Climate Change in Queensland under Enhanced Greenhouse Conditions

Final Report
1997 - 2002

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CSIRO Atmospheric Research

Climate Change in Queensland under Enhanced Greenhouse Conditions

Final Report, 1997-2002

Report on research undertaken for Queensland Departments of State Development, Main Roads, Health, Transport, Mines and Energy, Treasury, Public Works, Primary Industries, and Natural Resources

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Important Disclaimer

This report relates to climate change scenarios based on computer modelling. Models involve simplifications of the real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO or the QLD government for the accuracy of forecasts or predictions inferred from this report or for any person's interpretations, deductions, conclusions or actions in reliance on this report.

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List of Abbreviations and Acronyms

DARLAM	Division of Atmospheric Research Limited Area Model
ENSO	El Niño Southern Oscillation
GCM	General Circulation Model – also Global Climate Model
SOI	Southern Oscillation Index
SST	Sea Surface Temperature

Summary for Policy Makers

This report summarizes the work of the final year of a four-year project examining the effects of climate change on Queensland. The initial focus of the contract was the improvement of both the complicated physical models that are used to simulate climate and in addition improvements in the detail of climate change scenarios. Thus much of the reporting in the past few years has described the development of climate models and the improvements in the simulation of Queensland climate that have been achieved. However, the focus of the project has lately shifted towards studies designed to answer specific questions regarding the impact of climate change on various sectors: for instance, on building design standards (3rd Annual Report), or on the water quality of Moreton Bay (Final Report).

An essential first step in such projects is the construction of a climate change scenario, or a plausible range of future conditions. In an effort to improve confidence of both future temperature and rainfall scenarios, consensus predictions using a number of international and local climate models are now used. Whilst this has become the preferred method for producing future climate change scenarios, the range of potential change produced by this process is relatively large. Using this approach , projected climate changes for Queensland can be summarized as follows:

- By 2030, projected annual mean temperature increases over Queensland range from 0.3 to 2.0 degrees Celsius over 1990 values. Much larger ranges are projected for 2070, with increases from 0.8 to 6.0 degrees. For Brisbane, annual mean temperature may increase from 20 degrees to 20.3-22 degrees in 2030 and to 20.8-26 degrees by 2070.
- In Brisbane, the number of summer days with temperatures over 35°C is projected to increase from its present average of 3 days to 3-6 days by 2030 and 4-35 days by 2070.
- Because of some disagreement between the projections of different climate models, the range of projected rainfall changes over Queensland is large, although the confidence in direction of change has improved. In general, projected annual rainfall over Queensland remains roughly the same or slightly decreases. The most recent CSIRO climate model (Mark 3) simulates slight increases in annual rainfall, although these results must at present be considered experimental. For strategic decision making, the consensus scenarios should be preferred.
- The consensus scenario predictions of little change in annual rainfall, combined with increases in temperature, imply a general decrease in soil moisture over Queensland in a warmer world. This decrease is most pronounced in the far interior. Drier soil conditions in the future will have implications for the grazing industry in the far interior and other agricultural production elsewhere in the State.

These changes in temperature, rainfall and soil moisture will have impacts on infrastructure, agriculture and the environment. Climate impact studies performed for Queensland have previously been reviewed in Walsh et al. (2001) (the previous year's report). Since then, other studies have concluded the following:

- Tropical forests are sensitive to climate change. Hilbert et al. (2001) simulated large changes in the distribution of forest environments even for relatively modest climate change scenarios that assumed temperature changes of 0 to 1 degrees and

rainfall changes of –10% to +20%. Strongest effects were seen at the boundary between rainforest and open woodland.

- By 2050, average electricity demand in Queensland is projected to rise 1-4% (assuming no technological improvement), with peak demand rising by 1.5-7%. This is a relatively small increase compared with the likely increase in demand due to non-climatic effects.
- Increases in wheat yield may be possible in the short term, due to increased carbon dioxide concentrations in the atmosphere; however, as soil moisture continues to decrease the mitigating effects of enhanced carbon dioxide concentrations will become negligible and production will fall.
- Modest increases in tree growth are likely in parts of the semi-arid tropics, but declines in growth rates are likely in the monsoon tropics of tropical north Queensland, due to the adverse effects of warming on tree growth
- There are some obvious implications for water resources of the predicted decrease in soil moisture, including reduced runoff in some locations.
- There is an emerging consensus that maximum tropical cyclone wind speeds are likely to increase by 5 to 10%, by some time after 2050. This will be accompanied by increases of 20 to 30% in peak tropical cyclone precipitation rates. Little change in regions of tropical cyclone formation is projected, however.

While it is envisaged that climate models will still continue to be developed and improved, the focus of future work will increasingly shift towards climate impact studies. As rainfall simulations improve, more emphasis can be placed on assessing the potential impacts where rainfall is a critical consideration. This is particularly true with regard to assessing the impact of climate change on water resources in Queensland, an issue that needs to be addressed in more detail.

Extended Abstract

This report summarizes the work of the final year of a four-year project examining the effects of climate change on Queensland. The initial focus of the contract was the improvement of the complicated physical models that are used to simulate climate, as this was the only way that answers could be obtained on issues like the effect of climate change on Queensland rainfall. Thus much of the reporting in the past few years has described the development of climate models and the improvements in the simulation of Queensland climate that have been achieved. However, while model development continues to be an important issue, the demonstration of the strategic policy relevance of climate change scenarios has been the focus of the project over the last two years.

An essential first step in such projects is the construction of a “climate change scenario”, or a plausible range of future conditions. This is based on the consensus predictions of a number of state-of-the-art climate models. Recently, CSIRO (2001) released updated climate change scenarios for Australia that are summarized here.

Climate Change Scenarios for Queensland

Temperature

By 2030, projected annual mean temperature increases over Queensland range from 0.3 to 2.0 degrees Celsius over 1990 values. Much larger ranges are projected for 2070, with increases from 0.8 to 6.0 degrees. This range reflects the large range of emission scenarios used and different model sensitivity to future greenhouse gas emissions. However, increases in temperatures are projected to occur in all seasons. In summer, this has the effect of sharply increasing the number of hot days. In Brisbane, the number of summer days with temperatures over 35^{o}C is projected to increase from its present average of 3 days to 3-6 days by 2030 and 4-35 days by 2070.

Rainfall

Because of some disagreement between the projections of different climate models, the direction of rainfall changes over Queensland is still characterised by some uncertainty, although the confidence of projections has improved during the past few years in that uncertainty has been limited to regions and hence confidence increased. In general, the consensus projections of climate models suggest that projected annual rainfall over Queensland remains about the same or slightly decreases. However, the most recent CSIRO climate model, Mark 3, simulates slight increases in annual rainfall. When broken down by seasons, summer rainfall tends towards increases along the coast by 2030, with the exception of a region around Townsville, where there is a tendency towards decreases (Section 2.2.2). In the interior of the State, summer rainfall projections remain uncertain. In autumn, far north Queensland tends towards rainfall decreases, while in much of the rest of the State the direction of change is uncertain. In the far interior, a tendency towards rainfall increases is projected. In winter and spring, a tendency towards decreases is seen, along with regions of remaining uncertainty.

Most climate models also simulate an increase in extreme daily rainfall, leading to more frequent heavy rainfall events. This could occur even where average rainfall is projected to decrease, provided that the decreases are not large. This result has implications for water storage and flood-related impacts.

Moisture balance

Predictions of little change in annual rainfall combined with increases in temperature imply a general decrease in soil moisture over Queensland in a warmer world due to increased evaporation. This decrease is most pronounced in the far interior. Drier soil conditions in the future will have implications for agriculture in the State (Section 2.2.3).

Climate impact studies in Queensland

Climate impact studies performed for Queensland have previously been reviewed in Walsh et al. (2001) (the previous year's report). Since then, IAWG (2001) have published a summary document that details the likely and possible impacts of climate change for Australia. As stated in IAWG (2001), it is important to recognize that there will be both winners and losers from climate change. The value of better understanding of probable impacts is that adaptation strategies can be designed to minimize adverse impacts and optimize benefits. Here, we provide an update on studies performed since Walsh et al. (2001) (Section 2.3):

- Tropical forests are sensitive to climate change. Hilbert et al. (2001) simulated large changes in the distribution of forest environments even for relatively modest climate change scenarios. Strongest effects were seen at the boundary between different types of forest such as rainforest and open woodland. It is suggested that most forests in tropical Queensland will in the near future experience climates that are more appropriate to other forest types. Highland rainforests in particular demonstrated strong sensitivity.
- Peak electricity demand in Queensland is experienced during hot summer days, which are likely to increase in frequency in a warmer world. By 2050, average electricity demand in Queensland is projected to rise 1-4%, with peak demand rising by 1.5-7%, assuming no technological development. This is a small increase compared with the likely increase in demand due to non-climatic reasons.
- Increases in wheat yield may be possible in the short term, due to increased carbon dioxide concentrations in the atmosphere, despite reduced soil moisture and higher temperatures. However, if rainfall declines by 20%, wheat yield would increase for a 1^{o}C warming but decline for greater warmings.
- Modest increases in tree growth are likely in parts of the semi-arid tropics, but declines in growth rates are likely in the monsoon tropics of tropical north Queensland, due to the adverse effect of warming in these already warm tropical regions.
- There are some obvious implications for water resources of the predicted decrease in soil moisture, including reduced runoff in some locations. A related study for the Macquarie catchment in New South Wales found that changes to environmental flows were 0% to –15% by 2030, and –5% to –35% by 2070.

Simulation of climate change over Queensland using the CSIRO Mark 3 model

Climate impact studies rely upon the simulations of climate models. The latest version of the CSIRO climate model, the Mark 3 global coupled ocean/atmosphere model, has a greatly improved simulation of the climate of Queensland (Section 3.1). There is particularly good agreement between the simulated and observed seasonal variation of average rainfall. Simulated geographical patterns of rainfall also show reasonable agreement with observations. In addition, the Mark 3 model has a substantially improved simulation of the El Nino/ Southern Oscillation (ENSO) phenomenon, compared with its predecessor, the Mark 2 model. The size of ENSO variations in the Mark 3 model is now comparable with those observed, whereas ENSO variations in the previous Mark 2 model were only about a third of the observed size. The observed relationship between the year-to-year variations of ENSO and related variations in Queensland rainfall is also reasonably well simulated, although not all of the observed characteristics of ENSO are faithfully reproduced in Mark 3.

By 2050, the Mark 3 model simulates temperature increases over Queensland of between 0.4 and 1.2 degrees Celsius for January-June, and 0.8 to 1.6 degrees for July through September (Section 3.2). These ranges are towards the low end of the CSIRO (2001) climate change scenarios. The main reason for this is a more realistic representation in the Mark 3 model of sea ice and other high latitude processes, giving less change in these quantities in a warmer world. In addition, the future greenhouse gas concentrations in the Mark 3 model run are slightly lower than those assumed in some of the other model runs used to construct the consensus climate change scenarios.

Simulated rainfall changes by Mark 3 generally fall within the range of those given in the climate change scenarios. Overall, by 2050 the Mark 3 model projects average Queensland rainfall to increase slightly from January to June, and to remain the same from July-December. Considerable interannual and decadal variability is evident in the simulation. Unlike a number of other climate models, Mark 3 does not project a change in the mean climate of the Pacific to a more “El Niño-like” state. This issue needs to be examined more fully in subsequent analyses.

Regional model climate change simulation

While the quality of the Mark 3 simulation gives increasing confidence in its projections, it still has a resolution (distance between grid points) that is relatively coarse (a few hundred kilometres). This limits its ability to simulate regional climate change or the effect of climate change on smaller phenomena such as tropical cyclones. For these tasks, finer-resolution regional climate models are needed.

Recently, climate models have been developed that are *variable-resolution*, in that their resolution differs from place to place. The advantage of these models is that they retain the internal consistency of a global model while enabling fine resolution to be implemented over regions of interest (in this case, Queensland). Coarse resolution is specified over other parts of the globe so that the model runs faster.

The CSIRO variable-resolution conformal-cubic model (also known as Mark 4) has been implemented with a resolution over Queensland roughly equivalent to 60 km

(Section 3.3). It is "nudged" or slightly forced by the Mark 3 GCM, which also generates the sea surface temperatures used by Mark 4. Thus the Mark 4 GCM as used here is an atmospheric model rather than a coupled-ocean atmosphere model. The simulation of average screen temperature is good, with modest simulated biases (mostly less than 2 degrees). For maximum temperatures, biases are larger in a band in the north of the State. The reasons for this are being investigated.

Mark 4 has an excellent simulation of observed rainfall patterns over the State. The main advantage of Mark 4 over Mark 3 is this ability to better simulate the detailed pattern of rainfall, because of the better representation of topography in the more detailed variable-resolution model.

Under enhanced greenhouse conditions, the Mark 4 model over Australia warms up faster than does the Mark 3 model. Changes in rainfall tend to be noisier than those simulated by the Mark 3 model, but in agreement with the simulation of the Mark 3 model, Mark 4 projects annual rainfall over Queensland to change little.

Tropical cyclones and climate change

Considerable progress has been achieved in the past few years in our understanding of the effect of climate change on tropical cyclones. Five years ago, little was known about this issue. Since then, a general consensus has emerged that increases in tropical cyclone maximum wind speeds are likely over some areas. Studies performed as part of this project indicate that Queensland could be one such area where intensity will increase (Section 4).

Current understanding of this issue is summarized as follows:

- Little change in the regions of tropical cyclone formation is expected.
- Changes in numbers could be significant in some regions, mostly as a result of changes in the characteristics of ENSO, which has a substantially influence on tropical cyclone numbers in the Queensland region and other locations. A trend that is seen in a number of climate model simulations, towards a more "El Niño-like" climate in a warmer world, may lead to tropical cyclone formation that is more similar to that seen in El Nino years. All other things being equal, this may lead to some decrease in tropical cyclone numbers in the Queensland region, but as yet this decrease has not been properly estimated.
- There is an emerging consensus that maximum tropical cyclone wind speeds are likely to increase by 5 to 10%, by some time after 2050. This will be accompanied by increases of 20 to 30% in peak tropical cyclone precipitation rates.
- There is no genuinely convincing evidence yet that tropical cyclones will travel further poleward than they currently do.

New climate simulations using the CSIRO regional climate model DARLAM (nested with the Mark 2 global model), at finer horizontal resolution (30 km) than those previously attempted, support the above conclusions. These new model runs give an excellent simulation of the variation with latitude of observed tropical cyclone formation and a good simulation of the occurrence of observed tropical cyclones, or the numbers of tropical cyclones observed at various latitudes off the Queensland coast. Under enhanced greenhouse conditions, this modelling system predicts little change in tropical cyclone numbers or regions of formation, and suggests increases in typical maximum intensities of tropical cyclones. The simulation also does not show convincing evidence of a southward movement along the Queensland coast of typical tropical cyclone occurrence in a warmer world.

Future work

Climate models will still continue to be developed and improved. Whilst preliminary results from both Mark 3 and Mark 4 have been discussed in this final report, further investigation is is needed to clarify the direction of rainfall change over Queensland, to determine the response of ENSO to climate change, and to more accurately assess the effects of climate change on tropical cyclones. All attempts will be made to address aspect of rainfall scenario confidence in any future work agreement, with the State government. While a concerted effort would be made to explore improvement of rainfall scenarios any future work will also address issues specifically related to impacts. In particular, the impact of climate change on water resources in Queensland is an important issue that needs to be addressed in more detail. The general decrease in soil moisture predicted for Queensland will have impacts on agriculture that need to be adequately quantified. Building and infrastructure design standards may need to be re-evaluated due to projected increases in peak wind speeds and maximum rainfalls in northern Queensland. The value of climate change projections is that they can minimise the cost of under- or over-adaptation to the effects of climate change, decisions that will always be made based on predictions that contain at least some element of uncertainty (Section 5).

1 Introduction

This is the final report of a four-year consultancy (1997-2001) between CSIRO and the Government of Queensland. *The consultancy addresses the following aspects of climate change:*

- changes in average climate (temperature, rainfall and other relevant variables) from the present until the year 2100 and beyond,

- possible changes to ENSO, notably in its variability and amplitude, and related changes in drought and flood frequencies,

- possible changes to tropical cyclone frequency, intensity and location,

- potential changes in climatic variability, including daily, within-season, interannual and multi-decadal variability and extremes,

- the development of methodologies to assess the risk of occurrence of critical climatic thresholds for relevant impacts and adaptation measures,

- the identification of potential impacts of climate change across relevant sectors in Queensland, in collaboration with interested parties, and the facilitation of studies thereof, where appropriate through separately funded collaborative impact studies.

1.1 Progress against Milestones

Here we detail the achievements of the final year of the consultancy against the agreed milestones of the contract:

Item 2.4.1 Continue to refine climate change scenarios based on a combination of current modelling techniques, including variable-resolution coupled climate models (e.g. CSIRO Mark 4 if available).

- new climate change scenarios for Australia were released by CSIRO in 2001, and here the results of these scenarios are summarized for Queensland. In addition, the simulations of CSIRO climate models, including Mark 4, are discussed in the report in Section 3.

Item 2.4.2 Using a variable-resolution climate model (CSIRO Mark 4 if available), simulate the tropical cyclone climatology in the Australian region, and investigate the mechanisms governing tropical cyclone formation under El Niño and La Niña conditions.

- tropical cyclone simulations using Mark 4 were not available in time for this report. The current state-of-the-art of tropical cyclone modelling in the Australian region is discussed in Section 4, along with new simulations using DARLAM.

Item 2.4.3 Conduct a comprehensive modelling study using an improved high-resolution coupled ocean-atmosphere model of El Niño to determine the possible effects of climate change on El Niño, including extensive validation of the simulation of the state of El Niño in the present climate.

- this is discussed in detail in Section 3.

Item 2.4.4 In collaboration with selected impacts researchers, use OZCLIM to analyze impact of climate change scenarios on selected sectors or activities, assess risk and investigate management/adaptation strategies.

- results from a study of the impact of climate change on the Moreton Bay estuary are detailed in Section 2.4. Details of other recent climate impact studies are also included in Section 2.

2 Climate Change Scenarios and Impacts for Queensland (Milestone 2.4.1)

2.1 Introduction

Climate change scenarios are plausible projections of future climate conditions. As such, they contain two major sources of uncertainty: the differences between the projections of different climate models, which reflect our incomplete understanding of all of the physical processes involved; and the wide variation in predictions of the future amount of greenhouse gases in the atmosphere. Thus all climate change scenarios give a range of projections.

The construction of climate change scenarios is an important task, as scenarios are one of the main inputs for environmental models that are responsible for calculating the potential impacts of climate change. In recent years climate change scenarios have been constructed using the consensus predictions of a number of different climate models. In keeping with this methodology, CSIRO released updated climate change scenarios (CSIRO, 2001) and a summary of the likely impacts of climate change (IAWG, 2001). These scenarios update and replace an earlier climate change scenario document (CSIRO, 1996).

These projections are based on the range of global-average warmings predicted by nine different climate models. The regional response in terms of a local climate change (in degrees Celsius for temperature and percent for rainfall) is then calculated per degree of global warming. This range of local values is derived from the differing results of these nine climate models.

This section briefly summarizes the results of this work as it pertains to Queensland.

2.2 Projections of climate change

2.2.1 Temperature

Figure 2.1 depicts the climate change scenarios for temperature. Each colour is associated with a range of temperature for the year indicated, with the ranges becoming larger from 2030 to 2070. By 2030, projected annual mean temperature increases over Queensland relative to 1990 range from 0.3-2.0°C. Much larger ranges are projected for 2070, with increases ranging from 0.8-6.0°C. Note that it is controversial whether the upper end of this temperature range is realistic, as it is based upon the most extreme assumptions of future greenhouse gas emissions (known as the A1F1 IPCC SRES emission scenario; Nakicenovic et al., 2000). This "emissions scenario" assumes rapid future economic growth based on an intensive use of fossil fuels.

Increases in temperatures are projected to occur in all seasons. In summer, this has the effect of sharply increasing the number of hot days. In Brisbane, the number of summer days with temperatures over 35°C is project to increase from its present average of 3 days to 3-6 days by 2030 and 4-35 days by 2070, although again the upper extremes of this range again may be less likely.

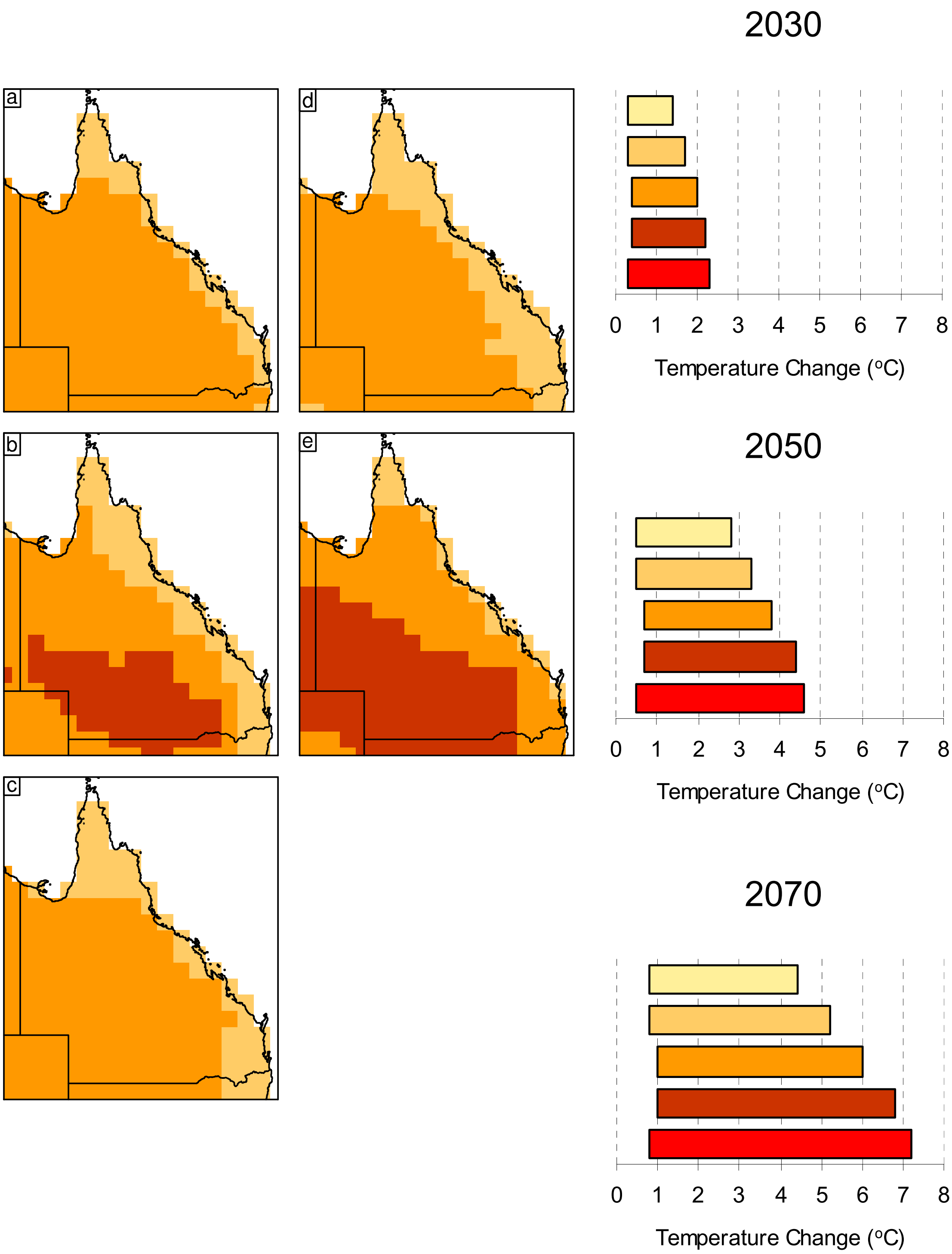


Figure 2.1. Temperature change scenarios for Queensland, interpolated to a 1 degree grid, for (a) annual mean; (b) summer; (c) autumn; (d) winter; and (e) spring. From CSIRO (2001).

