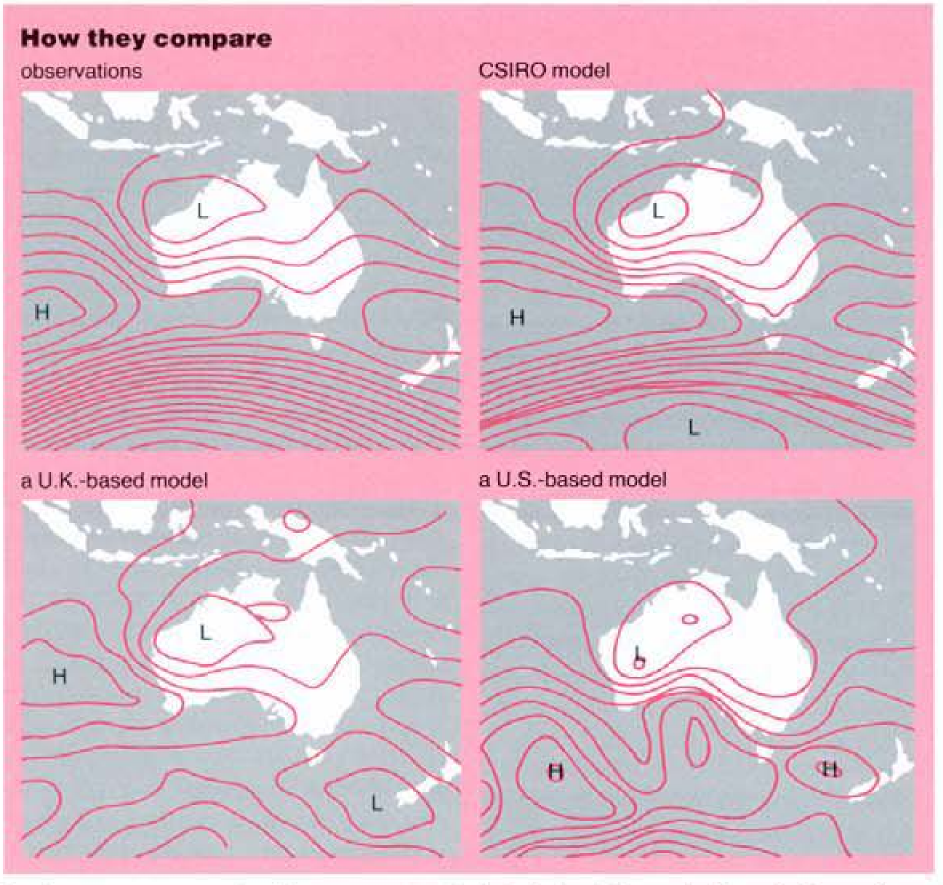
Climate change — what the models say

Imagine a sphere the size and mass of Earth orbiting the Sun in much the same way as Earth does. If the planet had no atmosphere, solar radiation would heat the surface to a global annual average temperature of about −18°C.



For January mean sea-level pressure, CSIRO's latest simulation gets closer to the real thing than some earlier overseas simulations.

Feedback loops feedback loops

Feedbacks in the climate system reflect its dynamic process; incorporating them into the GCMs is a challenging but essential task. Positive feedbacks enhance the global warming, while negative ones act to reduce it. Here are a few examples.

Clouds: Variations in cloud cover in response to global warming are particularly important because, depending on their altitude, clouds either mainly reflect solar radiation back to space thus reducing warming (low-altitude cloud, negative feedback) or reflect more heat back to Earth's surface thus increasing it (high-altitude cloud, positive feedback).

Water vapour feedback: Warmer oceans due to increased CO_2 levels will lead to increased evaporation and thus more water vapour in the atmosphere. As water vapour is a major 'greenhouse gas', this will add to the warming — a positive feedback.

Ice-albedo feedback: As the planet warms and ice or snow melt to reveal a darker underlying surface (be it ocean or land), its albedo — a measure of the amount of shortwave radiation reflected from Earth's surface — will decrease. Thus more sunlight will be absorbed at the surface, increasing the warming.

