The use and abuse of climate models

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Projections of future climate change depend largely on the results of computer models. Such models are becoming increasingly sophisticated, but they do not offer the certainties that policy-makers would like.

Humankind is performing a great geophysical experiment[1]. By modifying the Earth's environment in various ways, we are changing the climate. The extent and the rate of these changes are unclear, as is what (if anything) should be done about them, but that the experiment is underway is not in doubt. The environmental changes of most relevance are in land use (farming, building cities), storage and use of water (dams, reservoirs, irrigation), generation of heat, and — most notably — the burning of fossil fuels.

In particular, fossil-fuel combustion pollutes the atmosphere and alters the balance of radiation on Earth through both visible particulate pollution (called aerosols), and gases that change the composition of the atmosphere. These are known as greenhouse gases because they are relatively transparent to incoming solar radiation, but absorb and re-emit outgoing infrared radiation, thus creating a blanketing effect which results in warming. For example, as a consequence of human activities, carbon dioxide concentrations in the global atmosphere[2–4] have increased by about 30 per cent over pre-industrial values. Global warming and associated climate change is expected as a result, and the global mean temperatures have indeed risen over the past hundred years[5] (Fig. 1).

If this experiment turns out badly — however that is defined — we cannot undo it. We cannot even abruptly turn it off, because too many of the things we are doing now have long-term ramifications. For instance, carbon dioxide has an atmospheric lifetime of over a century[5] and simply stopping increases in emissions would still result in increases in atmospheric concentrations for many decades. The only way to reverse those trends is to reduce emissions to well below current levels[4,5]. Moreover, changes underway in the oceans would endure, because of the oceans' huge heat capacity.

If we had two planet Earths, identical in every respect except that the residents of one adopted measures to avoid polluting the atmosphere while residents of the other did not, we could see how the climates of the two planets would diverge, and what the consequences would be. But we don't and we can't. Instead we have to do the next best thing — try to understand the climate system well enough to build a good model of the planet Earth system and use this model to perform the experiments. We can indeed construct a miniaturized physical model of the Earth–Sun system; but we cannot readily include the effects of gravity, and the rich complexity of the atmosphere and oceans. The alternative is to build a virtual model of the Earth in a computer.

The models

These computer models are based upon physical laws represented by mathematical equations and expressions that are solved using numerical methods as applied to a three-dimensional grid over the globe. The most complete versions are referred to as 'Earth system models' and those which deal exclusively with climate are called 'climate models' or, if they are very comprehensive, 'climate system models'[6].

But how useful are these models in making projections of future climate? Opinion is polarized. At one extreme are those who take the model results as gospel; at the other are those who denigrate such results simply because they distrust models, or on the grounds that the model performance is obviously wrong in some respect or that a process is not adequately included. The truth lies in between. All models are of course wrong because, by design, they depict a simplified view of the system being modelled. Nevertheless, many — but not all — models are very useful.

A full climate system model[6] should deal with all of the physical, chemical and biological processes that occur in nature and the interactions among the components of the climate system (Fig. 2, overleaf). A major component of them is the so-called atmospheric general circulation models (AGCMs); these are designed to simulate the detailed evolution of weather systems and weather phenomena, as well as the physical and dynamical processes involved. For AGCMs, typical resolutions for climate simulations are about 250 km in the horizontal direction and 1 km in the vertical. These models are widely used and tested every day in making weather forecasts, although with finer resolution, and have predictive value out to about ten days ahead[7].

The theoretical limit to the predictability of weather is about two weeks, which stems from the phenomenon of chaos — small uncertainties in the analysis of current weather conditions rapidly grow and eventually become large enough to make the forecast worthless[8]. This essentially random-error component is overcome in climate forecasts by predicting only the statistics of the weather (that is, the climate). Accordingly, systematic influences of changing conditions in the ocean, sea ice, land surface, solar radiation or other factors are reflected in atmospheric variations on various time scales. The most obvious example is the climate change with the seasons. An ensemble of several climatic simulations, each of which begins from somewhat different starting conditions, can be used to establish which climatic features are reproducible in the simulations and thus are predictable with the model.

These features constitute the climate signal, while those which are not reproducible can be considered weather-related climate noise. Climate predictability is a function of spatial scales. Natural atmospheric variability is enormous on small scales and most effects on climate (forcings), such as from increases in greenhouse gases, are predominantly global. So the noise level of natural variability will mask a climate signal more as smaller regions are considered[5].

