The greenhouse effect, regional climate change and Australian agriculture

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Abstract

General circulation models used to predict the climatic changes due to the greenhouse effect do not at present have the spatial resolution, nor include enough physics, to give reliable and detailed regional predictions of climate change. Moreover, as climatic change will continue as long as greenhouse gases build up in the atmosphere, the future climate is a moving target. Best estimates of regional climatic change must therefore be based on a number of lines of reasoning, and are necessarily non-specific and uncertain. Nevertheless, there are useful things we can say, especially concerning the occurrence of critical temperatures, which at least highlight the future uncertainties and possibilities likely to affect Australian agriculture. These possibilities provide a focus for priority research both in climate and agriculture, and may give a small amount of useful planning guidance, at least in terms of placing a premium on protective conservation measures and on flexibility, adaptability and diversification.

Introduction

Given the current global increase in the greenhouse gases, which have kept the earth's surface warm enough to be habitable for millions of years, there is no doubt that we face a continuing warming trend. Whether or not this will be brought under control and limited some time in the 21st century is a matter for social and political will, and for the judgement of future historians. Meanwhile we have to try and anticipate and plan for the climatic changes which will come about over the next several decades.

Potentially this is best done using computer models of the climate system, known as general circulation models (GCMs). The best such models can already simulate fairly well the diurnal and seasonal cycles of the weather, and make fair estimates of the latitudinally averaged surface temperatures and rainfall under present conditions. However, they omit or greatly simplify many processes which may be important on a timescale of decades, especially when we envisage significant departures from the present climate. This raises uncertainty as to how accurate their predictions of a changed climate may be, and indeed different models give somewhat different predictions.

In addition, at the regional level at which we need to know the climatic changes, if we are to anticipate effects on agriculture, the climate models are far less satisfactory. This is largely because of the very large spacing, of the order of 500-1000 km. between the grid points at which most of the present generation of climate models calculate the atmospheric variables. Figure 1 shows typical grid point spacing over Australia for four of the overseas models which have been applied to the problem.

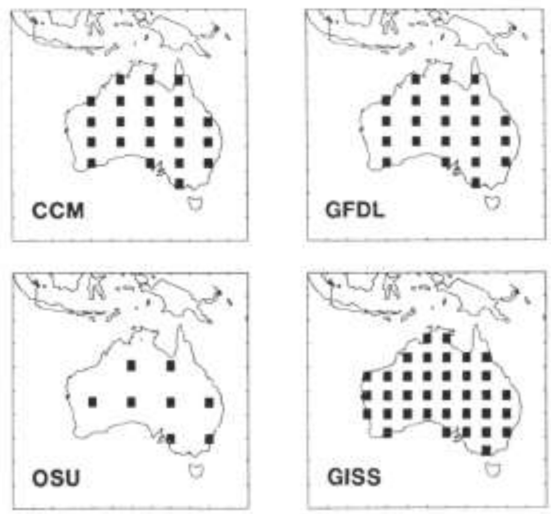

Figure 1. Grid point locations over Australia in each of four different global climate models (see text for details). The same grid spacing applies over the whole globe.

Clearly such coarse resolution does not allow adequate representation of the topography, vegetation cover, soil characteristics and coastline. Greater resolution in a global model is at present prohibitively expensive and presents technical problems. We are therefore working on an alternative strategy of "nesting", or at least of driving, a limited area model with high resolution within the global model. At 200 km resolution this would already give us a much improved representation of the major mountain ranges in Australia, while at 50 km resolution we should be able to give reasonable detail about regional climates.

We plan to make many other improvements to our climate models, including a better representation of the soil, interactions with the vegetation, the oceans, and variable cloud cover. However, all these improvements are for the future. Right now we have to rely on the broadscale results from models such as those indicated in Figure 1, which we can interpret regionally as best we can from our knowledge of how the regional climate is related to the larger scale climate, and on other lines of evidence. The other lines of evidence include possibly analogous warmer periods in the past, such as the so-called "climatic optimum" some 6,000 to 8,000 years ago, and climatic changes within the historical record of the last 80 to 100 years.

Towards regional scenarios for Australia

Temperature

As far as temperature is concerned, Table 1 shows a comparison of the Australia-wide average summer and winter temperatures generated by four overseas climate models for the present (1 x CO_2) and future (2 x CO_2) climates at some time when the CO_2 content of the atmosphere has doubled. Note that even for the present climate the models give significantly different answers (although all show summer to be warmer than winter!). The observed data give corresponding seasonal median values for summer of 28.6?C, and for winter 14.1?C, which are pretty close to the GFDL model predictions (although each of the models has its good and bad points and the GFDL model is not necessarily the most correct in all respects).

