Atmospheric Sciences:
- Atmosphere
- Solar radiation
- Atmospheric circulation
- Seasons

Atmospheric Sciences:
- Weather
  - Causes
  - Forecasting
  - Severe weather
- Climate
- Recent topics
- Global warming/CO2
- Ozone “hole,” pollution, acid rain

The Earth’s Atmosphere:
1. Composition:
   - N\textsubscript{2} \approx 78\%
   - O\textsubscript{2} \approx 21\%
   - Other elements and compounds (minor constituents):
     - (Ar, Ne, CH\textsubscript{4}, Kr, H\textsubscript{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\textsubscript{2} \approx 390 ppm*
   - CO \approx 100 ppm
   - O\textsubscript{3} \approx 0 – 10 ppm
   - SO\textsubscript{2} \approx 0 – 1 ppm
   - *ppm = parts per million; one ppm equals 0.0001%

Composition of Dry Air

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\textsubscript{2} in the present atmosphere is about 20% of the total atmosphere)
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)
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

Earth’s Atmosphere – a thin layer

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

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 would 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. As 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, the air pressure decreases. Air pressure decreases as we increase altitude.
http://www.grc.nasa.gov/WWW/K-12/airplane/atmosphere.html

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

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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])

http://www.nasa.gov/mission_pages/station/multimedia/gallery/iss030e031275.html

The Moon and Earth’s atmosphere


Notice the very thin, illuminated atmosphere

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

Vertical movements of air produce cooling for upward movement and heating for downward movement because of change in pressure (adiabatic cooling or heating - thermodynamics)

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.

\[ D = \text{Density of air (in g/cm}^3\text{)} \] – note that density of the atmosphere also decreases with altitude.

Figure 11.7, text

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.)

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- Severe weather (local, and changes over hours to days).

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

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)
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 (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)

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 40° 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

Area Covered by Different Sun Angles

Figure 11.14, text

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

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.

Figure 11.13, text

World Distribution of Mean Temperature - January

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.

Figure 11.37, text

World Distribution of Mean Temperature - July

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

Figure 11.38, text

Effect of Seasons on Average Temperatures by Latitude

Temperature ranges at various locations across different latitudes and months.
**Effect of Seasons on Length of Day by Latitude**

Length of Day for Various Latitudes (on the 21st Day of the Month)

- **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.

**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).

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

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

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 counterclockwise circulation around a low pressure area south of the Aleutian Islands (12:30 – 16:30 GMT, May 27, 2015).

Circulation (wind, near surface) around a High pressure area (map view, northern Hemisphere) – air moves from high pressure area to low pressure area

Expected direction:
Actual direction (Coriolis effect, deflection to the right):
Result is Clockwise circulation

Circulation (wind, near surface) around a Low pressure area (map view, northern Hemisphere) – air moves from high pressure area to low pressure area

Expected direction:
Actual direction (Coriolis effect, deflection to the right):
Result is Counterclockwise circulation

Infrared Satellite Loop 1330 – 1730 11/13 GMT

Radar/Surface Loop 1930 11/27 – 1615 11/28 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**
- **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)

**Elevation**

**Earth’s surface**

**Circulation (wind, near surface) around a Low pressure area**
- **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)

**Figure 13.7, text**

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

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

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, 30°-60° N) and counter-clockwise circulation around the Low.

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.

Clouds associated with a Low pressure area and cold front. Warm, moist air from south and gulf of Mexico and cold, dry air (from north) create the cold front. 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.

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
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.

VE ~ 22

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
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

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).

Note: rain forests mostly near equator
17

**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

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

Global circulation breaks into cells due to Coriolis effect and 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**

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.

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 SO₂ in the atmosphere can reduce average temperature from the ash or increase the average temperature from the SO₂ -- a greenhouse gas). (A natural phenomenon.)

5. CO₂ (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.)

Milankovitch Cycles

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

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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, and εsin(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 sea level and temperature, from ocean sediment and Antarctic ice respectively. Vertical gray line is current conditions, at 2 ky A.D.