Model errors

The latest coupled atmosphere–ocean–land–sea-ice models provide very good simulations of average climate conditions and

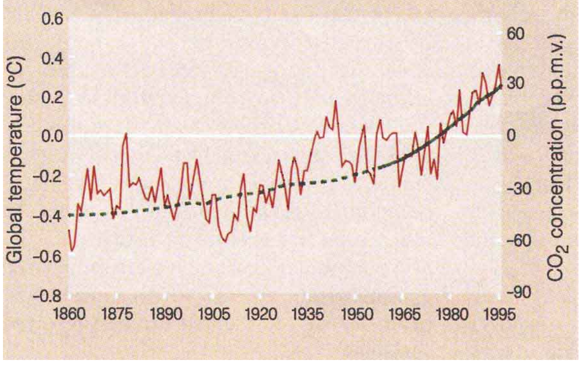

Figure 1 **Estimated changes in annual global mean temperatures[5] (red) and carbon dioxide (green) over the past 137 years relative to a 1961–90 base period. Earlier values for carbon dioxide are from ice cores[3] (dashed line), and for 1957 to 1995 from direct measurements made at Mauna Loa, Hawaii[2]. The scale for carbon dioxide is in parts per million by volume (p.p.m.v.) relative to a mean of 333.7 p.p.m.v.**

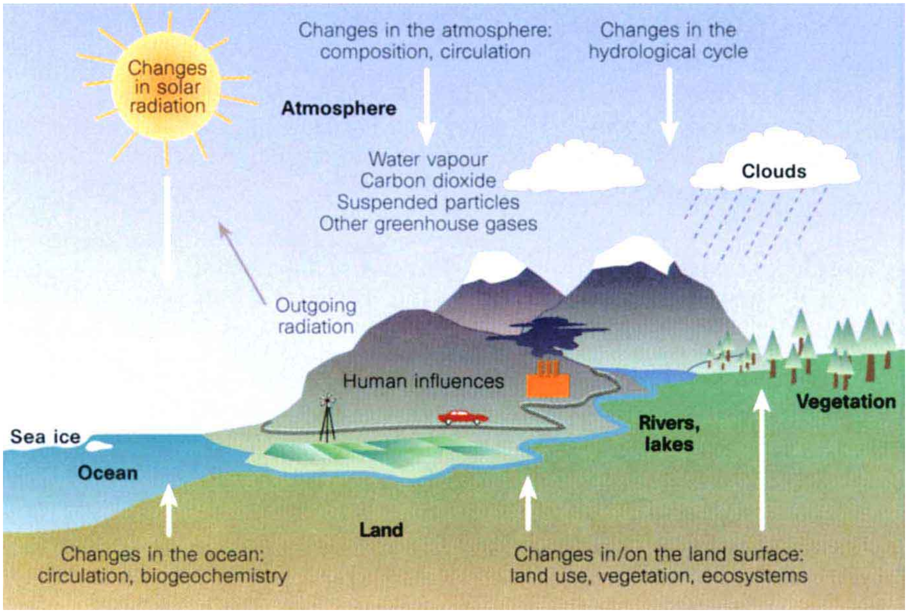

Figure 2 **Components of the global climate system — atmosphere, ocean, sea ice, land surface, surface hydrology and biosphere — their processes and interactions, and some aspects that may change.**

their evolution with the seasons. Nevertheless, climate models do contain obvious errors in some features when compared with observations. The climate modeller is then faced with a decision. The 'error fields' contain useful information about the performance of the model. Experiments performed with such a model have the advantage that they consistently include all the physical processes, but the disadvantage is that the systematic errors may distort the results because many feedback processes change in strength as the temperatures change. For example, if a model atmosphere is simulated to be too cold by 4 °C (not uncommon a few years ago)[9], the water-holding capacity of the atmosphere is typically reduced by about 20 per cent thereby greatly influencing evaporation and precipitation; places that should be receiving rain will instead have snow.

An alternative strategy is to include an artificial fix known as 'flux adjustment' to keep the simulated climate closer to that observed. The exchanges (fluxes) of energy, water and momentum between the model ocean and atmosphere are adjusted so that the modelled sea surface temperatures and other surface fields are close to those observed. These fixes are then held constant in any experiments. There are merits in approaches both with and without flux adjustment and the results can be compared, but both sets of results are open to the criticism that the model is clearly deficient in some ways. So a lot of research is focused on developing climate models that greatly reduce systematic errors and eliminate the need for flux adjustment.

