Atmospheric Sciences:
Atmosphere
Solar radiation
Atmospheric circulation
Seasons

Weather
Causes
Forecasting
Severe weather
Climate
Recent topics
Global warming/CO2
Ozone "hole," pollution, acid rain

The Earth’s Atmosphere:
1. Composition:
   \[ \text{N}_2 \approx 78\% \]
   \[ \text{O}_2 \approx 21\% \]

   Other elements and compounds (minor constituents):
   \[ \text{Ar, Ne, CH}_4, \text{Kr, H}_2, \text{etc.} \] \( \leq 1\% \)
   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):

- \( \text{CO}_2 \approx 400 \text{ ppm}^* \)
- \( \text{CO} \approx 100 \text{ ppm} \)
- \( \text{O}_3 \approx 0 – 10 \text{ ppm} \)
- \( \text{SO}_2 \approx 0 – 1 \text{ ppm} \)

*ppm = parts per million; one ppm equals 0.0001%
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)
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 Earth, 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. A layer on that ball, the atmosphere, would be very thin, less than a millimeter thick.

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 above 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.

The Earth’s atmosphere is all that stands between life on Earth and the cold, dark void of space. Our planet’s atmosphere has no clearly defined upper boundary but gradually thins out into space. The layers of the atmosphere have different characteristics, such as protective ozone in the stratosphere, and weather in the lowermost layer. The setting Sun is also featured in this image from ISS, 2008.

Notice the very thin, illuminated atmosphere.
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

Energy Transfer in the Atmosphere:
-- Radiation
-- Conduction
-- Convection (mass transport; wind and other atmospheric circulation)

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 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)

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)

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

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).

The geometry of the Earth’s tilt and the rotational axis pointing to Polaris.
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.
Global Atmospheric Circulation

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

Also, 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)

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. The resulting surface winds are the “Trade Winds” (prevailing winds).

Note descending dry air (~30° N)

Note rising moist air in tropical area (Figure 13.17, text)

January 07, 2009 12-24 UTC

SSMI Water Vapor ( Wentz algorithm)

Low ← Water vapor in the atmosphere → High

Note “atmospheric river” of moisture headed for the west coast, and the large amount of moisture in the tropical area (rising air in low latitudes).

http://www.esrl.noaa.gov/psd/atmrivers/events/
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

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)
Radar Loop 1400 – 1645 GMT 28 November 2005

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

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).

Circulation (wind, near surface) around a High pressure area (map view, northern Hemisphere)

- Expected direction:
- Actual direction (Coriolis effect):

Result is Clockwise circulation

Circulation (wind, near surface) around a Low pressure area (map view, northern Hemisphere)

- Expected direction:
- Actual direction (Coriolis effect, deflection to the right):

Result is Counter-Clockwise circulation

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

Radar/Surface Loop 1200 11/12 – 0900 11/13 GMT

Infrared Satellite Loop 1330 – 1730 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)

- 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)

Circulation (wind, near surface) around a **Low** pressure area (cross section view)

- 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)

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

Earth's surface
Circulation (wind, near surface) around High and Low pressure areas (map view, northern Hemisphere)

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

Clockwise

Figure 13.12, text

Counter-clockwise

Figure 14.14, text

Brief review of topics:

Composition and properties of the atmosphere – focus on lowest layer (troposphere) in which most weather phenomena occur, and pressure and temperature vs altitude

Reasons for seasons

Atmospheric circulation around high and low pressure systems; Coriolis effect

Today – more on atmospheric circulation, weather fronts, climate

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 14.12, text

Clouds associated with a Low pressure area and cold front

Cold, dry air

Warm, moist air

Figure 14.13, text

Warm, moist air
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.

Figure 14.8, text

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

VE ~ 22

Bathymetric profile (ocean depth) across the Atlantic Ocean, 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 – slope is actually very, very small!

No VE

No VE, but with true curvature of the Earth

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 counter-clockwise circulation about low pressure and west to east motion – 24-hr Radar Loop, 00:00 – 23:00 GMT April 11, 2013

24-hr Radar Loop 00:00 – 23:00 GMT April 11, 2013
Example of global circulation/climate effect: **Deserts**

Deserts (areas of very low precipitation, shaded yellow) occur at about 30 degrees from the equator (Hadley cells).

