David Whillas

Climate models –

Numerical model experiments by the CSIRO team, including global simulations of the ocean and atmosphere, use this Cray Y-MP supercomputer located at the University of Melbourne.

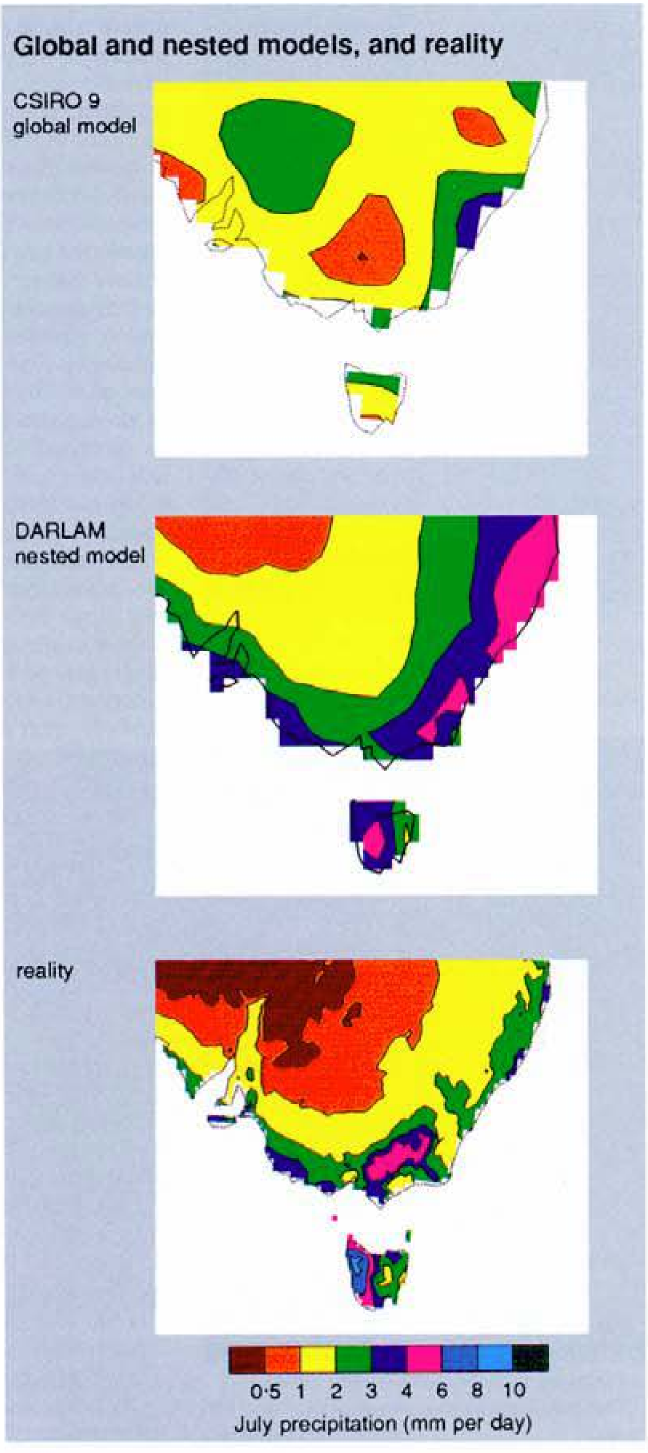
In the natural world, the air and the sea influence each other; scientists sometimes say the two systems are dynamically coupled. In the model world, where Nature is simulated on a computer, they live apart — in effect, like waves beneath an airless sky or a wind above an empty ocean.

Computer simulations or numerical models of climate are tools of the meteorologist and oceanographer — tools that generate no reality beyond the virtual, yet capable of revealing deep complexities in Nature. Such models comprise the engine of research into climate variability and change, making it possible to — for example — better understand the mechanism of monsoons and major ocean currents, estimate average global air temperatures 100 years hence or predict years of drought or higher-than-average cyclone activity.

Yet, despite their importance and success today, climate models are highly artificial and severely limited in their resolution, or degree of detail. For example, in the study of global warming, an advanced state-of-the-science atmosphere model may predict that doubling the atmospheric carbon dioxide concentration will lead to more rain in parts of Australia. Without knowing how the ocean may react to such a major change, scientists must treat the prediction with caution.