Table 1. The average surface temperature over Australia according to results for the control and 2 X CO2 simulations with the climate models at NCAR (CCM), the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Studies (GISS), and the Oregon State University (OSU). The resulting warmings due to an effective doubling of CO2 are shown in the last two columns. From M.C. MacCracken, personal communication and sec Crotch .

Again, for doubled CO_2, each of the models gives different predictions, but when we look at the differences between the present and doubled CO_2 predictions, or predicted effect of a doubling of CO_2, shown in the two right-hand columns, we see that all the models predict warmings for both summer and winter in the range of about 2.5 to 4.5 ?C. When we look at the model results for the daily temperature cycles (not shown) we again find predicted warmings over Australia in this same range for both daily maxima and overnight minima.

We now expect that an equivalent doubling of CO_2 will occur by about the year 2030, some 40 years hence, but that the warming may lag a decade or two behind due to the delaying effect of the huge heat capacity of the oceans. So, if we want to get some idea of what to expect around 2030-2050 based on Table I we might take, as a rough average figure, a general warming over Australia of about 3?C.

Next we might think about likely regional differences within Australia. As a matter of observation, as shown in Figure 2 for an extreme case at Halls Creek in WA, years of low rainfall during which the soil tends to be dry and there are fewer clouds tend to have higher average surface temperatures (especially daytime maximum temperatures) and more high temperature extremes than years of higher rainfall, when the soil tends to be wetter and is cooled more by evaporation. Indeed, not only the average temperature changes, but the shape of the frequency distribution of temperatures changes also. This has also been demonstrated by us in our climate model experiments on nuclear winter.

This suggests that, in those parts of Australia where seasonal rainfall might increase due to the greenhouse effect, warmings, especially of the daily maximum temperature, may be less than average. Conversely, in areas and seasons which are expected to get drier, warnings may be greater than average.

Model	1 x CO_2		2 x CO_2		Temp. change	
	Summer	Winter	Summer	Winter	Summer	Winter
CCM	26.0	15.1	30.8	17.8	4.7	2.7
GFDL	28.4	14.4	31.8	17.0	3.5	2.7
GISS	22.1	12.0	25.6	16.1	3.5	4.1
OSU	27.3	20.0	29.7	22.6	2.4	2.7

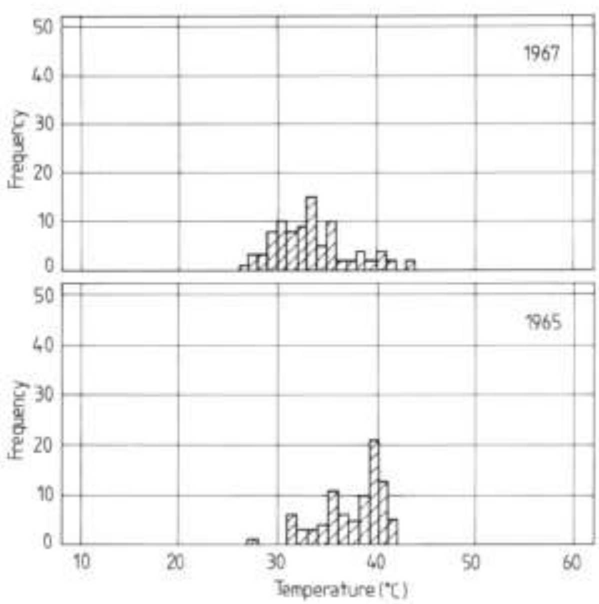

Figure 2. Frequency distributions of daily maximum screen temperatures at Halls Creek (W.A.) in (top) the summer (JFM) of 1967, when the total rainfall was 520 mm and the average maximum temperature was 33.7?C, and (bottom) summer (JFM) of 1965, when the total rainfall was 217 min and the average maximum temperature was 37.5?C.

Until we get more detailed regional predictions, however, it seems sensible just to explore the implications of a warming on rather simple assumptions. Initially, therefore, we are examining the possible consequences of a uniform warming of the daily maximum and minimum temperatures at all locations, ignoring the possible effects of changes in soil moisture and cloud cover and any possible changes in the shape of the frequency distributions. As part of our research for the Victorian State Government we have done this for Victoria. In particular we have examined the effect on the frequency of occurrence of extreme temperatures, and on runs of extreme warm or cold days, because of their potential importance for agriculture, species survival, human comfort and heating or cooling requirements.

