An Introduction to Climate Change

IPOL 8512
What determines Earth’s temperature?

- Earth’s temperature depends on the balance between energy entering and leaving.
  - When incoming energy from the sun is absorbed by the Earth system, Earth warms.
  - When the sun’s energy is reflected back into space, Earth avoids warming.
  - When energy is released back into space, Earth cools.
What could change the Earth’s energy balance and change the Earth’s temperature?

- Changes in solar input
  - Sun’s output
  - Earth’s position and orientation
  - Cosmic dust
- Changes in transparency of atmosphere to incoming shortwave energy
  - Clouds
  - Dust, ash, soot
  - O$_3$
- Changes in transparency of atmosphere to outgoing long wave radiant energy
  - Clouds
  - Greenhouse gases (H$_2$O, CO$_2$, CH$_4$, N$_2$O, O$_3$)
What could change the Earth’s energy balance and change the Earth’s temperature?

• Changes in reflectivity & evapotranspiration at the surface
  – Changes in extent of forests, grasslands, deserts
  – Changes in extent and condition of water
  – Changes in extent and condition of snow and ice

• Changes in heat added at the surface by human activities and geothermal sources
Climate Change

- Earth's average temperature has risen by about 0.8 °C (1.4 °F) over the past century, with about 2/3 of this since 1980.
- Projected to rise another 1 to 6 °C (2 to 11.5 °F) over the next hundred years.
- Small changes in the average temperature lead to large and potentially dangerous shifts in climate and weather. For example,
  - Changes in rainfall, resulting in more floods, droughts, or intense rain, as well as more frequent and severe heat waves.
  - Oceans are warming and becoming more acidic, ice caps are melting, and sea levels are rising.

http://www.epa.gov/climatechange/basics/
http://www.explainingclimatechange.ca/
Climate vs. Weather

- **Weather** = the conditions of the atmosphere over a short period of time and typically for a local area.
  - Familiar examples of weather characteristics include the daily temperature, humidity, or the amount of precipitation produced by a storm.
  - Weather also includes severe weather conditions such as hurricanes, tornadoes, and blizzards.
  - Because of the dynamic nature of the atmosphere, it is not possible to predict weather conditions in a specific location months or years in advance.

- **Climate** = the behavior of the atmosphere over a longer period of time and usually for a large area.
  - Climate is typically defined based on 30-year averages of weather.
  - Climate represents our expectations for the weather.
  - Scientists can compare recent and long-term observations of the climate to detect the influence of greenhouse gases on climate conditions.

[http://www.epa.gov/climatechange/science/](http://www.epa.gov/climatechange/science/)
Temperature Variation from 1880-present

Global Land–Ocean Temperature Index

Temperature Anomaly (°C)

-0.4
-0.2
0.0
0.2
0.4
0.6

Annual Mean

5–year Running Mean

1880 1900 1920 1940 1960 1980 2000

http://www.explainingclimatechange.ca/Climate%20Change/swf/videos/historical%20_temp.swf
Where is global warming going?

- Ocean: 93.4%
- Atmosphere: 2.3%
- Continents: 2.1%
- Glaciers & ice caps: 0.9%
- Arctic sea ice: 0.8%
- Greenland Ice Sheet: 0.2%
- Antarctic Ice Sheet: 0.2%
Effect on Glaciers

Average Glacier Thickness Change (cm/yr)

Cumulative Mean Thickness Change (meters)

Extent of Arctic summer ice in 1979 (top satellite image) and in August 2012 (lower satellite image).
Extent of ice melt in Greenland, 1992 and 2002

Arctic Climate Impact Assessment 2004
When permafrost temperature rises above the freezing point, and the permafrost melts, power lines, pipelines, and buildings built over the permafrost can topple, sag, and crack.
Why care about climate?

Climate governs:

• Distribution & abundance of species
• Productivity of farms, forests, & fisheries
• Geography of disease
• Livability of cities in summer
• Damages from storms, floods, wildfires
• Property losses from sea-level rise
• Expenditures on engineered environments
“Climate change” means a change in the means and extremes (variances about the mean) that define the climate, either globally or in a particular climate zone.

