The Temperature of the Earth

The equilibrium temperature of the Earth is when the incoming energy from solar radiation (visible) is equal to the outgoing energy from thermal (IR) radiation. This can be calculated by equating the incoming solar radiation with the outgoing thermal (IR) radiation (using the Stefan-Boltzmann law that we learned during the second week of class \( ER = \sigma_B T^4 \)) and taking into account the average Earth-sun distance (150 million km), and rearranging to give:

\[
T_e = \left[ \frac{F_s (1 - A_e)}{4 \varepsilon_e \sigma_B} \right]^{\frac{1}{4}}
\]

\( T_e \) is the equilibrium temperature of the Earth (in degrees Kelvin), \( F_s \) is the solar constant (which takes into account the distance of the Earth from the sun), \( A_e \) is the Earth’s albedo, \( \varepsilon_e \) is the thermal emissivity of the Earth (emissivity is the ratio of power radiated by a substance to the power radiated by a blackbody at the same temperature), and \( \sigma_B \) is the Stefan-Boltzmann constant. If we plug in values for, \( F_s = 1365 \text{ W m}^{-2}, A_e = 0.3 \) (i.e. 30% of visible light from the sun is reflected by the Earth’s surface and atmosphere), \( \varepsilon_e = 1.0 \) (assume the Earth is a perfect blackbody), and \( \sigma_B = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \), \( T_e = 255 \text{ K} \). This is equal to \(-18^\circ\text{C} \) \((^\circ\text{C} = K - 273)\), or \(-81^\circ\text{F} \) \((^\circ\text{F} = ^\circ\text{C} \times (9/5) + 32)\). Brrrrrr………

According to this equation, the Earth should be frozen. There would be no liquid water making it impossible for life on Earth to exist as we know it. Why isn’t it this cold? The warming is due to the natural greenhouse effect. The average emissivity \( (\varepsilon_e) \) of the Earth is \( \sim 0.75 \) (not 1), due to the presence of greenhouse gases in the atmosphere. Using this value in the above equation gives a surface temperature of 288 K \((15^\circ\text{C} \text{ or } 59^\circ\text{F})\).

The Greenhouse Effect and Greenhouse Gases

The Greenhouse Effect is the warming of the Earth’s lower atmosphere due to gases (both natural and anthropogenic) that transmit the sun’s visible radiation, but absorb and reemit the Earth’s thermal infrared (IR) radiation. The greenhouse effect gets its name from a greenhouse, or glass house, whose class walls/ceilings allow visible light to pass through, while only allowing a portion of the thermal IR radiation to escape.

What are the major greenhouse gases in the atmosphere and their sources? We have already talked about most of them. The major greenhouse gases include:

Water vapor: \( \text{H}_2\text{O} \)
Carbon dioxide: CO$_2$
Methane: CH$_4$
Nitrous oxide “laughing gas”: N$_2$O
Tropospheric ozone: O$_3$
Chlorofluorcarbons: CFCs
Hydrofluorocarbons: HCFCs
Perfluorocarbons: PFCs
Sulfur hexafluoride: SF$_6$

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Major natural sources</th>
<th>Major anthropogenic sources</th>
<th>Atmospheric lifetimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapor (H$_2$O)</td>
<td>evaporation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO$_2$)</td>
<td>Respiration, aerobic decay of vegetation, wildfires, outgassing by ocean</td>
<td>Fossil fuel burning, biomass burning, deforestation</td>
<td>&gt; 100 years</td>
</tr>
<tr>
<td>Methane (CH$_4$)</td>
<td>Bacterial (wetlands)</td>
<td>Leaks from the production of fossil fuels, ruminants (e.g. cows), rice paddies</td>
<td>10 – 15 years</td>
</tr>
<tr>
<td>Nitrous oxide (N$_2$O) “laughing gas”</td>
<td>Bacterial breakdown of nitrogen compounds in soils</td>
<td>Nitrogen fertilizers, combustion of fuels, industrial processes</td>
<td>120 years</td>
</tr>
<tr>
<td>Tropospheric Ozone (O$_3$)</td>
<td>Produced from chemical reactions in the atmosphere requiring NOx, sunlight, and CO/hydrocarbons</td>
<td>Produced from chemical reactions in the atmosphere requiring NOx, sunlight, and CO/hydrocarbons</td>
<td>hours to weeks</td>
</tr>
<tr>
<td>Chlorofluorcarbons (CFCs), Hydrofluorocarbons (HCFCs), Perfluorocarbons (PFCs)</td>
<td>none</td>
<td>Refrigeration, propellants (banned in developed countries)</td>
<td>50 – 150 years</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>CFC replacement</td>
<td>2 – 40 years</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>Aluminum smelting and semiconductor manufacturing</td>
<td>Up to 50,000 years</td>
</tr>
<tr>
<td>Sulfur hexafluoride (SF$_6$)</td>
<td>none</td>
<td>Insulator for electrical equipment</td>
<td>3,200 years</td>
</tr>
</tbody>
</table>

