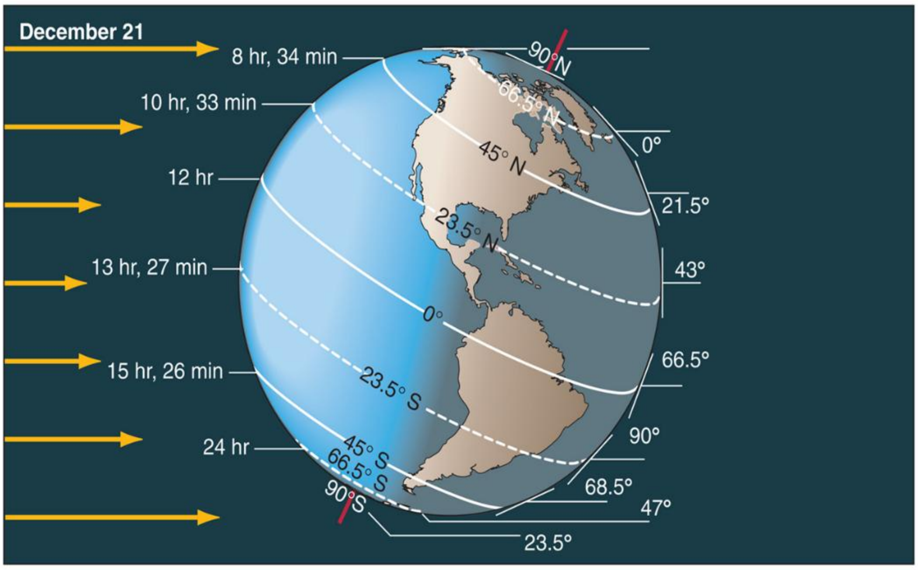


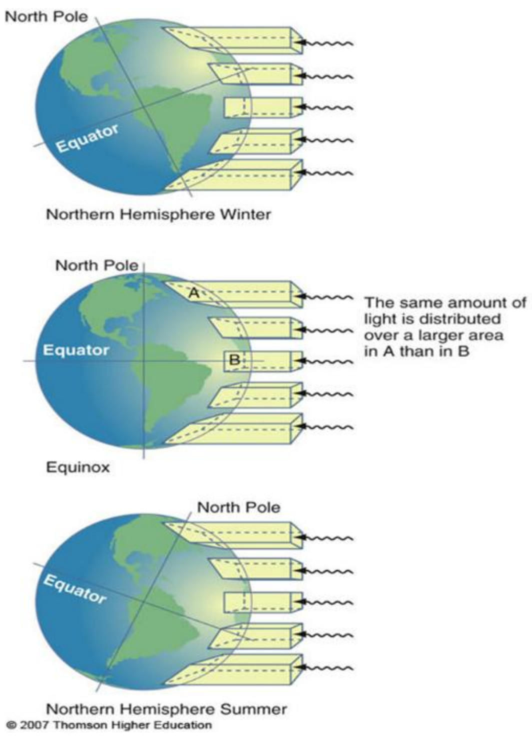

June 21
24 hr
15 hr, 26 min
13 hr, 27 min
12 hr
10 hr, 33 min
8 hr, 34 min
0 hr
90° N
66.5° N
45° N
23.5° N
0°
23.5° S
45° S
66.5° S
90° S
0°
23.5°
47°
68.5°
90°
66.5°
43°
21.5°
0°

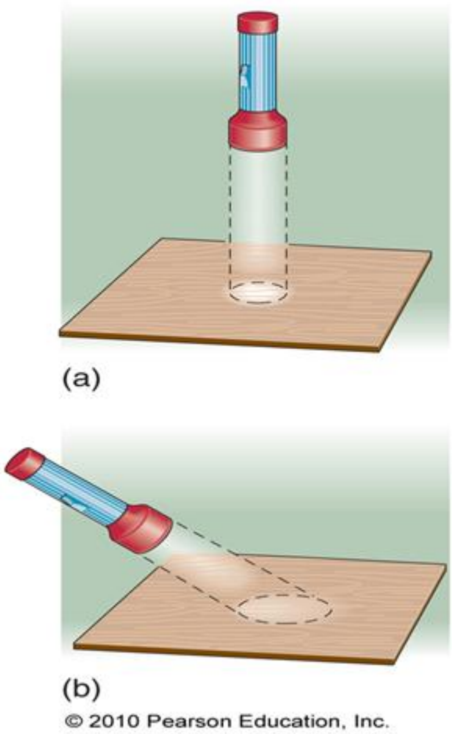
(b)


December 21
8 hr, 34 min
10 hr, 33 min
12 hr
13 hr, 27 min
15 hr, 26 min
24 hr
90° N
66.5° N
45° N
23.5° N
0°
23.5° S
45° S
66.5° S
90° S
0°
21.5°
43°
66.5°
90°
68.5°
47°
23.5°

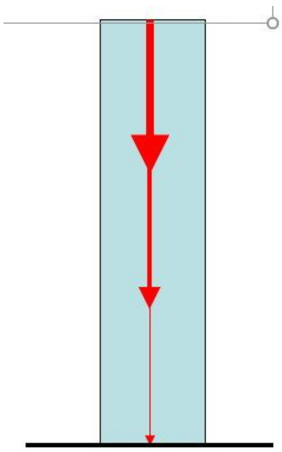
(c)

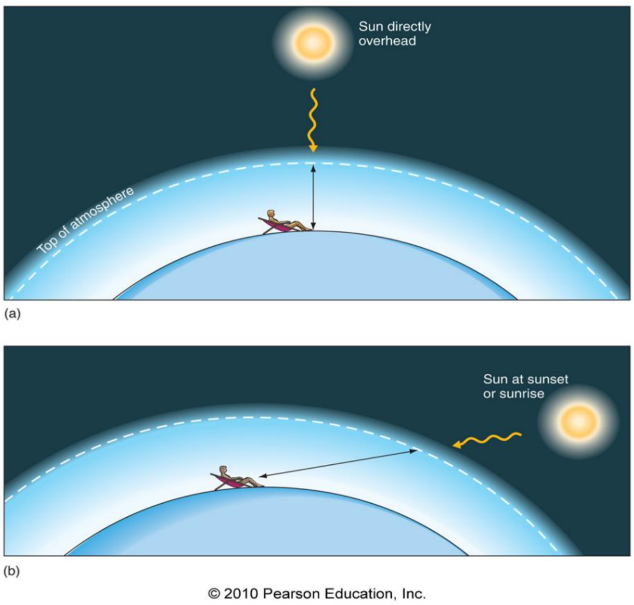
2) Solar Angle





3) Beam depletion





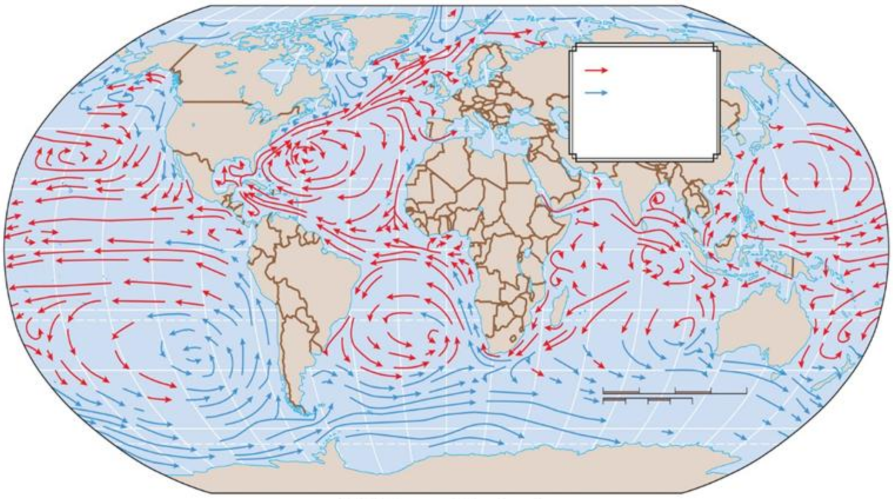
What's the end result of these 3 mechanisms and the tilt of the earth?

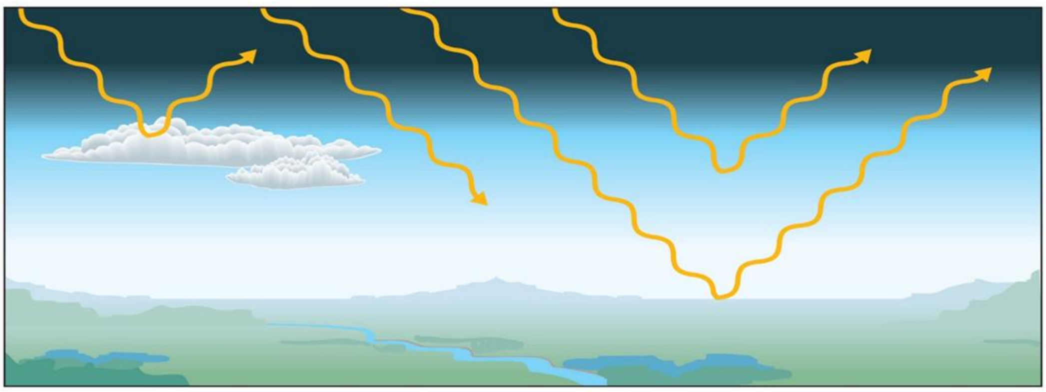
Weather as we know it!

Jet stream… Mid-latitude cyclones…fronts… Thunderstorms…winds

Chapter 3

Energy Balance and Temperature





Chapter Three

Energy Balance and Temperature

The Fate of Solar Radiation

- We owe it all to the sun…
- 3 things can happen to solar (and all) radiation:

1) Absorption
2) Scattering and Reflection
3) Transmission

Absorption

- **Absorption** – the full energy transfer from radiation to a substance
- Atmospheric absorption varies by substance:

UV – absorbed by O3 (stratosphere)

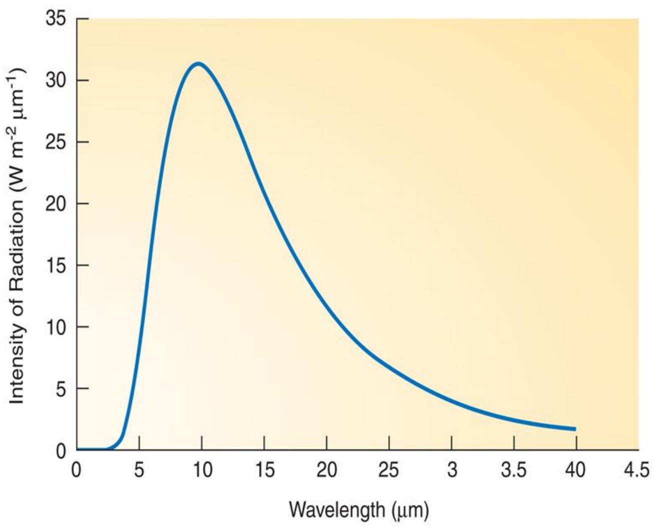
Visible – hardly absorbed (lucky for us)

Infrared – partially absorbed by water

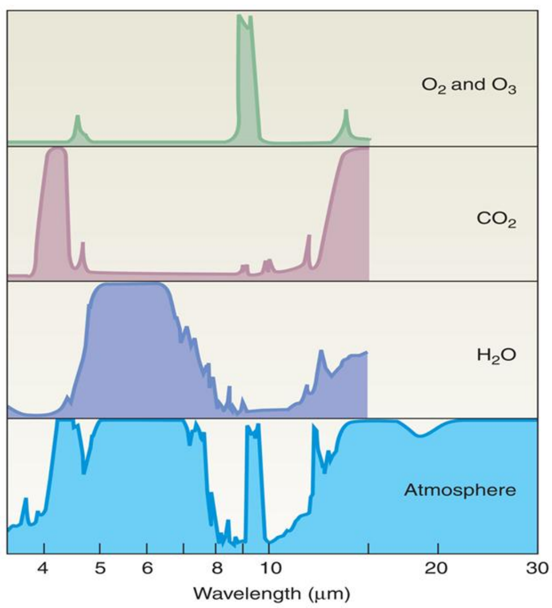
vapor, CO2 (less cooling in high humidity..)

The Atmospheric Window

- The atmospheric window is a band (8-12 μm) of very little absorption



Earth's surface emission



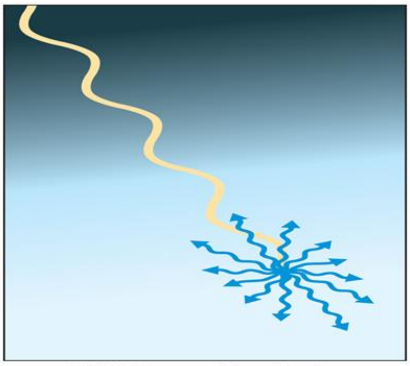
Atmospheric absorption

- Liquid water (i.e. clouds), however, are good absorbers of all longwave radiation
- Are cloudy or clear nights warmer???

Scattering and Reflection

Scattering – the deflection of radiation by a substance
Diffuse scattering – radiation deflected in many directions, becomes diffuse radiation

Reflection – a type of scattering, radiation is deflected back with equal intensity (mirror)
Albedo – the fraction of light reflected (earth's albedo is ~0.3)

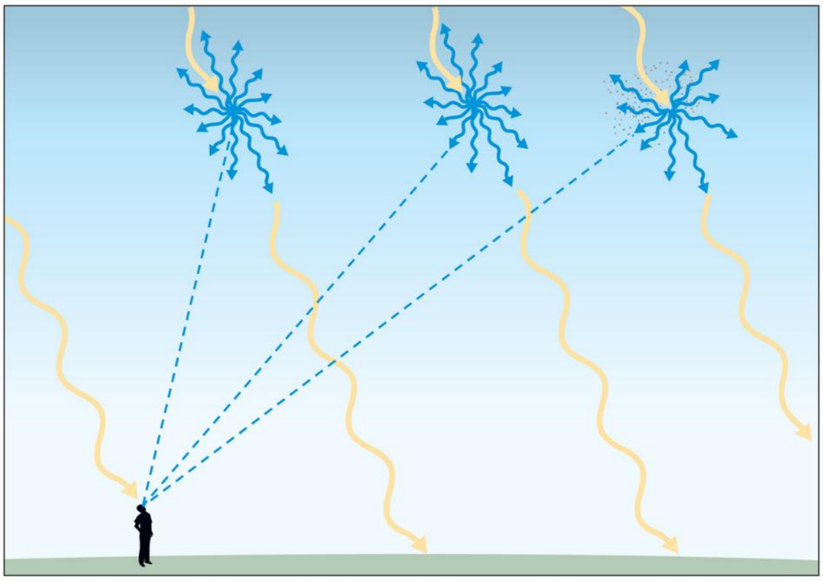


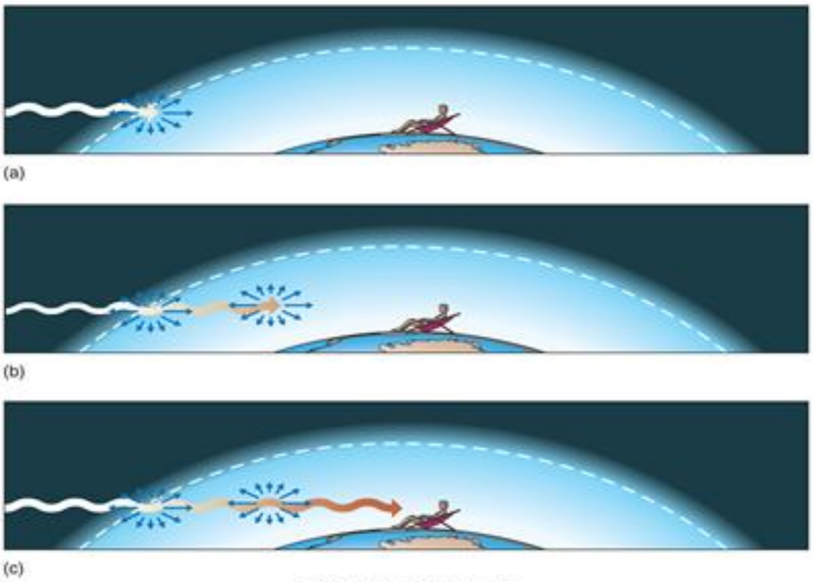
- Scattering affects many things:
  - Shaded areas still receive solar radiation (better buy more sunscreen!)
  - The sky is blue and sunsets are red (**Rayleigh scattering**)
  - Hazy or polluted days make the sky white or gray **(Mie scattering**)
  - Clouds are white (**nonselective scattering**)

Rayleigh Scattering

- Occurs when substance is small compared to wavelength of radiation (such as atmospheric gases)
- Scatters smaller wavelengths (blue) more than longer wavelengths (red)
- Makes the sky appear blue, sunsets red

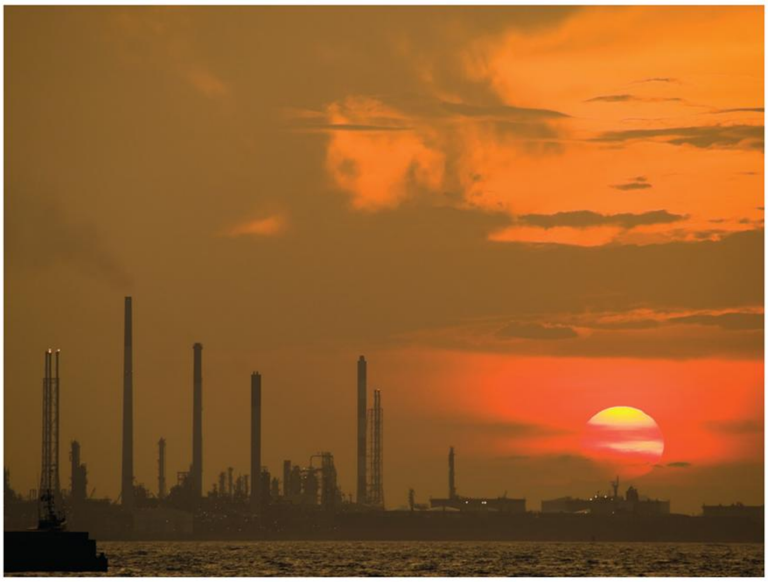
Rayleigh Scattering





Mie Scattering

- Occurs when substance is of comparable size to wavelength of radiation (such as aerosols)
- Unlike Rayleigh scattering, scatters all wavelengths more efficiently
- Makes hazy and polluted skies look white or gray, enhances sunsets



Nonselective Scattering

- Scattering by relatively large particles such as cloud droplets
- Scatters all wavelengths comparably
- Makes clouds white or gray