Unfortunately, our quantitative understanding of some of these feedback mechanisms is still sketchy. But scientists do know that feedback-induced changes have the potential to significantly enhance or reduce 'greenhouse' warming, so a lot of effort is going into quantifying the effects.

On Earth, we can thank our naturally occurring atmospheric 'greenhouse gases' — water vapour and CO_2 in particular — for absorbing outgoing long-wave radiation and raising the temperature to a life-supporting average of 15°C.

Of course, concern about the greenhouse effect is not directed at the fact that these heat-absorbing components are present in our atmosphere, but rather at the amounts of carbon dioxide and other greenhouse gases we've been adding. Ice records show that for 10 000 years prior to the industrial revolution the level of CO_2 stayed at about 280 parts per million (p.p.m.). In 200-odd years it has increased to 350 p.p.m. and is currently rising at 0·4% per year.

Over the same period, in tune with industrial and agricultural expansion, we've managed to release liberal quantities of other greenhouse gases: methane, up from 750 to 1700 parts per billion (p.p.b.); nitrous oxide, up from 285 to 310 p.p.b.; and chlorofluorocarbons, up from zero to 450 parts per trillion. But while scientists are certain that the composition of today's atmosphere differs from that of the not-so-distant past, they are less certain about just how these changes will influence climate.

Without any identical planets on which to experiment, we have to rely on computer models that simulate the dynamics of Earth's atmosphere as our main guides to understanding what will happen to global climate as the greenhouse blanket absorbs more and more heat. In a hierarchy of these models, the so-called General Circulation Models (GCMs) are the most sophisticated, but until recently none had been adequately coupled to fully interactive ocean models (two have been now). Moreover, these models still do not possess the spatial resolution that scientists need for a clear picture of what will happen regionally.

Nevertheless, they still offer our best hope for predicting future climatic trends and, more specifically, anomalies such as drought (see the box on page 11). In the CSIRO Division of Atmospheric Research, Dr Barrie Pittock and a team of scientists are using simulations from a number of GCMs, along with other information, as the basis for scenarios that describe the possible impact of climatic change in our region and across Australia.

Making fair weather of GCMs

If all connections between physical phenomena could be explained by simple

Identifying the onset of droughts

Water: it's a safe bet that, every year, somewhere in Australia will get too much too quickly or too little too late. After the catastrophic autumn floods in Queensland and New South Wales, the onset of drought this spring would seem a cruel irony. How likely that is, scientists are not certain.

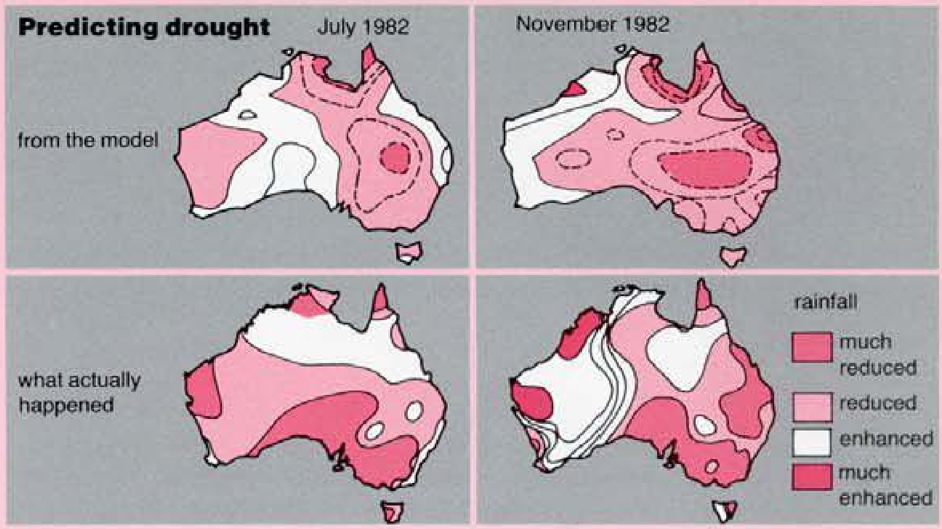
Unfortunately, predicting drought is not a high priority for many scientists studying climate. They tend to put most of their research effort (and computing power) into studying greenhouse-induced climatic changes, with a strong emphasis on changes in the concentrations of atmospheric CO_2. Mr Barrie Hunt of CSIRO's Division of Atmospheric Research is something of an exception. With Divisional colleagues Dr Roger Hughes and Dr Hal Gordon, and Dr Richard Kleeman of the Bureau of Meteorology Research Centre, he has been using General Circulation Models to help understand the onset of drought and to develop methods that will help predict them. He has recently used one of the Division's models to 'predict' the start and finish of some past major droughts, including the catastrophic one of 1982–83.