One of the major known determinants of drought in Australia, the El Niño–Southern Oscillation, is triggered by temperature anomalies in the Pacific Ocean, and many other important ocean–atmosphere links probably remain to be described. But serious mathematical problems arise when scientists attempt to simulate the entire climatic system. The models are also of limited use for making predictions about localised events, such as rainfall in a particular district.

Research groups around the world are working hard to improve the predictive capacity of the models and are reporting some successes. Researchers at CSIRO's Division of Atmospheric Research appear to have identified the source of some of the simulation problems, and found ways to improve resolution.



The nested model (DARLAM) produced a July rainfall pattern (centre) much closer to reality (bottom) than the CSIRO 9 global model (top).

for clues to the future

Models that simulate just the atmosphere can reproduce the chief features of climate, but they need a constant stream of observational data about sea surface temperatures (SSTs) in order to stay realistic. Those that simulate the oceans need a supply of observational data on the wind fields that drive the surface currents.

But the observational records, especially those from the remote oceanic regions of the Southern Hemisphere, are far from complete — and some of what does exist may not be accurate. In addition, as scientists do not fully understand the chemical and physical processes that dominate at the air–sea interface, there is a danger the processes may change in unexpected ways under the influence of global warming — hence making the existing data on SSTs and winds largely irrelevant for many of the pressing questions about climate change.

Instead, modellers reasoned, why not link an atmospheric model with an ocean model and a sea-ice model — in the way that their natural counterparts are linked — and let them provide each other with the data they need? As long ago as the late 1960s, researchers began experimenting with such 'coupled' models, intended to simulate the entire climatic system. However, new kinds of problems arose, and to date no fully coupled ocean–atmosphere model has succeeded in simulating the climatic system realistically. The best coupled models in use today still show marked regional discrepancies (such as cooling over the North Atlantic) compared with the best estimates of the impact of global warming made by the Intergovernmental Panel on Climate Change.

'Climate drift' is the term used to describe the failure of a model to maintain a realistic simulation. A model suffering from climate drift is so seriously out of equilibrium it cannot recover; the predictions get increasingly out of step (like two dancers with a different sense of rhythm) as the model seeks a new equilibrium. The problem is common to all coupled models. To solve it, scientists typically adjust the amounts of heat, momentum and fresh water being exchanged between the oceanic and atmospheric parts of the model, using a technique known as 'flux correction'.

In a series of experiments at the Division of Atmospheric Research in Melbourne, Dr Andrew Moore and Dr Hal Gordon joined CSIRO's global atmospheric model — currently used for enhanced greenhouse effect and drought studies — with a global ocean model based on one developed at Princeton University in the United States. Separately the two models worked well: each could, for example, simulate average surface temperatures in the month of January in good accordance with observed patterns. But after coupling, the models went badly awry.

In one run covering 10 years of simulated climate, the coupled model simulated a warming of the ocean near the Poles (up to 9°C near Antarctica), and dramatic falls in sea surface temperatures (up to 7°C in the North Atlantic) and air temperatures in the lower atmosphere. The average temperature of the atmosphere fell by as much as 11°C in some areas in less than a decade. (Bear in mind that current scientific theory indicates that the enhanced greenhouse effect will cause average air temperatures to rise 0·3°C a decade). The pattern of results — a clear case of climate drift — resembled those encountered with coupled models overseas.

So, what causes the drift? One source of the problem is the difference in time scales between atmospheric and oceanic processes. Events in the atmosphere may persist for days, weeks or months, but oceanic events can last for thousands of years. Such a wide disparity in time scales makes it hard to choose an appropriate time-step for each stage of calculation in the coupled model.

More importantly, according to Dr Moore and Dr Gordon, it appears we know too little about the physics of the air–sea interface — in particular, how the atmosphere and the ocean exchange heat.