- Sahara desert
- W. Australian desert
- SW U.S. desert
- SE Asia rain forest
- Middle East desert
- Patagonia rain forest
- Kalahari desert

**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

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**Idealized Global Circulation (close-up)**

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**

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

- Desert $\rightarrow$ ~ 30 deg. N
- Rising, moist air; precipitation
- Desert $\rightarrow$ ~ 30 deg. S
- Equator $\rightarrow$ South Pole
3. Recent climate change
- - Last glaciation (max ∼ 18,000 years ago; 
  \(\approx 8^\circ C\) cooler)
- - "Climatic Optimum" (\(\approx 6000\) 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

Explanations:
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 cooler 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\textsubscript{2} in the
   atmosphere can reduce average temperature
   from the ash or increase the average temperature
   from the SO\textsubscript{2} – 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 (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)

Eccentricity

Obliquity (23 +/- 1.5 degrees tilt)

Precession

Circular orbit of a planet

Elliptical orbit of a planet


Obliquity (change in tilt angle)


Axial Precession


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

![Milankovitch Cycles Diagram](http://en.wikipedia.org/wiki/Milankovitch_cycles)

Sum of the three cycles looks like:

![Sum of Milankovitch Cycles](http://en.wikipedia.org/wiki/Milankovitch_cycles)

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. $e$ is eccentricity, $\varpi$ is longitude of perihelion, $\varepsilon \sin(\varpi)$ 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.

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

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

Global CO₂ (ppm) – past 800,000 Years

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

For 800,000 years, atmospheric CO₂ was never higher than this level

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 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.

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)

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. CO₂ Production – mostly from burning of Fossil Fuels (CO₂ Emissions), U.S. contributes nearly 25% of the world’s greenhouse gas emissions!

U.S. annual per capita CO₂ production (Figure 11.27, L&T, 2014)

Reconstructed Temperature

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.

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


One half °F (0.28 °C) per decade increase


A high-resolution map of Thwaites Glacier’s thinning ice shelf. Warm circumpolar deep water is melting the underside of this floating shelf, leading to an ongoing speedup of Thwaites Glacier. This glacier now appears to be in the early stages of collapse, with full collapse potentially occurring within a few centuries. Collapse of this glacier would raise global sea level by several tens of centimeters, with a total rise by up to a few meters if it causes a broader collapse of the West Antarctic Ice Sheet.

San Francisco annual rainfall (inches), 1849–2013

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

Mean surface temperature change for the period 1999 to 2008 relative to the average temperatures from 1940 to 1980

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

The very rapid increase since 1980, 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.

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

CO₂, Energy Consumption, and Population

Correlation does not prove causality, but we know that large amounts of CO₂ emissions are from fossil fuels, and that CO₂ in the atmosphere causes warming.

Due to industrialization, world energy consumption is increasing more rapidly than population!

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

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]

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

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 ~ Energy produced in US in one year)
   - Solar radiation -- Heated air rises forming low pressure region, also provides moisture in atmosphere by evaporation from ocean

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 cm³ = 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

<table>
<thead>
<tr>
<th>Scale Number (category)</th>
<th>Central Pressure (millibars)</th>
<th>Winds (km/hr)</th>
<th>Storm Surge (meters)</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>980</td>
<td>119–133</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>210–250</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)

NOAA 2013 Atlantic Hurricane Forecast

<table>
<thead>
<tr>
<th>Storm Category</th>
<th>2013 Forecast</th>
<th>Long-term Average</th>
<th>2013 Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms</td>
<td>13 – 20</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>7 – 11</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Major Hurricanes</td>
<td>3 – 6</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

As you can see for the results of the 2013 hurricane season, hurricane forecasting is not always easy or accurate!

NOAA 2013 Atlantic Hurricane Forecast, May 24, 2013
http://www.noaanews.noaa.gov/stories2013/20130523_hurricaneoutlook_atlantic.html

Numbers of Atlantic Basin named storms, those that attain at least tropical storm strength, hurricanes, and hurricanes of Category 3 intensity forecast by The Weather Company and Colorado State University compared to the 30-year average.

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

In Sept. 1995, there were 5 hurricanes in the Atlantic at one time.
Video on Hurricane Camille (Category 5, 1969, before modern satellite images were available for forecasting).
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

Exploring Planet Earth
Hurricane Track Site:
http://hurricane.ssec.noaa.gov/hurricanes/viewer.html

Legend (hurricanes are red and dark red)

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

150 Years of Hurricanes
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.
Most intense landfalling U.S. hurricanes
Intensity is measured solely by central pressure

