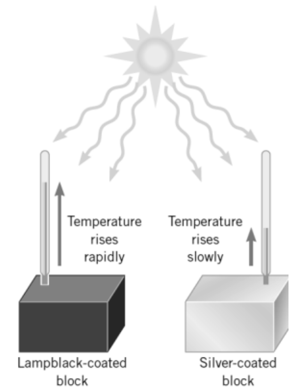
Climate Change

Black-Body Radiation

Factors that affect how an object absorbs, emits (radiates), and reflects EM radiation incident on them:

1) Nature of the surface: material, shape, texture, etc.



2) Color:
   a) Light-colored or silvery objects: absorb little energy, reflect most energy

   b) Dark objects: absorb most energy, reflect little energy

When the object is in thermal equilibrium with its surroundings, energy absorbed = energy radiated

$P_{in} = P_{out}$

$I_{in} = I_{out}$

An object that acts as a "black-body" will . . . absorb all incoming radiation, not reflect any, then radiate all of it.

Black-body radiation: radiation emitted by a "perfect" emitter

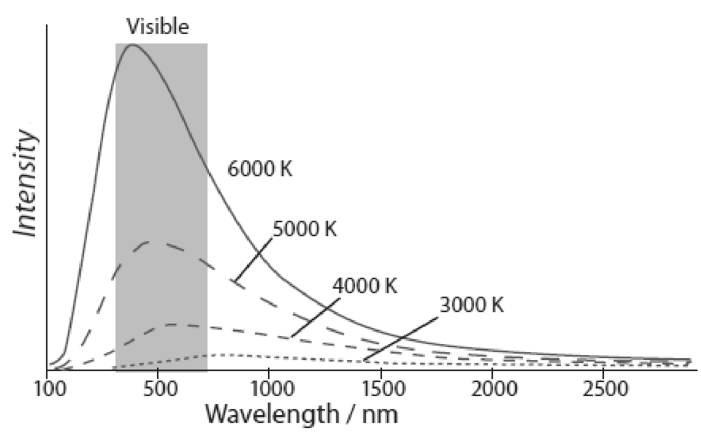
When heated, a low-pressure gas will . . .emit a discrete spectrum

When heated, a solid will . . . emit a continuous spectrum

Emission Spectra for Black-Bodies

1. Not all wavelengths of light will be emitted with equal intensity.
2. Emitted wavelength with highest intensity (λ_{max}) is related to . . . temperature.
3. Area under curve is proportional to . . . total power radiated by body
4. As body heats up, λ_{max} . . . decreases

   and total power . . . increases



Emission Spectra for Black-Body Radiation

Your Turn $\lambda_{max} \alpha$ 1/T (Wien's law)

Use the axes at right to sketch the emission spectra for a black-body radiating at low and high temperature. Be sure to label the axes and indicate which curve represents which temperature.

The Stefan-Boltzmann Law of Radiation

relates intensity of radiation to the temperature of the body

$$I = \sigma T^4$$

$$\frac{P}{A} = \sigma T^4$$

$$P = \sigma A T^4$$

where σ=Stefan-boltzmann constant

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

1. How does the energy radiated by an object change if its temperature doubles?

$$P \alpha T^4$$

$$2T \rightarrow 16P$$

2. The supergiant star Betelgeuse has a surface temperature of about 2900 K and a radius of 3×10^{11} m.

   a) Determine how much energy Betelgeuse radiates each second. 4×10^{30} W

   b) What is the intensity of Betelgeuse's radiation at its surface?

   c) What is the intensity of Betelgeuse's radiation at a location that is 3×10^{11} m from its surface?

d) What major assumption was made in calculating the power radiated by Betelgeuse?

That it acts as a black-body

Emissivity (e) – ratio of power emitted by an object to the power emitted by a black-body at the same temperature.

Formula:

$$e = \frac{P}{P_{BB}}$$

$$P = eP_{BB}$$

$$P = e\sigma AT^4$$

e) Compute the power radiated by Betelgeuse if its emissivity is measured to be only 0.90.

