By the end of this century, many climate scientists predict an Earth that is on average somewhere between 1 and 3 degrees warmer than it is today. A warmer climate would allow us through heat waves, storms, flooding, and changes in water supplies and agriculture. Types of natural vegetation would change, and ice sheets, glaciers and sea ice might melt. Some of these changes would be due to greenhouse gases in the atmosphere, partly caused by human activities such as the burning of coal and oil.

In order to be able to adapt to these changes in the way we live and perhaps prevent greater impacts in the future, we need to improve our knowledge of how the Earth works and how it responds to changes in the climate.

What is climate?

According to Ed Lorenz, one of the key figures in the science of climate and weather prediction, climate is what we expect weather is in the area and time. At any given day, month, or year, the average temperature might vary a small amount from 3°C, but the temperature would vary from location to location more than that. A more useful definition would include a description of how much this figure varied over, say, a period of 50 years or from place to place and time.
Box 1. Wien's law

The peak intensity \( I \) of energy emitted by a body is related to its temperature \( T \) as follows.

\[
I = \frac{C_n T}{d^2} \text{ [W m}^{-2} \text{K}^{-1} \text{]} 
\]

where \( C_n = 2.898 \times 10^{-3} \text{ m K} \).

For the Sun, \( T = 6000 \text{ K} \), giving \( I = 1.4 \times 10^{-3} \text{ W m}^{-2} \).

For the Earth, \( T = 288 \text{ K} \), giving \( I = 5.5 \times 10^{-5} \text{ W m}^{-2} \).

Thus, the Sun's energy is mainly emitted in the ultraviolet (UV) and visible parts of the spectrum and the Earth's in the infrared (IR).

Perhaps a description of rainfall or cloud cover. However, one figure in a simple pie chart allows us to think about the factors that might cause climate change.

Energy: the driving force of climate

Ultimately, the climate is determined by the amount of radiation received from the Sun and by the amount of radiation reflected to space by the Earth and atmosphere. The Earth receives visible and ultraviolet (UV) radiation from the Sun (see Figure 1). About 30% of this radiation is scattered back to space by clouds, molecules and particles in the atmosphere and by the bright parts of the Earth's surface; the remainder is absorbed. The Earth then warms up and thus emits radiation itself, but, since the Earth's temperature is much lower than that of the Sun, infrared (IR) radiation is emitted. Most of the gases that occur naturally in the atmosphere can absorb this radiation, preventing it from reaching space. The atmosphere itself emits IR radiation in all directions, including down towards the Earth's surface. Thus, the atmosphere acts like a blanket, keeping the surface of the Earth warmer than it would be without (see Figure 2). This is the greenhouse effect—a natural phenomenon which is necessary for life to exist on Earth. The major natural greenhouse gas is water vapor. Any activity (human or natural) that reduces extra greenhouse gases such as carbon dioxide or methane into the atmosphere can amplify this natural greenhouse effect and warn the Earth further.

Figure 2. The Earth's energy budget, showing the fate of incoming solar radiation and outgoing terrestrial radiation.

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Figure 3. Annual average radiation budget showing an equatorial and tropical energy surplus and a polar energy deficit. The atmospheric and oceanic circulations (winds and currents) transfer energy to the poles as part of a giant heat engine.

A simple climate model

Since the Earth is neither cold nor hot, it is possible to simplify climate models and predict the surface temperature. (see Figure 4.) In doing so, we can see that the atmosphere is responsible for a considerable 50% extra warmth at the Earth's surface.

Our simple model tells us the limits of what could govern climate change. A key variable in the model is the planetary albedo, the fraction of solar radiation scattered back to space. If this is currently 10%, but, if some of the sea ice melts, the albedo would decrease and more solar radiation would be absorbed by the Earth, leading to a temperature rise (see Box 2). If the amount of IR-absorbing gases in the atmosphere increases, the emissivity increases and the surface temperature increases. Although the Earth must be in energy balance as a whole, at any one location this balance between absorbed and emitted radiation does not hold. In fact, the tropics absorb more radiation than they emit (cloud-free skies and strong convection), while the poles emit more than they absorb (they receive no solar radiation for large parts of the year).

The winds in the atmosphere and currents in the ocean even out this difference somewhat, transferring energy from the equator to the pole (see Figure 4). The Earth is a giant heat engine; most energy is converted into mechanical energy of the winds and ocean currents.
Box 2 A simple energy balance model

We need to find expressions for the absorbed solar radiation and the outgoing infrared (IR) radiation.

Incoming solar radiation

The solar constant, $S_0$, measures the radiation flux incident on the Earth from the Sun, i.e., the power per unit area. The current measured value is $1361 \text{ W m}^{-2}$.

$S_0 = 1361 \text{ W m}^{-2}$

Seen from the Sun, the Earth looks like a disc of radius $r$. The total solar power incident on the Earth is therefore $\pi r^2 S_0$.