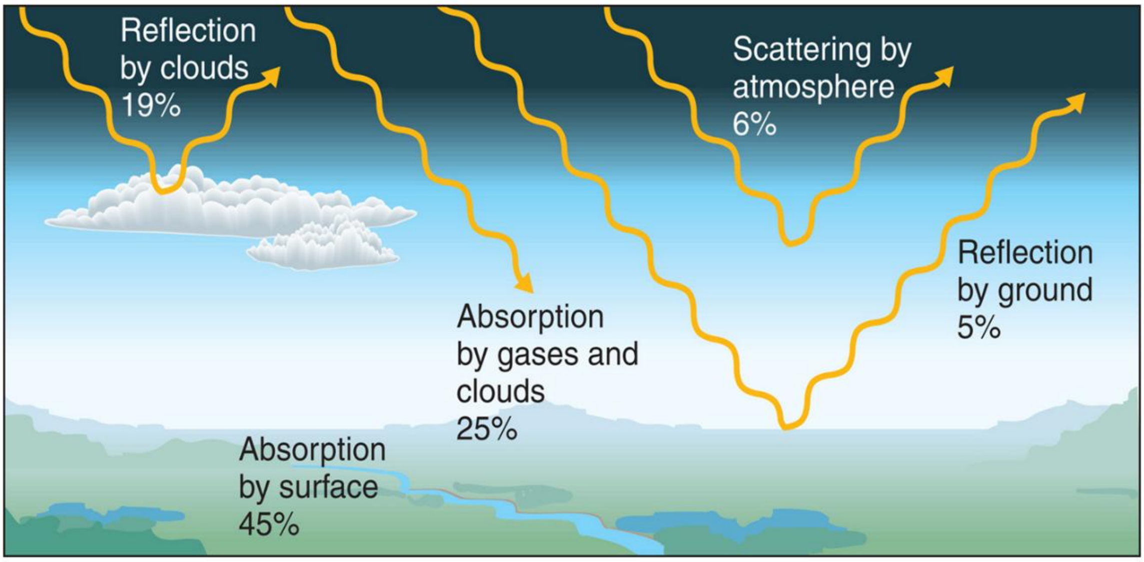
Transmission

- **Transmission** – radiation passes through a substance without being absorbed or scattered

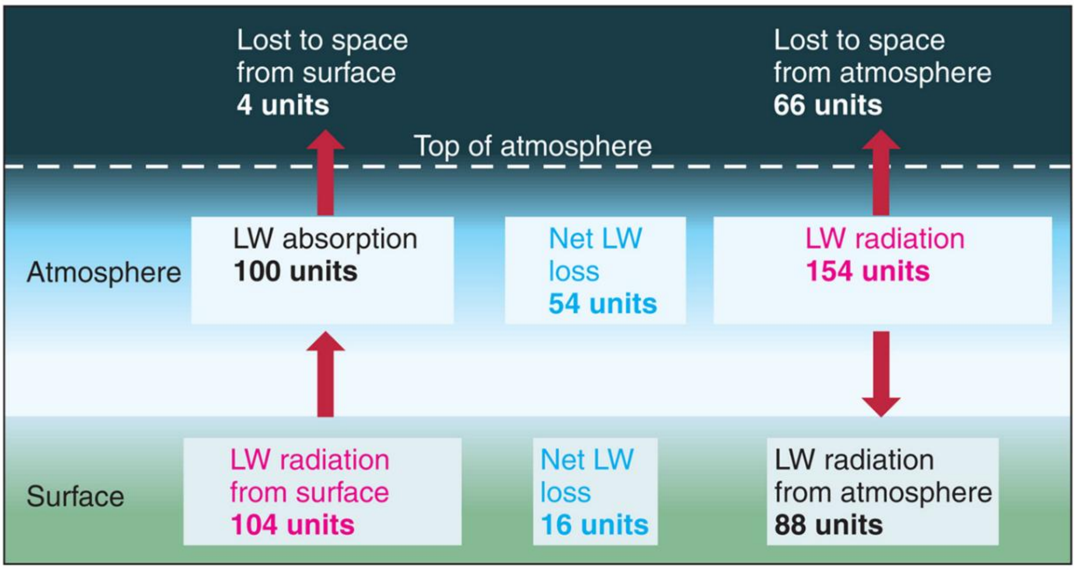
The Energy Balance of Earth

- Earth is generally neither warming or cooling (global climate change aside) – it is in steady-state, or equilibrium (just like a skydiver at terminal velocity…)
- This means the gain from solar radiation must be balanced by the loss from terrestrial radiation

The story begins with a net gain of solar radiation



The story ends with a loss of longwave radiation from earth and the atmosphere



But the story isn’t really over….

- Why don’t they?

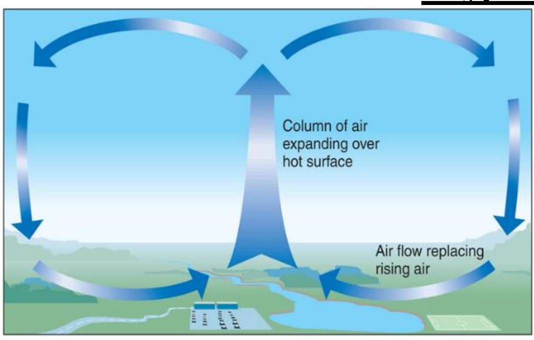
- Conduction and convection!!!

1) Conduction causes heat transfer to air in contact with ground
2) Convection causes this air near the surface to rise like a helium balloon, mixing heat throughout the atmosphere

→ **Sensible heat flux**

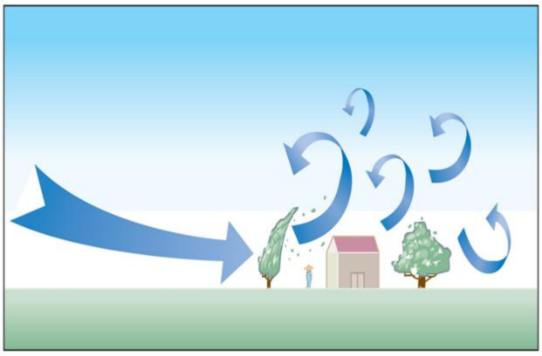
- Conduction and convection!!!

<u>2 types of convection</u>



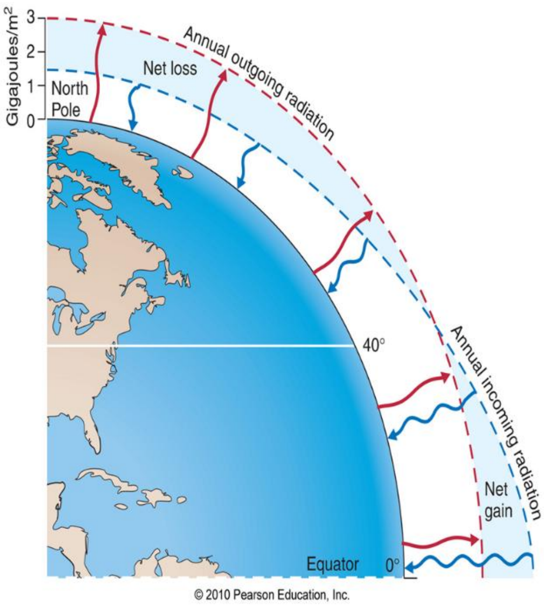
(a)

Free convection



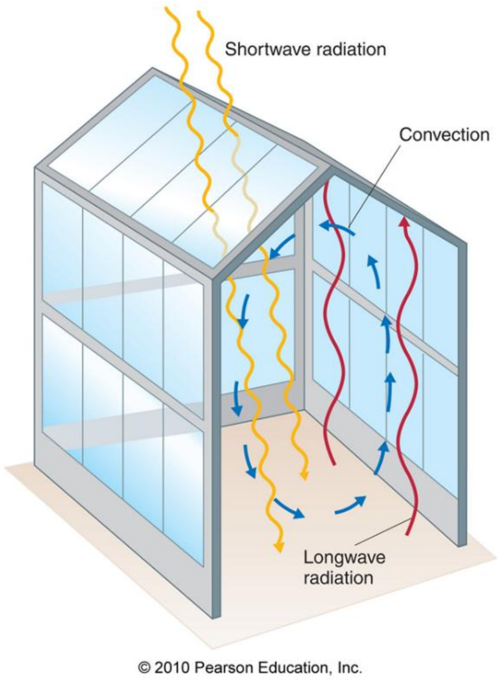
Forced convection

- Let's get specific – latitudinal variations also exist in the radiation budget
- But these are opposed by advection of heat through wind and ocean currents

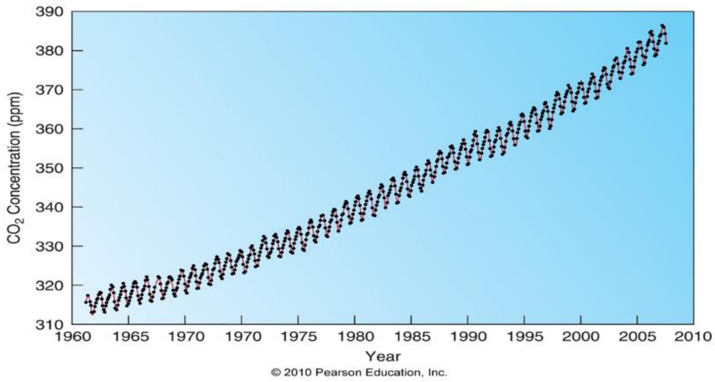


The Greenhouse Effect

- The atmosphere is kind of like a greenhouse, and kind of not
- Earth stays warm by atmospheric absorption/re-emission
- Without greenhouse gases, earth's equilibrium temperature would be much cooler (-17^{o} C instead of 15^{o} C



- Altering greenhouse gas (i.e. CO2) concentrations in the atmosphere will alter earth's equilibrium temperature

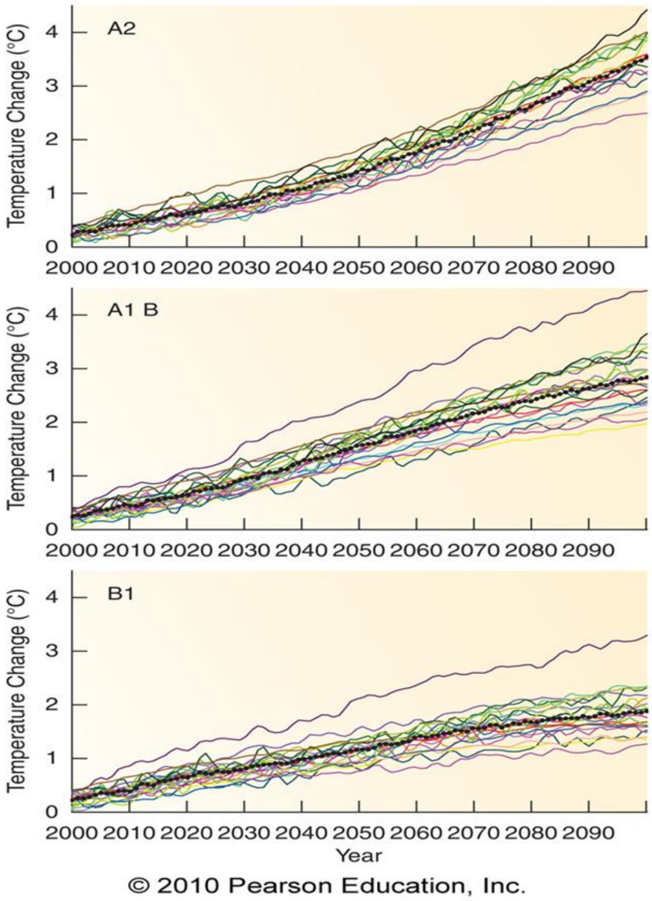


Global Climate Change

The Intergovernmental Panel on Climate Change (IPCC) stated in 2007 that:

1) Average global temperature is increasing (1.33oF in the last 100 years)
2) Temperatures are increasing faster now than they did earlier last century
3) Extreme warm events are increasing, extreme cold events are decreasing
4) Global snow cover is decreasing
5) All of the above is very likely due to anthropogenic greenhouse gas emissions

Predicted Global Temperature 2000-2100



Greenhouse gas emissions

High

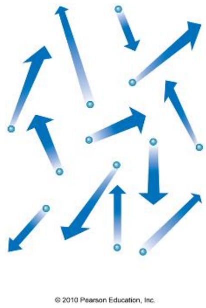
Medium

Low

- Uncertainties still exist for global warming predictions (effect of aerosols, cloud cover, greenhouse gas emission)
- Local climate change is a very important aspect of current research

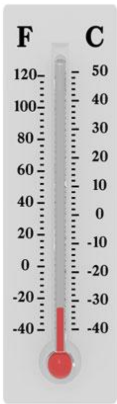
Temperature

- **Temperature** is a measure of the average kinetic energy of a substance

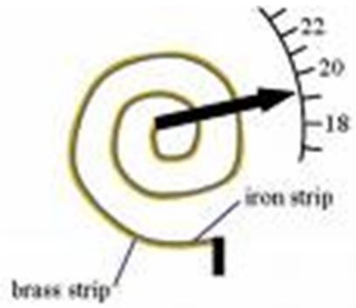


Measuring Temperature

- Mercury (or other fluid) **thermometer** – measures temperature by fluid expansion/contraction



- **Bimetallic strip** – measures temperature by different contraction/expansion of metal strips



- **Thermistor** – measure temperature based on resistance to electrical current (fast response)

- Instrument shelters used for surface observations

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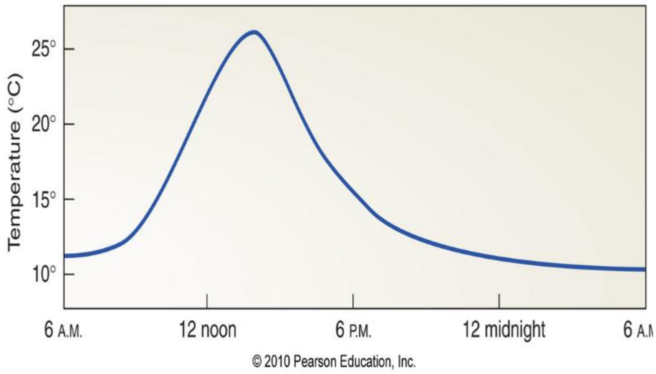
More Tidbits on Temperature…

Diurnal range – the range of temperatures over the night/day cycle at a given location



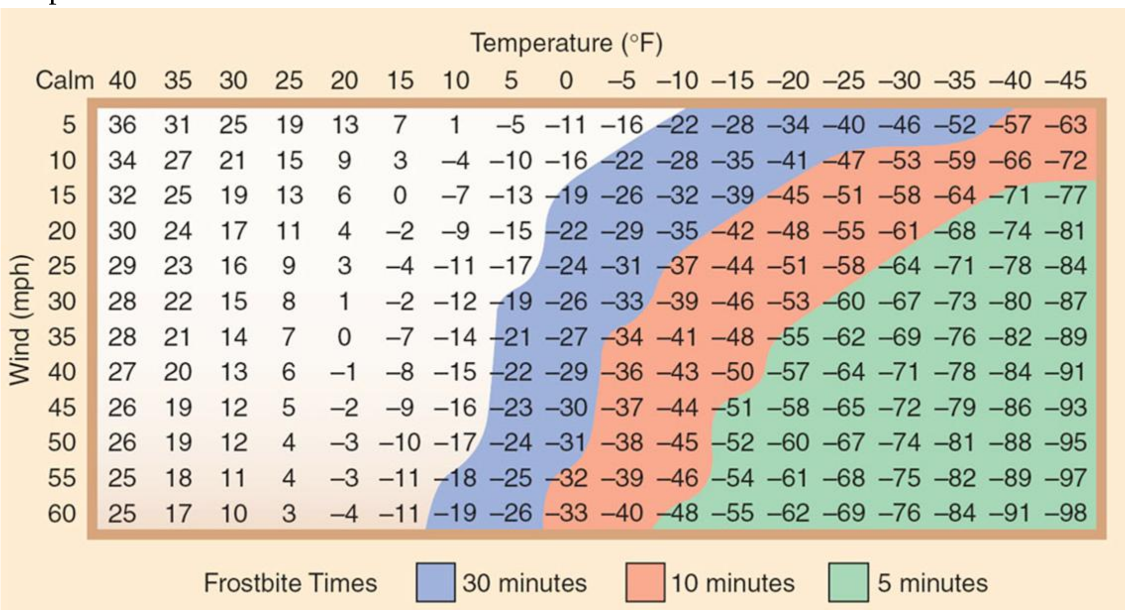
Highest temperature ever recorded on earth:

58°C in Libya

Lowest temperature ever recorded on earth:

-90°C in Antarctica

- Wind chill index – provides an estimate of the perceived temperature based on actual temperature and wind



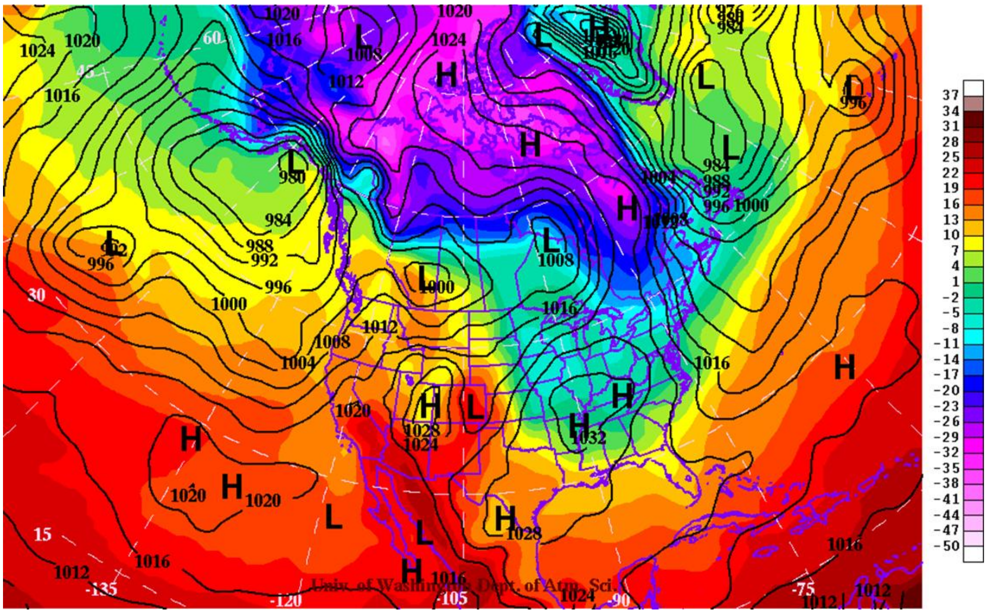
Temperature (°F)