Many Australians will remember 1982–83 as the time of the continent's most severe drought for 100 years. It was heralded by a huge manifestation of the atmospheric and oceanic perturbation known as ENSO (El Niño/Southern Oscillation) (see *Ecos* 49 and 63).

For atmospheric scientists like Mr Hunt with a special interest in droughts, El Niño events provide a strong focus for research. Records show that the phenomenon has always been associated with drought of some dimension in Australia, so it is confirmed as an important drought precursor. Similarly, sea-surface temperature (SST) anomalies in the tropical Atlantic Ocean have been identified as strongly linked with droughts in north-eastern Brazil. El Niño still attracts most interest, however, as it is the only large-scale SST anomaly that is also potentially predictable.

Ms Mary Voice, from the Bureau of Meteorology Research Centre, and Barrie Hunt performed the first general circulation experiment specifically designed to simulate ENSO-related drought in the early 1980s. By introducing SST anomalies into the model — in much the same way that 'greenhouse' researchers introduce double the current level of CO_2 — they obtained droughts over parts of Australia, southern Africa, South America, and North America.

More recently, a drought-prediction experiment by Barrie Hunt, Hal Gordon, Roger Hughes, and Richard Kleeman has, with some success, 'forecast' (or perhaps more accurately 'hindcast') the great Australian drought of 1982–83. With a simple model of the Pacific Ocean and observed winds for a 20-year period prior to 1 January 1982, they predicted the SST variations. At that point they assumed that no further observational information was available. The next stage was to couple a simple atmospheric model to the ocean model and to run the two for 18 months to simulate the El Niño monthly SST anomalies for January 1982 to June 1983. Finally, they inserted these temperatures into the global atmospheric model starting from normal January conditions of a control run.



In a drought-prediction experiment, model output simulated with some success what happened during Australia's great drought of 1982–83.

This model actually predicted the changes in rainfall both globally and, of more interest, over Australia. The results were encouraging and established the viability of the modelling scheme developed, including the break of the drought early in 1983 (see the maps). Interestingly — especially for followers of chaos theory — a repeat of the experiment commencing from a different year of the control run produced poorer results, indicating the sensitivity of the experiments to initial conditions. This latter outcome seems closely linked to the complex connections of the physical phenomena that drive our climate (mentioned in the main article), which Barrie Hunt and Hal Gordon believe are responsible for what they call 'naturally occurring drought' — droughts that do not necessarily have a distinctive precursor mechanism.

To test whether droughts due to SST anomalies other than El Niño could be satisfactorily 'predicted', Mr Hunt's and Dr Gordon's latest GCM experiments have focused on simulating the 1988 United States one. After inserting the observed monthly surface temperatures of the Pacific Ocean in 1988 into their model they obtained rainfall changes over the American continent that represented the general characteristics of the drought quite well.

These latest drought-related experiments of Mr Hunt's research team are most encouraging. They have brought the prospects for predicting drought using the general circulation models several steps nearer. Unfortunately, only in the case of SST anomalies associated with El Niño are the immediate prospects for predictions reasonably good.

But Mr Hunt hopes that his Centre for Drought Research — formed from the nucleus of drought-investigators in the Division of Atmospheric Research — will attract greater interest in and support for research into such prediction. Like many others, he looks forward to the day when some of the misery that drought so often brings to communities throughout the world will be ameliorated by a 'drought alert' warning one to two seasons in advance.

The problem of 'naturally'-occurring drought. B.G. Hunt and H.B. Gordon. *Climate Dynamics*, 1988, **3**, 19–33.

