ATMOSPHERIC POLLUTANTS
Acid Rain

- **Acid Rain** is the precipitation that carries higher-than-normal amounts of nitric or sulfuric acid
  - May also include “dry deposition”

- ‘Neutral’ rain is slightly acidic (pH around 5.6) due to naturally-occurring chemicals
  - pH of 7.0 is neutral; less than that is considered acidic, greater than that is alkaline
  - Each 1.0 decrease in the scale indicates a 10-fold from the next-higher number (e.g., water with a pH of 5.0 is 10 times more acidic than one with a pH of 6.0)
  - The most acidic rain in the U.S. (as of 2000 according to the EPA) had a pH of 4.3 (Colorado has seen highly acidic snow)

- Causes of Acid Rain:
  - Volcanic eruptions
  - Decomposition of organic matter
  - Burning wood
  - Burning fossil fuels

- Main *anthropogenic* (man-made) sources are sulfur dioxide (SO$_2$) and Nitrogen Oxides (NO$_x$) emitted by power plants, industry, and automobiles

Source: NASA
Impacts of Acid Rain

- **Surface Waters:**
  - Kills or sickens fish and other food sources (such as insects) upon which they rely
  - Excess nitrogen depletes oxygen (*eutrophication*), causing algae blooms and fish kills
  - Leaches heavy metals, particularly aluminum, from the soil, which is toxic to many fish and plants
  - Alkaline substances in the soil may counteract the effects of acid rain, but may become overwhelmed
  - May get a ‘shock’ with spring snowmelt, runoff

- **Forests:**
  - Acid buildup in soil weakens trees, making them more susceptible to other threats
  - Dissolves and washes away nutrients
  - Fog at higher elevations constantly bathe trees in acid, washing away nutrients

- **Materials:**
  - Causes blotches and fading of painted surfaces, including cars
  - Deterioration of stone, particularly marble and limestone
  - Corrosion of metals such as bronze and steel

- **Visibility:**
  - Molecules are larger and scatter more incoming light, reducing visibility
  - Accounts for 50-70% of visibility reduction in the eastern U.S.

- **Human Health:**
  - Increase in heart and lung disorders, including asthma and bronchitis
  - Causes an estimated $50 billion annually in premature mortality, hospital admissions, and emergency room visits
Reducing Acid Rain

- Monitor and Report

- Reduce smokestack emissions
  - Remove sulfur at the source; clean coal
  - Use scrubbers to remove SO$_2$ before it leaves the smokestack (chemical interactions that bind it with other substances that can be collected)
  - Use catalytic converters to remove NO$_x$ from automobile emissions

- Use alternative energy sources
  - Natural gas: still pollutes, but not as much
  - Nuclear energy
  - Hydropower
  - Renewable energy: wind, solar, geothermal
  - Electric vehicles

- Restore damaged environments
  - Limestone may be added to water to cancel out some of the acidity on a short-term basis (but very expensive)
Ozone

- The ozone layer is a concentration of ozone \((O_3)\) particles in the stratosphere.

- Ozone is very good at absorbing harmful high-energy ultraviolet radiation from the sun.

- During the 1980s it was discovered that chemicals, called chlorofluorocarbons (CFCs), were depleting the concentration of atmospheric ozone:
  - CFCs were commonly used in refrigeration, aerosol sprays, and solvents.
  - One chlorine atom can break apart more than 100,000 ozone molecules.

- The Montreal Protocol agreement in 1987 put in place a ban on CFCs:
  - Alternative chemicals and technologies have been developed to replace CFCs.

- As a result of these actions, the ozone layer is expected to recover by 2050.

Source: NASA
But I Thought Ozone Was Good...

- Up high, ozone filters harmful solar radiation...
- ...but it’s not a good thing to breathe
  - Can worsen bronchitis, asthma, and emphysema
  - Prolonged exposure can irritate and scar lung tissue
- Ozone can also harm vegetation and ecosystems and make trees more susceptible to disease
- Ozone is created from Nitrogen Oxides (NO\(_x\)) – the same bad guys as in acid rain
- Ultraviolet radiation from the sun converts NO\(_x\) near the surface into ozone
  - Strong sunlight and high temperatures accelerate the process
  - Winds may carry emissions far from their sources, so regions downwind may have similar air quality problems

Source: EPA
Carbon Dioxide

Carbon Dioxide (CO2) is a critical component of the Earth’s biosystems:
- Used by plants to convert to sugars (energy)
- Plants release oxygen as a waste product, which animals use
- Animals, in turn, release carbon dioxide as a waste product

However, high in the atmosphere, the radiative properties of CO2 cause trouble:
- Relatively transparent to incoming solar radiation but a good absorber of longer-wavelength radiation emitted by the Earth
- CO2 essentially allows in the sun’s energy but traps the outgoing energy from the Earth, causing temperatures to rise in what is known as the Greenhouse Effect

Carbon dioxide has been building in the atmosphere as a byproduct of the combustion of fossil fuels – coal, oil, and natural gas:
- Some CO2 is a good thing – recall that the Earth’s average temperature would be about 0° F without it