2.2.2 Rainfall

The direction of rainfall changes over Queensland still is characterized by some regional uncertainty, where model agreement could not be reached on the direction of change. However, there are regions within Queensland where the models all agree on the direction of change, hence providing greater confidence in projections. In general, the sign of annual rainfall changes over Queensland is either slightly negative, neutral or remains uncertain (Fig. 2.2). When broken down by seasons, summer rainfall tends towards increases along the coast by 2030 (-5% to +15%), with the exception of a region around Townsville, where slight decreases are projected. In the interior of the state, projected summer rainfall remains uncertain. In autumn, far north Queensland is affected by a tendency for rainfall decreases, while for much of the rest of the state projections remain uncertain, with the exception of the far interior, where increases in rainfall may predominate. In winter and spring, either rainfall decreases or remaining uncertainty are seen.

By 2070, the projected ranges expand substantially. For instance, for annual rainfall, changes over a large section of Queensland are projected to be between –35 to +35%. There is a similar expansion in the range of the region tending towards decreases, indicated in orange (-40 to +10%).

Most models also simulate an increase in extreme daily rainfall, leading to more frequent heavy rainfall events. This could occur even where average rainfall was projected to decrease, unless the decreases were large. This may have some implications for water storage and flood-related impacts.

Note that the most recent CSIRO climate model simulation, that of the Mark 3 model, projects slight increases in annual rainfall in Queensland by 2050 (about 7%; see Section 3.2). This is within the range of the remaining uncertainty in the current scenarios. Nevertheless, this highlights the importance of narrowing this range through future studies.

2.2.3 Moisture balance

In the remaining areas of uncertainty, the projected increases in rainfall are not substantial enough to overcome increased evaporative demand associated with temperature increases. The resultant increases in project temperature will result in a general decrease in the moisture content of the soil over Australia, and particularly over Queensland (Fig. 2.3). These changes are projected to occur in all parts of the State, and are most pronounced in the far interior.

It is important to emphasize that the general decrease in soil moisture occurs despite possible increases in rainfall in some locations. This is because the rainfall increases are more than counterbalanced by increases in evaporation caused by temperature increases. Since predictions of temperature increases have high confidence (a better than 9 out of 10 chance), predictions of decreased soil moisture over Australia also have reasonably high confidence, despite the considerably lower confidence of the rainfall predictions. This result would have likely implications for agriculture in Queensland.

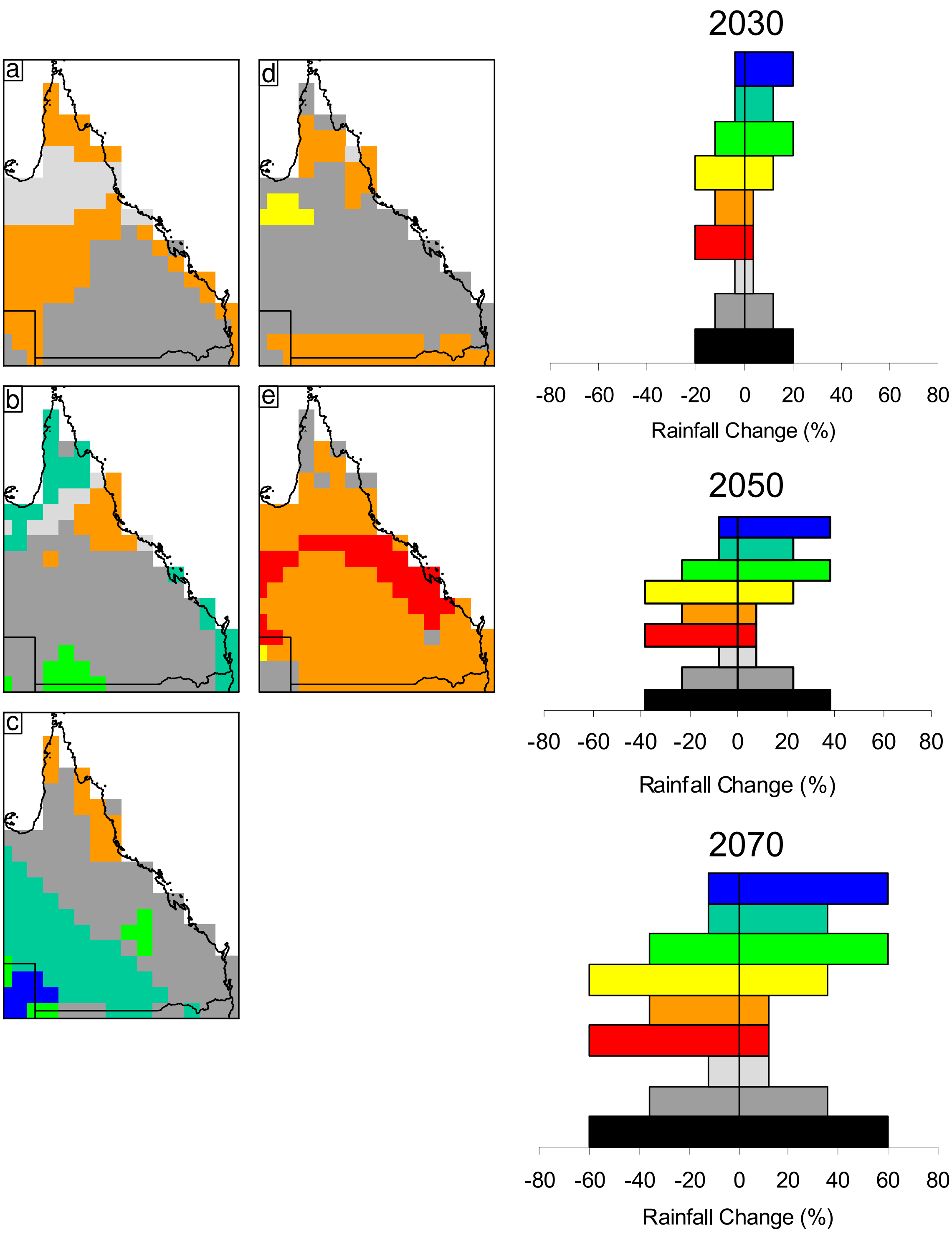


Figure 2.2. The same as Fig. 2.1 but for rainfall.

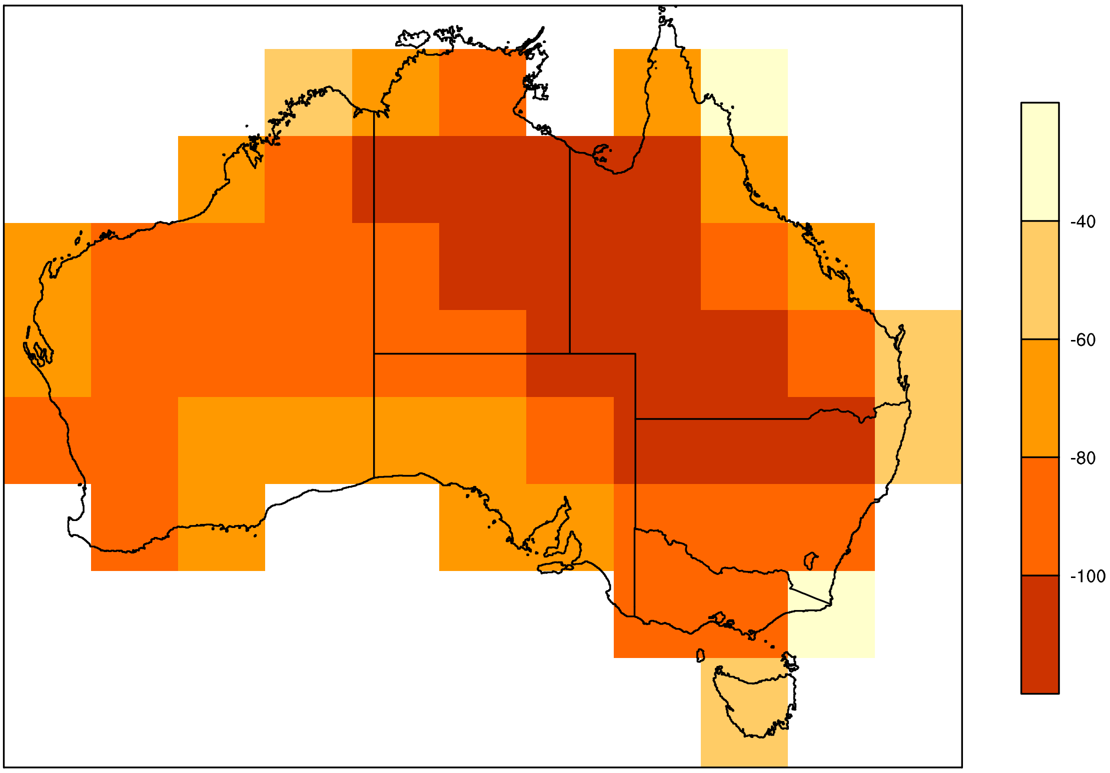


Figure 2.3. Average annual change (mm) in moisture balance for a 1°C global-average warming. The map is based on the average of eight climate model simulations. All regions experience increased moisture stress. From CSIRO (2001).

2.2.4 Reducing the uncertainty of rainfall predictions

Reduction of the uncertainty of rainfall predictions will only come from the development of climate models that can better represent both regional and local scale circulation patterns and important synoptic controls e.g. Pacific sea surface temperatures. Recently developed models have a much better simulation of ENSO (for example, the CSIRO Mark 3 model), and this gives cause for optimism regarding an early resolution of this issue (see Section 3).

2.3 Climate impact studies in Queensland

Walsh et al. (2001) gave a comprehensive review of work performed on the impacts of climate change in Queensland. Since then, IAWG (2001) have published a summary document that details these and other impacts for the Australian region. We provide an update on this work and also detail the results of climate impact studies performed as part of this year's consultancy.

As stated in IAWG (2001), it is important to realize that there will be both winners and losers from climate change. The value of better understanding of probable impacts is that adaptation strategies can be designed to minimize adverse impacts and optimize benefits.

2.3.1 Tropical forests

Work by Hilbert et al. (2001) suggests that the tropical forests of north Queensland are sensitive to climate change. Large changes in the distribution of forest environments were simulated even for relatively modest climate change scenarios. Significant shifts in the extent and spatial distribution of such forests were considered likely, with the strongest effects being felt in the boundary regions between different types of forest such as rainforest and open woodland (Fig. 2.4). It is suggested that most forests in tropical Queensland will in the near future experience climates that are more appropriate to other forest types. Highland rainforests in particular demonstrated strong sensitivity.

2.3.2 Electricity demand in Brisbane

The problem periods for electricity demand are hot summer days (Howden and Crimp, 2001), which are likely to increase in frequency with global warming. For projected temperature increases by 2050, average electricity demand in Brisbane is projected to increase by 1-4% (assuming no technological development), with peak demand increasing by 1.5-7%. However, projected increases in demand for non-climatic reasons are considerably larger than this.

2.3.3 Wheat yield

If recent wheat yield increases in the Emerald region are related to climate change, then this increased productivity is likely to continue into the future, as such initial increases in wheat yield, due to increased carbon dioxide concentrations, are a prediction of climate change impact studies in Queensland (Howden et al., 2001a). However, if rainfall declines by 20%, wheat yield would increase for a 1^{o}C warming but decline for greater warmings.

In contrast, the positive response of wheat to higher carbon dioxide levels may come at the price of lower grain protein content. Since low protein wheat is not suitable for making pasta or bread, farmers may need to add fertiliser to maintain protein content.

2.3.4 Forests

Howden et al. (1999) showed that a doubling of carbon dioxide concentration was likely to have a beneficial effect on native pastures. Howden et al. (2001b) extended this work to the mulga woodlands of southwest Queensland, examining management options under enhanced greenhouse conditions, investigating how the woodlands could be managed so that they could help absorb greenhouse gases. Because of a substantial increase in grass growth, fires were projected to increase in frequency, thus causing net carbon storage to decrease (and thus greenhouse gases to be emitted rather than stored). The response to increased carbon dioxide is likely to be limited in regions where soil nutrition is limited or where rainfall decreases substantially.

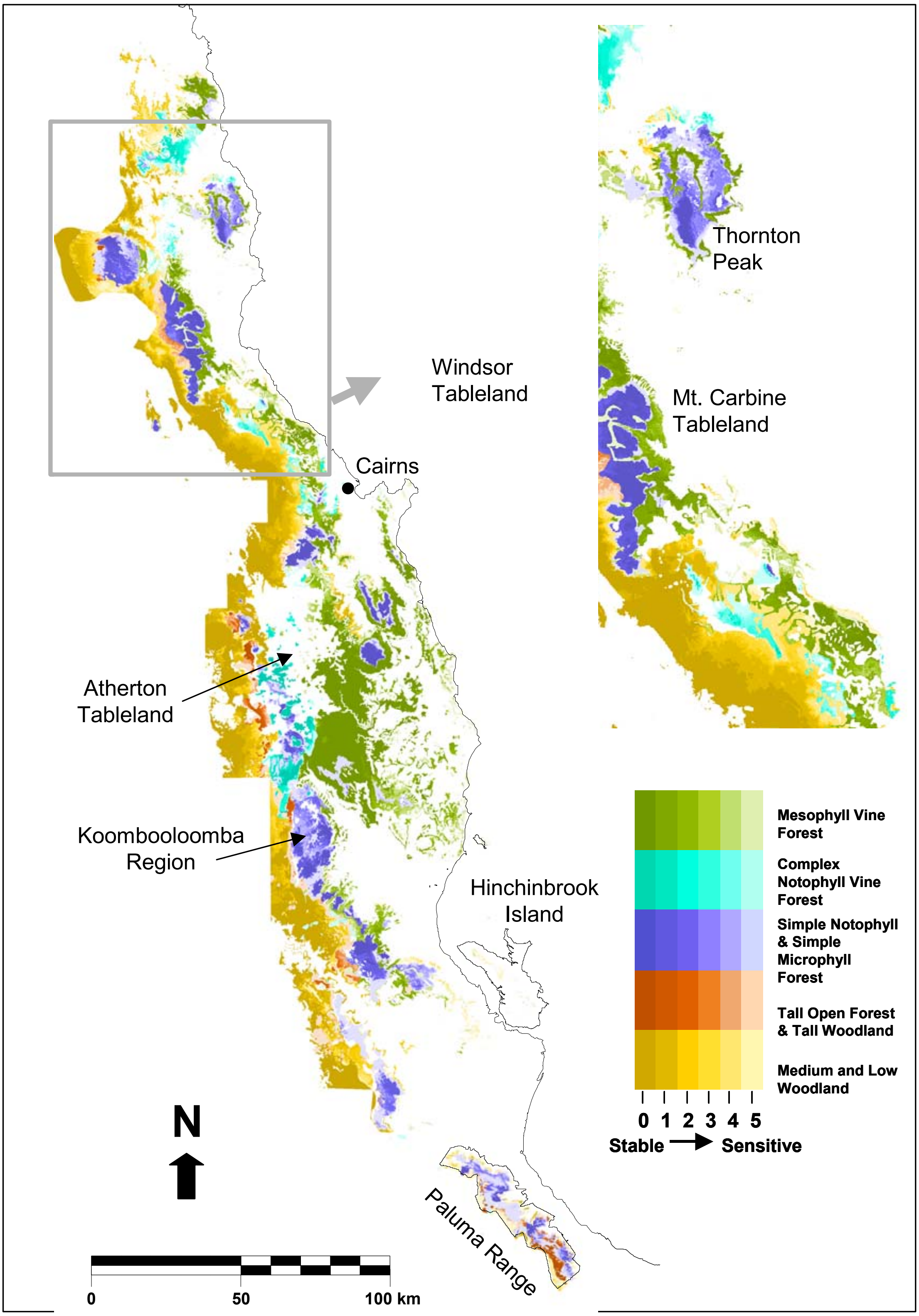


Figure 2.4. A map showing the sensitivity of different forest classes in north Queensland to climate change (for a 1°C warming). White areas are forest classes not included in the analysis. From DW Hilbert, N Ostendorf, MS Hopkins, "Sensitivity of tropical forests to climate change in the humid tropics of north Queensland", Austral Ecology (2001) Vol 26 (6) Dec: 590-603, Figure 6, reproduced with permission.

In general, modest increases in tree growth are likely in parts of the semi-arid tropics. However, over the monsoon tropics of far north Queensland, declines in growth rate of 25-50% are predicted due to the adverse effect of warming (Kirschbaum, 1999; see Fig. 2.5).

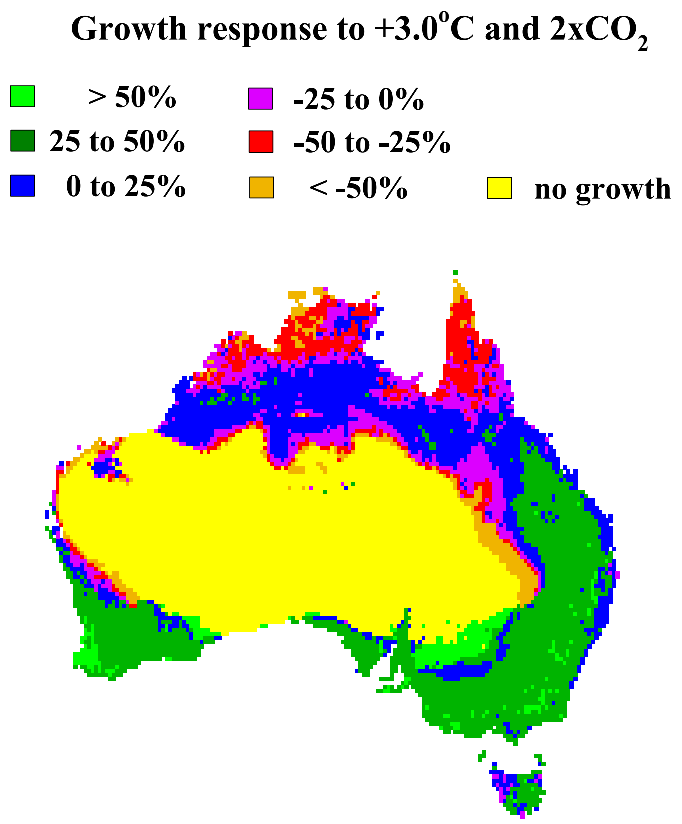


Figure 2.5. Growth response of forests to a doubling of carbon dioxide concentration to 700 ppm combined with a 3°C increase in temperature. From IAWG (2001).

2.3.5 Water resources and irrigation

There are some obvious implications of the predicted reduced soil moisture, including possible reduced runoff in some locations. A related study has recently been performed for the Macquarie catchment of Murray-Darling basin (Jones and Page, 2001). It was found that the most likely changes to mean annual Burrendong Dam storage, Macquarie Marsh inflows and irrigation allocations are 0% to –15% in 2030, and–5% to –35% in 2070.

Because of predicted sea level rise, water supplies in atolls and low-lying islands in the Torres Strait will be increasingly vulnerable to salt-water intrusion.

2.4 Future Water Quality in Moreton Bay (Milestone 2.4.4)

2.4.1 Introduction

An assessment has been performed of the possible impacts of climate change on the water quality of Moreton Bay in the year 2020. The results of this section will provide some insight for future water planning, particularly the South East Queensland Water Management Strategy being prepared by the Queensland Environmental Protection Agency and the Cooperative Research Centre for Coastal Zone, Estuary and Water Management. This assessment represents a preliminary analysis of the potential impact of climate change on water quality in Moreton Bay based on above average baseline conditions. Additional simulations using average and dry baseline conditions would provide a more detailed assessment but were unfortunately outside the scope of this report.

There is a comprehensive modelling system in place for simulating the water quality of Moreton Bay (Water Quality Modelling Unit, Queensland EPA, 1998a,b,c; see Fig. 2.6). This system employs a catchment model to simulate runoff, combined with a hydrodynamic, transport and water quality model to simulate the resulting effect on water quality in the Moreton Bay region. The hydrodynamic model is implemented on a variable-resolution mesh over Moreton Bay, comprising 5866 nodes and 2155 elements. The model runs on a time step of 15 minutes, with daily observations of environmental quantities interpolated to this time step and used as inputs to the model. Inputs include flows from river runoff, including nutrients such as nitrogen, and phosphorus, as well as suspended sediments; point source nutrients that mainly represent the outflow of sewage treatment plants; tidal variations; and time-varying observed quantities such as temperature, wind speed and wind direction. The model incorporates seasonal variability and simulates a number of different water quality constituents (including nitrogen, phosphorus, dissolved oxygen and suspended sediment).

The water quality formulation in the model is governed by a number of important factors. These include the biochemical oxygen demand, the concentrations of dissolved oxygen, organic nitrogen, ammonia, oxidised nitrogen, organic and inorganic phosphorus, the amount of chlorophyll-a (chl-a), the temperature and salinity, and the amount of suspended sediment. Of these variables, temperature and salinity are basic climate state parameters, or ones that are simulated by a climate model. Other basic state parameters that have effects on the above-mentioned model factors are runoff (which affects salinity), light, and wind (which influences water quality in specific locations through transport).