Figure 3 shows maps of the average number of days each winter in which the overnight minimum screen temperature is at or below (1?C under (a) present climatic conditions, and (b) with a 3?C warming. Figure 4 shows similar maps for days with maximum screen temperatures greater than or equal to 35?C. It is apparent that the frequency of such extreme events changes rapidly with changes in the mean. The probability of runs of days of extreme temperatures changes even more frequently.

Such results have serious implications for agriculture. This is especially so for crops requiring winter chill conditions or "vernalisation". Typical chilling requirements for a number of horticultural crops are given in Table 2. These should be compared with calculated seasonal chill units under the present and 3?C warmer conditions at a number of locations in Victoria, shown in Table 3.

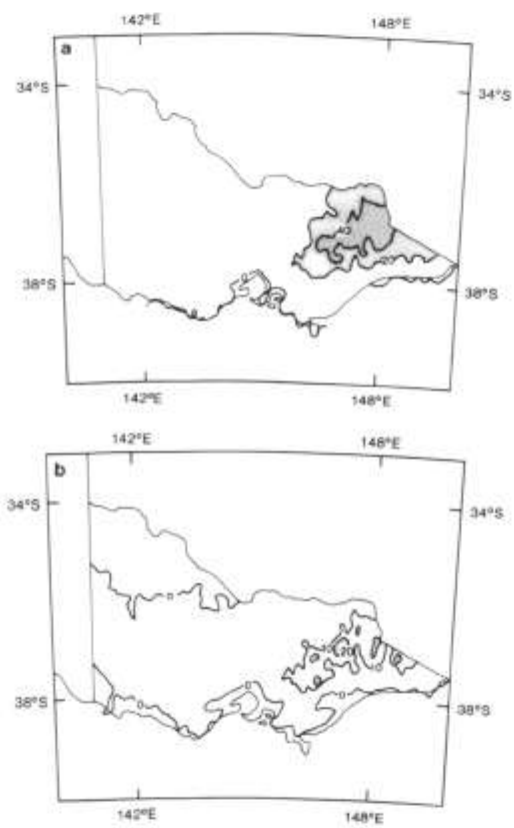

Figure 3. Contours of average number of days in winter (JJA) when daily minimum screen temperatures occur less than or equal to 0?C, (a) before, and (b) after a 3?C

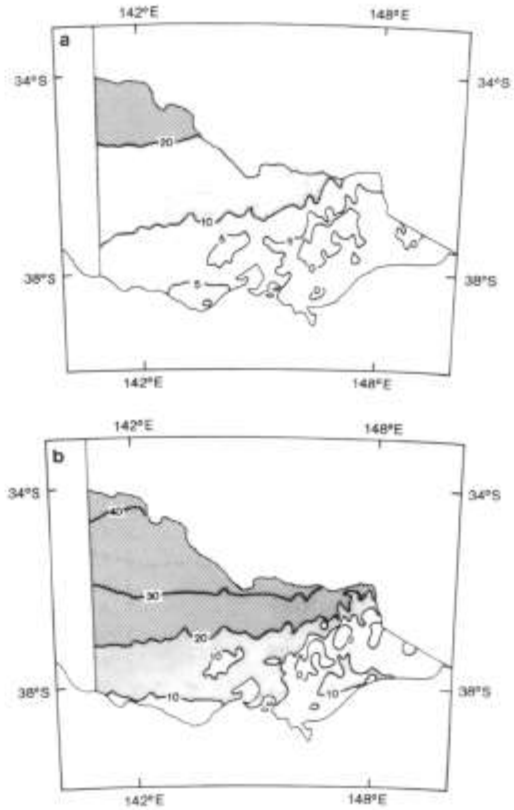

Figure 4. Contours of average number of days in summer (DJF) when daily maximum screen temperatures occur greater than or equal to 35?C,(a) before, and (b) after a 3?C uniform greenhouse warming.

Table 2. Chilling requirements for a number of (mils and nuts grown in Australia, expressed in "chilling units" (CU).[3] Estimates are based largely on research in the USA and may not be directly applicable to Australian varieties and conditions.

