Atmospheric Sciences:

Atmosphere

Solar radiation

Atmospheric circulation

Seasons

Atmospheric Sciences:

Weather

- Causes
- Forecasting
- Severe weather

Climate

Recent topics

Global warming/CO_2

Ozone "hole," pollution, acid rain

The Earth's Atmosphere:

1. Composition:

$N_2 \approx 78\%$
$O_2 \approx 21\%$

Other elements and compounds (**minor constituents**):

(Ar, Ne, CH_4, Kr, H_2, etc.) $\leq 1\%$

Water vapor $\approx 0 - 4\%$

Significant **trace elements** (although very small in volume in the Earth's atmosphere, these trace elements and water vapor have significant effects):

$CO_2 \approx 390$ ppm*

$CO \approx 100$ ppm

$O_3 \approx 0 - 10$ ppm

$SO_2 \approx 0 - 1$ ppm

*ppm = parts per million; one ppm equals 0.0001%

Composition of Dry Air

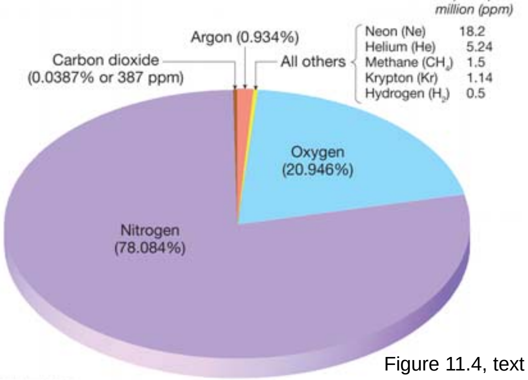


Figure 11.4, text

The Earth's atmosphere became oxygen rich in the last 2 billion years, through volcanic emissions and the growth of plant life. (100% of O^2 in the present atmosphere is about 20% of the total atmosphere)

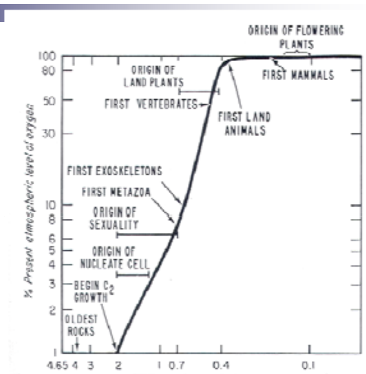


Figure 20. Apparent timing of events in biological evolution compared with hypothetical levels of atmospheric oxygen. Both scales are logarithmic in order to fit data into space available. (Adapted from P. Cloud, *Paleobiology* 2, no. 4, 1976.)

2. The atmosphere is layered by:

- Temperature (in lowest layer, temperature decreases with altitude)
- Pressure (pressure decreases with elevation)
- Moisture content (generally decreases with elevation; **why?**) – cold air (higher altitude) holds less moisture; source of most water is Earth's surface (oceans, lakes rivers, land surface)

Air Pressure Decreases with Altitude

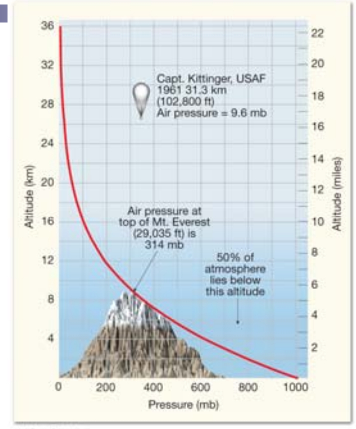


Figure 11.7, text

Air Pressure Decreases with Altitude – Because as altitude increases, there is less air above, and, the density of air decreases rapidly with altitude, the pressure versus altitude relationship is a curve

D = Density of air (in g/cm^3) – note that density of the atmosphere also decreases with altitude

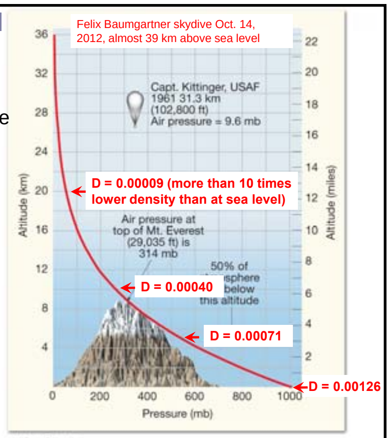


Figure 11.7, text

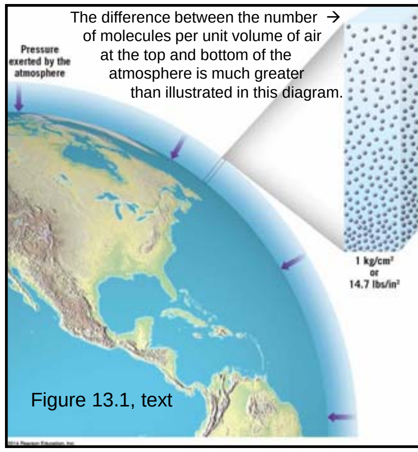


Figure 13.1, text

← Because it is a gas, the layer of atmosphere is not homogeneous, as a layer of water would be. So, there are more molecules of air per cubic meter (because of the weight of the overlying atmosphere) at lower levels of the atmosphere. This causes the curved pressure vs. altitude relationship seen in the previous slide.

Air Pressure Decreases with Altitude – Because as altitude increases, there is less air above, and, the density of air decreases rapidly with altitude, the pressure versus altitude relationship is a curve

D = Density of air (in g/cm^3) – note that density of the atmosphere also decreases with altitude

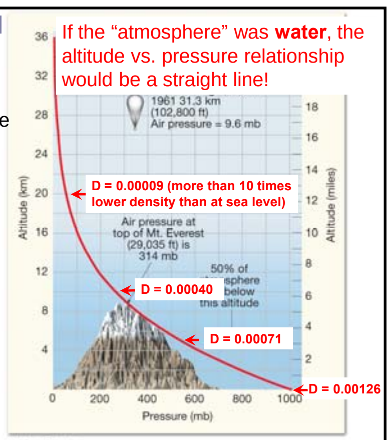
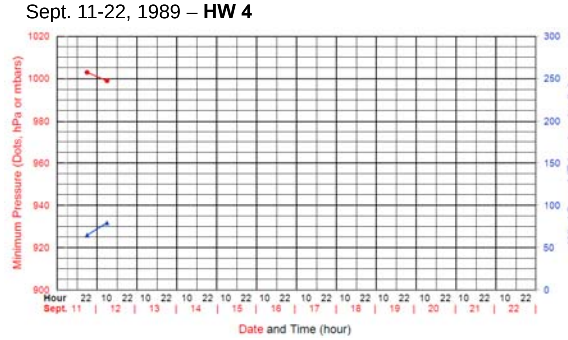
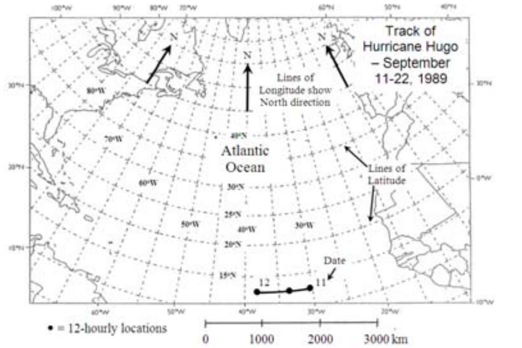


Figure 11.7, text

Graph for plotting Pressure and Wind Speed versus Time – Hurricane Hugo, wind speed (triangles) and pressure (dots) Sept. 11-22, 1989 – **HW 4**



Map for plotting Hurricane Hugo Track (note sample data near bottom of map; due to the map projection, the lines of longitude [meridians] show the North direction [as illustrated by heavy black arrows])



Homework #4 – Hurricanes Hugo and Katrina

Satellite photo of Hurricane Hugo (Time is UTC or GMT = EST + 5 hours), 2031 hours, 21 Sept. 1989

http://web.ics.purdue.edu/~braile/eas100/hwk4SatelliteImage.pdf

Earth's Atmosphere – a thin layer

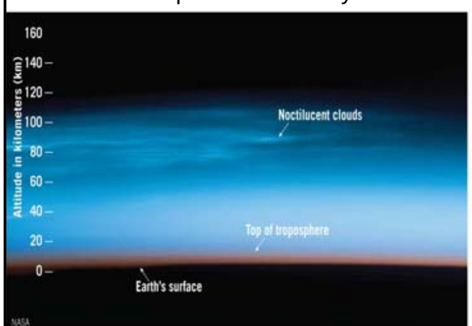
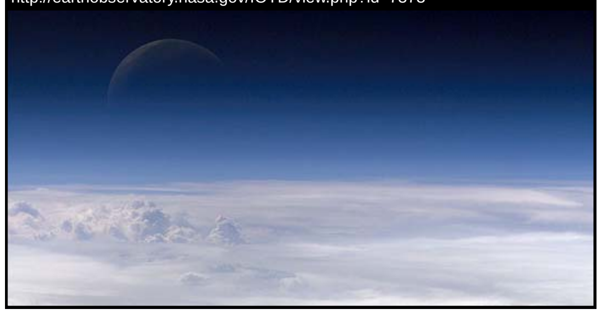


Image of the atmosphere taken from the space shuttle. The thin streaks, called noctilucent clouds, are 80 km (50 mi) high. It is in the dense troposphere that practically all weather phenomena occur.

Figure I.8, text

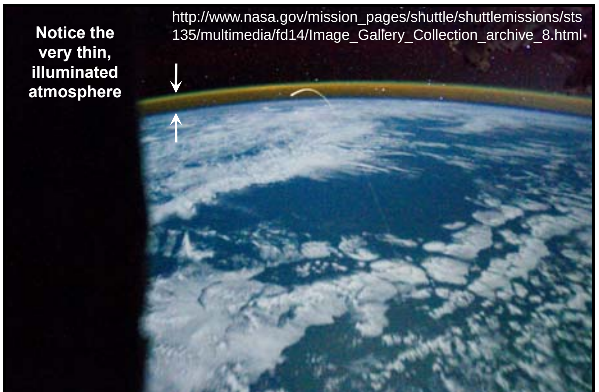
"Atmospheric gases scatter blue wavelengths of visible light more than other wavelengths, giving the Earth's visible edge a blue halo. At higher and higher altitudes, the atmosphere becomes so thin that it essentially ceases to exist. Gradually, the atmospheric halo fades into the blackness of space. This astronaut photograph captured on July 20, 2006, shows a nearly translucent moon emerging from behind the halo."
http://earthobservatory.nasa.gov/IOTD/view.php?id=7373



http://earthsky.org/space/view-from-space-layers-of-atmosphere-on-the-horizon

"The Earth's atmosphere is an extremely thin sheet of air extending from the surface of the Earth to the edge of space. The Earth is a sphere with a roughly 13,000 km diameter; the thickness of the atmosphere is about 100 km. In this picture, taken from a spacecraft orbiting at 300 km above the surface, we can see the atmosphere as the thin blue band between the surface and the blackness of space. If the Earth were the size of a basketball, the thickness of the atmosphere could be modeled by a thin sheet of plastic wrapped around the ball. At any given location, the air properties also vary with the distance from the surface of the Earth. The sun heats the surface of the Earth, and some of this heat goes into warming the air near the surface. The heated air rises and spreads up through the atmosphere. So the air temperature is highest near the surface and decreases as altitude increases. The pressure of the air can be related to the weight of the air over a given location. As we increase altitude through the atmosphere, there is some air below us and some air above us. But there is always less air above us than was present at a lower altitude. Therefore, air pressure decreases as we increase altitude."

http://www.grc.nasa.gov/WWW/K-12/airplane/atmosphere.html



Space Shuttle Atlantis leaving the International Space Station on the last NASA Space Shuttle Mission (STS 135) July 21, 2011.

Temperature variation with altitude (we will focus on the lowermost layer, the troposphere, where most weather phenomena occur)

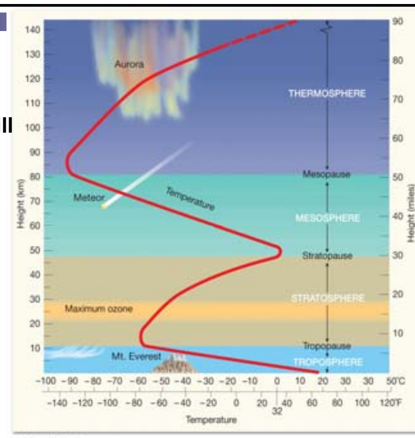


Figure 11.9, text

Temperature variation with elevation (lowest layer of the atmosphere, the troposphere, where most weather phenomena occur)

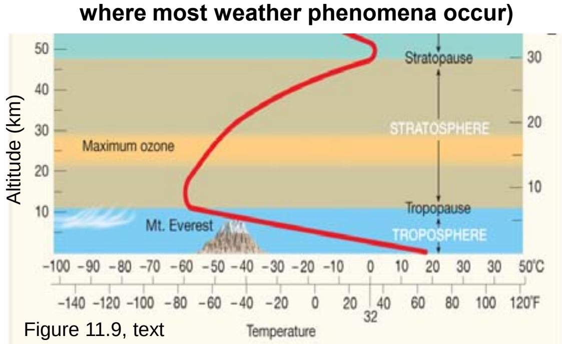


Figure 11.9, text

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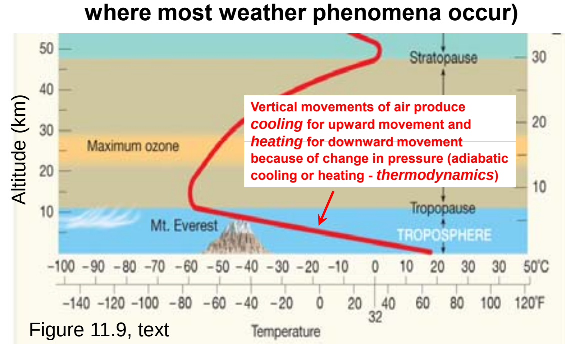
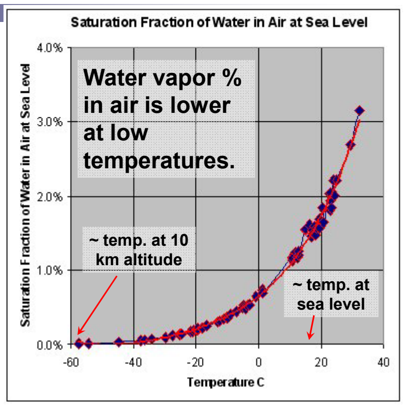


Figure 11.9, text

Because temperature decreases rapidly with altitude, water vapor % also decreases with altitude (remember very dry air on cold winter days!.)
(Atmospheric pressure also decreases with altitude and has an effect on water vapor %, but the temperature effect is more important.)



http://en.wikipedia.org/wiki/Water_vapor

Air Pressure Decreases with Altitude – Because as altitude increases, there is less air above, and, the density of air decreases rapidly with altitude, the pressure versus altitude relationship is a curve

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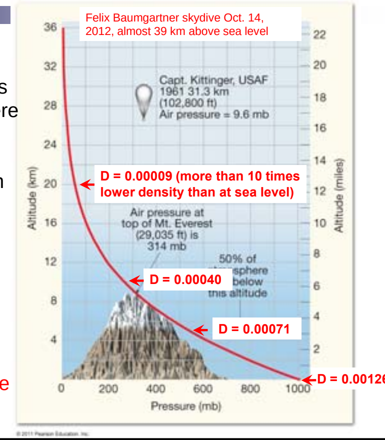

Figure 11.7, text

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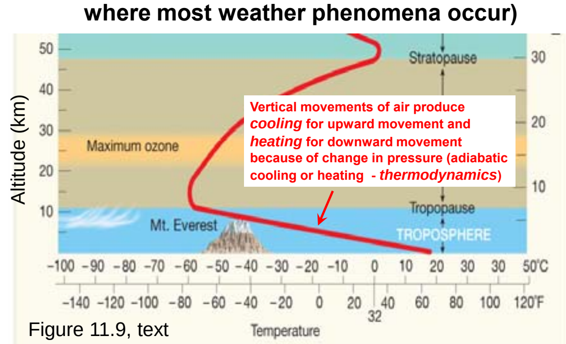

Figure 11.9, text

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3. Atmospheric circulation occurs on multiple scales of distance and time:

- Global pattern (large scale, changes over seasons as well as hundreds of years)
- Regional weather patterns (changes over days to weeks)
- Severe weather (local, and changes over hours to days)

(We will discuss atmospheric circulation at various time scales later.)

Solar Radiation:

Electromagnetic radiation/energy

Energy source for atmospheric circulation and weather

Solar Energy:

- 1 part in 10^9 strikes Earth
- in 1 minute, solar energy that strikes Earth is more than humans use in 1 year
- Solar emissions are mostly in visible, ultraviolet, and infrared parts of EM spectrum
- Energy is reflected, absorbed, transmitted through atmosphere
- Most energy eventually radiated back into space by Earth and atmosphere as infrared energy (so atmosphere is approximately in equilibrium)

Electromagnetic Spectrum

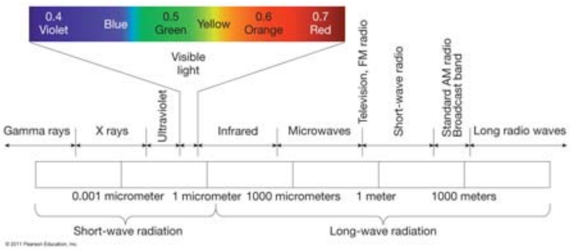
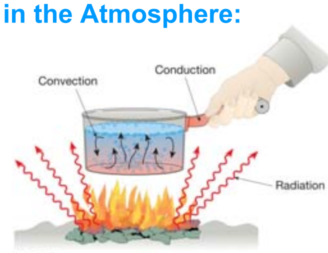


Figure 11.19, text

Energy Transfer in the Atmosphere:



-- Radiation

-- Conduction

-- Convection (mass transport; wind and other atmospheric circulation)

Figure 11.17, text

Temperature Changes:

- Heating near equator cooling in polar regions (variations with seasons, weather systems, length of day)
- Adiabatic heating and cooling (a thermodynamic effect)
  - volume of air which moves to lower pressure expands and cools;
  - volume of air which moves to higher pressure compresses and warms

Temperature Changes:

- Warm air rises (less dense) and cools
- Similarly, cool air sinks (more dense) and warms

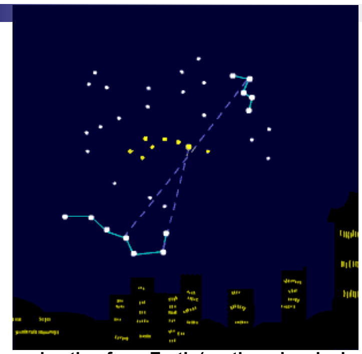
The Reason for Seasons:

Tilt of the Earth (results in less energy from the Sun per unit area hitting the Earth's surface in winter and more in summer)

The tilt also causes significantly different length of day (hours with sunlight and therefore heating) during seasons

Time-lapse (about one hour) photograph from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation)

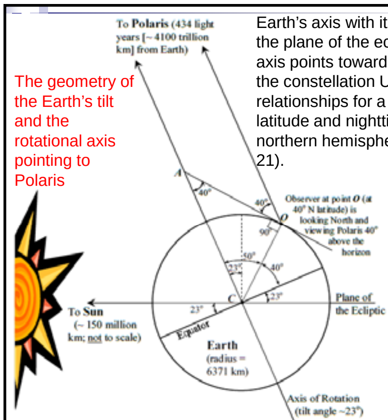
Time-lapse (several hours) photograph from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation)



Time-lapse animation from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation) (http://en.wikipedia.org/wiki/Circumpolar_star)

Time-lapse (several hours) photograph from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation)

The geometry of the Earth's tilt and the rotational axis pointing to Polaris



Earth's axis with its 23 degree tilt (relative to the plane of the ecliptic), the North directed axis points towards Polaris (the North Star in the constellation Ursa Minor), and angle relationships for a location at 40º North latitude and nighttime (~midnight) in the northern hemisphere summer solstice (June 21).

What would be the angle of Polaris above the horizon if you were standing at the Equator? At the North Pole? In Australia?

Earth-Sun Relationships

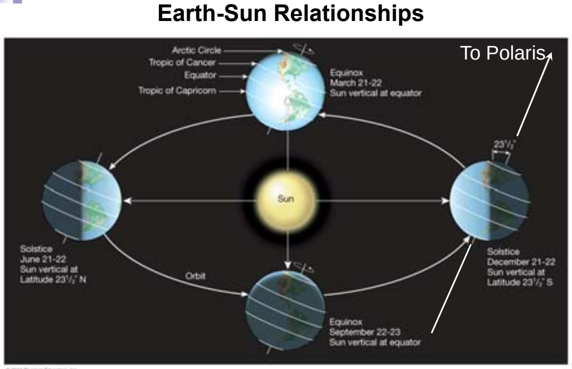


Figure 11.14, text

Area Covered by Different Sun Angles

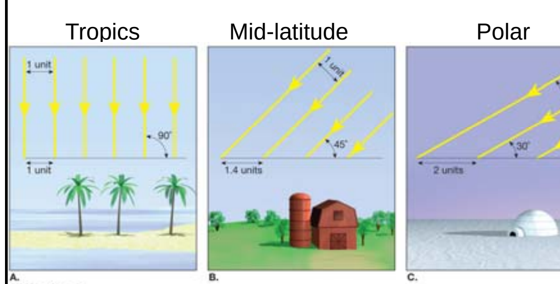


Figure 11.12, text

Sun Angle vs. Depth Rays Must Travel through Atmosphere to Reach Earth's Surface

Figure depicts winter in the northern hemisphere. Note low angle of Sun in polar regions and distance that rays travel through the atmosphere (atmospheric thickness greatly exaggerated).