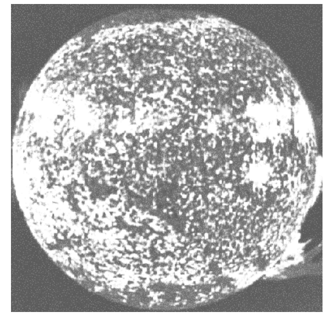
3. Calculate the power emitted by a square kilometer of ocean surface at 10^0C if its emissivity is 0.65.

4. Calculate the power radiated by the Earth if it is taken to be

a) a black-body at 300 K.

b) at 300 K with an effective emissivity of 0.62.

Solar Radiation

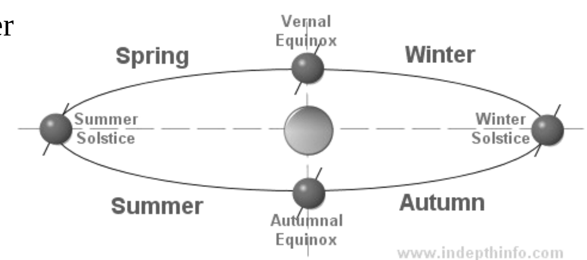


1. Calculate the power radiated by the Sun if it is taken to be a black-body at 5778 K and a mean radius of 6.96×10^8 meters.

2. What is the intensity of the solar radiation at the Sun's surface?

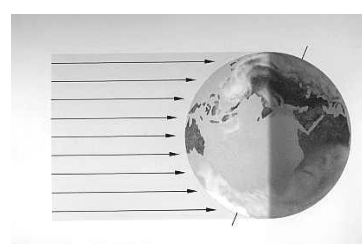
See pg. 3 of data booklet for 1.5×10^{11} m

3. What is the intensity of the solar radiation that reaches the upper atmosphere of Earth?



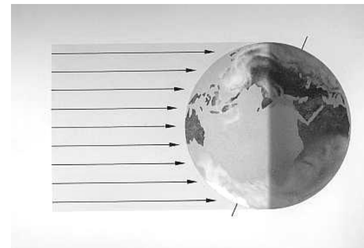
Solar constant:
1360-1370 W/m^2
Rounded 1400

4. How much solar energy is incident on the Earth every second?



Take solar constant and multiply by area of disc as cross-section
1.75×10^{17} W

5. What is the average intensity of the solar energy absorbed by the Earth?



Average 1.75×10^{17} W over whole surface area of Earth = 4 pi r^2
340 W/m^2

Albedo(α) – ratio of total solar power scattered to total solar power incident

Formula:

$$\alpha = \frac{\text{total scattered power}}{\text{total incident power}}$$

$$\alpha = \frac{P_{reflected}}{P_{in}}$$

Surfaces	Albedo %
Oceans	10
Dark soils	10
Pine forests	15
Urban areas	15
Light coloured deserts	40
Deciduous forests	25
Fresh snow	85
Ice	90
Whole planet	31

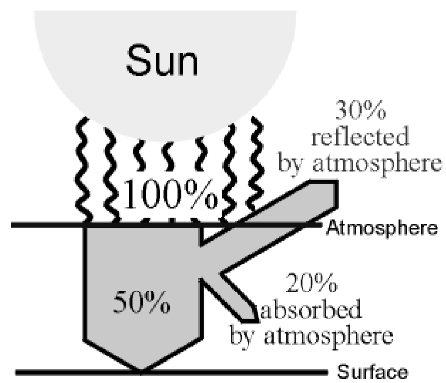
Albedo percentages of different surfaces

Meaning: fraction of the total incoming solar radiation that is reflected back out into space

6. What is the albedo of a black-body? 0 What is the emissivity of a black-body? 1

7. Use the diagram at right to determine the Earth's average albedo.

Atmosphere, clouds, and ground



Global annual mean albedo on Earth: 0.30 = 30%

The Earth's albedo varies daily and is dependent on:

1. season
2. cloud formations
3. latitude

8. How much energy is actually absorbed by the Earth each second?

$0.70 \times 1.75 \times 10^{17}$ W = 1.23×10^{17} W

9. Use the results of your prior calculations to estimate the equilibrium temperature of the Earth and comment on your answer.