Wind (mph) \ Calm	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	36	31	25	19	13	7	1	−5	−11	−16	−22	−28	−34	−40	−46	−52	−57	−63
10	34	27	21	15	9	3	−4	−10	−16	−22	−28	−35	−41	−47	−53	−59	−66	−72
15	32	25	19	13	6	0	−7	−13	−19	−26	−32	−39	−45	−51	−58	−64	−71	−77
20	30	24	17	11	4	−2	−9	−15	−22	−29	−35	−42	−48	−55	−61	−68	−74	−81
25	29	23	16	9	3	−4	−11	−17	−24	−31	−37	−44	−51	−58	−64	−71	−78	−84
30	28	22	15	8	1	−2	−12	−19	−26	−33	−39	−46	−53	−60	−67	−73	−80	−87
35	28	21	14	7	0	−7	−14	−21	−27	−34	−41	−48	−55	−62	−69	−76	−82	−89
40	27	20	13	6	−1	−8	−15	−22	−29	−36	−43	−50	−57	−64	−71	−78	−84	−91
45	26	19	12	5	−2	−9	−16	−23	−30	−37	−44	−51	−58	−65	−72	−79	−86	−93
50	26	19	12	4	−3	−10	−17	−24	−31	−38	−45	−52	−60	−67	−74	−81	−88	−95
55	25	18	11	4	−3	−11	−18	−25	−32	−39	−46	−54	−61	−68	−75	−82	−89	−97
60	25	17	10	3	−4	−11	−19	−26	−33	−40	−48	−55	−62	−69	−76	−84	−91	−98

Frostbite Times: 30 minutes | 10 minutes | 5 minutes

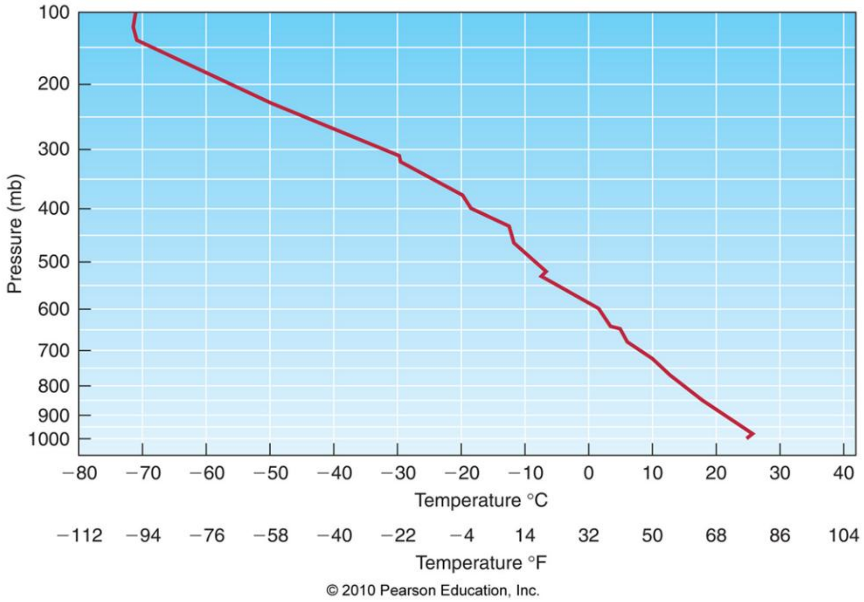
How Meteorologists Analyze Temperature

- In the horizontal…



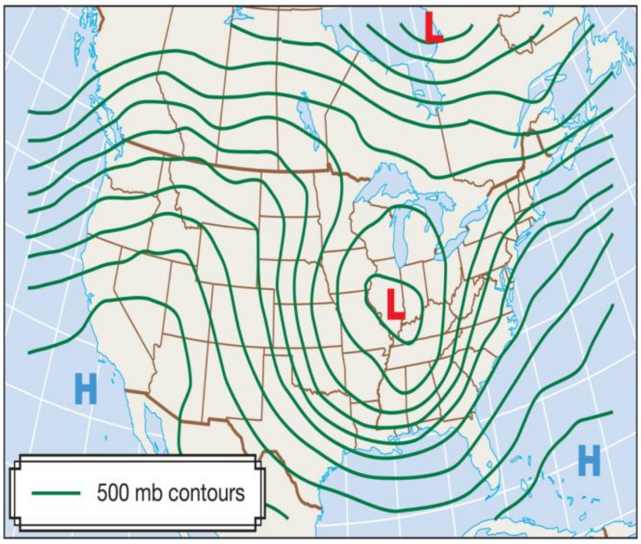
- In the vertical...

Stuve Diagram



Chapter 4

Atmospheric Pressure and wind



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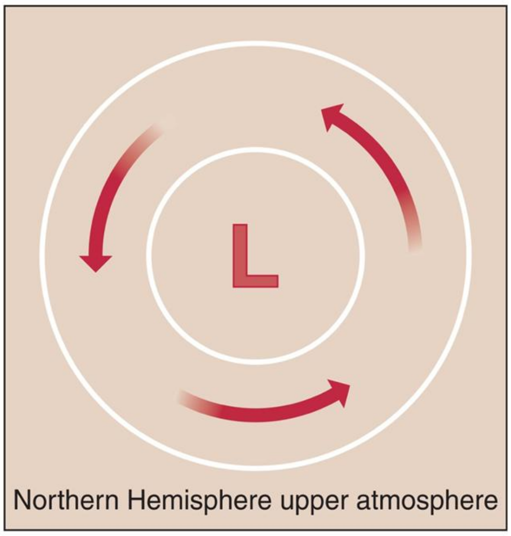


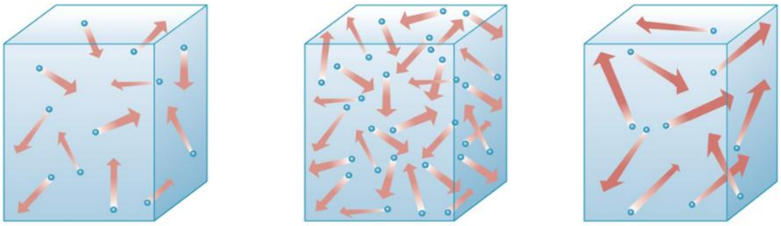
(b)

Chapter 4
Pressure and wind

Atmospheric Pressure

General Characteristics

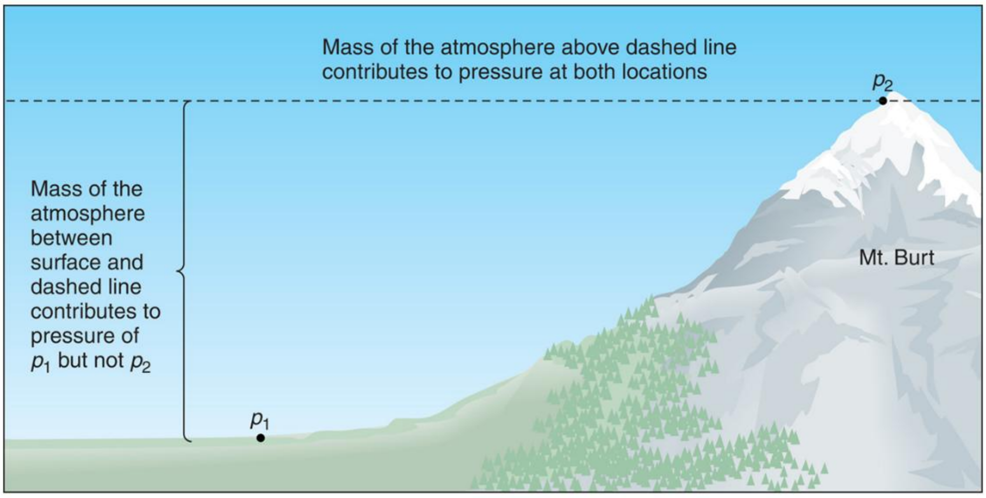
- Pressure is defined as force per unit area
- Pressure comes in different units:
  - Pascals(Pa), milibars(mb), inches of mercury (in Hg),
- pounds per square inch (psi)
- Pressure exists due to molecular collision



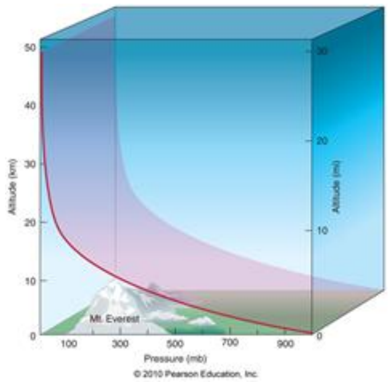
(1) (2)

Pressure increases with:
1) Higher density
2) Higher temperature

Pressure anywhere in the atmosphere is due to the weight of air above



- Pressure decreases faster near the surface, less so aloft (due to higher density near surface)
- Ultimately due to compressibility

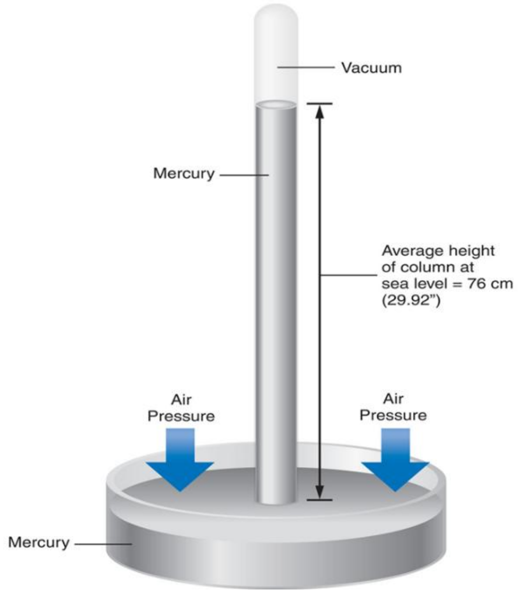


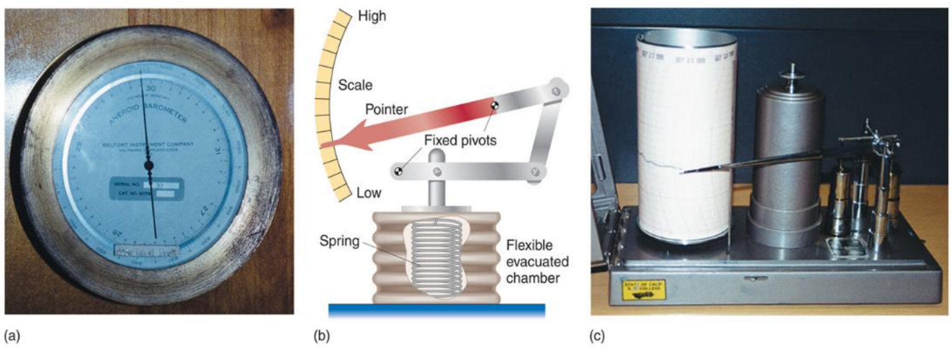
- The nature of atmospheric pressure explains much, including:
    1) My exploding bag of chips
    2) The gravity-defying upside-down cup of water (and the straw trick)

Measuring Pressure

Barometer – an instrument that measures pressure

1) Mercury barometer
2) Aneroid barometer



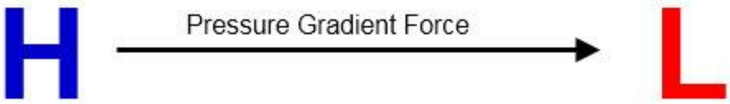


Horizontal Pressure Distribution

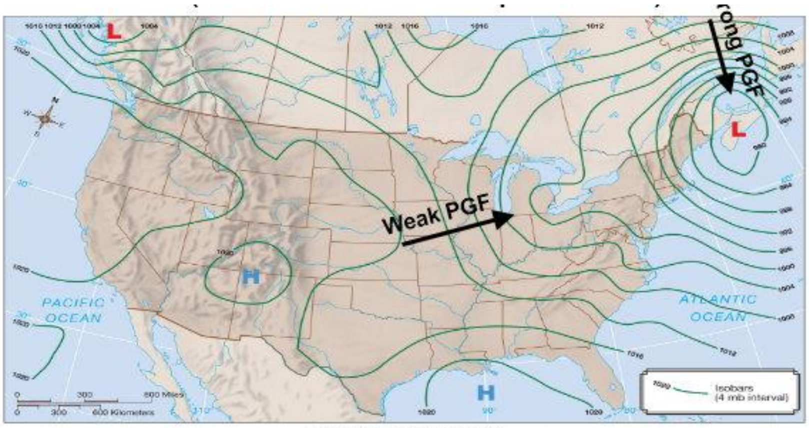
- Pressure gradients (change in pressure with distance) cause air to move
  - ➔ Wind!!!
- This wind is a direct application of how force equals mass times acceleration (F=m*a)
- In the case of wind, the force (F) is the pressure gradient force

Pressure Gradient Force

- The pressure gradient force always points from HIGH pressure toward LOW pressure!!!



- Pressure is viewed horizontally using **isobars** (lines of constant pressure)



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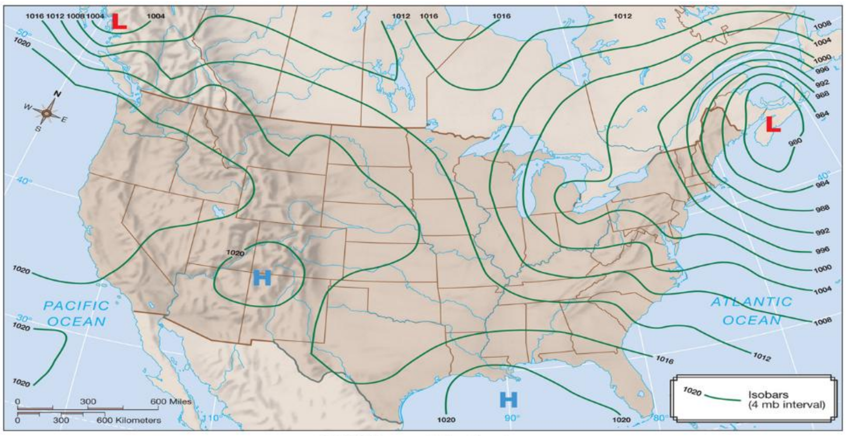
- Sea level pressure maps are a good weather analysis tool*, but wait a second…*



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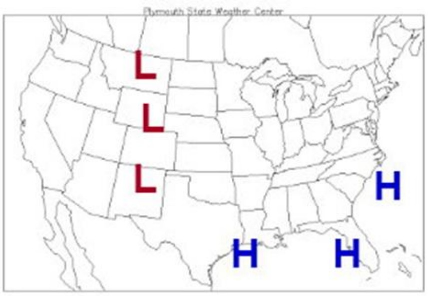
If Station Pressures Were Used

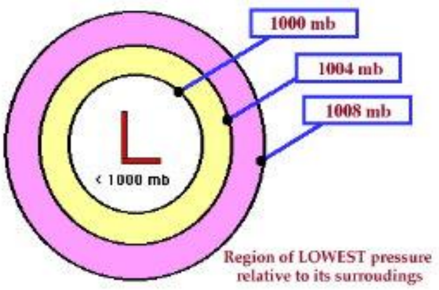
- Lower pressure in mountain areas
- Higher pressure in coastal areas
- Not a true picture of atmospheric effects



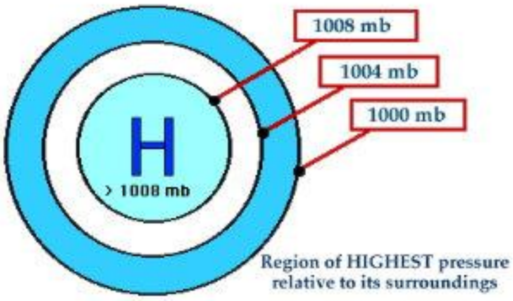
- Surface pressure observations are "reduced" to sea level (10 mb/100 meters is typical in lower atmosphere)
- These sea level pressure values are the numbers on sea level pressure maps

- The effects of elevation are removed, revealing a more useful horizontal pressure distribution

Lows and Highs



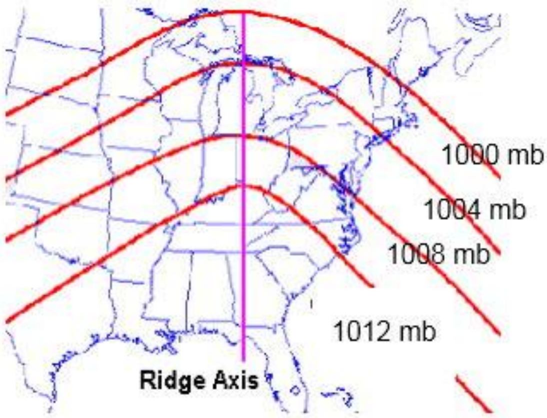
Cyclone



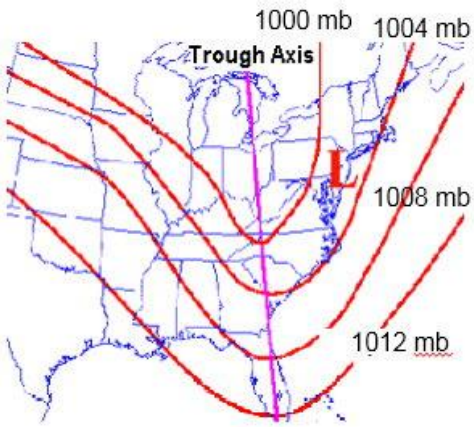
Anticyclone

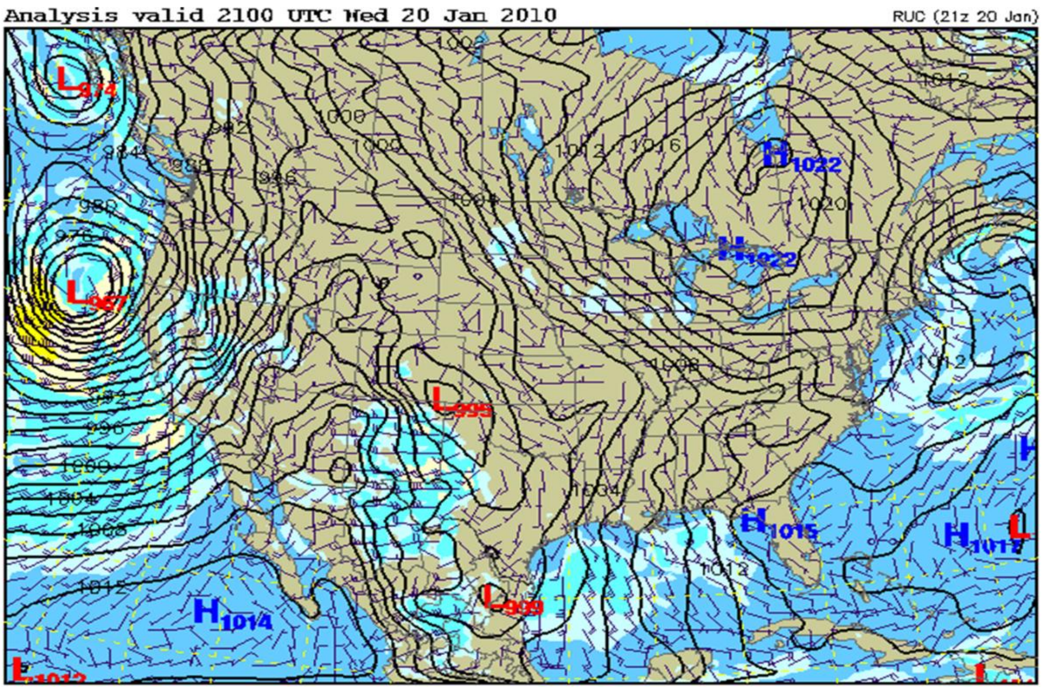
Ridges and Troughs

Ridge – a bow in isobars indicating a line of high pressure



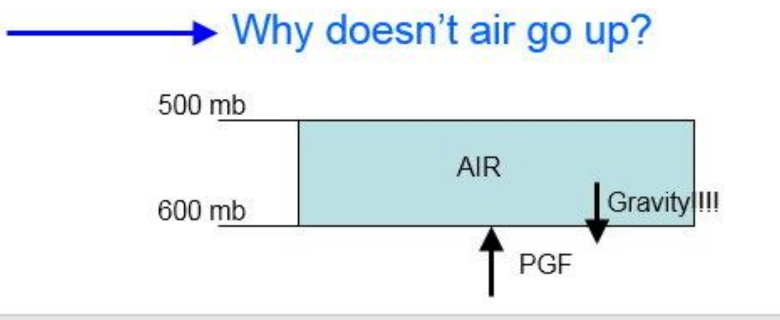
Trough – a bow in isobars indicating a line of low pressure