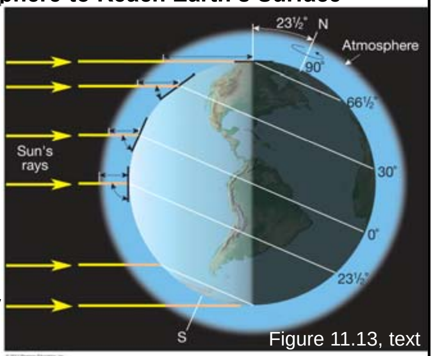


Figure 11.13, text

"Reasons for Seasons" – Earth and Sun orbit, tilt and Sun angle animations (Please view these animations and watch carefully; they will help you fully understand the "reasons for seasons"):

http://www.classzone.com/books/earth_science/terc/content/visualizations/es0408/es0408page01.cfm?chapter_no=04

http://www.mathsisfun.com/earth-orbit.html

Earth Orbit:
https://www.youtube.com/watch?v=R2lP146KA5A

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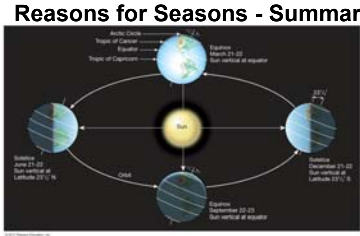
Reasons for Seasons - Summary



So, … ~23 degree tilt of the Earth causes:
1. Variable heating over the seasons; heating is also dependent on latitude (more heating near equator than near poles) because of angle of the Sun's rays hitting Earth.
2. Changes in length of day (versus night; winter versus summer).
3. More absorption of solar energy by the atmosphere in the polar regions because of the low angle of the Sun's rays.

World Distribution of Mean Temperature - January

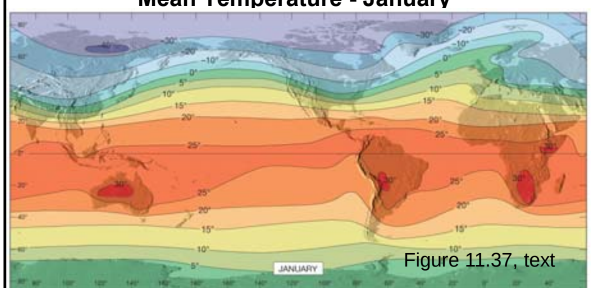


Figure 11.37, text

Note highest temperatures are south of the equator. Also note "moderation" of low temperatures in the N. Pacific and N. Atlantic areas due to exchange of heat from ocean.

World Distribution of Mean Temperature - July

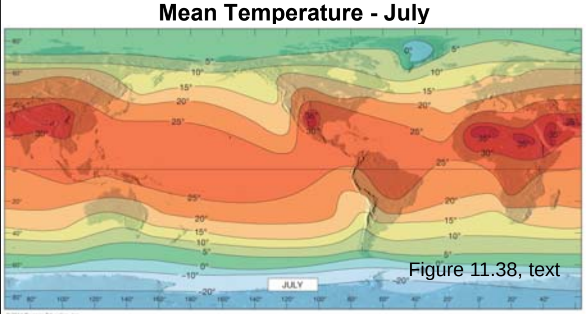
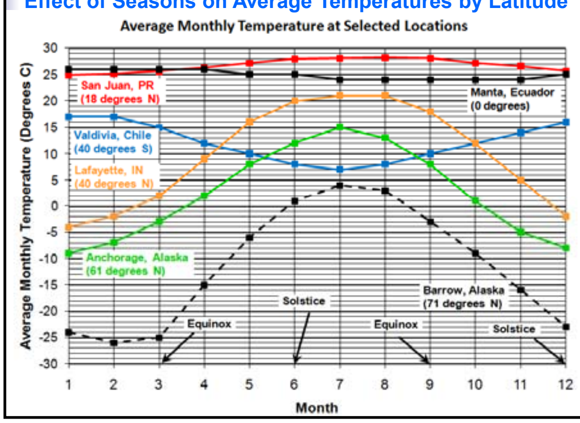


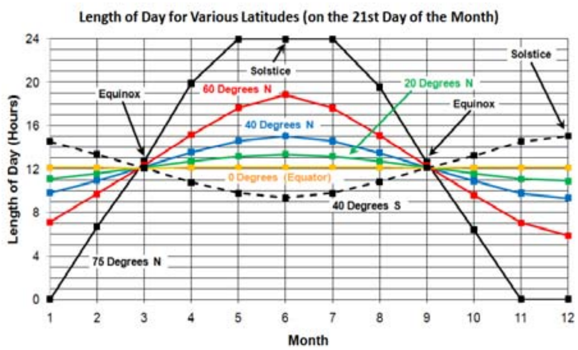
Figure 11.38, text

Note highest temperatures are north of the equator. Also note very cold temperatures in south polar region.

Effect of Seasons on Average Temperatures by Latitude



Effect of Seasons on Length of Day by Latitude



Global Atmospheric Circulation

Primarily the result of heating at the equator and cooling (less heating) at the poles.

Also, the **Coriolis effect** causes deflection, and therefore a modification of the expected circulation pattern.

Global Circulation on a Non-rotating Earth

Circulation (convection) pattern expected from heating near the equator and cooling near the poles.

Note that, because warm air rises near the equator, the surface winds would be expected to be **from pole to equator.**

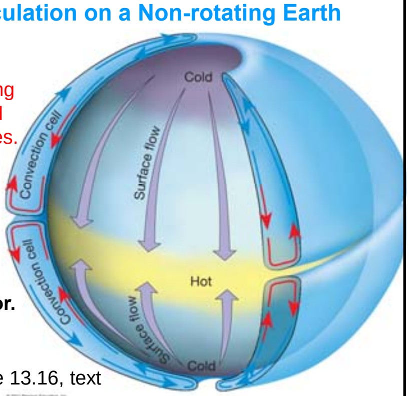


Figure 13.16, text

Idealized Global Circulation

Global circulation breaks into cells due to **Coriolis effect** and fact that it is too far from equator to pole (10,000 km) for air to retain temperature deviation. Note that the resulting surface winds are the "Trade Winds" (prevailing winds).

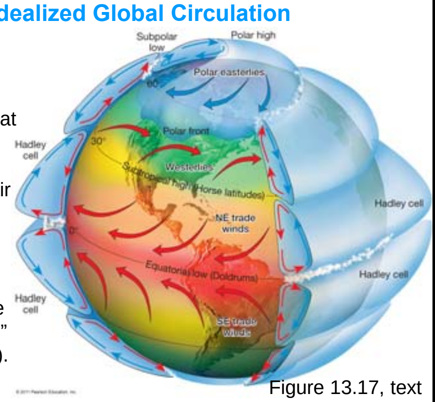
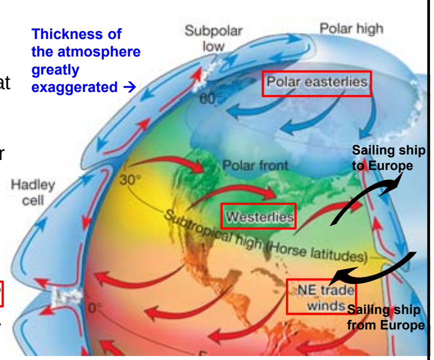


Figure 13.17, text

Idealized Global Circulation (close-up, 3-D)

Global circulation breaks into cells due to **Coriolis effect** and fact that it is too far from equator to pole (10,000 km) for air to retain temperature deviations. Note that the resulting surface winds are the "Trade Winds" (prevailing winds).

Thickness of the atmosphere greatly exaggerated →



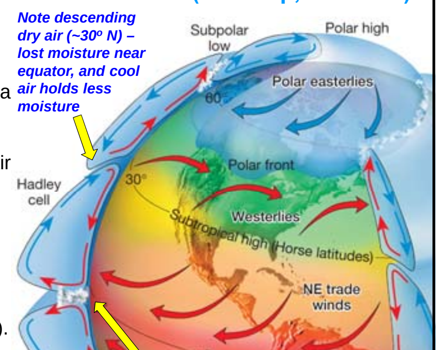
Note that most of the U.S. (30-60 degrees N) has westerly trade winds so weather systems mostly go from west to east

Figure 13.17, text

Idealized Global Circulation (close-up, 3-D View)

Global circulation breaks into cells due to **Coriolis effect** and fact tha it is too far from equator to pole (10,000 km) for air to retain temperature deviation. The resulting surface winds are the "Trade Winds" (prevailing winds).

Note descending dry air (~30° N) – lost moisture near equator, and cool air holds less moisture

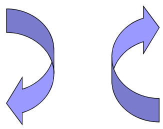


Note rising moist air in tropical area – air loses moisture by precipitation as it rises and cools (Figure 13.17, text)

The Coriolis Effect:

Results from Earth's rotation on its axis

Causes deflection to the right in the northern hemisphere



More explanation of the Coriolis effect…

Three demos…Foucault pendulum (2), record turntable

Artistic rendition (highly exaggerated) of a Foucault pendulum showing that the Earth is not stationary, but rotates. http://en.wikipedia.org/wiki/Universe

http://www.youtube.com/watch?v=_36MiCUS1ro

http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/fw/gifs/coriolis.mov

Smaller scale atmospheric circulation: Circulation (winds) around High and Low pressure systems

Variable heating and cooling of the atmosphere, vertical movements of air, day/night changes, and seasonal changes result in changes of temperature of air masses and the development of **High** and **Low** pressure areas

Circulation around the High and Low pressure areas is the result of the pressure differences and the **Coriolis effect**

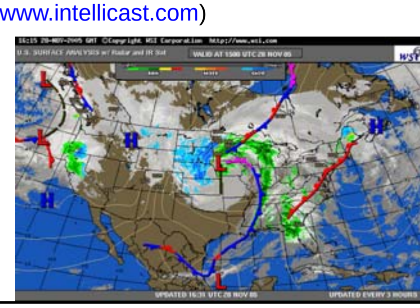
The greater the pressure differences (the closer the contour lines or "isobars") the higher the wind velocity

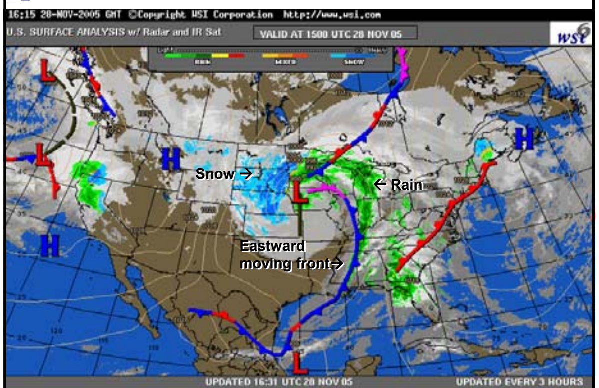
Smaller scale atmospheric circulation: Circulation (winds) around High and Low pressure systems

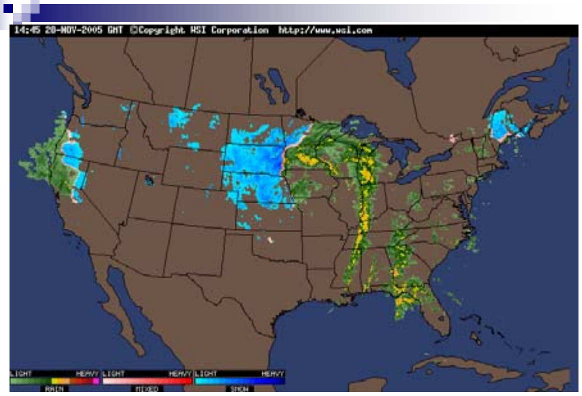
(more)

Smaller scale atmospheric circulation: Circulation (winds) around High and Low pressure systems

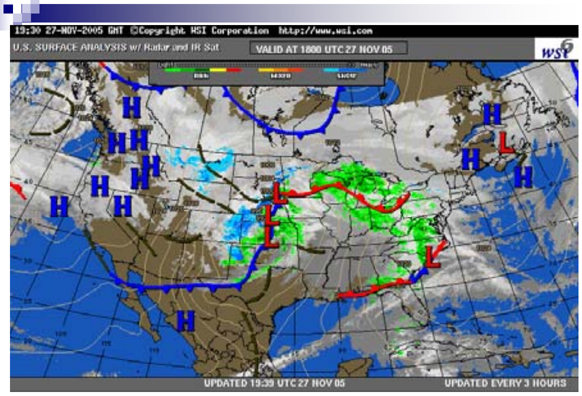
(example, Low pressure area of November 27-28, 2005, [more like spring low pressure system] images from www.intellicast.com)







Radar Loop 1400 – 1645 GMT 28 November 2005



Radar/Surface Loop 1930 11/27 – 1615 11/28 GMT

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Results from Earth's rotation on its axis

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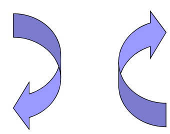
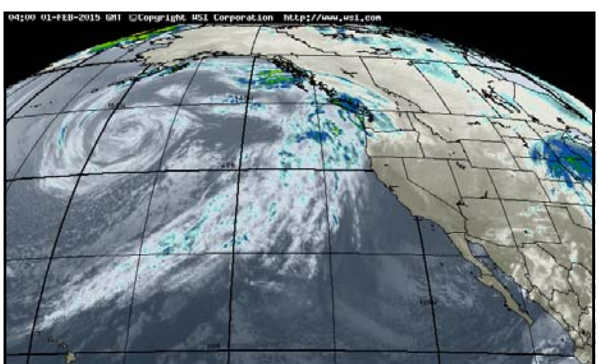
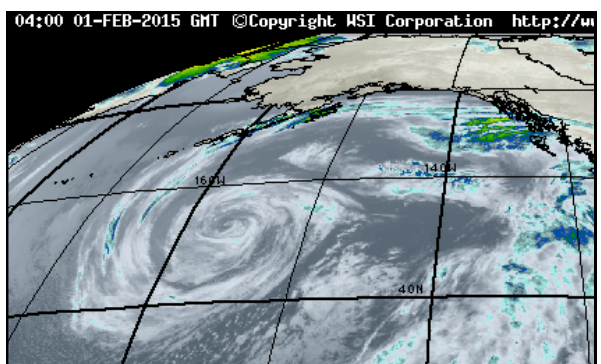


More explanation of the Coriolis effect…

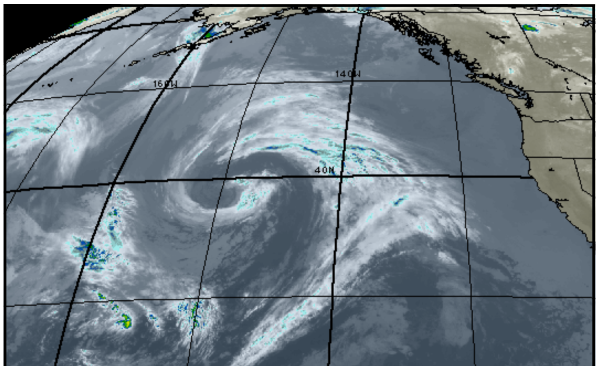
Three demos…Foucault pendulum (2), record turntable



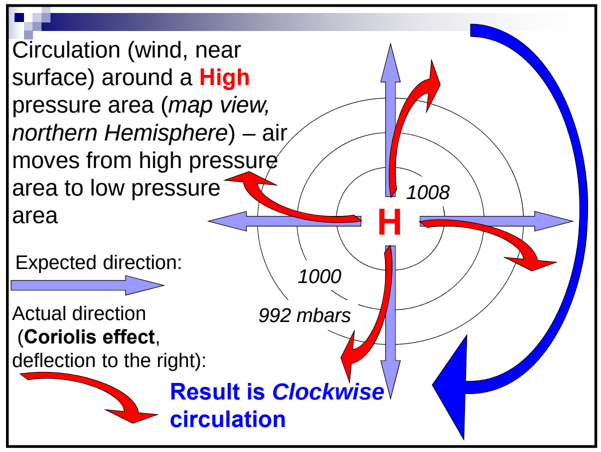
Infrared satellite loop over the Pacific ocean showing counter-clockwise circulation around a low pressure area south of the Aleutian Islands (04:00 – 08:00 GMT, Feb. 1, 2015).

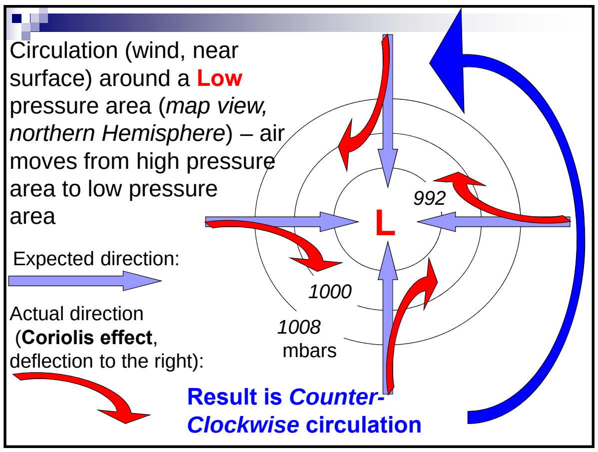


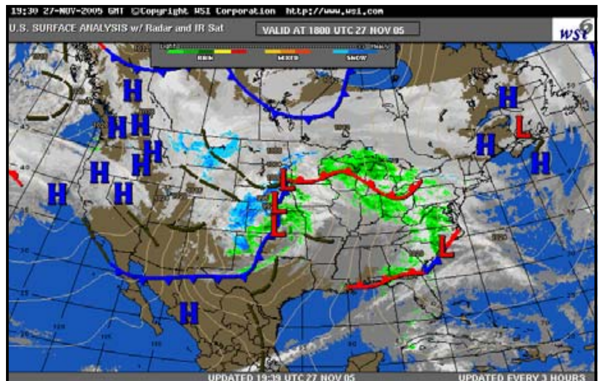
Infrared satellite loop over the Pacific ocean showing counter-clockwise circulation around a low pressure area south of the Aleutian Islands (04:00 – 08:00 GMT, Feb. 1, 2015).



Infrared satellite loop over the Pacific ocean showing counter-clockwise circulation around a low pressure area south of the Aleutian Islands (12:30 – 16:30 GMT, May 27, 2015).





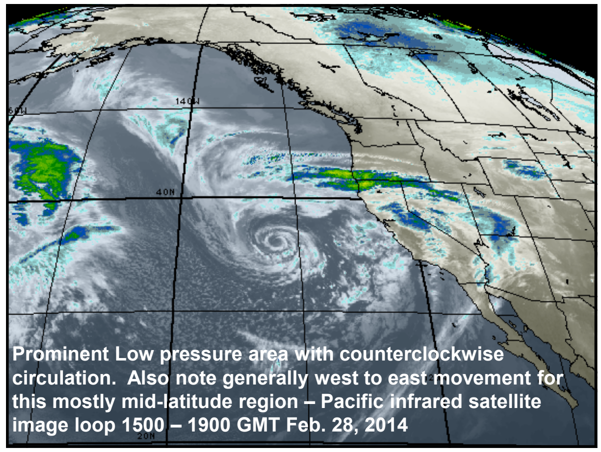


Radar/Surface Loop 1930 11/27 – 1615 11/28 GMT

Infrared Satellite Loop 1330 – 1730 11/13 GMT

Radar Loop 1600 – 1800 11/13 GMT

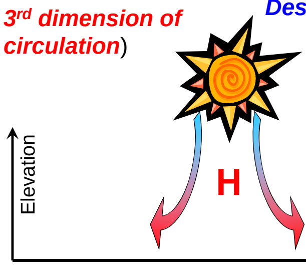
Radar Loop 1600 – 1800 11/13 GMT



Prominent Low pressure area with counterclockwise circulation. Also note generally west to east movement for this mostly mid-latitude region – Pacific infrared satellite image loop 1500 – 1900 GMT Feb. 28, 2014

Circulation (wind, near surface) around a **High** pressure area (***cross section view to show 3rd dimension of circulation***)

Cool (from high elev.), ***Dry***, (from high elev.), ***Descending*** (more dense) air.



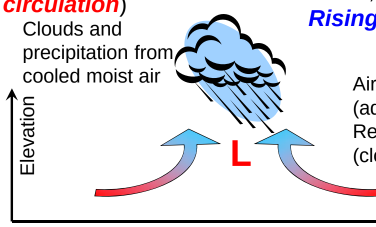
Air **warms** as it descends (adiabatic heating). Result is "good" weather (clear, dry)

Earth's surface

Circulation (wind, near surface) around a **Low** pressure area (***cross section view to show 3rd dimension of circulation***)

Clouds and precipitation from cooled moist air

Warm (from low elev.), ***Moist***, (from low elev.), ***Rising*** (less dense) air.



Air **cools** as it rises (adiabatic cooling). Result is "bad" weather (cloudy, precipitation)

Earth's surface

Typical atmospheric pressure pattern; note High and Low pressure air masses.

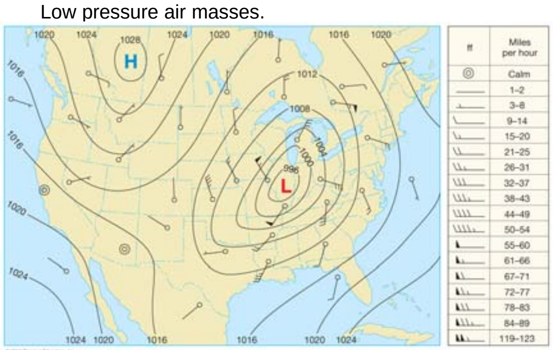
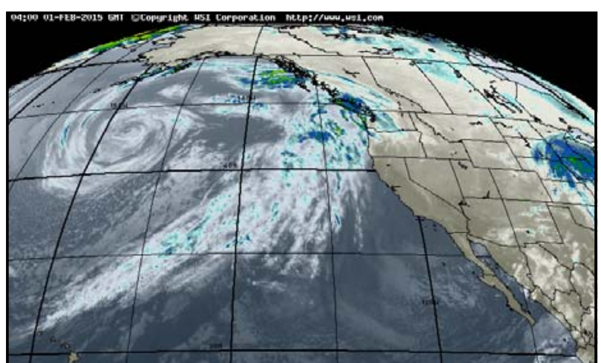
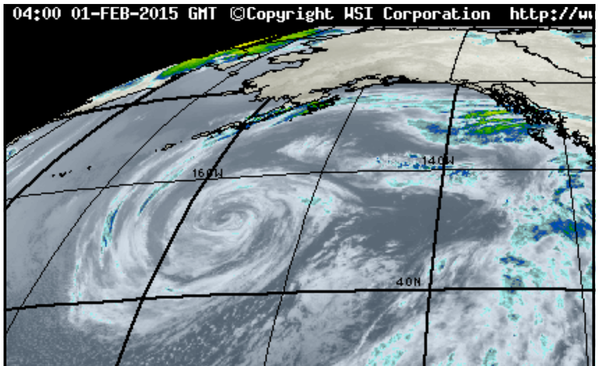


Figure 13.7, text



Infrared satellite loop over the Pacific ocean showing counter-clockwise circulation around a low pressure area south of the Aleutian Islands (04:00 – 08:00 GMT, Feb. 1, 2015).



