Thermal energy

Study Design

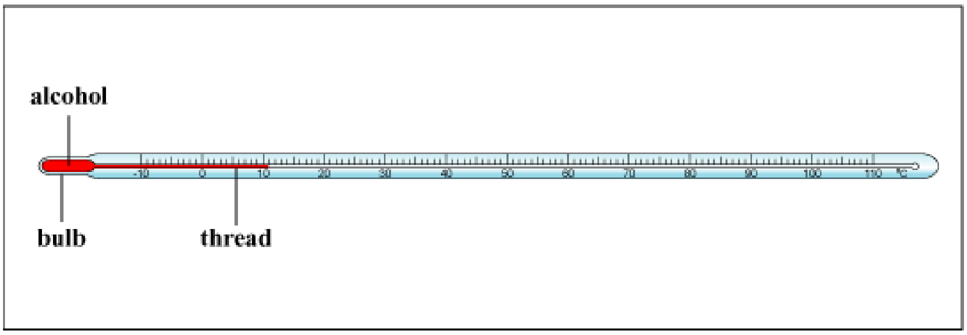
- convert between Celsius and kelvin scales
- describe how an increase in temperature corresponds to an increase in thermal energy (kinetic and potential energy of the atoms) of a system:
- distinguish between conduction, convection and radiation with reference to heat transfers within and between systems
- explain why cooling results from evaporation using a simple kinetic energy model
- investigate and analyse theoretically and practically the energy required to:
- raise the temperature of a substance: $Q = mc\Delta T$
- change the state of a substance: $Q = mL$
- apply concepts of energy transfer, energy transformation, temperature change and change of state to climate change and global warming.

Temperature

Temperature is a measure of how “hot” something is. The human sense of touch is capable of determining if one thing is hotter than another, but can’t tell us how hot something is. We need to quantify temperature.

Thermometers

Thermometers are used to measure temperature. The typical thermometer uses the expansion of a liquid (often mercury or alcohol) to measure the temperature. These are made of glass and have a bulb at one end containing the dyed alcohol. When the temperature rises the alcohol expands (reasonably linearly) and moves along the thread. Alcohol doesn’t turn solid until -115 ºC, so can be used to measure temperatures below 0 ºC.



Other thermometers use variations in the electrical resistance of wires, the pressure or volume of a gas, or the colour of certain chemicals to measure temperature.

Temperature Scales

There are a range of temperature scales commonly used. In Physics we use either the **Celsius** scale (this used to be called the Centigrade scale), or the **Kelvin** scale.

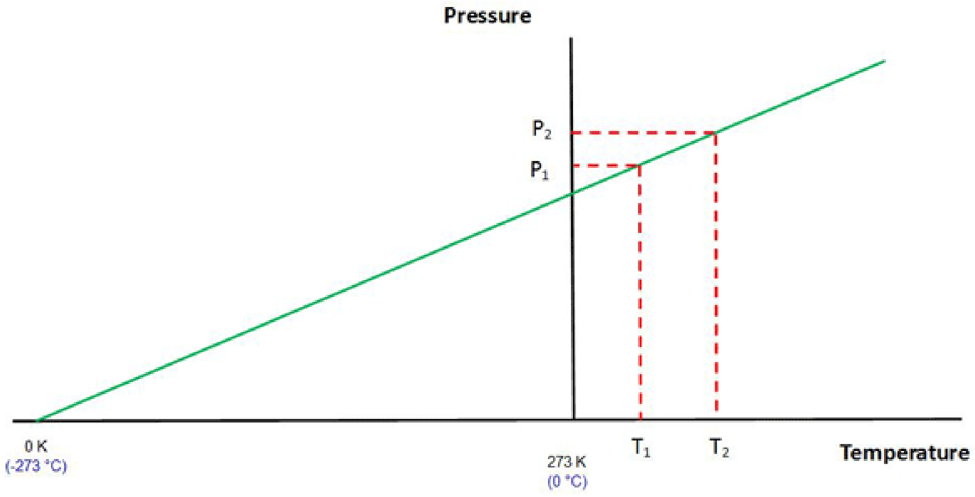
Celsius is defined by a freezing point of water at 0 °C and boiling point of water at 100 °C. The lower fixed point (or ice point) is the temperature at which pure ice melts at normal atmospheric pressure. The upper fixed point (or steam point) is the temperature at which pure water boils under normal atmospheric pressure.

In 1848, Lord Kelvin proposed an **absolute temperature scale** with zero set at -273 °C. The Kelvin scale uses units of kelvin (K), and has the same divisions as the Celsius scale. This is the scale we use most commonly in physics.

Absolute Zero

Absolute zero is the lowest possible temperature where nothing could be colder and no thermal energy (heat) remains in a substance. Absolute zero is the point at which the fundamental particles of nature have minimal vibrational motion, retaining only quantum mechanical, so-called “zero-point energy” induced particle motion. All molecular motion does not cease at absolute zero, but no energy from molecular motion (i.e, heat energy) is available for transfer to other systems. Therefore, the energy at absolute zero is minimal.

The idea that there was a lowest temperature comes from the contraction of gases at low pressures. The pressure of an ideal gas, at constant volume, decreases linearly with temperature. A real gas condenses to a liquid or a solid at a temperature higher than absolute zero; therefore, the ideal gas law is only an approximation to real gas behaviour. However, if the graph is extrapolated, it intersects at -273.15 °C, as can be seen below.



Absolute zero is defined as precisely 0 K on the Kelvin scale and -273.15 ºC on the Celsius scale. This temperature cannot be reached; it can only be approached. Scientists have reached temperatures within nano-degrees of 0 K.

Absolute temperature in kelvin = temperature in ºC + 273

There is no upper limit on temperature, except the limit of the amount of energy in the Universe.

Thermal energy

Heat is a form of energy, just like kinetic energy, potential energy, electrical energy, chemical energy, light energy, etc. The SI unit for energy is the **joule (J)** after James Prescott Joule. One joule of thermal energy is the heat required to raise the temperature of 1 g of dry air by 1 K or 1 g of water by 0.24 K.

The model we use to understand heating as an energy transfer is the kinetic particle model. Kinetic energy is the energy a body possesses due to its motion. The kinetic theory of matter states that matter is made up of extremely tiny particles (ions, atoms or molecules) which can move at different speeds because of the kinetic energy they possess. The way these particles are arranged determines whether the substance is a solid, liquid or gas. These particles are in continuous motion, their motion, and hence state can be changed by adding or removing energy (in the form of heat).

The higher the temperature, the faster the particles are moving (or vibrating) hence the greater the kinetic energy. This kinetic energy is associated with the random, incoherent movements (or vibrations) of the particles. This is different from the kinetic energy associated with the collective movement of the particles, which occurs when the whole container or object moves.