To further reduce the effects of any model errors on results, a strategy has been designed for carrying out climate experiments which removes much of the effects of these errors and flux adjustments. First, a 'control' climate simulation is run with the model. Then the climate-change simulation is run, for example with increased carbon dioxide in the model atmosphere. Finally the difference is taken to provide an estimate of the change in climate. This differencing technique removes the effects of flux adjustment, as well as the systematic errors that are common to both runs. But comparison of different model results makes it apparent that the nature of some errors influences the outcome, so that complicated feedback effects do take place.

An example of a problem that cannot be alleviated by this approach occurs, for instance, if the control climate produces no rainfall in a monsoon area where it should occur (the monsoon rains may be in the wrong location). Then it is impossible for the rainfall to be reduced in a climate experiment and the only possible outcome is an increase in rainfall.

Although it is desirable for a model to be as realistic as possible, this is not always feasible. Indeed, a full model of the climate system would be just as complex as the system itself and almost as difficult to understand, except that complete model datasets could be created for analysis and experiments could be performed. Some processes or influences are so complex and so poorly understood, or simply cannot be resolved by the scales represented in a model (which is related to computer limitations), that it may be better to leave them out altogether. In other cases, attempts are made to include the average influences using a physically based 'parametrization', in which unresolved processes are represented through resolved variables.

Probably the single greatest uncertainty in climate models stems from their treatment of clouds[10]. The enormous variety of cloud types, their variability on all space scales (ranging from sub-millimetre to thousands of kilometres) and time scales (microseconds to weeks) poses a special challenge, particularly in depicting their influence on incoming solar and outgoing infrared radiation and their role in precipitation.

Model validation

Climate models that have been developed thus far for application to the greenhouse-gas problem have largely centred on the physical climate system. Typically, the concentrations of constituents of the atmosphere, including radiatively important species such as ozone and carbon dioxide, have either been fixed or specified as varying functions of time. In such 'scenarios', the concentrations of the gases do not depend on the climate changes going on in the model even though, in nature, changes in rainfall or temperatures may profoundly affect the sources and sinks of some of the greenhouse gases. Similarly, land surface processes have been greatly oversimplified in the models, and biological, ecological and chemical processes may not be included at all. Nevertheless, these approximations and omissions are appropriate for addressing certain scientific questions.

In all circumstances 'sensitivity tests' should be carried out to check how sensitive the result is to small changes in what is done. For instance, simplification of land surface processes seems to be justified for very large spatial scales, but not for studying regional effects. To explore all possible scenarios and the effects of approximations and assumptions, simpler models are also widely used. They are 'tuned' to the more complex climate models and have the advantage of using much less computer time. All of these models may be useful tools provided their limitations are properly taken into account.

Model results should be judged by considering all the assumptions (such as certain things being held constant) and approximations involved. It is generally inappropriate to take the model result at face value because it must be comprehensively evaluated. Thus the model performance in simulating the annual cycle, interannual variability, the past climate record including what is known about climates of the distant past (palaeoclimates), and in simulating responses to a volcanic eruption, must also be factored into how much weight is given to the result.

This process requires comparison of the model to observations and the assembling of the necessary data sets. It also requires initializing the model with observations of the current or starting state of many model variables, especially those which vary over many years (land surface, sea ice, ocean). If flux adjustment is applied to a model then some results may be deceptively good and the magnitude of the flux adjustments must be factored into the evaluation. If the simulations are judged to be realistic, the model may prove to be a useful tool for applications to scientific, economic and social questions, including making assessments and projections of possible future climates.

The best models encapsulate the current understanding of the physical processes involved in the climate system, the interactions between them, and the performance of the system as a whole. They have been extensively tested and evaluated using observations. The complexity and nonlinearity of the climate system is such that good models often provide the only means of quantifying the result of a perturbation to that system.

As regards alternative approaches, statistical and empirical results are not reliable because the possible outcomes usually fall well outside the realm of conditions previously experienced, and the observed record on which to base such extrapolations is far too short; moreover, projections about how the climate may or may not change based upon indirect experience or intuition are effectively making use of a vastly cruder model. It is easy to criticize a model. But the challenge to any proponent of, say, a missing process is to insert it into one of these models (several are available) and demonstrate that it makes a quantitative difference to the outcome. The burden of proof that a model result is not valid should be on the critic, not the modeller.