*The ones in pink are regulated by the Kyoto Protocol*
**Recent and Historical Temperature and Greenhouse Gas Trends**

How has the Earth’s temperature and greenhouse gas concentration varied in the past, and how are they changing now due to human influence?

We get information about past climates from paleoclimate reconstruction methods, which take advantage of chemical, physical, and biological parameters that reflect past changes in the environment where the proxy grew or existed. The relevance of deep past climates (prior to 3 million years ago) is that they were often warmer than today and associated with higher CO\textsubscript{2} levels. In that sense they may be thought of as partial analogues of future climate changes (partial in the sense that global biology and geology were increasingly different than they are today). In general, these warmer climates are associated with higher greenhouse gas concentrations.

Holocene – current warm period
- last 10,000 years of Earth’s history
- the time since the last major ice age
- period of stable climate

Agriculture began ~8,000 years ago.

**Climate versus Weather:**
Weather – state of the atmosphere as we experience it instantaneously
Climate – average weather over an extended period of time in a specific region
Global climate – globally averaged weather over an extended period of time
Global average temperature is a stable parameter for climate.

Estimating changes in global average temperature, from either direct measurements or proxy data, requires a compilation of measurements over different regions (both northern and southern hemisphere), and a statistical analysis of the data with respect to how a particular data set may represent global average temperatures. These global reconstructions are difficult because most available data is from the Northern Hemisphere.

The instrumental temperature record is much more certain (generally, the farther back in time you go, the larger the uncertainty). Global average temperatures are compiled from many different temperature measurements all over the globe.


**Climate Feedbacks**

Why is future climate change so hard to predict? Response of global temperature change to changes in CO\textsubscript{2} and other greenhouse gases is not completely predictable due to other mechanisms, called feedbacks, in the Earth’s climate system.
Climate feedbacks can be both negative and positive.

**Positive feedback** – climate response mechanism that causes temperatures to change further in the same direction as that of the initial temperature perturbation

**Negative feedback** – climate response mechanism that causes temperatures to change in the opposite direction from that of the initial temperature perturbation

Examples of positive and negative feedback mechanisms:

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Negative feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapor – temperature rise</td>
<td>Low Clouds</td>
</tr>
<tr>
<td>High clouds</td>
<td>Plant – CO₂</td>
</tr>
<tr>
<td>Snow albedo</td>
<td>Phytoplankton (DMS)</td>
</tr>
<tr>
<td>CO₂ solubility</td>
<td></td>
</tr>
<tr>
<td>Bacterial decomposition – CO₂</td>
<td></td>
</tr>
<tr>
<td>Permafrost – CH₄</td>
<td></td>
</tr>
</tbody>
</table>

**Evidence and Possible Consequences of Global Warming**

Greenhouse gas concentrations in the atmosphere are highly correlated with surface temperatures throughout the geological record, and greenhouse gas concentrations are increasing at an unprecedented rate due to human activities since the Industrial Revolution. This alone suggests that the global mean surface temperatures are and will continue to increase with increasing greenhouse gas emissions. What are the consequences of a warmer world?

- Temperature change
- Change in cloudiness and precipitation
- Melting ice caps and glaciers
- Increase in sea levels (3 slides)
- Increase in extreme weather events (hurricanes, droughts, heat waves, etc)
- Increased heat related illness and mortality
- Ocean acidification
- Enhanced air pollution
- Shifts in agriculture
- Shifts in ecosystems
- Effects on human health
- Effects on stratospheric ozone
- Impacts on ocean circulation

**Climate Impacts Group (CIG) at the UW**

Regulatory Control of Greenhouse Gases and Global Warming

Global warming is an international problem. Greenhouse gases are relatively long lived, so that emissions in one country will be transported across the globe, affecting everyone. Governments have done relatively little to combat global warming. The reasons for this are economic – fossil fuels are currently the cheapest energy source.