A key example is a change in average surface temperature. Another is occurrence of more extreme events - heat waves, droughts, hurricanes, etc.
The Greenhouse Effect

Solar radiation:
343 Watts per m²

Some of the solar radiation is reflected by the atmosphere and the Earth's surface.

Outgoing solar radiation:
103 Watts per m²

Some of the infrared radiation passes through the atmosphere and out into space.

Outgoing infrared radiation:
240 Watts per m²

Solar radiation passes through the atmosphere.

Incoming solar radiation:
240 Watts per m²

About half the solar radiation is absorbed by the Earth's surface.

Absorption solar radiation:
168 Watts per m²

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules.

Radiation is converted to heat energy, causing the emission of longwave (infrared) radiation back to the atmosphere.
Radiant Energy

- **Radiant Energy** is electromagnetic energy that behaves like a stream of particles.
- It has a dual Nature
  - Particle
    - photons = tiny packets of radiant energy
    - $10^{17}$ photons/second from a flashlight bulb
  - Wave
    - oscillating electric and magnetic fields
    - describes effect on space, not true nature of radiant energy
A Light Wave’s Electric and Magnetic Fields

- **Source**
- **Wavelength, \( \lambda \), the distance between two peaks**
- **Electric field, perpendicular to magnetic field**
- **Magnetic field, perpendicular to electric field**
- **Radiant energy**
Radiant Energy Spectrum

- **gamma rays**: from radioactive decay
- **x-rays**: used for medical and dental x-rays
- **ultraviolet (UV)**: causes tanning, skin cancer, genetic damage
- **visible**
- **infrared (IR)**: released when bodies cool
- **microwaves**: used for microwave ovens, radar, and space vehicle communication
- **television and radio waves**: used for communication and entertainment

Photon energy vs. wavelength (μm)
Greenhouse gases

- **Greenhouse gas** = Any gas that absorbs infrared radiation in the atmosphere. Each gas absorbs radiation at specific wavelengths as function of its structure.

- Without them, Earth's surface would be on average about 33 °C (59 °F) colder than at present.

- *Important greenhouse gases:*
  - Water vapor (H₂O)
  - Carbon dioxide (CO₂)
  - Methane (CH₄)
  - Nitrous oxide (N₂O)
  - Chlorofluorcarbons (CFCs)
  - Halogenated fluorocarbons (HCFCs)
  - Ozone (O₃)
  - Hydrofluorocarbons (HFCs).

**Individual Emissions**
http://www.epa.gov/climatechange/ghgemissions/individual.html
Vibration Modes of Greenhouse Gas Molecules

• As the Earth cools, it emits infrared (IR) photons.
• When a greenhouse gas molecule absorbs an IR photon, the molecule gets excited to a higher vibrational energy.
• When the molecule returns to a more stable vibrational energy, it emits an IR photon in a random direction.
• Some of the remitted photons return to Earth.

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CO2_html/CO2_page.html
http://www2.ess.ucla.edu/~schauble/MoleculeHTML/H2O_html/H2O_page.html
http://www2.ess.ucla.edu/~schauble/MoleculeHTML/N2O_html/N2O_page.html
http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CH4_html/CH4_page.html
http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CHClF2_html/CHClF2_page.html
http://www.explainingclimatechange.ca/Climate%20Change/swf/irwindows/IRwindows2.swf
Composition of Air

Average composition of dry atmosphere (mole fractions)

**Gas**

<table>
<thead>
<tr>
<th>Gas</th>
<th>from NASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen, N₂</td>
<td>78.084%</td>
</tr>
<tr>
<td>Oxygen, O₂</td>
<td>20.946%</td>
</tr>
<tr>
<td>Argon, Ar</td>
<td>0.934%</td>
</tr>
</tbody>
</table>

**Minor constituents (mole fractions in ppm)**

- Carbon dioxide, CO₂: About 395 and rising
- Neon, Ne: 18.18
- Helium, He: 5.24
- Methane, CH₄: 1.7
- Krypton, Kr: 1.14
- Hydrogen, H₂: 0.55