Infrared satellite loop over the Pacific ocean showing counter-clockwise circulation around a low pressure area south of the Aleutian Islands (04:00 – 08:00 GMT, Feb. 1, 2015).

3-D view of circulation around High and Low pressure areas.

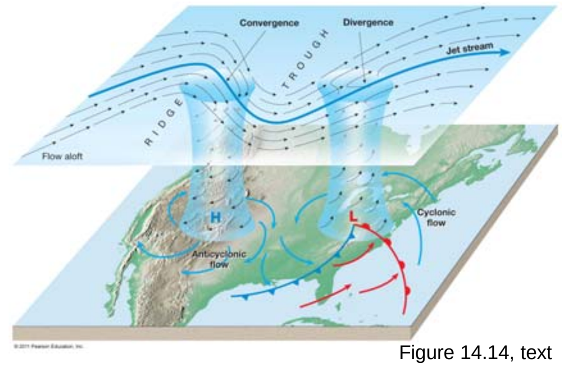


Figure 14.14, text

Circulation around Low pressure area often results in formation of a **cold front**. Collision of dry, cold air with warm, moist air results in precipitation and, possibly, thunderstorms and tornadoes.

Cold front moves from west to east due to trade winds (westerlies, in mid-latitudes, 30º-60º N) and counter-clockwise circulation around the Low

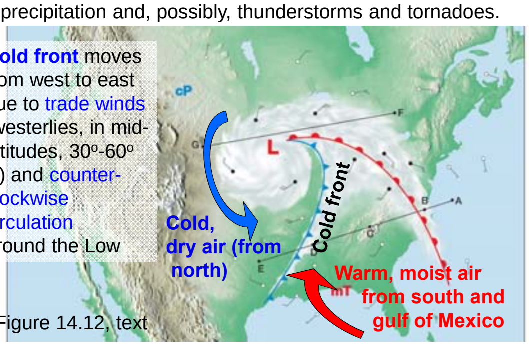


Figure 14.12, text

Clouds associated with a Low pressure area and cold front

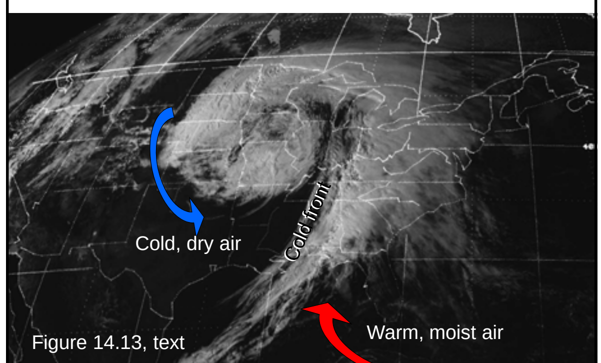


Figure 14.13, text

Cold air (moving east) is more dense so it stays near the Earth's surface and causes the adjacent warm moist air to rise along the front producing clouds, precipitation and storms.

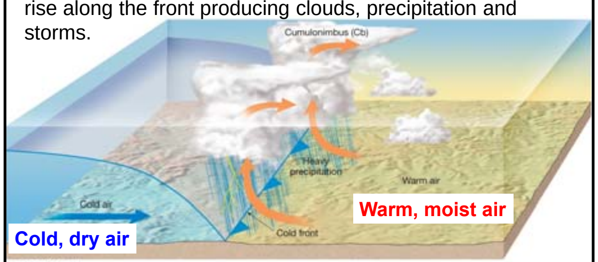
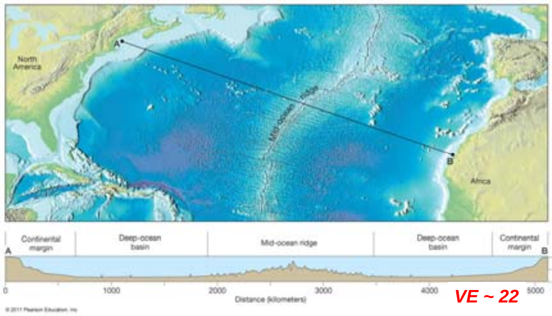


Figure 14.8, text

Photo and caption by Santiago Borja. "A colossal Cumulonimbus flashes over the Pacific Ocean as we circle around it at 37000 feet [~11.3 km] en route to South America." http://photography.nationalgeographic.com/nature-photographer-of-the-year-2016/gallery/week-1-landscape/6

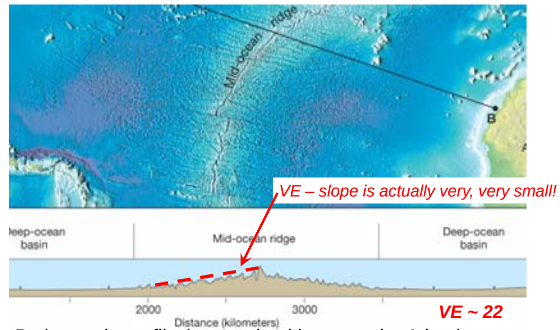
Rising warm moist air expands and cools as it rises (adiabatic cooling) and flows outward at the top of the Troposphere (~12 km altitude) as there is warmer air (due to ozone content) above in the Stratosphere.

Review of Ocean Bathymetry Exercise – Bathymetric Profile (Hwk #3) – and the concept of vertical exaggeration in figures.



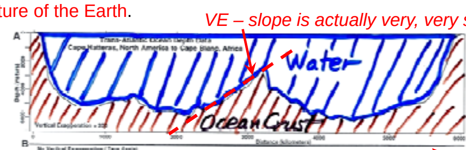
Bathymetric profile (ocean depth) across the Atlantic Ocean, Figure 9.15, text.

Review of Ocean Bathymetry Exercise – Bathymetric Profile (Hwk #3) – and the concept of vertical exaggeration (VE) in figures.

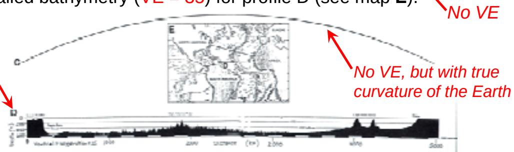


Bathymetric profile (ocean depth) across the Atlantic Ocean, zoomed in, Figure 9.15, text.

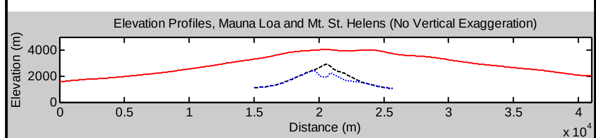
A. The bathymetry profile from homework #3; the ocean topography is vertically exaggerated (**VE**) about **200 times** so that we can see details. **B.** The same figure at 1-to-1 (no VE) or true scale. Note that we cannot see any details of the bathymetry because the horizontal distance is so large compared to the depth. **C.** Same as B except including the curvature of the Earth.

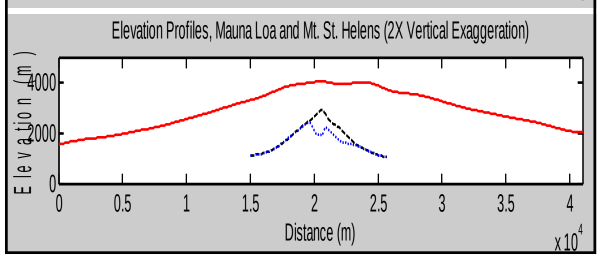


D. Detailed bathymetry (VE = 35) for profile D (see map **E**).



VE example: Elevation profiles for Mt. St. Helens (before & after 1980 eruption) and Mauna Loa volcanoes at true scale (top) and 2x VE (bottom).





Seeing Volcanoes in 3-D – Mt. St. Helens, before and after the 1980 eruption

Styrofoam topography models – each layer represents a contour line of elevation

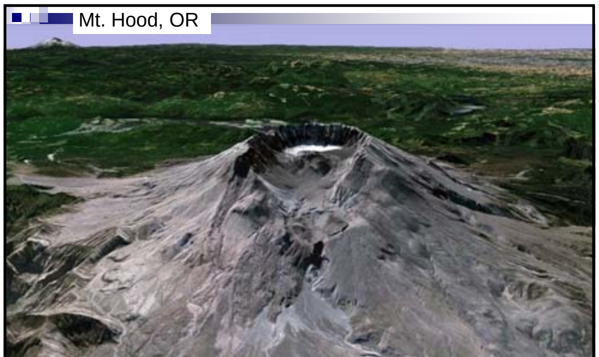
What is Vertical Exaggeration?

True scale, or 1 to 1, or no vertical exaggeration

Vertical scale times 3

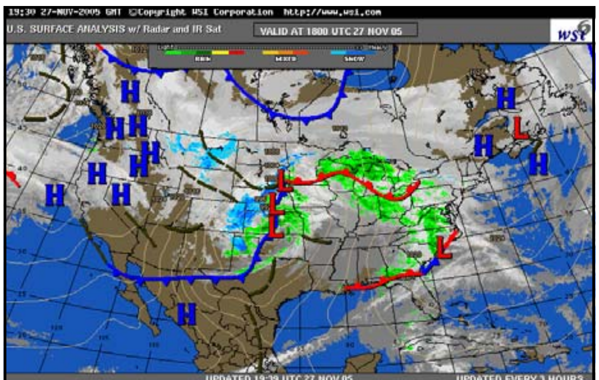
Horizontal scale same

3X vertical exaggeration (VE)



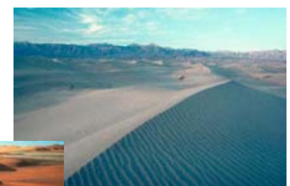
Google Earth perspective view (as if you were viewing from an airplane) of **Mt. St. Helens volcano** with no vertical exaggeration (1-to-1 scale), view looking ~South.

Google Earth perspective view of **Mt. St. Helens volcano** with 2x vertical exaggeration (VE).



Radar/Surface Loop 1930 11/27 – 1615 11/28 GMT, note front and counter-clockwise circulation around Low

Example of global circulation/climate effect: **Deserts**



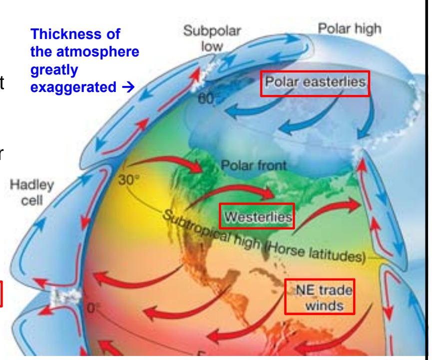
Death Valley, CA, NPS

Namib Desert, USGS

http://www.earthscienceworld.org/imagebank/

Idealized Global Circulation (close-up, 3-D)

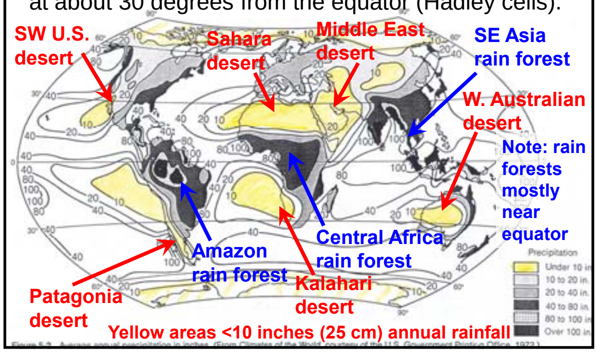
Global circulation breaks into cells due to Coriolis effect and fact that it is too far from equator to pole (10,000 km) for air to retain temperature deviations. Note that the resulting surface winds are the "Trade Winds" (prevailing winds).



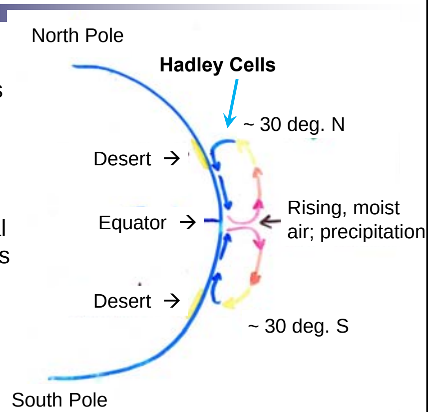
Note that most of the U.S. (30-60 degrees N) has westerly trade winds so weather systems mostly go from west to east

Figure 13.17, text

Example of global circulation/climate effect: **Deserts** (areas of very low precipitation, shaded yellow) occur at about 30 degrees from the equator (Hadley cells).

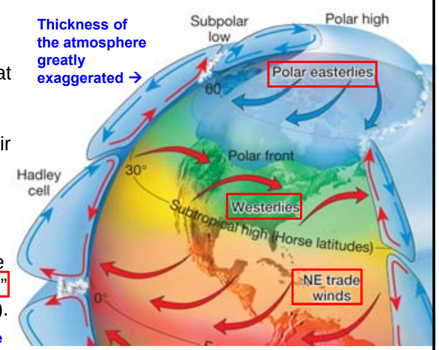


Cross section view of Earth's atmosphere (thickness greatly exaggerated) showing global circulation cells near equator.



Idealized Global Circulation (close-up, 3-D)

Global circulation breaks into cells due to Coriolis effect and fact that it is too far from equator to pole (10,000 km) for air to retain temperature deviations. Note that the resulting surface winds are the "Trade Winds" (prevailing winds).



Note that most of the U.S. (30-60 degrees N) has westerly trade winds so weather systems mostly go from west to east

Figure 13.17, text

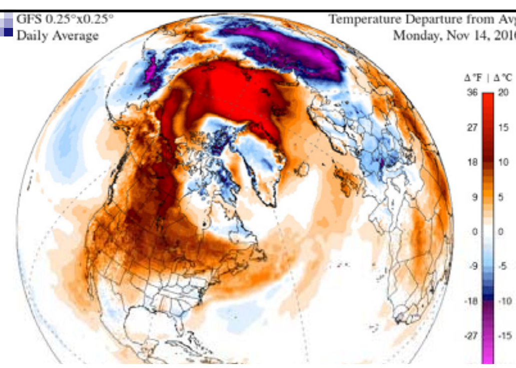
Climate (average or long term weather and atmospheric conditions – of Earth, region or specific location):

1. Classification (tropical, desert, alpine, etc.) - - Based on average temp. and precip.

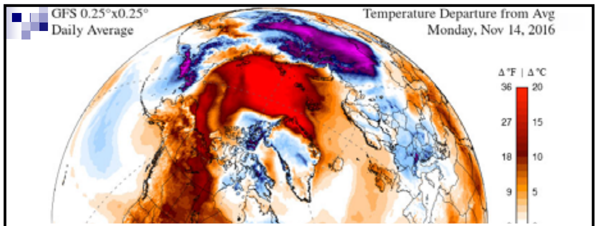
2. Methods of climate study (climate change):
   - - Average weather statistics
   - - Paleo-records, infer temp.
     - ice cores (oxygen isotopes)
     - sediment cores (fossils, pollen)
   - - Numerical modeling of atmospheric circulation

3. Recent climate change
   - - Last glaciation (max ≈ 18,000 years ago; ≈ 8°C cooler)
   - - "Climatic Optimum" (≈ 6000 years ago; 2 – 4°C warmer)
   - - "Little Ice Age" (1500-1900; 1 – 2°C cooler)
   - - Since 1900 – Significant warming

Glaciation (Ice Age): Maximum extent of glacial ice ~20,000 years ago, Northern Hemisphere



This is primarily a short-term weather pattern (will likely change soon), not an measure of climate change (although the pattern of short-term changes can be influenced by climate change).
https://apod.nasa.gov/apod/image/1611/WarmTempsNA2_CCI_722.jpg



Explanation: Why is it so warm in northern North America? Usually during this time of year -- mid-November -- temperatures average as much as 30 degrees colder. Europe is not seeing a similar warming. One factor appears to be an unusually large and stable high pressure region that has formed over Canada, keeping normally colder arctic air away. Although the fundamental cause of any weather pattern is typically complex, speculation holds that this persistent Canadian anticyclonic region is related to warmer than average sea surface temperatures in the mid-Pacific -- an El Niño -- operating last winter. North Americans should enjoy it while it lasts, though. In the next week or two, cooler-than-average temperatures now being recorded in the mid-Pacific -- a La Niña -- might well begin to affect North American wind and temperature patterns.

https://apod.nasa.gov/apod/image/1611/WarmTempsNA2_CCI_722.jpg

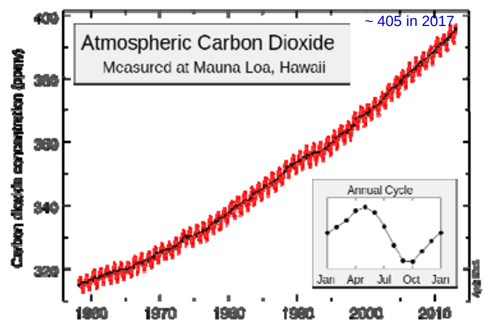
Causes of Climate Change:

1. Astronomical effects (Milankovitch Cycles)- - Long-term changes in Earth's orbit produce small changes in solar heating at any location on Earth. (A natural phenomenon.)

2. Plate tectonics (continental drift - - **very** long-term changes) (A natural phenomenon.)

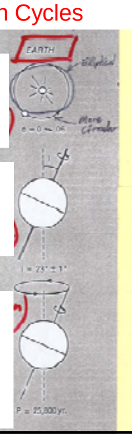
3. Changes in solar constant (the "solar constant" is not really a constant but a measure of energy output)? The total amount of solar energy (the solar constant) may change over long time periods or may vary periodically over shorter time periods. (A natural phenomenon.)
4. Periods of intense volcanism (ash and SO_2 in the atmosphere can reduce average temperature from the ash or increase the average temperature from the SO_2 – a greenhouse gas). (A natural phenomenon.)

5. CO_2 (and other greenhouse gases) increases and greenhouse effect. There has been a rapid increase in greenhouse gases in the past century due to burning of fossil fuels and other industrial processes. (Primarily a human-caused phenomenon.) http://en.wikipedia.org/wiki/Carbon_dioxide



Milankovitch Cycles

Milankovitch Cycles (astronomical effects on climate): Eccentricity (stretch in orbit), Obliquity (change in tilt angle), Precession (change of direction of axis [precession] and major axis of elliptical orbit)

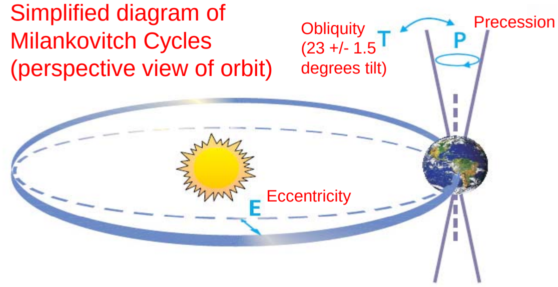


1. Eccentricity (stretch of orbit) Period ~ 100,000 yrs

2. Changes in obliquity (tilt of axis) Period ~ 41,000 yrs

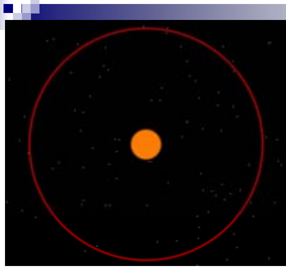
3. Precession (of axis direction and major axis of elliptical orbit) Periods ~ 26,000 and 23,000 yrs

Simplified diagram of Milankovitch Cycles (perspective view of orbit)

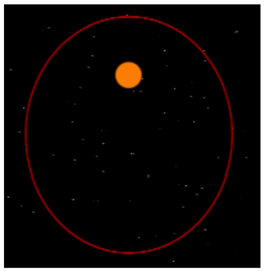


Milankovitch Cycles. *Schematic of the Earth's orbital changes (Milankovitch cycles) that drive the ice age cycles. 'T' denotes changes in the tilt (or obliquity) of the Earth's axis, 'E' denotes changes in the eccentricity of the orbit (due to variations in the minor axis of the ellipse), and 'P' denotes precession, that is, changes in the direction of the axis tilt at a given point of the orbit. Source: Rahmstorf and Schellnhuber (2006).*

http://www.global-greenhouse-warming.com/Milankovitch-cycles.html



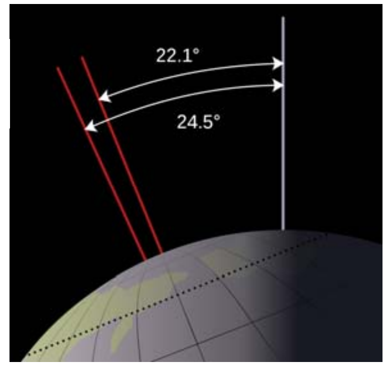
Circular orbit of a planet



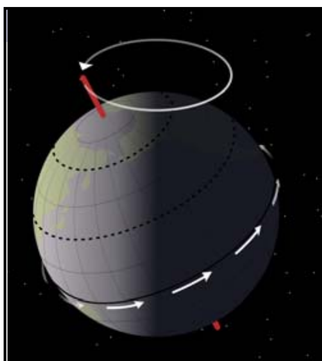
Elliptical orbit of a planet

http://www.globalwarmingart.com/wiki/Wikipedia:Milankovitch_cycles

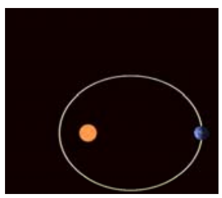
Obliquity (change in tilt angle)



http://www.globalwarmingart.com/wiki/Wikipedia:Milankovitch_cycles



Axial Precession



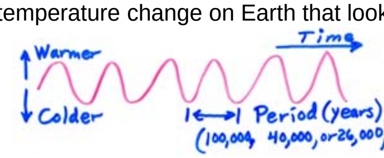
Precession of the major axis of the elliptical orbit (ellipticity exaggerated)

http://www.globalwarmingart.com/wiki/Wikipedia:Milankovitch_cycles

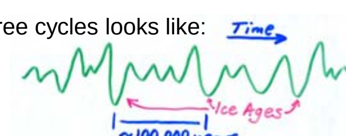
Time-lapse (about one hour) photograph from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation)

Time-lapse (several hours) photograph from Earth (northern hemisphere) showing position of Polaris ("the North star") and other stars that *appear* to circle Polaris (actually due to Earth's rotation)

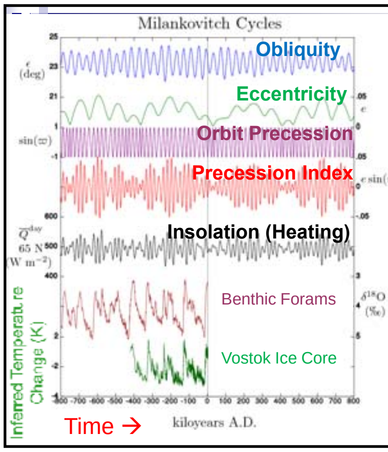
Each of the three Milankovitch (orbital) cycles predicts a temperature change on Earth that looks like:



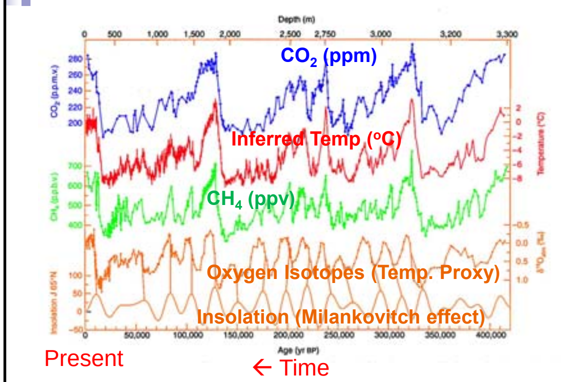
Sum of the three cycles looks like:



The cooling periods predicted by the Milankovitch cycles correlate well with times of ice ages.