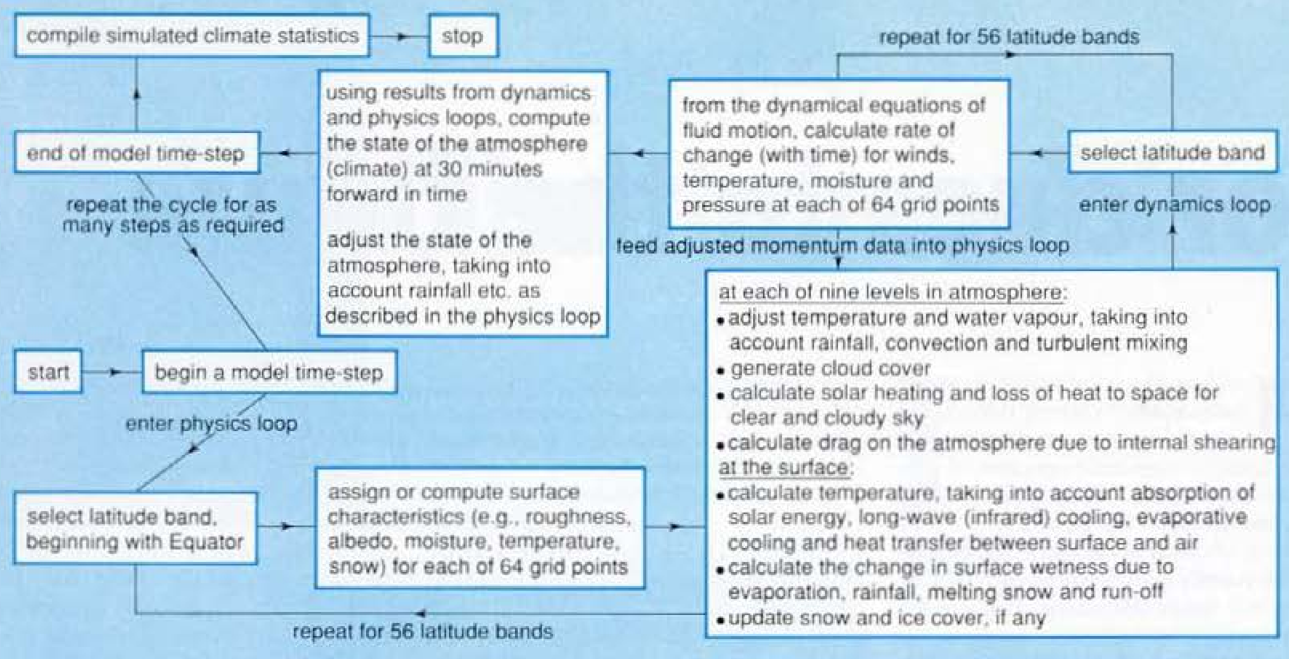
The researchers compared the ocean model's estimates of the average annual amount of heat (expressed in watts per sq. m) being exchanged between the air and the sea surface against real observations and corresponding estimates derived from the atmosphere model. The ocean model's estimates, while deficient in some respects (especially near the Poles), were much closer to the observed values than those generated by the atmosphere model. For example, in the mid latitudes, the atmosphere model predicted a net flow of heat out of the ocean, in disagreement with both the ocean model and observations. At higher latitudes, the atmosphere model predicted large heat flows (up to 40 watts per sq. m in the south) into the ocean, whereas observations and the ocean model suggest that more heat flows out of the ocean than into it.

Suspecting the atmosphere model, they next examined the net solar radiation at the sea surface, comparing observations with the figures for the January average over 10 years as predicted by the atmosphere model. Net radiation — the difference between the short-wave solar energy absorbed by the sea and long-wave radiation emitted back into space — is often used to measure the effect of cloud cover; clouds affect both short-wave radiation (by reflecting sunlight back into space) and long-wave radiation (by absorbing sunlight and emitting heat taken up during the evaporation of water).

Dr Moore and Dr Gordon found that the model's prediction of large amounts of heat going into the ocean at high latitudes was closely linked with its tendency to overestimate net solar radiation in these areas. That tendency — a common fault in global models — was the consequence of too little simulated cloud cover in the summer months. Correspondingly, the atmosphere model underestimated net radiation in the tropics — an indication perhaps of too much cloud cover resulting from an excess of simulated evaporation at the sea surface.

The scientists believe the errors generated by the atmosphere model are ultimately caused by poor mathematical representation of wind speed factors (which influence heat release)

CSIRO 9 in action



Because of the huge number of calculations required, simulation of just one day's atmospheric action takes about 35 seconds on the supercomputer.

What is a climate model?

A climate model is a simplified mathematical representation of a part of the climatic system (atmosphere, oceans or sea-ice), which allows scientists to do indoor climate experiments. Such models are an essential research tool — the world's climate does not lend itself to researchers manipulating variables under controlled conditions or repeating tests at will. Nor, of course, is it possible to describe the movement of every single air or water molecule in the climatic system.

What the modellers do instead is try to describe in mathematical terms the major dynamic and physical processes that determine the average behaviour of the climatic system, and then simulate those processes in a numerical form on a high-speed computer.