The internal energy of a body is the sum of the potential and the kinetic energy of all its particles. It is measured in joules. The energy of the particles may be associated with their rotational motion. Internal energy may also be in the arrangement of the particles, heating may increase the internal energy by causing a rearrangement of the particles to give a change of phase (e.g. from a solid to a liquid). It is only the increase in the kinetic energy (or vibrational energy) of the particles which cause a change in temperature.

The definition of the Kelvin scale is that absolute zero is when the particles have zero thermal movement.

States of matter

There are four recognised main states of matter: **solid, liquid, gas** and **plasma**. Substances can change their states when physical conditions such as temperature or pressure alter.

Solids

In a solid the particles are held tightly together in a set array. The particles cannot move away from each other, but they can vibrate about a mean position. The speed at which the particles vibrate depends on the temperature of the solid. The higher the temperature the faster the particles vibrate and the more kinetic energy the particles will have.

Liquids

The particles are further apart than in a solid. They are in constant motion and are free to move about. Liquids do not have a definite shape and can flow. Forces of attraction cause the particles to occupy a definite volume.

Gases

The particles of a gas are almost completely free of each other's influence. They are free to move wherever they wish. They have no particular shape. The particles are moving much faster than those in a liquid or a solid. Elastic collisions occur between particles and the forces of attraction between particles are weak.

The average translational kinetic energy (KE) of a monoatomic molecule of an ideal gas is directly proportional to the absolute temperature of the gas.

This can be summarised as: $KE_{ave} = \frac{1}{2}mv^2_{ave} = \frac{3}{2}kT$

Where m is the mass in kg, v_{ave} is the average translational speed of the gas molecules, $k = 1.38 \times 10^{-23}$ J K^{-1} (the Boltzmann constant) and T is the temperature in kelvin.

If two gases, initially at different temperatures, are combined within a single container, molecules of the hotter gas will transfer energy through intermolecular collisions to the molecules of the cooler gas until thermal equilibrium is established at a single final temperature.

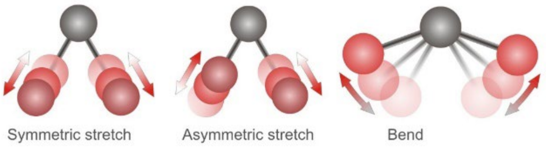
Heating

When you heat a substance, you add energy to it.

For a solid, the molecules and atoms vibrate faster. As atoms vibrate faster, the space between atoms increases. The motion and spacing of the particles determines the state of matter of the substance. The end result of increased molecular motion is that the object expands and takes up more space.

It is more complex for a gas. If the gas is monatomic, (eg Neon), the atoms move more when heat (energy) is added. If the gas is diatomic, (eg Oxygen, O_2) the molecules can also spin and stretch. If the gas is multi-atom, (eg Water H_2O), the molecules can move more, spin, stretch and twist.

Liquids exhibit features of both solids and gases.



Heat capacity

The temperature of a body depends on its internal energy, to raise the temperature, energy needs to be transferred to the body. Experimentally it has been found that the thermal energy (Q) transferred is proportional to the increase in temperature ΔT.

$$\therefore Q \propto \Delta T$$

This can be written as $Q = C \Delta T$, where C is a constant called the heat capacity of the body. A larger body requires more heat to produce a given rise in temperature. Experimentally it has been found that $Q \propto m$ (for a given rise in temperature).

This gives $\mathbf{Q = mc \Delta T}$, where c, is called the **specific heat capacity** of the material.

The specific heat capacity (c) is the energy transferred by heating required to increase the temperature of 1 kg of the substance by 1 K or °C.

The specific heat capacity of a substance is a property of the substance and does not depend on the size, nor shape of the substance.

The specific heat capacity has units of J kg^{-1} K^{-1}.

Substance	Specific heat capacity (J kg^{-1} K^{-1})
Water	4 186
Air	1 000
Alcohol	2 500
Human body (average)	3 500
Aluminium	900
Copper	380
Iron	490
Glass	600
Ice	2 093
Mercury	140
Hydrogen	14 320
Helium	5 167

Water

Water has a high specific heat capacity. This is a very useful property.

- Water is used in the cooling systems of cars because it takes a lot of energy to raise the temperature of the water
- Seawater takes a much longer time than land to heat up and cool down. The small temperature change in water results in coastal areas being cooler in summer and milder in winter than inland areas.
- The human body contains a lot of water. This means that we respond slowly to changes in the external temperatures.

Conservation of Energy

When two bodies of different temperatures are placed in contact inside an insulated container, energy is transferred from the body at a higher temperature to that at a lower temperature. The energy transfer stops when they reach the same temperature. During the transfer process, **the energy lost by one body is equal to the energy gained by the other body.**

This agrees in principle with the **law of conservation of energy.** In reality, there will be some energy transferred to the outside environment.

Latent Heat

Melting point

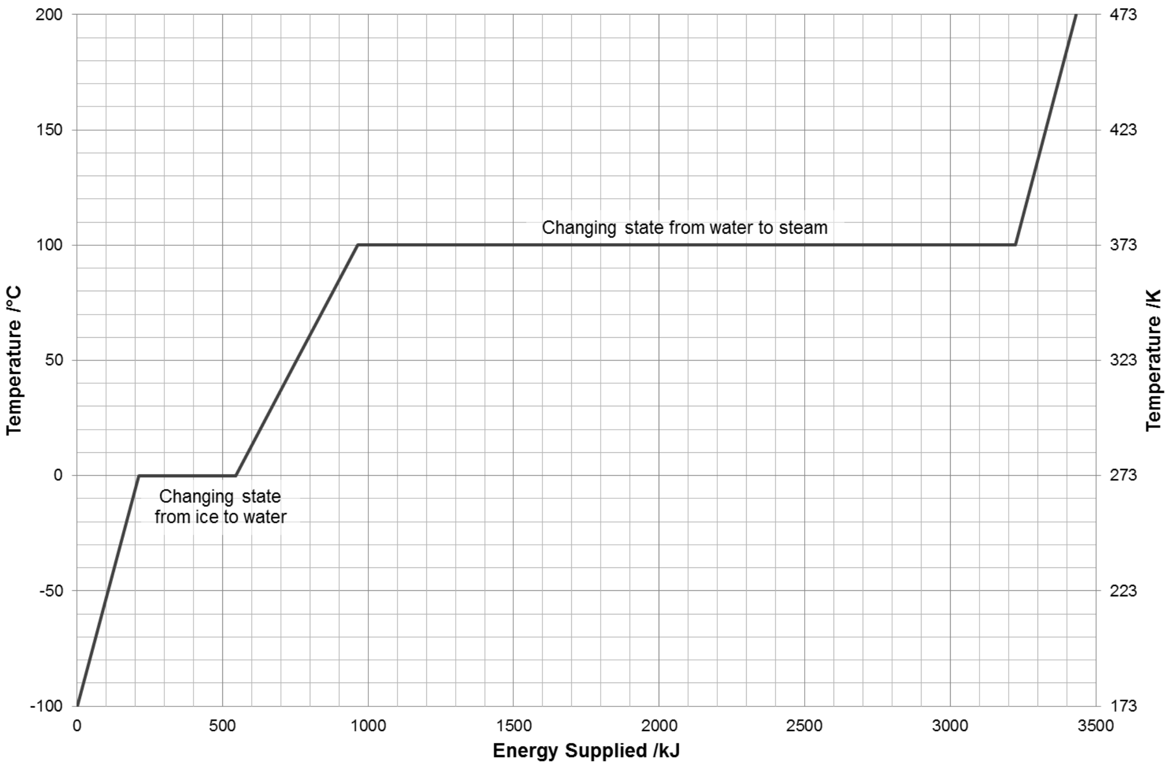
When a solid is heated its temperature remains constant as it changes into a liquid. This is called the melting point. The freezing point and melting point are the same for each substance. The term melting point is used to describe a solid into a liquid and the term freezing point is used to describe a liquid into a solid.