The modelling system has been extensively calibrated (Water Quality Modelling Unit, Queensland EPA, 1998a,b,c) and shows good agreement between observations and simulated results for most water quality constituents. Remaining model inaccuracies included the tendency of the catchment model to overestimate peak flows in wet years. Also, the hydrodynamic model is 2-D rather than 3-D, which usually should not be an issue in a well-mixed system such as Moreton Bay, but could cause some differences during extreme flow events. An improved sediment model may also improve the simulation of chl-a.

To construct a climate change scenario that would be appropriate for use in Moreton Bay, the sensitivity of the model variables to climatic variation was examined using a subset of parameters previously examined by the Queensland Waterways Scientific Services Group (Water Quality Modeling Unit, Queensland EPA, 1998a,b,c).

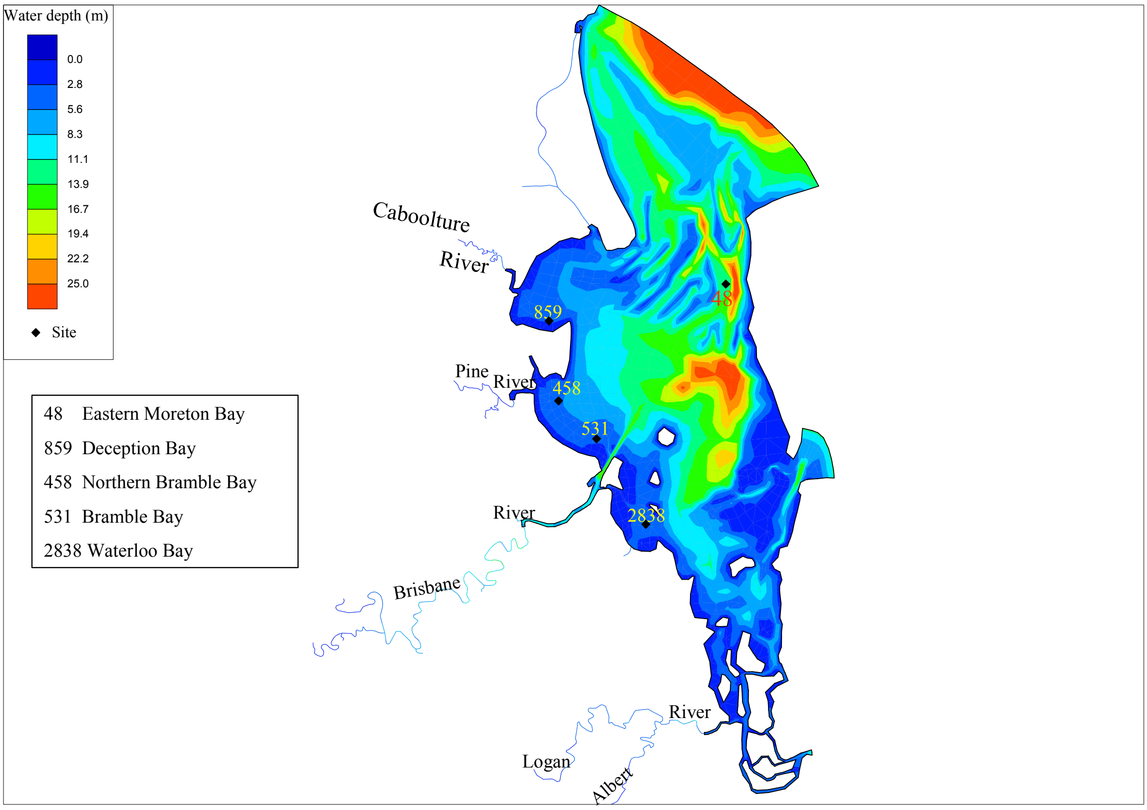


Figure 2.6. Map of Moreton Bay estuary and inflowing rivers. Numbers refer to locations in the analysis.

2.4.2 Temperature

Many variables in the water quality model are sensitive to changes in temperature. For example, one of the most important parameters for growth of phytoplankton, the maximum algal growth rate *G*, has a sensitivity to temperature *T* (in ^{o}C) modelled using a form of the Arrhenius equation, where

$$G \sim (T-20)^{a}$$

where *a* is a constant. Thus the algal growth rate increases strongly with increasing water temperature. Currently, temperature variations are included in the modelling system through an input file that contains a seasonal variation.

Projections of temperature change for Moreton Bay may be estimated from the climate change scenario results presented in Section 2.2. Based on CSIRO (2001), water temperature increases for the years around 2020 could range from about 0.5-1.2^{o}C over 1990 values. In the water quality simulations for 2020, the upper and lower temperature limits of the CSIRO (2001) range were added to the existing seasonal variation in the observed data, in order to maintain some degree of observed seasonal variability in the ocean and river temperatures.

2.4.3 Salinity

Salinity is a prognostic (predicted) variable in the model rather than a direct input. As temperature and runoff are key variables in determining salinity, changes made to these variables will produce variations in predicted salinity.

2.4.4 Runoff

Runoff is an output of the catchment modelling system and an input into the water quality modelling system. The actual climate change response of this variable is likely to be complex, as climate change would likely have different effects on the many different riverine systems that flow into the bay. However, a decrease in runoff is a likely consequence of climate change in many parts of Australia, particularly in south-east Queensland where projections indicate the probability of reduced rainfall by 2030 (e.g. Hassall and Associates, 1998; CSIRO, 2001). Because of a general decrease in soil moisture content in south-east Queensland predicted as a result of increased evaporation, runoff might also be predicted to decrease in this region. The magnitude and spatial variation of the runoff change would be difficult to determine without performing a specific runoff assessment of the catchment regions surrounding Moreton Bay under assumptions of climate change conditions, including increases in temperature and changes in rainfall.

Two possible impacts of runoff on water quality could occur. These impacts are governed by very different meteorological conditions. Intense rainfall events produce significant runoff and hence provide extra nutrients to the river system, causing pollutant indicators to increase. However, events causing sewage plumes may not be due to higher than normal runoff, although the extent of their penetration into the bay may be governed in part by the amount of runoff that occurs. Periods of reduced runoff could serve to lower the nutrient input into the river system and possibly reduce pollutant levels.

As a full spatial analysis of runoff was outside the scope of this study, an average value for runoff reduction in 2020 was calculated. Based on the CSIRO (2001) scenarios, a rainfall change of +5 to –10% was assumed. Previous studies (e.g. Hassall and Associates, 1998) using similar rainfall changes suggest decreases in environmental flows in the Murray-Darling basin of 12-32% by 2030. Therefore, for this study runoff was reduced by 20% in two of the climate change scenarios simulated.

2.4.5 Light

Some of the important variables in the water quality modeling system are sensitive to amounts of light received at the surface. Thus if a change in cloudiness occurred under climate change, the amount of light input at the surface would also change. There has been little work performed on constructing climate change scenarios of cloud amount. Given the current limitations of the simulation of clouds in GCMs, the light parameter was left unchanged.

2.4.6 Wind

Increased pollution events close to the coast are often associated with spells of onshore winds (Simon Bell, personal communication, 2002). Thus any substantial increase in the proportion of onshore winds in Moreton Bay may have an affect on the intensity of inshore sewage plume episodes.

Climate models have a reasonable simulation of wind patterns (Fig. 2.7), and thus it may be useful to construct a climate change scenario for wind patterns and use the changed winds to force the hydrodynamic component of the water quality model in the climate change simulations. At present, the hydrodynamic component uses observed wind speed and direction every three hours at three locations surrounding Moreton Bay, and interpolates between these observations to force the model. Nervertheless, the current climate simulations show close agreement over most of Australia with observations (Fig. 2.7), and climate change simulations do not exhibit significant changes in wind speed and direction for south-east Queensland (not shown). For this reason, wind speed and direction measured for 1999 remain unchanged in the climate change simulations.

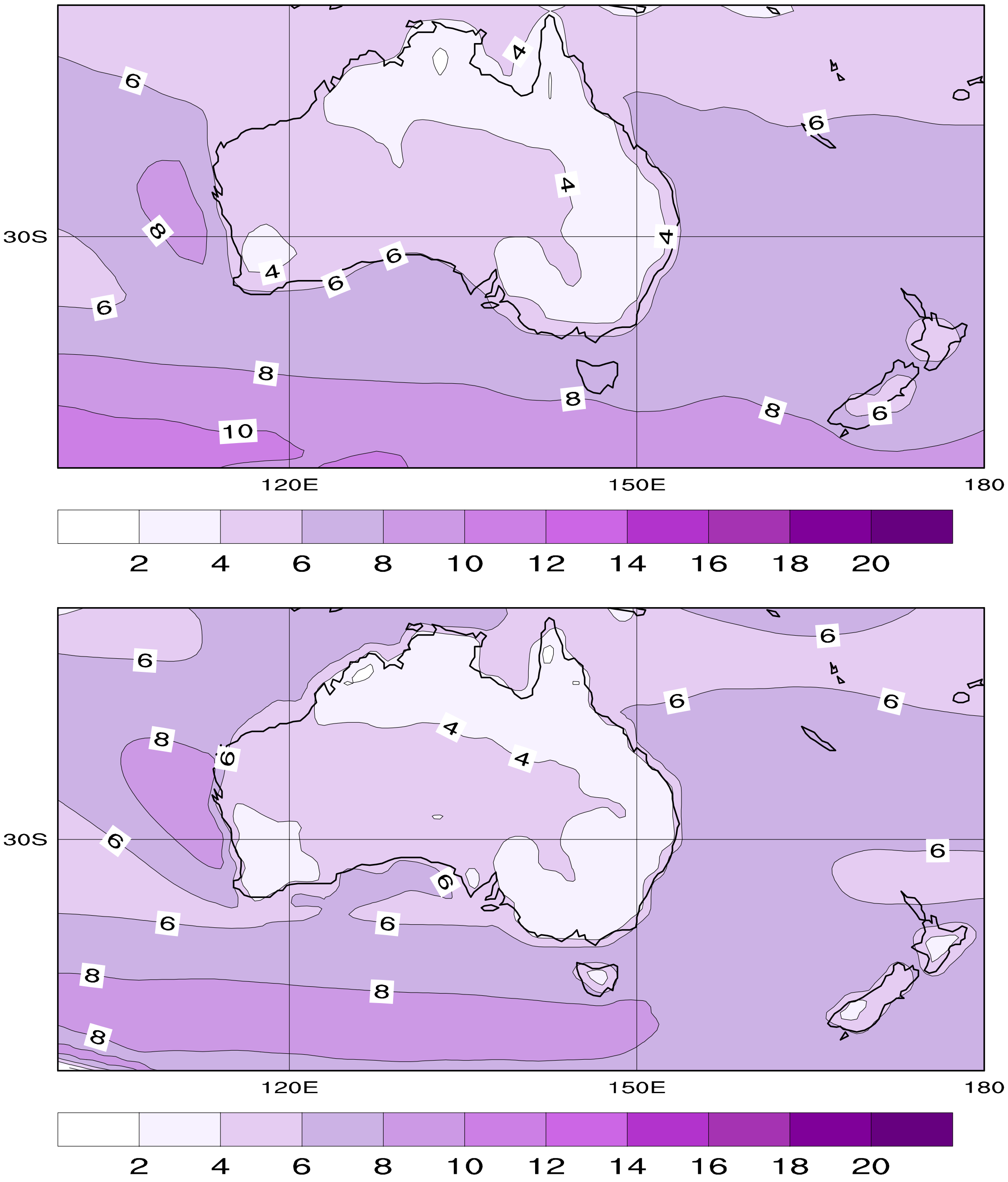


Figure 2.7. Mean December-February wind speed for (a) observations; (b) DARLAM climate model simulation.

2.4.7 Climate change sensitivity experiments

Four climate change experiments were performed using a modified 1999 baseline climate. In two experiments, average temperature was increased by 0.5 and 1.2 degrees Celsius respectively. In the other two experiments, runoff was reduced by 20% in addition to the increases in average temperature. The differences in the chlorophyll-a (chl-a) concentrations (a proxy for water quality i.e higher chl-a concentrations are associated with lower water quality) from the above simulations were then compared with the baseline 1999 run performed with unchanged climate conditions, at five locations in the Moreton Bay region (shown in Fig. 2.6). The year 1999 was chosen as a slightly above-average rainfall year.

Time series of the 20% reduced runoff simulations for the eastern Moreton Bay area show moderate increases in chl-a concentrations for most of the year, with increases mostly greater than those produced by temperature increases alone (Fig. 2.8). By August, simulated chl-a concentrations in all scenarios begin to decline rapidly. This may be a response to non-sustainable nutrient concentrations. By October, the simulated chl-a concentrations show substantial departures from the baseline concentrations. This may be caused by increases in sedimentation resulting from summer rains combined with very low nutrient concentrations. The reduced runoff, +0.5°C simulation gives the greatest reduction in chl-a concentration.

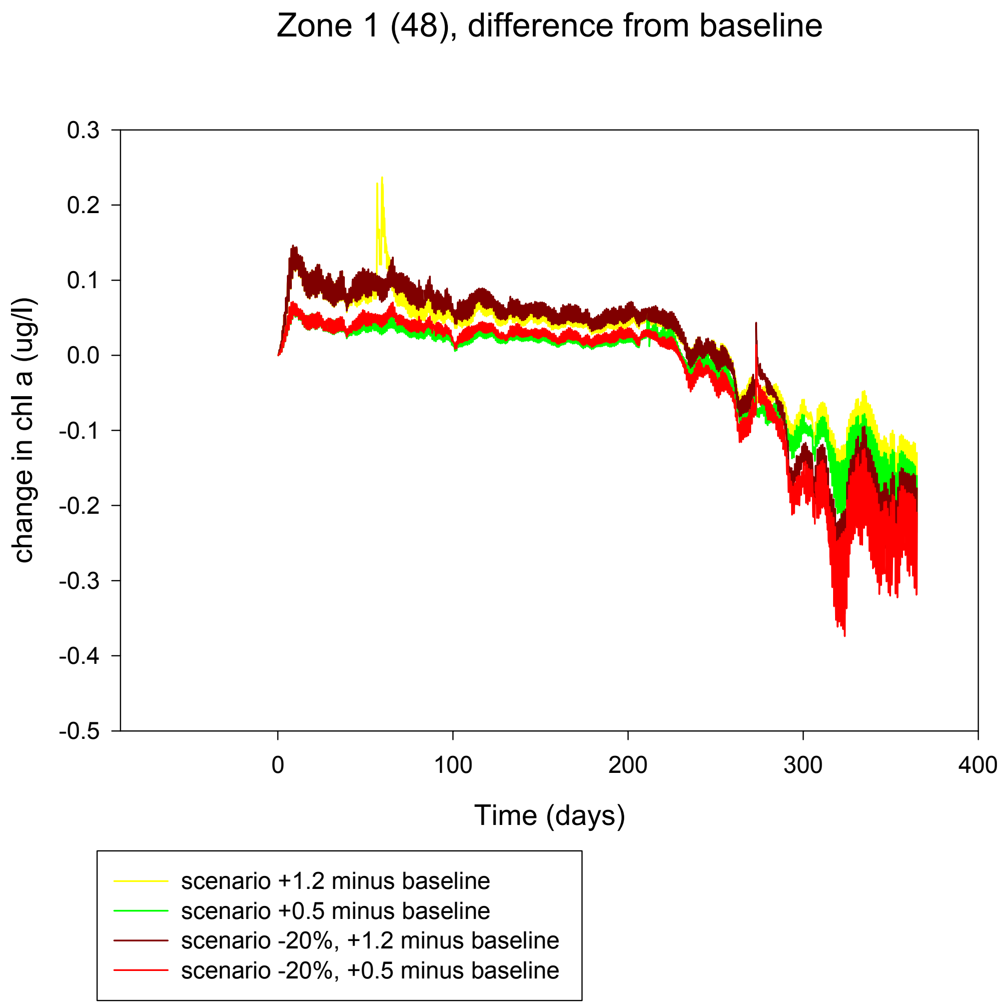


Figure 2.8. Chlorophyll-a concentration (in μg/l) for the difference of each scenario run from the baseline simulation.

In contrast, Fig. 2.9 shows the same results for a point close to the coast (458 on Fig. 2.6, near the outflow of the Pine River). Here, the concentrations trend upwards through the year, relative to the baseline. Additional changes in runoff appear to have little impact on the chl-a concentrations except for isolated events where larger reductions in chl-a concentrations occur (Fig. 2.10). The impact of increased temperature clearly causes increased concentrations of chl-a in this area. The difference in response between eastern Moreton Bay (48) and northern Bramble Bay is a function of the bottom topography and proximity to a river system. In northern Bramble Bay, the ocean depth is small (0 to 2.8 m). Thus in this location small increases in ocean temperature encourage chl-a growth throughout the entire depth.

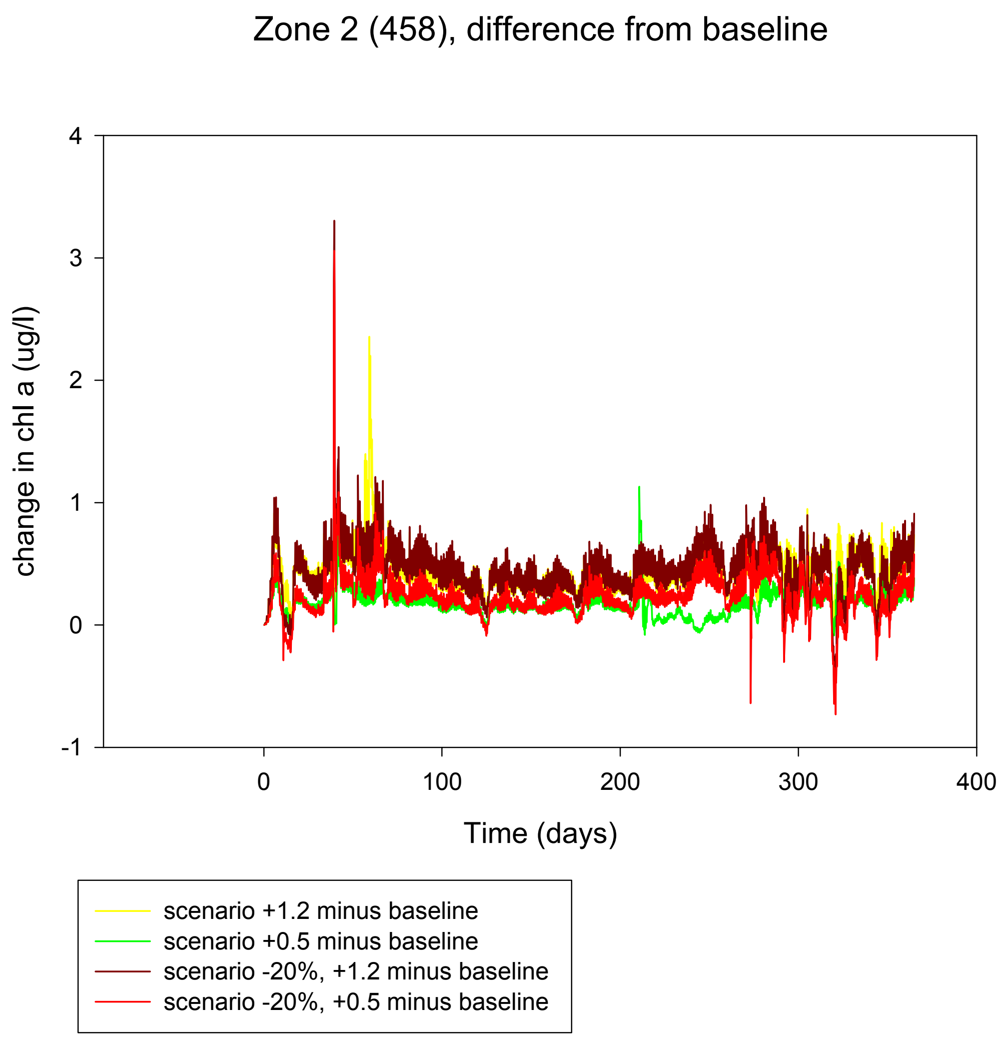


Figure 2.9. Same as Fig. 2.8, but for point 458.

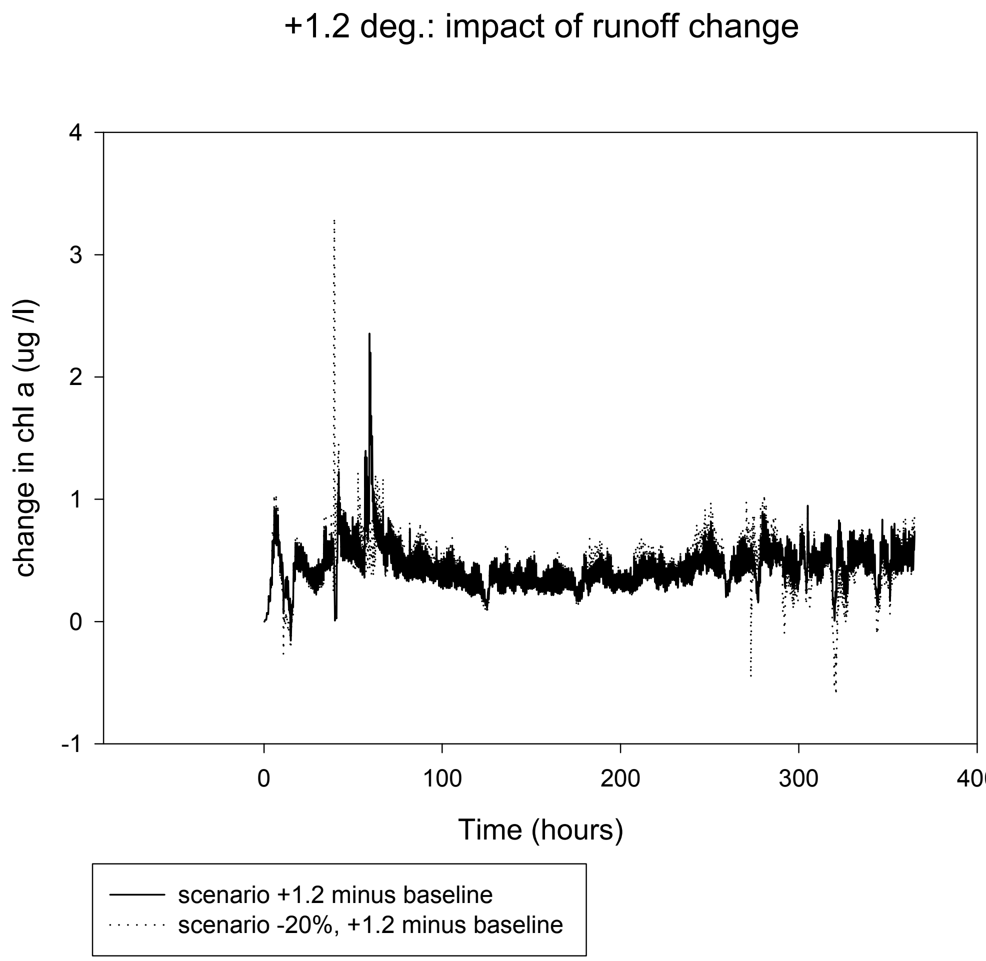


Figure 2.10. Same as Fig. 2.9 but impact of change in runoff for +1.2 degree Celsius temperature increase.

