DIY climate prediction

Sylvia Knigh

Scientists are studying ways of predicting climate change. Such studies involve extensive computer modelling and are limited both by chaos and by the amount of computer power available. One of these studies requires a calculation so large that people all over the world have been asked to help carry it out. With so many computers involved, the project is out-performing the world's fastest computer.

There has been a lot of recent publicity on the topic of climate change. Since the information comes from scientific studies of the Earth's climate, both politicians and the general public look to scientists to give further information on what is likely to happen in the future. One of the studies being carried out is the **climate*prediction*.net** experiment, based at Oxford University.

http://www.climateprediction.net/

Since the experiment requires an enormous amount of calculation, it invites people around the world to donate spare computer time to help produce the most extensive forecast of twenty-first century climate change ever attempted.

Figure 1 shows some of the graphical output from the calculation. Why is the calculation so large and what is being calculated?

Why?

The concentration of carbon dioxide (CO_2) in the atmosphere has increased from about 282 parts per million (ppm) to about 340 ppm in the past 200 years. Predictions for the next 100 years suggest that the carbon dioxide concentration will carry on increasing and might reach as much as 900 ppm. Such changes in the composition of the atmosphere must affect the climate and we need to find out what the effect is likely to be.

Climate change and our response to it are issues of global importance, affecting food production, water resources, ecosystems, energy demand, insurance costs and much else. There is a broad scientific consensus that the Earth is likely to warm over the coming century, but estimates of how much vary hugely. The climate system is chaotic, so it is impossible to tell exactly what will happen over the next 100 years. The best we can do is to make a probability-based forecast, so that the policy-makers who need to plan for climate change know what is likely and, probably more importantly, what is not likely to happen.

Climate

As discussed in Eleanor Highwood's article on pages 2–5, the temperature of the Earth's surface, atmosphere and oceans is primarily determined by the balance between incoming an outgoing radiation. Incoming solar radiation is fairly constan changing only due to slight variations in the Sun's electro magnetic activity and to very small changes in the Earth's orb around the Sun. Solar radiation is mainly short wavelengt visible and ultraviolet (UV) radiation, which passes largel unhindered through the Earth's atmosphere: only 22% reflected by clouds and aerosol (volcanic dust); the remainin 78% is absorbed by the land and oceans, causing them to hea up. The amount of outgoing radiation depends upon th Earth's temperature: this is given by the Stefan–Boltzmann law which says that the amount of energy emitted per unit area proportional to T^4, where T is the temperature in kelvin.

If the Earth had no atmosphere, the incoming solar radiatio would precisely balance the outgoing terrestrial radiation an the Earth would be 33 °C colder than it actually is. The outgoir terrestrial radiation is mainly in the thermal infrared (IR) pa of the electromagnetic spectrum and this is absorbed by th so-called 'greenhouse gases' in the atmosphere (the ter

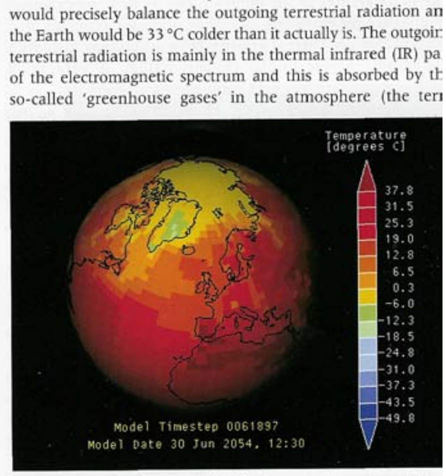


Figure 1 The graphics supplied with the computer program allow users to follow the development of the climate on their unique version of the world.