Boiling point

When bubbles of vapour are formed throughout a liquid the liquid is said to be boiling. Boiling is a change of state from liquid to gas (vapour).

Evaporation and Boiling

Evaporation and boiling are both a change of state from liquid to vapour (gas). Evaporation is a surface phenomenon and takes place at all temperatures. Boiling takes place throughout a liquid at a fixed temperature.



The energy required to change 1 kg of a substance from solid to liquid state without a change in temperature is called the **specific latent heat of fusion (l_f).** (the subscript is 'f' for fusion) The energy required to change 1 kg of a substance from liquid to gaseous state without a change in temperature is called the **specific latent heat of vaporisation (l_v).** The SI unit for specific heat is J kg^{-1}.

$Q = ml$ where Q the energy (J), m is the mass (kg) and l the specific latent heat (J kg^{-1})

How does sweating cool humans?

Molecules with enough energy can escape from water (sweat) on the surface of the skin. As the most energetic molecules escape from the water, the less energetic ones are left behind. This means that the internal energy of the water is then lower, so its temperature is lower.

Alternatively, energy is required for water (sweat) on the surface of skin to evaporate. The energy needed for the water to evaporate comes from the rest of the water. This means that as the water evaporates it cools.

This is how evaporative cooling systems work to cool buildings. Scientists can also use this same process to lower the temperature of atoms down to the order of nano-kelvins (10^{-9} K).

Transferring energy

If a hot metal cube is placed into cool water, the water gets warmer and the metal cube cools down. There is a transfer of energy from the hot metal cube to the water, due to the temperature difference between the water and the cube. This transfer process is called heating. The internal energy of the metal cube decreases, while the internal energy of the water increases.

There are three ways to transfer heat; conduction, convection, and radiation.

Conduction

Conduction is the movement of heat throughout a material without carrying any of the material with it. Heat causes the particles to vibrate faster, these faster vibrations cause adjacent particles to vibrate faster. In this way heat, via the vibrations, travels.

Conduction can occur in solids, liquids or gases, but it occurs fastest in solids. Most metals are good conductors of heat, liquids and gases tend to be poor conductors of heat. In metals the presence of free electrons which move through the lattice, colliding with a series of rapidly oscillating ions transfers thermal energy very rapidly.

Substance	Thermal conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)
Silver	420
Copper	400
Aluminium	240
Steel	79
Ice	1.7
Glass, concrete, brick	0.8
Water	0.59
Animal muscle, fat	0.2
Paper, cardboard, wood	0.08
Wool, felt, rock-wool	0.04
Air	0.024
Down	0.019
Styrofoam	0.01

The amount of energy lost due to conduction is given by $Q = \frac{kA(T_{body} - T_{external})t}{d}$,

where Q is the amount of energy, k, the thermal conductivity, A, the area of contact, t, the time and d, the distance between the two objects.

Expansion

Materials that expand when heated, contract when cooled. Usually the change in size is too small to be noticed. But it can cause problems for train/tram lines (as they can buckle when heated). Solids expand when heated, the particles vibrate more rapidly, and take up more space, thus the particles push each other further apart.

Substance	Expansion of 1 metre bar when heated to 100 ºC
Pyrex	0.3 mm
Glass	0.9 mm
Concrete	1.0 mm
Steel	1.0 mm
Brass	2.0 mm
Aluminium	3.0 mm

Convection

Convection is the transfer of heat by the flow of particles in the heated material. Convection is the usual method for heat to travel through liquids and gases. In convection the less dense (hotter) material rises taking the heat with it.

Wind chill

A warm body exposed to still air will heat the air around it, creating a layer of warmer air around it. When there is wind this warm layer is blown away and replaced with new cooler air. The larger temperature differential means that heat transfer speeds up. This is the transfer of heat due to convection. It is similar to conduction,

$$Q = \frac{hA(T_{body} - T_{external})t}{D},$$

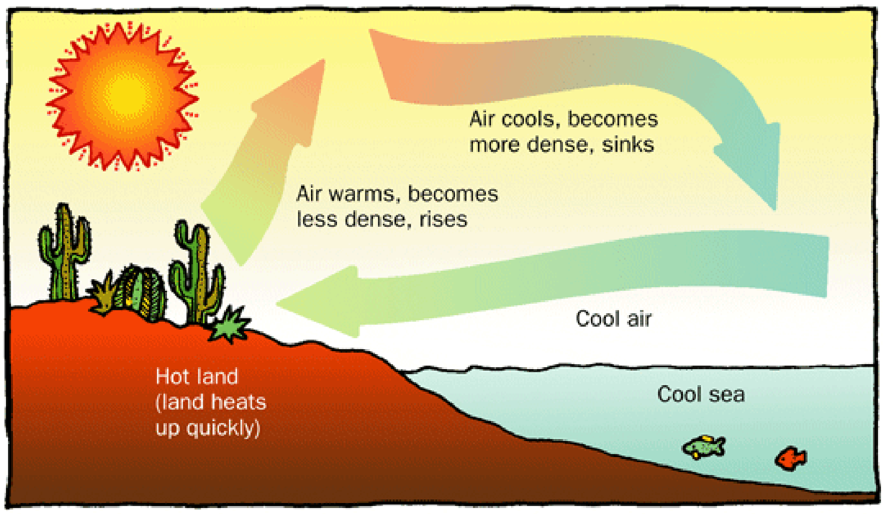
Where D is the thickness of the convection layer, h is a constant for a given situation. Both D and h are very difficult to identify.

We often use a table of “Apparent temperature” instead.