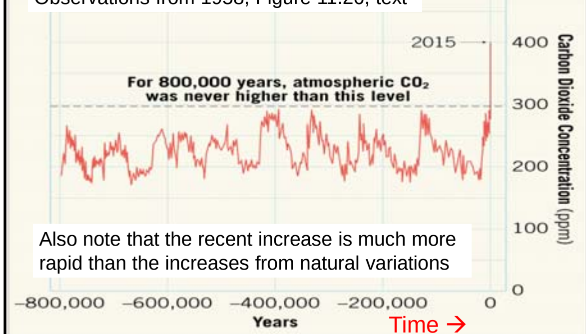
Past and future Milankovitch cycles. Prediction of past and future orbital parameters with great accuracy. **ε** is obliquity (axial tilt). ***e*** **is** eccentricity. **ϖ** is longitude of perihelion. ***e*****sin(ϖ)** is the **precession index**, which together with obliquity, controls the seasonal cycle of insolation. **Q** is the calculated daily-averaged insolation at the top of the atmosphere, on the day of the summer solstice at 65 N latitude. *Benthic forams* and *Vostok ice core* show two distinct proxies for past global sealevel and temperature, from ocean sediment and Antarctic ice respectively. Vertical gray line is current conditions, at 2 ky A.D.



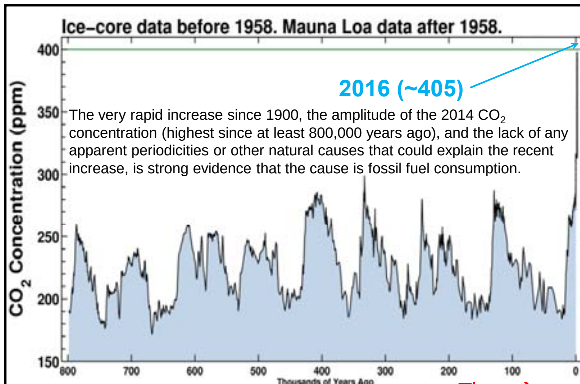
From ice core data (http://en.wikipedia.org/wiki/Global_warming)

Global CO_2 (ppm) – past 800,000 Years

Data from Ice Cores; Mauna Loa Observations from 1958, Figure 11.26, text



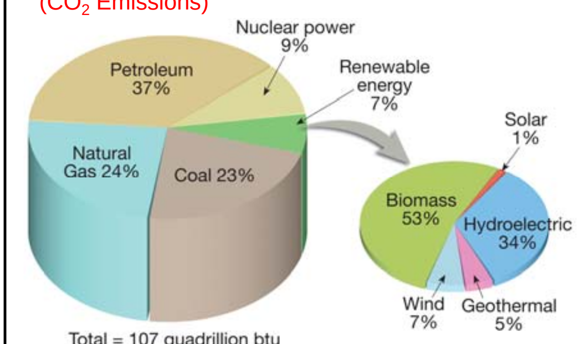
Also note that the recent increase is much more rapid than the increases from natural variations



The very rapid increase since 1900, the amplitude of the 2014 CO_2 concentration (highest since at least 800,000 years ago), and the lack of any apparent periodicities or other natural causes that could explain the recent increase, is strong evidence that the cause is fossil fuel consumption.

Last 800,000 years of CO_2 levels in the atmosphere (Scripps,http://keelingcurve.ucsd.edu/)

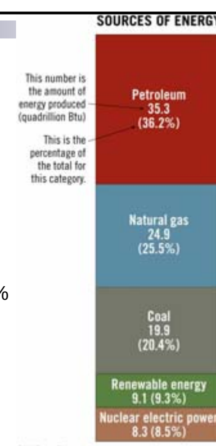
U.S. Energy Consumption – 2008, 84% Fossil Fuels (CO_2 Emissions)



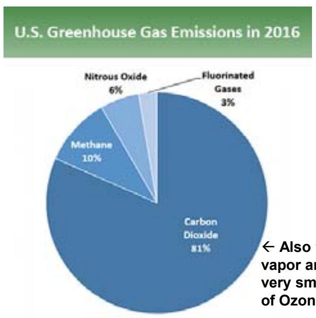
World Energy Consumption ~95% Fossil Fuels. Also see Figure 11.24, text

U.S. Energy Consumption, sources of energy – 2011, 83% (81% in 2014) Fossil Fuels

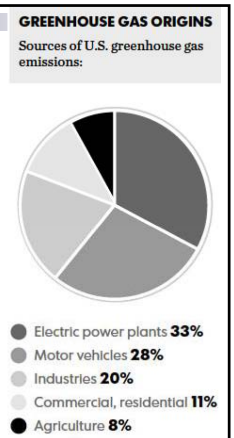
World Energy Consumption ~95% Fossil Fuels. Also see Figure 11.24, text



U.S. Greenhouse **gases** and **emissions** by source, 2013 (USAToday, February 20, 2014) →



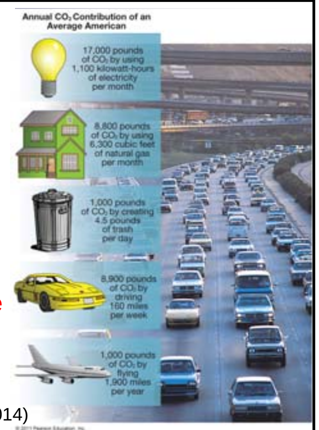
← **Also water vapor and very small % of Ozone**



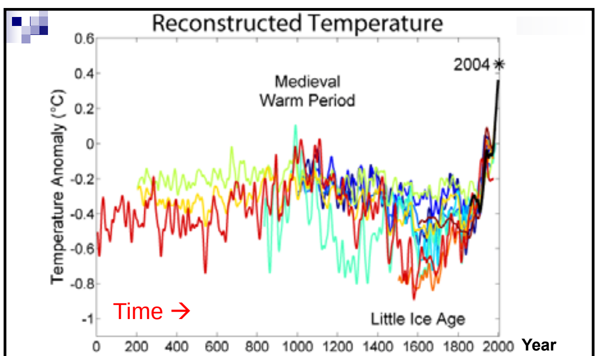
https://www.epa.gov/ghgemissions/overview-greenhouse-gases

U.S. CO_2 Production – mostly from burning of Fossil Fuels (CO_2 Emissions), U.S. contributes nearly 25% of the world's greenhouse gas emissions!

Important: See Worksheet (no class 11/20) and AtmsNotes.pdf material to understand the greenhouse effect (also acid rain, ozone)



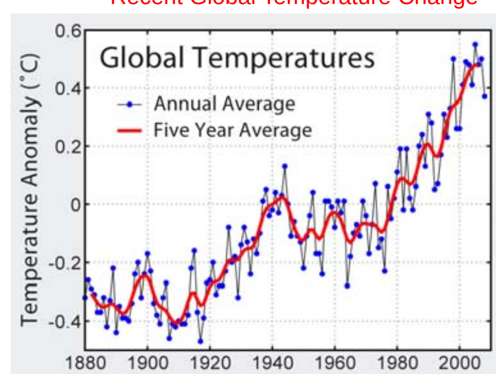
U.S. annual per capita CO_2 production (Figure 11.27, L&T, 2014)



Two millennia of mean surface temperatures according to different reconstructions, each smoothed on a decadal scale. The unsmoothed, annual value for 2004 is also plotted for reference.

http://en.wikipedia.org/wiki/Global_warming

Recent Global Temperature Change

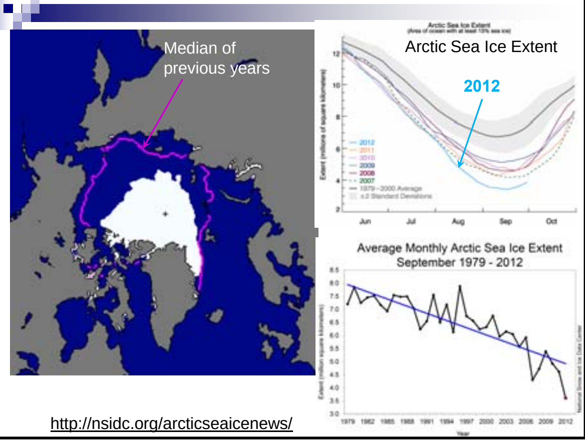


http://en.wikipedia.org/wiki/Global_warming

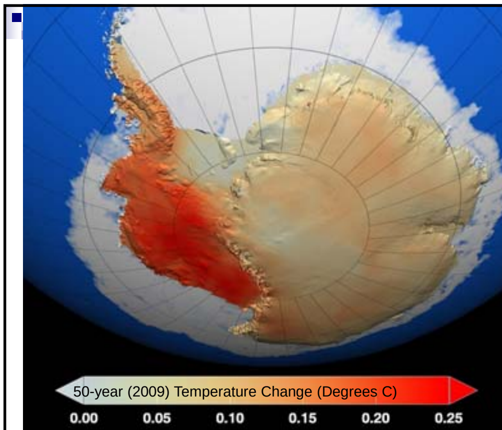
http://svs.gsfc.nasa.gov/Gallery/ArcticSeaIceResources.html

Also, a 2012 report shows that N. Hemisphere snow cover in June has decreased by about 18% per decade since 1979 (http://www.arctic.noaa.gov/report12/snow.html)

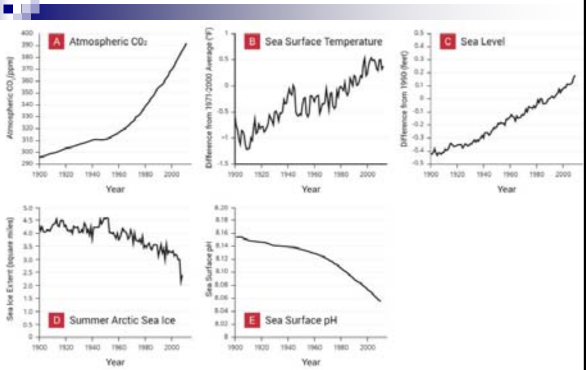
http://svs.gsfc.nasa.gov/Gallery/ArcticSeaIceResources.html



http://nsidc.org/arcticseaicenews/

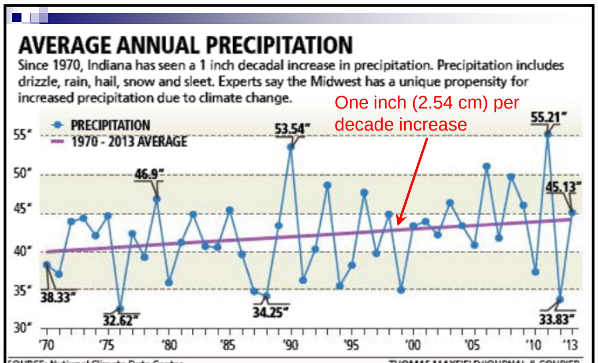


http://www.nasa.gov/topics/earth/features/warming_antarctica.html

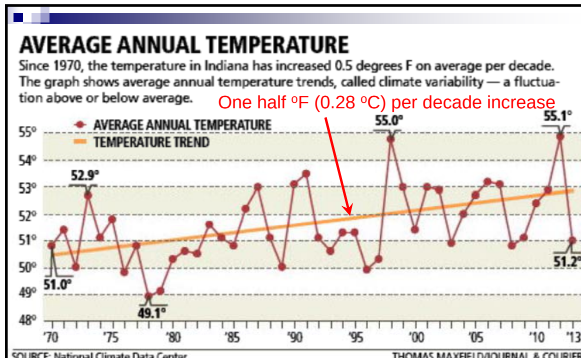


Ocean climate change indicators, 1900-2013
(http://nca2014.globalchange.gov/highlights/report-findings/oceans)

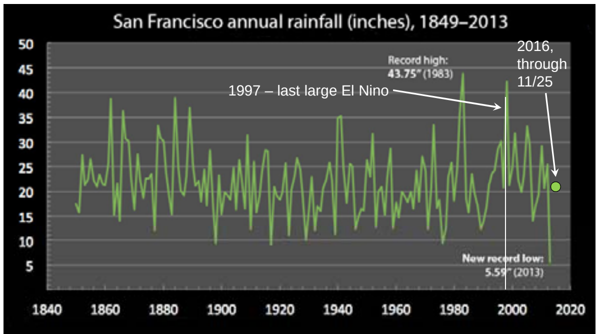
Climate video (example of Sahara desert [dry winds] in northern Africa and rain forest in central, equatorial Africa) illustrates global circulation pattern (Hadley cells).



Climate Change: The local view – Indiana Precipitation data, 1970 – 2013 (Lafayette Journal and Courier, September 28, 2014)

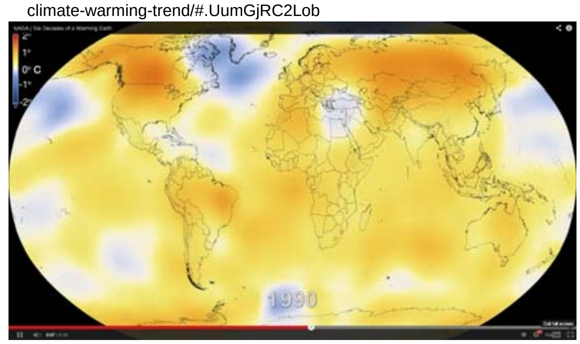


Climate Change: The local view – Indiana Temperature data, 1970 – 2013 (Lafayette Journal and Courier, September 28, 2014)



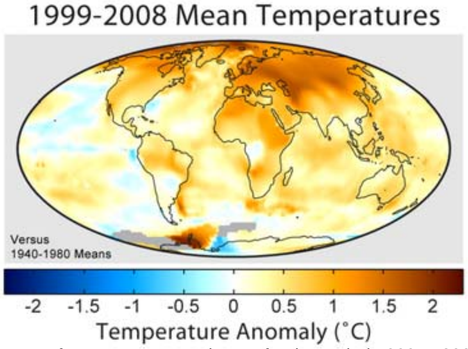
Climate Change: The local view – San Francisco, CA rainfall data. Note, no significant long term trend until at least the year 2000. Also, the drought (beginning in 2011-12) appears to be unusual, and may not last very long, if it is similar to previous low rainfall periods. (http://www2.ucar.edu/atmosnews/perspective/10879/california-dryin)

Climate Change Video from NASA - ***Six Decades of a Warming Earth***
http://www.nasa.gov/content/goddard/nasa-finds-2013-sustained-long-term-climate-warming-trend/#.UumGjRC2Lob

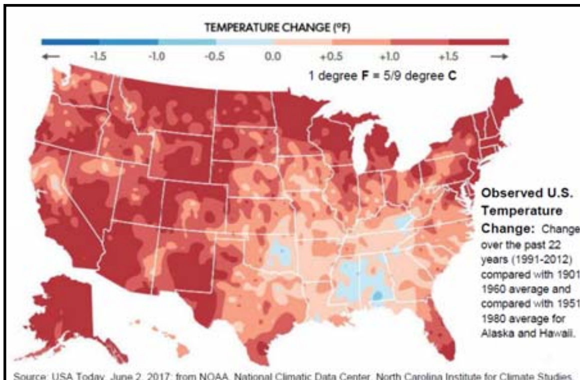


http://www.youtube.com/watch?v=gaJJtS_WDmI

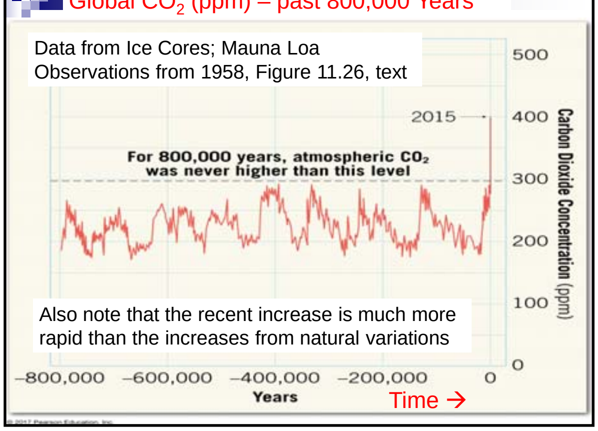
1999-2008 Mean Temperatures

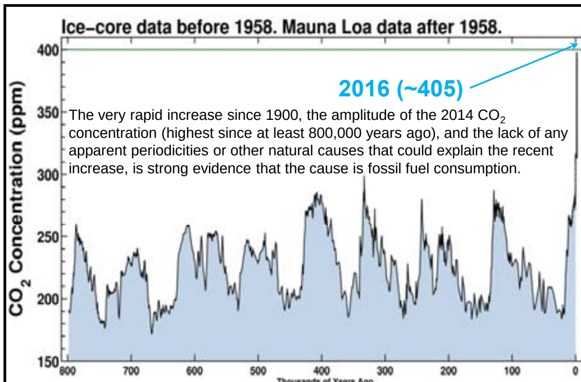


Mean surface temperature change for the period 1999 to 2008 relative to the average temperatures from 1940 to 1980
http://en.wikipedia.org/wiki/Global_warming



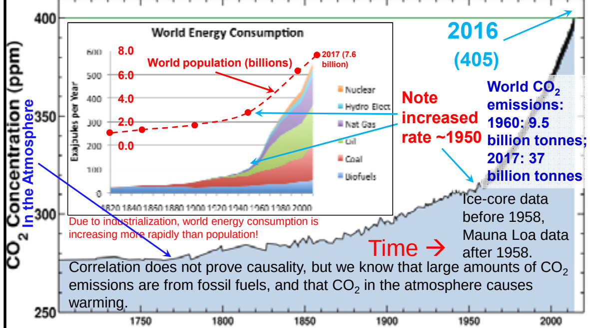
Global CO_2 (ppm) – past 800,000 Years





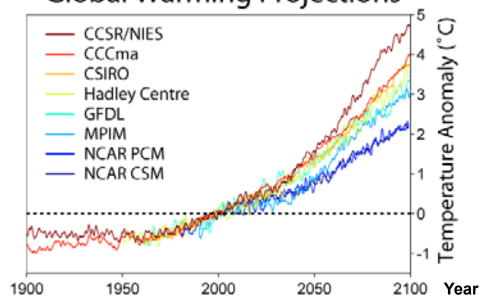
Last 800,000 years of CO_2 levels in the atmosphere (Scripps,http://keelingcurve.ucsd.edu/)

CO_2, Energy Consumption, and Population



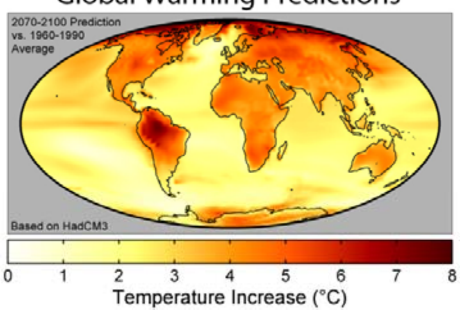
1700 to present - CO_2 levels in the atmosphere (Scripps, http://keelingcurve.ucsd.edu/) (World Energy: http://ourfiniteworld.com/2012/03/12/world-energy-consumption-since-1820-in-charts/). **Growth since 1950: CO_2 ~0.3x (30%); Population ~2.5x (250%); Energy consumption ~5.5x (550%).**

Global Warming Projections



Calculations of global warming prepared in or before 2001 from a range of climate models under the SRES A2 emissions scenario,. which assumes no action is taken to reduce emissions and regionally divided economic development
http://en.wikipedia.org/wiki/Global_warming

Global Warming Predictions



The geographic distribution of surface warming during the 21st century calculated by the HadCM3 climate model if a business as usual scenario is assumed for economic growth and greenhouse gas emissions. In this figure, the globally averaged warming corresponds to 3.0 °C (5.4 °F).
http://en.wikipedia.org/wiki/Global_warming

Human influences on the atmosphere

1. **Greenhouse Effect:**

1. Greenhouse gases: CO_2, methane, nitrous oxides, water vapor, ChloroFlouroCarbons (CFC)
   -- natural and human-caused
   -- CO_2 increased by 30% in last 100 years
2. Greenhouse gases are primarily from industrialization
   (1/3 vehicles, 1/3 electricity generation)

Greenhouse Effect (cont.)