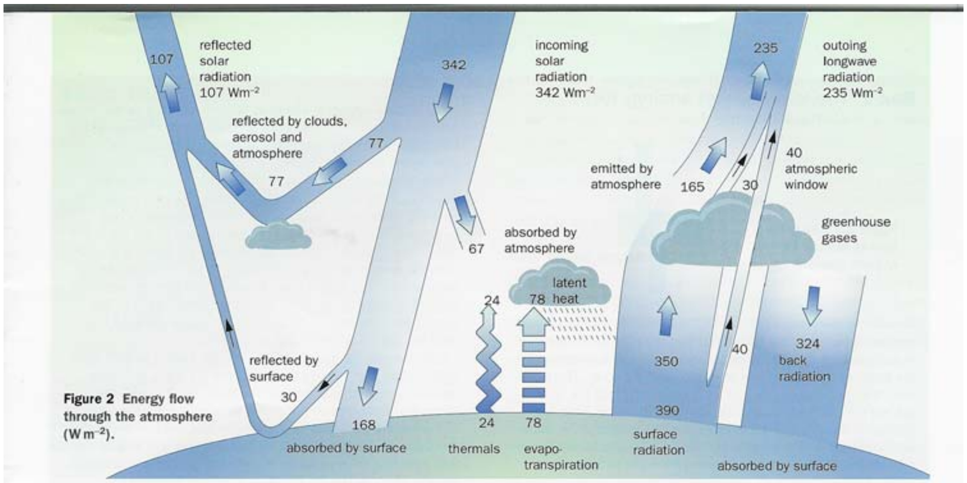


Figure 2 Energy flow through the atmosphere ($W m^{-2}$).

'greenhouse effect' is, in fact, inappropriate, as greenhouses work by preventing convection rather than radiation). Water vapour, carbon dioxide and methane are the principal gases involved. They work by reradiating the thermal radiation in all directions, and so 83% of the thermal radiation emitted by the Earth is reabsorbed by the Earth's surface, causing it to be warmer than it would otherwise be. A more complete picture of energy flow within the Earth's atmosphere is shown in Figure 2. How the energy flow affects the equilibrium temperature is described in Box 1 on page 8.

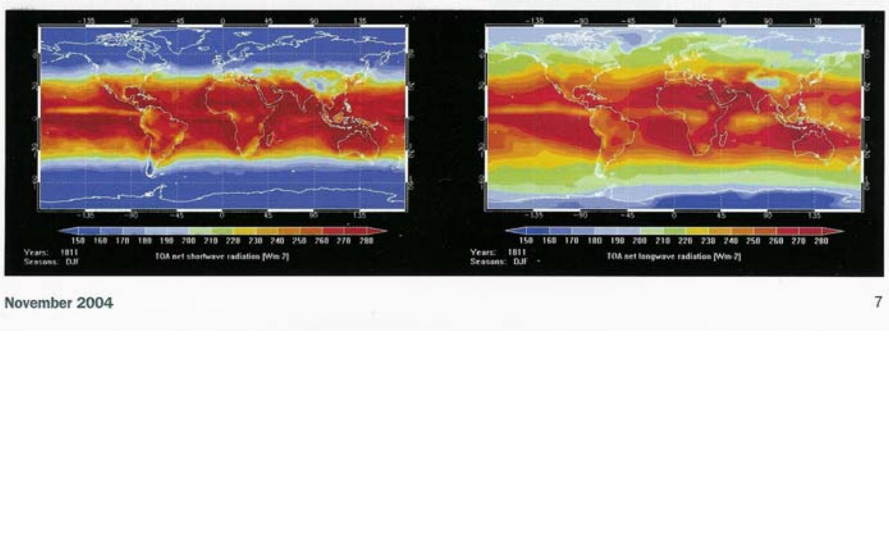
Not only is energy transported vertically between the Earth's surface and space, it is also transported around the world, largely by winds and ocean currents. Figure 3 shows the variation in the amount of energy received from the Sun over the Earth compared with the energy emitted, averaged over 1 year. It can be seen that most solar radiation is incident in the tropics, whereas outgoing radiation comes from a much wider region. Clearly, for there to be a balance between incoming and outgoing energy at each point on the Earth's surface, heat must be transported towards the poles from the tropics. If this were not the case, the tropics would be constantly heating up and mid-latitudes and polar regions would be cooling down. The transport is by large-scale winds and ocean currents, turbulence (storms) and the latent heat take-up and release associated with the evaporation of water and condensation of rain.

What is a climate model?

The computer models used for climate prediction are the same as those used for day-to-day weather forecasts. Each model divides the atmosphere and oceans into boxes. Within each box, it is assumed that temperature, wind velocity, air pressure and humidity are constant. Each box exchanges energy, air and water with surrounding boxes in a way that is governed by basic physical principles. This requires solving equations of motion and applying laws of conservation of energy, air and water to all the boxes covering the whole globe. To start the calculation off, each model is given a set of initial conditions that represent, to the best of our knowledge, the current state of the atmosphere and oceans. The equations are then solved to find out what the climate system will look like, say, half an hour later. That information can then be used to calculate what will happen in the next half hour and so on until you have produced a forecast for the next 100 years.