Water vapor: Highly variable; typically makes up about 1%
Radiative Forcing

- **Radiative forcing** = anything that changes the radiation balance at earth’s surface
- Measured in W/m²
- A change in radiative forcing leads to a change in surface temperature
- Both natural and anthropogenic
  - adding greenhouse gases
  - adding aerosols
  - changing albedo (land use, black carbon)
  - change in solar radiation
Natural and Anthropogenic Greenhouse Effect

NATURALLY MODERATED GREENHOUSE EFFECT

ANTHROPOGENIC GREENHOUSE EFFECT - ADDING GHG’S, INCREASING RADIATIVE FORCING
The Climate Change Story Line

Human Activities →
GHG Emissions and Land Use Changes →
Change in Atmospheric Concentrations →
Change in Radiative Forcing →
Change in Average Surface Temperature →
Direct & Indirect Feedbacks →
Direct & Indirect Biogeophysical Impacts →
Societal Impacts →
Policy Response?
  Change in GHG Emissions? (Mitigation)
  Adapting to Changes? (Adaptation)
  Suffering the Consequences? (Suffering)
Public Opinion of Climate Change

Is global warming happening?*

[Graph showing trends over time with data points for different polls and years.]

Source: Leiserowitz, 2012

*asked using differently worded questions
GHG Atmospheric Lifetimes and Global Warming Potential

• Each GHG has its own atmospheric residence time, governed by the sinks that remove it from the atmosphere.

• The global warming potential (GWP) of each GHG is measured relative to CO$_2$. GWP combines the GHG’s efficiency at trapping IR radiation with its residence time in the atmosphere.

• Example: Over a 100 year period, a molecule of CH$_4$ contributes as much radiative forcing as 25 molecules of CO$_2$. 

Global Warming Potential (GWP) = radiative impact of a GHG per molecule relative to impact of CO₂, taking into account its radiative properties and atmospheric lifetime.

Atmospheric lifetime and GWP relative to CO₂ at different time horizon for various greenhouse gases.

<table>
<thead>
<tr>
<th>Gas name</th>
<th>Chemical formula</th>
<th>Lifetime (years)</th>
<th>20-yr</th>
<th>100-yr</th>
<th>500-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>See above</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>12</td>
<td>72</td>
<td>25</td>
<td>7.6</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O</td>
<td>114</td>
<td>289</td>
<td>298</td>
<td>153</td>
</tr>
<tr>
<td>CFC-12</td>
<td>CCl₂F₂</td>
<td>100</td>
<td>11,000</td>
<td>10,900</td>
<td>5,200</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>CHClF₂</td>
<td>12</td>
<td>5160</td>
<td>1810</td>
<td>549</td>
</tr>
<tr>
<td>Tetrafluoromethane</td>
<td>CF₄</td>
<td>50,000</td>
<td>5210</td>
<td>7390</td>
<td>11,200</td>
</tr>
<tr>
<td>Hexafluoroethane</td>
<td>C₂F₆</td>
<td>10,000</td>
<td>8630</td>
<td>12,200</td>
<td>18,200</td>
</tr>
<tr>
<td>Sulphur hexafluoride</td>
<td>SF₆</td>
<td>3200</td>
<td>16,300</td>
<td>22,800</td>
<td>32,600</td>
</tr>
<tr>
<td>Nitrogen trifluoride</td>
<td>NF₃</td>
<td>740</td>
<td>12,300</td>
<td>17,200</td>
<td>20,700</td>
</tr>
</tbody>
</table>
Fast Carbon Cycle

The movement of carbon between land, atmosphere, and oceans in billions of tons of carbon per year. Yellow numbers are natural fluxes, red are human contributions in Gt of carbon per year. White numbers indicate stored carbon.
CO₂ Concentrations

http://www.eoearth.org/article/Greenhouse_gas
Role of Humans in the CO₂ Increases

- About 65% of anthropogenic CO₂ to atmosphere is from combustion of fossil fuels.
- Remaining 35% from deforestation and the conversion of prairie, woodland, and forested ecosystems primarily into less productive agricultural systems.
- Natural ecosystems can store 20 to 100 times more carbon dioxide per unit area than agricultural systems.

http://www.eoearth.org/article/Greenhouse_gas
Role of Humans in the CO$_2$ Increases

- The main human sources of CO$_2$ – deforestation and fossil-fuel burning – are quite well quantified. The observed CO$_2$ build-up in the atmosphere matches these human inputs, after subtraction of estimated rates of uptake in the oceans and northern forests.