Assume black-body emiss=1
Pin=Pout
Use SB T= 255 k = -18^{o}C too cold

10. At present, the average temperature of the Earth is measured to be 288 K.

a) Calculate the average emissivity of the Earth.

b) Comment on why this might be.

Actually warmer since atmosphere absorbs some of the radiation emitted by Earth surface

Start to separate "Earth" into its parts – atmosphere vs. ground

The Greenhouse Effect

Greenhouse Gases: each has natural and man-made origins

1) Water Vapor (H_2O): evaporation
2) Carbon Dioxide (CO_2): product of photosynthesis in plants, product of fossil fuel combustion
3) Methane (CH_4): product of decay and fermentation and from livestock, component of natural gas
4) Nitrous Oxide (N_2O): product of livestock, produced in some manufacturing processes

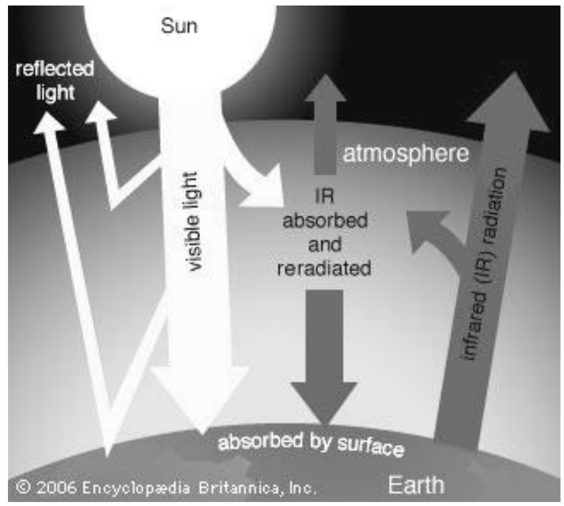
Greenhouse Effect –

a) Short wavelength radiation (visible and short-wave infrared) received from the Sun causes the Earth's surface to warm up.

b) Earth will then emit longer wavelength radiation (long-wave infrared) which is absorbed by some gases in the atmosphere.

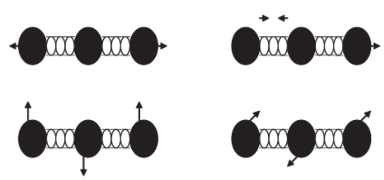
c) This energy is re-radiated in all directions (scattering). Some is sent out into space and some is sent back down to the ground and atmosphere.

d) The "extra" energy re-radiated causes additional warming of the Earth's atmosphere and is known as the Greenhouse Effect.



1. What is the molecular mechanism by which greenhouse gases absorb infrared radiation?

Resonance – a transfer of energy in which a system is subject to an oscillating force that matches the natural frequency of the system resulting in a large amplitude of vibration



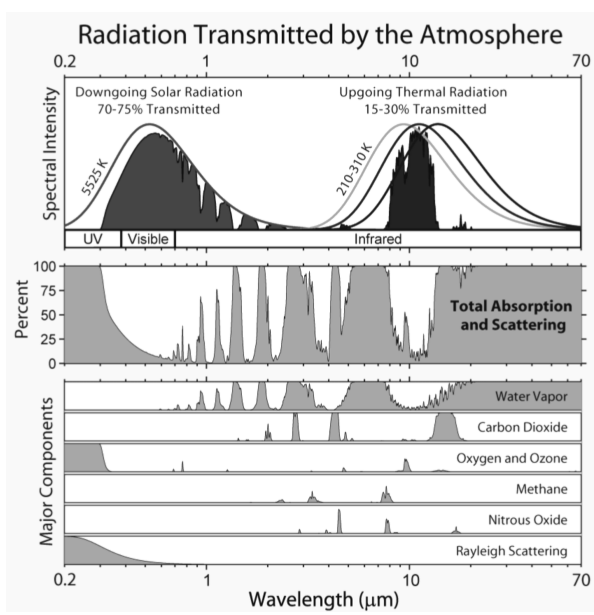
Vibrational modes of carbon dioxide

Application to the greenhouse effect:

The natural frequency of oscillation of the molecules of the greenhouse gases is in the infrared region (1 – 300 μm)

2. What do the following transmittance and absorption graphs show about the atmosphere?

Sun radiates in visible
Earth radiates in infrared
Water vapor absorbs incoming solar radiation and outgoing IR radiation
CO2 absorbs outgoing IR radiation



Outgoing energy

The average albedo (reflectivity) of the Earth is about 0.3, which means that 30% of the incident solar energy is reflected back into space, while 70% is absorbed by the Earth and reradiated as infrared. The planet's albedo varies from month to month, but 0.3 is the average figure. It also varies very strongly spatially: ice sheets have a high albedo, oceans low. The contributions from geothermal and tidal power sources are so small that they are omitted from the following calculations.

So 30% of the incident energy is reflected, consisting of:

- 6% reflected from the atmosphere
- 20% reflected from clouds
- 4% reflected from the ground (including land, water and ice)

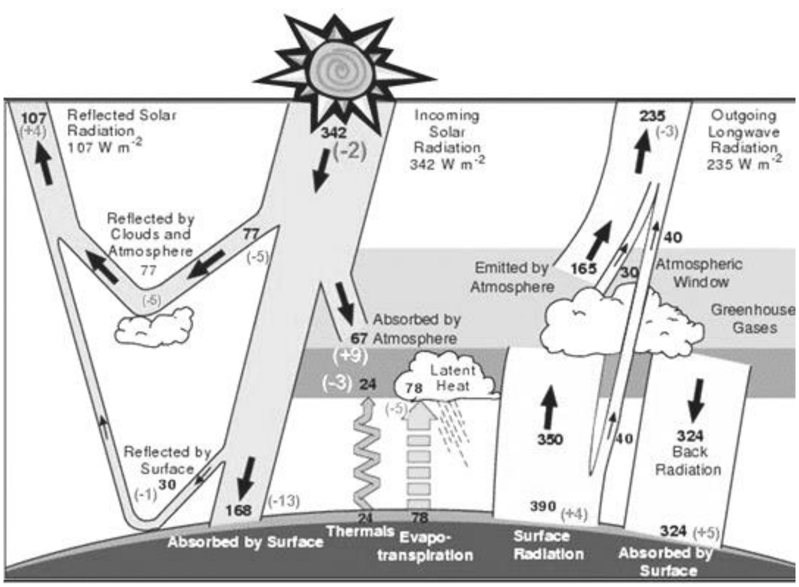
The remaining 70% of the incident energy is **absorbed**:

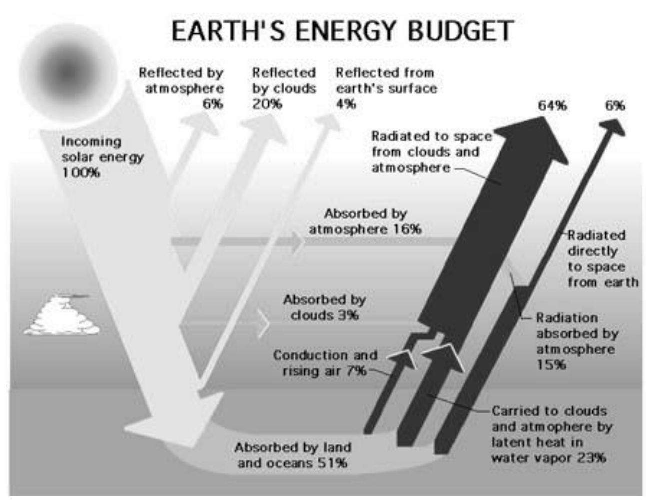
- 51% absorbed by land and water, then emerging in the following ways:
  - 23% transferred back into the atmosphere as latent heat by the evaporation of water, called latent heat flux
  - 7% transferred back into the atmosphere by heated rising air, called Sensible heat flux
  - 6% radiated directly into space
  - 15% transferred into the atmosphere by radiation, then reradiated into space
- 19% absorbed by the atmosphere and clouds, including:
  - 16% reradiated back into space
  - 3% transferred to clouds, from where it is radiated back into space