For the best possible forecast, the sizes of the boxes should be as small as possible, so that every individual cloud or gust of wind can be resolved. However, as all the equations have

Figure 3 The incoming, solar, short-wave radiation (left) and outgoing, terrestrial radiation (right) in 1 modelled year, plotted using the visualisation package which can be downloaded from the climate*prediction*.net website.



Box 1 The leaky bucket analogy for climate change

Figure 1.1 The leaky bucket analogy for climate change.

Consider a leaky bucket. If you fill the bucket at a constant rate, the level of water in the bucket will rise until the water pressure is sufficient for the rate of water leaking out of the bucket to be the same as the rate of flow of water into the bucket. The water level then remains constant. If you now try to block the leak, but are only partially successful, the hole the water flows out through is smaller and the velocity must be greater if the same amount of water is to escape. For this to be possible, the water pressure must be greater, so the level of water in the bucket rises until it establishes a new equilibrium.

The climate system is like this. With no changes to the atmospheric composition, the amount of solar radiation reaching the Earth, or the amount of volcanic dust in the atmosphere, the climate will be in equilibrium, i.e. the amount of incoming solar energy is equal to the amount of outgoing terrestrial energy. However, if the atmospheric composition changes, causing more outgoing radiation to be absorbed by the atmosphere and reradiated towards the Earth, the temperature of the Earth will rise — the amount of energy absorbed by the Earth is greater than the amount of energy it emits — in the same way as the water level in the bucket rose. However, the amount of energy emitted is proportional to T^4, so, as the temperature of the Earth rises, the amount of outgoing terrestrial radiation rises until the system is once again in equilibrium.

Unfortunately for modellers, the climate system is a lot more complicated than a leaky bucket. There are many feedback mechanisms, both positive and negative. For example, the amount of carbon taken out of the system by tiny animals living in the oceans increases as the temperature rises — a negative feedback. On the other hand, as temperatures rise and ice melts, less incoming solar radiation is reflected back to space and more is absorbed by the Earth — a positive feedback.

to be solved for every box at each point in time, there is a limit to the total number of boxes that can be handled. A compromise has to be made between the size of the boxes and the length of computer time it would take to run the model. A short, 5-day weather forecast can obviously be run with a much finer resolution than a 100-year climate forecast. Figure 4 shows the arrangement of boxes for the **climate*prediction*.net** experiment. There are 19 layers in the atmosphere, but only one in the oceans. Each box covers 2.50° in longitude and 3.75° in latitude.

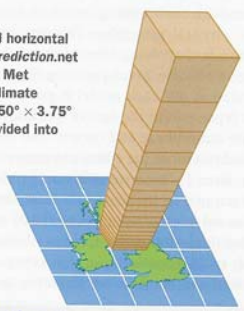


Figure 4 The vertical and horizontal grid used in the climate*prediction*.net experiment that uses the Met Office's state-of-the-art climate model. The grid size is 2.50° × 3.75° and the atmosphere is divided into 19 vertical levels.

World-wide computers

Why do we need to use the computers of people around the world? Why can't we just run the model once on a computer in Oxford? The problem is that there are three major sources of uncertainty in climate models.

(1) Parameters

Every climate model has constants, 'parameters', which are given fixed values, but these are not known for sure. Any value within a certain range could be equally realistic. The experiments will investigate the effect on the modelled climate of varying the values of 20 of the most poorly understood parameters in the model, such as the relationship between the number of raindrops in a cloud and the rainfall. It is possible that some combinations of parameters may replicate the past climate equally well, but produce widely different forecasts for what might happen in the future. Some combinations of parameters will not work at all, making the model numerically unstable and producing a completely unrealistic climate. For example, the Earth may boil or freeze, or the temperature may oscillate between very hot and very cold every couple of years.

(2) Forcing

Some things that are not directly part of the climate system may nevertheless have a huge impact. Examples are volcanoes, which put a lot of ash high in the atmosphere (after Mount Pinatubo erupted in 1991 the ash it emitted affected the climate for several years), changes in solar activity or the composition of the atmosphere.

(3) Initial conditions

'The flap of a butterfly's wings in Brazil can set off a tornado in Texas.' This famous quotation from a meteorologist sums up the fact that very small changes to the present can have huge effects on the future. The so-called 'butterfly effect' is one of the symptoms of chaos (Box 2) which must be taken into account in all weather forecasting and climate prediction. As we cannot have perfect knowledge about what is going on now (down to the scale of individual butterflies), the only way to produce a reliable forecast is to try a range of initial conditions in separate calculations and find out what is the most likely outcome. This requires a large number of calculations.