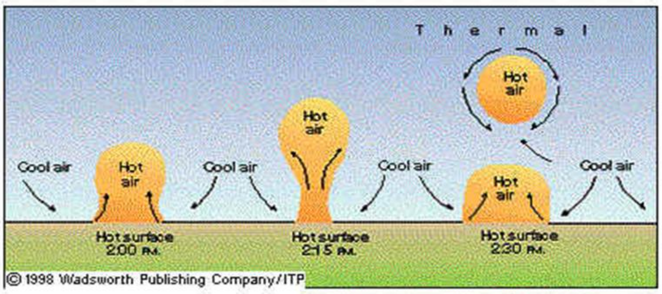
Vertical Pressure Distribution

- Pressure always decreases with height
  - Fastest near the surface
  - Vertical pressure gradients many times greater than horizontal pressure gradients



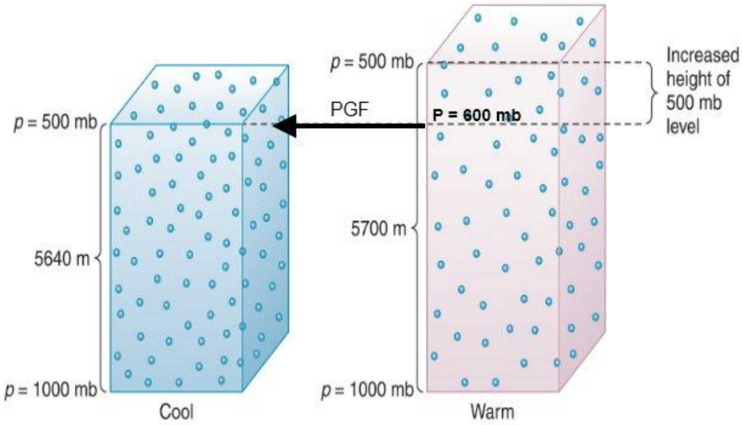
Hydrostatic Balance

- Hydrostatic balance (or equilibrium) is the balance between the pressure gradient and gravity forces in the vertical
  - Exists almost always in the atmosphere
  - Exception is convection and thunderstorms

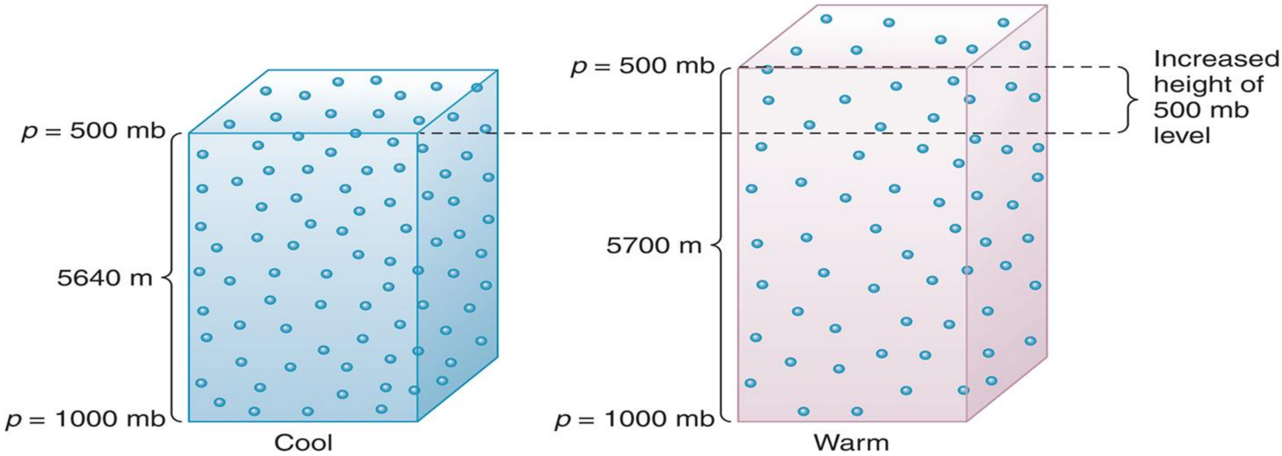


Horizontal Pressure Maps Aloft

- The height of a pressure level depends on temperature

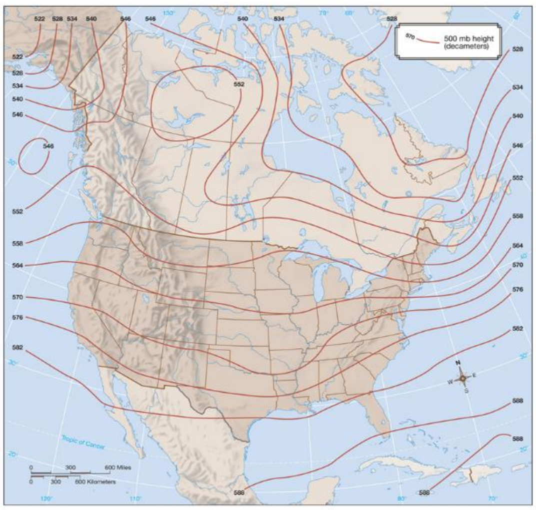


- Stronger temperature difference = stronger pressure gradients
- Higher heights mean higher pressure



The 500 mb Map

- Closer lines = larger slopes = stronger PGF
- Higher heights to the south (warmer)
- Ridges and troughs (Important – they make the weather!)
- Lines of constant height = isohypse (isoheight)



Other Standard Pressure Levels

- In addition to 500mb, other standard levels are:

  850mb - 1500m
  700mb - 3000m (10000')
  300mb - 10000m (33000')

Forces Affecting the Wind

- Pressure gradient force (PGF, directed from high pressure to low pressure)
- **The Coriolis Force**
  1) Due to earth's rotation
  2) Known as an apparent force
  3) Conservation of angular momentum (N-S)
  4) Centrifugal force (E-W)
- An apparent force because of different frames of reference

- In the N-S direction, conservation of angular momentum produces the Coriolis Force

  angular momentum = R2 * Ω
  R = radius
  Ω = rate of rotation

  - deflects right as one moves equator to North Pole (and vice-versa)
  - deflects left as one moves equator to South Pole (and vice-versa)
- In the E-W direction, changing the centrifugal force produces the Coriolis Force

  Northern Hemisphere
  - deflects right as one moves east
  - deflects right as one moves west

  Southern Hemisphere
  - deflects left as one moves east
  - deflects left as one moves west
- Main points to remember:
  1) Coriolis Force deflects moving things right (NH) or left (SH)
  2) There is no Coriolis Force at the equator, and it is maximum at the poles
  3) The Coriolis Force is proportional to speed

4) The Coriolis Forces changes only direction, not speed
5) Coriolis force is slow to act (noticeable only after a few hours)

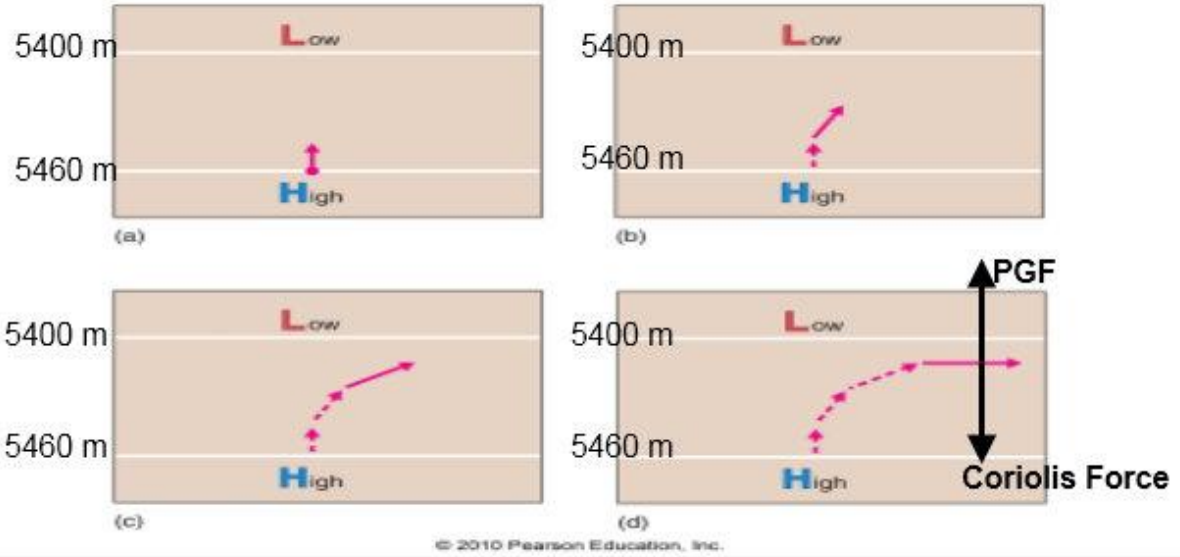
Forces Affecting the Wind –Summary

- Pressure gradient force (PGF, directed from high pressure to low pressure)

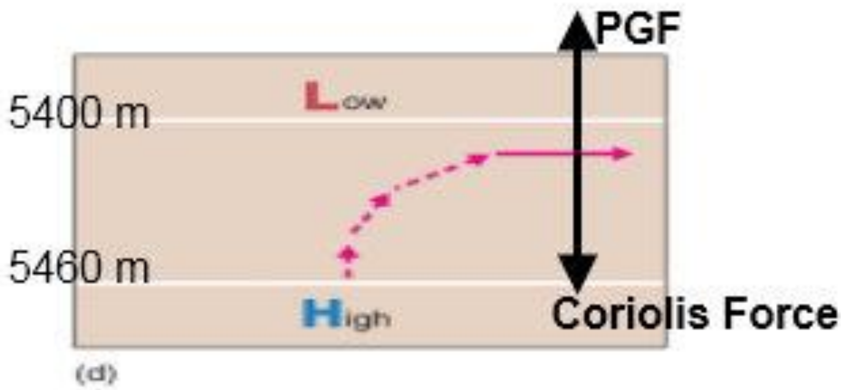
- The Coriolis Force
  1) Due to earth's rotation
  2) Known as an apparent force
  3) Conservation of angular momentum (N-S)
  4) Centrifugal force (E-W)
- Friction (from the ground, within the planetary boundary layer)

How the Wind Blows (The Upper Atmosphere Version)

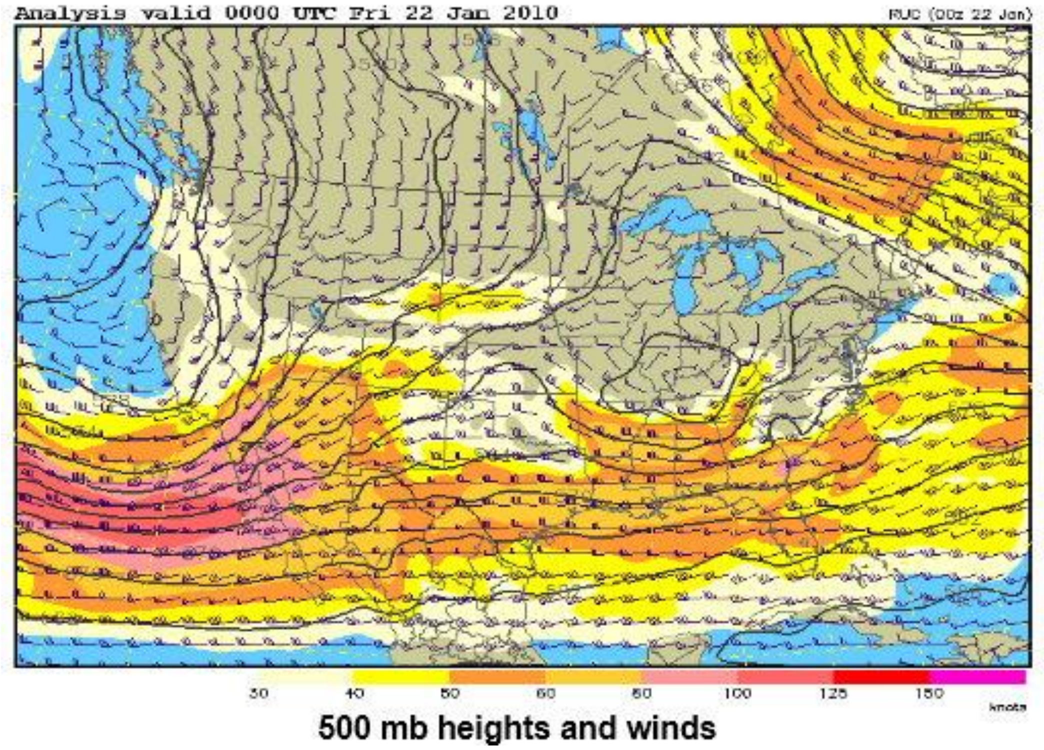
- Forces acting on air above the boundary layer are the PGF and the Coriolis Force



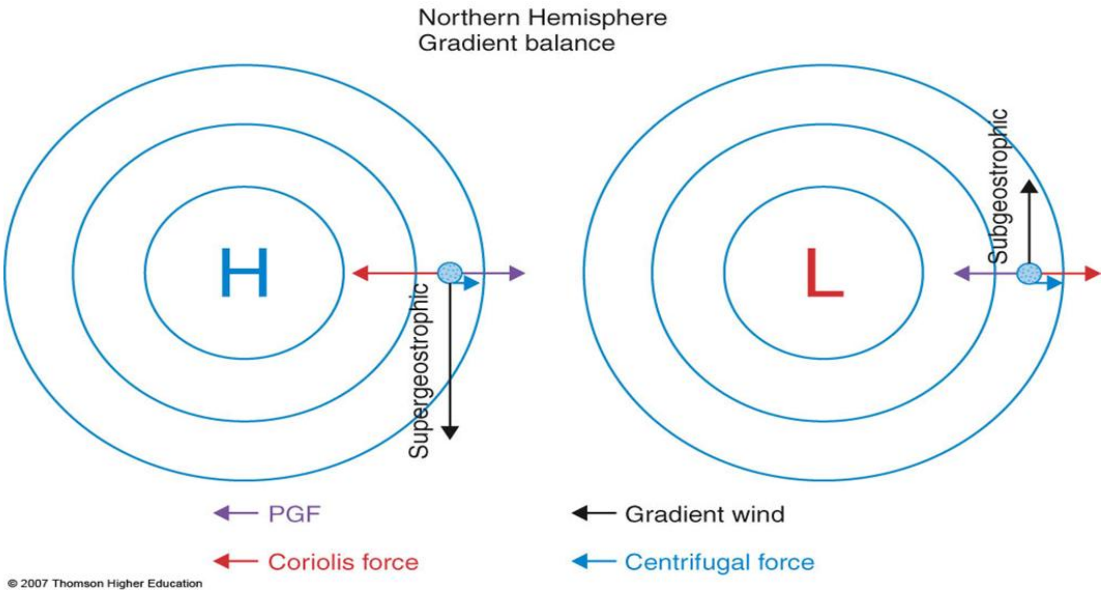
- The balance between the PGF and the Coriolis Force is called geostrophic balance (wind is geostrophic wind)



Geostrophic Balance



In curved flow, another force comes into play – centrifugal force (results in gradient wind balance)

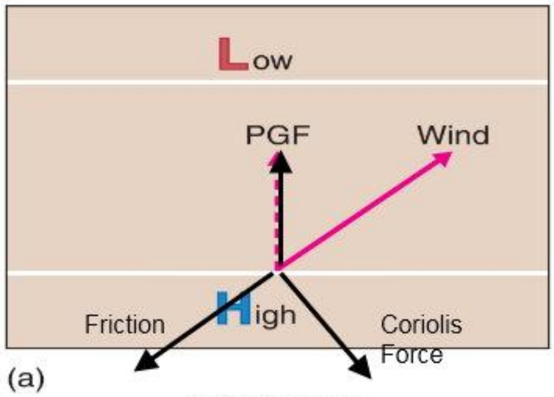


- **Subgeostrophic** flow occurs around Lows
- **Supergeostrophic** flow occurs around Highs

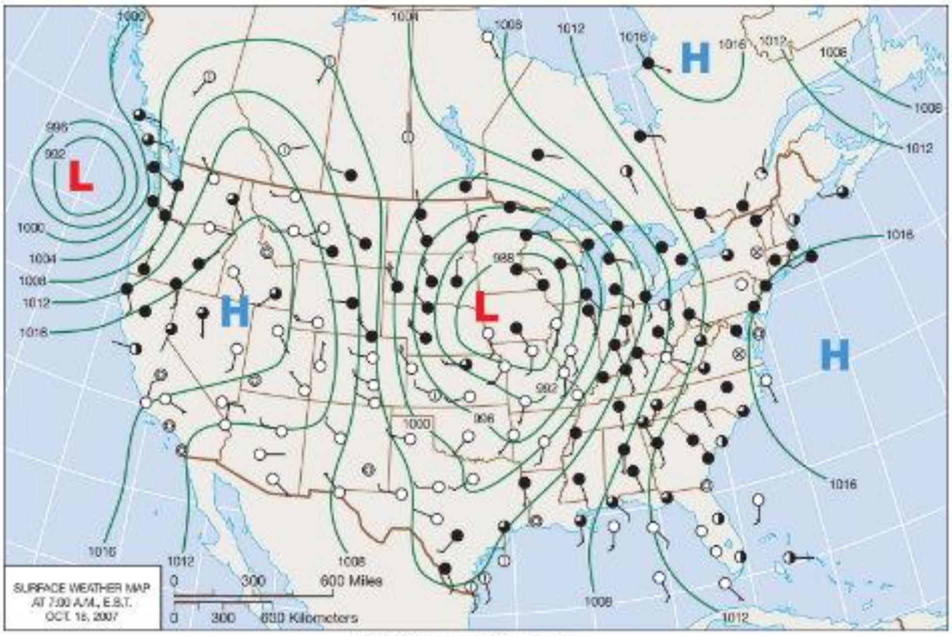
key: wind speed is proportional to the Coriolis Force