When the Earth is at thermal equilibrium, the same 70% that is absorbed is **reradiated**:

- 64% by the clouds and atmosphere
- 6% by the ground

Some energy balance climate models for the Earth





Predict increase in planet's temp using SB law like test question

Surface Heat Capacity (C_S) – energy required to raise the temperature of a unit area of a planet's surface by 1 K.

Formula:

$$C_S = \frac{Q}{A\Delta T}$$

$$Q = AC_S\Delta T$$

Units:

$$\frac{J}{m^2K}$$

Surface heat capacity of Earth: $C_S = 4.0 \times 10^8$ J m^{-2} K^{-1}

1. How much solar energy is needed to increase the surface temperature of one square kilometer of Earth's surface by 2 K?

Temperature change formula:

$$C_S = \frac{Q}{A\Delta T} \qquad C_S = \frac{(I_{in} - I_{out})\Delta t}{\Delta T}$$

$$C_S = \frac{P\Delta t}{A\Delta T} \qquad \Delta T = \frac{(I_{in} - I_{out})\Delta t}{C_S}$$

2. If the Earth is in thermal equilibrium, it will emit as much radiation as is incident on it from the Sun (344 W/m^2). Suppose a change causes the intensity of the radiation emitted by Earth to decrease 10%.

   a) Suggest a mechanism by which this might happen.

   Increased amounts of greenhouse gases cause more solar radiation to be trapped in atmosphere

   b) Calculate the new intensity of radiation emitted by Earth. 0.90(340) = 306 W/m^2

   c) Calculate the amount by which Earth's temperature would rise over the course of a year as a result.

$$\Delta T = \frac{(I_{in} - I_{out})\Delta t}{C_S}$$

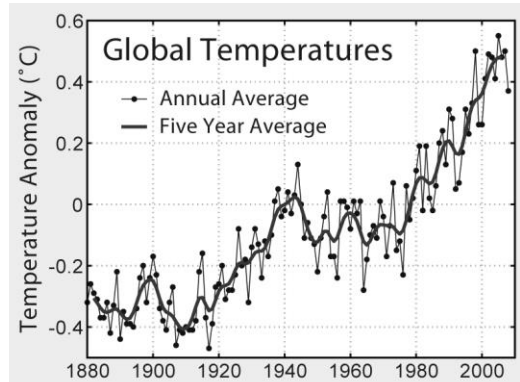
$$\Delta T = \frac{(340 - 306)(365)(24)(3600)}{4.0 \text{ x } 10^8}$$

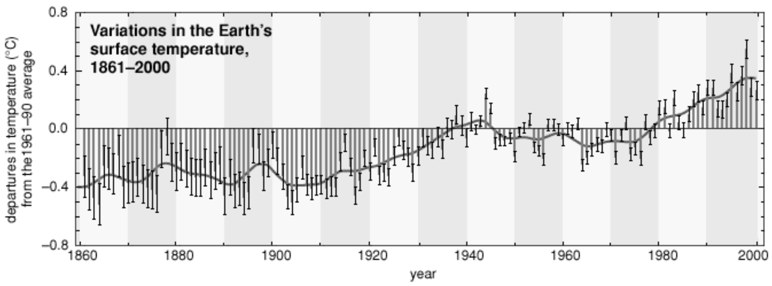
$$\Delta T = 2.7K$$

Global Warming: records show that the mean temperature of Earth has been increasing in recent years.