Simulations for other locations give somewhat different results. For point 531, near the outflow of the Brisbane River (Fig. 2.11), there is initially an increase in chl-a concentration for all scenarios, compared with the baseline run. Of particular note is a "spike" near day 70 (in early to mid-March) in the run where only temperature was changed by +1.2 degrees. The cause of this is currently under investigation, and also occurs at Deception Bay and Waterloo Bay (not shown).

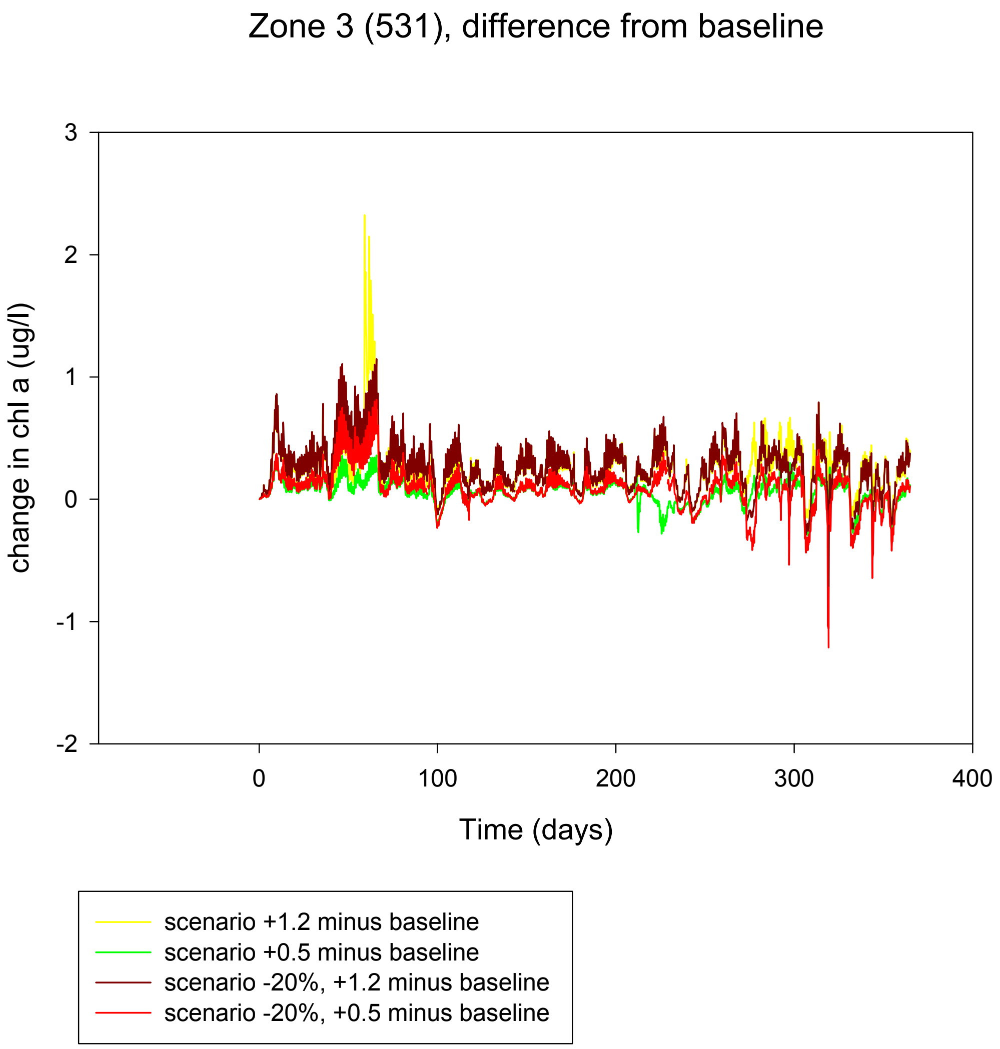


Figure 2.11. Same as Fig. 2.8 but for point 531, Bramble Bay.

By decreasing the runoff in the Bramble Bay area, reductions in concentration are produced by the end of the year. As in the northern Bramble Bay area, temperature increases cause higher concentrations of chl-a. The two effects tend to compete with each other here, however, with highest chl-a concentrations associated with temperature increases and lower values associated with reduced runoff. For this reason the scenario with the greatest temperature increase is associated with slight increases in chl-a whereas the smallest temperature increment (+0.5 degrees) and reduced runoff is associated with lowest chl-a concentrations. The 1.2 degrees and 20% reduction in runoff scenario would appear to produce chl-a concentrations above the 0.5 degree temperature increase scenario. This again demonstrates the importance of temperature effects with heightened temperatures overriding the effect of reduced runoff.

The seasonal variation in concentration can be grasped from horizontal plots of the chl-a concentration. Fig. 2.12 shows results for summer conditions. Concentrations are highest close to the coast and decrease out into the Bay. The sensitivity studies in general showed that increased temperature tended to increase chl-a concentration and decreased runoff decreased it. Thus maximum chl-a concentrations might be simulated by increasing only the temperature by 1.2 degrees, and lowest chl-a concentrations by increasing the temperature by 0.5 degrees and decreasing the runoff by 20%. Results from these two scenarios are compared to the baseline results in Fig. 2.12. There is a systematic downward trend in concentration in the eastern parts of Moreton Bay in both scenario runs compared with the baseline, as mentioned earlier. Chl-a concentrations are rather similar in both climate change scenarios. Winter conditions show much lower concentrations (Fig. 2.13). There appears to be little overall sensitivity to climate change scenarios in winter, although small changes in concentrations are evident at some locations.

In summary, there is some simulated sensitivity of chl-a concentrations in Moreton Bay to imposed changes in climate. Temperature increases usually increase concentrations, whereas runoff decreases generally lower them. From this analysis temperature change seems to produce greater variations than reduced runoff, so future temperature change will play an important role in determining Moreton Bay water quality. However, the response is not the same at all locations: some locations show a general downward trend in concentrations for all scenarios during the simulated year relative to the baseline simulation, while other locations show an upwards trend. The cause of these trends needs to be investigated. In addition, other years need to be simulated before a comprehensive evaluation of these results can be attempted.

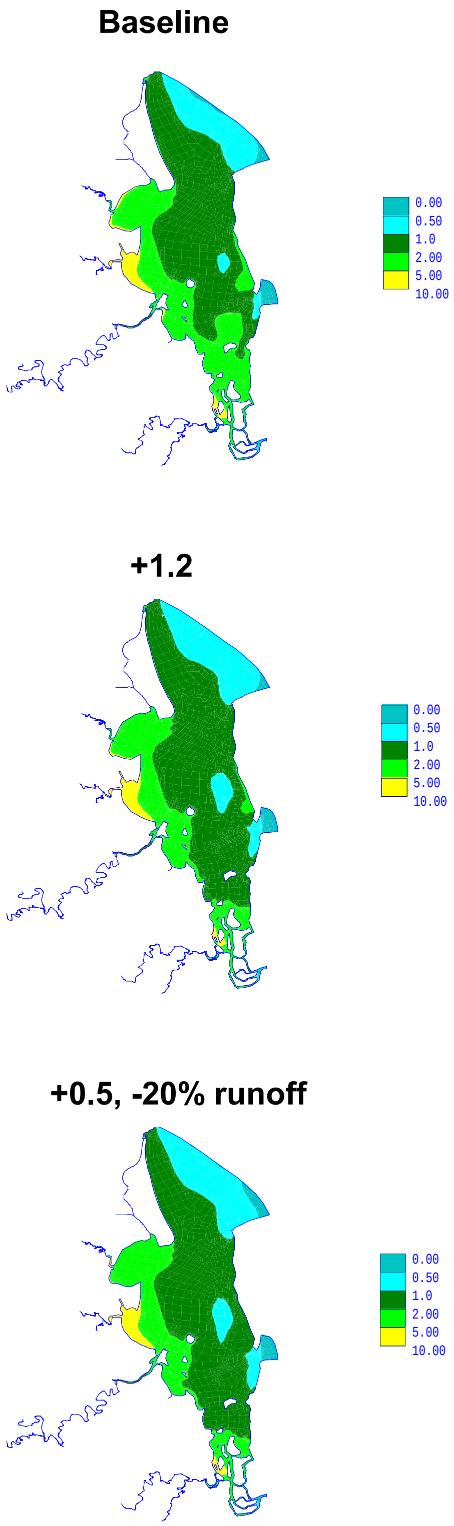


Figure 2.12. Chl-a concentration (µg/l) in Moreton Bay for summer conditions. Variable contour interval.

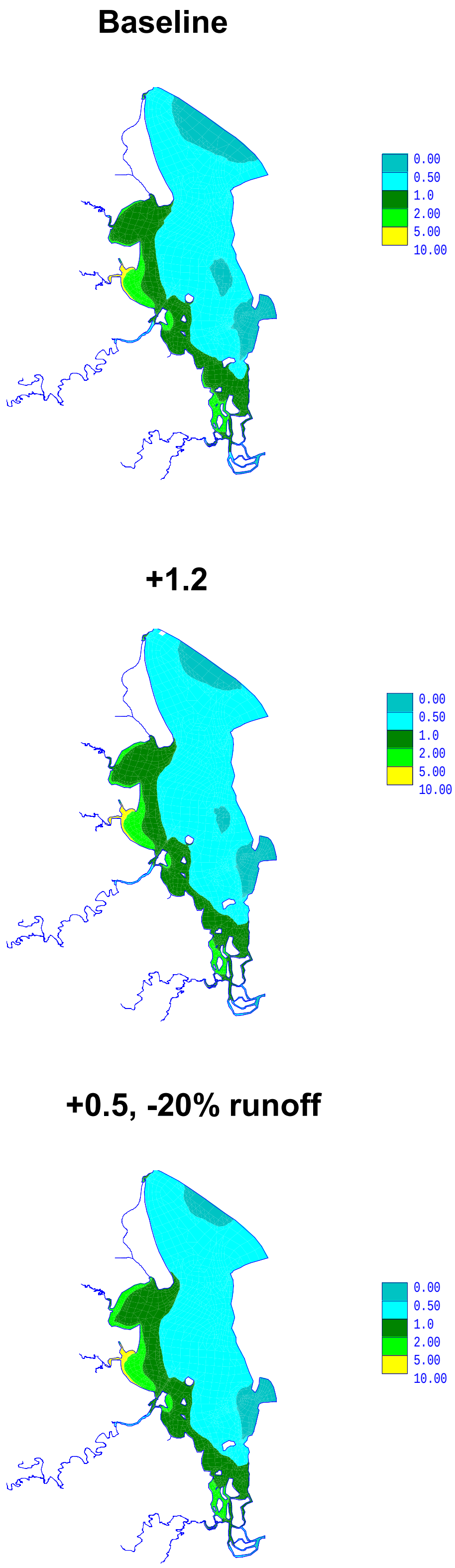


Figure 2.13. The same as Fig. 2.12 but for winter conditions.

2.5 Climate Change and Water Supply in the Burnett River Catchment (Milestone 2.4.4)

2.5.1 Introduction

In this Section, we report on potential changes in mean annual flows for the Burnett catchment expected from climate change in 2030. These results were produced by coupling OzClim, the Australian climate scenario generator, to the river management model used to plan and allocate water resources in the Burnett catchment. This study builds on previous research undertaken for Queensland including the development of scenarios for potential evaporation (Ep) reported in Walsh et al. (2000, 2001).

The Burnett River catchment (Fig. 2.14) covers 33,000 km^2 and rises in the Great Dividing Ranges near Kingaroy extending some 400 km east towards the coast, and flowing into the sea at Burnett Heads. The catchment contains 7 dams and 26 weirs with a total storage capacity of 1,269,440 ML, fed by a nominal supply of 319,385 ML/year (a storage/inflow ratio of 4:1). About 70–75% of water use is for irrigated agriculture, with urban water demand currently exceeding allocations and growing at 900 ML/year. In the Burnett catchment area the 1990s represented a period of stress due to drought impacting on available water resources. Planning options for the future are detailed in Burnett Catchment's Water Allocation and Management Plan (WAMP), which establishes the principles for environmental flows of the catchment and includes an improved specification of existing licences and allowance for transferable water allocations, as well as protecting the rights of existing water users and identifying the potential for further infrastructure development. The possible impacts of climate change have not been dealt with in detail by this process.

2.5.2 Model and Methodology

The OzClim climate scenario generator was coupled with the Integrated Quality Quantity Model (IQQM) for the Burnett River catchment to estimate possible changes in streamflow by 2030. The Burnett IQQM was constructed by the Queensland Department of Natural Resources and Mines (QDNRM) to develop and test management strategies for the Burnett WAMP.

The IQQM is a hydrologic modelling tool developed by the New South Wales Department of Land and Water Conservation (DLWC, 1995a) for planning and evaluating water resource management policies. The model is currently applied to rivers in both NSW and Queensland. IQQM operates at a daily time step and can be used to simulate river system flows for periods up to hundreds of years (DLWC, 2000). The key component of the model is the quantity module, which routes water down a river system subject to tributary inflows, losses to irrigation and other extractions. Water allocation rules are built into the model and are catchment-specific. IQQM also uses the Sacramento rainfall-runoff model to generate daily streamflows in each of the tributary subcatchments.

The Sacramento model (Burnash et al., 1984) is a lumped parameter rainfall-runoff model. Modelled runoff for each subcatchment in the Burnett has been calibrated with actual streamflow data from gauged stream segments by QDNRM. The Sacramento model requires daily rainfall and point potential or A-Class pan evaporation data. Monthly evaporation coefficients are specified for each IQQM sub-catchment to convert point potential evaporation data contained in the input data file to areal potential evaporation. The IQQM was used, in this project, as constructed by QDNRM without changing any of the parameters in the Sacramento model.

The input data are 1890–1996 historical daily values for P and Ep for each subcatchment, with the routing and management modules simulating the operation of modern infrastructure and allocation rules. There are five sub-models for different reaches, each with several subcatchments. Each subcatchment has a separate input climate file. OzClim initially rescales these input records of daily rainfall and potential evaporation using monthly patterns of P and Ep from seven climate models (Table 2.1) before running IQQM. These state-of-the-art models were chosen because of the quality of their simulations and the availability of their output data. IQQM is run in batch mode from OzClim, so multiple scenarios can be generated. The results produced are end of system flows in the Burnett River expressed in terms of changes to mean annual flow. After coupling the system, it was tested using a scenario based on current climate, which was found to produce the same output as obtained by DNRM hydrologists.

***Table 2.1**. Model runs used to produce the regional scenarios used to drive OZCLIM.*

Centre	Model	Emission Scenario	Features	Years
CSIRO, Australia[1]	Mk2	IS92a equivalent CO_2	No sulphates, GM ocean	1881–2100
CSIRO, Australia[2]	DARLAM 125 km	IS92a equivalent CO_2	Nested in CSIRO Mk2	1961–2100
DKRZ, Germany[3]	ECHAM4/OPYC3	IS92a	No sulphates	1860–2099
DKRZ, Germany[3]	ECHAM3/LSG	IS92a	No sulphates	1880–2085
Hadley Centre, UK[4]	HADCM2	1% CO_2 pa	No sulphates	1861–2100
Canadian CCMA[5]	CGCM1	1% CO_2 pa	No sulphates	1900–2100
NCAR USA[6]	DOE-PCM	IS92a	No sulphates	1960-2099

[1]Gordon and O'Farrell (1997)
[2]McGregor and Katzfey (1998)
[3]DKRZ-Model User Support Group (1992), Oberhuber (1992), Maier-Reimer and Mikolajewicz (1991)
[4]Johns et al. (1997)
[5]Flato et al. (2000)
[6]Washington et al. (2000)

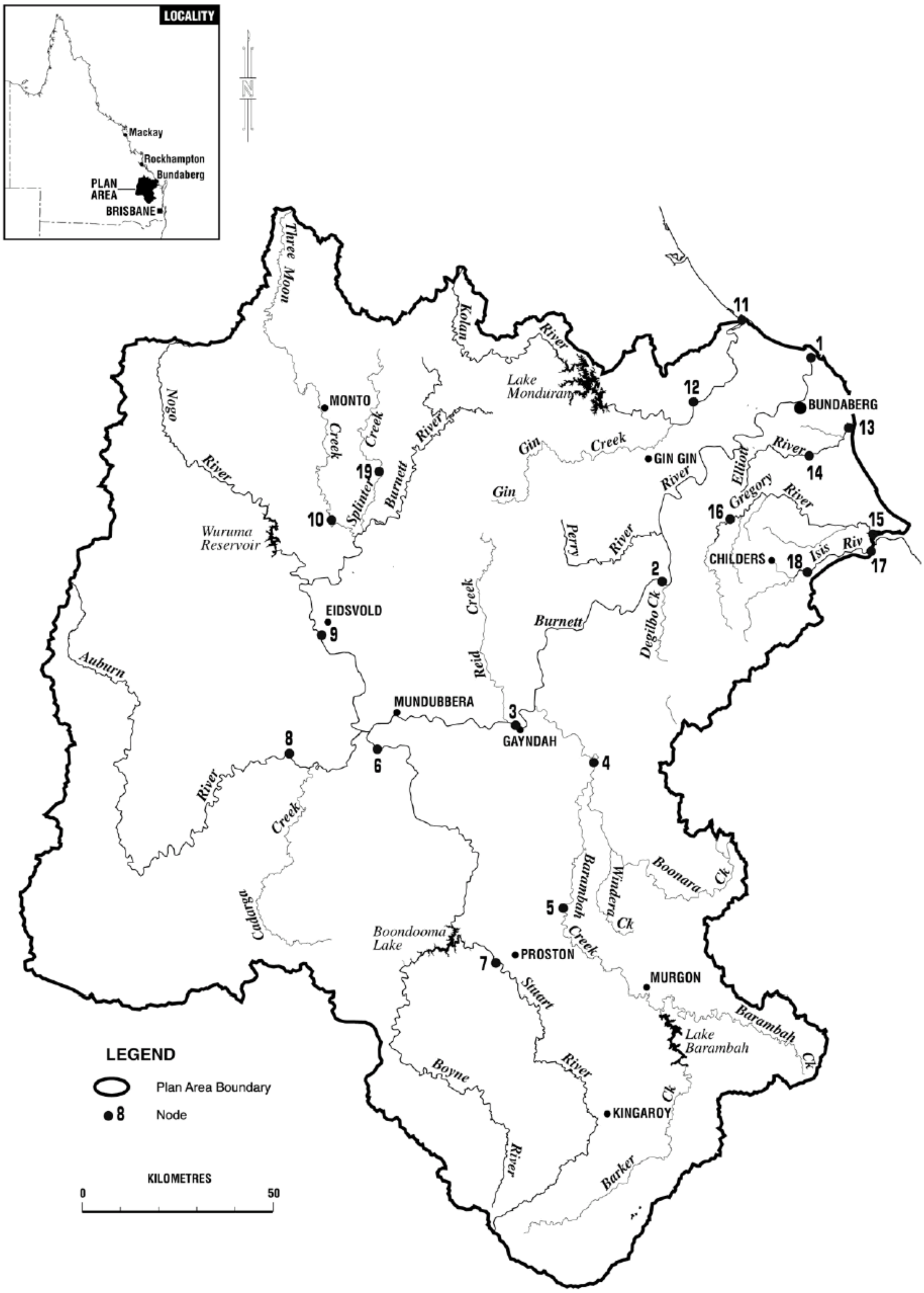


Figure 2.14. Map of Burnett catchment plan area.

Monthly P and Ep change patterns from each of the seven climate models were calculated and scaled to represent local change per degree of global warming. The technique of pattern scaling removes the global warming signal from each model grid point, converting GCM output into local change per degree of global warming. This allows a much greater range of uncertainty to be sampled, allowing the investigation of a multitude of warming pathways, compared with the limited range of emissions scenarios shown in Table 2.1. The method used here is to regress the change for P and Ep in each grid cell against global warming to determine local change per degree of global warming in terms of percent change (Whetton et al., 2001). This procedure eliminates the individual climate sensitivities of different GCMs, allowing the comparison of regional patterns from those models and the subsequent construction of projected ranges of regional change utilising the full range of projected global warming. The scenario construction techniques used here are described in detail in IPCC-TGCIA (1999), and Mearns and Hulme (2001). This method of pattern scaling has been investigated by Mitchell (in press), who showed it to be suitable for the uses described here.

Each scenario is calculated by multiplying a scaled model pattern by a global warming scenario, created from a greenhouse emission scenario and value of climate sensitivity (the temperature response of the atmosphere to an increase in greenhouse gas concentrations). A total of 28 scenarios were run based on four scenarios of global warming (SRES B1 low sensitivity, giving a global warming of 0.55°C; SRES A1 mid sensitivity at 0.85 °C; SRES A2 high sensitivity at 0.90°C; and B2 mid sensitivity at 0.93°C) for each of the seven models listed in Table 2.1.

2.5.3 Results

Figure 2.15 shows changes to rainfall and potential evaporation over the Burnett River catchment in terms of change per degree of global warming. Rainfall changes are biased towards increases during the mid to late wet season (summer–autumn) and decreases in the late dry – early wet season (winter–spring). Annual changes per degree of global warming are shown in Table 2.2. The Hadley Centre model HADCM3 is the driest, losing 5% of rainfall per degree of global warming, and the German ECHAM4 model is the wettest gaining 3.7% per degree.