How the Wind Blows (The Lower Atmosphere Version)

- Now we have PGF, the Coriolis Force, and friction:



- Wind blows across isobars toward lower pressure



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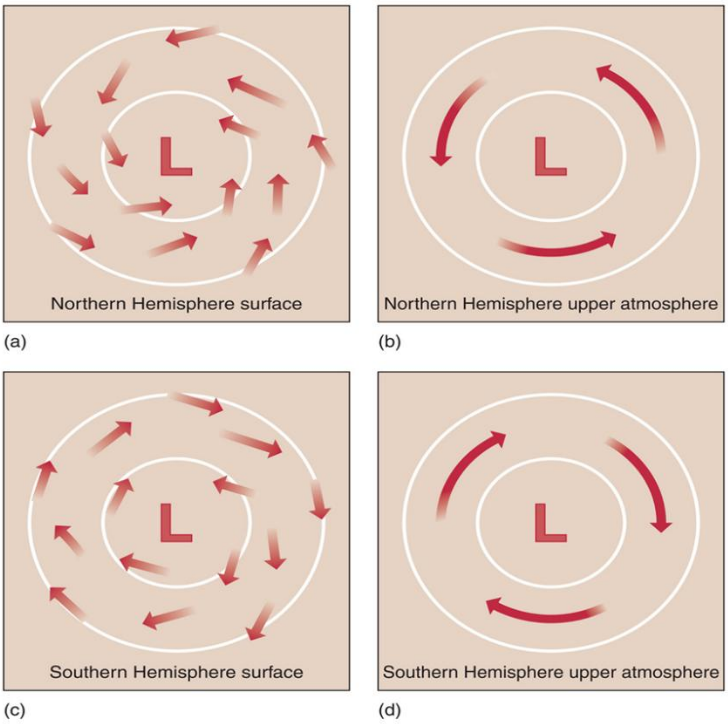
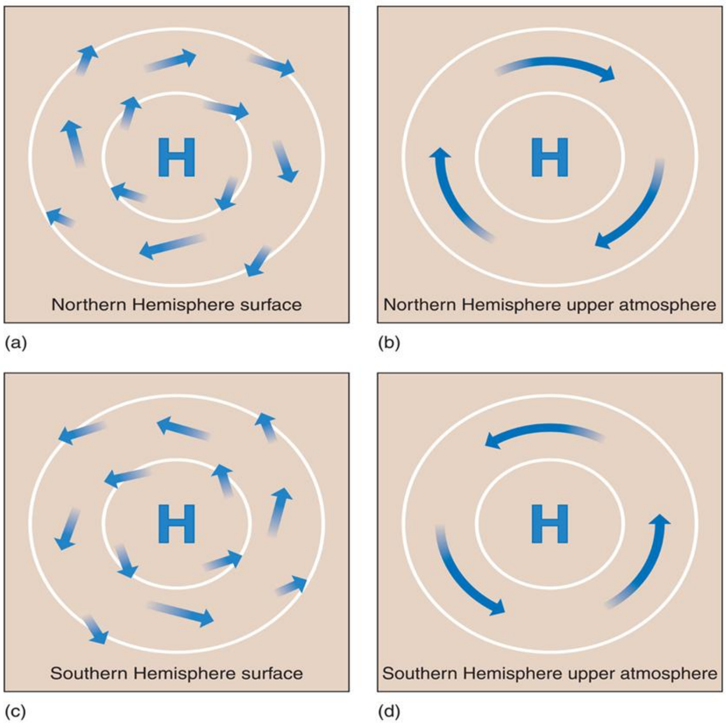
Surface SLP and winds

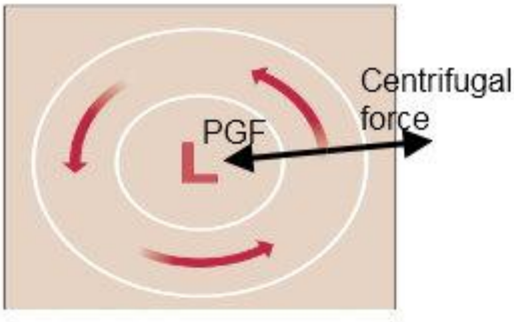
Upper vs. Lower Atmospheric Winds





Cyclostrophic Balance

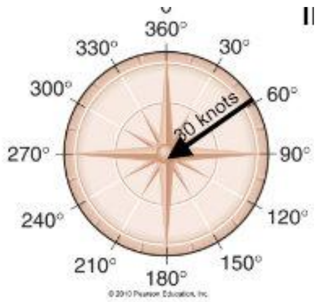
- Wind field achieves a balance between the centrifugal force and the PGF
- This occurs on short time scales (tornadoes) before the Coriolis Force can act (think draining bathtub drains…)



Measuring Wind

- Both wind speed and direction are measured
  direction: measured as the direction where the wind blows **from** in degrees clockwise from **North**

wind is 30 knots at
60^o
1 kmph = 1.85 * knots (30 knots = 55.5 kmph)



Wind vane – measures wind direction only

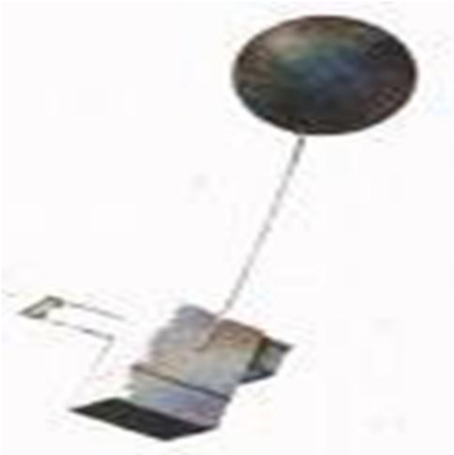
Anemometer – measures wind speed only

Aerovane – measures wind speed and direction

The Observational Network

Upper-air observations

Radiosondes – a package of instruments launched twice daily on weather balloons from stations around the globe



- Launched globally at 0000 UTC and 1200 UTC

  UTC – Universal Time Coordiante – same time everywhere on earth (as opposed to local time)

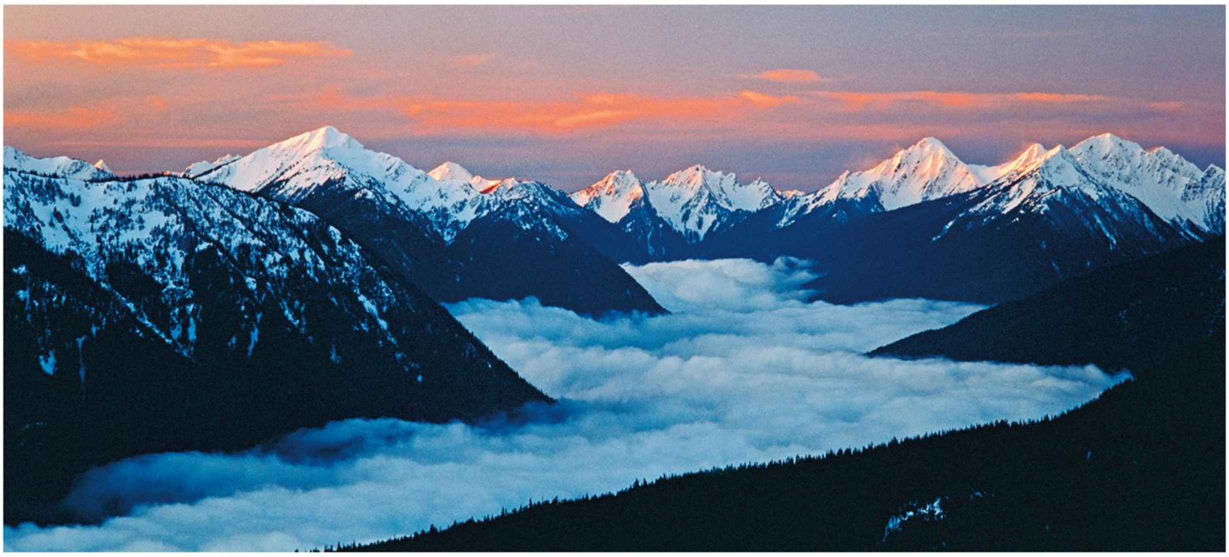
  Local Baghdad time = UTC time + 3 hours

Surface observations

- Automated Surface Observing System (ASOS) – the primary U.S. surface observing network, observation stations located at airports
-

Chapter 5

Atmospheric Moisture



Chapter Four

Atmospheric Moisture

Water Vapor

Saturation – air that contains as much water vapor as possible (at a given temperature) such that additional water vapor would result in condensation

Unsaturated – air that contains less water vapor (at a given temperature) than possible

Supersaturation – air that contains more water vapor than possible (at a given temperature)

Vapor Pressure – The portion of total pressure exerted by water vapor

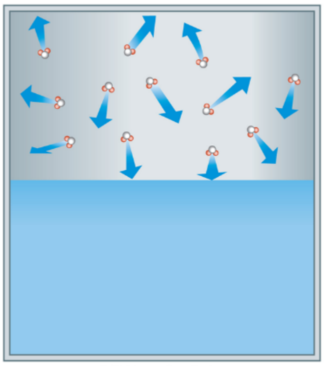
Water Vapor vs. Ice/Water

Evaporation – The transition of liquid molecules into the gaseous phase (water in a bowl disappears)

Condensation – The transition of gaseous molecules into the liquid phase (beads of water on a cold pipe)

Sublimation – The transition of solid molecules into the gaseous phase (an ice museum vanishes)

Deposition – The transition of gaseous molecules into the solid phase (frost on a cold morning)



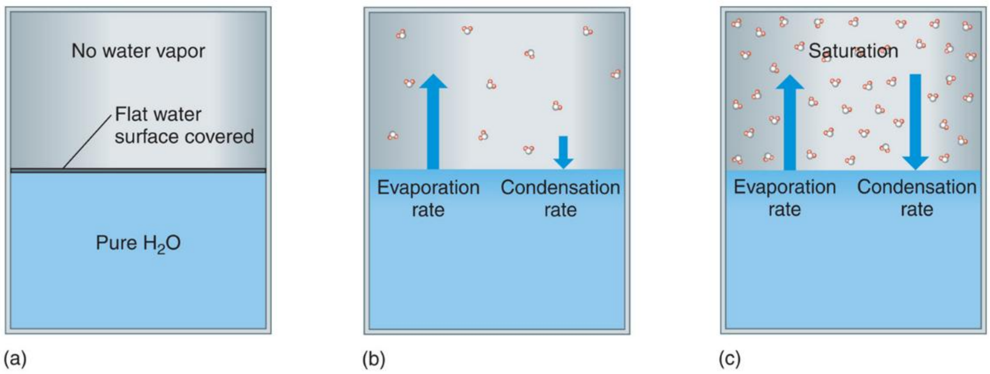
Evaporation and Condensation

<u>2 independent, competing effects</u>

1) Rate of evaporation depends on temperature only
2) Rate of condensation depends on vapor pressure only

Eventually → rate of evaporation = rate of condensation

Saturation (and saturation vapor pressure)



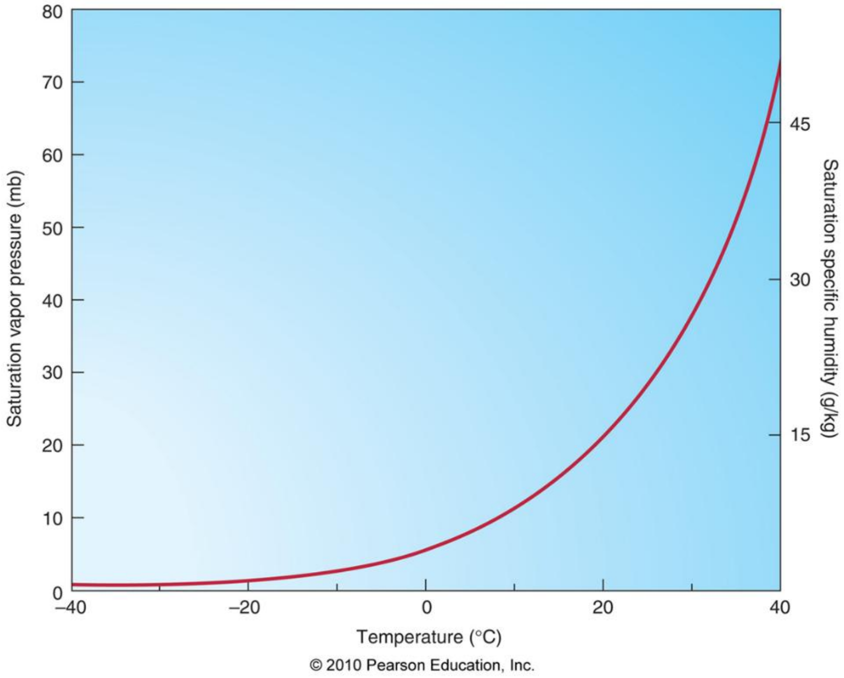
Vapor Pressure

Key ideas:

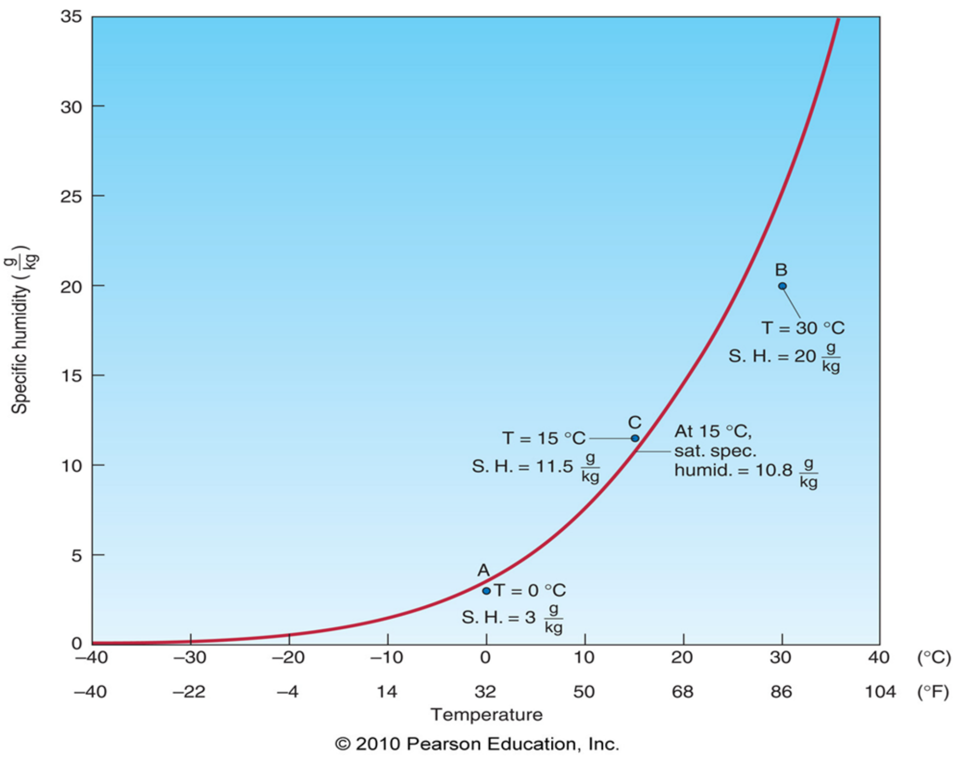
1) Vapor pressure indicates how much water vapor is in the air

2) Saturation vapor pressure indicate how much water vapor could be in the air (depends on temperature)

Saturation Vapor Pressure



Seeing your breath is explained by this curve (as is teakettle steam and steam fog)



Useful Indices of Atmospheric Water Vapor Content

- **Vapor pressure** – the portion of total pressure exerted by water vapor (mb)

- **Saturation vapor pressure** – the vapor pressure at saturation (mb)
- **Specific humidity** – the mass of water vapor in a given mass of air (g/kg)

$$q = \frac{m_v}{m} = \frac{m_v}{m_v + m_d}$$

- **Saturation specific humidity** – the specific humidity at saturation (g/kg)

- **Mixing ratio** – the mass of water vapor per mass of dry air (g/kg)

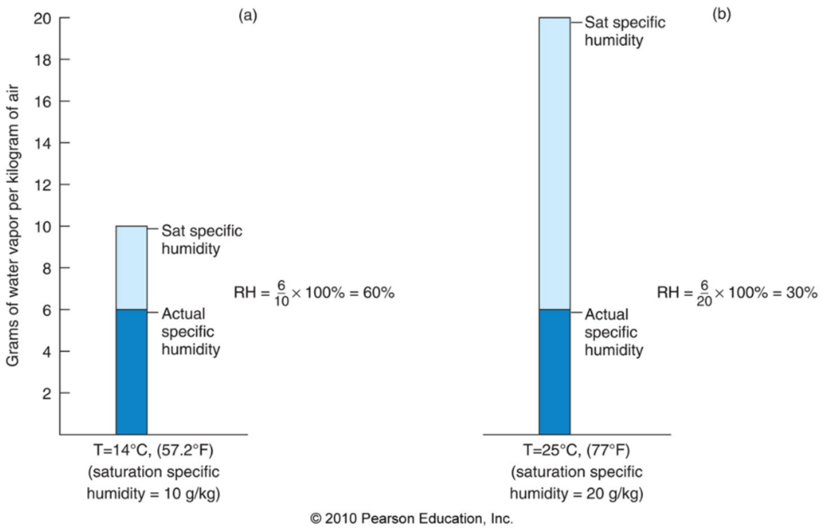
$$r = \frac{m_d}{m_v}$$

- **Saturation mixing ratio** - the mixing ratio at saturation (g/kg)
- **Relative humidity** – the amount of water vapor in the air relative to the maximum possible amount of water vapor in the air (%)