Crop	CU
delicious apples	1200
pears	1200
hazelnuts	800-1200
walnuts	800-1200
cherries	900
high-chill nectarines	800
high-chill peaches	800
apricots	720
almonds	>700
plums	>700
berries	>700
citrus	<400
grapes	<400
low-chill nectarines	<400
low-chill peaches	<400
macadamias	<400
mangos	<400

Table 3. The effect of a 3?C warming on accumulated winter (May-Aug) chilling units (CU), calculated using the Richardson model] from interpolated hourly screen temperatures at various Victorian stations.

Station	Average CU		% of winters with CU >700	
	Before	After	Before	After
Ararat	1883	966	100	89
Beechworth	2089	1461	100	100
Benalla	1596	689	100	53
Bendigo	1763	761	100	40
Bright	1805	1108	100	100
Casterton	1439	331	100	3
Donald	1508	476	100	9
Echuca	1390	353	100	10
Geelong	1308	147	100	0
Hamilton	1810	823	100	77
Horsham	1499	468	100	3
Kerang	1313	231	100	0
Lakes Entrance	1176	-26	100	0
Lismore	1657	548	100	17
Mildura	1041	-74	100	0
Nhill	1462	459	100	6
Orbost	1251	126	100	0
Swan Hill	1246	136	100	0
Tatura	1563	652	100	33
Wangaratta	1594	681	100	43

It must he stressed that these calculations are made on a number of rather crude assumptions, and so should not be taken as any more than a guide to the potential for impacts on horticulture. Nevertheless, if our assumptions are even approximately correct, the viability of various horticultural crops is threatened in a number of key areas. For example, most stone fruits would no longer be viable in the Goulburn Valley, and grape growing would he seriously at risk in the Mildura area. It is of course not so much the average conditions which are critical, but the change in the year-to-year risk of not having an economic crop.

Selection or breeding of low-chill varieties may to some extent reduce the potential impact of the expected climatic changes.

At the high temperature end of the frequency distribution, the results may be almost as disturbing, with a much increased frequency of days over 35?C and of runs of such days. Table 4 shows the effect of a 3?C warming on the average recurrence interval of a run of 5 consecutive days with maximum temperatures greater than or equal to 35?C at least once each sum- mer.

These are days of extremely high potential evaporation, which put great stress on most field crops. Given a dry spell they also imply a rapid drying of the soil and vegetation, with a much greater risk of fire. Warmer conditions earlier in the season may also lead to earlier maturation of crops, with reduced time for grain filling and lower yields.

We can also calculate the number of degree-days, or thermal time available for crop growth, and how this may change with a warming. This is the accumulated excess heat above some minimum temperature necessary for crop growth. Different crops have different minimum requirements of thermal time to reach maturity. Again, even a relatively small increase in the average temperature can mean a large increase in the available thermal time, which may mean that certain crops with large requirements may be grown further south under warmer conditions. The absence of frosts, and increased thermal time, may enable a number of tropical and subtropical crops to be grown further south or at higher elevations.

Table 4. Recurrence interval (years) for a 5-day run of summer daily maximum temperatures of 35?C or more, before and after a warming of 3?C.

Station	Before	After
Ballarat	31.0	5.2
Beechworth	28.0	2.6
Bendigo	9.7	1.7
Bright	16.0	1.2
Casterton	6.8	3.9
Hamilton	21.0	5.3
Mangalore	18.0	1.6
Melbourne	14.8	6.1
Mt. Beauty	10.0	1.3
Nhill	2.6	1.2
Orbost	14.0	7.0
Tatura	11.0	1.6

Rainfall and soil moisture

When it comes to rainfall and soil moisture our prognostications about the future necessarily become even more uncertain. I believe that the weight of evidence from GCM modelling of past cold and warm epochs (the last glacial. and the warmer period some 5,000 to 8,0(X) years ago), and of greenhouse and simulated nuclear winter conditions, is that under colder conditions there is less rain in tropical and monsoonal areas, and conversely that under warmer conditions there is more rain in these regions.[2,5,6] This is borne out in Australia by fossil pollen evidence of reduced in the last glacial period and of more rainfall during the post-glacial warm period.

This suggests that we might expect to see increases in the summer rainfall regimes of the northern half of Australia, and the extension southward of this influence as the greenhouse warming takes place. There is some evidence to support such a tendency over Australia during the last 80 years or so, with the greatest increases in summer rainfall occurring in central NSW[8] , coincident with a significant rise in average southern hemisphere mid-latitude temperatures. However, it is much less clear what rainfall tendency we should expect in southern Australia. The computer models are at present not detailed enough to tell us, and the other lines of argument are somewhat contradictory. 0ne argument is that conditions should look more like summer, with the rainfall belts further south: this would mean that southern Australia should get drier, especially in winter. The paleoclimatic evidence from 5,000-6,000 years ago, on the other hand, suggests that southern Australia was in fact wetter. And if we look at the trend observed over the last 80 years or so, when the average temperature in the southern hemisphere has warmed by about half a 8 degree, we see that it has got drier in the SW of Western Australia, but wetter in western Tasmania.