Wind speed ($km\ hr^{-1}$)	Temperature (ºC)							
	5	**0**	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**
8	2	-3	-8	-12	-18	-24	-29	-34
16	-1	-8	-14	-20	-26	-32	-39	-45
24	-4	-12	-19	-25	-33	-40	-47	-54
32	-7	-15	-22	-29	-36	-43	-50	-58
40	-9	-17	-23	-30	-38	-45	-53	-62

Convection in the atmosphere

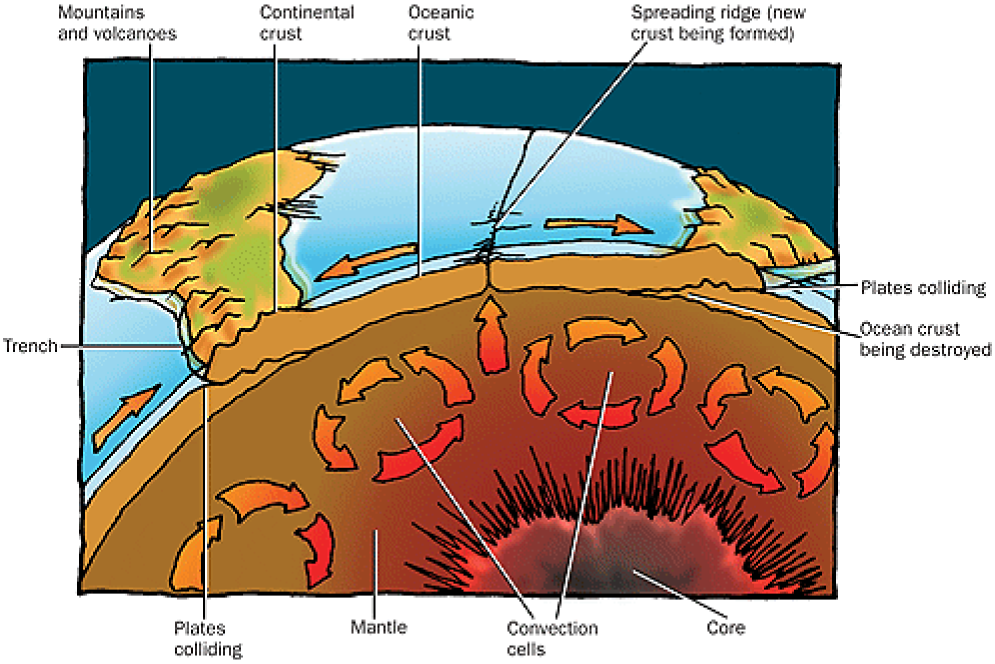
Convection also accounts for changes in temperature in the atmosphere as shown in the diagram below. As the air heats up it becomes less dense and therefore rises and new cooler air comes in to replace the hot air, creating wind.



Convection also occurs in the oceans in the same way, creating ocean currents. The oceans are the principal means by which the earth evens out its temperature. The warm seas at the equator flow towards the cold poles.

Convection in the Earth's mantle

While convection typically only occurs in liquids and gases, convection is the force that drives tectonic shifts. The mantle is heated from below (the core), and in areas that are hotter it rises upwards, whereas in areas that are cooler it sinks down. This results in convection cells in the mantle, and produces horizontal motion of mantle material close to the Earth surface. This convection takes place in mantle rock (a mixture of silicate minerals) that at any given time would appear solid. Yet, when the forces of buoyancy are applied over millions of years, this seemingly solid material moves, behaving like an extremely viscous fluid.



Radiation

All atoms (above absolute zero) give off radiation, but depending on their temperature they give off different levels of radiation. Hot objects give off more radiation than cooler objects. This electromagnetic radiation travels at the speed of light, c, and can travel through a vacuum. This is how heat from the sun reaches earth.

An object, such as a bar radiator at 500 ºC produces mainly infra-red radiation; an object such as an incandescent light globe at 1200 ºC radiates some visible light as well as infra-red; and an object as hot as the sun at 6000 ºC radiates a significant amount of ultraviolet radiation as well as visible and infrared radiation. The gases that are found between the galaxies of our universe are at a temperature of about 3 K (-270 ºC) and radiate microwaves or radio waves.

Black matt surfaces are better absorbers than white shiny surfaces (which tend to reflect radiation).

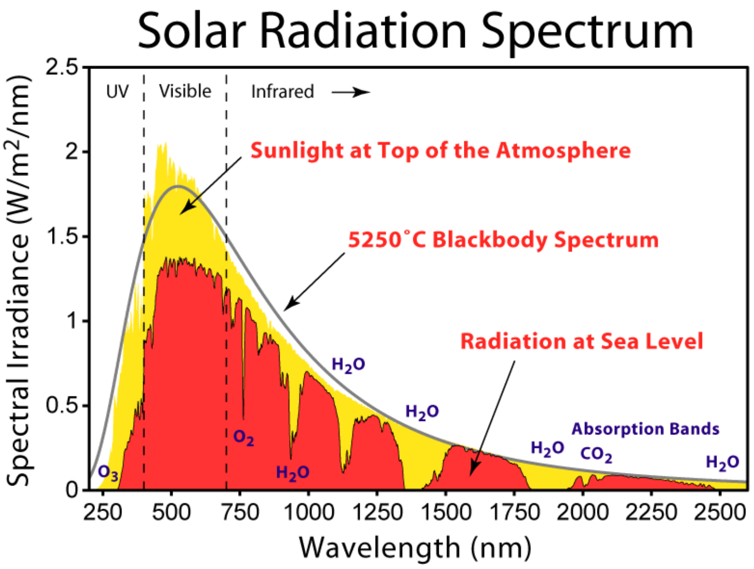
Temperature of the Sun

Thanks to the work of Max Planck and that of Wilhelm Wein we can measure the temperature of the Sun based upon its *spectrum.* All objects emit radiation on the electromagnetic spectrum, the hotter the object the shorter the length of the radiation emitted.

This is why humans can be seen to glow using an infrared camera. When we get towards very hot objects like stars and they can appear very bright and sometimes blue (shorter wavelength).

Using this information, we can take a spectrum of the Sun as shown below:

This shows that the radiation emitted from the sun is mainly ultraviolet, visible and infrared.



Using the Sun's spectrum from above we can see the peak emission of approximately 502 nm, 502 x 10^{-9} m to find the approximate surface temperature of the Sun:

Now we can employ Wien's law:

$$\lambda = \frac{2.9\times10^{-3}}{T}$$

$$T = \frac{2.9\times10^{-3}}{\lambda}$$

$$= \frac{2.9\times10^{-3}}{5.02\times10^{-9}}$$

$$= 5\,776\ \text{K}$$

Wien's law can also be used to calculate the peak wavelength of the re-radiated electromagnetic radiation from Earth.