Benthic Forams
Vostok Ice Core

<table>
<thead>
<tr>
<th>Obliquity</th>
<th>Eccentricity</th>
<th>Orbit Precession</th>
<th>Precession Index</th>
<th>Insolation (Heating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time →</td>
<td>ε</td>
<td>e</td>
<td>ϖ</td>
<td>εsin(ϖ)</td>
</tr>
</tbody>
</table>

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

Global CO₂ (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

Last 800,000 years of CO₂ levels in the atmosphere (Scripps, http://keelingcurve.ucsd.edu/)

U.S. Energy Consumption – 2008, 84% Fossil Fuels (CO₂ Emissions)

U.S. Energy Consumption, sources of energy – 2011, 83% (61% 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 (USA Today, February 20, 2014)

U.S. CO₂ Production – mostly from burning of Fossil Fuels (CO₂ 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 CO₂ production (Figure 11.27, L&T, 2014)

Recent Global Temperature Change


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
Arctic Sea Ice Extent 2012
Median of previous years
http://nsidc.org/arcticseaicenews/

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

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


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)

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


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/#.UumGjRC2Uob

Global CO₂ (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

2016 (~405)

The very rapid increase since 1900, the amplitude of the 2014 CO₂ 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.
Greenhouse Effect:

1. Greenhouse gases: CO₂, methane, nitrous oxides, water vapor, ChloroFlouroCarbons (CFC)
   -- natural and human-caused
   -- CO₂ 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.
Greenhouse Effect (cont.)

5. “Complications:”
-- How much CO₂ storage in oceans?
-- Human vs. natural causes?
-- Political -- industrialized vs. developing countries
-- Deforestation compounds the problem by removing CO₂-consuming and O₂-producing plants, and adding CO₂ to atmosphere by burning.

See pages 371-381 in Text.

So, CO₂ in Atmosphere is “good” – Earth’s atmosphere would be ~ 30°C colder without the greenhouse effect!

But, CO₂ is increasing in atmosphere (global warming); Current CO₂ emissions:

US 5 tons/year/person
World < 1 ton/year/person

It’s now about 405
### 2012 CO₂ emissions

**World CO₂ emissions from Energy**

<table>
<thead>
<tr>
<th>Region</th>
<th>Share of CO₂ emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>18.3%</td>
</tr>
<tr>
<td>South Central Asia</td>
<td>19.8%</td>
</tr>
<tr>
<td>Mexico</td>
<td>6.4%</td>
</tr>
<tr>
<td>Europe</td>
<td>28.0%</td>
</tr>
<tr>
<td>Latin America</td>
<td>4.7%</td>
</tr>
<tr>
<td>Middle East</td>
<td>4.2%</td>
</tr>
<tr>
<td>South Asia</td>
<td>19.6%</td>
</tr>
<tr>
<td>Australia / New Zealand</td>
<td>17.0%</td>
</tr>
<tr>
<td>Africa</td>
<td>3.4%</td>
</tr>
<tr>
<td>China</td>
<td>26%</td>
</tr>
<tr>
<td>USA</td>
<td>15%</td>
</tr>
<tr>
<td>India</td>
<td>7%</td>
</tr>
<tr>
<td>Russia</td>
<td>5%</td>
</tr>
<tr>
<td>Japan</td>
<td>4%</td>
</tr>
</tbody>
</table>

USA Today, September 22, 2014

### 2012 CO₂ 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

### Europe CO₂ emissions, 2000 to 2013

**Europe's Attack on Carbon Emissions**

<table>
<thead>
<tr>
<th>Country</th>
<th>Change in Carbon Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>4.36%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>-2.7%</td>
</tr>
<tr>
<td>France</td>
<td>-13%</td>
</tr>
<tr>
<td>Italy</td>
<td>-11%</td>
</tr>
<tr>
<td>Greece</td>
<td>-19%</td>
</tr>
</tbody>
</table>

USA Today, September 23, 2014

### USA Today, August 20, 2013


http://www.usatoday.com/2012-emissions-revisited/

http://www.usatoday.com/2014-09-23-europe-carbon-emissions/
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

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)

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):

\[
\begin{align*}
\text{Cl} + O_3 & \rightarrow \text{ClO} + O_2 \quad (1) \\
\text{ClO} + O_3 & \rightarrow \text{Cl} + 2 O_2 \quad (2)
\end{align*}
\]

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

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

The result of this chain reaction is:

1. $2 \text{O}_3 \rightarrow \text{O}_2 + 2 \text{O}_2$ [loss of Ozone]
2. $\text{Cl} \rightarrow \text{Cl}$ [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).