In specific terms, an increase of 1 or more Celsius degrees in a period of one hundred to two hundred years would be considered global warming. Over the course of a single century, an increase of even 0.4 degrees Celsius would be significant. The Intergovernmental Panel on Climate Change (IPCC), a group of over 2,500 scientists from countries across the world, convened in Paris in February, 2007 to compare and advance climate research. The scientists determined that the Earth has warmed .6 degrees Celsius between 1901 and 2000. When the timeframe is advanced by five years, from 1906 to 2006, the scientists found that the temperature increase was 0.74 degrees Celsius.

Global mean surface temperature anomaly relative to 1961–1990





Source: Intergovernmental Panel on Climate Change; World Meteorological Organization; United Nations Environment Programme

The global average surface temperature range for each year from 1861 to 2000 is shown by solid red bars, with the confidence range in the data for each year shown by thin whisker bars. The average change over time is shown by the solid curve.

Possible models suggested to explain global warming:

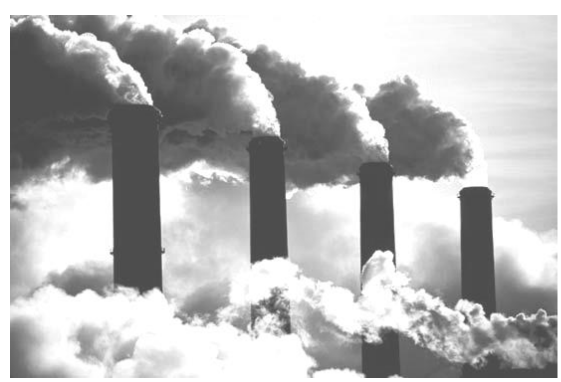
1. changes in the composition of greenhouse gases may increases amount of solar radiation trapped in Earth's atmosphere
2. increased solar flare activity may increase solar radiation
3. cyclical changes in the Earth's orbit may increase solar radiation
4. volcanic activity may increases amount of solar radiation trapped in Earth's atmosphere

A column of gas and ash rising from Mount Pinatubo in the Philippines on June 12, 1991, just days before the volcano's climactic explosion on June 15.

In 2007, the IPCC report stated that:

"*Most of the observed increase in globally averaged temperature since the mid-20th century is very likely due to the increase in anthropogenic [human-caused] greenhouse gas concentrations*." (the **enhanced greenhouse effect**)

Enhanced (Anthropogenic) Greenhouse Effect – Human activities have released extra carbon dioxide into the atmosphere, thereby enhancing or amplifying the greenhouse effect.



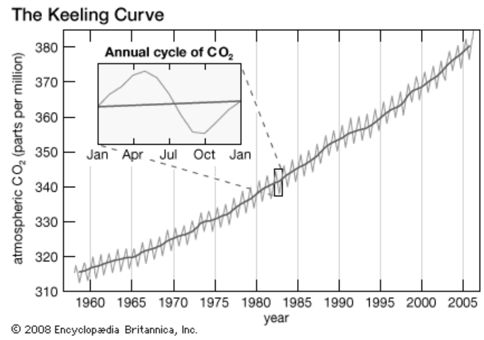
Major cause: the burning/combustion of fossil fuels

Possible effect: rise in mean sea-level

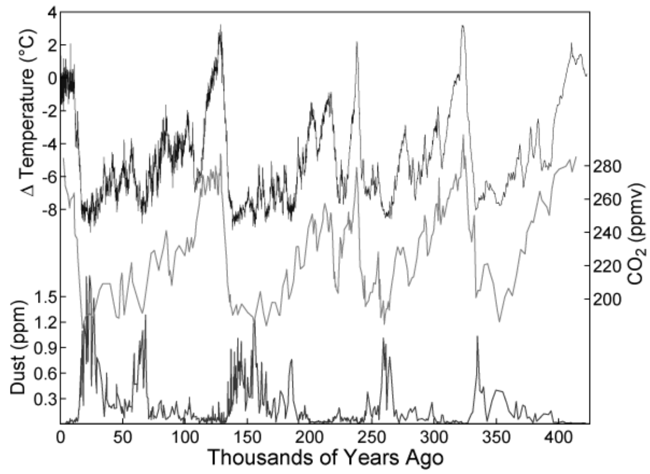
Outcome: climate change and global warming

Evidence linking global warming to increased levels of greenhouse gases

1) The Keeling Curve: Named after American climate scientist Charles David Keeling, this tracks changes in the concentration of carbon dioxide (CO2) in Earth's atmosphere at a research station on Mauna Loa in Hawaii. Although these concentrations experience small seasonal fluctuations, the overall trend shows that CO2 is increasing in the atmosphere.