In the United States, no federal regulation to date has directly confronted this issue. Air pollution legislation, such as the Clean Air Act, have reduced CO$_2$ emissions indirectly – i.e. improvements in vehicle fuel mileage.

International Regulation:

The first international negotiations to combat climate change began in 1992 at the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC is an international environmental treaty produced at the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro, Brazil. It called on signatory nations to develop current and projected emission inventories for greenhouse gases, devise policies for reducing emissions, and promote technologies for reducing emissions. The treaty sets no mandatory limits on greenhouse gas emissions for individual nations and contains no enforcement provisions; it is therefore legally non-binding. The treaty included provisions for updates, called protocols, that would set mandatory emission limits. The principal update is the Kyoto Protocol, which has become much better known than the UNFCCC itself. The objective of the treaty was to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. 154 nations signed the UNFCCC. Since the UNFCCC entered into force, the parties have been meeting annually in Conferences of the Parties (COP). The latest conference of the parties, COP-11, is being held in Montreal, Canada, November 28 to December 9, 2005.

In December 1997, the UN met again to design an international agreement called the Kyoto Protocol. The Kyoto Protocol called on industrialized nations to reduce greenhouse gas emissions by 2008-2012, by a certain percentage relative to their 1990 (for CO$_2$, CH$_4$, N$_2$O) or 1995 (all other greenhouse gases) emissions. Some countries were allowed to increase emissions. The net change in emissions would be 5.2% below 1990 levels. (For comparison, US emissions increased by 14% in the 1990s.) Countries could meet their targets by:

1. Reducing their own emissions, and increasing their own carbon sinks (e.g. forests)
2. Clean Development Mechanism: Financing emission-reduction projects in developing countries that are not subject to the Kyoto Protocol. Examples of activities include tree planting, protecting forests, improving energy efficiency, using alternative energy sources, reducing emissions at their sources, etc.
3. Emissions trading and joint implementation with other developed countries. Joint Implementation provides for developed countries to
implement projects that reduce emissions, or remove carbon from the atmosphere (for example by planting trees, managing forests, or curbing deforestation).

In order for Kyoto to be implemented, it had to be ratified by at least 55 countries that represented at least 55% of global 1990 CO\textsubscript{2} emissions. It entered into force on Feb. 16, 2005 following ratification by Russia. 156 countries have ratified the treaty as of September 2005. Notable exceptions include the US and Australia. Developing countries have no restrictions under Kyoto to avoid restrictions on growth.

Many critics and environmentalists question the value of the Kyoto Protocol because of its small requirements for emissions reductions. They also argue that without mandatory limits on developing countries such as China and India, the treaty will be ineffective. Proponents argue that it is a necessary first step, and would promote the use of more sustainable practices more quickly in developing countries through the clean development mechanism. Also, they demonstrate commitment to the precautionary principle. The precautionary principle, a phrase first used in English in 1988, is the idea that if the consequences of an action are unknown, but are judged to have some potential for major or irreversible negative consequences, then it is better to avoid that action.

**Recent initiatives in the US:**

In the absence of federal action, three western (California, Oregon, and Washington) and nine northeastern (Connecticut, Delaware, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont) states are currently attempting to pass legislation to create mandatory reductions in CO\textsubscript{2} emissions from power plants and automobiles. Power plants may undergo a market based cap and trade system. These initiatives are facing opposition from the power and automobile industries. Automakers in Detroit and Tokyo are suing the states to attempt to block them from enforcing new fuel efficiency rules for automobiles. The auto industry says that the rules should be set nation-wide (not by individual states), but the Bush administration shows no sign of doing this.

**Asia Pacific Partnership on Clean Development and Climate:** Non-binding international agreement announced on July 28, 2005 between the US, Australia, China, India Japan and South Korea focusing on voluntary measures to “create new investment opportunities, build local capacity, and remove barriers to the introduction of clean, more efficient technologies” (similar to the clean development mechanism). There’s no mandatory enforcement mechanism with this agreement - it’s entirely voluntary.

**Climate Stewardship Act:** A bill, proposed by McCain and Lieberman, was voted on in October 2003 by the US Senate and did not pass (although 44 senators voted in favor of it). The bill proposed to place a cap on the most intensive polluting sectors in the economy (industrial, commercial, transportation, and utility), and established a market-based emissions trading program.