Interannual variability of the simulated hydrology in a climatic model — implications for drought. H.B. Gordon and B.G. Hunt. *Climate Dynamics*, 1987, **1**, 113–30.

Nonlinear influences — a key to short-term climatic perturbations. B.G. Hunt. *Journal of the Atmospheric Sciences*, 1988, **45**, 387–95.

linear equations — such as 'doubling the wind speed would lead to twice the evaporation rate would lead to twice the rainfall' — climate predictions for the next 20 years could be performed simply in an hour or two on your home computer.

Unfortunately for modellers, life's not like that. The atmosphere–ocean system is extremely complex, highly non-linear, and full of interactive processes with many feedback loops (see the box on page 10). So, despite the fact that today's super-computers can make millions of calculations in the blink of an eye, simulating our planet's dynamic atmosphere for a decade or two can take more than a month.

Of course, GCMs don't perform magic tricks. They simply solve a set of mathematical equations that predict the value of the winds, temperature, humidity, and pressure. They then use these predicted values to calculate the rainfall, cloud cover, radiative heating, and so on.

Typically, the models solve each equation for a number of points formed by dividing Earth's surface into a horizontal grid — a mesh of 500 km gives about 35 points over Australia and some 2000 points covering the globe. But the models don't stop there. For, although in general conversation we talk about 'the atmosphere', its constituents and behaviour do of course vary considerably, depending on altitude. So all the models are also three-dimensional, with grid points extending into the stratosphere on a series of levels. (Modellers tend to talk about GCMs on the basis of the number of levels — 4-level, 9-level, 15-level, etc.)

A stark reminder of Australia's climatic extremes.

To run a 15-level model based on a 500-km mesh, we would have to solve equations for 30 000 points before we could advance it one time-step. If this interval is 10 minutes, one model month would require this set of calculations to be carried out 4500 times. Assuming that most super-computers would take about 5 hours to advance the simulation a month, climate modelling is clearly not for the poor or faint-hearted.

World-wide, about 16 GCMs exist; nearly all of them have been built by research institutions in the Northern Hemisphere — a fact that has tended to keep their focus on how accurately they represent the climates of Europe and North America. Recently, Barrie Pittock and his Divisional colleague Dr Peter Whetton have examined six simulations from five of the world's largest models, including a model developed by the Division's Mr Barrie Hunt and Dr Hal Gordon, to determine how well these simulate climate over Australia. (One of these models was run with two different ways of representing the oceans, hence the extra simulation.) As they expected, the match between simulations of the present climate and the real thing differed quite markedly between models (see the maps on page 10).

Understandably, those that more successfully simulate today's climate under current levels of CO_2 are viewed with more confidence by scientists using them to simulate the result of doubling CO_2 concentration. Most of the models include a coarse, but fairly realistic, geography, an interactive cloud scheme, seasonal and perhaps day/night radiation cycles, and some mechanism for calculating precipitation, sea-ice and snow cover, evaporation, and soil moisture.

However, the simulations available to the Division's scientists so far still use a relatively simple representation of the ocean — a 'poor man's' or a 'slab ocean' — that takes limited account of circulation. And as *Ecos* 63 reported, the rate of uptake of heat by the deep oceans and any consequent change in deep ocean circulation may turn out to be major determinants of the impact of the greenhouse effect.

Scientists are developing fully coupled ocean–atmosphere models, but the limits of computer size, compounded by the much longer time-scales associated with deep oceanic circulations, create new computational problems. Early attempts to couple the two types of model together led to the realism of the simulation becoming gradually poorer.

Limited computer power is also the major barrier to achieving better regional estimates. As the illustrations show, the distance between grid points determines how well a model represents continental boundaries. Even the best do this crudely; reasonable regional representation will not be available until grid points are no more than 50 km apart. At the moment, for climatic time-scales, the world's biggest super-computer simply cannot cope with calculations of the resultant number and complexity.

The Division uses two GCMs — the CSIRO model, mentioned earlier, developed by Mr Hunt and Dr Gordon, and one originally built by the Australian Numerical Meteorology Research Centre. Given the importance of the ocean and of phenomena such as El Niño in Australia's climate, the Division's scientists — working with colleagues from the Division of Oceanography and the Centre for Environmental Mechanics (see *Ecos* 63) — have attached top priority to building a fully interactive ocean into the models.