Human influences on the atmosphere

3. Acid Rain
   - $\text{SO}_2$, 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

The 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

U.S. Acid Rain

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)

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 ($\pm 5 - 20^\circ$ latitude; not right at the equator because of small Coriolis Effect)

2. Energy for storm (Energy for one day of a hurricane $\approx$ 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 ($> 28^\circ$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 ($\approx 10 - 50$ 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

<table>
<thead>
<tr>
<th>Scale Number (category)</th>
<th>Central Pressure (milibars)</th>
<th>Winds (km/hr)</th>
<th>Storm Surge (meters)</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2980</td>
<td>119–153</td>
<td>1.2–1.5</td>
<td>Minimal</td>
</tr>
<tr>
<td>2</td>
<td>965–979</td>
<td>154–177</td>
<td>1.6–2.4</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>945–964</td>
<td>178–209</td>
<td>2.5–3.6</td>
<td>Extensive</td>
</tr>
<tr>
<td>4</td>
<td>920–944</td>
<td>210–230</td>
<td>3.7–5.4</td>
<td>Extreme</td>
</tr>
<tr>
<td>5</td>
<td>&lt;920</td>
<td>&gt;250</td>
<td>&gt;5.4</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

Table 14.2 L&T, 2017
CSU Atlantic Hurricanes forecasts for 2012 and 2013 seasons (USA Today, April 11, 2013)

<table>
<thead>
<tr>
<th>Name</th>
<th>Dates active</th>
<th>Storm category at peak intensity</th>
<th>Max 1-min wind mph (km/h)</th>
<th>Min. press. (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arlene</td>
<td>April 19 – 21</td>
<td>Tropical storm</td>
<td>50 (85)</td>
<td>990</td>
</tr>
<tr>
<td>Bret</td>
<td>June 19 – 20</td>
<td>Tropical storm</td>
<td>45 (75)</td>
<td>1007</td>
</tr>
<tr>
<td>Cindy</td>
<td>June 20 – 23</td>
<td>Tropical storm</td>
<td>60 (95)</td>
<td>982</td>
</tr>
<tr>
<td>Four</td>
<td>July 6 – 7</td>
<td>Tropical depression</td>
<td>30 (45)</td>
<td>1008</td>
</tr>
<tr>
<td>Don</td>
<td>July 17 – 19</td>
<td>Tropical storm</td>
<td>50 (85)</td>
<td>1007</td>
</tr>
<tr>
<td>Emily</td>
<td>July 31 – August 2</td>
<td>Tropical storm</td>
<td>45 (75)</td>
<td>1006</td>
</tr>
<tr>
<td>Franklin</td>
<td>August 7 – 10</td>
<td>Cat. 1 hurricane</td>
<td>85 (140)</td>
<td>981</td>
</tr>
<tr>
<td>Gert</td>
<td>August 13 – 17</td>
<td>Cat. 2 hurricane</td>
<td>100 (165)</td>
<td>967</td>
</tr>
<tr>
<td>Harvey</td>
<td>Aug. 17 – Sept. 1</td>
<td>Cat. 4 hurricane</td>
<td>130 (215)</td>
<td>938</td>
</tr>
<tr>
<td>Irma</td>
<td>Aug. 30 – Present</td>
<td>Cat. 5 hurricane</td>
<td>185 (295)</td>
<td>914</td>
</tr>
<tr>
<td>Jose</td>
<td>Sept. 5 – Present</td>
<td>Cat. 4 hurricane</td>
<td>150 (250)</td>
<td>938</td>
</tr>
<tr>
<td>Katia</td>
<td>Sept. 5 – Present</td>
<td>Cat. 2 hurricane</td>
<td>105 (165)</td>
<td>972</td>
</tr>
<tr>
<td>Maria</td>
<td>Sept. 16 – 20</td>
<td>Cat. 5 hurricane</td>
<td>175 (280)</td>
<td>908</td>
</tr>
</tbody>
</table>

Also (after Maria): Nate (H), Ophelia (H), Philippe (TS), Rina (TS)

2017 Atlantic hurricane season (June 1-November 30)

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
5. Names for Hurricanes ("just for interest"):
- Atlantic Ocean: Hurricanes
- W. Pacific Ocean: Typhoons
- Indian Ocean: Cyclones
- Australia: Willy-Willys

Note intensification and weakening of storm with time.
Track of Hurricane Andrew, 1992 (orange and red dots indicate Hurricane strength winds)