3. Greenhouse warming process: Greenhouse gases in air allow solar radiation to pass through atmosphere to heat surface of the Earth. Infrared heat (longer wavelengths radiated by Earth's surface) is absorbed and reflected by greenhouse gases in the atmosphere causing warming.
4. Effects:
   -- Global warming
   -- Sea level rise
      ≈ 0.3 – 0.5 m/100 years
   -- Possible droughts, increased deserts, etc.

Electromagnetic [EM] Spectrum/Energy/Radiation

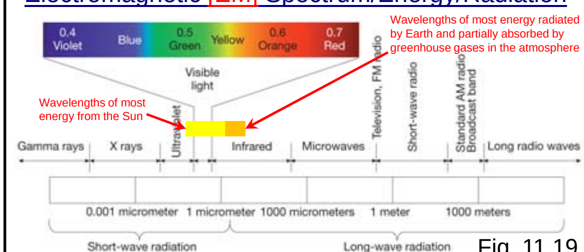
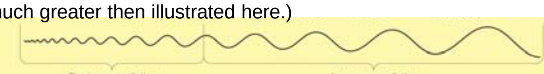


Fig. 11.19 Text

Schematic illustration of wavelengths of EM energy (change in wavelength from short to long is much, much greater then illustrated here.)



Greenhouse Effect (cont.)

5. "Complications:"
   - -- How much CO_2 storage in oceans?
   - -- Human vs. natural causes?
   - -- Political -- industrialized vs. developing countries
   - -- Deforestation compounds the problem by removing CO_2 -consuming and O_2-producing plants, and adding CO_2 to atmosphere by burning.

See pages 371-381 in Text.

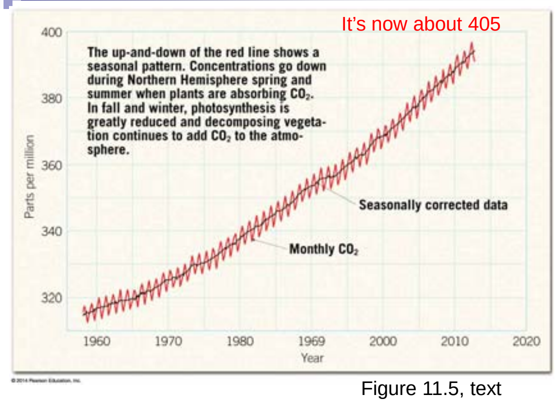
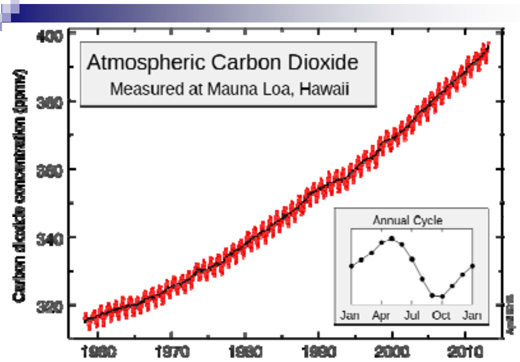
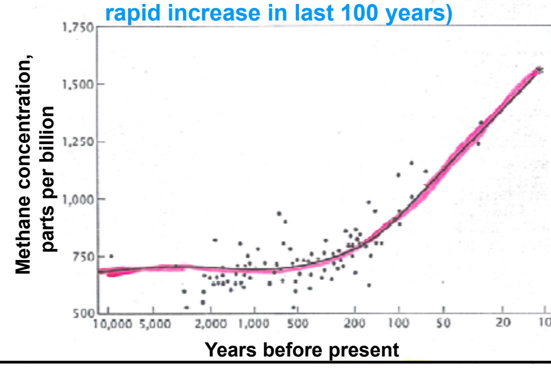


Figure 11.5, text



Recent atmospheric carbon dioxide (CO_2) increases. Monthly CO_2 measurements display seasonal oscillations in overall yearly uptrend; each year's maximum occurs during the Northern Hemisphere's late spring, and declines during its growing season as plants remove some atmospheric CO_2. http://en.wikipedia.org/wiki/Global_warming

Growth in Atmospheric Methane (data from Greenland ice cores, note logarithmic time scale and rapid increase in last 100 years)



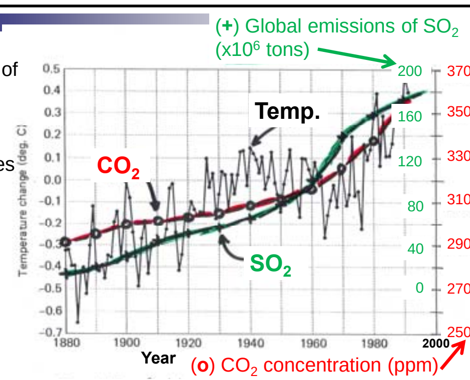
So, CO_2 in Atmosphere is "good" – Earth's atmosphere would be ~ 30°C colder without the greenhouse effect!

But, CO_2 is increasing in atmosphere (global warming); Current CO_2 emissions:

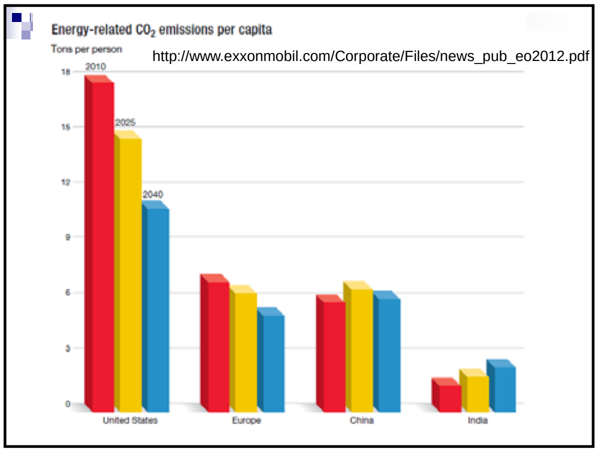
US 5 tons/year/person

World < 1 ton/year/person

Correlation of emissions and global average temperatures



Correlation of global average temperature, industrial SO_2 emissions and CO_2 concentration in the atmosphere, 1880-2000.



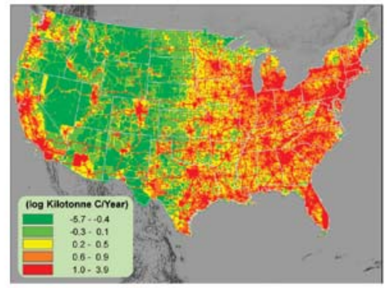
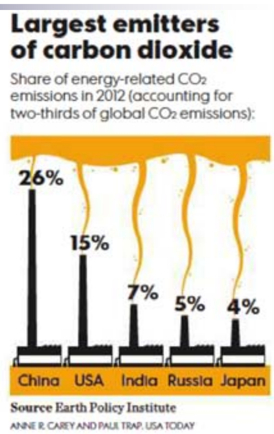


FIGURE 2. Total contiguous U.S. fossil fuel CO_2 emissions for the year 2002 represented on a 10 km × 10 km grid (units: $\log_{10}$ GgC 100 km^{-2} $year^{-1}$).

http://vulcan.project.asu.edu/pdf/Gurney.EST.2009.pdf

2012 CO_2 emissions



USA Today, August 20, 2013

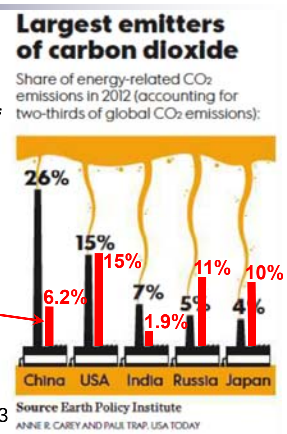
2012 CO_2 emissions, re-visited…

Population (millions, and % of world population):

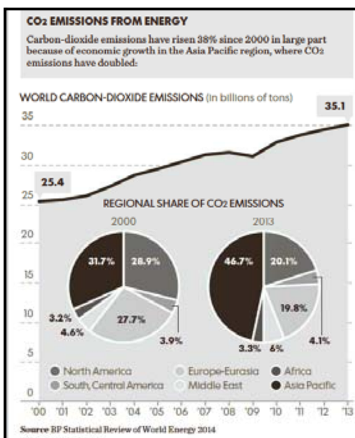
China	1360	19%
USA	316	4.5%
India	1210	17%
Russia	143	2.0%
Japan	128	1.8%

Normalized by Population

http://en.wikipedia.org/wiki/World_population



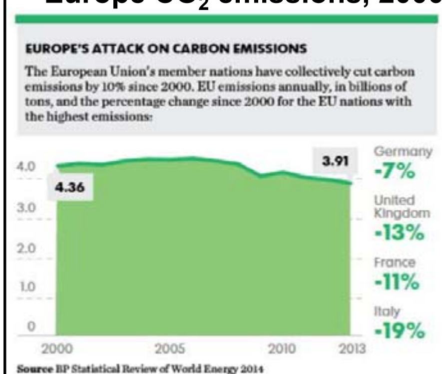
USA Today, August 20, 2013



World CO_2 emissions from Energy

USA Today, September 22, 2014

Europe CO_2 emissions, 2000 to 2013



USA Today, September 23, 2014

November, 2009 Icebergs near South Island of New Zealand (some >200 m long) that broke off (total of >30 km² area of ice sheet) on the Antarctic ice sheet due to warming

http://svs.gsfc.nasa.gov/Gallery/ArcticSeaIceResources.html

Also, a 2012 report shows that N. Hemisphere snow cover in June has decreased by about 18% per decade since 1979 (http://www.arctic.noaa.gov/report12/snow.html)

http://svs.gsfc.nasa.gov/Gallery/ArcticSeaIceResources.html

Human influences on the atmosphere

2. Ozone “Layer”:

1. Ozone = O_3

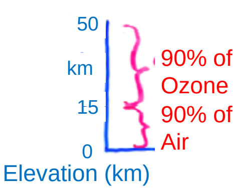
 -- Only 3 ppm in atmosphere

 -- Most Ozone is in stratosphere (10-50 km above Earth)

 -- CFCs in upper atmosphere rapidly destroys Ozone

See pages 357-360 in Text.

Two Chlorine reactions (“**chain reactions**”) which take place in the upper atmosphere (stratosphere, ~ 10-50 km elevation):



$Cl + O_3 \rightarrow ClO + O_2$ (1)

$ClO + O_3 \rightarrow Cl + 2\,O_2$ (2)

(ClO reacts with another ozone)

Because Cl is very reactive, these conversions are rapid (1 s to 1 min)

Note that after the second reaction, O_3 is gone and Cl is still present (and can react with and destroy another O_3 molecule – chain reaction!).

The result of this chain reaction is:

1. $2\,O_3 \rightarrow O_2 + 2\,O_2$ [loss of Ozone]
2. $Cl \rightarrow Cl$ [Chlorine remains, perpetuating the chain reaction]

Ozone "Layer" (cont.)

2. Effects:

- -- Ozone is highly corrosive; damages crops, contributes to smog, and is a health hazard (lung damage) in the lower atmosphere
- -- In the upper atmosphere (stratosphere) , Ozone blocks harmful UV radiation

So, Ozone in the upper atmosphere is "Good" (but is being depleted by CFCs);

Ozone in the lower atmosphere is "Bad" (pollution).

Ozone Hole

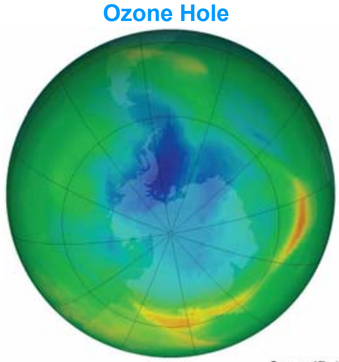


Figure 11.17, text

Ozone Hole

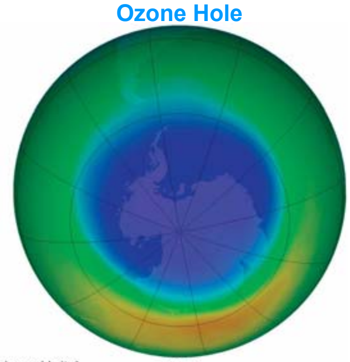


Figure 11.17, text

Ozone Hole

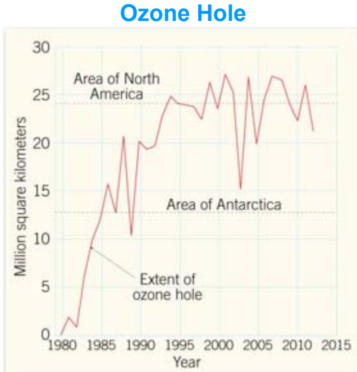


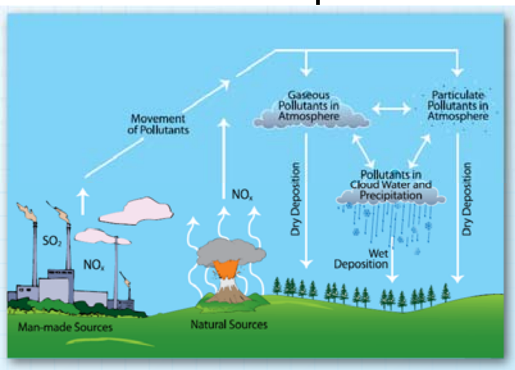
Figure 11.17, text

Human influences on the atmosphere

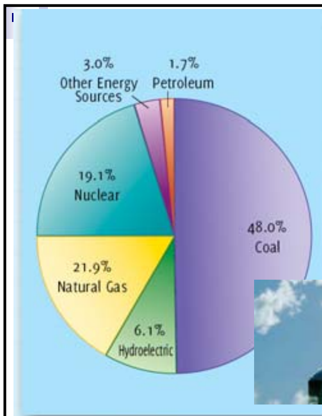
3. Acid Rain

- SO_2, NOx $\Rightarrow$ sulfuric and nitric acids in atmosphere and in precipitation
- Produced by burning fossil fuels
- Destroys
  - wildlife in lakes
  - forests
  - building stone, concrete

Illustration of acid rain processes



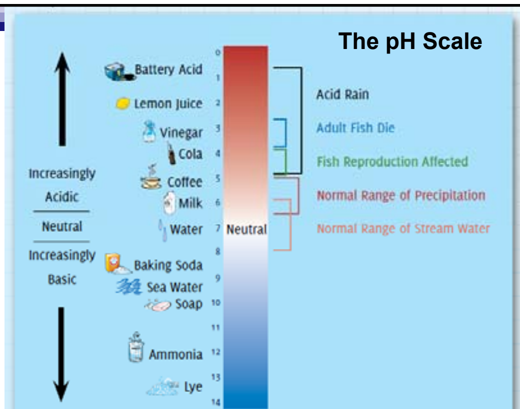
http://www.epa.gov/acidrain/education/teachersguide.pdf



U.S. Electricity generation – In Indiana, 90% of electricity is generated by coal-burning power plants

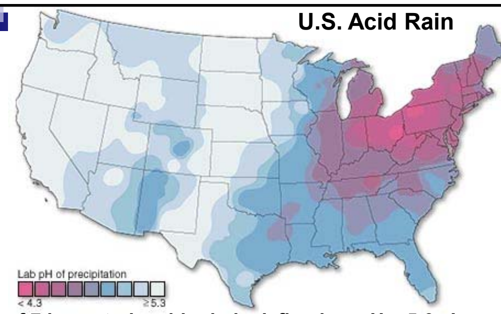
http://www.epa.gov/acidrain/education/teachersguide.pdf

The pH Scale

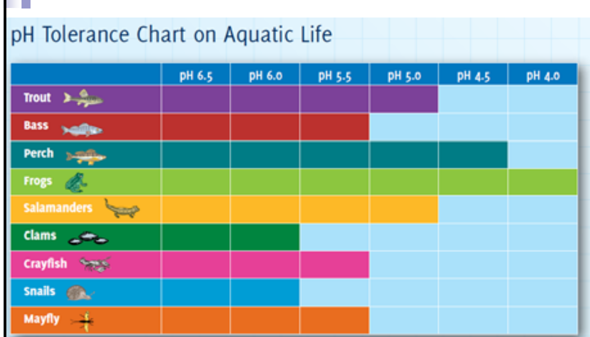


http://www.epa.gov/acidrain/education/teachersguide.pdf

U.S. Acid Rain



pH of 7 is neutral; acid rain is defined as pH < 5.6. Increase of acid rain to the east is caused by west to east trade winds (relatively clean air from the Pacific) and large number of sources (power plants, vehicle emissions)) in the midwest and east. (http://www.mhhe.com/biosci/esp/2001_es/folder_structure/ph/m2/s2/index.htm)



http://www.epa.gov/acidrain/education/teachersguide.pdf

Acid rain damage to buildings and monuments

The picture on the left was taken in 1908. The picture on the right was taken in 1968.

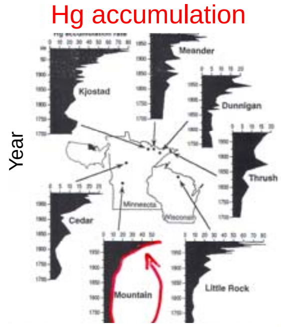
http://www.epa.gov/acidrain/education/teachersguide.pdf

Human influences on the atmosphere

4. Other pollutants (example, Mercury in the environment)

Hg accumulation

Mercury comes from batteries placed in landfills and from burning of coal. Graphs show accumulation of Hg in MN and WI lake sediments with time from 1700 to 1980.



Note ~ exponential increase

Hurricanes:

1. Form in Tropical marine areas (≈ 5 - 20° latitude; not right at the equator because of small Coriolis Effect)

2. Energy for storm (Energy for one day of a hurricane ≈ Electricity produced in US in one year)
   - Solar radiation -- Heated air rises forming low pressure region, also provides moisture in atmosphere by evaporation from ocean

(Note: some Hurricane examples and discussion were presented in class earlier in the semester and are included in the IntroNotes.pdf and EarthNotes.pdf files)

Hurricanes (cont.)

- Exchange of heat from warm (≥ 28°C) ocean to atmosphere; therefore, storms form in late summer in oceanic areas

- Latent heat of condensation further drives storm by heating air when moisture in air condenses to form rain (heating 1 cm^3 = 1 g of water to evaporation takes 1 calorie [adding energy to the water to make it water vapor], so when the water vapor condenses [precipitation], it releases this energy).

Hurricanes (cont.)

3. Circulation
   - Hurricanes move according to the trade winds (≈ 10 – 50 km/hr)
   - Circulation in hurricane is around low pressure (counter-clockwise in N. Hemisphere); higher velocity near center because of conservation of angular momentum (like spinning figure skater)

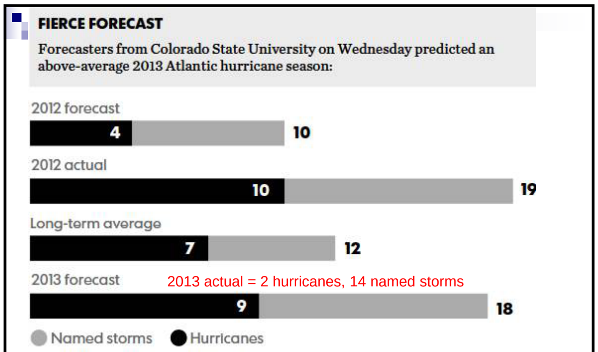
Hurricanes (cont.)