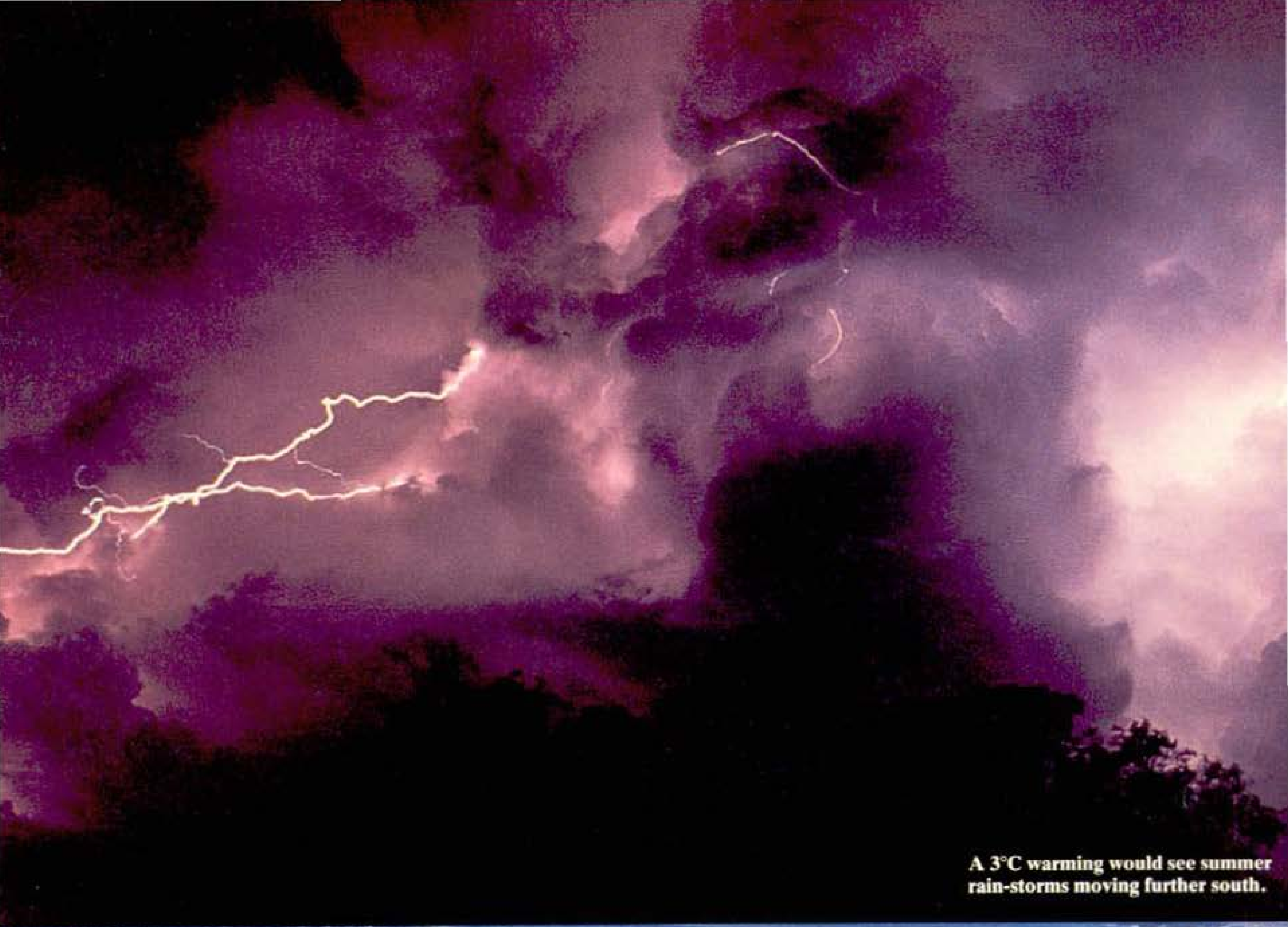
They have been encouraged by initial comparisons that show the Hunt and Gordon model to be one of two giving the best representation of the current or 'control' climate over Australia. These comparisons help the Division's scientists to identify and to correct particular problems in the model.

