Hot times ahead?

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You will have noticed that weather forecasts are often unreliable more than 2 or 3 days into the future, yet we hear many doom and gloom warnings of 'global warming' and 'climate change' over the next century. How can we put any confidence in forecasts of the Earth's climate in 50 years' time, when we have trouble forecasting the weekend's weather? Climate is driven by the ***energy*** *received as* ***electromagnetic radiation*** *from the Sun and by properties of the Earth's surface and atmosphere that influence its* ***thermal radiation***.

By the end of this century, many climate scientists predict an Earth that is on average somewhere between 1 and 5 degrees warmer than it is today. A warmer climate would affect 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 previous increases in the amount of 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 changes on the way and perhaps prevent greater impacts in the future, we need to use basic physical concepts to predict climate change.

What is climate?

According to Ed Lorenz, one of the key figures in the science of chaos and weather prediction, 'Climate is what we expect; weather is what we actually get.' So, we could describe the climate of the Earth in recent years as having an average surface temperature of around 15 °C. On any given day, month or year this average temperature might vary a small amount from 15 °C, but the temperature would vary from location to location a great deal more than that. A more useful definition would include a description of how much this figure varied over, say, a period of 10 years or from place to place and,

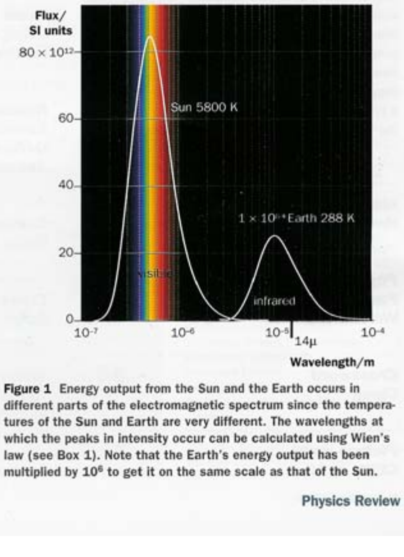


Figure 1 Energy output from the Sun and the Earth occurs in different parts of the electromagnetic spectrum since the temperatures of the Sun and Earth are very different. The wavelengths at which the peaks in intensity occur can be calculated using Wien's law (see Box 1). Note that the Earth's energy output has been multiplied by 10^6 to get it on the same scale as that of the Sun.

Box 1 Wien's law

The peak intensity λ_{max} of energy emitted by a body is related to its temperature T as follows.

$$\lambda_{max}T = 2.898 \times 10^{-3}\,\text{mK}$$

For the Sun, $T \approx 5800\,\text{K}$, giving $\lambda_{max} = 5.00 \times 10^{-7}\,\text{m}$, i.e. 0.5 microns.

For the Earth, $T \approx 288\,\text{K}$, giving $\lambda_{max} = 1.01 \times 10^{-5}\,\text{m}$, i.e. 10 microns.

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 is a simple place to start and allows us to think about the factors that might cause climate change.

Energy: the driving force for climate

Ultimately, the climate is determined by the amount of radiation absorbed from the Sun and by the amount of radiation released to space from the Earth and atmosphere. The Earth intercepts 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 (ice or desert) of the Earth's surface; the remainder is absorbed. The Earth heats up and thus emits radiation itself, but, since the Earth's temperature is much lower than that of the Sun, infrared (IR) radiation (see Box 1) is emitted. Many of the gases that occur naturally in the atmosphere can absorb this IR 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 otherwise (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 vapour. Any activity (human or natural) that releases extra greenhouse gases such as carbon dioxide or methane into the atmosphere can amplify this natural greenhouse effect and warm the Earth further.

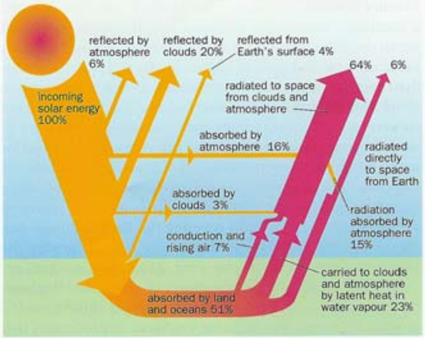


Figure 2 **The Earth's energy budget, showing the fate of incoming solar radiation and outgoing terrestrial radiation.**