The average temperature of the Earth is 15 ºC = 288 K.

$$\lambda = \frac{2.9\times10^{-3}}{T}$$

$$= \frac{2.9\times10^{-3}}{288}$$

$$= 1.0\times10^{-5}\ \text{m}$$

Climate Change

By nature, every object tries to reach a point of thermal equilibrium with its surroundings. In order to achieve this the object must emit the same amount of energy that it receives. If an object emits more energy than it receives the object will cool down, causing it to emit less energy, this will continue until it is in thermal equilibrium with its surroundings. The opposite is true if it emits less energy that it is receiving.

The Earth is also trying to achieve thermal equilibrium. The average energy received from the sun is 342 W m^{-2}, however about 100 W m^{-2} is reflected back into space by the white surfaces on Earth (e.g. clouds, ice sheets). This means that to be in thermal equilibrium the Earth must emit on average 242 W m^{-2}.

Using the Stefan-Boltzmann relationship we can determine the temperature the Earth would need to be in order to emit 242 W m^{-2} on average.

$$P = \sigma T^4$$

$$P = \sigma T^4$$

$$\backslash\ T = \sqrt[4]{\frac{P}{\sigma}}$$

$$= \sqrt[4]{\frac{242}{5.67\times10^{-8}}}$$

$$= 255.6\ \text{K}$$

$$= {}^{-}17.4\ ^{\circ}\text{C}$$

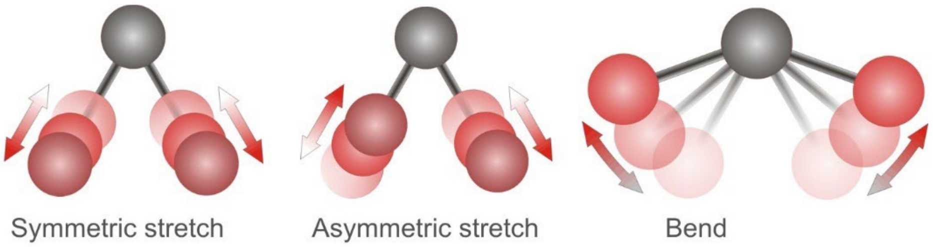
This does not mean that the average temperature of the earth is actually this temperature. Rather it is the temperature of the upper atmosphere, and neglects the effects of the atmosphere on the surface of the planet. The greenhouse gases in Earth's atmosphere (mostly water and carbon dioxide), trap heat keeping the Earth warmer.

The atmosphere's effects on the incoming solar radiation

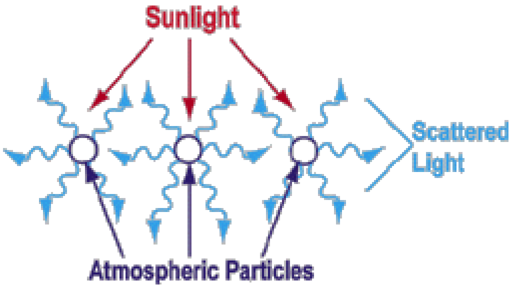
The quantities of different gases in the atmosphere can be seen in the table below. Each molecule interacts differently with the incoming solar radiation, absorbing and transmitting various parts of the spectrum. From the table it is clear that the majority of the atmosphere is made up of nitrogen and oxygen (mostly nitrogen!).

Gas	**Dry Volume**
nitrogen (N_2)	78.08%
oxygen (O_2)	20.95%
water vapour (H_2O)	1% - 4%
argon (Ar)	0.93%
carbon dioxide (CO_2)	0.038%
neon (Ne)	0.002%
helium (He)	0.0005%
methane (CH_4)	0.0002%
hydrogen (H_2)	0.00005%
nitrous oxide (N_2O)	0.00003%
ozone (O_3)	0.000004%

Molecules made up of two atoms, like nitrogen and oxygen, will absorb and re-emit ultraviolet radiation, but transmit visible and infrared radiation leaving their paths unaltered. Molecules with three atoms are more flexible than those with two atoms, and have three different ways of stretching or bending (as shown by the diagrams below), as well as oscillations around three axes. This allows molecules such as water and carbon dioxide to absorb and re-emit infrared radiation. Methane, with five atoms, is even more flexible. These molecules absorb different parts of the infrared spectrum, and so contribute independently to the greenhouse effect.