A few uncertainties

It's hardly surprising that predicting climatic change is difficult. A brief reflection on our planet's inherent climatic variability and the complexities of the interactions between Earth's atmosphere, oceans, topography, plants, and animals reminds us that it would be a Gargantuan task to simulate the whole process. The GCMs don't attempt to do that, of course, but gradually modellers are incorporating more feedback mechanisms into their models to take into account key natural processes — the capacity of plants to modify surface evaporation, the way oceans will store and distribute increased heat, and the effect of clouds.

But regardless of the way various feedback mechanisms eventually slow down or speed up the warming, simple physics requires that the additional infrared radiation absorbed by greenhouse gases must go somewhere. The challenge is to work out how global and regional climate responds to this additional heat distributed around the planet.

Dr Pittock's team argues that, although we may have to face a further decade, or more, of uncertainty before a clear picture emerges of the local impacts of the



A 3°C warming would see summer rain-storms moving further south.

A significant rise in sea level would change the look of some of our famous beach-fronts.

Regional impacts

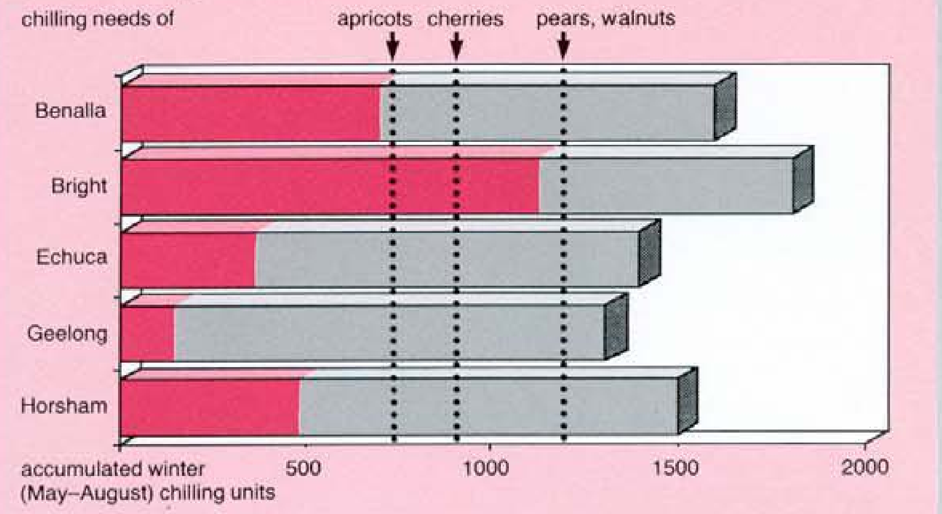
At the regional scale, the various GCMs do not agree well. A glance at the illustrations will show why this is hardly surprising; the models use grid points — typically some 500–700 km apart — that lead to a severe smoothing of coastal and topographic features. Given that weather conditions can vary over a few kilometres (annual rainfall either side of the Great Dividing Range, for example), describing regional climatic changes presents quite a challenge.

It is for this reason that, until the resolution of the models improves, Dr Pittock's team is not considering the full range of possible regional climatic changes but just concentrating on the impact of a uniform warming. They are drawing on knowledge about temperature tolerances of plants, along with evidence of the way ecosystems have responded in periods warmer than the present — according to evidence of variations in lake levels, fossil records, and changes in vegetation recorded by pollen preserved in sediment. The scientists are currently developing preliminary climate-change scenarios for Victoria, Western Australia, New South Wales, and the Northern Territory and they plan (as funds become available) to develop scenarios for the remaining States.

For the first regional study — covering Victoria — Dr Pittock and his Divisional colleague Mr Kevin Hennessy assumed a general 3°C rise in temperature throughout the year. This could occur some time in the next 30–60 years. They ignored the effects of possible changes in soil moisture and cloud cover, and the fact that the rise would probably not be distributed evenly at all sites across the State. The researchers emphasise that even small temperature changes are known to make big impacts. For example, when Shakespeare was writing 'The Winter's Tale' during the last little ice age — a period when the Thames was frequently frozen over — the average temperature is believed to have fallen only 1°C. In Australia, 3°C is the difference in annual mean temperatures between Melbourne and Sydney, or Sydney and Brisbane.