<table>
<thead>
<tr>
<th>Rank</th>
<th>Hurricane</th>
<th>Year</th>
<th>Landfall pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&quot;Labor Day&quot;</td>
<td>1935</td>
<td>892 mbar (hPa)</td>
</tr>
<tr>
<td>2</td>
<td>Camille</td>
<td>1969</td>
<td>909 mbar (hPa)</td>
</tr>
<tr>
<td>3</td>
<td>Katrina</td>
<td>2005</td>
<td>918 mbar (hPa)</td>
</tr>
<tr>
<td>4</td>
<td>Andrew</td>
<td>1992</td>
<td>922 mbar (hPa)</td>
</tr>
<tr>
<td>5</td>
<td>Indiana</td>
<td>1886</td>
<td>925 mbar (hPa)</td>
</tr>
<tr>
<td>6</td>
<td>&quot;Florida Keys&quot;</td>
<td>1919</td>
<td>927 mbar (hPa)</td>
</tr>
<tr>
<td>7</td>
<td>&quot;Okeechobee&quot;</td>
<td>1928</td>
<td>929 mbar (hPa)</td>
</tr>
<tr>
<td>8</td>
<td>Donna</td>
<td>1960</td>
<td>930 mbar (hPa)</td>
</tr>
<tr>
<td>9</td>
<td>&quot;New Orleans&quot;</td>
<td>1915</td>
<td>931 mbar (hPa)</td>
</tr>
<tr>
<td>10</td>
<td>Carla</td>
<td>1961</td>
<td>931 mbar (hPa)</td>
</tr>
</tbody>
</table>

Source: U.S. National Hurricane Center

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

<table>
<thead>
<tr>
<th>Rank</th>
<th>Hurricane</th>
<th>Year</th>
<th>Cost (2004 USD)</th>
</tr>
</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

Costliest Atlantic Hurricanes, 1851-2007 (Katrina, 2005, not shown) [soh:isc-maps-q.csc.noaa.gov/hurricanes]
Today: Tornadoes

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, 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)


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

Vilonia, AR, EF-3 (NWS) tornado April 27, 2014


Note that damage is very localized (USA Today, April 29, 2011)

Data from NOAA - http://www.ncdc.noaa.gov/sotc/tornadoes/

Vilonia, AR, EF-3 (NWS) tornado April 27, 2014

At least 26 tornado deaths in SE U.S., April 27-28, 2014

Note that damage is very localized (USA Today, April 28, 2014)
Tornadoes:
1. Form in intense thunderstorms caused by collision of cold air and warm moist air along a front.

Tornado and flying debris, Chapter 14, text

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.

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).

Clouds associated with a Low pressure area and cold front.

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.
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

---

Table 14.1, text, L&T, 2008

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

Table 14.1, text, L&T, 2014

---

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

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

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

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


Multiple-Vortex Tornado

Tornado Videos

Figure 14.22, text

Figure 14.21, text
Average number of tornadoes, tornado days, and annual tornado incidence each month in the U.S. (Figure 14.23, text)

USA Today April 11, 2012

Disaster Type:
- Population increased by ~37 million


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

Disaster Type:
- Flooding
- Hurricane
- Tornadoes
- Wind
- Winter storms
- Heat waves

Population increased by ~37 million
Human influences on the atmosphere

1. 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 (radiated by Earth’s surface) is absorbed and reflected by greenhouse gases in the atmosphere.

4. Effects:
   - Global warming
   - Sea level rise
     \[ \approx 0.3 \text{ to } 0.5 \text{ m/100 years} \]
   - Possible droughts, increased deserts, etc.

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 343-348 in Text.

Greenhouse Effect (cont.)

It's now about 400

Figure 11.5, text

Recent atmospheric carbon dioxide (CO₂) increases. Monthly CO₂ 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 CO₂. [http://en.wikipedia.org/wiki/Global_warming](http://en.wikipedia.org/wiki/Global_warming)
So, CO₂ in Atmosphere is "good" – Earth’s atmosphere would be ~ 30°C colder without greenhouse effect!

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

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

Correlation of emissions and global average temperatures.

Correlation of global average temperature, industrial SO₂ emissions and CO₂ concentration in the atmosphere, 1880-2000.

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

November, 2009 Icebergs near South Island of New Zealand (some >200 m long) that broke off (total of >30 km$^2$ 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 332-333 in Text.

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

- \[ \text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \] (1)
- \[ \text{ClO} + \text{O}_3 \rightarrow \text{Cl} + 2 \text{O}_2 \] (2)

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. \(2 \text{O}_3 \rightarrow \text{O}_2 + 2 \text{O}_2\) [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).
3. Acid Rain

- SO₂, NOx \rightarrow \text{sulfuric and nitric acids in atmosphere and in precipitation}
- Produced by burning fossil fuels
- Destroys
  - wildlife in lakes
  - forests
  - building stone, concrete
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