- The ice-core data show that atmospheric CO$_2$ has not been above 300 ppm in the last 400,000 years (it’s over 390 ppm today) and that natural fluctuations in atmospheric CO$_2$ over the past 10,000 years have been only $\pm 10$ ppm (compared to the 90 ppm increase since the start of the Industrial Revolution).

- Carbon-14 analysis of tree rings back to 1800 confirms the fossil-fuel contribution to the atmospheric CO$_2$ burden in the last 200 years.
Carbon-14

- Carbon-14 is produced in the atmosphere when neutrons are absorbed by nitrogen atoms.
- Carbon-14 then undergoes beta decay, emitting an electron and an antineutrino and forming nitrogen-14.
- Carbon-14 has a half-life of 5730 years.
Measuring CO$_2$ from fossil fuels by Measuring $^{14}$CO$_2$/$^{12}$CO$_2$ Ratio

- About one in a trillion CO$_2$ molecules naturally contain $^{14}$C, but the carbon locked up in fossil fuels, such as coal and oil has none.
- Because the half-life of $^{14}$C is 5730 years, the carbon-14 in fossil fuels decayed to $^{14}$N millions of years ago
  \[ ^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + 0_{-1}\text{e} \]
- Therefore, as the amount of CO$_2$ in the atmosphere from fossil fuels rises, the ratio of $^{14}$CO$_2$/$^{12}$CO$_2$ decreases in a measurable way.
Measuring CO$_2$ from fossil fuels by Measuring $^{14}$CO$_2$/$^{12}$CO$_2$ Ratio

- Monitoring stations in the Swiss Alps and in Antarctica found that the $^{14}$CO$_2$/$^{12}$CO$_2$ is now about 0.5% lower in the Northern Hemisphere than in the Southern Hemisphere.
- Reversal since preindustrial days…tree ring records show that the Southern Hemisphere had less $^{14}$CO$_2$ because upwelling of deep waters in the southern oceans brought radiocarbon-depleted CO$_2$ to the surface.
Measuring CO$_2$ from fossil fuels by Measuring $^{14}$CO$_2$/$^{12}$CO$_2$ Ratio

- Uncertainties in estimates of fossil-fuel emissions from $^{14}$CO$_2$ are still large, because accurate modeling depends on knowing all possible sources of both radioactive and nonradioactive CO$_2$.
- One confounding factor is emissions from nuclear power plants, which generate a significant amount of $^{14}$C in regions where nuclear plants are concentrated, offsetting at least 20% of the reduction in $^{14}$CO$_2$ due to fossil fuels.
Naturally Occurring Methane

• Naturally occurring methane is mainly produced by the process of methanogenesis, a multistep process is used by microorganisms as an energy source. The net reaction is:

\[ \text{CO}_2 + 8 \text{H}^+ + 8 \text{e}^- \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O} \]

• Methanogenesis is a form of anaerobic respiration used by organisms that occupy landfill, ruminants (e.g., cattle), and the guts of termites.
Atmospheric Methane Sources

• Biogenic sources (>70% of total)
  – Wetlands
  – Rice agriculture
  – Livestock
  – Landfills
  – Biomass burning
  – Forests
  – Oceans
  – Termites

• Non-biogenic sources
  – Emissions from fossil fuel mining and burning
  – Natural gas, petroleum and coal
  – Waste treatment
  – Geological sources (methane clathrates)
  – Fossil CH₄ from natural gas seepage
  – Geothermal/volcanic CH₄
Methane Concentrations 1000-2000 AD

http://www.eoearth.org/article/Greenhouse_gas
Methane Concentrations and Radiative Forcing

IPCC = Intergovernmental Panel on Climate Change [http://www.ipcc.ch/](http://www.ipcc.ch/)
Feedback Example

Original Increase in Greenhouse Gases Because of Human Activities

Global Warming

Additional Warming

Melting of Methane Clathrates

Release of Methane Gas to Atmosphere

http://www.eoearth.org/article/Greenhouse_gas
Estimated Global Methane Balance (Tg CH₄/yr)