As atmosphere and oceans are both fluids, it is possible to describe their behaviour in terms of the mathematical formulae of fluid dynamics. Essentially these equations are specific cases of the basic laws of conservation of mass, energy and momentum. Other mathematical equations describe (approximately) the physical processes that modify the fluid flow, including the processes of evaporation, convection, ice formation, rainfall, transpiration by plants, surface roughness, cloud formation and the reflection, adsorption and emission of radiation.

The motion of the atmosphere, for example, is primarily governed by the way the Sun's energy is absorbed by the air and differentially emitted back into space. In the tropics, more solar energy is absorbed than emitted into space; whereas in the high latitudes (towards the Poles), more solar energy is emitted than absorbed. This geographical imbalance in the distribution of net energy flow (combined with the effect of the Earth's rotation) tends to make the climatic system unstable and forces the atmosphere to continually adjust in order to conserve mass, energy and momentum.

Adjusting (or returning to a state of equilibrium) creates most of the major atmospheric features of climate, including average temperature, pressure, humidity and prevailing wind patterns. The equations used by the climate modellers describe how the fluid atmosphere or ocean adjusts over time as solar energy enters the climatic system at the top of the atmosphere, heating and cooling the air, sea and land, determining wind direction and intensity and ocean currents, melting ice, forming water vapour and clouds and producing rain and snow.

Because of the size of the planet, and the complexity of the physical processes linking temperature, humidity, pressure, salinity and many other factors, it is not possible to solve the governing equations in a general sense and calculate precisely what the climatic system is doing at any point in time and space. So the modellers deliberately make the model simpler than reality by leaving out some of the less-important physical processes, and solving the equations only at a limited number of points in space.

Solutions at each point are then taken to represent on average the climate for a specified area (sometimes called a gridbox) around that point. The CSIRO's own 9-level global atmospheric model (known as CSIRO 9) calculates temperature, pressure, wind velocity and moisture at about 3600 points near the surface of the Earth, and repeats the calculation at the same points of latitude and longitude at eight higher altitudes. The method is rather crude compared with reality — for example, the climatic conditions at just one point represent the whole of Tasmania, while the calculations made for just 40 points cover the whole of Australia's climate.

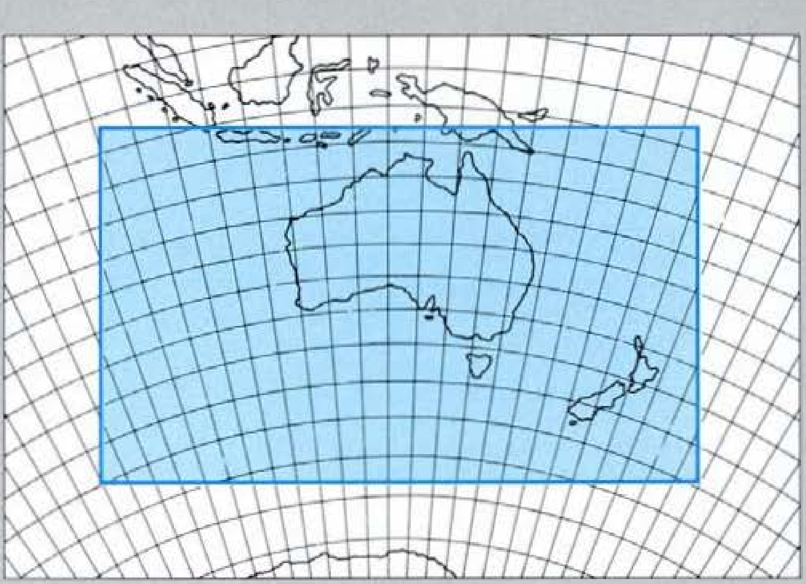
As the climate equations are not simple (scientists say their relationships are non-linear), time-dependent solutions to them can only be obtained 'iteratively', or in small time-steps. To predict global climate in 2002, say, the modeller feeds in an initial set of solutions (today's climate, for example), moves the model's clock forward (perhaps 30 minutes) and recalculates the solutions in each gridbox. The new solutions are fed back into the model and the procedure repeated until the model has calculated 10 years worth of climatic records. Each time-step is called an integration. Such procedures require enormous numbers of calculations and are often performed on supercomputers in order to obtain results in a reasonable time. Even using one of the world's fastest calculators, a Cray Y-MP supercomputer, CSIRO scientists need about 35 seconds to calculate one day of simulated climate with the CSIRO 9 model.