A warmer Australia simply won't be cold enough for some Victorian orchardists.

Greenhouse, and fruit set



The chart shows estimated chilling requirements for some fruits and nuts, and average chilling unit totals for five districts in Victoria now and following a 3°C 'greenhouse'-induced warming (red section of bars). The data may signal problems ahead for fruit-growers.

They examined what a 3°C warming would mean to the frequency of occurrence of various critical temperatures and runs of temperatures across Victoria, considering such agriculturally important variables as chilling units — a measure of the coldness critical for some plants to break flower-bud dormancy and to set most nuts and stone fruit. When they calculated the number of days in which the overnight temperature is at or below 0°C under present climatic conditions and compared this figure with what would happen with a 3°C warming, they came up with results that have serious implications for Victorian agriculture. As the chart above shows, even allowing for topographical influences, most stone fruits would no longer be viable in the important fruit-growing Goulburn Valley, and grape-growing, especially for white-wine grapes, would be at risk in much of the northern part of the State.

At the other end of the thermometer, the number of days over 35°C would double in most parts. More importantly, the frequency of a succession of hot days would increase. A succession of five such days would put great stress on most field crops and other vegetation. Warmer conditions earlier in the season may also lead to earlier maturation of crops and subsequently lower yields.

Clearly, for people earning their living from the land in southern Australia the impacts would be significant. For some, switching to new varieties or new crops may be one solution; for others, moving further south may appeal. Tasmania could become the new Mecca for Australian wine-growers.

Some things, of course, cannot be relocated easily — examples include our southern snow-fields, which may find they start to experience too many warm winters. And what of changes to our natural ecosystems currently preserved in national forests, parks, and reserves, and the impact on fisheries, the spread of pests and diseases, changing water supply, and infrastructure problems? The list seems endless.

Given the potentially dramatic impacts of warming, the more time we have for planning our responses the easier it will be to adapt. Unfortunately, we'll have to wait for improved GCMs and higher spatial resolution before we will know precisely what is likely to happen in any particular location. At the moment, not many scientists would recommend that you move just yet.

Regional impact of the greenhouse effect on Victoria. A.B. Pittock and K.J. Hennessy. *Victorian Government Greenhouse Program, First Annual Report*. 1988–89.

increased greenhouse gas levels, the eventual economic and social consequences are likely to be so great that we cannot afford not to consider them now.

To provide some focus for debate, the scientists have been using the best data available to prepare the most detailed scenarios possible on the impact on Australia and our near neighbours. While emphasising the uncertainties, they argue that decision-makers need the best possible advice at the time they are planning long-term projects.

Impacts... Southern Hemisphere

A rise in temperature, a change in the distribution and amount of precipitation, and altered sea level are the major expected outcomes of greenhouse. The way GCMs represent cloudiness is an important factor in determining the magnitude of the global warming predicted. On current projections for a doubling of CO_2 — expected by about 2030 — the range for global average warming is roughly from 2 to 5°C. But, because of delays due to the large heat capacity of the oceans, this 'equilibrium' warming will not be reached until about 2050. Of course, continued increases in greenhouse gas concentrations mean that the warming will increase beyond 2050.

All models show an increase in global precipitation of about 10% and some (including the Hunt and Gordon model) suggest that rainfall belts will move further polewards. In the Southern Hemisphere, summer-rainfall regimes may start to extend, as well as moving further south, with the rainy period starting earlier in spring and lasting longer in autumn. It is possible that the frequency, intensity, and range of tropical cyclones will increase. (Dr Pittock has recently recruited a scientist, Dr Jenni Evans, to work specifically on the question of how tropical cyclones will respond.)