2) International Ice Core Research: Between 1987 and 1998, several ice cores were drilled at the Russian Antarctic base at Vostok, the deepest being more than 3600 meters below the surface. Ice core data are unique: every year the ice thaws and then freezes again, forming a new layer. Each layer traps a small quantity of the ambient air, and radioactive isotopic analysis of this trapped air can determine mean temperature variations from the current mean value and carbon dioxide concentrations. The depths of the cores obtained at Vostok means that a data record going back more than 420,000 years has been built up through painstaking analysis.



Inspect the graphical representation of the ice core data and draw a conclusion.

There is a correlation between Antarctic temperature and atmospheric concentrations of CO_2

Mechanisms that may increase the rate of global warming

1. Global warming reduces ice and snow cover, which in turn reduces the albedo. This will result in an increase in the overall rate of heat absorption.

2. Temperature increase reduces the solubility of CO_2 in the sea and increases atmospheric concentrations.

3. Continued global warming will increase both evaporation and the atmosphere's ability to hold water vapor. Water vapor is a greenhouse gas.

4. The vast stretch of permanently frozen subsoil (permafrost) that stretches across the extreme northern latitudes of North America, Europe, and Asia, also known as tundra, are thawing. This releases a significant amount of trapped CO_2.

5. Deforestation results in the release of more CO_2 into the atmosphere due to "slash-and-burn" clearing techniques, as well as reduces the number of trees available to provide "carbon fixation."

Smoldering remains of a plot of deforested land in the Amazon rainforest of Brazil. Annually, it is estimated that net global deforestation accounts for about 2 gigatons of carbon emissions to the atmosphere.

Rise in Sea-levels

Generally, as the temperature of a liquid rises, it expands. If this is applied to water, then as the average temperature of the oceans increases, they will expand and the mean sea-level will rise. This has already been happening over the last 100 years as the sea level has risen by 20 cm. This has had an effect on island nations and low-lying coastal areas that have become flooded.

Coefficient of Volume Expansion (β) – fractional change in volume per degree change in temperature

Formula:

$$\beta = \frac{\Delta V}{V_o \Delta T}$$

$$\Delta V = \beta V_o \Delta T$$

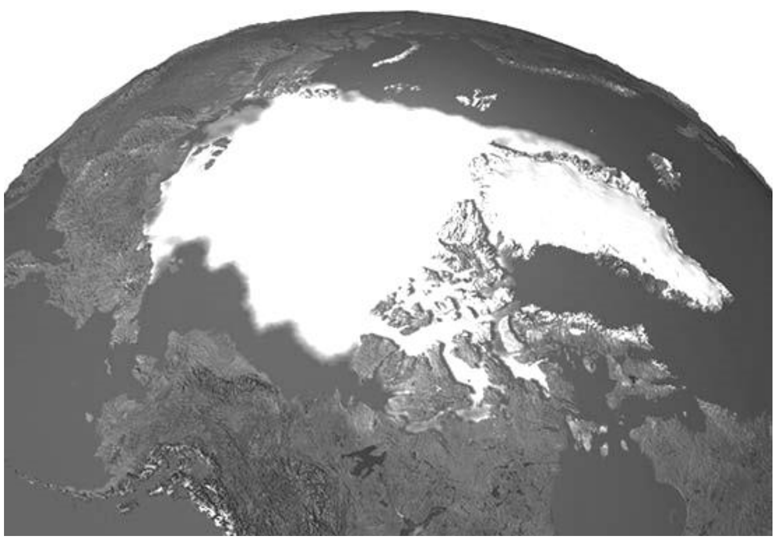
Units: $\frac{1}{K}$

1. The coefficient of volume expansion for water near 20^o C is 2×10^{-4} K^{-1}. If a lake is 1 km deep, how much deeper will it become if it heats up by 20^o C? 0.4 m