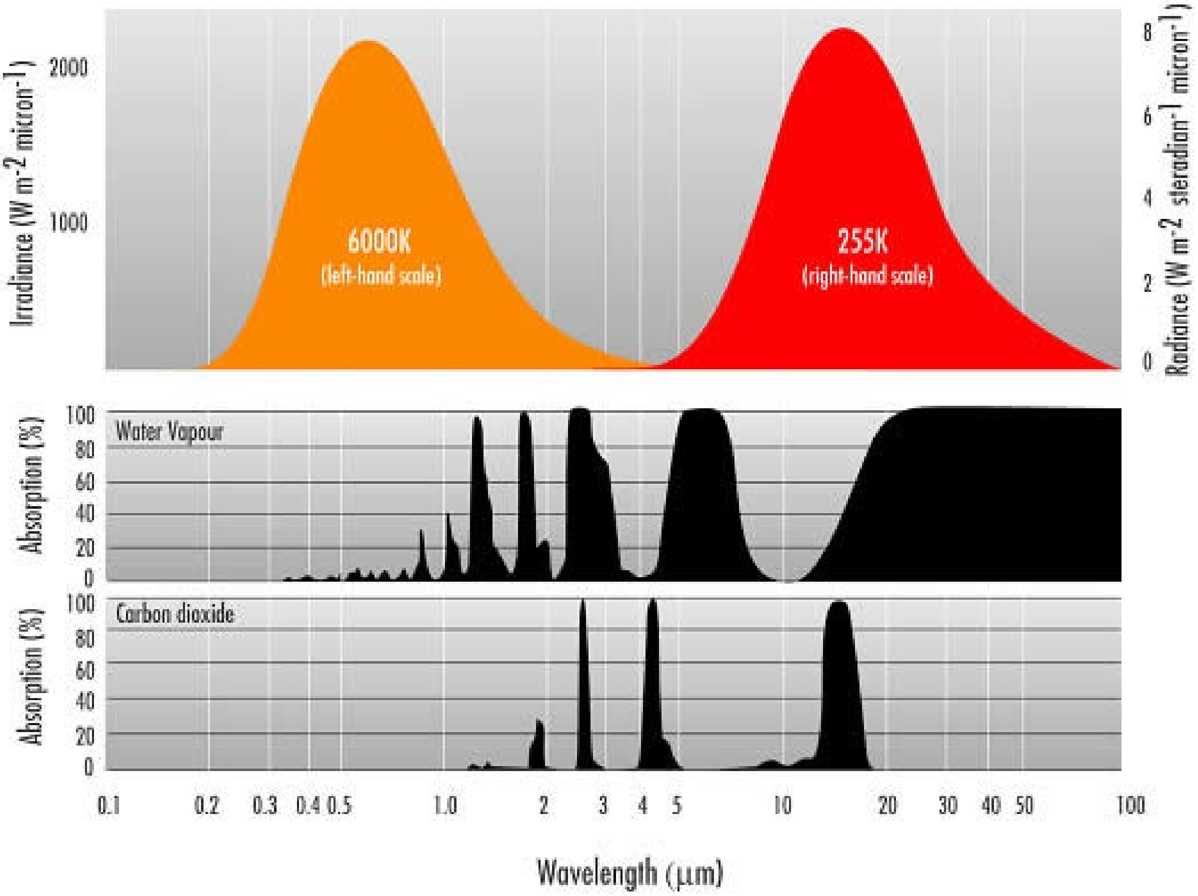


When a molecule has absorbed radiation it re-emits it, however it does this in a random direction. This means that the nitrogen and oxygen (and ozone) in the atmosphere scatter the ultraviolet radiation coming from the sun. The radiation that is scattered back out into space continues in that direction, but the radiation that is scattered toward Earth is likely to be absorbed and re-emitted by parts of the atmosphere closer to the Earth, to be scattered further. Therefore, only a very small amount of the ultra violet radiation coming from the sun reaches the Earth's surface, which is lucky as otherwise it would be very difficult for life on Earth to survive.

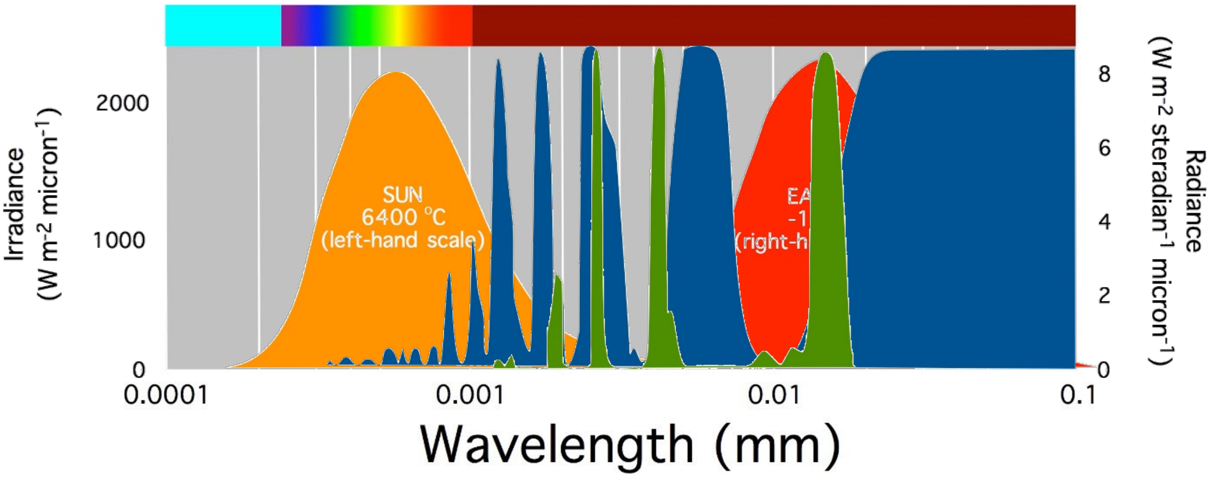


The greenhouse gases do the same thing with the infrared radiation being emitted by the Earth, scattering the radiation so more than half of the infrared radiation being emitted by the Earth is reflected back down to Earth, keeping it warm. Again, this is useful, as otherwise the Earth would be very cold. However, it is also important that the Earth doesn't get too hot!

The graphs below show the radiation that reaches the Earth from the Sun (top left), the radiation that the Earth emits (top right), and the absorption spectra for water (middle) and carbon dioxide (bottom).



Overlaying the two absorption spectra on the emission spectra it can be seen that the combination of water and carbon dioxide in the atmosphere blocks a significant amount of the outgoing radiation.

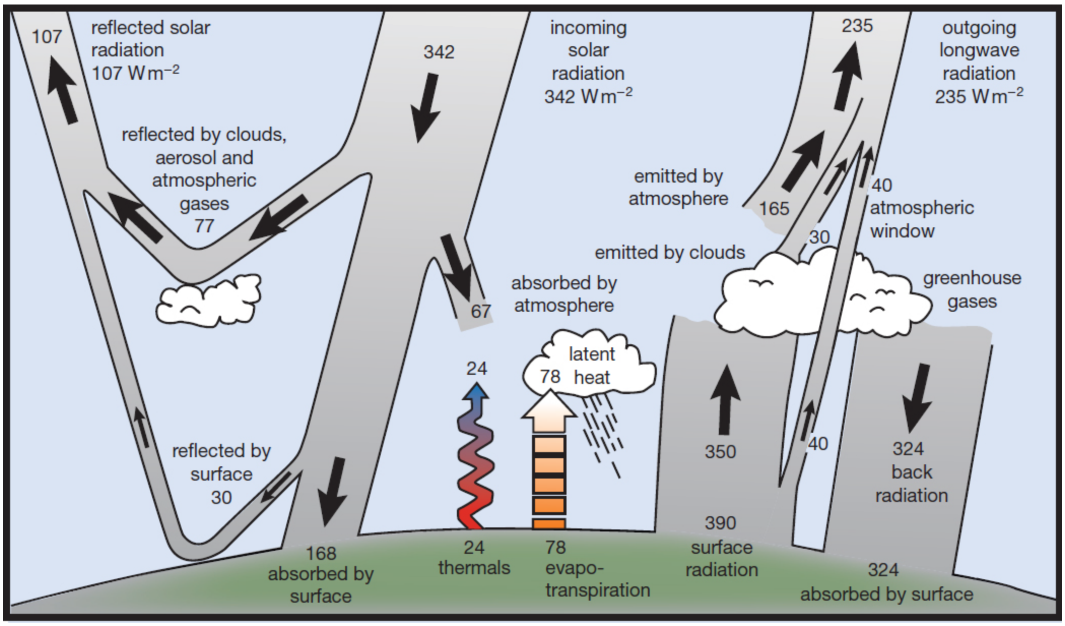


All parts of the Earth’s climate interact, so changing one thing has effects on everything else, this is known as feedback. For example, as the Earth heats up ice caps melt, reducing how much radiation is initially reflected back into space. As the oceans warm up more water vapour enters the atmosphere, increasing the greenhouse effect. These are examples of positive feedback, as the effects add to the cause (more heat!). Negative feedback is where the effect aims to do the reverse of the cause (cooling the planet down). For example, as the Earth heats up more it emits more radiation in order to cool the Earth. However, if there are too many greenhouse gases in the atmosphere it is difficult for this radiation to escape.