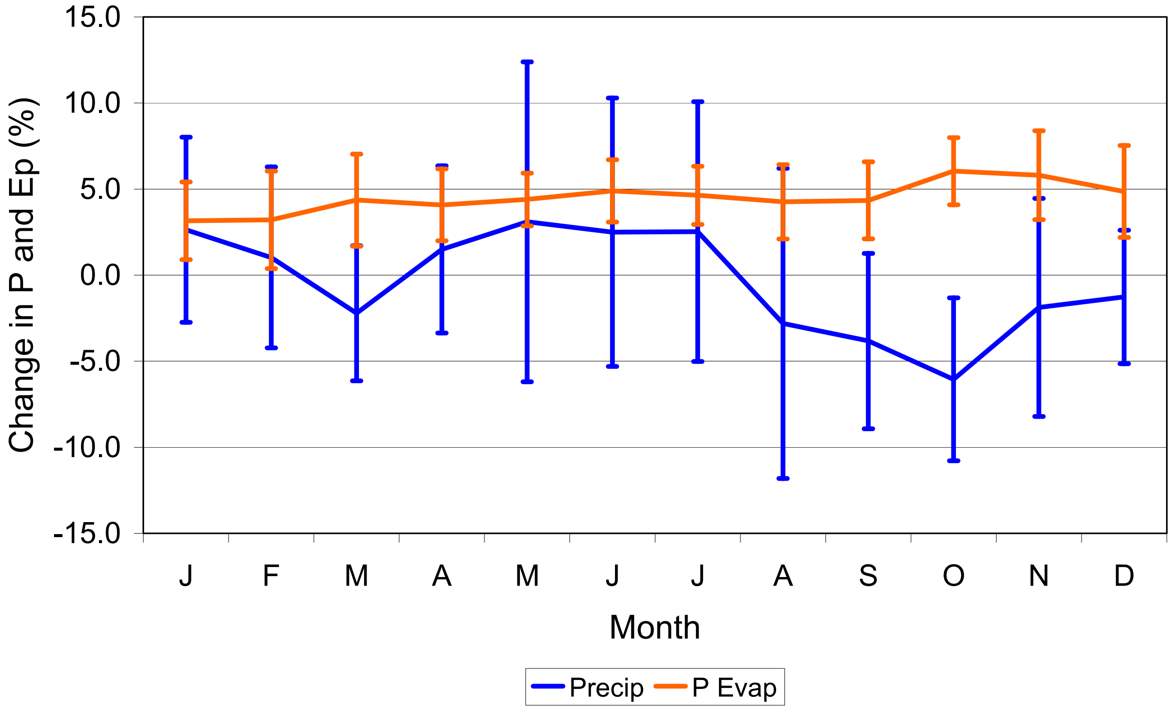


Figure 2.15. Monthly precipitation and potential evaporation changes over the Burnett River catchment in terms of change per degree of global warming from a suite of seven climate models (see Table 2.1), showing one standard deviation either side.

***Table 2.2**. Average annual change for precipitation and potential evaporation from the seven climate models in Table 2.1, in percentage change per degree of global warming. Based on the 1960–1989 climatology for the Burnett catchment from OzClim.*

Model	Precip	P. Evap
CSIRO Mk2	-3.6	5.8
CCM1	-2.7	4.6
DARLAM	2.0	5.0
ECHAM3	1.2	3.3
HADCM3	-5.0	7.6
ECHAM4	3.7	1.9
NCAR-DOE	2.4	3.3

The width of the bars in Figure 2.15, representing the uncertainties between models, shows that uncertainty over rainfall increases is larger than the uncertainty surrounding decreases. During the months where the average rainfall shows an increase, the bars of one standard deviation width straddle both positive and negative outcomes, whereas a reduction in rainfall in September to November appears more likely. This is consistent with the results for the rest of Australia, where summer and autumn rainfall changes are dominated by either increases or large uncertainties (see Section 2.2). Potential evaporation increases in all seasons and shows an inverse relationship with rainfall. The consistent increases in Ep are a response to global warming and the rate of increase is influenced by variations in cloud cover, radiation and atmospheric moisture content accompanying simulate rainfall changes. Where rainfall decreases, the increases in Ep tend to be larger. This relationship was presented and discussed in last year's report (Walsh et al., 2001).

Table 2.3 shows the projected range of changes in mean annual end-of-system flows as a function of global warming. Both increases and decreases in flow are possible, although there is a slight bias towards increase with the suite of climate models used here. The increases in ECHAM4 model are driven by significant increases in simulated summer rainfall. The rainfall simulations of the CSIRO Mk2, HADCM3 and CCM1 models are all dominated by decreases, with the CCM1 model showing some increase in autumn. The other three models produce slight increases in mean flows, although their seasonal changes are not consistent with each other. Figure 2.16 reproduces the results in Table 2.3 showing how the range of change increases with global warming.

Table 2.3. *Results from the 28 simulations, showing changes in mean annual end-of-system flows, in percent change from the baseline mean.*

Model	Global Warming (°C)			
	0.55	0.85	0.90	0.93
CSIRO Mk2	-8.1	-12.8	-13.3	-14.2
CCM1	-7.4	-11.9	-12.2	-12.3
DARLAM	1.8	3.1	4.0	4.3
ECHAM3	2.0	2.6	4.0	4.1
HADCM3	-8.6	-13.6	-14.0	-14.4
ECHAM4	8.8	14.3	16.5	16.5
NCAR-DOE	2.8	5.4	6.4	6.3

The range of global warming in 2030 according to the IPCC (2001) is 0.55 to 1.25°C (rounded to the nearest 0.05°C). Although the direction of annual rainfall change remains unpredictable, the magnitude of change will increase with global warming. If the relationship between global warming and change in mean annual flow shown in Figure 2.6 is extended to 1.25°C then the maximum change possible is ±20%.

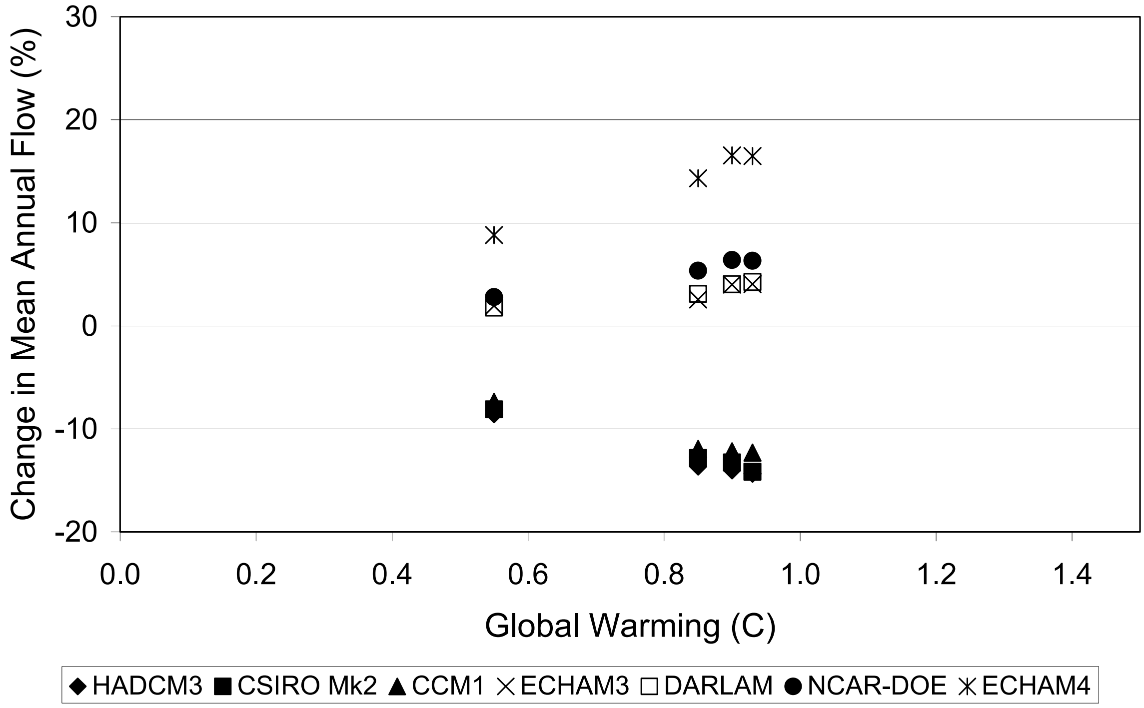


Figure 2.16. Changes in mean annual flow from seven climate models shown as a function of global warming.

2.5.4 Discussion and Conclusion

Using similar techniques, results obtained from southern catchments, the Macquarie River in NSW (Jones et al., 2001; Jones and Page, 2001) and Ryan's Creek in Victoria (Maheepala et al., 2001), show that simulated changes in flow in a warmer world are overwhelmingly negative. These reductions are due to the robust decreases in rainfall simulated by climate models in late winter-spring, affecting the winter-spring dominated flows of southern Australia. In contrast, the changes in the Burnett catchment are a reflection of the increasing summer rainfall dominance towards the north of the country, combined with significant summer rainfall increases in the climate models named above.

Analyses for the Macquarie catchment show that the direction and magnitude of rainfall change explains almost two-thirds of the total uncertainty of the results, with global warming explaining one quarter and changes in Ep about one-eighth (Jones and Page, 2001). Given the range of changes per degree of global warming is similar to those used here, these proportions of uncertainty would be similar for the Burnett River simulations. Although the direction of mean flow changes remains unclear, the most critical period is December to April. If rainfall increases during this period and decreases at other times are limited, then current flows are likely to be maintained or enhanced. If rainfall remains constant or decreases during this period then flows will decrease. Rainfall decreases in the period August through November seem likely, because they occur in almost all models examined, so compensating increases in summer rainfall will be needed to maintain annual flow rates.

There are a number of caveats that apply to this work. The major changes taken into account are changes in mean P and Ep applied to coupled rainfall-runoff, river routing and management models that have been optimised to operate under historical climate. Lumped parameter rainfall-runoff models have the advantage of being robust under current climate. A major advantage of applying a model developed and operated by the managing authority of a catchment is that they understand its strengths and weaknesses, aiding in the interpretation of the results. The disadvantages are that the parameterisation of such models assumes constant relationships for factors such as land-use change, soil-water relationships and plant water-use relationships. Lumped parameter rainfall-runoff models have limited testing under climate change, and the only study that we are aware of produced substantial differences in results from model to model (Boorman and Sefton, 1997). However, the results here are based on changes from a number of climate models and have produced consistent results in three states utilising two different rainfall-runoff models.

We believe that the changes to P and Ep are the most important inputs for estimating change and that for 2030, most other plausible changes affecting water supply are likely to be less important unless there is significant modification of the catchment. The uncertainty surrounding changes to P and Ep under climate change is likely to be much larger than the internal catchment response to P and Ep change. Other factors that may need to be assessed are changes in the water-use efficiency of vegetation under higher CO_2 altering transpiration and runoff and possible changes in climate variability. Such changes can be investigated with more physically explicit models but they are resource intensive and cannot typically incorporate large ranges of input uncertainty, so the lumped parameter rainfall-runoff model remains the most suitable method for the moment.

Possible changes to three important aspects of rainfall variability were not accounted for in these simulations: daily, interannual and decadal-scale variability. By scaling historical rainfall, its variability is assumed constant. Daily variability is likely to change, with increases in rainfall intensity being simulated by most models under increasing, constant or even slightly decreasing mean rainfall. At present, we are investigating ways to incorporate such changes probabilistically, but they are not yet operational. Interannual rainfall changes are largely dependent on how ENSO behaves in future. GCM simulations show that ENSO continues to oscillate under greenhouse conditions of climate change but also show wide variations in its possible behaviour. The null position is that Australia's interannual climate variability will remain high. By utilising long (>100 years) historical climate records, a wide range of existing variability can be examined, and it would be possible to use our results to investigate flood and drought behaviour.

Decadal-scale variability can produce significant swings in mean annual streamflow and streamflow variability. Historical rainfall changes for the Macquarie catchment produced swings in streamflow of greater then 20% from the long-term mean in the Macquarie IQQM (Jones et al., 2001). Jones et al. (2001), and Jones and Page (2001) conclude the central issue for the long-term planning of water resources is the combination of decadal-scale rainfall change and P and Ep change due to climate change. Unfortunately, our knowledge of the dynamics of long-term climate variability is scant and we are unable to predict its behaviour. It is possible though, to assess the risk of exceeding critical thresholds under various combinations of climate change and known current decadal variability (Jones and Page, 2001).

The purpose of this exercise has been to show that by coupling OzClim and IQQM and investigating the full range of mean P and Ep changes expected under climate change, we can narrow down the ranges of uncertainty for future hydrological change. Further work may shed more light on the distribution of risk throughout the ranges of climate change projected for the Burnett catchment, similar to the assessment carried out for the Macquarie catchment. However, we believe risk assessments should be carried out in collaboration with the managing authority as stakeholder involvement is an important part of such studies. Process studies may also shed more light on whether the wet season on the east coast is likely to be enhanced or reduced under climate change, and the long-term rainfall variability is likely to affect Queensland in the future.

In summary, the current uncertainty in projected summer rainfall changes in the Burnett do not make it possible to determine definitively the future direction of changes in end-of-system runoff in the Burnett catchment.

3 Simulation of Climate Change by the CSIRO Mark 3 GCM (Milestone 2.4.3)

3.1 Evaluation of current climate simulation of the CSIRO Mark 3 GCM

The climate impact studies described in the previous section rely upon the results of climate model simulations. This section discusses progress on the development of a significantly improved climate model, the CSIRO Mark 3 global climate model (GCM).

The Mark 3 GCM represents a considerable improvement on its predecessor, Mark 2 (Gordon and O'Farrell, 1997). Most importantly, Mark 3 gives a greatly improved simulation of El Niño/ Southern Oscillation (ENSO) variations. The size of the ENSO variations in Mark 3 is comparable to those observed in reality, whereas in the Mark 2 GCM they were only about a third as large. Since one of the crucial unresolved questions regarding the effect of climate change on Queensland is exactly how climate change will affect ENSO, it is important that a state-of-the-art climate model has a good simulation both of Queensland rainfall and its year-to-year variability associated with ENSO. Both Mark 2 and Mark 3 are coupled ocean-atmosphere models that produce ENSO variations as part of their internal dynamics.

In general, the simulation of climate variables by the CSIRO Mark 3 GCM is very good; in particular, there is a realistic simulation of the observed annual cycle of Queensland rainfall. Given the importance of the ability of the CSIRO Mark 3 GCM to simulate Queensland rainfall, this discussion focusses on this variable.

The Mark 3 simulations reported here have an approximate horizontal resolution of 200 km and a model climatology was calculated over a 30-year period. Maps of the Australian rainfall climatology of the Mark 3 model are shown in Fig. 3.1. Comparison of the observed Australian rainfall patterns to those simulated suggests generally good agreement, with some exceptions. Over Queensland for January-March, the model captures the observed north-south gradient of rainfall well above 25º south, while below 25º south and west of 145º east (central and southern Australia) rainfall is under-simulated. For April-June, there is generally good agreement in both the pattern and magnitude of rainfall over Queensland, although coastal rainfall is under-estimated. For July-September, the seasonally dry observed rainfall conditions are simulated, although simulated south-east Queensland rainfall is under-estimated. Finally, for October-December, while rainfall is underestimated in northern coastal Queensland, there is a good simulation of rainfall in the interior.

The seasonal cycle of rainfall averaged over all of Queensland is particularly well simulated as shown in Fig. 3.2. There is an excellent representation of the observed seasonal cycle, although the model somewhat underestimates rainfall over most of the year.

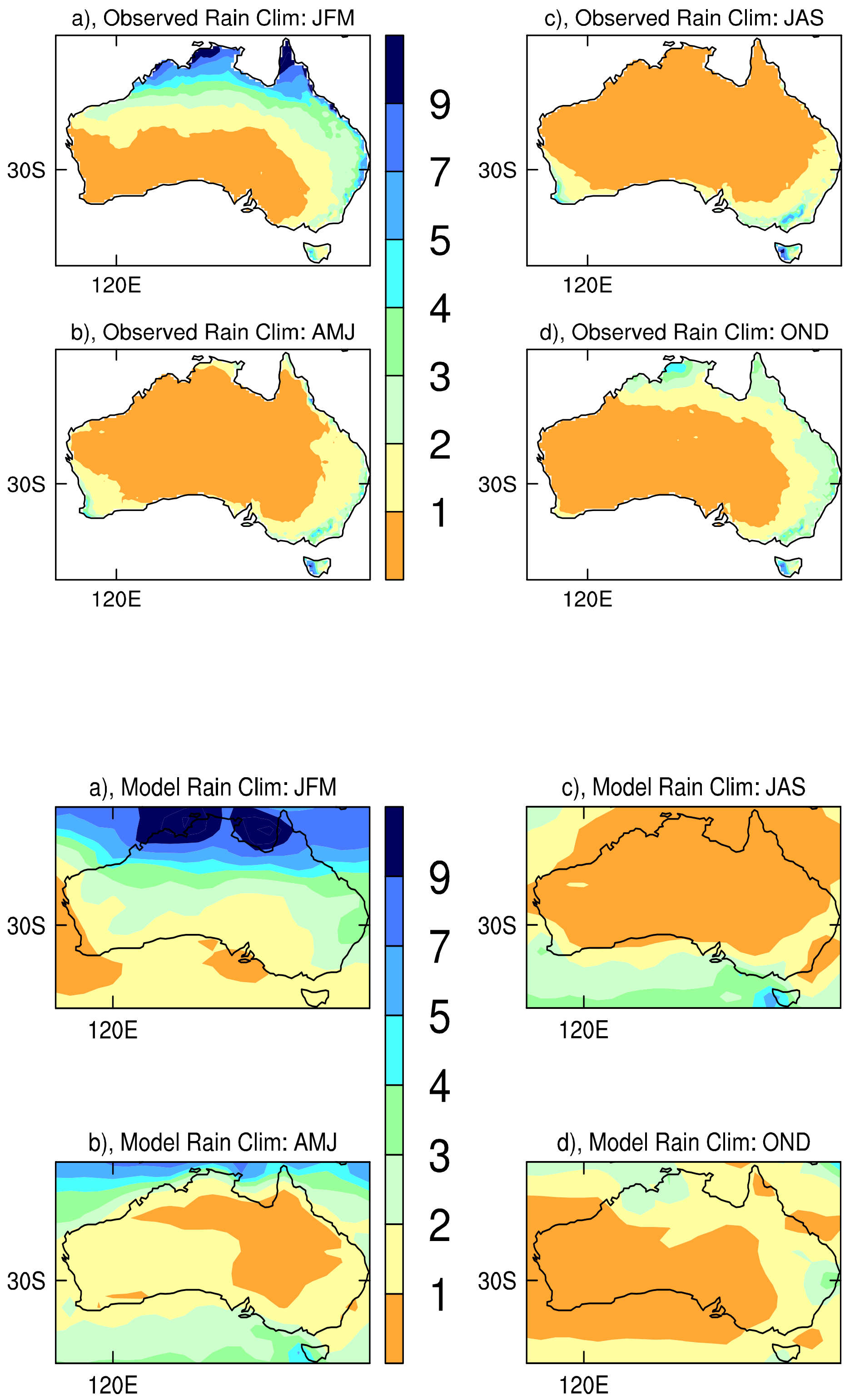


Figure 3.1. (top) Observed seasonal rainfall over Queensland; (bottom) simulated seasonal rainfall from CSIRO Mark 3 GCM. Observations from Jeffrey et al. (2001).

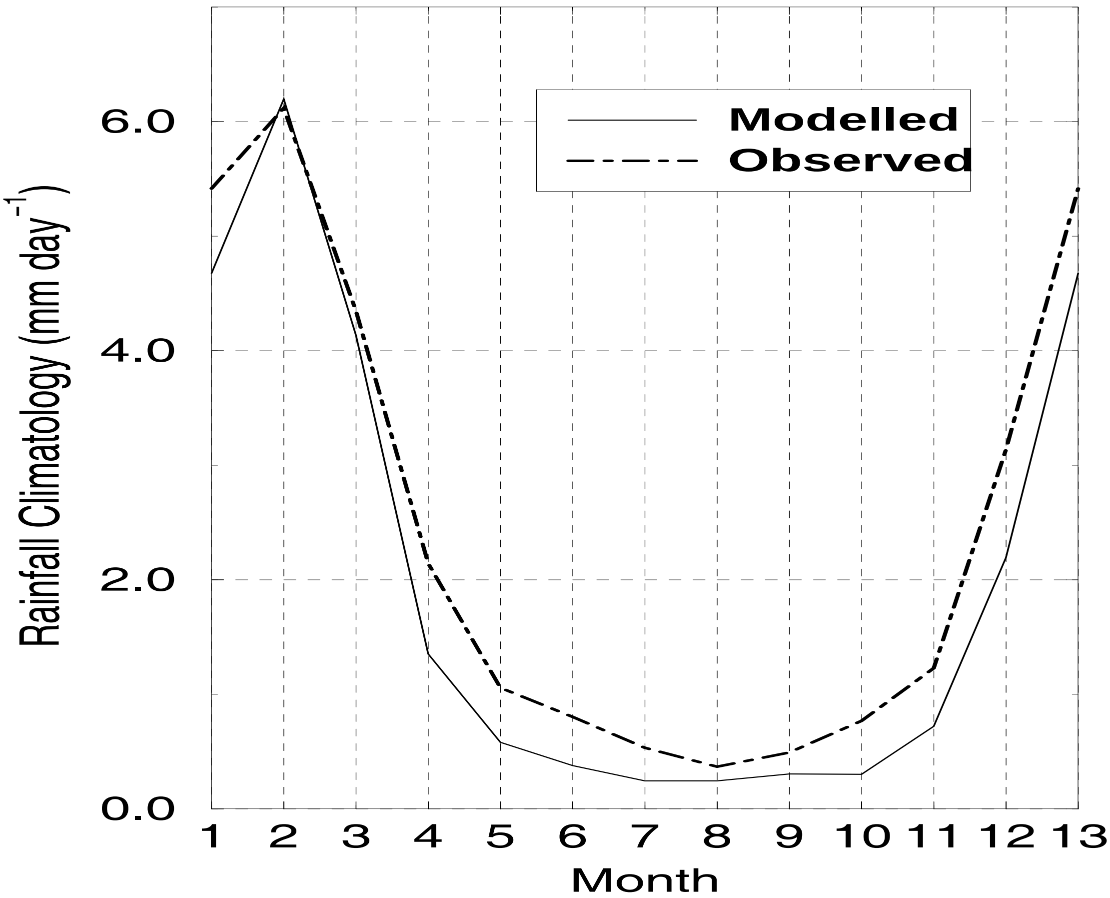


Figure 3.2. Comparison between observed seasonal cycle of rainfall over Queensland and Mark 3 simulation. Month 13 is the same as month 1 (January).