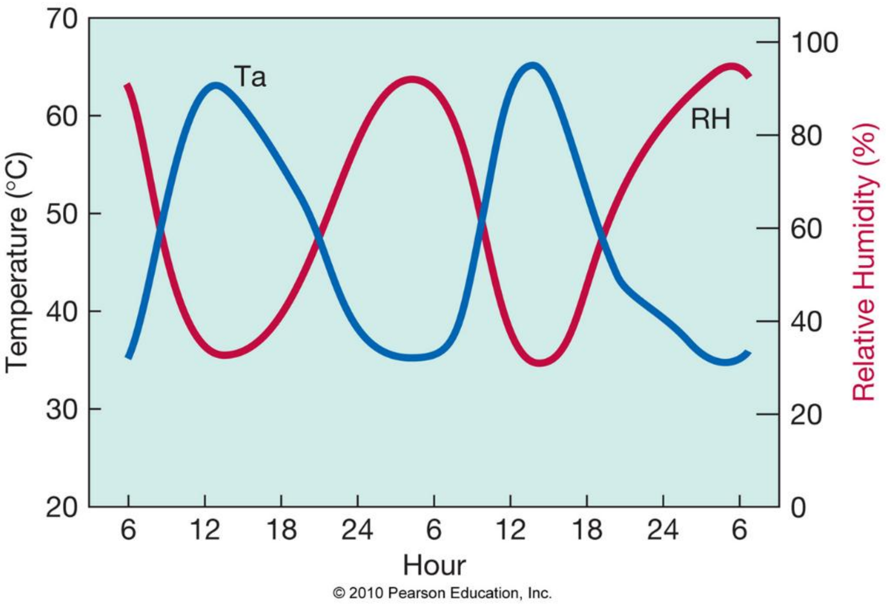
$$RH = \frac{q}{q_s} \times 100\%$$

q = specific humidity

q_s = saturation specific humidity

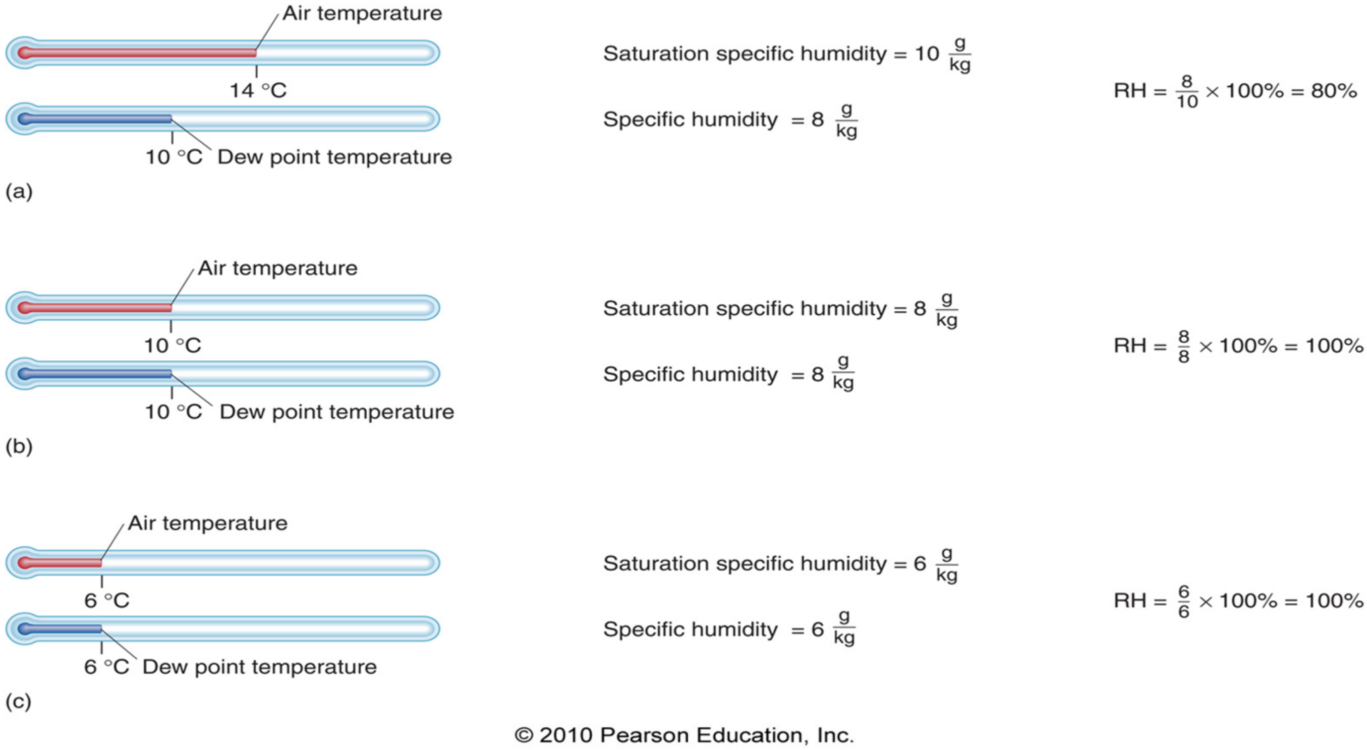


Interesting tidbits
RH doesn't tell you the amount of water vapor in the air
RH does tell you the "evaporative" power of the air
Explains why people need humidifiers indoors in cold climates



Dew Point – the temperature to which air must be cooled to reach saturation

- The dew point tells you how much water is in the air
- The dew point reveals the “evaporative” power of the air through the dew point depression



Dew Point – Exposing a Myth

Have you ever heard somebody say, "It's 35 degrees with 100% humidity"?

They're lying!!!

Here's Why

- Dew points are equal to or less than the temperature of their water source
- The highest dew points occasionally hit 30

<u>A hot, muggy day</u>

Air temperature = 30°C

Dew point = 28°C

Saturation specific humidity at 30°C air temperature = 30 g/kg

Specific humidity at 28°C dew point = 24 g/kg

RH = 24/30 x 100 = 80%

= 67% if Td is 25°C

How much water vapor does exist?

- At a given temperature, air can contain an amount of water vapor equal to or less than the amount at saturation
- Dewpoint reveals how much water does exist in air

Moisture Variables

1) **Vapor pressure**
2) **Specific humidity, mixing ratio**
3) **Relative humidity**
4) **Dew point**

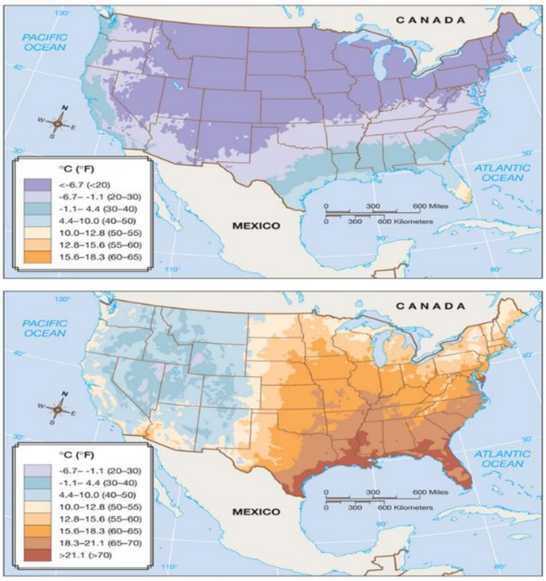
Unsaturated air	Saturated air
Vapor pressure = 14mb	Vapor pressure = 21mb
Saturation Vapor pressure = 21mb	Saturation Vapor pressure = 21mb
Specific humidity = 9 g/kg	Specific humidity = 16 g/kg
Saturation specific humidity = 16 g/kg	Saturation specific humidity = 16 g/kg
Mixing ratio = 9 g/kg	Mixing ratio = 16 g/kg
Saturation mixing ratio = 16 g/kg	Saturation mixing ratio = 16 g/kg
Relative humidity = 56%	Relative humidity = 100%
Dew point = 11oC	Dew point = 20oC

Dew Point – a Forecasting Tool

The dew point is frequently used to forecast nighttime low temperatures – Why?

1) Latent heat release during condensation
2) Absorption and re-emission of longwave radiation by cloud droplets

Distribution of Water Vapor



Measuring Humidity

Sling psychrometer – a pair of thermometers, one with moist cotton around the bulb, that are "slung" around until the wet bulb temperature is reached

Wet bulb temperature (T_w) – the temperature air would have if water was evaporated into it until saturation was reached

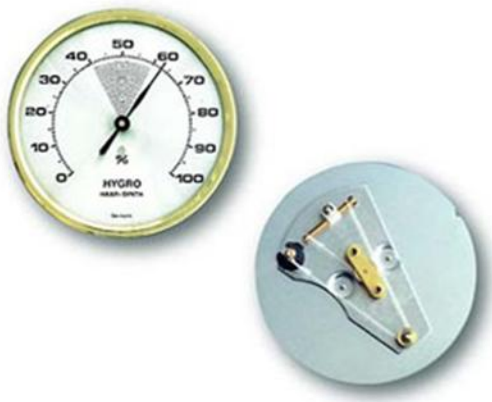
- Tw is always equal to or less than T
- Tw is always equal to or greater than the dew point

Wet bulb depression – the difference between the temperature and the wet bulb temperature

- The wet bulb depression is large for dry air
- The wet bulb depression is small for moist air
- The wet bulb depression is zero for saturated air

Aspirated psychrometers – like a sling psychrometer, but has a fan instead of having to be "slung"

Hair hygrometer – measures humidity based on the expansion and contraction of a strand of hair



Condensation in the Atmosphere

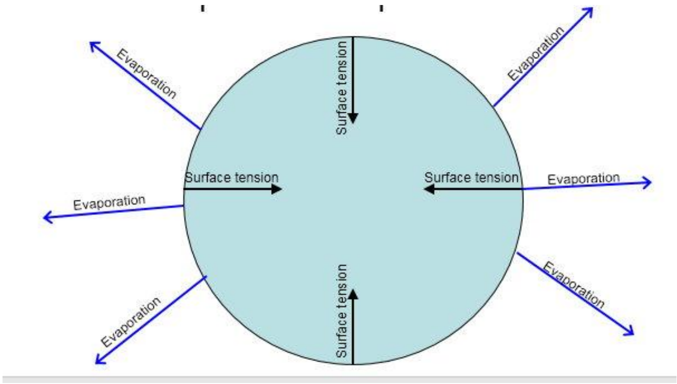
- Condensation is how clouds and fog form
- Condensation occurs when air cools below its dew point
- Condensation requires the presence of atmospheric aerosols

Nucleation – the formation of an airborne water droplet by condensation

Homogeneous nucleation – the formation of water droplets by random collisions of water vapor molecules in the absence of aerosols

- Surface tension "squeezes" the water droplet, forcing rapid evaporation
- ~400% saturation needed for cloud formation!!!

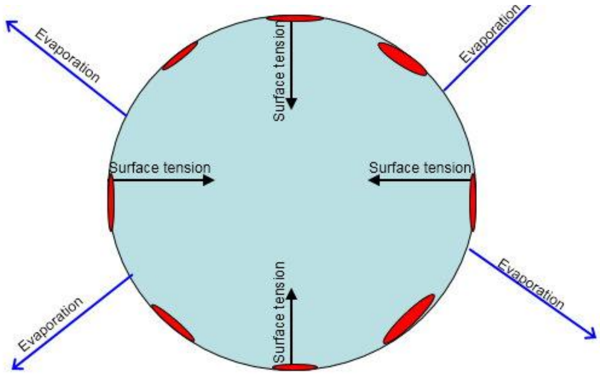
A microscopic water droplet



Heterogeneous nucleation – the formation of water droplets onto aerosols (condensation nuclei)

- Aerosols dissolve in water
- Occurs near saturation
- Can also occur with large, insoluble aerosols (curvature not a strong effect)

A microscopic water droplet (with dissolved aerosol)



Ice Nuclei

Ice nucleii – ice look-a-like aerosols on which ice forms at saturation

- Ice nucleation depends on temperature
  $0^oC > T > -4^oC$ no ice nucleation
  $-4^oC > T > -10^oC$ little ice nucleation
  $-10^oC > T$ moderate ice nucleation
- The result is that supercooled water exists as fog and clouds at temperatures between 0^oC and -10^oC
- Below -10^oC there is a mix of supercooled water and ice

Cloud- and fog-forming condensation results from cooling in two forms

- Diabatic cooling – heat is removed from the air by its surroundings (example – nighttime cooling of surface air)
- Adiabatic cooling – no heat is exchanged between the air and its surroundings (example – rising air)

Adiabatic Cooling

1st Law of Thermodynamics:

Energy is conserved

Heat added must equal work done plus a change in internal energy (temperature)

$$\Delta H = dw + dq$$

However, no heat is exchanged between air and its surroundings with adiabatic processes

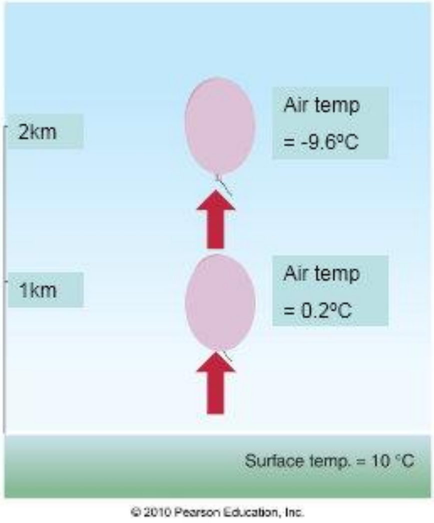
Work done must equal change in temperature ($0 = dw + dq$ or $dw = -dq$)

Adiabatic Cooling and Warming

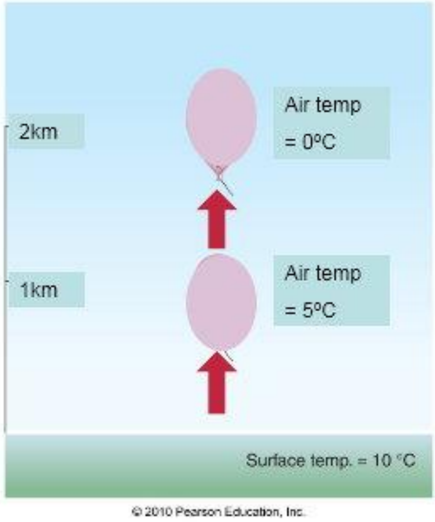
- Dry adiabatic lapse rate – the rate at which unsaturated air cools (warms) as it rises (sinks)
  = 9.8°C/km (constant)
- Moist adiabatic lapse rate – the rate at which saturated air cools (warms) as it rises (sinks)

  ~ 5°C/km (variable)

  Less than the dry adiabatic lapse rate???

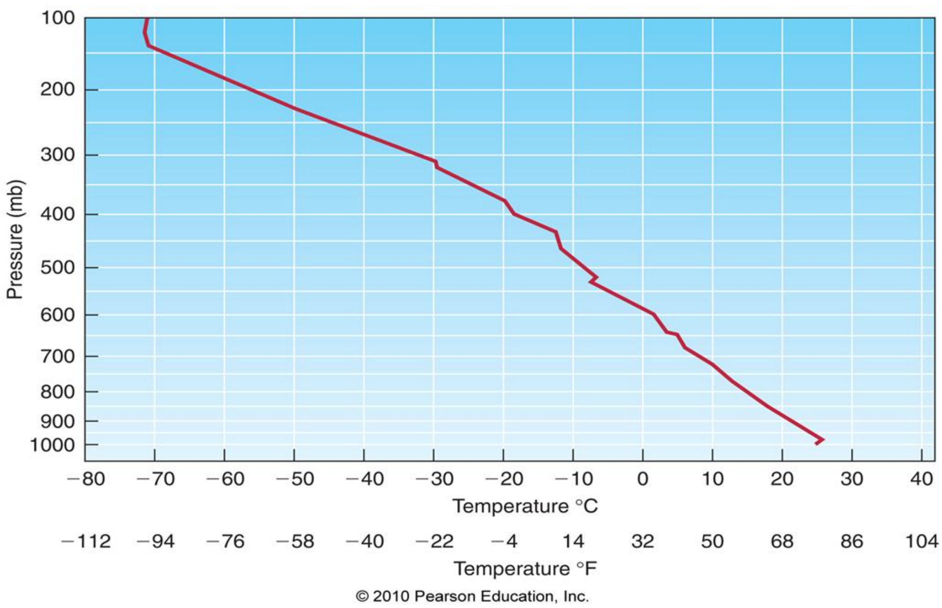


Unsaturated Air (9.8°C/km)



Saturated Air (5°C/km)

Environmental lapse rate – the rate at which still air changes with height



Types of Condensation

Dew – condensation of water vapor onto the ground or objects on the ground

Frost – deposition of water vapor onto the ground or objects on the ground

Frozen dew – condensation that freezes

Fog – condensation of water vapor onto airborne aerosols, forming a cloud in contact with the ground

Clouds – condensation of water vapor onto airborne aerosols aloft

Dew

(a)

Frost

(b)

Fog

- **Radiation fog** – fog that forms overnight due to the cooling of air in contact with the ground
  Associated with temperature inversions
- **Advection fog** – fog that forms when warm, moist air moves over a cool surface and cools
- **Upslope fog** – fog that forms due to the cooling of air as it rises up a gentle slope
- **Steam fog** – fog that forms when warm, moist air mixes with cooler air
- **Precipitation fog** – fog that forms when rain evaporates and adds water vapor to ambient air, which then condenses

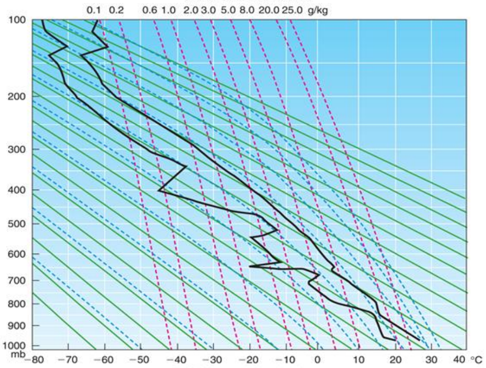
Advection fog

Steam fog

Chapter 6

Cloud Development and Forms

(a)



Chapter 6

Cloud Development and Forms

Cloud Formation

- Condensation (i.e. clouds,fog) results from:
  - Diabatic cooling (important for fog)
  - Adiabatic cooling (important for clouds)
- Clouds form due to adiabatic cooling in rising air

  Γ_d = 9.8ºC/km (unsaturated lapse rate)

  Γ_m ~ 5ºC/km (saturated lapse rate)

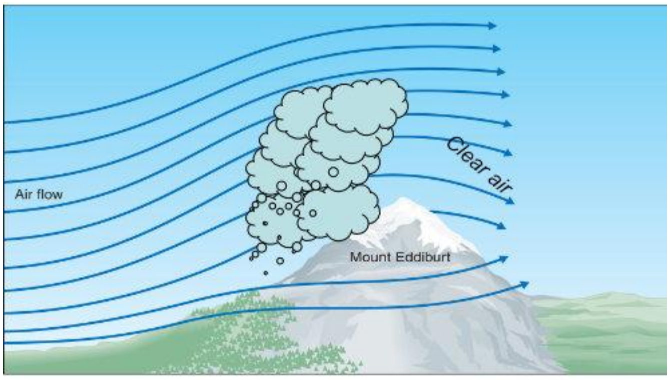
How Does Air Rise?