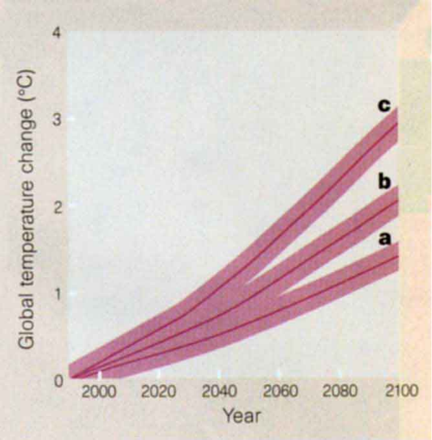

Figure 3 **Projected changes in global mean temperature from 1990 to 2100, corresponding to an emissions estimate[12] involving increases in both carbon dioxide from 350 to 700 p.p.m.v. and in sulphate aerosol (a 'mid-range scenario'). The three curves show the average changes and the scatter (shading) from natural variability corresponding to models with low (a), best estimate (b) and high sensitivity to change (c).**

Future developments

Several major laboratories around the world are hard at work on model development, and impressive progress is being made. Necessarily, such research is multidisciplinary and involves experts in many different areas collaborating to produce a climate system model that is more than just the compilation of the components. Because it takes thousands of years for a model that includes a deep ocean to come into equilibrium, integration of a full climate model can use all of the computer time available on the biggest and fastest computers. For example, the climate system model at the National Center for Atmospheric Research[11] (NCAR, the institution for which I work) runs with an AGCM resolution of 2.8° latitude/longitude and 18 levels in the vertical; it has a non-eddy resolving ocean model with 45 levels, and a coarse horizontal resolution (nominally 2°); and it includes dynamical sea ice and land surface components. It takes about 3.5 hours on a Cray C90 machine with 16 dedicated processors to run for one simulated year.

Computing power is one key to future progress. To carry out comprehensive numerical climate experiments and understand the results, a supercomputer has to be dedicated to the task for many months. That is an ideal that is seldom achieved. The NCAR model has been run for over 200 simulation years and has a stable climate quite close to the observed without flux adjustment. This has been achieved through improvement in representations of physical processes in both the model atmosphere and ocean, which is the second key to progress.

Projections of global warming

But what of the issue that most exercises the public — the changes in atmospheric composition arising from human activities and the consequent effects on climate? The Intergovernmental Panel on Climate Change (IPCC; ref. 5) has made projections of future global warming based upon model results to the year 2100. Because human actions are not predictable in any deterministic sense, such projections necessarily contain a 'what if' element to account for differing patterns and amounts of pollution emission in the future. Results depend greatly upon these scenarios which detail the expected rates of increases of the greenhouse gases and aerosols.

In addition, for a given scenario, the rate of increase in global mean temperature depends on the model and features such as how clouds are depicted, so that for a doubling of carbon dioxide concentrations, for example, typical equilibrium global warming ranges from 1.5 to 4.5 °C with a best estimate of 2.5 °C. Natural variability also blurs the picture from a single model result, producing a scatter of about ±0.2 °C. Accordingly, the projections for a mid-range emissions scenario, in which carbon dioxide concentrations increase from 350 p.p.m.v. (parts per million by volume) in 1990 to 700 p.p.m.v. in 2100 produce global mean temperature increases ranging from 1.3 °C to 2.9 °C above 1990 values with a best estimate of about 2 °C (Fig. 3; ref. 12). Although these projections include crude estimates of the effects of sulphate aerosol, they deliberately omit other possible human influences such as changes in land use. Moreover, many other climate changes accompany global warming, such as altered extremes of rainfall and the availability of fresh water, and these may have much greater consequences for human society. A major concern is that the rates of climate change as projected exceed anything seen in nature in the past 10,000 years.

Statements such as these, given with appropriate caveats, are likely to be the best that can be made because they factor in the substantial understanding of many processes included in climate models. Such projections cannot offer certainty, but they are far better than declaring ignorance and saying nothing at all. If they prove to indicate sufficiently adverse effects on climate, then it is generally assumed that action will be taken to prevent those effects. What constitutes 'sufficiently adverse' is of course a matter for debate, as is what, if any, remedial measures should be taken. Such debates are not just for scientists, but for politicians and the peoples of the world whom they serve — and they have to be based on an appreciation of both the strengths and the weaknesses of climate models. □

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