These apparent contradictions may relate to the lag effects of the oceans, which may locally change the land-sea temperature contrasts and thus the local atmospheric circulations. We hope to clarify this issue in future research. Meanwhile the possibility of such transient effects serves to highlight the ongoing nature of any greenhouse-induced climatic change. Results from models simulating equilibrium conditions with doubled CO_2 may not truly represent conditions when CO_2 has actually doubled as part of a continuing increase. In any case, a doubling and its associated climatic change will be only one stage in a continuing process. Thus farmers will have to place a premium on adaptability in the face of continuing change, rather than plan for some different but stable future climate.

Soil moisture content is determined by a running balance between rainfall and runoff and evaporation, with the local soil moisture capacity determining how quickly the soil may dry out once rainfall ceases. In general a 3?C warming means roughly a 10-15% increase in evaporation rate, so that soil moisture will only be maintained at present average levels if rainfall in the region also increases by 10-15%. Even where this is the case, rainfree periods will experience higher evaporation rates under warmer conditions, so that for a given soil moisture capacity the soil will tend to dry out faster. This means that in summer many areas will he subject to more frequent episodes of dry soil, and that, given the occurrence of dry spells, conditions suitable for bushfires may occur more frequently.

We should also note that increased surface temperatures under moist conditions allow higher absolute humidities to be present to feed orographic rainfall (that released as air is forced up over mountains) and convective storms. This means that the same rate of rise of an air column can lead to a greater rate of condensation and thus higher rainfall rates. In the case of convective storms a greater rate of release of latent heat of condensation would also cause the storm to intensify. Thus in general we may expect that under greenhouse conditions we will experience more intense rainfall, with higher runoff rates, and greater potential for soil erosion and flash floods.

Other factors

Several other factors will influence future climatic conditions. In Australia perhaps the most important is the behaviour of the El Nino-Southern 0scillation (ENSO) system which already dominates year-to-year variability in rainfall over most of northern and eastern Australia. When there is a major El Nino event, as in 1982-3 we have serious droughts, with widespread impact on primary production and the economy.[13] Anti-El Nino years, on the other hand, tend to be years of widespread rains and flooding, as in 1974-5 and again in 1988-9.

So far, our general circulation models do not reproduce ENSO behaviour very well, and we have only scanty evidence as to its past behaviour under changed climatic conditions. What evidence there is suggests that at least some El Nino events occurred during the Little Ice Age" [14,15] and even during the last glaciation. This suggests that its behaviour may not change very much as the climate warms, but the evidence is slim. A continuation of the occasional occurrence of El Nino years means that widespread drought years would continue to occur. These would be accentuated by higher average temperatures and evaporation.

The future behaviour of tropical cyclones in the Australian region is another matter of concern. Theoretical considerations suggest that in general we might expect some more severe cyclones to occur as the oceans warm up, and that they could become more frequent and occur at higher latitudes.[17] Whether this will happen in the Australian region, however, depends on local changes in sea surface temperature and atmospheric circulation, which are at present uncertain.

Agriculture will also be affected directly, and beneficially in general, by changes in the concentration of CO_2 in the atmosphere, but may be adversely affected by any decrease in stratospheric ozone, which would cause an increase in biologically damaging ultraviolet radiation (U V-B).

0ur knowledge of the direct effects of increased CO_2 concentrations on field crops is quite inadequate, and the considerations quite complex. As Dr. Gifford is speaking at this conference I will leave this subject to him, except to say in the broadest terms that the potential changes in water use efficiency. interspecies competition, plant morphology and phenology, and possibly in the behaviour of plant pests, induced by changing concentrations of CO_2 may require significant changes in farm management. Moreover, our present state of relative ignorance on these matters should be a matter for considerable concern.

Much the same should be said about the potential impact of increased UV-B radiation. We know even less about its effects on relevant species than we do about ambient CO_2 effects, but we know that in general the effects will be deleterious. Table 5 summarises the effects of increases in both CO_2 and UV-B on plants in general, and is based on ref.19.