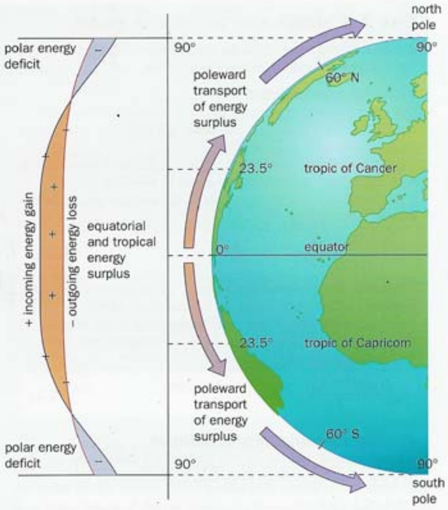


Figure 3 **Annual average radiation budget showing an equatorial and tropical energy surplus and a polar energy deficit. The atmospheric and oceanic circulations (winds and currents) transfer energy to the poles as part of a giant heat engine.**

A simple climate model

Since the Earth has neither boiled nor turned into a snowball recently, the climate is stable and the Earth must therefore be in a state of approximate *energy balance*. The amount of solar radiation absorbed by the Earth and atmosphere must be equal to the amount of IR radiation emitted to space. We can use this concept to build a simple climate model and predict the surface temperature (see Box 2 on page 4). In doing so, we can see that the atmosphere is responsible for a considerable 30 °C extra warmth at the Earth's surface.

Our simple model tells us the kinds of things that could give us climate change. A key variable in the model is the planetary albedo, that fraction of solar radiation scattered back to space. This is currently 30%, but, if some of the sea ice melted, 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 close to 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 sunshine), 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, transporting energy from the equator to the poles (see Figure 3). The Earth is a giant heat engine; heat 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 terrestrial (mainly 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 1376 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 arriving per unit area, P_{in}, is

$$P_{\mathrm{in}} = \frac{\pi r^2 S_0}{4\pi r^2} = \frac{S_0}{4} \tag{2.1}$$

However, not all the energy incident on the Earth is absorbed. A fraction α_p, which is known as the planetary albedo, is scattered straight back to space. The average power actually absorbed per unit area, P_{abs}, is therefore obtained from Equation 2.1 and we have

$$P_{\mathrm{abs}} = \frac{S_0(1-\alpha_p)}{4} \tag{2.2}$$

Outgoing terrestrial infrared radiation

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

$$P = \sigma T_s^4$$

where P is the power emitted per unit area and σ 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 clearly in order to calculate the temperature.

Let us assume a layer of atmosphere that behaves as a 'grey body' with emissivity ε. For a grey body, Kirchhoff's law says that a fraction ε of the radiation is absorbed, giving the atmosphere a temperature T_a, so that an amount $\varepsilon\sigma T_a^4$ is emitted. Therefore, at the top of the atmosphere, the total power emitted per unit area is

$$P_{\mathrm{em}} = (1-\varepsilon)\sigma T_s^4 + \varepsilon\sigma T_a^4 \tag{2.3}$$

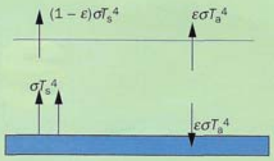


Figure 2.1 A simple model for predicting surface temperature.

Predicting surface temperature

Finally, we need to put the two halves together and use the concept of energy balance to give us an equation for T_s. The average power absorbed per unit area must be equal to the average power emitted (otherwise the temperature would change), so we must equate expressions 2.2 and 2.3.

$$P_{\mathrm{abs}} = P_{\mathrm{em}}$$
$$\frac{S_0(1-\alpha_p)}{4} = (1-\varepsilon)\sigma T_s^4 + \varepsilon\sigma T_a^4 \tag{2.4}$$

But we still have T_a as well as T_s in the equation. Just thinking about the atmosphere by itself, if it is in energy balance we know that absorbed power is equal to emitted power. The absorbed power is that received from the surface, i.e. $\varepsilon\sigma T_s^4$. Half the radiated power goes into space ($\varepsilon\sigma T_a^4$) and half goes back to the surface (also $\varepsilon\sigma T_a^4$), so that

$$\varepsilon\sigma T_s^4 = 2\varepsilon\sigma T_a^4 \tag{2.5}$$

We can rearrange this to get T_a in terms of T_s and substitute into Equation 2.4, ending up with an equation for T_s that is

$$T_s = \left(\frac{S_0(1-\alpha_p)}{2\sigma(2-\varepsilon)}\right)^{\frac{1}{4}} \tag{2.6}$$

Using values of $\varepsilon = 0.77$, $\alpha_p = 0.3$, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} and $S_0 = 1376$ W m^{-2} gives

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

If there was no atmosphere we would have $\varepsilon = 0$ and $T_s = 255$ K.