The experiment

The experiment run by **climate*prediction*.net** is the first of three and is more about learning how the model reacts to changes in initial conditions and parameters than about actually trying to replicate the Earth's climate. For this reason, the model used has a sophisticated atmosphere, but a simplified ocean — only a single layer. This means that some aspects of the climate system (such as oceanic currents, and the El Niño

Box 2 Chaos

How do we stand a chance of predicting the climate in 100 years time, if we can't even manage to predict the weather in 5 days' time? The uncertainty in a weather forecast is mainly due to the uncertainty in the initial conditions.

Luckily, chaos theory stipulates that the statistics of the system are easier to predict than the variability of the system itself. Think of it as a game of roulette — it is not possible to predict how much money there will be in the bank after the next spin of the wheel, but it is possible to predict that over a number of spins, the money in the bank will increase. If you change the way the bank operates — for example, if the amount of money that is won for a particular bet is reduced — you stand a good chance of predicting how, on average, the amount of money in the bank will change.

For articles on chaos see PHYSICS REVIEW (1996) Vol. 5, No. 4, *What is chaos?* and Vol. 5, No. 5, *Unpredictable physics of chaos.*

oscillation) are not replicated, but the model runs a lot faster and more calculations can be completed.

The first experiment consists of three separate phases. Each model that is distributed completes all three phases from a unique set of initial conditions.

Calibration step (phase 1)

This involves running the model for 15 years to make sure the atmosphere and the ocean are 'in balance', i.e. in a stable state where large-scale measures, such as the average temperature on the world's surface, do not change substantially from year to year.

Preindustrial carbon dioxide step (phase 2)

The levels of greenhouse gases in the model atmosphere are kept constant at preindustrial levels. If the combination of parameters is reasonable, the model should remain in a stable, equilibrium state throughout the 15 years.

Double carbon dioxide step (phase 3)

In this phase, the levels of greenhouse gases are doubled and the model is run for a further 15 years. In a good model, the atmosphere should adjust to this change in forcing and eventually settle in a new equilibrium state (which may be the same, warmer or cooler).

By comparing the single and doubled carbon dioxide steps, the climate sensitivity of the models can be calculated (the difference in the globally averaged surface temperature between the model with preindustrial carbon dioxide and the model with doubled carbon dioxide), a useful measure of how a climate model has behaved.

The second experiment

The second experiment (due to start at the end of 2004) will include a more complete ocean model, with 20 vertical levels and the same horizontal resolution as the first model. This means the ocean is able to respond more to changes in the atmosphere than in the first experiment, giving us a more complete simulation of the climate system.

The experiment will use:

- the combinations of parameters that were identified in Experiment 1 as producing a numerically stable, realistic climate
- the same range of initial conditions as that used in Experiment 1
- the levels of atmospheric carbon dioxide and volcanic emissions that were observed from 1950 to 2000

By using each model to produce a 'forecast' for 1950–2000, and then comparing the spread of forecasts with what actually happened, we will get an idea of how good our models are. This will let us rank individual models.

The third experiment

The third experiment is a continuation of Experiment 2 except that, instead of observations of forcing mechanisms, it will use a range of possibilities for what might happen in the next 100 years in terms of greenhouse gas emissions, volcanic eruptions, solar activity and so on.

When this experiment finishes in 2006, we shall have a range of forecasts for the twenty-first century climate.

The final stage is to 'weight' the forecast of each model according to its ranking in Experiment 2. So, for example, if a model that did really well in Experiment 2 predicts a warming of 2 degrees, and one that did badly in Experiment 2 predicts a warming of 10 degrees, we will believe the first one more than the second.

See how it runs

Even with a top-of-the-range brand new PC, 45 model years take 2–3 weeks to run. The **climate*prediction*.net** experiment currently has about 29 000 models running on people's home, school and work computers and is outperforming the world's largest supercomputer, the Earth Simulator in Japan. You can see where all these people are in Figure 5.

Figure 5 Since September 2003, 75 000 people around the world have registered for the climate*prediction*.net experiment.

To find out more about the **climate*prediction*.net** experiment or to join in, go to the website. If you decide to participate, you will need to download the model from the website; it will run automatically in the background whenever your computer is switched on and should not interfere with anything else you use the computer for. When the experiment has finished, it will prompt you to connect to the internet again to return the results to the project team. While the experiment is running, you can use the computer graphics supplied with the program to watch the climate in your unique version of the world develop. ■

Sylvia Knight *works in the Department of Atmospheric, Oceanic and Planetary Physics at Oxford University.*