Table 5. Summary of UV-B and CO2 effects on C3 plants.

Plant characteristic	Enhanced UV-B	Doubling of CO_2
photosynthesis	decreases in many plants	increase up to 100%
leaf conductance	no effect in many plants	decreases
water use efficiency	decreases in most plants	increases
yield	decreases in many plants	almost doubles
leaf area	decreases in many plants	increases
crop maturity	no effect	accelerated
drought stress	becomes less sensitive to	more tolerant to drought
UV-B but not tolerant to drought		

The future depletion of stratospheric ozone in our latitudes due to CFCs and other global pollution is at present uncertain, as the outcome will depend in large measure on a strengthening of the Montreal Protocol on the protection of the ozone layer, and on how well its provisions are adhered to by the international community. Hopefully we will not experience more than a 10% decrease in stratospheric ozone over Australia in the next 40 or 50 years, which would mean no more than an additional 20% UV-B. How much this would affect plant productivity is at present uncertain, although it is well within the normal seasonal variation and the variation with latitude within Australia. As the ozone layer is normally thinnest in summer and autumn, ozone depletion may be an additional factor favouring the planting and harvesting of cereal and other crops earlier in the season.

Impact on agriculture

We have seen that in addition to the strictly climatic factors of rainfall and temperature, productivity in Australia will be influenced by a range of other factors related to global change. These include international commodity prices which will be strongly influenced by supply and demand in other countries, the cost of energy in the form of fertilisers and fuel, and of course the direct effects on plants of increased ambient CO_2 concentrations and increased UV-B intensity. More complex climate-related factors such as fire frequency, the frequency of extreme rainfall and temperature events, the occurrence and severity of tropical cyclones, and the incidence of plant diseases and pests will also have significant effects. The following are some of the main impacts which I foresee may occur in relation to a number of agricultural industries.

Wheat and other cereal crops

Wheat production in Australia is highly sensitive to rainfall fluctuations. Thus Australian wheat production in the 5 years ending 1981-82 averaged 14 million tons, but in 1982-83 this total was reduced by one third due to the widespread drought associated with the major El Nino event in that year. In the eastern states production fell by more than two thirds, while in Western Australia, where there was no drought, production increased by almost 50%. New South Wales and Victoria commonly show reductions in productivity in drought years by more than 50%.

Considering only simple scenarios of increased summer rainfall, decreased winter rainfall, and a general warming, application of the Miami model of net primary productivity[20], suggests that wheat production in Australia could increase in all states except Western Australia, where increased aridity might cause a significant reduction. However, this model takes no proper account of seasonality, soil structure and fertility, plant diseases and pests, or other factors such as increased CO_2 concentrations and UV-B and changes in energy subsidies. Wheat, being a C3 plant, may benefit considerably by increased CO_2 concentrations, but it could suffer from increased exposure to UV-B.

The major impacts of suggested climatic changes would probably be on the drier frontiers of arable cropping. Increases in rainfall in subtropical areas could result in the expansion of sorghum cultivation instead of wheat in areas having high soil water holding capacity.[21] However, sorghum is a C4 crop and thus is not likely to benefit from increased CO_2.

As already noted, in areas dominated by winter rainfall there is a delicate balance between rainfall accumulated in the soil and evaporation in spring and summer, so that higher temperatures could lead to increased aridity in the later part of the growing season, leading to early maturation and reduced yields.

The great sensitivity of wheat yields to year-to-year variability in rainfall is a major factor in the economics of farming in Australia. It will thus be of critical importance how the El Nino-Southern 0scillation system responds to global warming. In any case, however, a southward extension of summer rainfall dominance will probably lead to increased variability in rainfall and crop yields.

Variations in global supply and demand will also play a major role in Australian wheat and other crop productivity, as areas under crop cultivation have varied enormously in response to fluctuations in commodity prices, with many farmers shifting emphasis from one crop to another, or to sheep and cattle as seemed appropriate. This is especially so in these industries because of the high fraction of production which goes to export.

Wool

As indicated by the preliminary modelling by Pittock and Nix[20] , in general pastoral productivity in Australia might be expected to increase, with a corresponding potential increase in wool production. However, market forces may well dominate any changes.

At first sight global warming might be expected to decrease the demand for woollen clothing, but this effect could be largely counteracted by restrictions on the use of fossil fuels for heating, leading to an overall reduction in household heating and a greater reliance on warm clothing in cool weather. I am not aware of any studies on this point.