4 mechanisms cause air to rise:

1) **Orographic lift** – air that rises because it is going over a mountain
2) **Frontal lift** – air that rises at a front
3) **Horizontal convergence** – air that is forced to rise because it is converging
4) **Convection** – air that rises because it is less dense that its surroundings

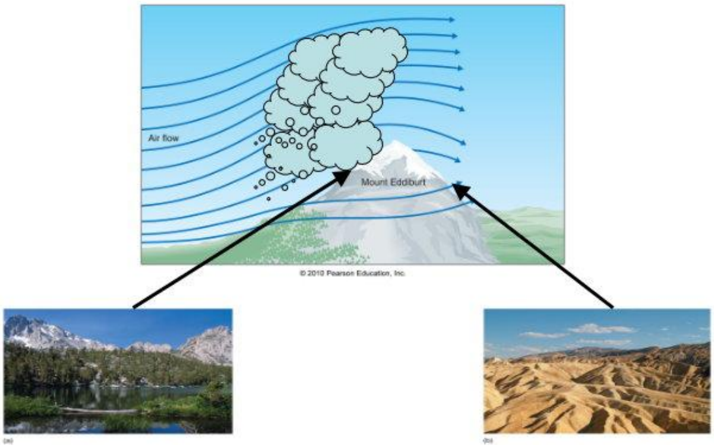
Orographic Lift

Air rises as it approaches a mountain peak



Rain Shadow

- A rain shadow is an area of less precipitation and clouds on the downwind side of a mountain (the anti-cloud!)
  - Air descends downwind of a mountain peak
  - Air warms adiabatically due to compression
  - Precipitation and clouds evaporate to form rain shadow



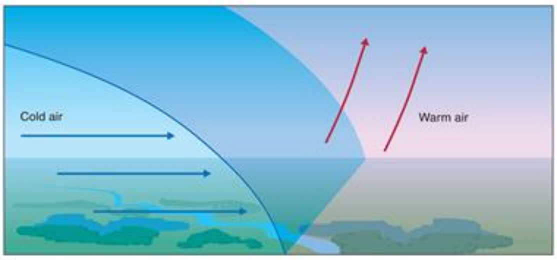
Frontal Lifting

Front – a zone of rapidly changing temperature (strong temperature gradient)

<u>Types of Fronts</u>

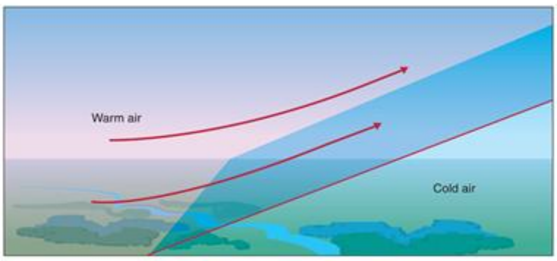
1) Cold Front – cold air is advancing
2) Warm Front – warm air is advancing
3) Stationary Front – front isn't moving
4) Occluded Front – you'll find out later

Cold Front
(cold air pushes warm air up)



(a)

Warm Front
(Warm air overruns cold air)



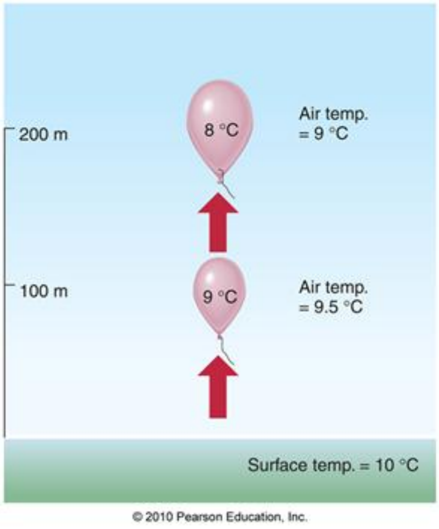
(b)

Convergence

- Air must rise when it converges

- Air "bubbles" or "parcels" rise when they are warmed and become less dense than their surroundings (exactly the same way a helium balloon does)

- This is how thunderstorms form!



Atmospheric Stability

Atmospheric stability – a measure of the atmosphere's susceptibility to vertical motion

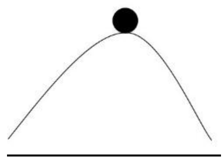
Atmospheric stability depends on the **environmental lapse rate** (Γ_e)

Atmospheric stability comes in 3 flavors:

1) **Absolutely stable**
2) **Absolutely unstable**
3) **Conditionally unstable**

Absolutely Unstable Air

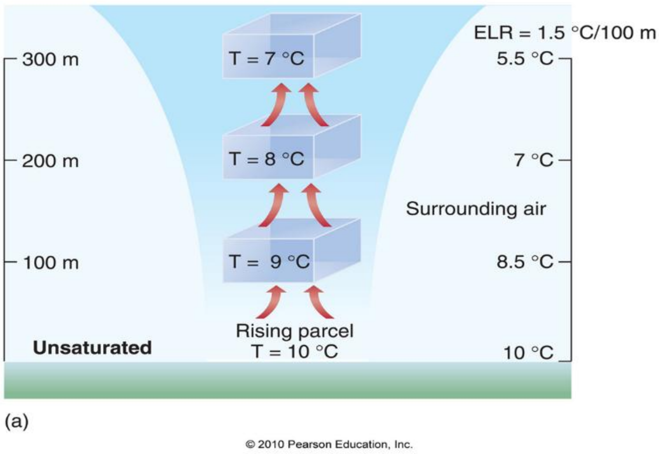
The slightest nudge sends the ball accelerating away…



Absolutely unstable: $\Gamma_e > \Gamma_d$ (unsaturated air)

Γ_e = 1.5°C/100m

Γ_d = 1.0°C/100m

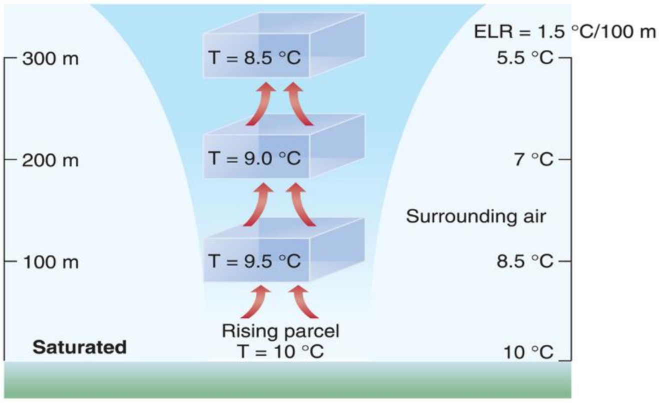


(a)

Absolutely unstable: $\Gamma_e > \Gamma_m$ (saturated air)

Γ_e = 1.5°C/100m

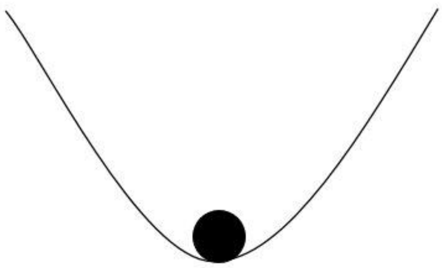
Γ_m = 0.5°C/100m



(b)

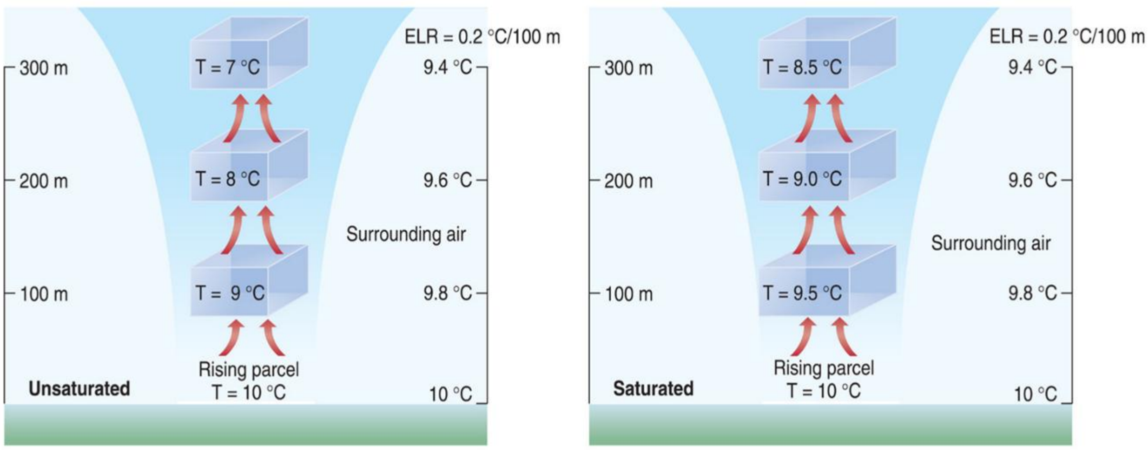
Absolutely Stable Air

Any push and the ball will go back to the valley and come to rest again…



Γ_d = 1.0°C/100m
Γ_e = 0.2°C/100m

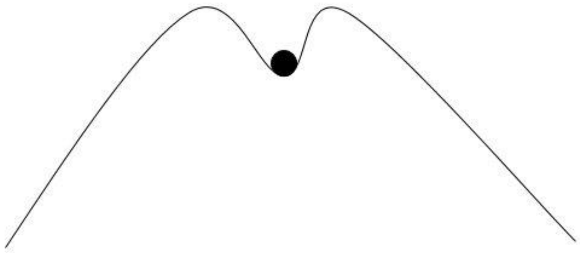
Γ_m = 0.5°C/100m
Γ_e = 0.2°C/100m



(a) (b)

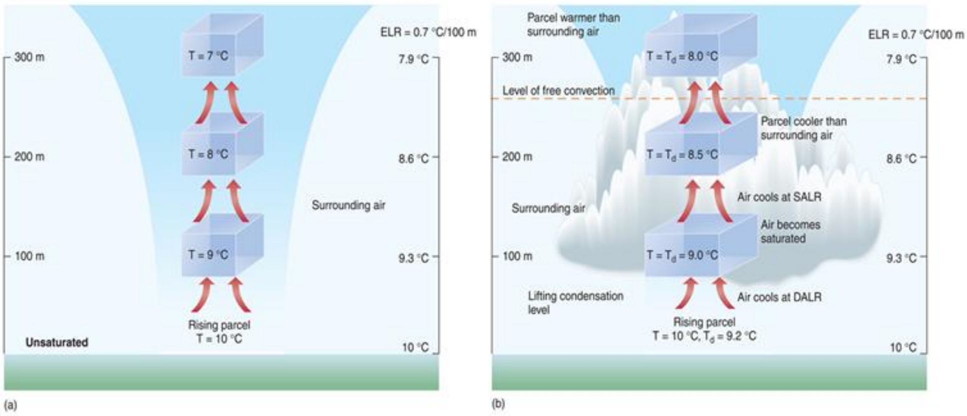
Conditionally Unstable Air

If the ball is pushed high enough, it will go over the hump and accelerate away… (otherwise it comes back to rest)



Γ_d = 1.0°C/100m Γ_m = 0.5°C/100m

Γ_e = 0.7°C/100m Γ_e = 0.7°C/100m



<u>Stability Summary</u>

Absolutely unstable:

$\Gamma_e >$ both Γ_d and Γ_m

Absolutely stable:

$\Gamma_e <$ both Γ_d and Γ_m

Conditionally unstable

$\Gamma_d > \Gamma_e > \Gamma_m$

Limitations on Convection

- What stops vertical motion?
  - The only "stopper" is if air becomes more dense (colder) than its surroundings!!
- This happens in 2 ways:

1) Stable air aloft
2) Entrainment – intake of drier air from surroundings

- **Lifting condensation level (LCL)** – The level at which a cloud forms (altitude of cloud base)

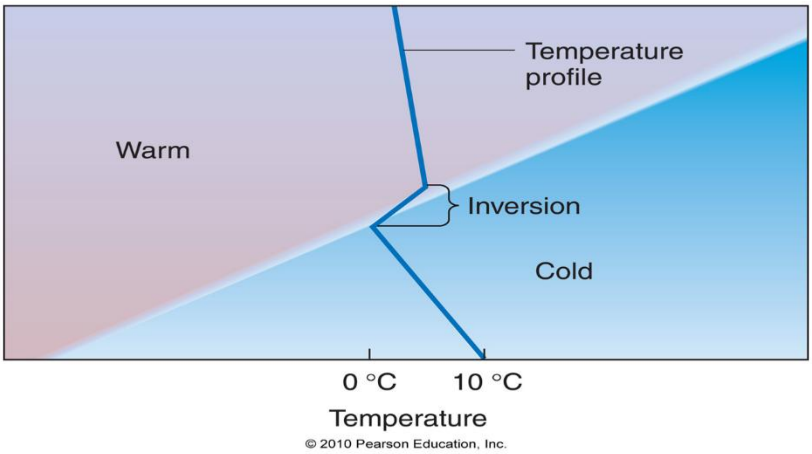
- **Level of Free Convection (LFC)** – the level at which air becomes less dense (warmer) than its surroundings

Inversions – Extremely Stable Air

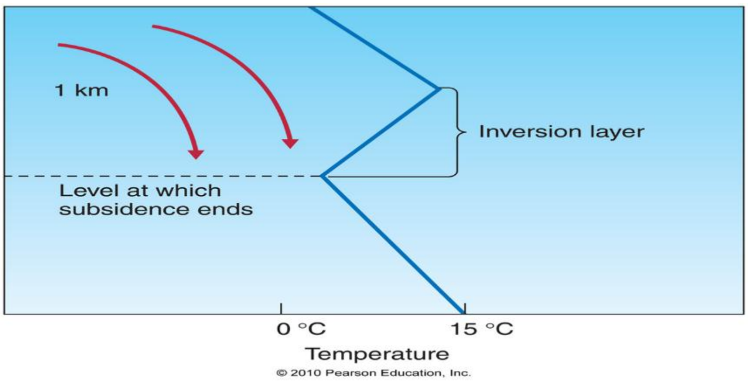
Inversion – when temperature increases with height

Types of Inversions

1) Radiation inversion – caused by nighttime cooling of surface air
2) Frontal inversion – occurs at fronts



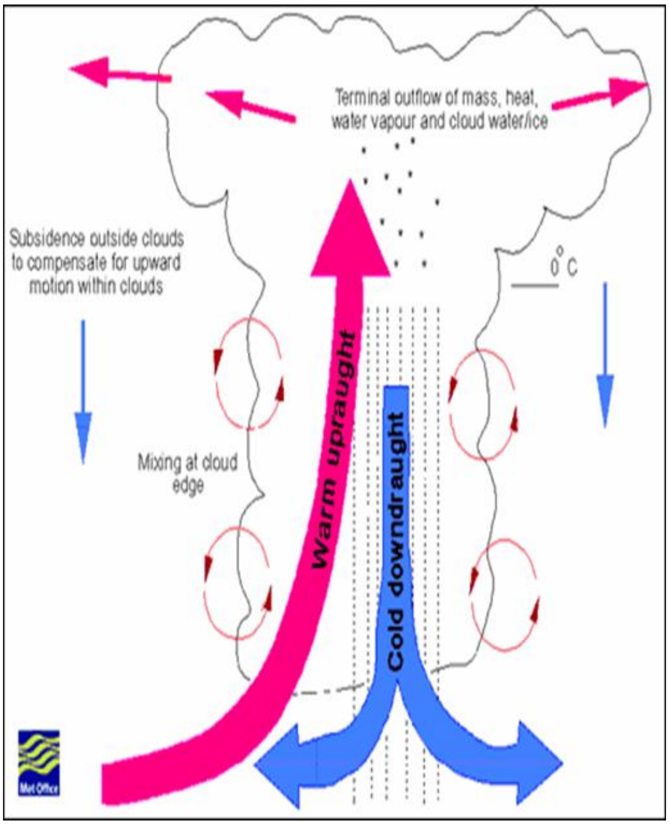
3) Subsidence inversion – caused by sinking air above a static layer



Entrainment

- Mixing with surrounding drier, cooler air cools rising parcels through:

1) Mixing
2) Evaporation



Cloud Types

Old classification of clouds

1) Cirrus (high, thin, wispy)
2) Stratus (layered)
3) Cumulus (puffy, vertically-developed)
4) Nimbus (rain-producing)

New classification of clouds

1) High clouds (higher than 6 km)
2) Middle clouds (b/w 2 and 6 km)
3) Low clouds (below 2 km)
4) Clouds with vertical development

High Clouds (> 6 km)

- Composed of ice crystals
- Principal types:
  1) Cirrus
  2) Cirrostratus
  3) Cirrocumulus

Cirrus

Cirrostratus

Cirrocumulus

Other High Clouds - Contrails

Middle Clouds (between 2 and 6 km)

- Composed mostly of supercooled water
- Principal types:
  - Altostratus
  - Altocumulus

Altostratus

Altocumulus

Low Clouds (< 2 km)

- Composed of liquid water
- Principal types:
  1) Stratus
  2) Nimbostratus
  3) Stratocumulus

Stratus

Nimbostratus

Stratocumulus

Cumulus Clouds

Cumulus clouds can extend the entire depth of the atmosphere

Principal types:

1) Cumulus

   - cumulus humilis (fair-weather cumulus)

   - cumulus congestus (fortress-like)

2) Cumulonimbus

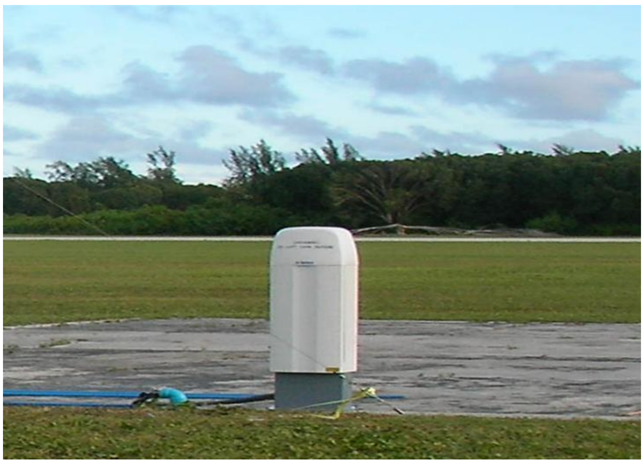
Cumulus Humilis

Cumulus Congestus

Cumulonimbus

Observing Clouds

- **Ceilometers** – automated instrument that measures the height of the cloud base, or ceiling, as well as coverage



Cloud Coverage

TABLE 6–3 Cloud Coverage

Amount of Cloud Coverage	Condition
0	Clear
1/8 to 2/8	Few*
3/8 to 4/8	Scattered
5/8 to 7/8	Broken
8/8	Overcast

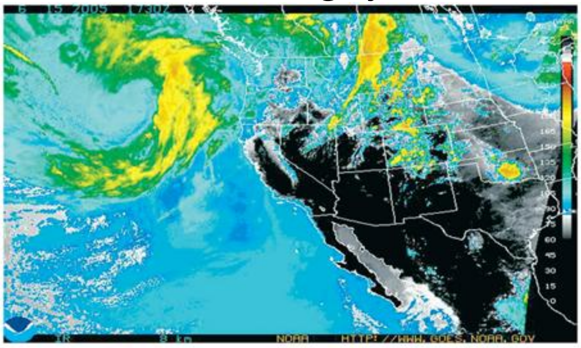
* *Any cloud coverage at all up to 2/8 is classified as "few."*