Year-to-year observed variations in rainfall over Queensland are substantially related to variations in ENSO (variations in Pacific Ocean temperatures account for between 20 and 45% of Queensland's rainfall). Thus an important test of the ability of the Mark 3 GCM is to simulate the observed interannual variations, as they affect Queensland rainfall. The ability of the model to simulate the observed pattern of variability is assessed through measurement of the correlation between simulated Queensland rainfall and model-simulated indices of ENSO, compared with similar correlations between observed Queensland rainfall and observed ENSO indices. The correlation coefficient is a measure of the relationship between two time series, where a correlation of 1 indicates perfect agreement between the two, a correlation of –1 means they are exactly out of phase, and a correlation of 0 means no relationship (see, for example, Spiegel, 1972). In climatological analysis, a correlation with a magnitude of 0.5 or more (either positive or negative) often represents a strong relationship. Figure 3.3 shows this comparison for rainfall correlated with two indices of ENSO, the Niño 3.4 SST (an area average of central/eastern equatorial SSTs, over the region 170°E to 120°W, 5°N to 5°S) and the Southern Oscillation Index (SOI) (expressed as a function of the pressure differential between Darwin and Tahiti). Both show considerable agreement between the seasonal variation of the model correlations and observed correlations. For the correlations with the SOI, both model and observed correlations are higher in the summer half of the year than the winter half, and both have similar magnitudes, with the exception of the observed breakdown of correlations in the autumn, which is less well simulated than for other months. For the Niño 3.4 SST correlations, the model also fails to simulate the breakdown in observed correlations in autumn, but there is still considerable agreement between the observed and simulated curves. Little change in the correlations is projected under enhanced greenhouse ("transient") conditions, except that there appears to be a longer period of low correlation in the transient simulation than in the control simulation.

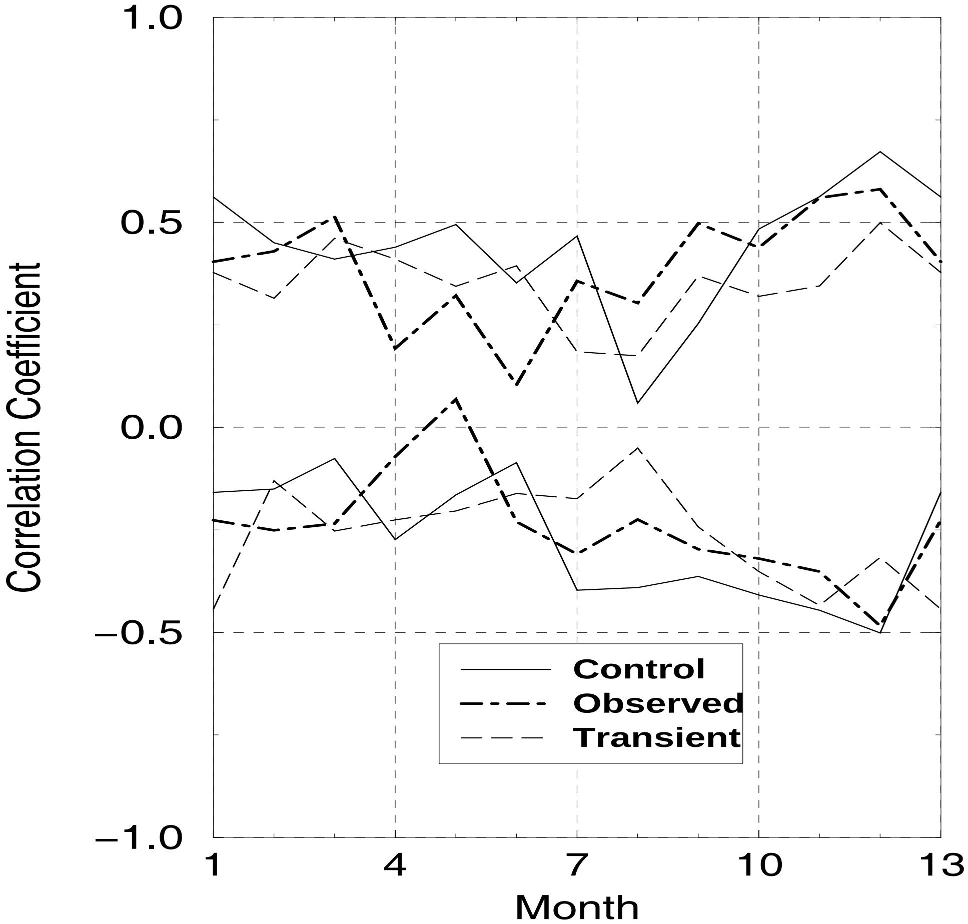
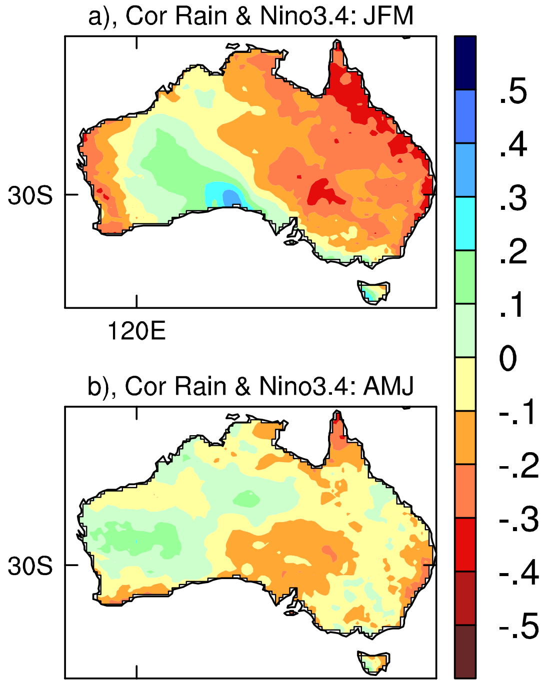


Figure 3.3. Correlations between Queensland average rainfall and (top lines) the SOI; and (bottom lines) the Niño 3.4 SST index, for observed, control and transient (enhanced greenhouse) conditions.

Maps of these correlations are shown in Fig. 3.4, for both model and observations. Both show some similarity in that correlations in general are higher in the east of the country than in the west (except in JFM). Model correlations in the western half of the continent are considerably larger than observed, however. As in the observations, highest correlations are simulated in the spring (OND).



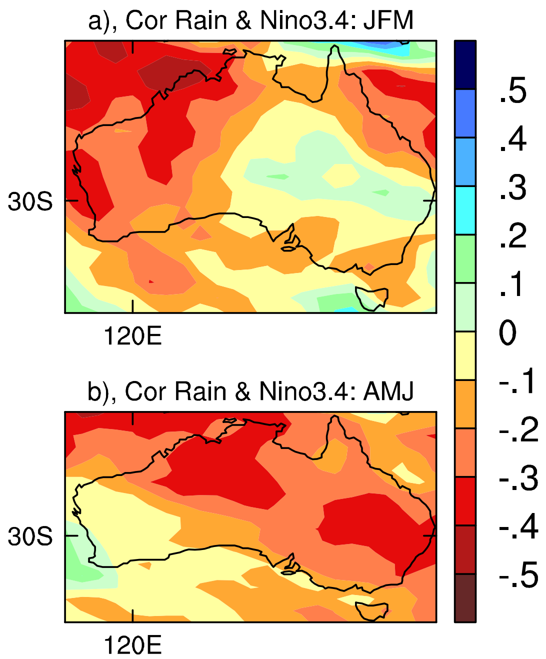


Figure 3.4. (top) Correlation between observed rainfall and observed Niño 3.4 SST index; (bottom) the same correlation for Mark 3 results

Over Queensland, largest observed correlations occur in the north and east of the State, with best correlations in October-December. In January-March, observed correlations are highest in the north-east and decrease towards the south, and the simulated values capture this broad pattern, (although under-representing the observed correlation). In April-June, the time of the observed “breakdown” in correlations between ENSO indices and Australian rainfall, the simulated values remain high compared with observations, suggesting that the mechanism causing the breakdown is not well simulated in the model. In July-September, observed correlations are higher in the south-east of Queensland than further north and west, and this pattern is also simulated. Finally, poor spatial agreement is found in October-December, where the observed pattern again shows highest correlations in the north-east, decreasing towards the south and west, whereas in the model, highest correlations are in the east of the State.

A particularly instructive way to compare the variations inherent in the Mark 3 GCM with observations is to perform a power spectrum analysis of the Niño 3.4 sea surface temperatures, as observed and simulated. A power spectrum shows the size of oscillations in the data (known as the power density) versus the frequency of those oscillations, here expressed in cycles per month. For example, a period of one year would correspond to about 0.083 cycles per month. In this analysis, the annual cycle is removed before the power spectrum is calculated. This analysis compares the main cycles of oscillation observed in nature with those simulated in Mark 3, in order to examine whether the GCM is generating the right magnitude and period of oscillations, such as those due to ENSO. The results are shown in Fig. 3.5. While there are certain similarities between the two graphs, there are important differences also. The main ENSO periodicities at 0.023 and 0.03 cycles per month (2-4 years) are seen in both the observations and the model. However, there is a large simulated peak at about 2 years (0.04 cycles per month) that is not observed in reality. Also, the simulated peak at about 5 years (about 0.017 cycles per month) is rather stronger than that observed. There is little indication in either the observed or simulated spectrum of statistically significant power at decadal time scales (less than 0.0083 cycles per month).

In general, the CSIRO Mark 3 GCM has a good simulation of the seasonal variation of mean rainfall over Queensland. Its simulation of the observed year-to-year variability is less good. Refinements are continuing to Mark 3 that may remove some of the reported discrepancies.

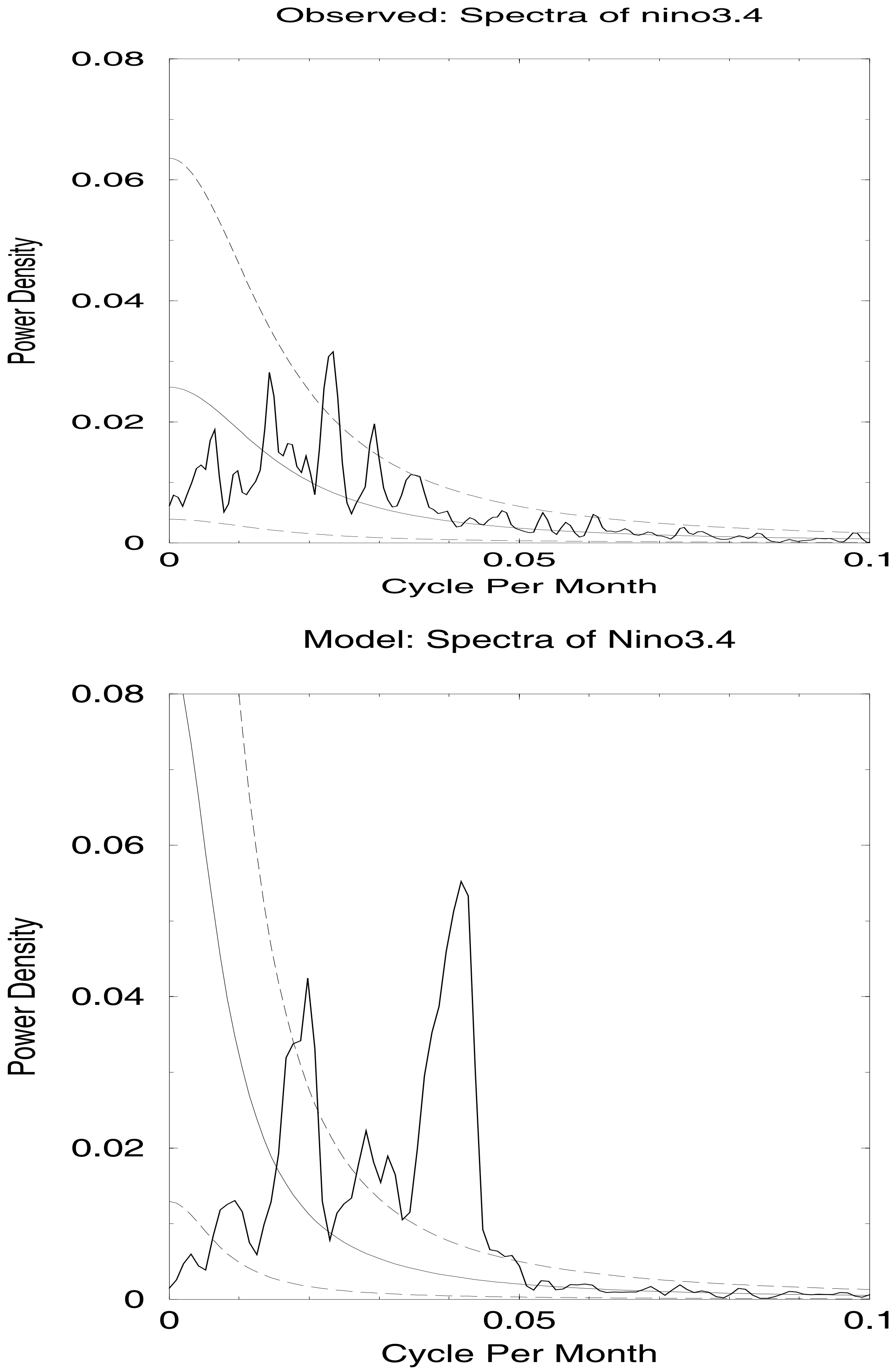


Figure 3.5. (top) Observed spectrum of Niño 3.4 SSTs; (bottom) Mark 3 simulated spectrum. Dashed lines indicate 95% significance levels; peaks above or below these lines are statistically significant.

3.2 CSIRO Mark 3 GCM climate change simulation

The Mark 3 GCM has been run for gradually increasing greenhouse gas concentrations, for the period encompassing 1960 to 2100. Technically, the increase in greenhouse gas concentrations assumed was the so-called "SRES A2 draft marker scenario" (Nakicenovic et al., 2000). This scenario assumes continually increasing carbon dioxide concentrations with no concerted effort to reduce emissions, and thus is a good test of the implications for global climate if little action is taken on greenhouse gas emissions. Fig. 3.6 shows a comparison between the future concentration of carbon dioxide assumed in this scenario and in a scenario that assumes a 1% per annum compounding increase, an emissions scenario used in several of the climate model runs used to construct the consensus climate change scenarios discussed in Section 2. Changes in climate are presented for thirty-year averages centred on 2050 relative to similar averages for 1990. These years were chosen because 1990 is the baseline year used for both the CSIRO (2001) climate change scenarios and the IPCC (2001) report, and 2050 is a time frame that is within the planning horizon of a number of activities in Queensland.

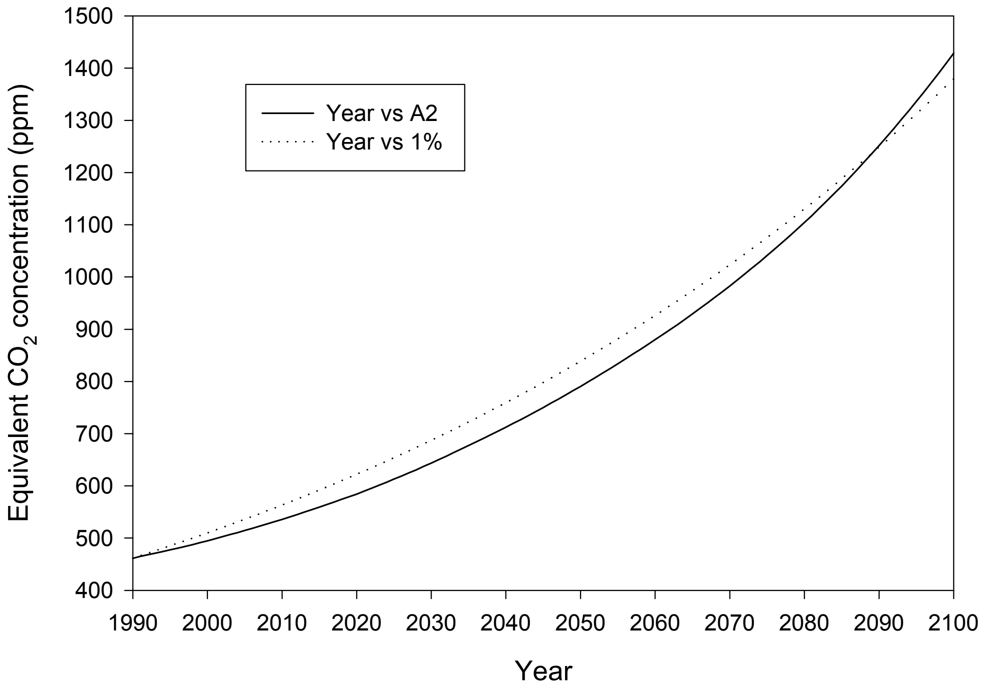


Figure 3.6. Comparison between the future equivalent concentration of carbon dioxide assumed for the SRES A2 scenario (solid line) and the 1% per annum compounding scenario (dotted line).

Temperature changes (Fig. 3.7) are compared with those for CSIRO (2001), rescaled to 2050 (see Fig. 2.1). The Mark 3 simulation gives temperature increases over Queensland by 2050 of 0.4-1.2 degrees C for January-June, and 0.8-1.6 degrees for July through December. These ranges are at the low end of the CSIRO (2001) projections for 2050, which range from 0.8-3.8 degrees for the annual mean. Mark 3 is less sensitive to increases in greenhouse gases than many of the previous generation of climate models, and may perhaps be more realistic in this regard. The main reason for the lower climate sensitivity of the Mark 3 GCM compared with the Mark 2 results is a more realistic representation of sea ice and other high latitude processes in Mark 3, giving less change in these quantities in a warmer world. The use of the SRES A2 emissions scenario assumes slightly lower CO_2 concentrations than the 1% compounding emissions scenario (Fig. 3.6) used in some of the climate models used to construct the consensus climate change scenarios discussed in Section 2, which may partially explain the smaller climate response of the Mark 3 GCM. One way to compare the temperature predictions of the Mark 3 GCM to those of other climate models is shown in Fig. 3.7. Here, the Mark 3 temperature increase projected for 2050 is compared with the lowest and highest model predictions for 2050 of those models used to construct the consensus climate change scenarios. The Mark 3 projections fall between these extremes, tending towards the lower rather than the higher end of the different model projections.

The direction of simulated Mark 3 rainfall changes shown in Fig. 3.8 generally fall within the projected ranges to those shown in the climate change scenarios (Fig. 2.2), with some differences. For January through March (Fig. 3.8a), there are mostly increases in rainfall simulated over Queensland, some decreases, and a large area that could be described as little change (0.-0.4), similar to the scenario pattern for summer. The mean rainfall over the state increases by about 11% for January-March, which may not be enough to change substantially the constructed summer scenario (Fig. 2.2(b)) if Mark 3 were included as one of the climate models used to construct a new scenario.

For April-June (Fig. 3.8(b)), however, simulated rainfall in Mark 3 increases by about 25%, which may be enough to change somewhat the scenario pattern shown in Fig. 2.2(c) to give more areas of tendency towards increases. For July-September, mostly no change or slight increases are simulated, while for October-December, mostly no change or slight decreases are simulated. Little change is simulated for the Queensland average in these seasons, which is within the range of the scenarios shown in Fig. 2.2(d) and 2.2(e). Average rainfall for Queensland (Fig. 3.9) shows these changes more clearly, with slight rainfall increases by 2050 in the first half of the year, and little change in the second half.

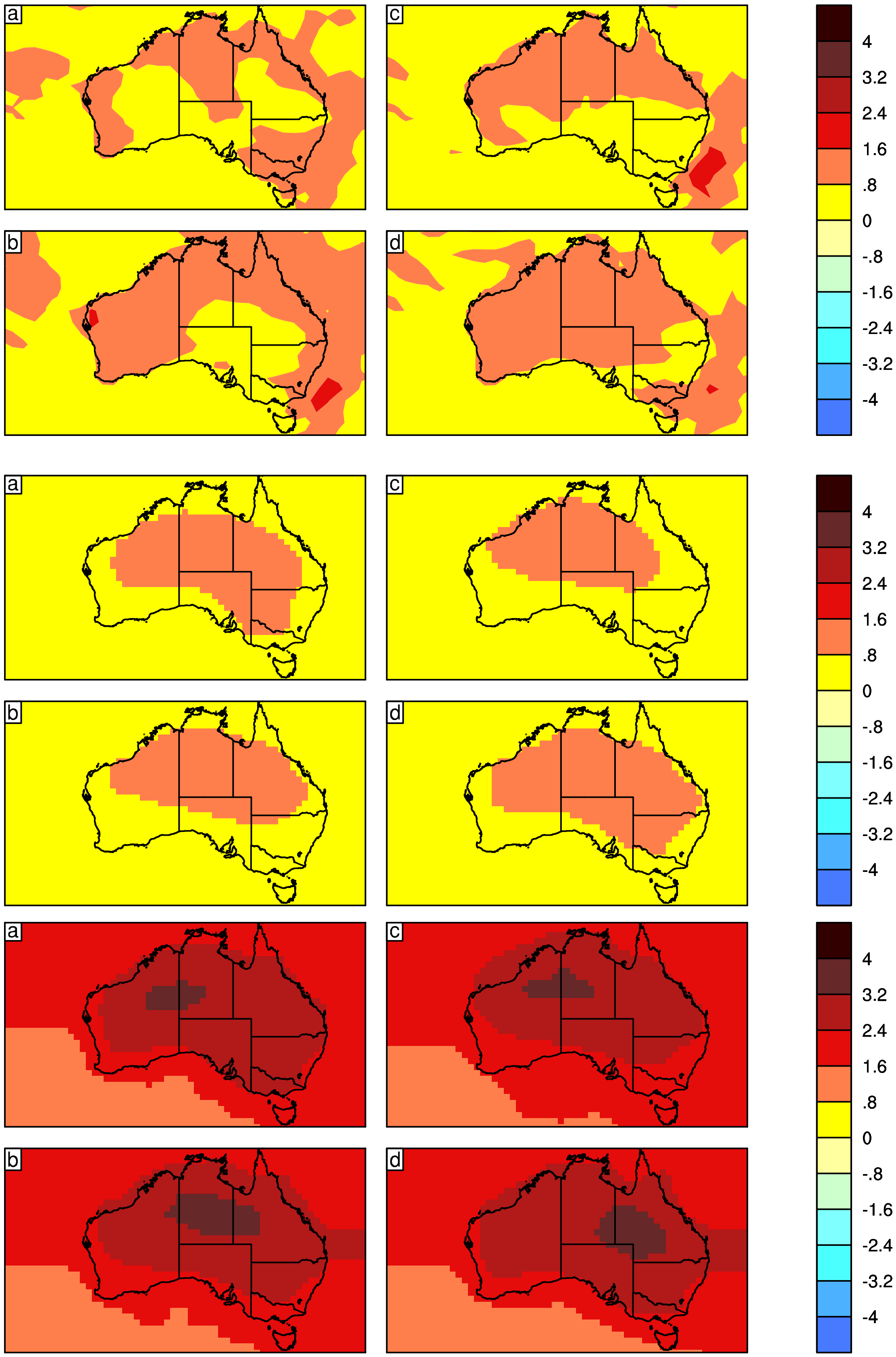


Figure 3.7. (top) Changes in temperature in degrees C simulated by Mark 3, for 30 years centred on 2050 minus 30 years centred on 1990, for each season: (a) summer; (b) autumn; (c) winter; and (d) spring; (middle) the same for the climate model with the lowest sensitivity included in the CSIRO (2001) projections; and (bottom) the same for highest sensitivity.