Precise predictions regarding the rise in sea-levels are hard to make for such reasons as:

a) Anomalous expansion of water: Unlike many liquids, water does not expand uniformly. From 0^0C to 4^0C, it actually contracts and then from 4^0C upwards it expands. Trying to calculate what happens as different bodies of water expand and contract is very difficult, but most models predict some rise in sea level.

b) Melting of ice: Floating ice, such as the Arctic ice at the North Pole, displaces its own mass of water so when it melts it makes no difference. But melting of the ice caps and glaciers that cover land, such as in Greenland and mountainous regions throughout the world, causes water to run off into the sea and this makes the sea level rise.



Glaciers on land melting:
raise sea level

Sea ice glaciers melting:
don't raise sea level

Possible solutions for reducing the enhanced greenhouse effect

1. Greater efficiency of power production.

   To produce the same amount of power would require less fuel, resulting in reduced CO_2 emissions.

2. Replacing the use of coal and oil with natural gas.

   Gas-fired power stations are more efficient (50%) that oil and coal (30%) and produce less CO_2.

3. Use of combined heating and power systems (CHP).

   Using the excess heat from a power station to heat homes would result in more efficient use of fuel.

4. Increased use of renewable energy sources and nuclear power.

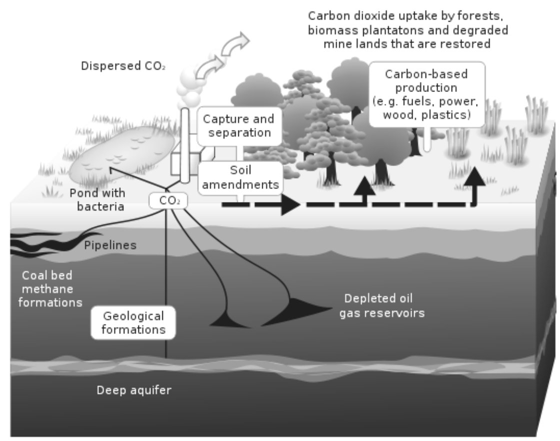
   Replacing fossil fuel burning power stations with alternative forms such as wave power, solar power, and wind power would reduce CO_2 emissions.

5. Use of hybrid vehicles

   Cars that run on electricity or a combination of electricity and gasoline will reduce CO_2 emissions.

6. Carbon dioxide capture and storage (carbon fixation)

   A different way of reducing greenhouse gases is to remove CO_2 from waste gases of power stations and store it underground.



International efforts to reduce the enhanced greenhouse effect

1. **Intergovernmental Panel on Climate Change (IPCC):** Established in 1988 by the World Meteorological Organization and the United Nations Environment Programme, its mission is not to carry out scientific research. Hundreds of governmental scientific representatives from more than 100 countries regularly assess the up-to-date evidence from international research into global warming and human induced climate change.

2. **Kyoto Protocol:** This is an amendment to the United Nations Framework Convention on Climate Change. In 1997, the Kyoto Protocol was open for signature. Countries ratifying the treaty committed to reduce their greenhouse gases by given percentages. Although over 177 countries have ratified the protocol by 2007, some significant industrialized nations have not signed, including the United States and Australia. Some other countries such as India and China, which have ratified the protocol, are not currently required to reduce their carbon emissions.

3. **Asia-Pacific Partnership of Clean Development and Climate (APPCDC):** This is a non-treaty agreement between 6 nations that account for 50% of the greenhouse emissions (Australia, China, India, Japan, Republic of Korea, and the United States.) The countries involved agreed to cooperate on the development and transfer of technology with the aim of reducing greenhouse emissions.