Other gasses can also add to the greenhouse effect, particularly methane

Source: Washington Department of Ecology
Carbon Dioxide Variations

The Industrial Revolution Has Caused A Dramatic Rise in CO₂

Ice Age Cycles

CO₂ Concentration (ppmv)
The Greenhouse effect

Solar radiation passes through the clear atmosphere.
Incoming solar radiation: 343 Watt per m²

Some solar radiation is reflected by the atmosphere and earth’s surface.
Outgoing solar radiation: 103 Watt per m²

Net incoming solar radiation: 240 Watt per m²

Some of the infrared radiation passes through the atmosphere and is lost in space.
Net outgoing infrared radiation: 240 Watt per m²

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules. The direct effect is the warming of the earth’s surface and the troposphere.
Surface gains more heat and infrared radiation is emitted again

Solar energy is absorbed by the earth’s surface and warms it...
168 Watt per m²

... and is converted into heat causing the emission of longwave (infrared) radiation back to the atmosphere
Other stuff that may affect our climate
Factors Affecting Climate

- Orbital Variations (millennia)
  - **Eccentricity** – the shape of the orbit around the sun (90,000-100,000 years)
  - **Obliquity** – changes in the angle that Earth’s axis makes with the plane of Earth’s orbit (40,000 years)
  - **Precession** – the change in the direction of the Earth’s axis of rotation (25,800 years)
Factors Affecting Climate

- Orbital Variations (millennia)
- Solar Variations (decades)
  - A fairly regular 9-14 year (average 11) cycle in solar energy output, seen through the number of sunspots
  - Last solar maximum was in 2001; next is predicted for May 2013

Source: NASA
Factors Affecting Climate

- Orbital Variations (millennia)
- Solar Variations (decades)
- Oceanic Circulations (decades)
  - Periodic episodes of warming or cooling in different ocean basins
  - May combine with other circulation patterns to reinforce or counteract other climate trends

Source: NASA
Factors Affecting Climate

- Orbital Variations (millennia)
- Solar Variations (decades)
- Oceanic Circulations (decades)
- Volcanic Emissions (1-2 years)
  - Sulfate aerosols block solar radiation from surface, causing much lower temperatures (lasts 1-2 years)
  - Only eruptions whose plumes penetrate the lower stratosphere cause large variability; very few volcanoes do so

Source: NASA
Colorado Statewide Mean Annual Temperature

Annual 1901 - 2000 Average = 44.87 degF
Annual 1895 - 2007 Trend = 0.16 degF / Decade

1993 – likely cold due to large tropical volcanic eruption in previous year
Factors Affecting Climate

- Orbital Variations (millennia)
- Solar Variations (decades)
- Oceanic Circulations (decades)
- Volcanic Emissions (1-2 years)
- Change in Land Cover (gradual changes, affecting *albedo*)
  - Deforestation: more vegetation creates cooler, wetter surface conditions; less vegetation leads to warmer, drier conditions
  - Ice cover: more ice reflects more sunlight, leading to cooling; less ice allows more sunlight to be absorbed, warming the surface

Source: NASA, USDA
The recent warming is unusual...

2000 Year Northern Hemisphere Reconstruction of Surface Air Temperatures

Source: Moberg et al *Nature* 2005
...and solar variability cannot explain it
So here comes the question -- What happens next??

CLIMATE CHANGE PROJECTIONS for COLORADO

-- for this topic, we borrow from a recent series of presentation developed by the Western Water Assessment at CU and their CWCB-funded Colorado Climate Roadshow presentations
Scenarios of Climate Change in Colorado

Joe Barsugli
University of Colorado at Boulder

http://wwa.colorado.edu/climate_change/drought09.html

Not just for water managers!
Climate change information is difficult to integrate into resource management.

- First, the climate is no longer “stationary”; the past is becoming a less reliable guide to the future.
- Second, the century time scales of climate change are remote from human experience.
- Third, even individuals trying to stay up-to-date can face confusion in conceptually melding the burgeoning climate change impacts literature.

Adapted from .. CCSP 5.1, Chapter 5, “Decision Support for Water Resources Management”, Holly C. Hartmann, lead author.
“Cognitive Challenges”

“There’s been an accident, but it doesn’t involve me.”

Finally, the impacts may seem distant from the cause.....
The Intergovernmental Panel on Climate Change (IPCC) formed in 1988 under the auspices of the United Nations. Its purpose is to provide assessments of the science of climate change from published research.

- **Working Group I:** Physical Science
- **Working Group II:** Impacts and Adaptation
- **Working Group III:** Mitigation

- **Mitigation:** actions taken to reduce climate change such as reduction in GHG emissions, reforestation, carbon sequestration.

- This presentation will be about the physical science and potential impacts in Colorado.
Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth’s surface and lower atmosphere.

About half the solar radiation is absorbed by the Earth’s surface and warms it.