4. Damage from hurricane
   - High winds (> 122 km/hr [75 mph])
   - Torrential rains (up to 25 cm in a few hours)
   - Salt water flooding of fresh water region

Table 14.3 Saffir-Simpson Hurricane Scale

Scale Number (category)	Central Pressure (millibars)	Winds (km/hr)	Storm Surge (meters)	Damage
1	≥980	119–153	1.2–1.5	Minimal
2	965–979	154–177	1.6–2.4	Moderate
3	945–964	178–209	2.5–3.6	Extensive
4	920–944	210–250	3.7–5.4	Extreme
5	<920	>250	>5.4	Catastrophic

Table 14.2 L&T, 2017



Source Colorado State University
DOYLE RICE AND JULIE SNIDER, USA TODAY

CSU Atlantic Hurricanes forecasts for 2012 and 2013 seasons (USA Today, April 11, 2013)

Name	Dates active	Storm category at peak intensity	Max 1-min wind mph (km/h)	Min.press. (mbar)
Arlene	April 19 – 21	Tropical storm	50 (85)	990
Bret	June 19 – 20	Tropical storm	45 (75)	1007
Cindy	June 20 – 23	Tropical storm	60 (95)	992
Four	July 6 – 7	Tropical depression	30 (45)	1008
Don	July 17 – 19	Tropical storm	50 (85)	1007
Emily	July 31 – August 2	Tropical storm	45 (75)	1005
Franklin	August 7 – 10	Cat. 1 hurricane	85 (140)	981
Gert	August 13 – 17	Cat. 2 hurricane	105 (165)	967
Harvey	Aug. 17 – Sept. 1	Cat. 4 hurricane	130 (215)	938
Irma	Aug. 30 – Present	Cat. 5 hurricane	185 (295)	914
Jose	Sept. 5 – Present	Cat. 4 hurricane	155 (250)	938
Katia	Sept. 5 – Present	Cat. 2 hurricane	105 (165)	972
Maria	Sept. 16 – 20	Cat. 5 hurricane	175 (280)	908

Also (after Maria): Nate (H), Ophelia (H), Philippe (TS), Rina (TS)
2017 Atlantic hurricane season (June 1-November 30)
(https://en.wikipedia.org/wiki/2017_Atlantic_hurricane_season)

Atlantic 2017 Tropical Storms History

	Named Storms	Hurricanes	Major Hurr. (Cat. 3+)
Average (1981–2010)	12.1	6.4	2.7
Record high activity	28	15	7
Record low activity	4	2	0
Actual	17	10	6

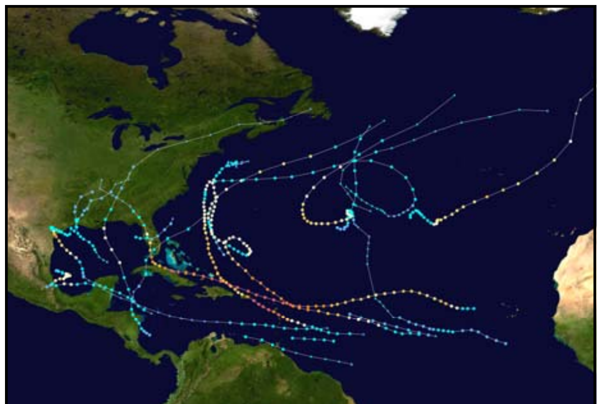
Atlantic Tropical Storm Season Forecasts 2017

Source*	Named Storms	Hurricanes	Major Hurr. (Cat. 3+)
TSR	11	4	2
CSU	11	4	2
TWC	12	6	2
NOAA	(11-17) 14	(5-9) 7	(2-4) 3

Predicted

* April, 2017 except for NOAA, May, 2017
** TSR – Tropical Storm Risk, U. College, London; CSU – Colorado State University; TWC – The Weather Channel; NOAA – U.S. National Oceanic and Atmospheric Administration
Note accurate predictions (compare predicted and actual) are challenging!

https://en.wikipedia.org/wiki/2017_Atlantic_hurricane_season



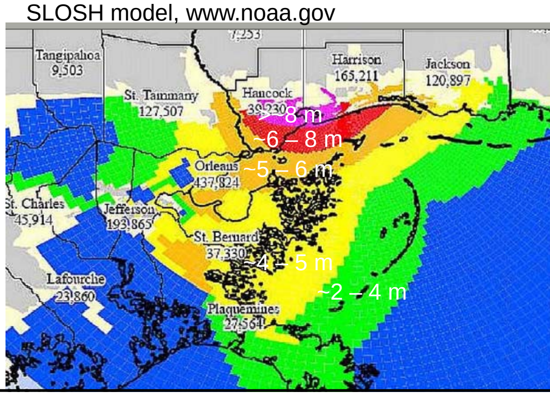
https://upload.wikimedia.org/wikipedia/commons/c/c6/2017_Atlantic_hurricane_season_summary_map.png 2017 Atlantic Hurricanes

https://weather.com/storms/hurricane/news/2016-hurricane-season-forecast-noaa-the-weather-company-csu Aug. 31, 2016

Hurricanes (cont.)

- Storm surge (up to 7 m of local, temporary sea level rise; most significant cause of damage and loss of life)
  - -- Low pressure (as low as 900mb produces 1 m of surge)
  - -- Storm buildup (especially for “bay-like” coastlines, “focusing”)
  - -- Wave action
  - -- High tides can compound the storm surge

Calculated storm surge, Katrina, 29 August, 2005, SLOSH model, www.noaa.gov



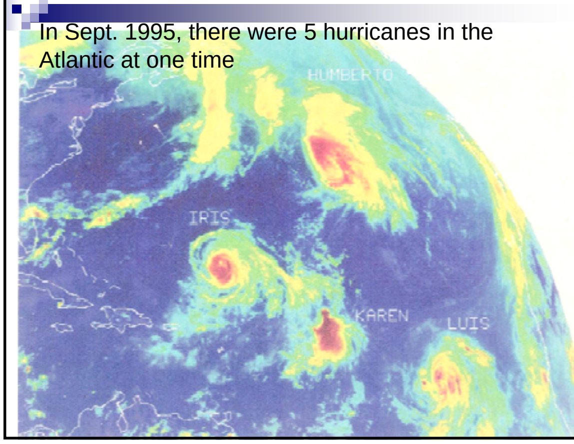
Storm surge

Hurricanes (cont.)

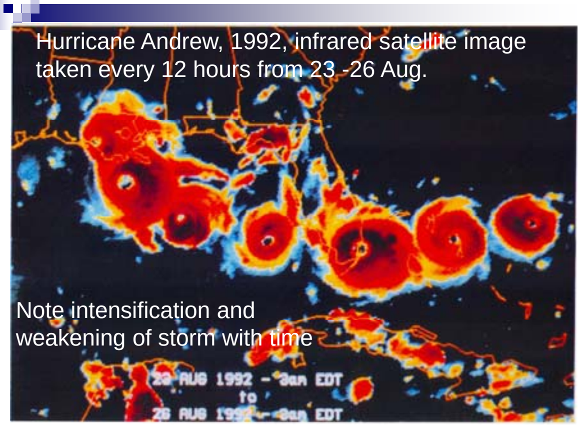
5. Names for Hurricanes ("just for interest"):

- Atlantic Ocean: Hurricanes
- W. Pacific Ocean: Typhoons
- Indian Ocean: Cyclones
- Australia: Willy-Willys

In Sept. 1995, there were 5 hurricanes in the Atlantic at one time

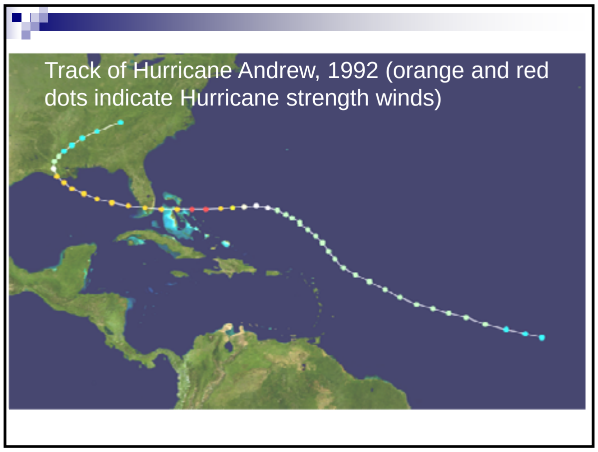


Hurricane Andrew, 1992, infrared satellite image taken every 12 hours from 23 -26 Aug.

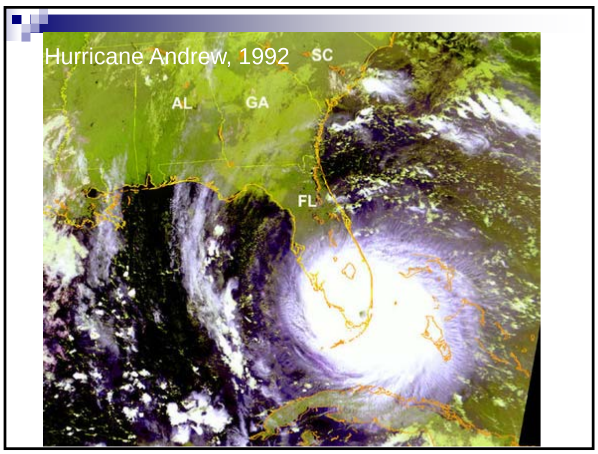


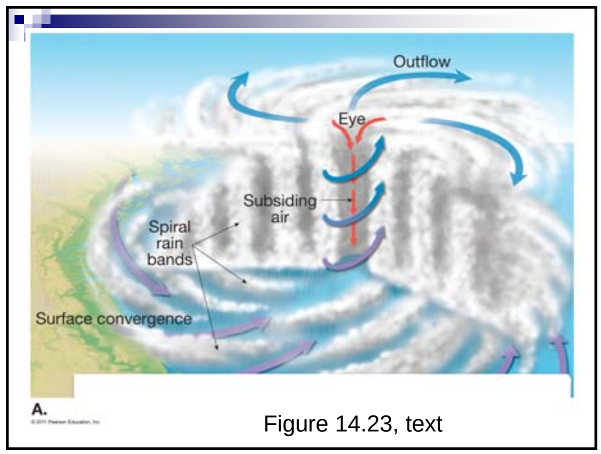
Note intensification and weakening of storm with time

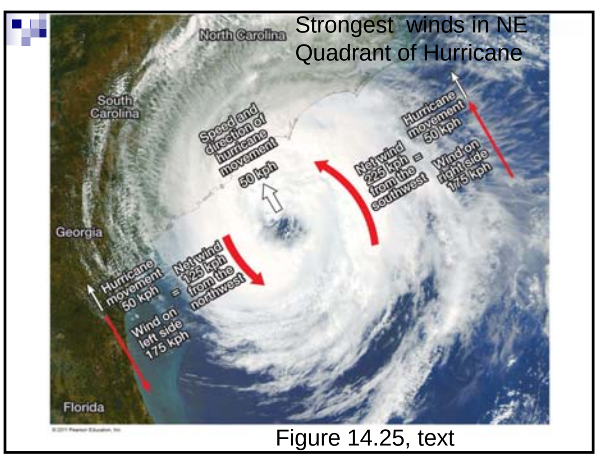
Hurricane Andrew, 1992 in Gulf of Mexico


Track of Hurricane Andrew, 1992 (orange and red dots indicate Hurricane strength winds)


Hurricane Andrew, 1992
FLORIDA
Hurricane Andrew
NOAA-12 AVHRR HRPT
Multi-spectral False Color Image
August 23, 1992 @ 12:31 UTC


Hurricane Andrew, 1992
SC
AL
GA
FL


Outflow
Eye
Subsiding air
Spiral rain bands
Surface convergence
A.
Figure 14.23, text


Strongest winds in NE Quadrant of Hurricane
North Carolina
South Carolina
Georgia
Florida
Speed and direction of hurricane movement 50 kph
Net wind 225 kph = from the southwest
Hurricane movement 50 kph
Wind on right side 175 kph
Net wind 125 kph = from the northwest
Hurricane movement 50 kph
Wind on left side 175 kph
Figure 14.25, text


Hurricane Andrew, 1992

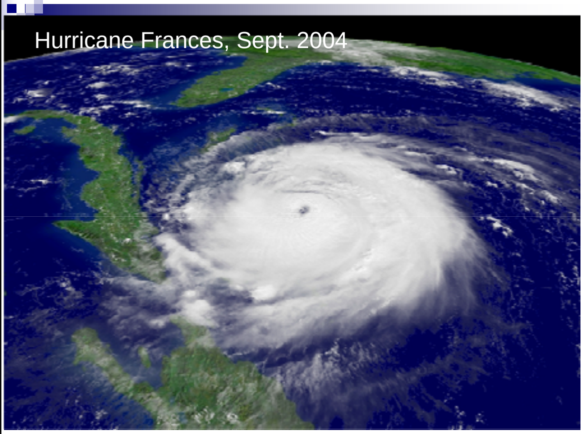
Hurricane Andrew, 1992

Hurricane Andrew, 1992

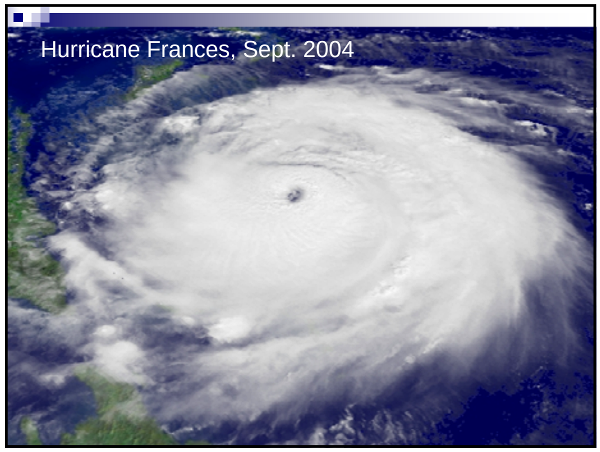
Hurricane Camille, 1969, Richelieu Apartments, Pass Christian, Mississippi

Hurricane Camille, 1969

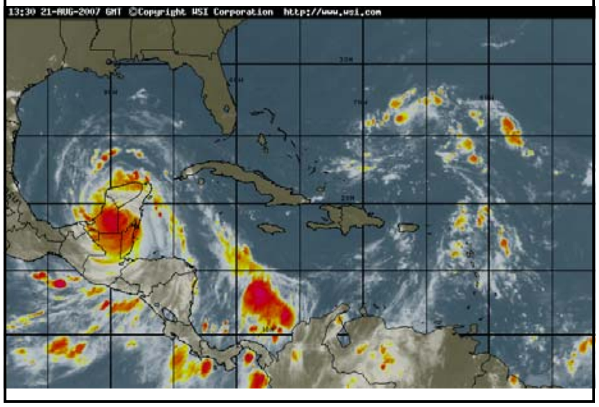
Hurricane Frances, Sept. 2004



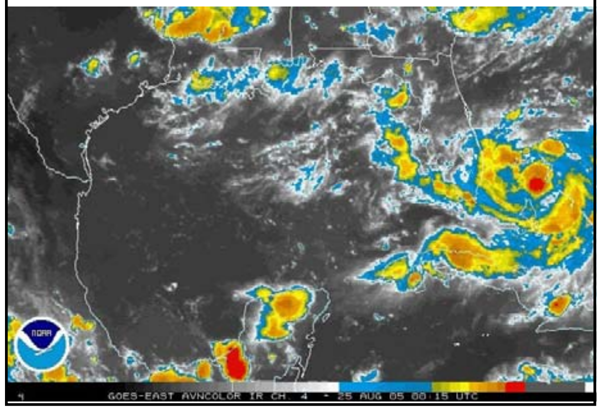
Hurricane Frances, Sept. 2004



Hurricane Dean, Aug. 2, 2007



Hurricane Katrina, Aug. 25-30, 2005

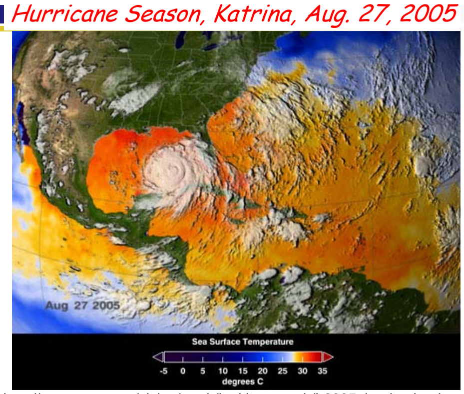


Hurricane Season – June 8 to August 29, 2005:

6/8-6/13 TS Arlene
7/3-7/7 Hurr. Cindy
7/7-7/10 Hurr. Dennis
7/14-7/20 Hurr. Emily
7/21-7/29 TS Franklin
8/3-8/8 TS Harvey
8/7-8/18 Hurr. Irene
8/25-8/30 Hurr. Katrina
…
…
9/18-9/24 Hurr. Rita
…
Total of 21 storms in 2005

http://www.nasa.gov/vision/earth/lookingatearth/h2005_katrina.html
http://svs.gsfc.nasa.gov/vis/a000000/a003200/a003279/index.html

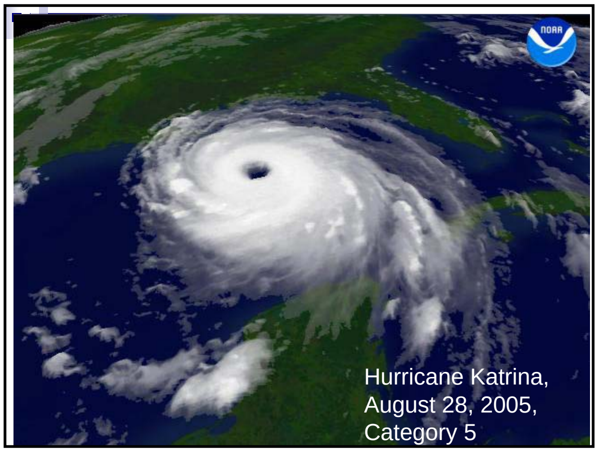
Hurricane Season, Katrina, Aug. 27, 2005

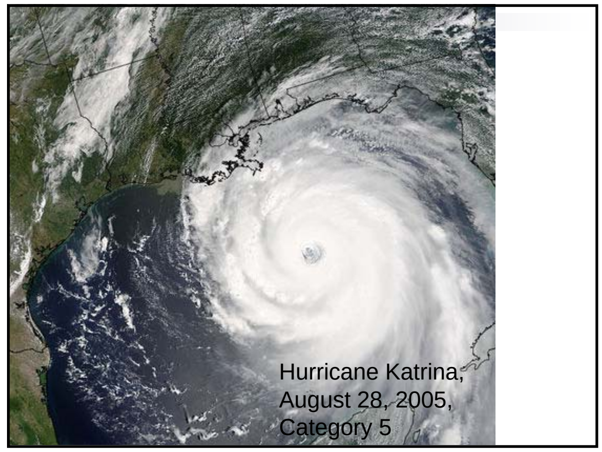


http://www.nasa.gov/vision/earth/lookingatearth/h2005_katrina.html

Hurricane Katrina, Aug. 28-29, 2005

Hurricane Katrina, 2005

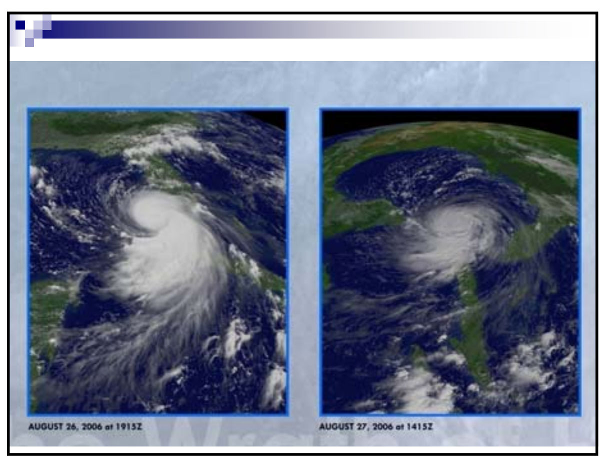

Hurricane Katrina,
August 28, 2005,
Category 5

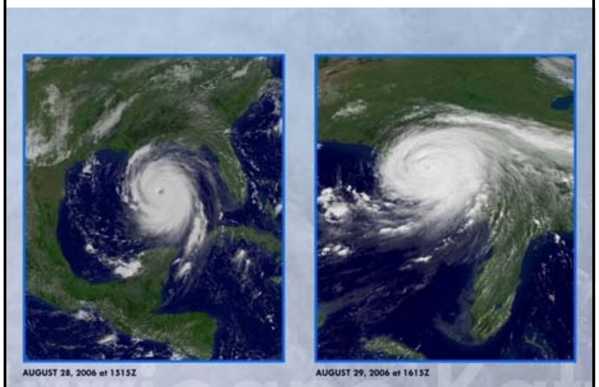

Hurricane Katrina,
August 28, 2005,
Category 5


Hurricane Katrina, 2005

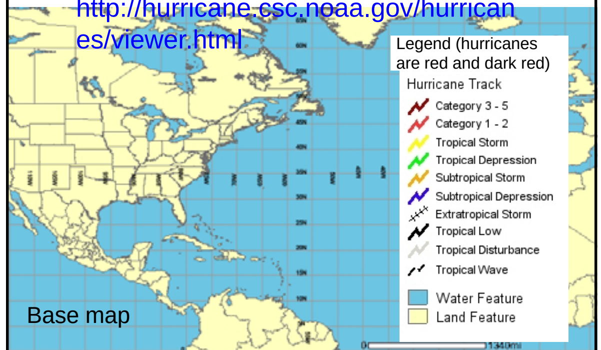

Hurricane Katrina, 2005


The Wrath of Hurricane Katrina.