- Satellite imagery is also a primary tool for observing clouds and cloud motions
    - ➢ Visible satellite imagery
    - ➢ Infrared satellite imagery
    - ➢ Water vapor satellite imagery

Visible Satellite Imagery

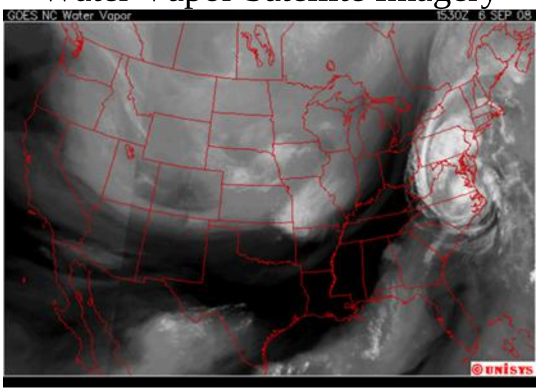
(a)

Infrared Satellite Imagery



(c)

Water Vapor Satellite Imagery



Chapter 7

Precipitation Processes

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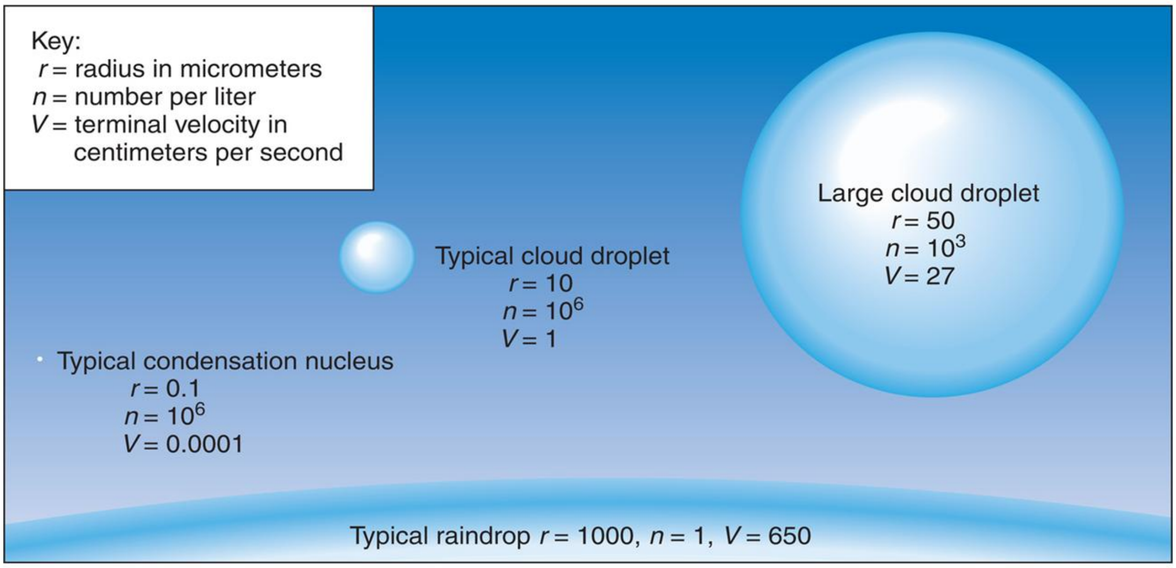
Clouds

- Clouds are composed of tiny water droplets from condensation onto CCN



Clouds -> Precipitation

Cloud droplet fall speeds are way too low to become precipitation

-→ For clouds to produce precipitation, cloud droplets must get bigger!

Growth of Cloud Droplets

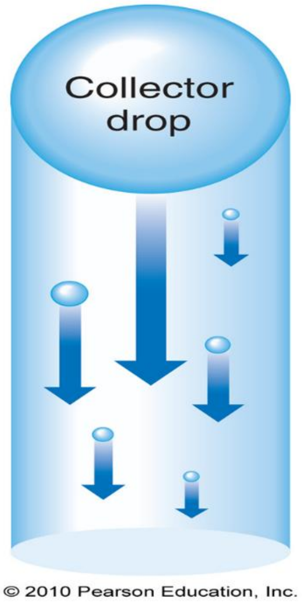
- Condensation is only effective from nucleation up to around radii of 0.02 mm
  - → There's just too many drops, too little moisture
- So, for precipitation, we need another mechanism!
- This other mechanism depends on the type of cloud:
  1) Warm clouds (totally > 0^{o}C)
  2) Cool and cold clouds (at least partially below 0^{o}C)

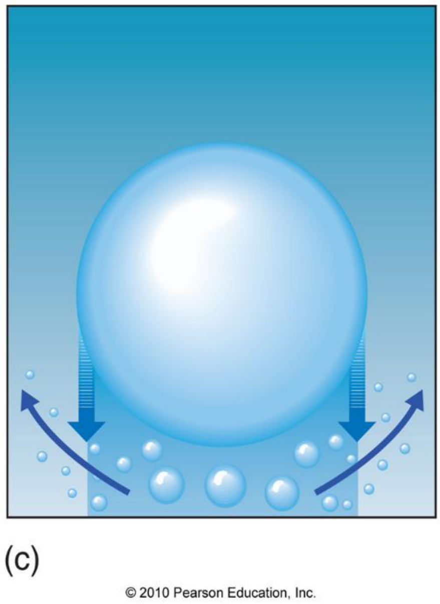
Precipitation in Warm Clouds

- Warm clouds – clouds with only liquid water above 0oC
- 2 processes produce warm cloud precipitation:
  1) Collision
  2) Coalescence

Collision in Warm Clouds

- Collision – when cloud droplets collide with each other
- Collision efficiency depends on relative size of a collector drop and droplets below
  - Low efficiency for very small drops
  - Low efficiency for same-size drops
  - High efficiency for drops in between these sizes





Coalescence in Warm Clouds

- **Coalescence** – when colliding cloud droplets stick together
- Coalescence efficiency is assumed to be near 100% (all drops stick together if they collide)

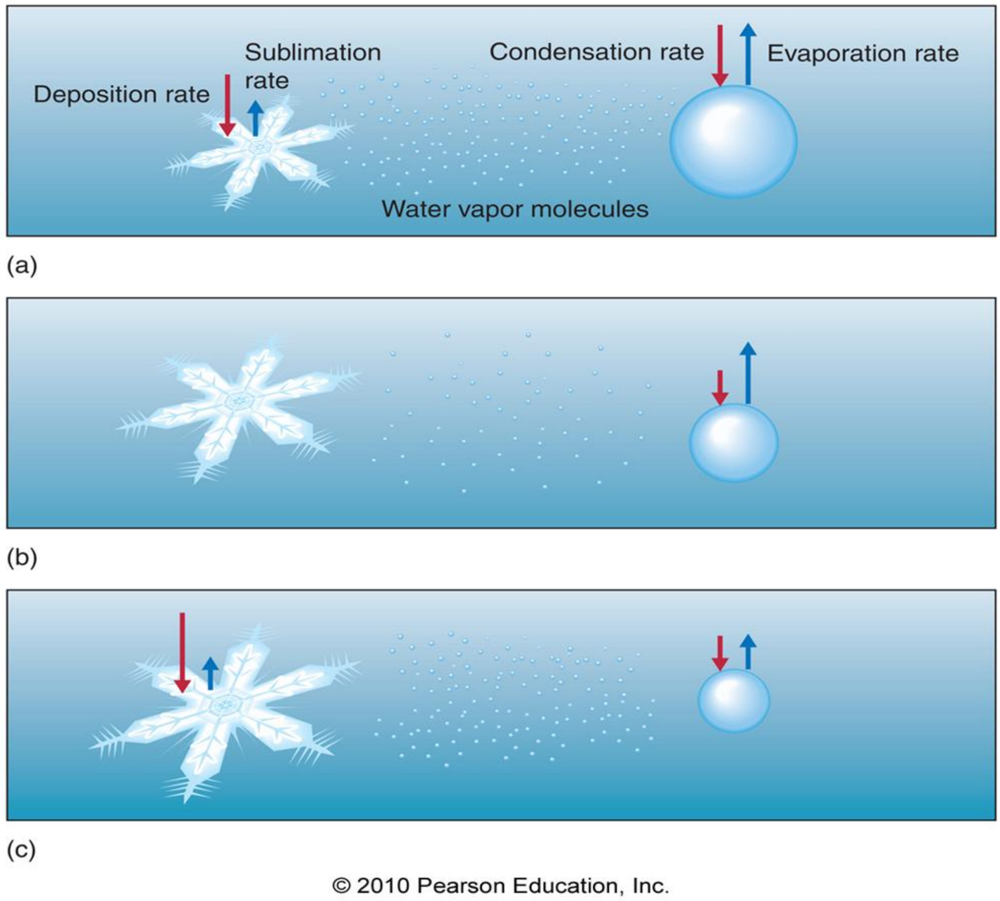
Precipitation in Cool and Cold Clouds

- **Cold cloud** – a cloud entirely below 0°C that may contain supercooled water, ice, or both
- **Cool cloud** – a cloud with regions both above and below 0°C
- Precipitation in cool and cold clouds relies on a mixture of supercooled water and ice

<u>Key Concept</u>

Saturation vapor pressure over ice is less than Saturation vapor pressure over water

→ The Bergeron Process



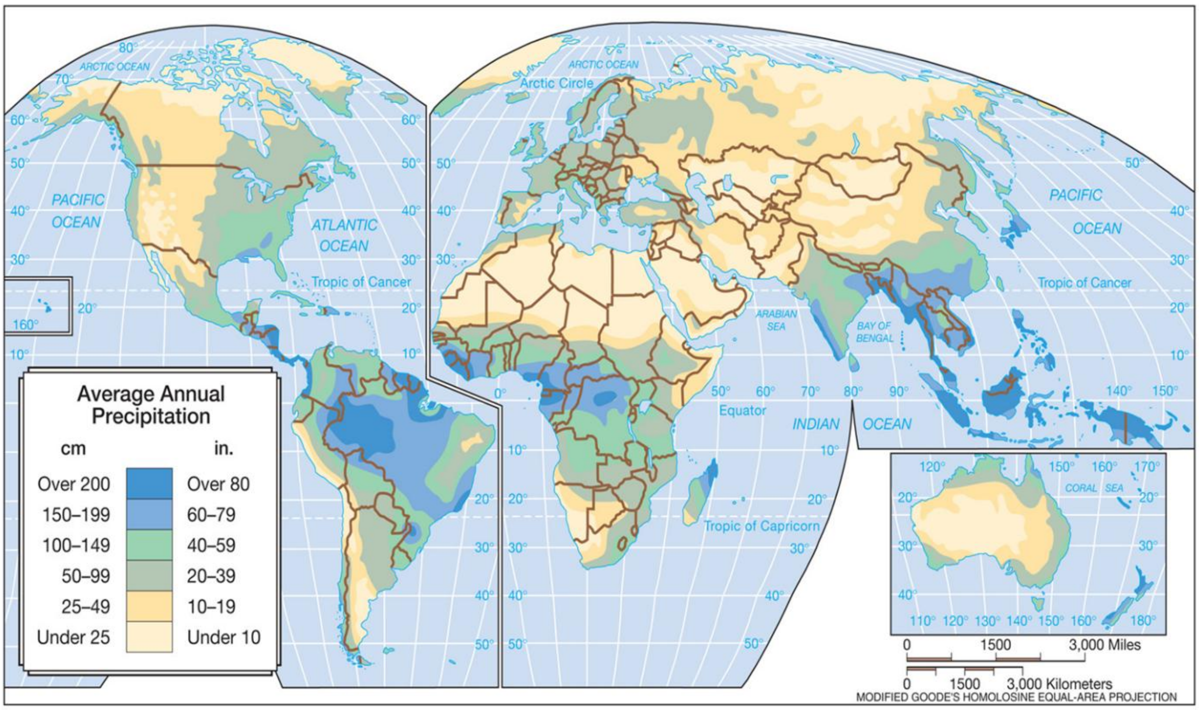
The Bergeron Process

- For air with both supercooled water and ice:
  1) Amount of water vapor is in equilibrium with water (saturated)
  2) Amount of water vapor is not in equilibrium with ice (supersaturated)
  3) Water vapor deposits onto ice, lowering the amount of water vapor, causing evaporation of water
  4) The cycle continues – ice grows and water vanishes

- Once the Bergeron Process takes place, ice becomes big enough to fall, and 2 additional processes occur:
  1) Riming – ice collides with supercooled water which freezes on contact
  2) Aggregation – ice crystals collide and stick together

Precipitation Distribution

- 38.8 in/year annual average precipitation
- Each year (for the last ~100 years) has been within 2 in of this average

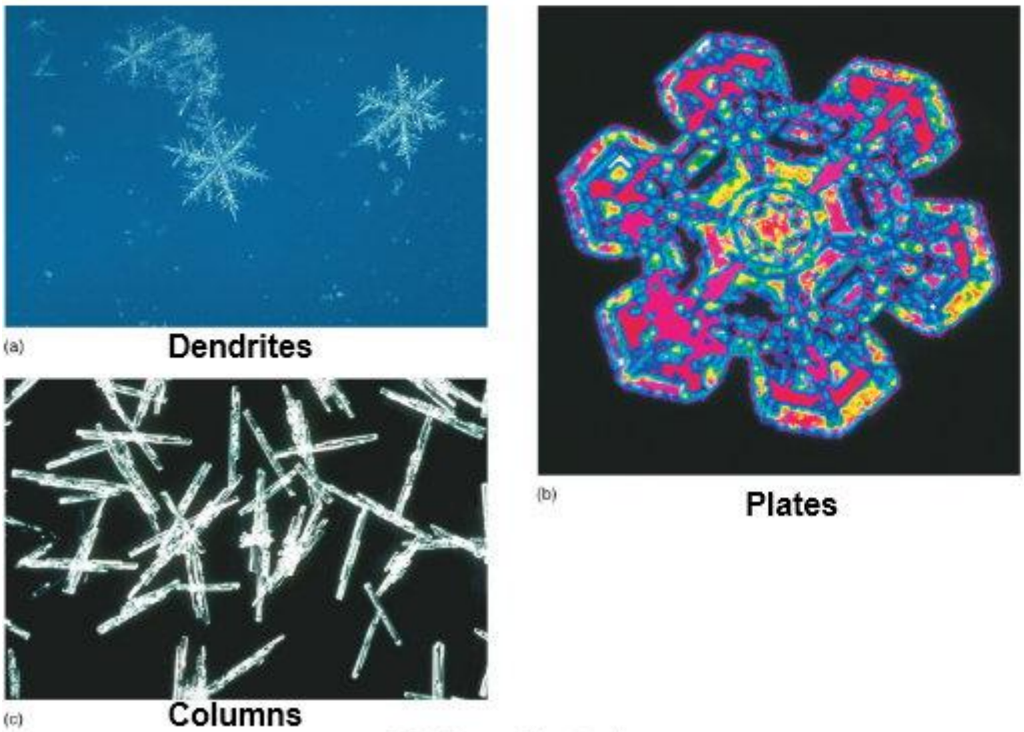


Types of Precipitation

- Several types of precipitation exist and depend on the atmospheric temperature profile:
  1) Snow
  2) Rain
  3) Graupel and hail
  4) Sleet
  5) Freezing rain

Snow

- Snow occurs from the Bergeron process, riming, and aggregation
  - ➢ The nature of snowflakes depends on temperature and moisture content



Rain

- The nature of rain formation typically depends on location:
    1) Tropics – warms clouds - rain forms by condensation, collision, and coalescence
    2) Mid-latitudes – cool clouds – rain forms as snow then melts

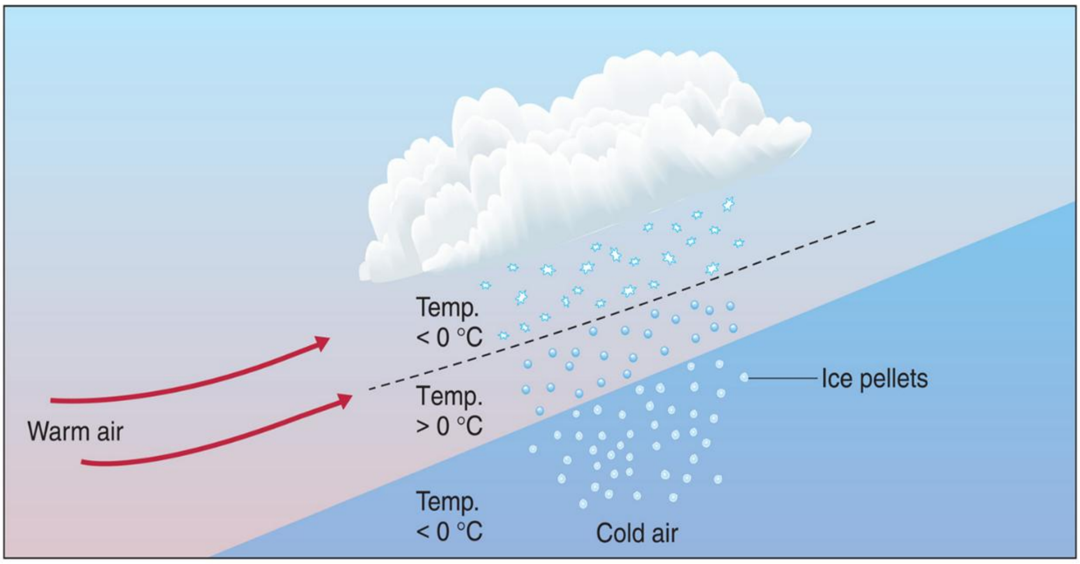
- Rain is also classified in terms of how it lasts in time
    1) Steady (stratiform) rain – rain that lasts for long periods of time (hours)
    2) Showers (cumuliform) rain – rain that is short-lasting (minutes)

Graupel and Hail

- **Graupel** – ice crystals that undergo riming upon collisions with supercooled water
- **Hail** – Severely rimed ice crystals resulting from repeated upward and downward motions in a thunderstorm

Freezing Rain and Sleet

- **Freezing rain** – supercooled rain that freezes on contact or shortly after contact with surface
- **Sleet** – raindrops that have frozen while falling, reaching the surface as ice pellets



Measuring Precipitation

Raingage – A cylindrical container that collects rainfall and measures its depth

(a)

Tipping-bucket gage – a raingage that also measures timing and intensity

(b)

Radar – a very useful tool for measuring rain over large area

Cloud Seeding

Cloud seeding – injecting foreign materials into clouds to initiate precipitation by the Bergeron process

1) Dry ice is used to cool clouds to very cold temperatures, causing ice crystals to form
2) Silver iodide (similar structure to ice) is used as ice nucleii