Infrared radiation is emitted from the Earth’s surface.
Climate Change: CO2 Emissions & Concentration

**Emissions**

<table>
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<th>Year</th>
<th>Fossil Fuel Emission (Gt C/y)</th>
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<tr>
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<tr>
<td>1870</td>
<td>0</td>
</tr>
<tr>
<td>1890</td>
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<tr>
<td>1990</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>9</td>
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</table>

**RECENT GLOBAL MONTHLY MEAN CO2**

<table>
<thead>
<tr>
<th>Year</th>
<th>Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>376</td>
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<tr>
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</tr>
<tr>
<td>2009</td>
<td>386</td>
</tr>
<tr>
<td>2010</td>
<td>388</td>
</tr>
</tbody>
</table>

**CO2 emissions → accumulation of CO2 in atmosphere**

- Pre-Industrial: 270 ppm
- 2009: 386 ppm
Global Indicators of Warming

(a) Global mean temperature

(b) Global average sea level

Difference from 1961-1990 average

- 1.4°F
- 0.5 ft
How do we attribute recent trends to manmade greenhouse gases?

- Models that **include** manmade greenhouse gases along with natural drivers of climate (red) **do** reproduce recent trends (black)
- Models that **leave out** human-caused greenhouse gases (blue) **do not** reproduce recent trends

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*Solomon, 2007* (Meehl et al., 2004)
In North America, “human-induced warming has likely caused much of the average temperature increase over the past 50 years” (CCSP 3.3).

Climate models show a 1°F warming in the West in the last 30 years in response to greenhouse gas emissions.

Source: CO Climate Report, 2008
Regardless of GHG emissions, temperature increases by 2025 and 2050 will be about the same.
Climate models (GCMs) simulate the complex interactions among the land, oceans, atmosphere.

- **Climate models have improved** in their ability to simulate the climate
- **A number of climate models are available** from different research groups and countries
- It is very important to **compare results from different models, and to consider multi-model averages.**
Climate models divide the globe into gridcells

- Typical grid size: 60-180 mi (100-300 km)
- Vertical: ~30 layers of varying depth
All this fits in a single global climate model grid cell!

Probably better if you are in Kansas!

Bottom line: Need to use additional analysis to relate climate model output to local impacts
A climatological average in the future will be like taking a snapshot of moving object…
Climate models project Colorado will warm by
2.5°F by 2025
4°F by 2050
relative to the 1950-1999 baseline

**Temperature**
Colorado: range
+4°F Annual [2.5-5.5]
+3°F Winter [2-5]
+5°F Summer [3-7]

Multi-model average of 22 climate models; 4 - 12 gridcells cover Colorado, depending on the model.

Source: CO Climate Report, 2008
Winter temperatures shift northward on the plains.

Temperatures creep upwards in the mountains in all seasons.

What would the projected changes mean for Colorado’s varied climate?

January

Source: CO Climate Report, 2008
Temperatures (1950–1999)

July

Temperatures (Projected 2050)

Source: CO Climate Report, 2008

Projections: Temperature

What would the projected changes mean for Colorado’s varied climate?

Temperatures creep upwards in the mountains in all seasons

Summer temps shift westward on the plains bringing the temperatures of the Kansas border to the Front Range.
Area around Granby, CO

Projections: Annual Cycle of Temperature

- Summers warm more than winters
- Average summer temps similar to hottest days in the past few years
- Earlier spring
Area around Grand Junction, CO

Annual average temperature

Projections: Time-evolving vs. “snapshots”

Multi-model average projection
Projections: Heat Waves

As average temperatures shift so do the extremes

No. of days that hit 100°F would increase from <10/year to 20-60/year at lower elevations in Colorado by 2080-2099

High Confidence

Annual U.S. precip will increase in the northeast and decrease in the southwest
Model projections do not agree whether annual mean precipitation will increase or decrease in Colorado by 2050.

**Precipitation**
Colorado is in a zone of small projected precipitation changes.

**Model Agreement for Precipitation**
Colorado is in a region of weak model agreement.
Precipitation will continue to be variable
More mid-winter precipitation and less in late spring and summer
Uncertainty in precipitation projections for all seasons: Summertime (monsoon) precip. not well simulated. Future changes to ENSO also very uncertain.
Increase in heavy precipitation events projected for the United States

More water vapor $\rightarrow$ heavier precipitation

Conflicting analyses for Colorado
Recap

- Temperature projections (relative to 1950-1999)
  + 2.5°F by 2025
  + 4°F by 2050

- Precipitation projections
  - Annual precipitation trends uncertain
  - Some agreement on more mid-winter precipitation and less in late spring and summer

- Both temperature and precipitation trends have implications for the hydrologic cycle
Societal response is key

Multi-model Averages and Assessed Ranges for Surface Warming

Global surface warming (°C)

Year
Temperature Projections: A Range of Possibilities

Societal Response

Green Response

Middle Road

Maximum Growth
Winners and Losers

“There will be winners and losers from the impacts of climate change, even within a single region, but globally the losses are expected to far outweigh the benefits.” – from the National Academies’ report “Understanding and Responding to Climate Change”.

Congratulations!!

- It’s Break Time!