Increased heat stress on sheep could play a significant role in shifting wool production southward within Australia, with the possibility of sheep replacing agriculture in some southern locations, especially if commodity prices make this an attractive option.

Cattle

The cattle industry is very adaptable to changing climatic conditions, with breeds available which are suitable for most conditions, ranging from cool to hot and arid to humid. Changes in the cattle industry may therefore be largely determined by market forces, including the supply and demand for meat on the domestic and overseas markets, and the relative profitability of alternative agricultural or wool production on the available land. It may he that, if extreme measures are taken to minimise greenhouse gas emissions, there could he a shift away from meat consumption to a more predominantly vegetarian diet. However, at this stage such a possibility is highly speculative. Changes in the distribution of cattle diseases and pests may also be a significant factor.

Horticulture

As we have seen above, a warming of the order of 3?C would greatly reduce the accumulated winter chilling units necessary for crop production, making many areas currently under production for apples, pears, stone fruits, nuts and berries no longer suitable, at least for the varieties presently grown. Conversely, large increases in the frost-free season and in frost-free regions would enable many tropical and subtropical fruits to be grown further south.

Consequently, we would expect to see a large shift southward and to higher elevations in the pattern of horticulture in Australia, with Tasmania assuming a much greater role as a producer of temperate climate fruits and as a wine-growing area. Marked southward shifts would also occur in the distribution of plant diseases and pests.

These changes could be cushioned by a shift to low chill varieties and selective breeding programs to make this possible in areas where suitable varieties may not presently exist.

Forests

While forestry does not normally fall within the scope of agronomy, I will include it here for two reasons. Firstly, by early next century it is clear that commercial forestry will be dominated by plantations, in which trees are grown essentially as a field crop. Secondly, reforestation will be a major strategy to mitigate the greenhouse effect by the storage of additional carbon and as a remedy for other environmental problems such as salinisation and soil erosion.

Farmers will increasingly be planting a proportion of their land to trees as a commercial proposition and as a measure to protect their land.

Clearly any large change in the temperature and rainfall conditions will significantly affect forest productivity. So too will increased ambient CO_2 concentrations. Barlow and Conroy found that doubled CO_2 doubled the rate of photosynthesis of *Pinus radiata* and increased the total plant dry weight by some 40% when phosphorus and soil moisture were not limiting. There was no response when phosphorus was limiting, but a greater gain under drought conditions. Different families of *Films radiata* gave different responses, and the response of most Australian native trees is unknown. In addition, very little is known about the response of these species to increased UV-B, although in general response is expected to he negative.

Studies by Booth and McMurtrie[24] on *Pinus radiata* indicate that some existing plantations would suffer significant reductions in productivity due to one scenario of climatic change, while other plantations would benefit. They also comment on the probably significant change in the distribution of serious plant diseases affecting production. In this regard it is interesting to note that commercial forestry is generally not viable in northern Australia because of the widespread activity of termites which infest most mature trees. Any warming trend associated with high humidity could see termites spread further south.

Changes in productivity overseas, and in demand both overseas and in Australia, could also greatly affect market prices for sawn timber and pulpwood, and thus the profitability of Australian timber production.[25]

To date none of these factors have been adequately studied, but they will undoubtedly have serious consequences for Australian timber production and the survival and profitability of particular forests and plantations. Monoculture plantations, which are confined to a relatively narrow range of optimum conditions and susceptible to outbreaks of plant diseases and pests, will be particularly vulnerable.

Concluding remarks

It is clear that over the next several decades climatic changes due to the increase in the greenhouse effect will change not only mean growing conditions but also the extremes and variability in ways which will profoundly affect the risk and profitability of practically all sectors of primary industry in Australia. These changes will be compounded by the direct effects of increasing carbon dioxide concentrations in the atmosphere, increases in damaging UV-B radiation, and significant changes in market forces due to changes in supply and demand partly arising from the greenhouse effect. Significant rises in the cost of fossil fuel energy will also impact on the farming community.

Unfortunately the best current predictions of the coming climatic changes are still highly uncertain, especially at the regional and local level. In Australia a concerted effort is being made to reduce these uncertainties (see Figure 5), with a significant increase in research funding earmarked for this problem by the Federal and some State governments. A core research program on improved climate modelling is being undertaken, with Federal funding, by CSIRO in collaboration with the Bureau of Meteorology. A more applied program aimed at regional climate impact studies is being undertaken by CSIRO, with funding from various State governments, and the collaboration of State government departments and other instrumentalities. Additional funding is to be made available on a competitive basis by the Federal government.