An everyday example of feedback is when a microphone is placed too close to its speaker, the sound through the microphone is amplified and played through the speaker, which is picked up by the microphone, amplified and so on, which creates a loud, high pitched noise.

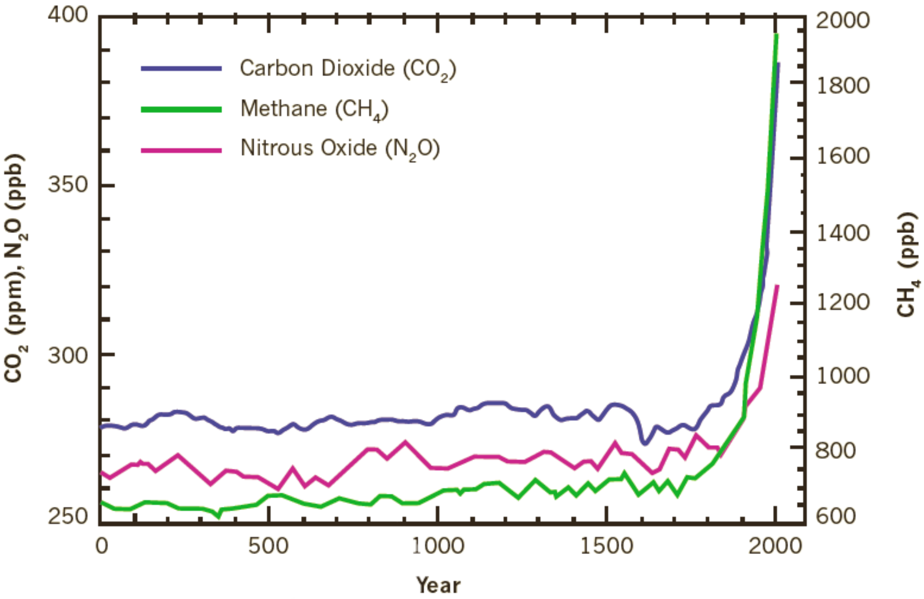
The risk in a feedback loop is that there is a tipping point beyond which the system cannot restabilise. An example of this is Venus’ atmosphere with its runaway greenhouse effect. Venus’ atmosphere is about 90 times thicker than Earth’s and is 96% carbon dioxide. The temperature at the surface of Venus is 740 K (467 °C).

The diagram below shows where energy comes from and goes to, showing the complex nature of the Earth’s climate. Changing any one of the numbers in the diagram will have an effect in numerus other places.



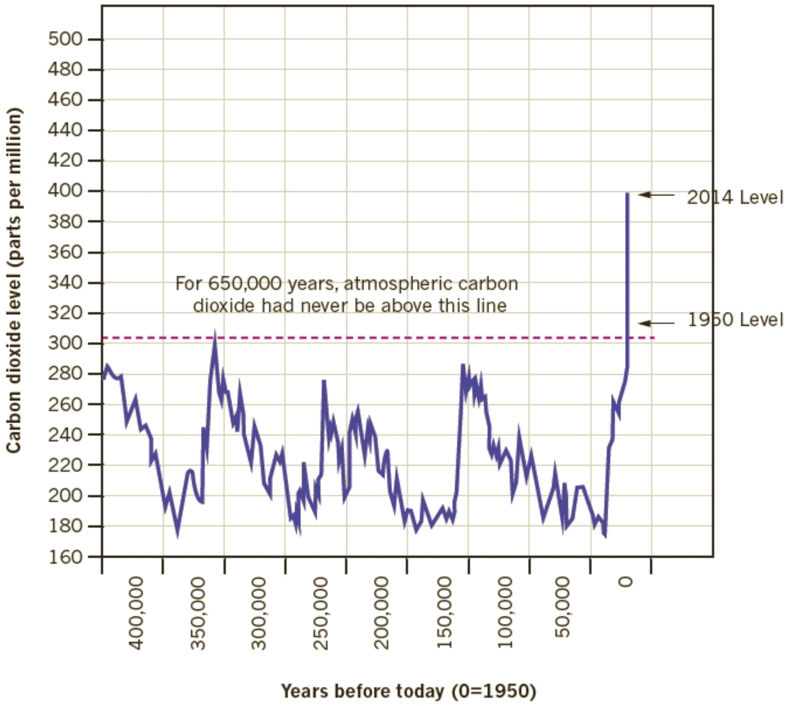
The human contribution to global warming

While humans are not the biggest cause of the greenhouse gasses, the human contribution on top of the natural fluctuations mean that there are now more greenhouse gases in the atmosphere than there have been in the last 400 000 years. Human activities such as the burning of fossil fuels, agriculture and clearing land all increase the concentrations of greenhouse gases in the atmosphere. The top graph on the following page shows the levels of different greenhouse gases over the last 2000 years, showing a significant increase in all the greenhouse gases from the 1700s onward (around the beginning of the industrial era).



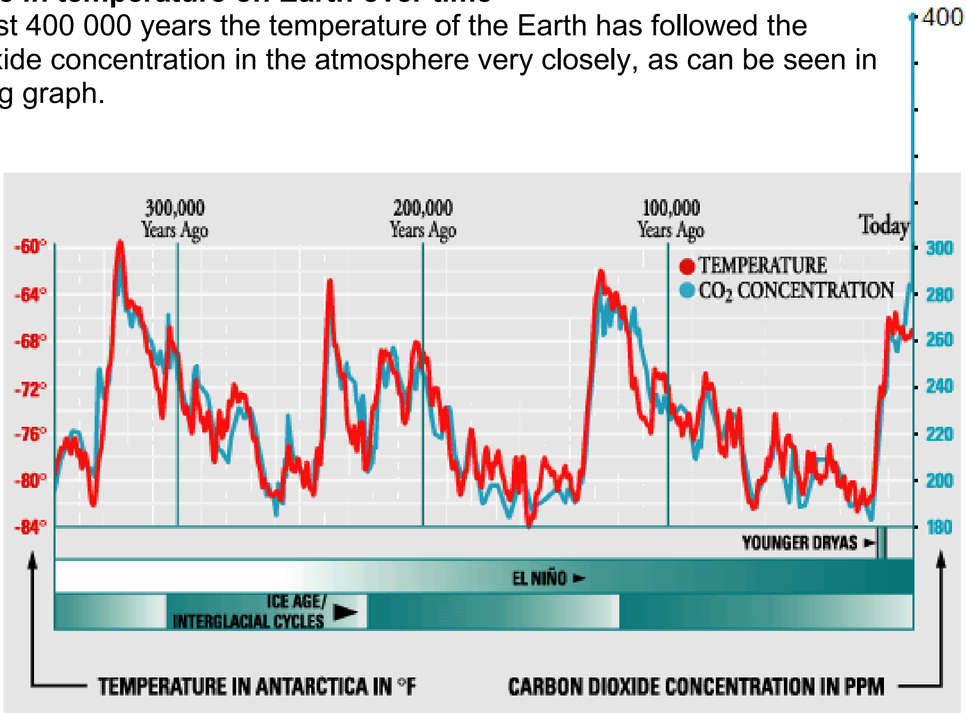
The following graph shows carbon dioxide levels in the atmosphere for the past 400 000 years (about the time that modern humans evolved). It shows that while the carbon dioxide levels fluctuate considerably over long timespans, the current levels are considerably higher than modern humans have ever seen. If the Earth becomes too hot changes will occur across the entire planet that will significantly affect the Earth's ability to sustain the current way of life.