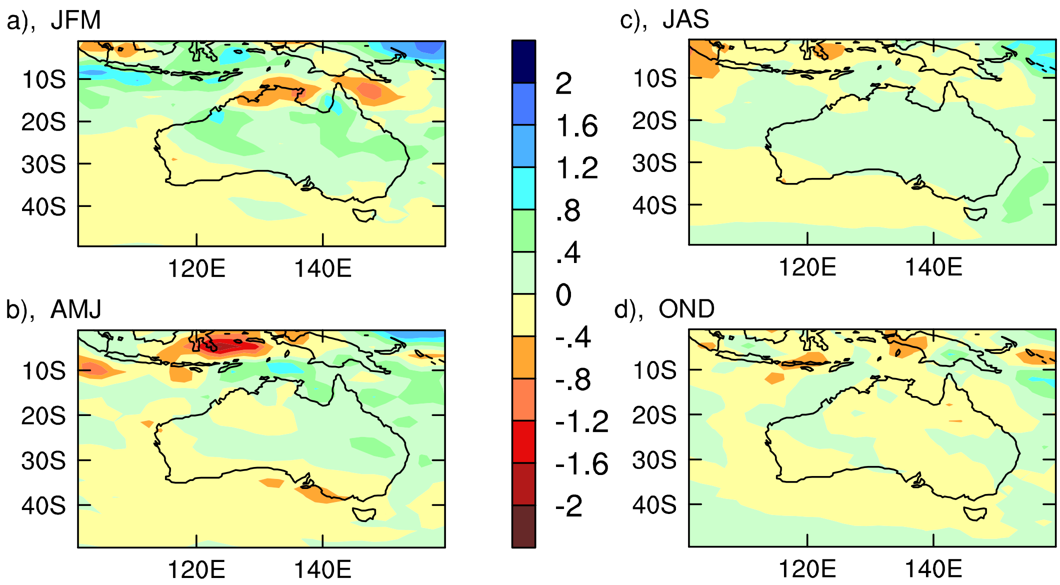


Figure 3.8. Rainfall changes (mm per day) simulated by Mark 3 for 2050 minus 1990, for the months indicated.

Time series of simulated Queensland temperature and rainfall changes from 1960 to 2100 are shown in Fig. 3.10. Trends in rainfall in any one season are difficult to identify. There is considerable interannual and decadal variability in a warmer world, as there is in the current climate, with interannual variability primarily associated with ENSO events. Such variability will continue to dominate Queensland summer rainfall under enhanced greenhouse conditions. By 2050, average Queensland temperatures have increased by roughly 1 degree over 1990 values, but by 2100, increases are more than 3 degrees in all seasons.

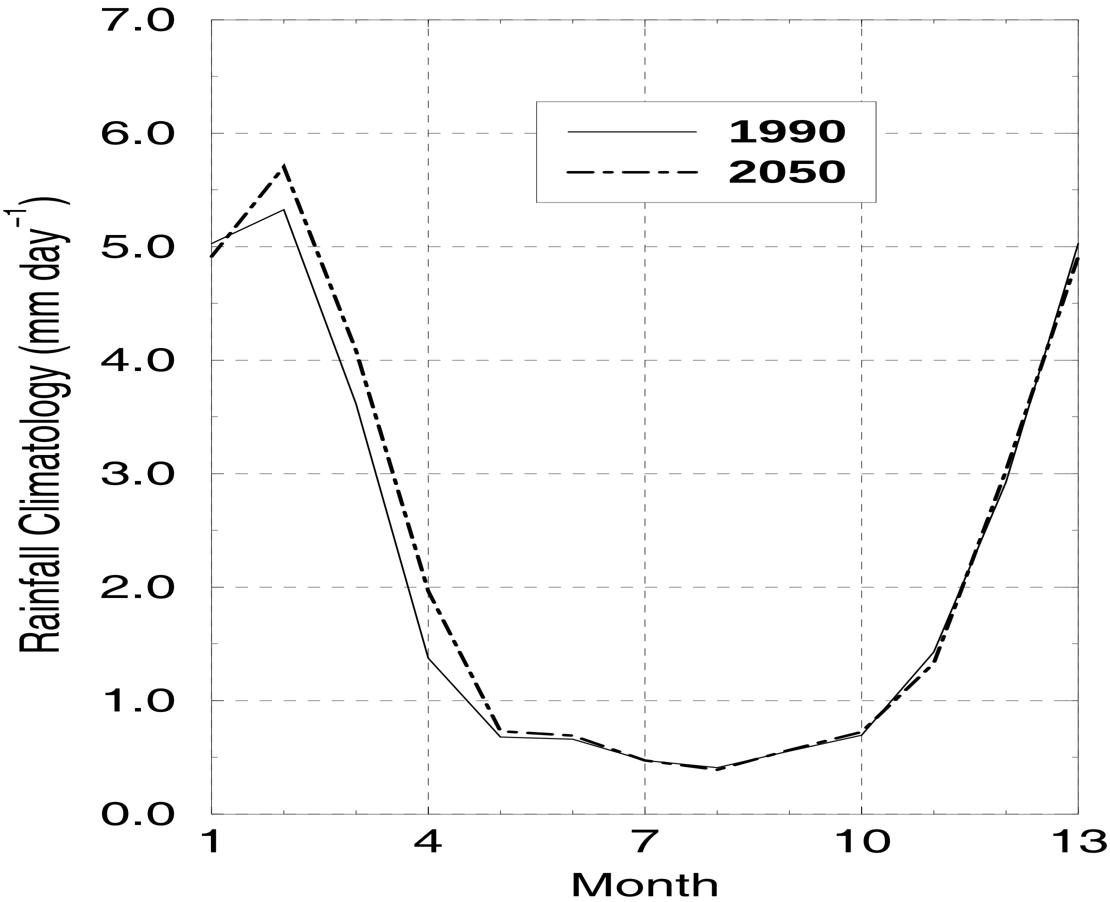


Figure 3.9. Mark 3 simulated seasonal variation of rainfall, 1990 versus 2050.

In CSIRO (2001) and in Section 2.2 of this report, it was pointed out that soil moisture would decrease in Queensland in a warmer world because there did not seem to be a large rainfall increase predicted that would compensate for the increase in evaporation caused by increasing temperature. The simulations of the Mark 3 GCM do not necessarily contradict this prediction, but examination of the actual soil moisture simulated in the Mark 3 model shows slight increases until the latter decades of the 21st century, followed by sharp decreases (not shown). This is likely due to the slow warming of the Mark 3 model accompanied by slight increases in rainfall (Fig. 3.10), followed by a rapid rise in temperature and a slight decrease in rainfall towards the end of the century.

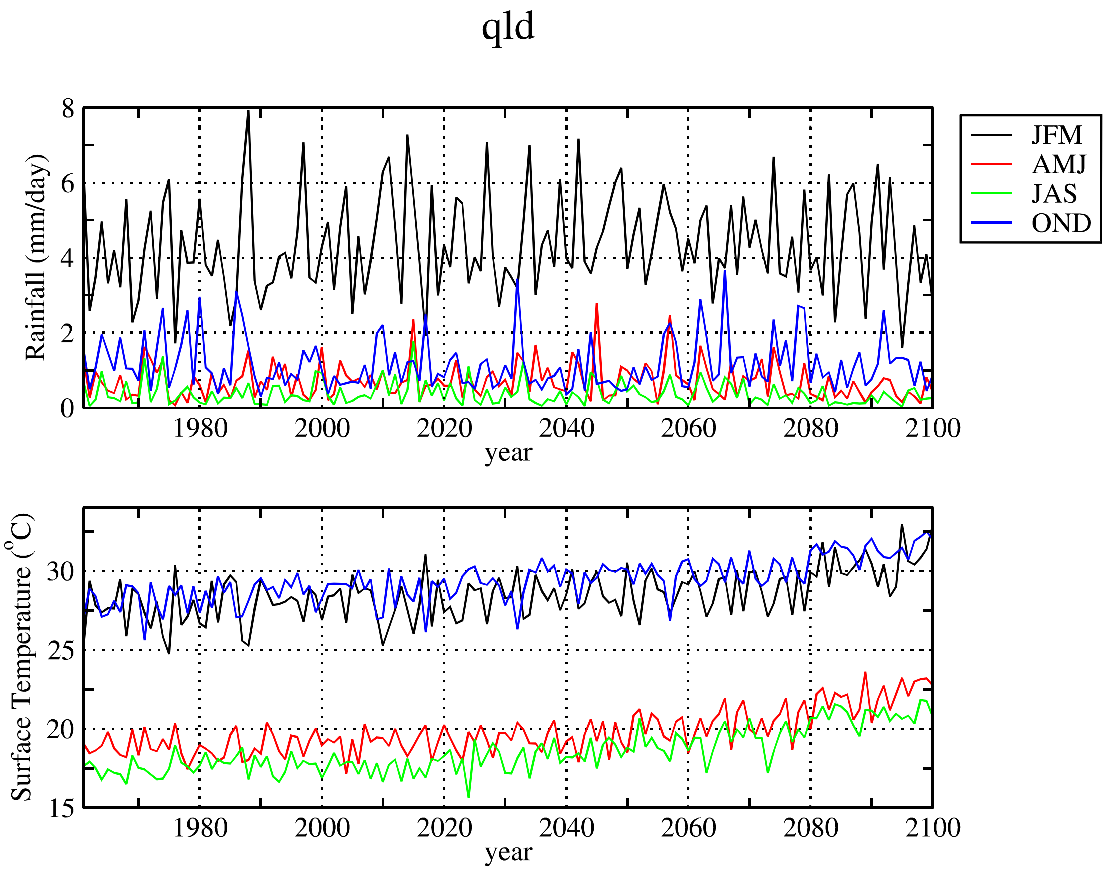


Figure 3.10. Time series of Mark 3 simulated average rainfall and surface temperatures for Queensland, 1960-2100, for each season.

It is important to put the results of the Mark 3 GCM in the wider context of the effect of climate change on the mean climate and variability of the Pacific, specifically the effect on ENSO. One needs to differentiate the effect of changes in mean climate (that is, whether the average conditions become more "El Niño-like", for instance), from any changes in the variability (whether El Niños become more frequent and/or stronger).

A good starting point to examine this issue is an evaluation of Mark 3's overall simulation of Pacific sea surface temperatures (SSTs), shown in Fig. 3.11. Mark 3 shows a reasonable simulation of Pacific SSTs and its mean seasonal variation, with the exception of a region along the equator. Pattern correlations (with the zonal average removed) between the simulated and observed SSTs range from greater than 0.6 for January-March and April-June, to about 0.45 for July-September and October-December. This represents good agreement, but there is a region of unrealistically strong upwelling (cold water rising from the deeper ocean) along the equator. A number of other state-of-the-art climate models also have this problem (McAvaney et al., 2001).

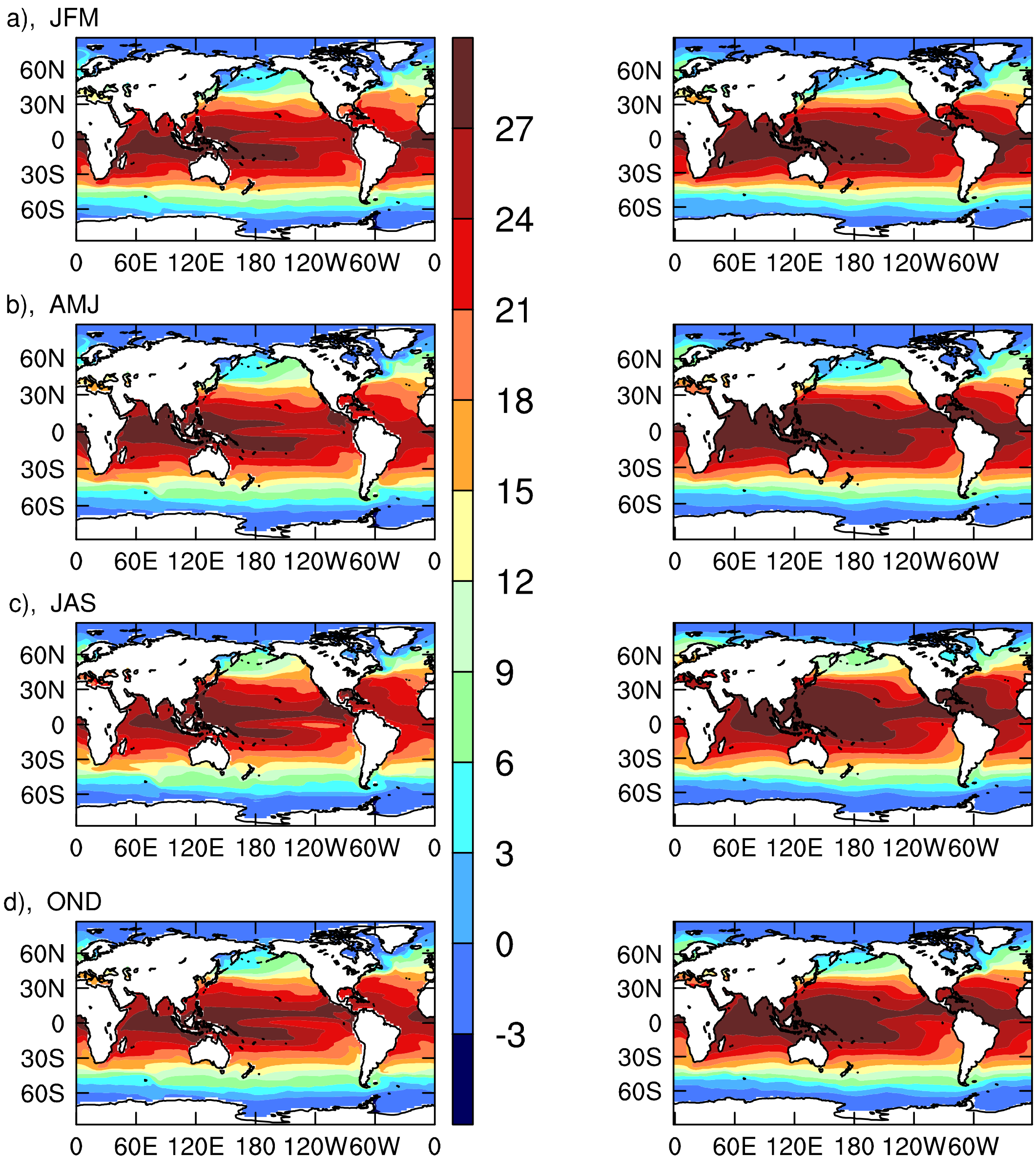


Figure 3.11. Comparison between seasonal variation of Mark 3 simulated (left) and observed SST (right), in degrees C. Observations from Parker et al. (1995).

A way of determining whether a particular model simulation is more "El Niño-like" in a warmer world is to examine the geographical pattern of SST changes. A more El Niño-like state would be characterized by faster warming in the eastern Pacific than in the western Pacific. Changes in SST simulated by CSIRO Mark 3 are shown in Fig. 3.12. It can be seen that the climate state in a warmer world in this model is perhaps only weakly more El Niño-like, if at all.

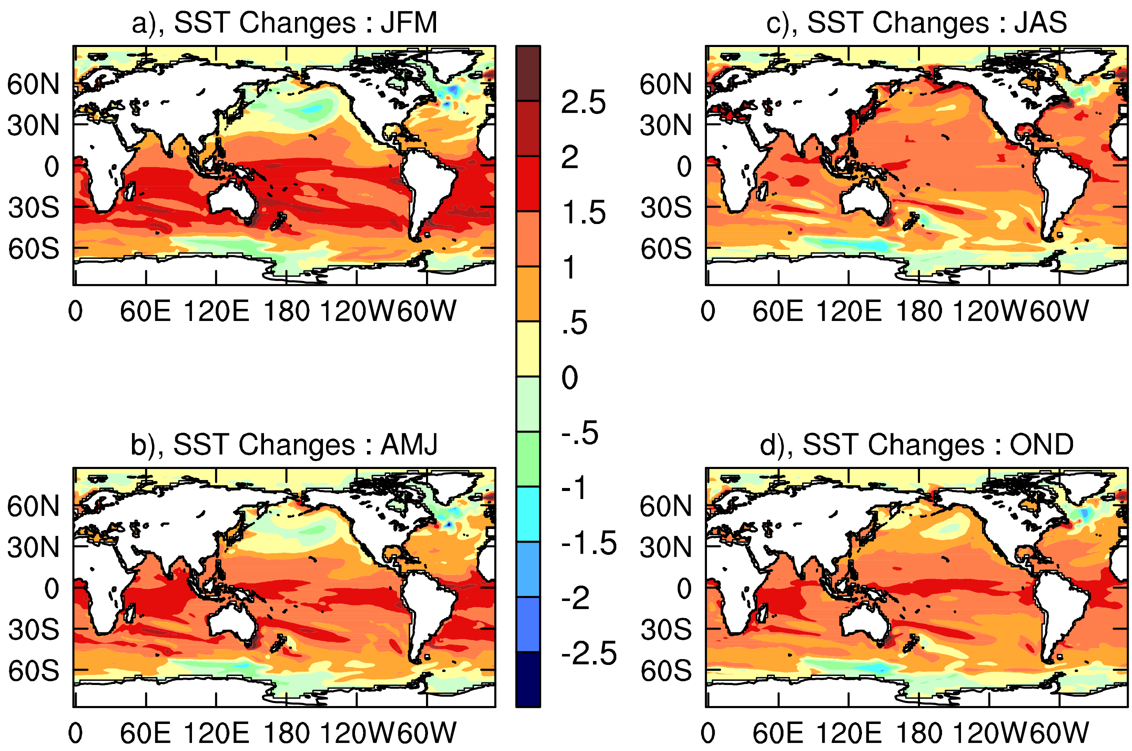


Figure 3.12. Changes in SST in degrees C, average of 2020-2100 ("transient" run) minus control.

Rainfall changes across the Pacific simulated by Mark 3 also do not reflect a genuine systematic trend towards more El Niño-like conditions (not shown).

In summary, the CSIRO Mark 3 GCM has a reasonable simulation of average temperature and rainfall over Queensland, and a reasonably good simulation of year-to-year variability. Simulated changes in temperature as a result of global warming tend towards the low end of the current model predictions, but mostly do not contradict the results of previously published climate change scenarios for Queensland. Simulated changes in rainfall are also largely consistent with these scenarios, but with a trend towards increased rainfall in the first half of the year. The overall climate of the model does not substantially drift towards a more El Niño-like state, as do the majority of current climate models.

3.3 Regional model climate change simulation

3.3.1 Introduction

While the quality of the Mark 3 global model simulations gives increasing confidence in its projections, it still has a relatively coarse resolution, or distance between grid points. This limits its ability to make inferences about regional changes in climate or to simulate the effects of climate change on smaller phenomena such as tropical cyclones. For these tasks, finer-resolution models are needed. The CSIRO regional climate model DARLAM has been developed for this purpose (McGregor and Katzfey, 1998; see also Walsh et al., 2001).

Recent developments in regional modelling included the construction of variable-resolution climate models, where the distance between grid points varies depending upon location. The CSIRO conformal-cubic model (also known as Mark 4; McGregor and Dix, 2001) is such a model, as it is implemented on a variable resolution grid that can be described by a mapping on a conformal-cubic projection (Fig. 3.13). There are advantages of this grid structure over the fixed-resolution grid used for DARLAM. Mark 4 is a global atmospheric model that is "nudged" by the Mark 3 simulation. Therefore the problems (such as anomalous precipitation) that are often seen at the edge of DARLAM, where DARLAM tries to match the global simulation but sometimes has difficulty doing so, are largely absent in Mark 4. In addition, since Mark 4 is of variable resolution, fine resolution is specified over the area of interest (in this case, Queensland) and coarse resolution is used in other parts of the globe where fine detail is not needed. The resolution of this Mark 4 simulation over Queensland is about 60 km. The SSTs used in the Mark 4 simulation come from the Mark 3 model output.

It was originally envisaged that the milestone described here would be satisfied by nesting DARLAM within the Mark 3 climate model simulation described in the previous section. The milestone for this project, however, indicated that the variable-resolution Mark 4 climate model would be used if it were available (see Section 1.1). During this year, the development of Mark 4 reached a point where it could be considered for use in satisfying this milestone. Accordingly, the Mark 4 model was nested within the Mark 3 simulation and the results are discussed here. Note that since the Mark 4 model is forced to a large degree by the output of the Mark 3 model, a number of the biases inherent in the Mark 3 model will also appear in Mark 4. Briefly summarized, the Mark 4 results for temperature are roughly comparable in quality to the previous Mark 2/DARLAM nested results discussed in Walsh et al. (2001) (last year's report), but the precipitation simulation is markedly better.

3.3.2 Mark 4 model simulation

3.3.2.1 Temperature

Figure 3.14 shows the observed average screen temperature over Queensland for the four seasons, while Fig. 3.15 gives the Mark 4 simulation, and Fig. 3.16 the differences between the two. Observations of temperature are taken from Jones and Trewin (2000). In general, Mark 4 gives a good simulation of observed average screen temperature. Biases are generally modest in all seasons, mostly less than 2 degrees C., with the exception of parts of the southwest of the state, where the model is more two degrees too cool in winter, spring and autumn. The simulation is best in summer and worst in spring .