Figure 14.23, text

Figure 14.25, text

Strongest winds in NE Quadrant of Hurricane

Figure 14.25, text

Hurricane Andrew, 1992

Figure 14.23, text

Hurricane Andrew, 1992

Figure 14.25, text

Hurricane Andrew, 1992
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 Katrina, Aug. 28-29, 2005

Hurricane Season, Katrina, Aug. 27, 2005

http://www.nasa.gov/vision/earth/lookingatearth/h2005_katrina.html
Hurricane Track Site: http://hurricane.csc.noaa.gov/hurricanes/viewer.html

Legend (hurricanes are red and dark red)

- Hurricane Track
- Category 3 - 5
- Category 1 - 2
- Tropical Storm
- Tropical Depression
- Subtropical Storm
- Subtropical Depression
- Extratropical Storm
- Tropical Cyclone
- Tropical Disturbance
- Tropical Wave

150 Years of Hurricanes

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

Note that the entire east and gulf coasts of the US have been impacted by hurricanes

Tropical Storms and Hurricanes 1842-2013

Note that the entire east and gulf coasts of the US have been impacted by hurricanes
From USA Today, Aug. 22, 2012

Most intense landfalling U.S. hurricanes
Intensity is measured solely by central pressure

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<th>Rank</th>
<th>Hurricane</th>
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Source: U.S. National Hurricane Center

Costliest U.S. Atlantic hurricanes
Cost refers to total estimated property damage.

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Intensity is measured solely by central pressure

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Source: U.S. National Hurricane Center

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</thead>
<tbody>
<tr>
<td>1</td>
<td>Katrina</td>
<td>2005</td>
<td>$80 billion</td>
</tr>
<tr>
<td>2</td>
<td>Andrew</td>
<td>1992</td>
<td>$43.672 billion</td>
</tr>
<tr>
<td>3</td>
<td>Charley</td>
<td>2004</td>
<td>$15 billion</td>
</tr>
<tr>
<td>4</td>
<td>Wilma</td>
<td>2005</td>
<td>$14.4 billion</td>
</tr>
<tr>
<td>5</td>
<td>Ivan</td>
<td>2004</td>
<td>$14.2 billion</td>
</tr>
</tbody>
</table>

Main article: List of costliest U.S. Atlantic hurricanes
Today: Tornadoes

Surface Conditions – Nov. 17-18, 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)


http://www.youtube.com/watch?v=vz8xiHpBGNM&feature=related
http://www.youtube.com/watch?v=6U1asLiDYB0&feature=related


http://www.youtube.com/watch?v=vz8xiHpBGNM&feature=related
http://www.youtube.com/watch?v=6U1asLiDYB0&feature=related
April 27-28 Tornado Outbreak, 2011

Recent update on tornadoes per year, USA Today, August 21, 2013
Tornadoes EF1 or greater 2014: Through April 21, 2014 – only 20 tornadoes and no tornado deaths

USA Today, April 23, 2014 (total: 401 (EF1+) with 45 deaths in 2014)

Tornadoes:

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

![Diagram showing cold air and warm air colliding](image)

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

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.

Tornado and flying debris, Chapter 14, 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.

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
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.

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).

Supercell Thunderstorm

Lightning from Thunderstorm, Figure 14.12, text

Figure 14.8, text

Figure 14.9, text

Figure 14.6, text

Figure 14.13, text
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

Table 14.1 Fujita Intensity Scale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Km/Hr</th>
<th>Mi/Hr</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>&lt;116</td>
<td>&lt;72</td>
<td>Light damage</td>
</tr>
<tr>
<td>F1</td>
<td>116–180</td>
<td>72–112</td>
<td>Moderate damage</td>
</tr>
<tr>
<td>F2</td>
<td>181–253</td>
<td>113–157</td>
<td>Considerable damage</td>
</tr>
<tr>
<td>F3</td>
<td>254–332</td>
<td>158–206</td>
<td>Severe damage</td>
</tr>
<tr>
<td>F4</td>
<td>333–419</td>
<td>207–260</td>
<td>Devastating damage</td>
</tr>
<tr>
<td>F5</td>
<td>&gt;419</td>
<td>&gt;260</td>
<td>Incredible damage</td>
</tr>
</tbody>
</table>

Table 14.1, text, L&T, 2008

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.
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

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).


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

Where Is Tornado Alley?

"Old" Tornado Alley

"New" Tornado Alley

Sources: Employees, National Weather Service Center.

USA Today April 11, 2012

Disaster Type:
Population increased by ~37 million

Note increased number of events and large-loss events