**NATURAL SOURCES** 220
- Wetlands 175
- Termites 20
- Ocean 15
- Hydrates 10

**HUMAN SOURCES** 380
- Energy 110
- Landfills 40
- Ruminants 115
- Waste treatment 25
- Rice agriculture 50
- Biomass burning 40

**TOTAL SOURCES** 600

**NATURAL SINKS** 580
- Soils 30
- Tropospheric OH 510
- Stratos. destruction 40

**TOTAL SINKS** 580

**ANNUAL IMBALANCE**
\[ = \text{ SOURCES} - \text{ SINKS} \]
\[ = 600 - 580 = +20 \]
Role of Humans in the N₂O Increases

• The average concentration of nitrous oxide in the atmosphere is now increasing at a rate of 0.2 to 0.3% per year.

• Sources for the increase of nitrous oxide in the atmosphere include land-use conversion, fossil fuel combustion, biomass burning, and soil fertilization.
  – Most of the nitrous oxide added to the atmosphere each year due to human activities comes from agricultural soils, where nitrogen-rich fertilizer and manure is converted to nitrous oxide by soil bacteria. Nitrous oxide is also released into the atmosphere when fossil fuels and biomass are burned.

http://www.eoearth.org/article/Greenhouse_gas
N$_2$O Concentrations

http://www.eoearth.org/article/Greenhouse_gas
## Global Nitrous Oxide Balance (Tg(N)/yr)

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Flow (Tg(N)/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural Sources</strong></td>
<td>9.6</td>
</tr>
<tr>
<td>Oceans</td>
<td>3.0</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.6</td>
</tr>
<tr>
<td>Tropical soils</td>
<td>4.0</td>
</tr>
<tr>
<td>Temperate soils</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Human Sources</strong></td>
<td>5.4</td>
</tr>
<tr>
<td>Agriculture</td>
<td>3.0</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>0.5</td>
</tr>
<tr>
<td>Industry/energy</td>
<td>1.3</td>
</tr>
<tr>
<td>Cattle/feedlots</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total Sources</strong></td>
<td>15.0</td>
</tr>
</tbody>
</table>

**Only sink is**...

- Destruction in stratosphere: 11.0

**Total Sink**: 11.0

**Annual Imbalance** = INFLOWS - OUTFLOW

= 15.0 – 11.0 = 4.0 Tg N/y
CFC Concentrations

NOAA global flask sampling network, [http://www.esrl.noaa.gov/gmd/ccgg/](http://www.esrl.noaa.gov/gmd/ccgg/)
Projected impacts of climate change

<table>
<thead>
<tr>
<th>Global temperature change (relative to pre-industrial)</th>
<th>0°C</th>
<th>1°C</th>
<th>2°C</th>
<th>3°C</th>
<th>4°C</th>
<th>5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food</strong></td>
<td></td>
<td></td>
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<tr>
<td>Falling crop yields in many areas, particularly...</td>
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<tr>
<td>Possible rising yields in some high latitude regions</td>
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<tr>
<td>Falling yields in many developed regions</td>
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<tr>
<td><strong>Water</strong></td>
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<tr>
<td>Small mountain glaciers disappear – water supplies threatened in several areas</td>
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<tr>
<td>Significant decreases in water availability in many areas, including Mediterranean and Southern Africa</td>
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<tr>
<td>Sea level rise threatens major cities</td>
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<tr>
<td><strong>Ecosystems</strong></td>
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<tr>
<td>Extensive Damage to Coral Reefs</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rising number of species face extinction</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Extreme Weather Events</strong></td>
<td></td>
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<tr>
<td>Rising intensity of storms, forest fires, droughts, flooding and heat waves</td>
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<tr>
<td><strong>Risk of Abrupt and Major Irreversible Changes</strong></td>
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<tr>
<td>Increasing risk of dangerous feedbacks and abrupt, large-scale shifts in the climate system</td>
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</tbody>
</table>
SOME EXAMPLES OF CLIMATE CHANGE IMPACTS

- Biodiversity
- Coral Reefs
- Disease vectors
- Extreme Weather
- Sea level rise
- Water supplies
- Wildfires