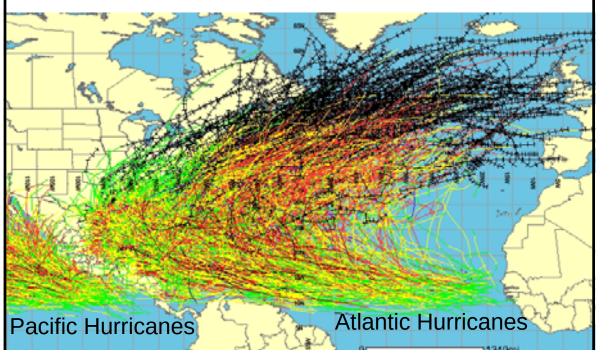

AUGUST 26, 2006 at 1915Z
AUGUST 27, 2006 at 1415Z



Hurricane Track Site: http://hurricane.csc.noaa.gov/hurricanes/viewer.html

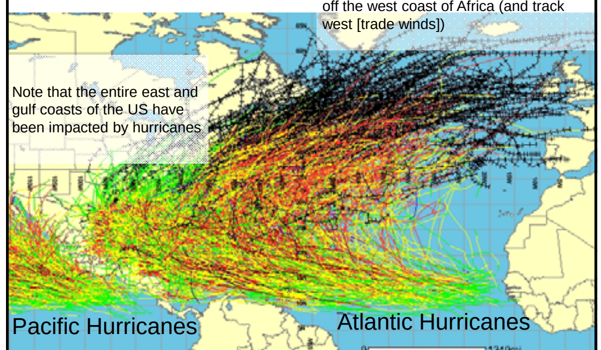


150 Years of Hurricanes

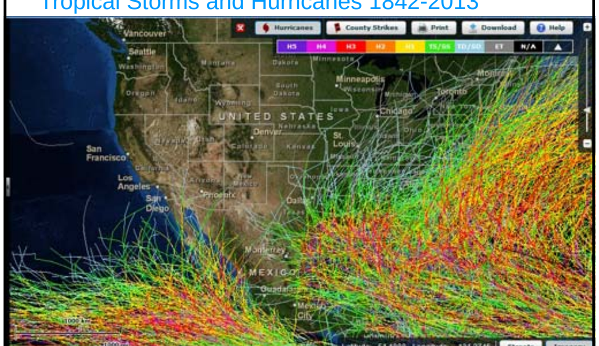


150 Years of Hurricanes

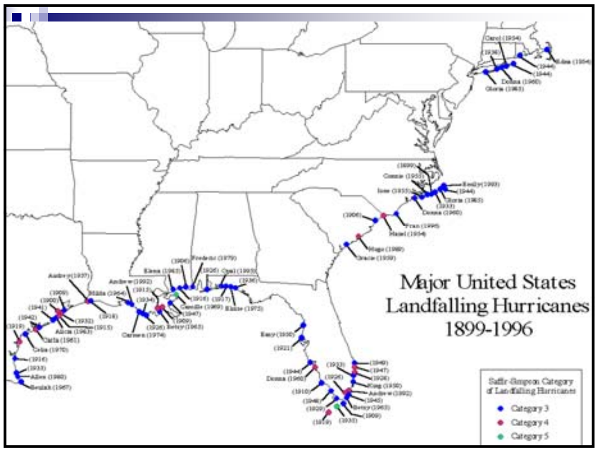
Note that many Atlantic hurricanes form off the west coast of Africa (and track west [trade winds])



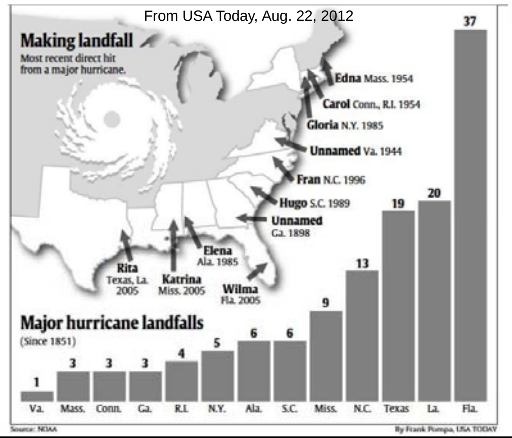
Tropical Storms and Hurricanes 1842-2013



Tropical Storms and Hurricanes 1842-2013

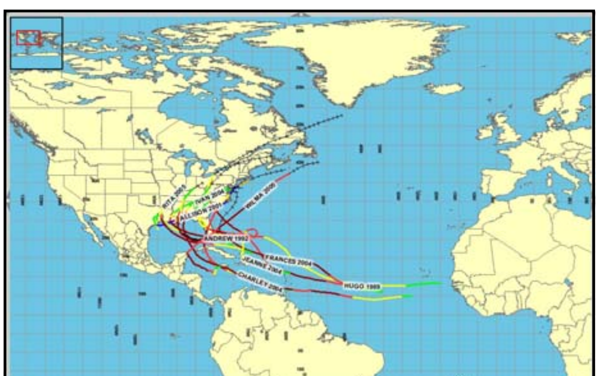


From USA Today, Aug. 22, 2012

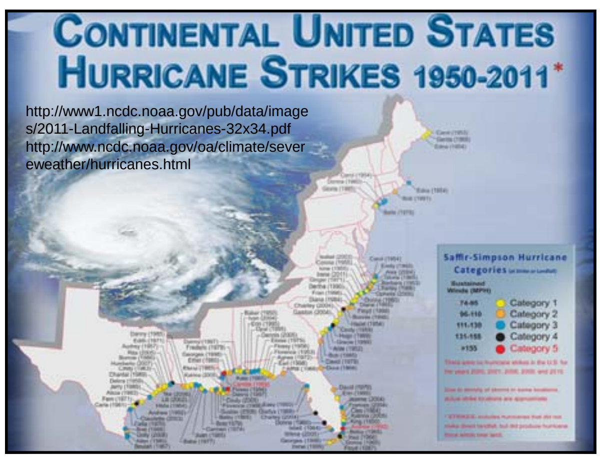


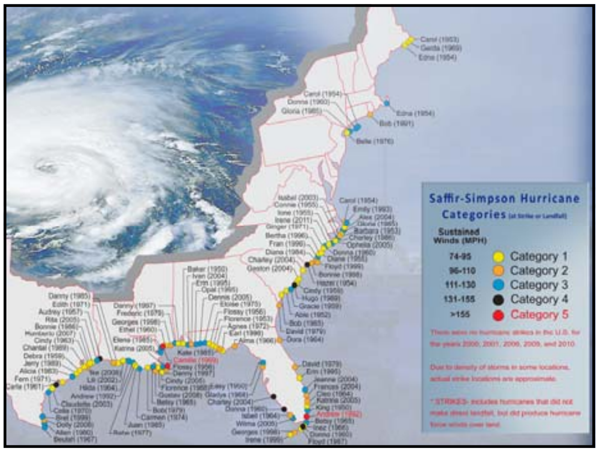
Most intense landfalling U.S. hurricanes Intensity is measured solely by central pressure			
Rank	**Hurricane**	**Year**	**Landfall pressure**
1	"Labor Day"	1935	892 mbar (hPa)
2	Camille	1969	909 mbar (hPa)
3	Katrina	2005	918 mbar (hPa)
4	**Andrew**	1992	922 mbar (hPa)
5	Indianola	1886	925 mbar (hPa)
6	"Florida Keys"	1919	927 mbar (hPa)
7	"Okeechobee"	1928	929 mbar (hPa)
8	Donna	1960	930 mbar (hPa)
9	"New Orleans"	1915	931 mbar (hPa)
10	Carla	1961	931 mbar (hPa)
Source: U.S. National Hurricane Center			

Costliest U.S. Atlantic hurricanes Cost refers to total estimated property damage.			
Rank	**Hurricane**	**Year**	**Cost (2004 USD)**
1	Katrina	2005	$80 billion (2005 USD)
2	**Andrew**	1992	$43.672 billion
3	Charley	2004	$15 billion
4	Wilma	2005	$14.4 billion (2005 USD)
5	Ivan	2004	$14.2 billion
Main article: List of costliest U.S. Atlantic hurricanes			

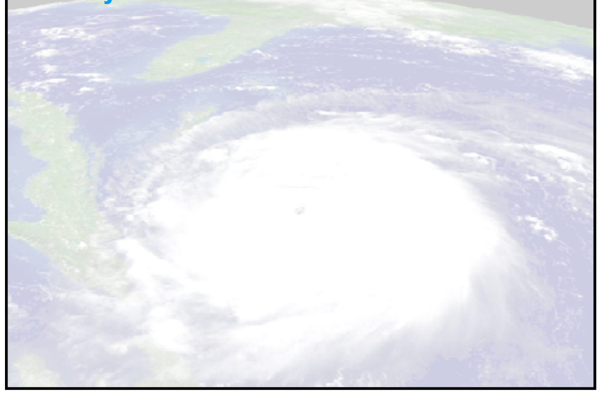


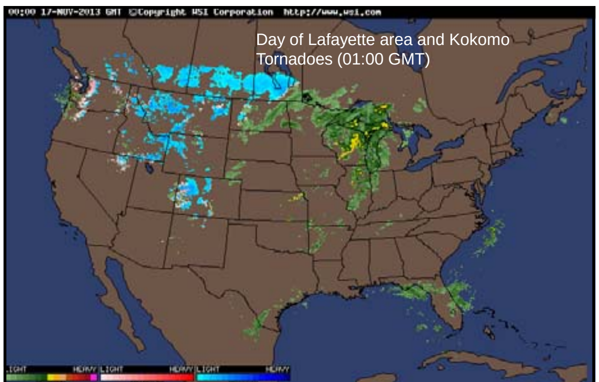
Costliest Atlantic Hurricanes, 1851-2007 (Katrina, 2005, not shown) http://csc-s-maps-q.csc.noaa.gov/hurricanes/



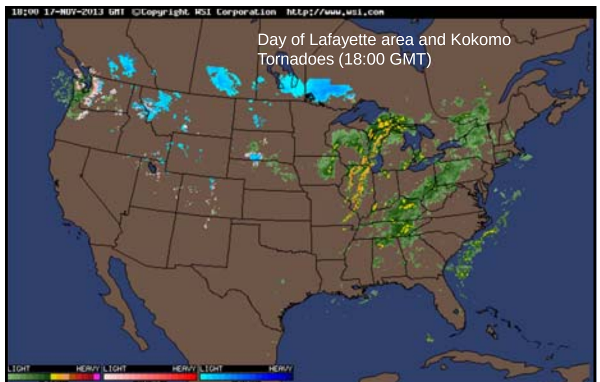


Today: Tornadoes

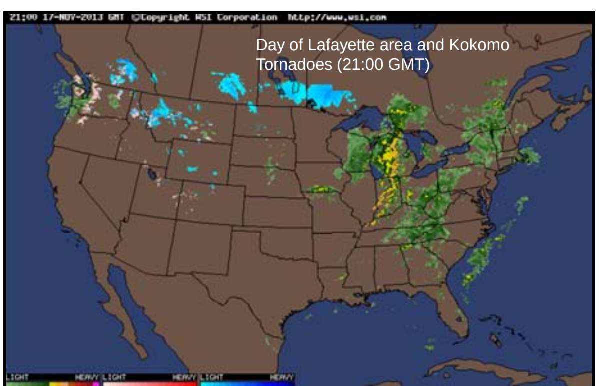




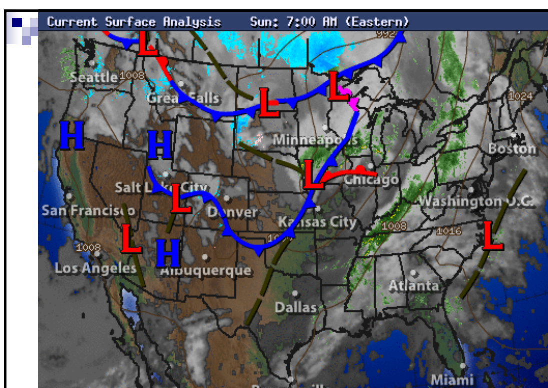
24-hr Radar Loop 00:00 – 23:00 GMT Nov. 17, 2013



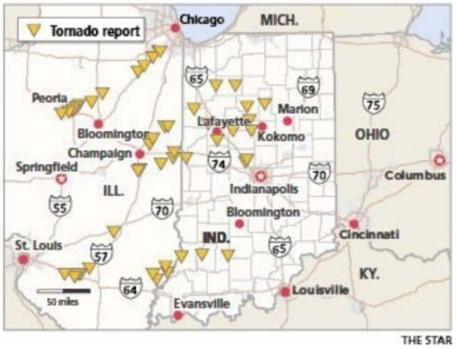
24-hr Radar Loop 00:00 – 23:00 GMT Nov. 17, 2013



24-hr Radar Loop 00:00 – 23:00 GMT Nov. 17, 2013



Surface Conditions – Nov. 17-18, 2013



Illinois and Indiana tornadoes, Nov. 17, 2013 (J&C, 11/18/2013)

Tornado Damage, Washington, IL, Nov. 17, 2013 (news.yahoo.com)

Tornado Damage, Washington, IL, Nov. 17, 2013 (USAToday, 11/19/2013)

Tornado Damage, Washington, IL, Nov. 17, 2013 (USAToday, 11/19/2013)

Tornado Damage, Washington, IL, Nov. 17, 2013 (news.yahoo.com)

Tornado Damage, Washington, IL, Nov. 17, 2013 (news.yahoo.com)

Tornado Damage, Washington, IL, Nov. 17, 2013 (news.yahoo.com)

Tornado Damage, Washington, IL, Nov. 17, 2013 (news.yahoo.com)

Tornado near Lebanon, IN, Nov. 17, 2013 (J&C, 11/18/2013)

Tornado Damage, Kokomo, IN, Nov. 17, 2013 (news.yahoo.com)

he extensive damage caused by Sunday's high winds is seen from the air Monday at Voestalpine Rotec Inc. JOHN CONGREAVE/FOR THE JOURNAL & COURIER

Tornado Damage, Lafayette, IN, Nov. 17, 2013 (J&C, 11/19/2013)

he south wall was ripped off the gymnasium at Southwestern Middle School on Sunday. Below, firefighters survey damage at Mintonye Elementary School. PHOTOS BY JOHN TERHUNE/J&C

Tornado Damage, Southwestern Middle School, Lafayette, IN, Nov. 17, 2013 (J&C, 11/18/2013)

Tornado Damage, Southwestern Middle School, Lafayette, IN, Nov. 17, 2013 (J&C, 11/18/2013)

Tornado near Lebanon, IN, Nov. 17, 2013 (J&C, 11/18/2013)

Tornadoes in SE US – April 27-28, 2011: At least 160 tornadoes in "outbreak", at least 291 deaths, 10 states.

http://www.nytimes.com/2011/04/29/us/29tornadoes.html

http://www.youtube.com/watch?v=vz8xiHpBGNM&feature=related

http://www.youtube.com/watch?v=6U1asLiDYB0&feature=related

Tornadoes in SE US – April 27-28, 2011: At least 160 tornadoes in "outbreak", at least 215 deaths.

http://www.youtube.com/watch?v=vz8xiHpBGNM&feature=related

http://www.youtube.com/watch?v=6U1asLiDYB0&feature=related

Tornadoes in SE US – April 27-28, 2011: At least 160 tornadoes in "outbreak", at least 215 deaths.

http://www.youtube.com/watch?v=vz8xiHpBGNM&feature=related

http://www.youtube.com/watch?v=6U1asLiDYB0&feature=related

Home ravaged: Daniel Hinton looks through the remains of his house Thursday in Tuscaloosa, Ala.

By Oren Dorell
USA TODAY

Communities across the Southeast are preparing to bury the dead this weekend after the deadliest day of tornadoes in 37 years killed at least 291 people.

President Obama, who visits Alabama today, said Thursday the damage in six Southeast states is "nothing short of catastrophic." He called the region's first responders heroes and pledged that the federal government will do everything it can to help states recover and rebuild.

Obama issued a disaster declaration for Alabama. It frees federal funds to help state and local authorities.

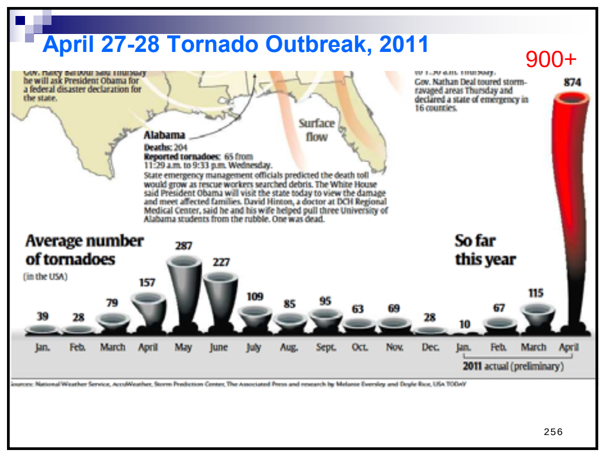
Alabama Gov. Robert Bentley said his state had 204 confirmed deaths. There were 33 deaths in Mississippi, 33 in Tennessee, 15 in Georgia, five in Virginia and one in Kentucky. The tornadoes injured thousands of people — 600 alone in Tuscaloosa, Ala., home of the University of Alabama. As many as 1 million homes and businesses in Alabama were without power.

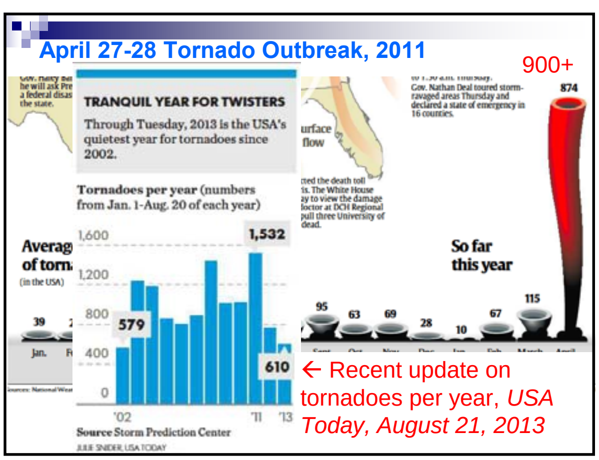
Several twisters that hit Wednesday were monsters more than a mile wide, stayed

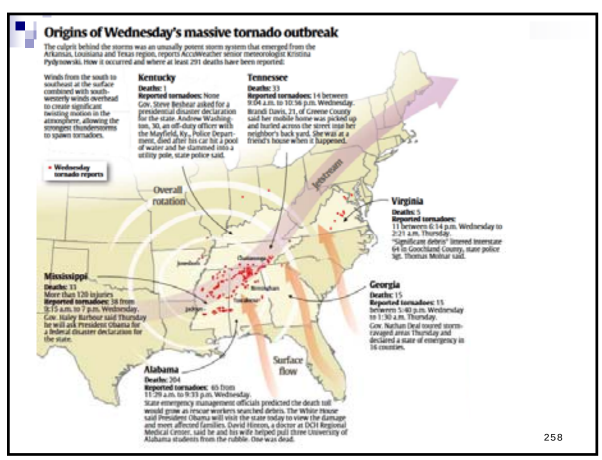

Before and After

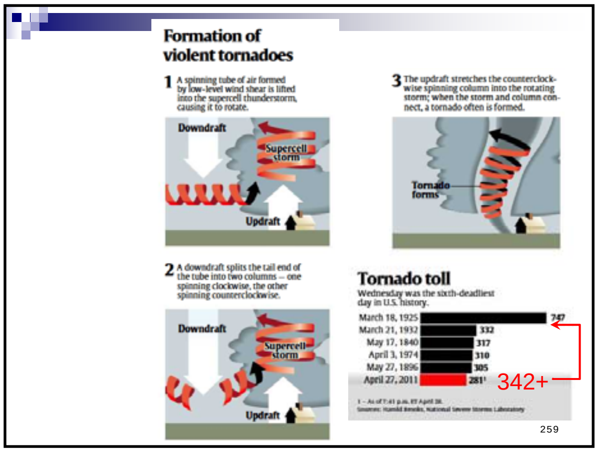

Before and After

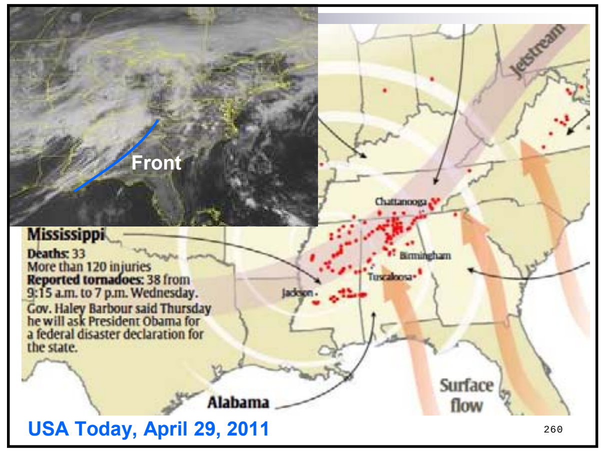

Community wiped out: Wednesday's tornado destroyed the Rosedale Court housing community in Tuscaloosa, Ala.