Major international research efforts are also under way, coordinated by the World Meteorological 0rganization and the United Nations Environment Program, which have set up an Intergovernmental Panel on Climate Change which will report to the United Nations General Assembly late in 1990. Australia is closely involved in this international research and policy development effort.

In the field of agriculture and forestry in Australia it is my view that the research effort is at present totally inadequate to cope with the coming problems. Too little is known about the climatic tolerances of most of our native plant species and of many of our crops, and almost nothing about their reaction in field conditions to changes in CO_2 concentrations and UV-B levels. High priority should be given to researching and developing suitably adaptable strains of cereal and horticultural species for the coming changing conditions. Research is also needed on the possible effects of environmental change on the distribution and virulence of plant and animal diseases and pests ranging from insect-borne diseases to locusts, ticks, rust in wheat, soil fungi and termites.

As regards adaptation strategies for farmers, it is clear that a number of complex considerations will determine changed optimum strategies in terms of varieties of crops, planting, irrigation. fertilising and other aspects of farm management. Financial risks, given changes in year-to-year variability, will alter, so that the economics of any particular enterprise will have to be carefully assessed. Clearly a premium must be put on adaptability and flexibility, with a recognition of the advantages of diversity and the disadvantages of monocultures in changing and often unpredictable conditions.

The increased danger of severe soil aridity in dry spells, and of higher rainfall rates in more intense convective storms, points to a need for increased care to avoid soil erosion by wind and water. Tree planting for shelter belts and along waterways and on steep slopes is an obviously desirable measure, which would also contribute to an alleviation of the downstream salinity problem and the reduction of the rate of increase in the CO_2 concentration worldwide.

Particular attention should also be paid to likely increases in the cost of fossil fuel, as international efforts are made to reduce greenhouse gas emissions. Such cost increases would affect tillage, transport, and the cost of fertilisers and other farm chemicals. This will give a competitive advantage to farming systems requiring low energy inputs.

Finally, a wary eye should be cast on the possible impact of all these factors on the global supply and demand of farm products which will determine the profitability of farming in Australia. It could well be that the greatest impact of the greenhouse effect on farming in Australia may derive from the impact of the greenhouse effect on international commodity prices.

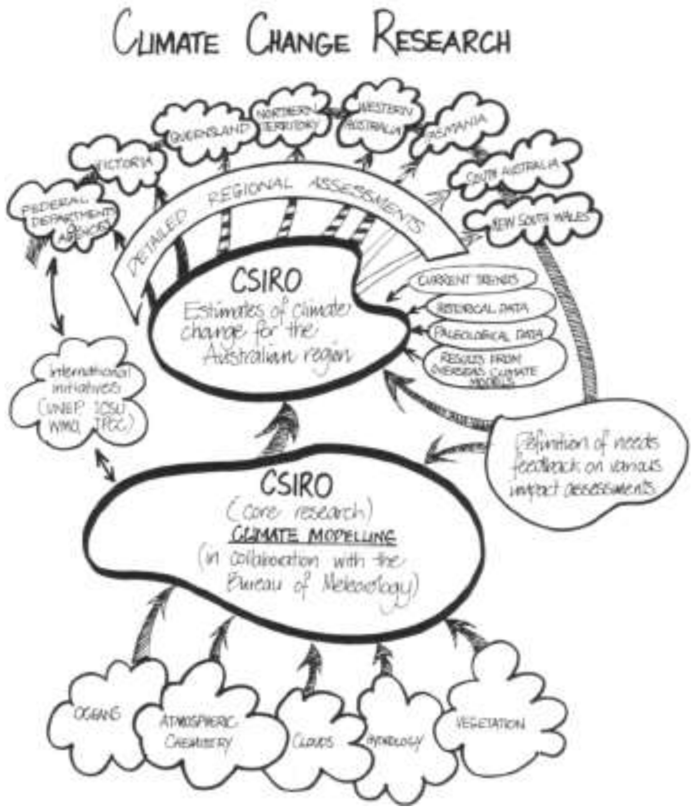

Figure 5. Schematic diagram showing the interactions involved in the current organisation of climate change research in Australia, which involves a collaborative program between CSIRO and the Bureau of Meteorology, with Federal and State government funding. Additional research is going on in some universities and elsewhere. The Federal Government is setting up a competitive research grant scheme which will be operative in 1990.

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