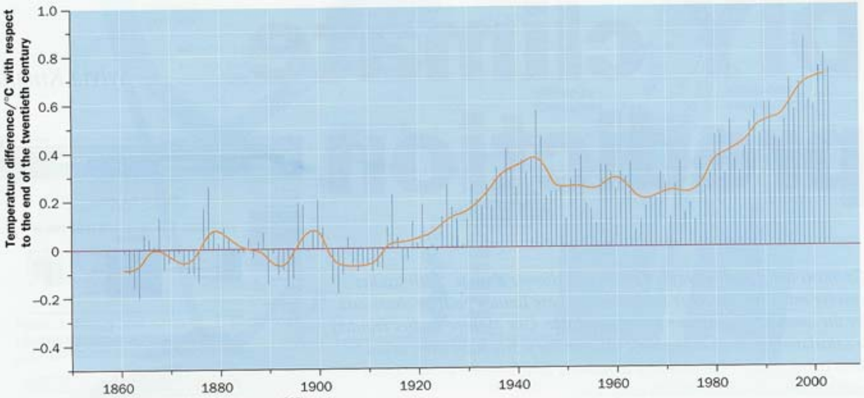
Are we balanced?

Satellite observations of incoming and outgoing radiation at the op of the atmosphere show that the Earth is very close to being n balance. About 2 W m^{-2} more energy is absorbed than mitted. This is less than a 1% imbalance in the energy budget; he excess would power something like two Christmas tree ight bulbs for every square metre of the Earth's surface and is nough to cause the planet to warm slowly.

We have seen a rise of about 0.6 °C in global average emperature over the past 150 years (see Figure 4). The easons for this rise are complex and include both natural rocesses and human activities, Before the mid-eighteenth entury (the Industrial Revolution) the Earth's temperature ppeared to be following a natural cooling trend. In 2001, the ntergovernmental Panel on Climate Change reviewed all the ecent results and decided: 'An increasing body of observations ives a collective picture of a warming world and other changes n the climate system.... There is new and stronger evidence hat most of the warming observed over the past 50 years is ttributable to human activities.'

What happens next?

In order to predict climate change during this century we need a computer model that can represent the atmosphere and ocean circulations and many other processes. We use equations based on Newton's laws of motion for air and water, thermodynamics for radiation, condensation of water vapour into cloud droplets and heating of air parcels, and the concepts o conservation of mass, energy and momentum. We have to simplify some things as we need to run climate simulations for many hundreds or even thousands of years. In particular, we can only do calculations to tell us temperature and other quantities roughly every 200 km. These points then represent averages for a box in a grid covering the Earth's surface (see Figure 5). This is why we may not be able to predict the temperature in York in the year 2100, but we can say something about the temperature of northeast England. Different simplifications are used in different climate models around the world. We are more confident in predictions that are similar in many of the models than in those from only one. These simulations currently tell us that the global average



Based on Jones et al. (1999) and Parker et al. (1995)

Figure 4 Global average near-surface temperatures, 1861–July 2003, showing mean temperature change since 1850, plotted as the difference in temperature compared to an average over the end of the twentieth century (figures from the Met Office website).

temperature is set to rise by between 1.2 and 5.8 °C between now and 2100.

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 simplify processes, and partly due to differences in the inputs 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 Idaho and causing a hurricane in the Pacific Ocean. This sort of uncertainty is more important for short-term weather forecasts than for long-term climate forecasts, and that is why we can seldom predict the weather more than a few days in advance but can get away with predicting climate 50 years ahead.

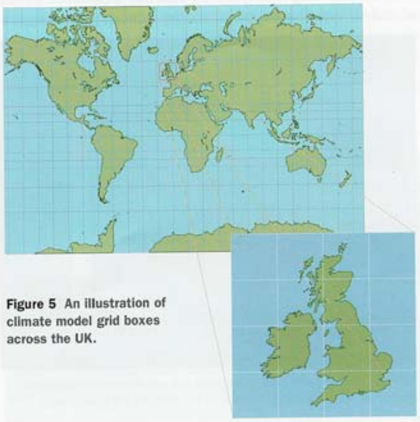


Figure 5 An illustration of climate model grid boxes across the UK.

To find out the size of these uncertainties, we run several slightly different versions of the same model (an *ensemble experiment*), building up a probability graph for surface temperature change. We can see which results are possible, but very unlikely, and can tell you 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 prediction; then we can use physics and maths to concentrate on understanding and representing these parts of the climate system better in the next generation of climate models. ■

Websites

You can read about one particular model in Sylvia Knight's article on pages 6–9, which includes website 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.met.rdg.ac.uk

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