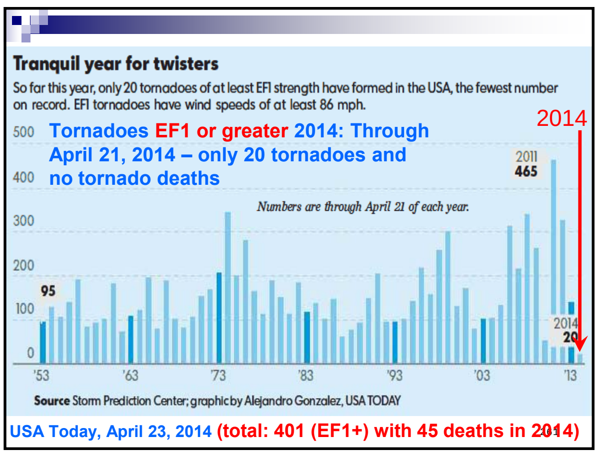

April 27-28 Tornado Outbreak, 2011
900+
874
Surface flow
Alabama
Average number of tornadoes
(in the USA)
So far this year
39
28
79
157
287
227
109
85
95
63
69
28
10
67
115
Jan.
Feb.
March
April
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
March
April
2011 actual (preliminary)
256

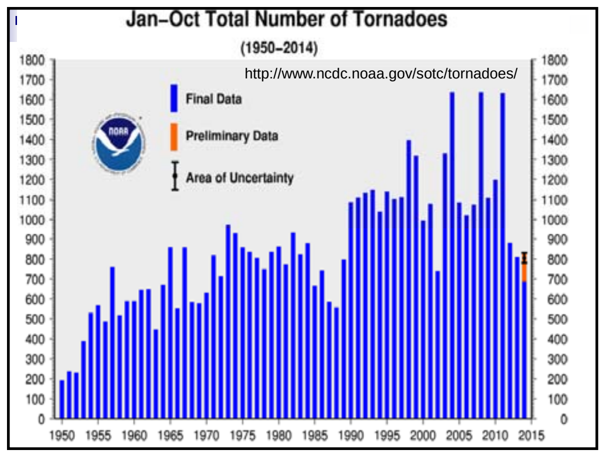

April 27-28 Tornado Outbreak, 2011
900+
874
TRANQUIL YEAR FOR TWISTERS
Through Tuesday, 2013 is the USA's quietest year for tornadoes since 2002.
Tornadoes per year (numbers from Jan. 1-Aug. 20 of each year)
1,600
1,200
800
400
0
1,532
579
610
'02
'11
'13
Source Storm Prediction Center
JULIE SNIDER, USA TODAY
So far this year
← Recent update on tornadoes per year, USA Today, August 21, 2013

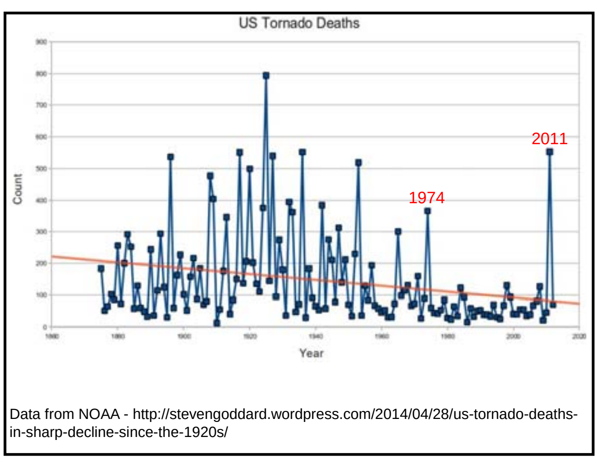

Origins of Wednesday's massive tornado outbreak
Kentucky
Tennessee
Virginia
Mississippi
Georgia
Alabama
Overall rotation
Jetstream
Surface flow
258

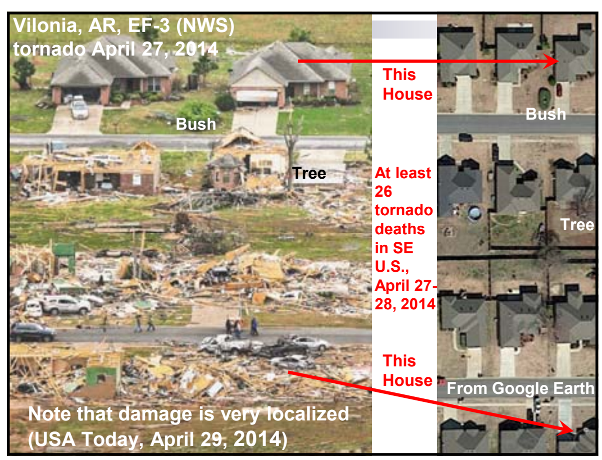

Formation of violent tornadoes
1 A spinning tube of air formed by low-level wind shear is lifted into the supercell thunderstorm, causing it to rotate.
Downdraft
Supercell storm
Updraft
3 The updraft stretches the counterclockwise spinning column into the rotating storm; when the storm and column connect, a tornado often is formed.
Tornado forms
2 A downdraft splits the tail end of the tube into two columns – one spinning clockwise, the other spinning counterclockwise.
Downdraft
Supercell storm
Updraft
Tornado toll
Wednesday was the sixth-deadliest day in U.S. history.
March 18, 1925 747
March 21, 1932 332
May 17, 1840 317
April 3, 1974 310
May 27, 1896 305
April 27, 2011 281
342+
259


Front
Jetstream
Chattanooga
Birmingham
Tuscaloosa
Jackson
Mississippi
Deaths: 33
More than 120 injuries
Reported tornadoes: 38 from 9:15 a.m. to 7 p.m. Wednesday.
Gov. Haley Barbour said Thursday he will ask President Obama for a federal disaster declaration for the state.
Alabama
Surface flow
USA Today, April 29, 2011
260


Tranquil year for twisters
So far this year, only 20 tornadoes of at least EF1 strength have formed in the USA, the fewest number on record. EF1 tornadoes have wind speeds of at least 86 mph.
2014
Tornadoes EF1 or greater 2014: Through April 21, 2014 – only 20 tornadoes and no tornado deaths
2011
465
Numbers are through April 21 of each year.
95
2014
20
'53 '63 '73 '83 '93 '03 '13
Source Storm Prediction Center; graphic by Alejandro Gonzalez, USA TODAY
USA Today, April 23, 2014 (total: 401 (EF1+) with 45 deaths in 2014)

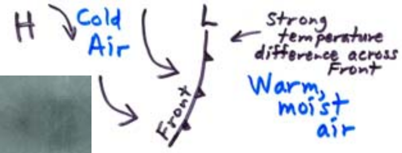

Jan–Oct Total Number of Tornadoes
(1950–2014)
http://www.ncdc.noaa.gov/sotc/tornadoes/
Final Data
Preliminary Data
Area of Uncertainty
NOAA


US Tornado Deaths
2011
1974
Count
Year
Data from NOAA - http://stevengoddard.wordpress.com/2014/04/28/us-tornado-deaths-in-sharp-decline-since-the-1920s/


Vilonia, AR, EF-3 (NWS) tornado April 27, 2014
This House
Bush
Bush
Tree
At least 26 tornado deaths in SE U.S., April 27-28, 2014
Tree
This House
From Google Earth
Note that damage is very localized (USA Today, April 29, 2014)

Tornadoes:

1. Form in intense thunderstorms caused by collision of cold air and warm, moist air along a Front.



Elkhart, Indiana, 1965 April 11; note “twin funnels”.

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Near Howard, South Dakota, 1884 August 28 (oldest known photo of a tornado), note funnel clouds that have or are descending from very dark “wall cloud”. Also note debris around funnel cloud.

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Tornado and flying debris, Chapter14 , text

Tornadoes (cont.)

2. Midwest US is most prominent location (“tornado alley”)
   - -- moisture from Gulf of Mexico
   - -- Cold air from Canada moving south and east and “guided” by Rocky Mtns. and Appalachians
3. Mostly in Spring due to climatic conditions of warm air in Gulf of Mexico and SE U.S and occasional cold air and front moving south and east from cold Canadian air mass.

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Tornadoes (cont.)

4. Conditions for formation:
   - -- unstable air -- cold air over-riding warm (warm air below then rises due to lower density, cold air above descends due to higher density leading to strong vertical movements)
   - -- rising, warm, moist air
   - -- precipitation, evaporation (and cooling) cause down-drafts when warm air contacts cold air along the front
   - -- Tornado occurs in updraft region

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Circulation around Low pressure area often results in formation of a **cold front**. Collision of dry, cold air with warm, moist air results in precipitation and, possibly, thunderstorms and tornadoes.

Cold front moves from west to east due to trade winds (westerlies) and counter-clockwise circulation around the Low

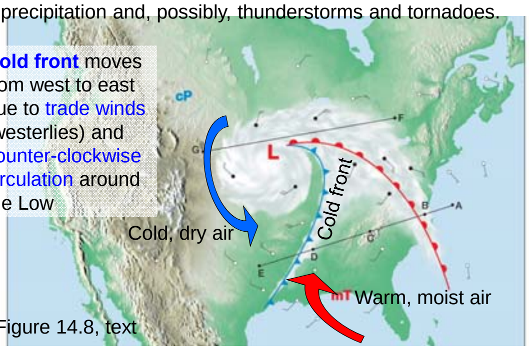

Figure 14.8, text

Clouds associated with a Low pressure area and cold front

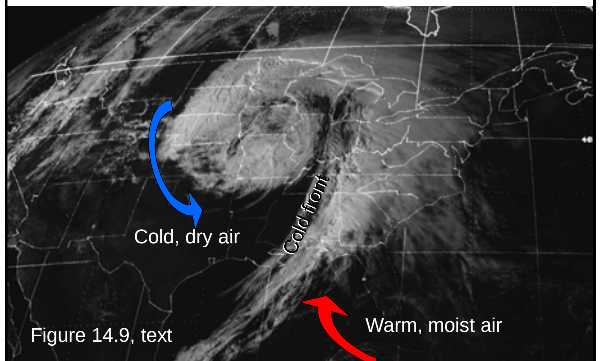

Figure 14.9, text

Cold air is more dense so it stays near the Earth's surface and cause the adjacent warm moist air to rise along the front (shows cross section view equivalent to profile E to C of Figure 14.8, text)

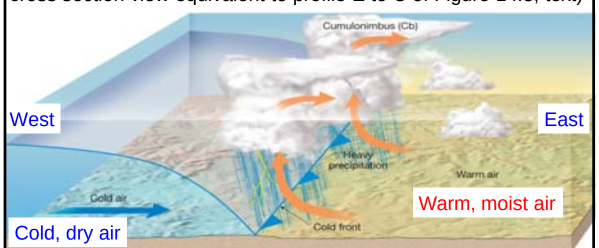

Figure 14.6, text

Reduce

A supercell thunderstorm moves from Nebraska toward Lusk, Wyo., on a fall evening.

By Kresta Meng Leimser

Supercell Thunderstorm

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Lightning from Thunderstorm, Figure 14.12, text

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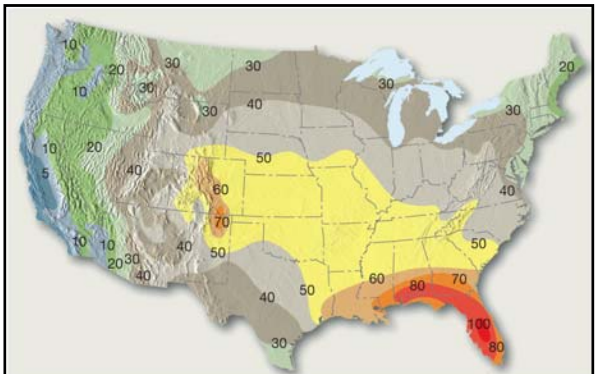
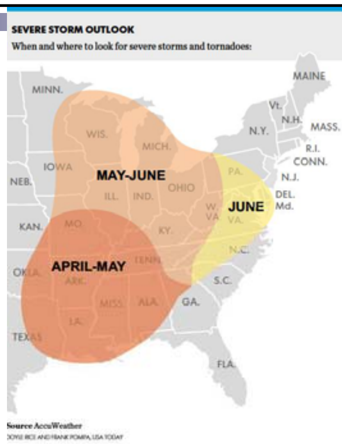


B. Average number of days per year with thunderstorms.

Figure 14.13, text

Severe storms areas by month (USA Today, April 8, 2013)



Tornadoes (cont.)

5. Characteristics:
   - -- Weak F0 to F1 (winds <180 km/hr)
   - -- Strong F2 to F3 (winds 181- 332 km/hr)
   - -- Violent F4 to F5 (winds >333 km/hr)
     (about 20/yr violent; peak in April; most deaths and damage result from the small number of violent [F4 to F5] tornadoes each year)
   - -- Intensity of tornado is ~ proportional to the amount of water vapor in air

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Table 14.1 Fujita Intensity Scale

Scale	Wind Speed Km/Hr	Wind Speed Mi/Hr	Damage
F0	<116	<72	Light damage
F1	116–180	72–112	Moderate damage
F2	181–253	113–157	Considerable damage
F3	254–332	158–206	Severe damage
F4	333–419	207–260	Devastating damage
F5	>419	>260	Incredible damage

Table 14.1, text, L&T, 2008

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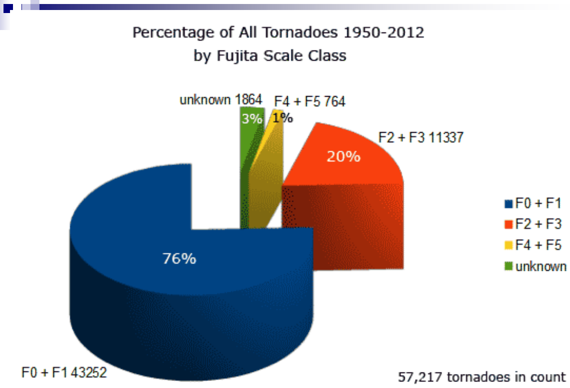
Table 14.1, text, L&T, 2014

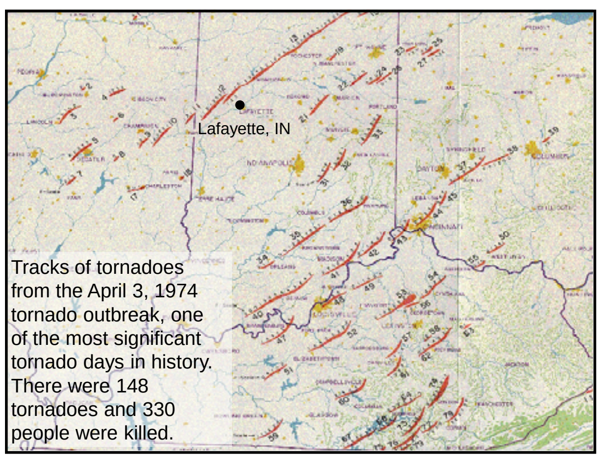
TABLE 14.1 Enhanced Fujita Intensity Scale*

Scale	Wind Speed Km/Hr	Wind Speed Mi/Hr	Damage
EF-0	105–137	65–85	*Light.* Some damage to siding and shingles.
EF-1	138–177	86–110	*Moderate.* Considerable roof damage. Winds can uproot trees and overturn single-wide mobile homes. Flagpoles bend.
EF-2	178–217	111–135	*Considerable.* Most single-wide homes destroyed. Permanent homes can shift off foundations. Flag-poles collapse. Softwood trees debarked.
EF-3	218–265	136–165	*Severe.* Hardwood trees debarked. All but small portions of houses destroyed.
EF-4	266–322	166–200	*Devastating.* Complete destruction of well-built residences, large sections of school buildings.
EF-5	>322	>200	*Incredible.* Significant structural deformation of mid- and high-rise buildings.

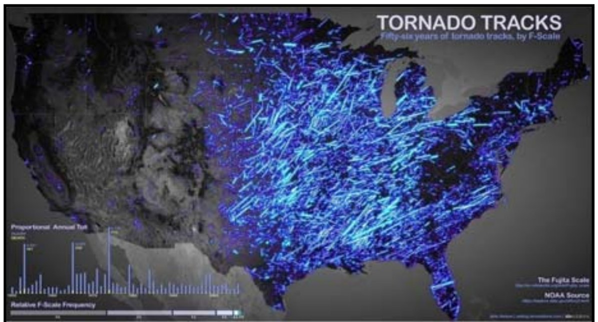
*The original Fujita scale was developed by T. Theodore Fujita in 1971 and put into use in 1973. The Enhanced Fujita intensity scale is a revision that was put into use in February 2007. Wind speeds are estimates (not measurements) based on damage, and represent 3-second gusts at the point of damage.



http://www.tornadoproject.com/cellar/fscale.htm

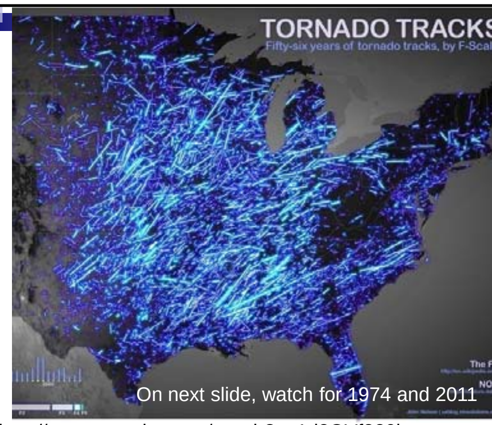


Tracks of tornadoes from the April 3, 1974 tornado outbreak, one of the most significant tornado days in history. There were 148 tornadoes and 330 people were killed.



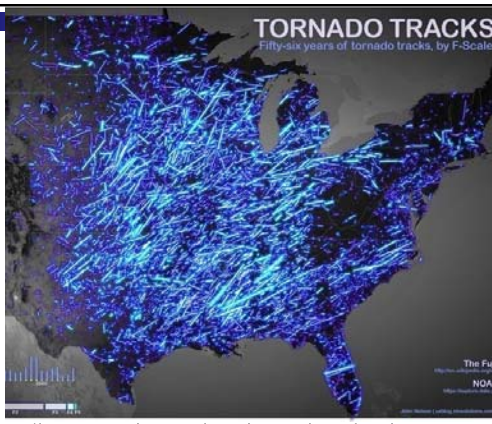
http://uxblog.idvsolutions.com/2012/05/tornado-tracks.html

Watch the YouTube video to see the tornado tracks (1950-2011) by year: http://www.youtube.com/watch?v=1d8OVf829kw



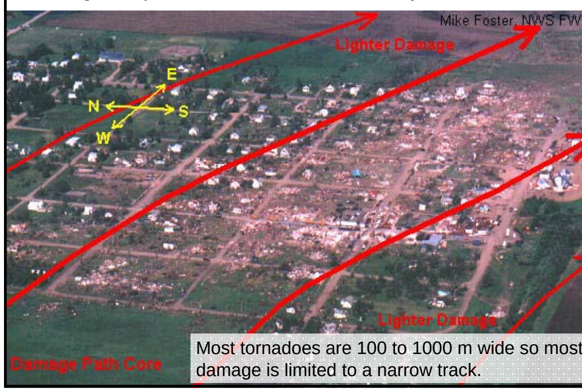
On next slide, watch for 1974 and 2011

http://www.youtube.com/watch?v=1d8OVf829kw



http://www.youtube.com/watch?v=1d8OVf829kw

Damage in Spencer, South Dakota from May 30, 1998 tornado



Most tornadoes are 100 to 1000 m wide so most damage is limited to a narrow track.

Tornado damage and track, F3 Moore, OK, May 8, 2003, NASA Earth Observatory image

Tornado damage, F5 Moore, OK, May 3, 1999.

Tornado damage, Moore, OK, May 3, 1999. Maximum wind speed measured at over 500 km/hr (~300 mi/hr)

Tornado damage, Moore, OK, May 3, 1999.

April 28, 2011 photo shows tornado damage in Pleasant Grove, Ala. Jconline Mar. 20, 2013.

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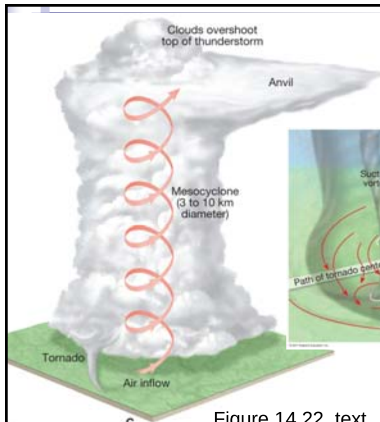
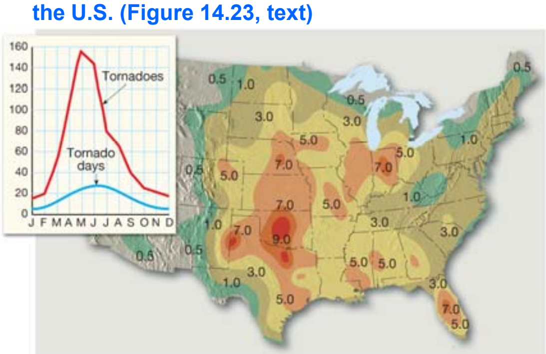


Multiple-Vortex Tornado

Figure 14.21, text

Figure 14.22, text

Average number of tornadoes, tornado days, and annual tornado incidence each month in the U.S. (Figure 14.23, text)



Where is Tornado Alley?

"Tornado Alley" typically includes the Plains states from the Dakotas to Texas. A new study shows that the frequency and severity of tornadoes are actually much more widespread, so Tornado Alley should also include several states in the upper Midwest and Deep South, along with Florida.

Sources: CoreLogic; Storm Prediction Center

By Doyle Rice and Julie Snider, USA TODAY

USAToday April 11, 2012

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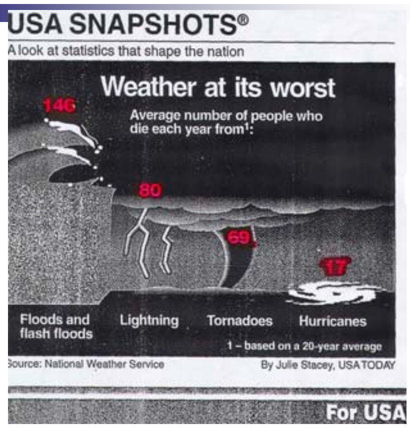

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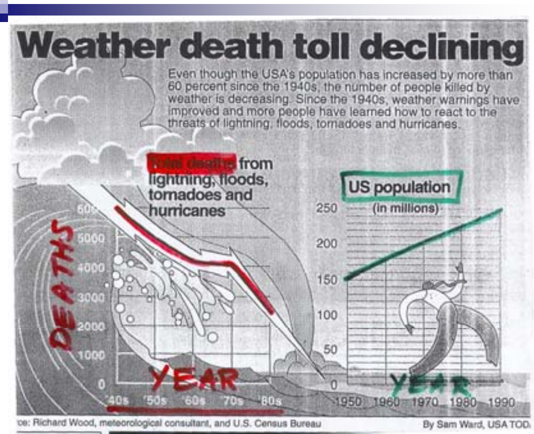

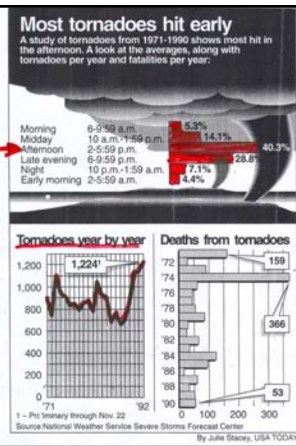

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U.S. Weather related disasters 1980-1995: 46 disasters (at least $1 billion in damages, March 2012 dollars).

Total losses = $339 billion.
(National Geographic, Sept., 2012)

Disaster Type:

Population increased by ~ 37 million

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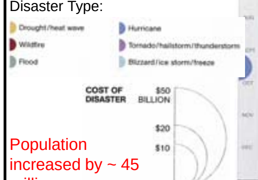
U.S. Weather related disasters 1996-2011: 87 disasters (at least $1 billion in damages, March 2012 dollars).

Total losses = $541 billion.
(National Geographic, Sept., 2012)

Disaster Type:



Population increased by ~ 45 million

Note increased number of events and large-loss events

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