Large numbers of buildings also help to keep the heat in, adding to the Earth's temperature.

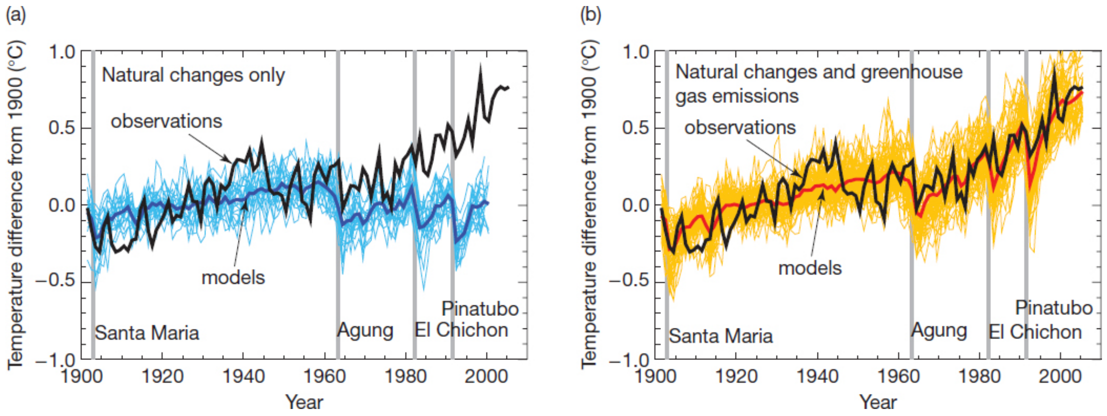


The change in temperature on Earth over time

Over the last 400 000 years the temperature of the Earth has followed the carbon dioxide concentration in the atmosphere very closely, as can be seen in the following graph.



To investigate this further, we can look at the more recent history to see how well climate models fit the observed data. Climate models attempt to calculate future trends and account for past observations. The solid black line on both the graphs below shows the global average surface air temperature. The graph on the left shows what climate models predict would have happened if greenhouse gas levels remained constant from 1900. The solid blue line is the average of numerous models. The graph on the right depicts the same models, but this time with updated greenhouse gas levels. This suggests that the increasing levels of greenhouse gases in the atmosphere has led to an increase in global temperatures.

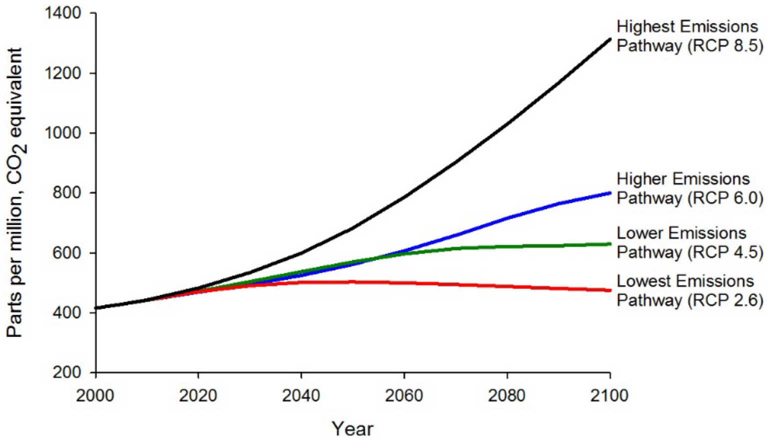


Models like these ones can be used to make predictions into the future about temperature changes and to investigate how long the Earth’s atmosphere would take to respond to significant reductions in greenhouse gas emissions.

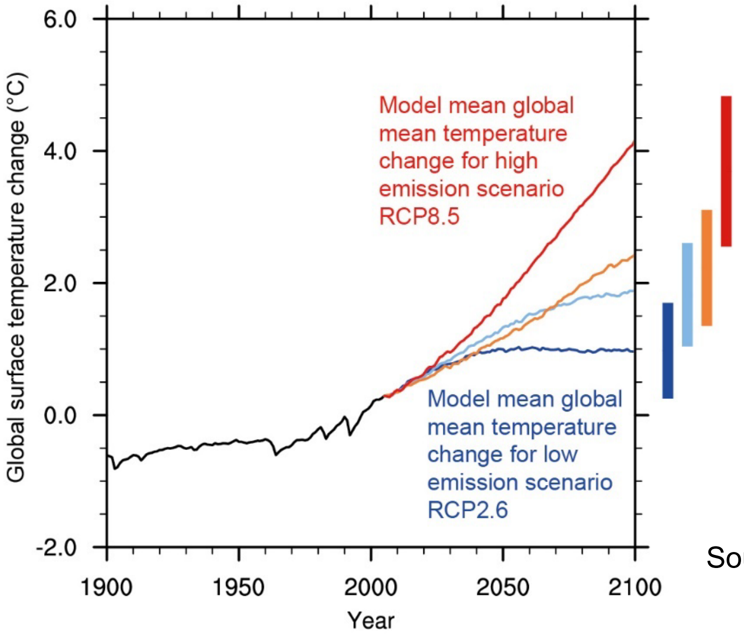
Studies predict that even if carbon dioxide emissions were cut to zero tomorrow, the carbon dioxide in the atmosphere would continue to heat the Earth for hundreds of years.

The graph below shows projected greenhouse gas concentrations for four different emissions pathways. The top pathway assumes that greenhouse gas emissions will continue to rise throughout the current century. The bottom pathway assumes that emissions reach a peak between 2010 and 2020, declining thereafter.

Projected Atmospheric Greenhouse Gas Concentrations



How the temperature of the planet will look in the future depends on our ability to cut greenhouse gas emissions. The graph below shows predicted changes to the mean surface temperature, based on the emission on the pervious page. The vertical bars at right show likely ranges in temperature by the end of the century, while the lines show projections averaged across a range of climate models. Changes are relative to the 1986-2005 average.



Source: [IPCC, 2013]