As the Earth's surface area is $4\pi r^2$, the average solar power reaching per unit area is $P_{in}$:

$$P_{in} = \frac{\pi r^2 S_0}{4\pi r^2} = \frac{S_0}{4}$$

However, not all the energy incident on the Earth is absorbed. A fraction $\alpha$, which is known as the planetary albedo, is scattered straight back into space. The average power actually absorbed per unit area, $P_{in} \alpha$, is therefore given from Equation 2.2.

$$P_{in} \alpha = \frac{S_0(1 - \alpha)}{4}$$

Outgoing, terrestrial infrared radiation

We can assume that the Earth's surface is a black body, consequently it emits radiation according to Kirchoff's law:

$$P = \sigma T^4$$

where $P$ is the power emitted per unit area and $\sigma$ is the Stefan-Boltzmann constant. Some of this energy gets trapped in the atmosphere and the atmosphere itself emits radiation, so we need to think carefully in order to calculate the temperature.

Let us assume a layer of atmosphere that behaves like a grey body with emissivity $\varepsilon$. For a grey body, Kirchoff's law says that a fraction $\varepsilon$ of the radiation is emitted, giving the atmosphere temperature $T_{atm}$, so that an amount $\alpha P_{in} \varepsilon$ is emitted. Therefore, at the top of the atmosphere, the total power emitted per unit area is:

$$P_{out} = (1 - \alpha) P_{in} \alpha + \alpha P_{in} \varepsilon = \frac{S_0(1 - \alpha - \varepsilon)}{4}$$

Predicting surface temperature

Finally, we need to put the two models together and use the concept of energy balance to derive an equation for $T_s$. The average power absorbed by an unit area must equal the average power emitted (otherwise the temperature would change), so we must equate expressions 2.3 and 2.4.

$$P_{in} \alpha = \frac{S_0(1 - \alpha)}{4} = \frac{S_0(1 - \alpha - \varepsilon)}{4} + \sigma T_s^4$$

But we still have $T_s$ as well as $T_{atm}$ in the equation. Let's define the temperature that the atmosphere emits, $T_{atm}$, and equate this with the temperature at the surface, $T_s$.

$$T_s = \frac{S_0(1 - \alpha - \varepsilon)}{4\sigma}$$

We can rearrange this to give $T_s$ in terms of $T_{atm}$ and substitute into Equation 2.4, ending up with an equation for $T_s$ that is:

$$T_s = \frac{S_0(1 - \alpha - \varepsilon)}{4\sigma(1 - \varepsilon)} = \frac{S_0(1 - \alpha)}{4\sigma}$$

Using values of $\alpha = 0.35$, $\varepsilon = 0.3$, and $S_0 = 1361 \text{ W m}^{-2}$ and $T_{atm} = 255 \text{ K}$ gives:

$$T_s = 288 \text{ K}$$

If there was no atmosphere, we would have $\alpha = 0$ and $T_s = T_{atm} = 255 \text{ K}$.

The way we balanced the gains and losses of energy at the top of the atmosphere was to assume that the Earth's surface is a black body, and that the atmosphere emits radiation. We can now use this to calculate the temperature at the surface, $T_s$.

What happens next?

In order to determine the effect of climate change on our planet, we need to use a computational model that can represent the atmosphere and ocean circulation, as well as the Earth's surface and human activities. The key factor is the availability of energy. We use a computer model based on the principles of the greenhouse effect, the carbon cycle, and the effects of human activities. The model can then be used to predict the future climate change and its impact on the environment and human activities.
Figure 4: Global average near-surface temperature, 1850–July 2005, showing recent temperature change since 1880, plotted as the difference in temperature compared to an average over the period from 1961 to 1990 (figures from the Met Office website).

Dealing with the uncertainties

Why do climate models produce such a range of answers for temperature change in 2100, and what error bars must we put on our predictions? We know the range is partly due to slight differences in the way the models simulate processes, and partly due to differences in the input to our models, for example greenhouse gas emissions depending on social, economic and political changes. There is a third type of uncertainty to do with the chaotic nature of the climate system. A very small difference in the state of the atmosphere at the beginning of two simulations can multiply and produce a large difference in the state of the atmosphere at the end of the simulation. You may have heard of this in terms of a butterfly flapping its wings in Brazil and causing a hurricane in the Pacific Ocean.

Understanding this is more important for short-term weather forecasts than for long-term climate forecasts, and that is why we can still predict the weather more than a few days in advance but can get away with predicting climate 95 years ahead.

To find out the size of these uncertainties, we ran several slightly different versions of the same model (an ensemble experiment), building up a probability graph for surface temperature change. We can use these results to get a feel for how likely each scenario is, and for us determine how likely it is for the probability of the temperature in 2100 being 3 degrees warmer than today. This is the kind of information needed by people studying the impact and prevention of climate change.

These experiments tell us which parts of our model have the most impact on our predictions, and also show us how optimistic we can be about our models.

Websites

You can read about one particular model in Sylvia Knight’s article on page 6-9, which includes websites addresses.

Research into climate processes and climate change is carried out in the Department of Meteorology at the University of Reading. The department offers a full range of undergraduate and postgraduate degrees in meteorology, which all involve studying the physical and mathematical basis for the many amazing weather and climate phenomena we observe every day. You can find more information at

http://www.reading.ac.uk

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