The initial conditions are usually long-term climate data drawn from observations, but they can be simulated data from another model or data that have been modified to reflect a hypothetical change in climate, such as the enhanced greenhouse effect. A climate model has to be allowed to run for a period of time after initiation — perhaps 10 years of simulated climate — to ensure that the physical processes described within it are in equilibrium with each other and no longer dependent on the initial conditions. It is then said to be 'spun-up' — that is, like a spinning top, it is changing with time but in a uniform, stable manner. Only when spun-up is the model ready for climate experiments, such as study of the climatic consequences of doubling the CO_2 concentration in the atmosphere or of joining continents together (see page 18).

and the processes controlling differences in humidity levels at the air–sea interface. Further investigations comparing the superseded CSIRO 4 atmosphere model with the more sophisticated CSIRO 9 model currently in use have produced better estimates of heat flow at the sea surface, thereby reducing climate drift in the coupled model, but not yet to a level acceptable for reliable climate simulations.

Dr Moore has concluded that climate drift is a problem inherent in the coupled model, rather than the result of inappropriate initial conditions or the way the ocean and atmosphere models are joined together. In effect, he says, the two component models are mutually incompatible. So until we can improve our understanding of the atmospheric processes governing cloud cover, convection and surface wind speed, climate drift will continue to plague the model world.

Nesting for better regional results



The area covered by the DARLAM nested model, which is producing encouraging regional climate predictions.

Global climate models can, nevertheless, successfully simulate large-scale features in the world's climate, but they are of limited use in the study of small-scale events such as local rainfall patterns. Most global atmosphere models have a horizontal resolution of between 350 and 600 km — which means in effect they can generate climatic predictions for areas no smaller than about 50 000 sq. km, or about one-fifth of the area of Victoria.

The resolution of a climate model can in theory be as fine as we like, but the demands on computing time are enormous. For example, one day of simulated climate on the CSIRO 9 atmosphere model requires nearly 4 billion separate calculations. Doubling the horizontal resolution would require an 8-fold rise in computer power — more than 30 billion calculations per day of predicted climate, or about 6 minutes of computing time on a supercomputer.

To overcome the problem, researchers at the Division of Atmospheric Research are experimenting with nested models — putting a fine-resolution model that covers a limited area inside a coarse-resolution model that covers the entire globe. Known as a limited-area model, the nested model can calculate regional climate patterns while leaving the global model to determine the large-scale features.

Dr John McGregor and Dr Kevin Walsh have developed a limited-area nested model (known as DARLAM) for the Australasian region. The model currently has a horizontal resolution of up to 125 km, and can be operated on its own or embedded within a global model (see the diagram above). At each time-step, the outermost five rows and columns of grid points are fed the global model's calculations of surface pressure, temperature, winds and moisture at different altitudes. As the model run continues, these data from the global model work their way through the network of gridpoints in the nested model.

In their early work with DARLAM, Dr McGregor and Dr Walsh nested the model within a global model developed by the Bureau of Meteorology Research Centre, and compared its performance (at a horizontal resolution of 250 km) against the global model and real climatic observations over Australia, New Zealand and parts of the Indian, Pacific and Southern Oceans.

One experiment simulated average rainfall; the scientists ran the global model for 300 days of constant January weather (equivalent in duration to about 10 years of climate) with and without DARLAM. While the global model shows the major features of the observed rainfall pattern, it wrongly centres the rainfall maximum for the Australian region over the southern part of the Gulf of Carpentaria, rather than the north-eastern coast and near Darwin, as shown in the observations. By contrast, the DARLAM simulation shows a rainfall peak over Arnhem Land — very similar in pattern to the observations.

The improvement by DARLAM in simulating reality is due largely to the use of a more detailed map of the land surface, which helps the model take account of how the hilly and elevated landscape east of Darwin affects rainfall. To use a high-resolution topography map for the entire globe would increase computing time impossibly, but use of the nested model limits the extra computing required to just the region of interest.

In the early experiments, using a Cray Y-MP supercomputer, DARLAM added less than 30% to the computing time, yet was able to achieve significant improvements in regional climate prediction. More recently, DARLAM has been incorporated into CSIRO's own 9-level atmosphere model — with outstanding results (see the maps on page 14). Research is continuing into improving the nested model's performance with more detailed descriptions of cloud cover and soil moisture within the region.

Brett Wright

More about the topic

Summertime climate simulations for the Australian region using a nested model. J. L. McGregor and K. Walsh. *Proceedings of the Fifth Conference on Climate Variations, Denver, 1991*, 515–8.

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