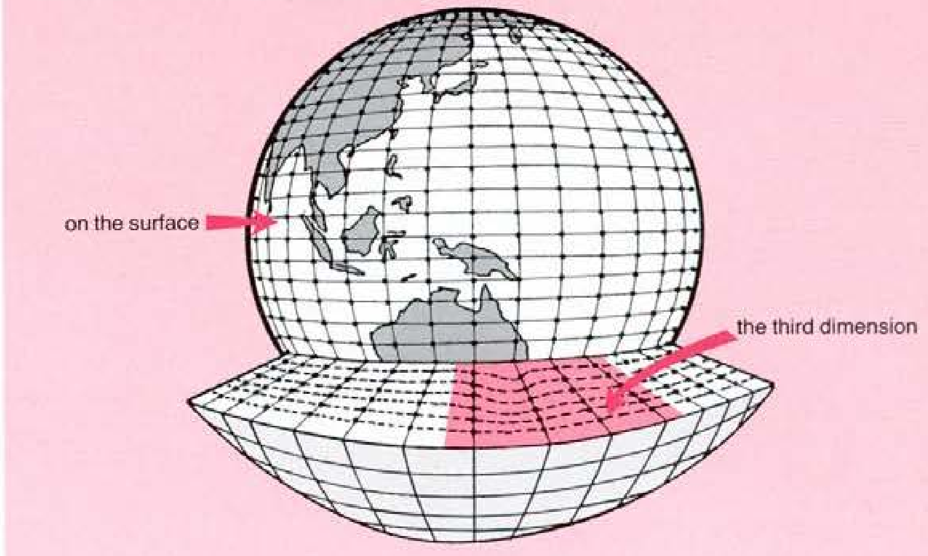
How the warming will affect the El Niño Southern Oscillation (ENSO) phenomenon — see *Ecos* 49 and 63 — is uncertain. Current GCMs cannot accurately reproduce ENSO behaviour; this requires a coupled dynamic ocean model. The change in winter-rainfall regimes is less clear than for summer, but if the mid-latitude rainfall belt moves significantly and uniformly polewards the Mediterranean-type climatic zones of southern Australia, Africa, and South America may well receive reduced winter rains.

In Australia's region, many poorer nations will face major challenges if sea levels rise as predicted. Within 20 years after the global temperature has increased by 3°C, thermal expansion of the oceans, retreating mountain glaciers, and other melting of land-based ice could add between 10 and 50 cm to average sea heights. The contribution that the Antarctic and Greenland ice sheets may make to this rise is not clear — increased precipitation over them resulting from warmer conditions may, in the short term, tend to lower sea level as more snow accumulates in the interior of the ice sheets.

However, if warming continues in the longer term and more ice melts at the margins than is formed in the interior, extensive low-lying coastlines, including our own, will become vulnerable. An important factor in the local impact of the rise will be any change in the meteorological conditions that affects extreme sea-level events, such as low atmospheric pressures and the occurrence of onshore winds and tropical cyclones.

While 'Surfers' may become less of a paradise, it is the intensively cultivated river deltas of Thailand and Bangladesh and low-lying coral atolls such as the Maldives (with many islands only 1·5 m above sea level) that potentially face the gravest economic and social upheaval. As a first step in helping our neighbours prepare for change over the next few decades, Australia is funding a network of stations in the South Pacific region to monitor climate and sea level. The network — co-ordinated by the Australian Marine Science and Technology Project Office — will collect data on sea level, sea-surface and air temperatures, atmospheric pressure, and wind velocity and complement a similar set of baseline sea-level monitoring stations being established around our own continent.

The world according to a GCM



General circulation models solve equations to predict temperature, humidity, and pressure at grid points around Earth's surface and at various altitudes. Vast numbers of calculations are required to simulate events over only a short time period, so a great deal of computing power is required.

In the case of the coral atolls it is possible that the coral reefs will grow fast enough to keep up with the predicted sea-level rise, and that broken coral washed up by storms will build up the central atolls. However, this is by no means assured and countries such as the Maldives and Kirabati are, understandably, anxious about the future.

As good as they are, the current General Circulation Models still have limited ability to simulate the real world's fickle weather patterns. But as computers get more powerful — enabling the models to process much more data, to focus on smaller regions, and to make better connections between atmosphere, oceans, and the living parts of our planet — scientists will become more and more confident about predicting future trends.

David Brett

More about the topic

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