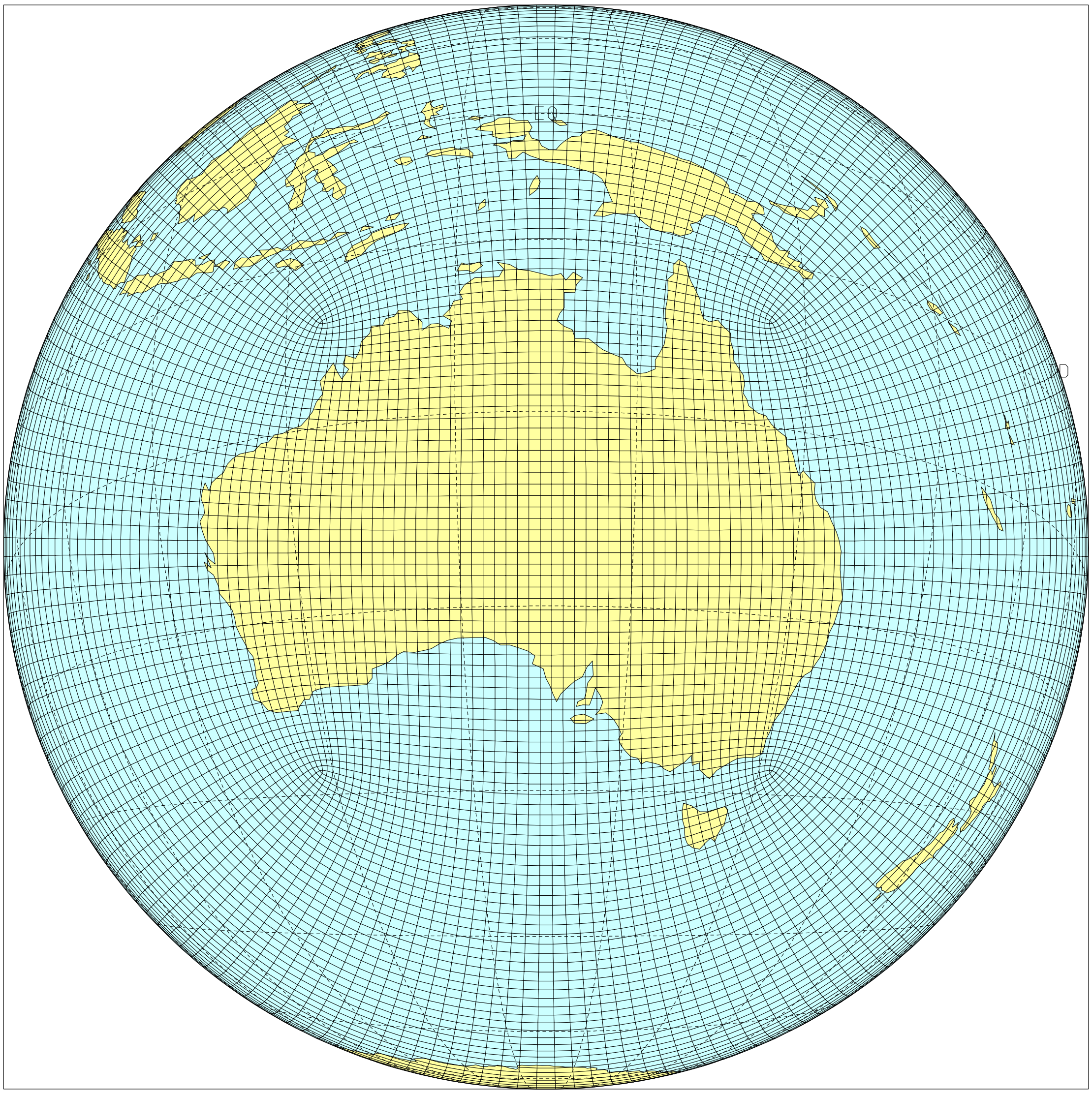


Figure 3.13. Grid of the conformal-cubic model (Mark 4) over Australia.

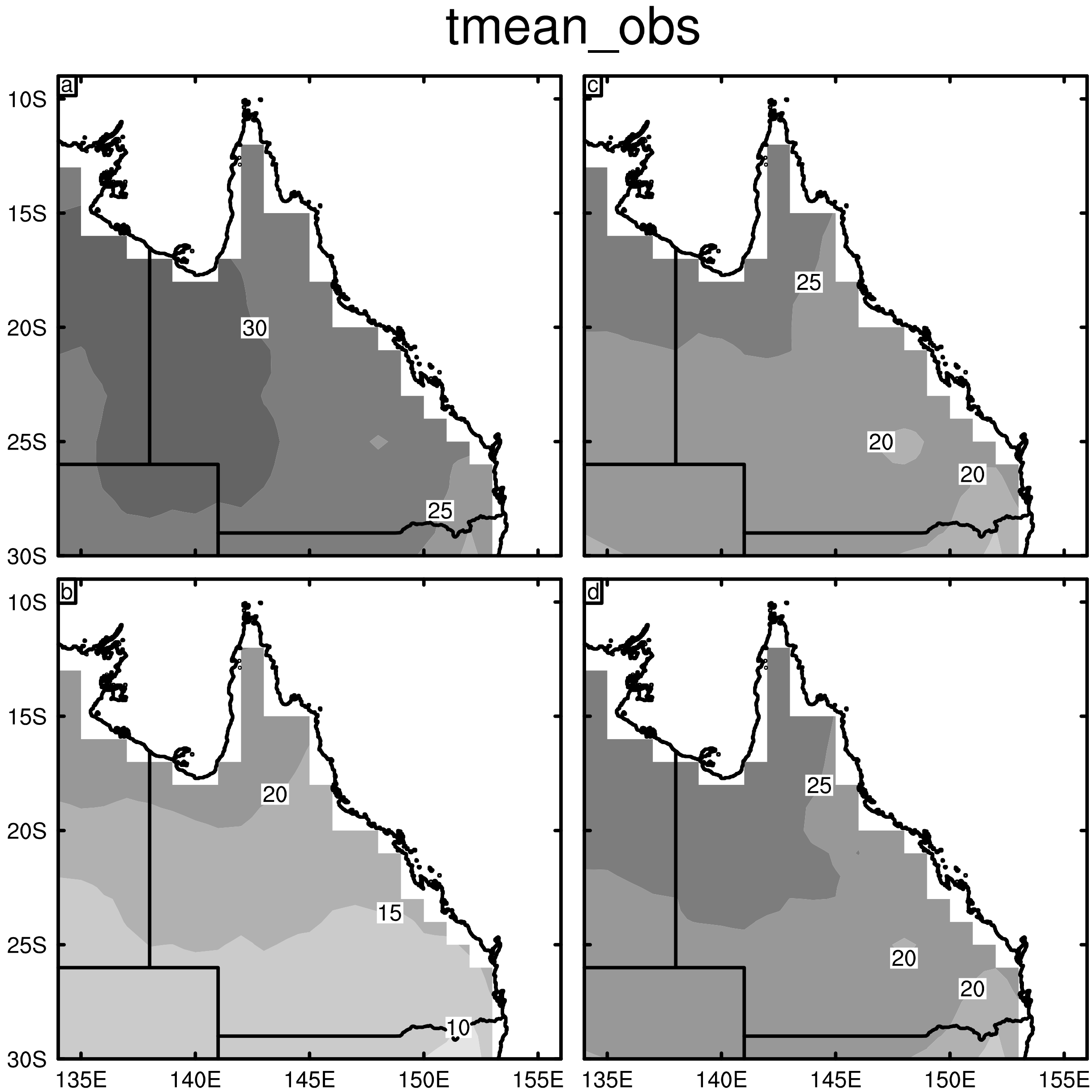


Figure 3.14. Observed average screen temperature, in degrees C., over Queensland, for (a) summer (Dec. – Feb.); (b) winter (June-Aug.); (c) autumn (March-May); and (d) spring (Sept.-Nov.). Contour interval is 5 degrees. After Jones and Trewin (2000).

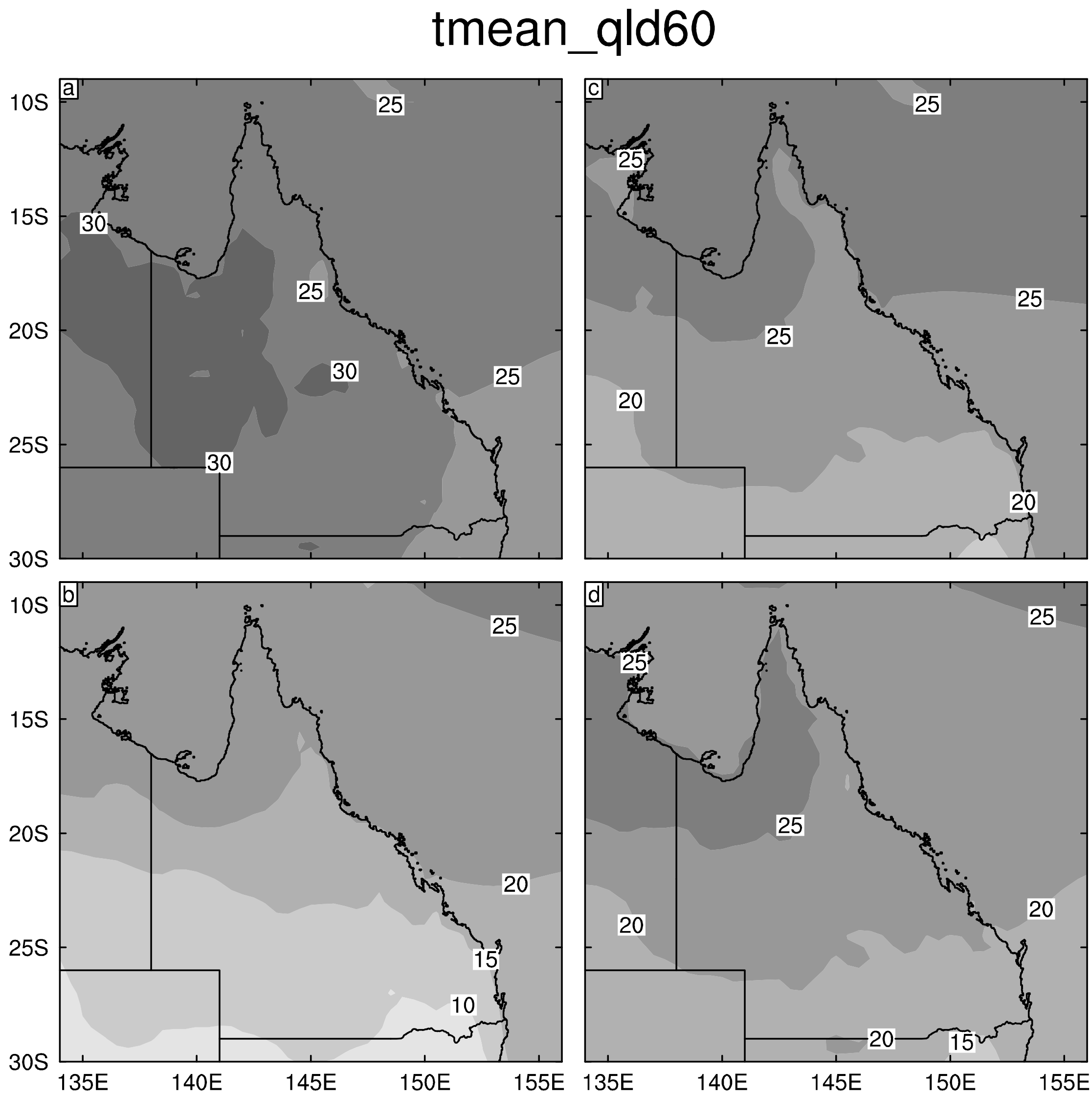


Figure 3.15. Same as Fig. 3.14 except for the Mark 4 simulation.

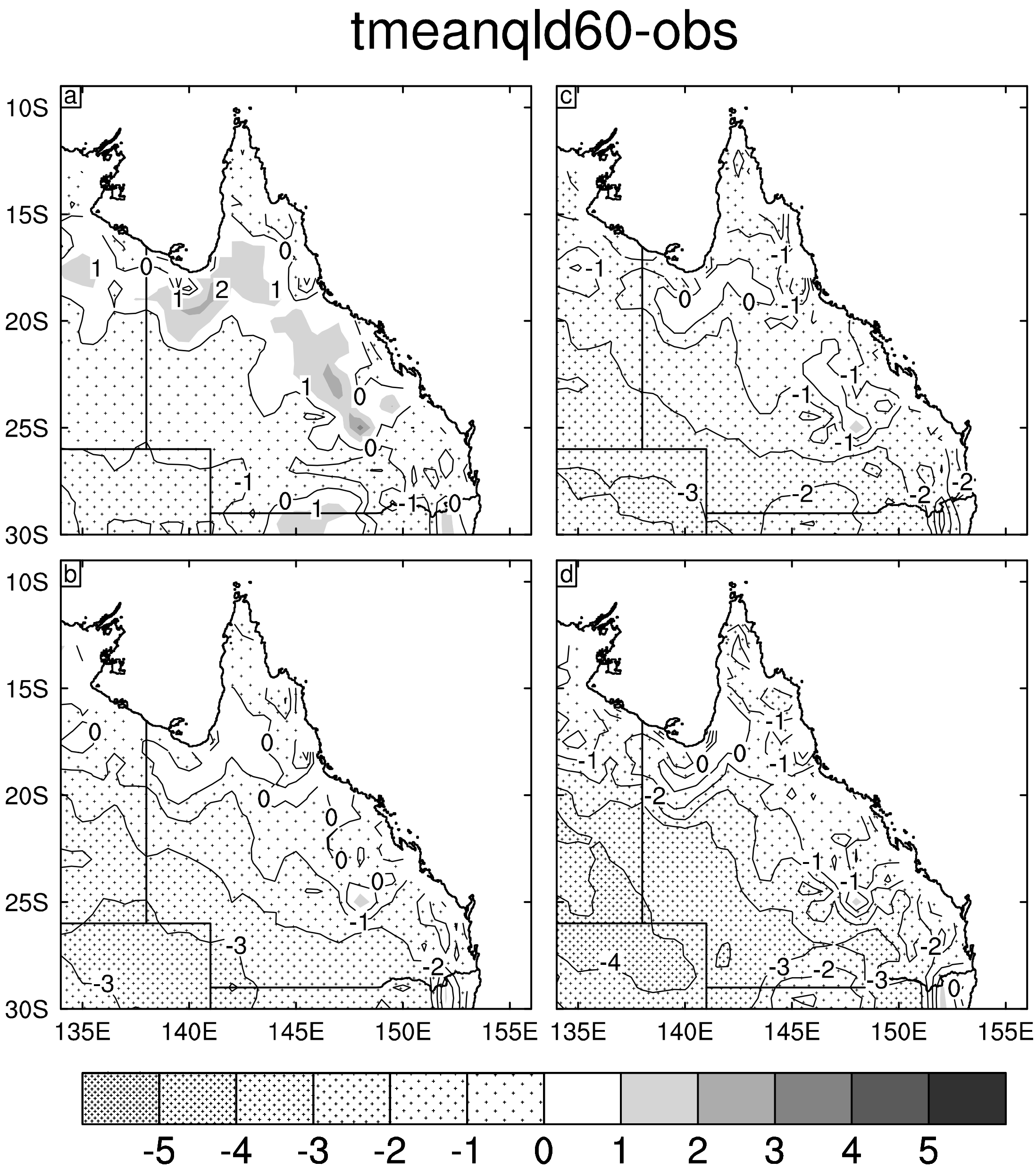


Figure 3.16. The same as Fig. 3.15 except the difference, Mark 4 minus observed.

Turning to minimum temperature (Figs. 3.17-3.19), Mark 4 also has a very good simulation of minimum temperature in all seasons and in all parts of the state. Biases are almost all below two degrees, with more negative values than positive.

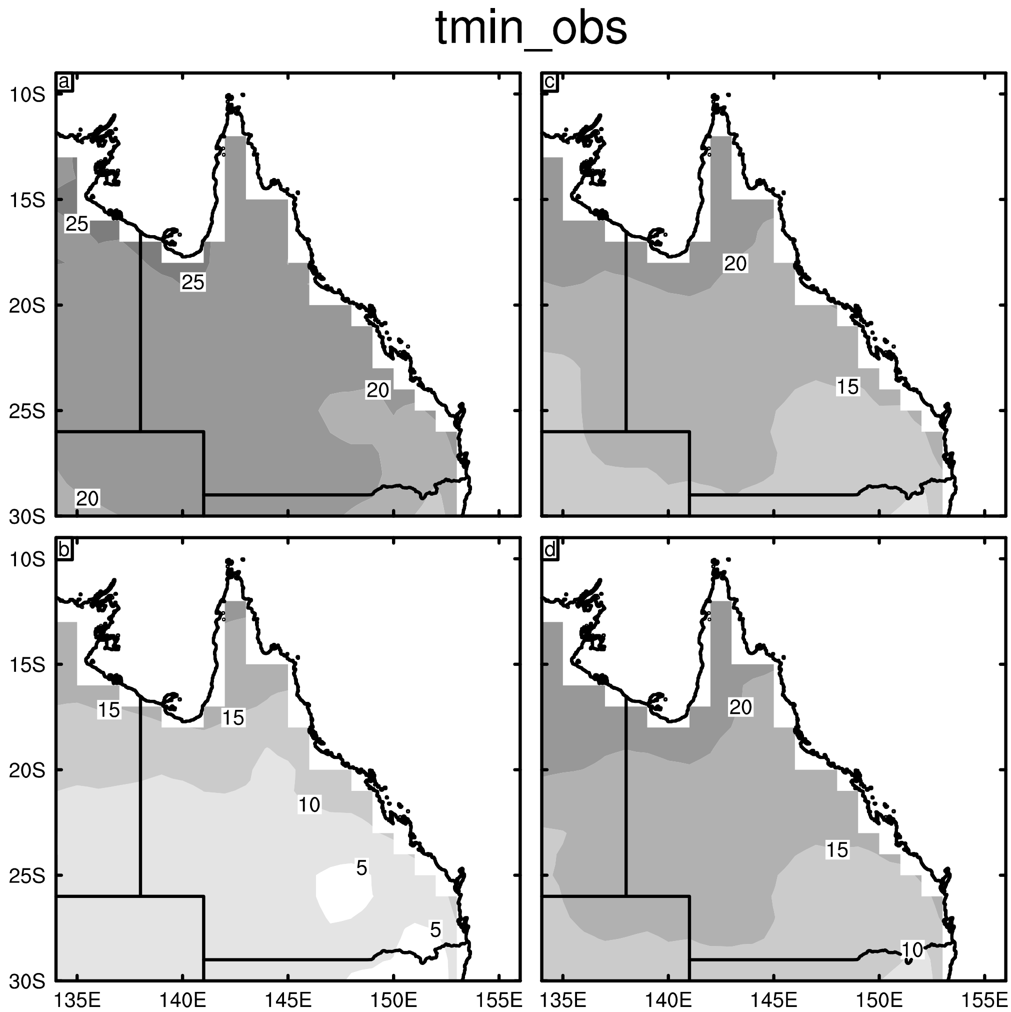


Figure 3.17. The same as Fig. 3.14 but for minimum temperature.

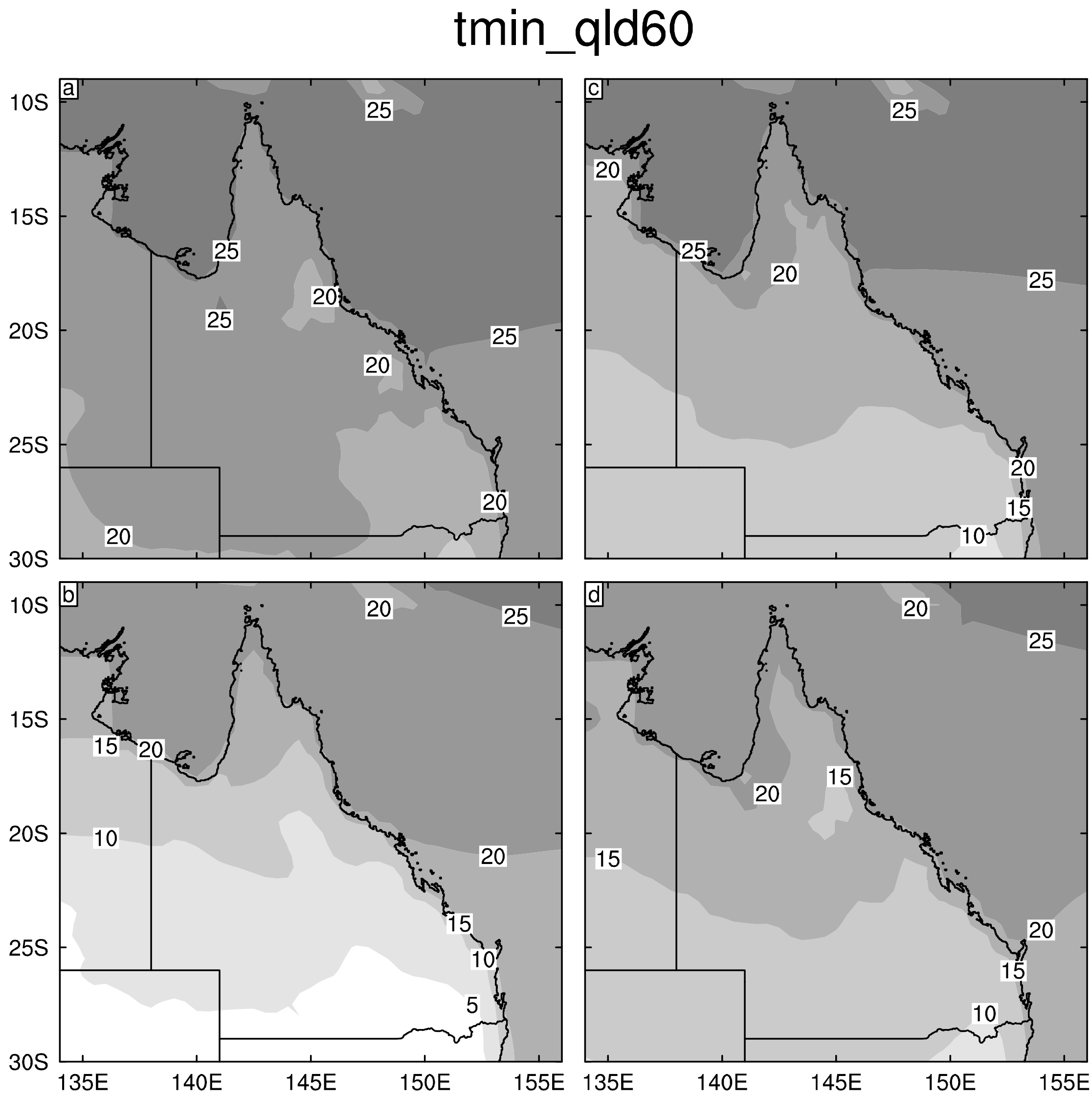


Figure 3.18. The same as Fig. 3.17 but for the Mark 4 simulation.

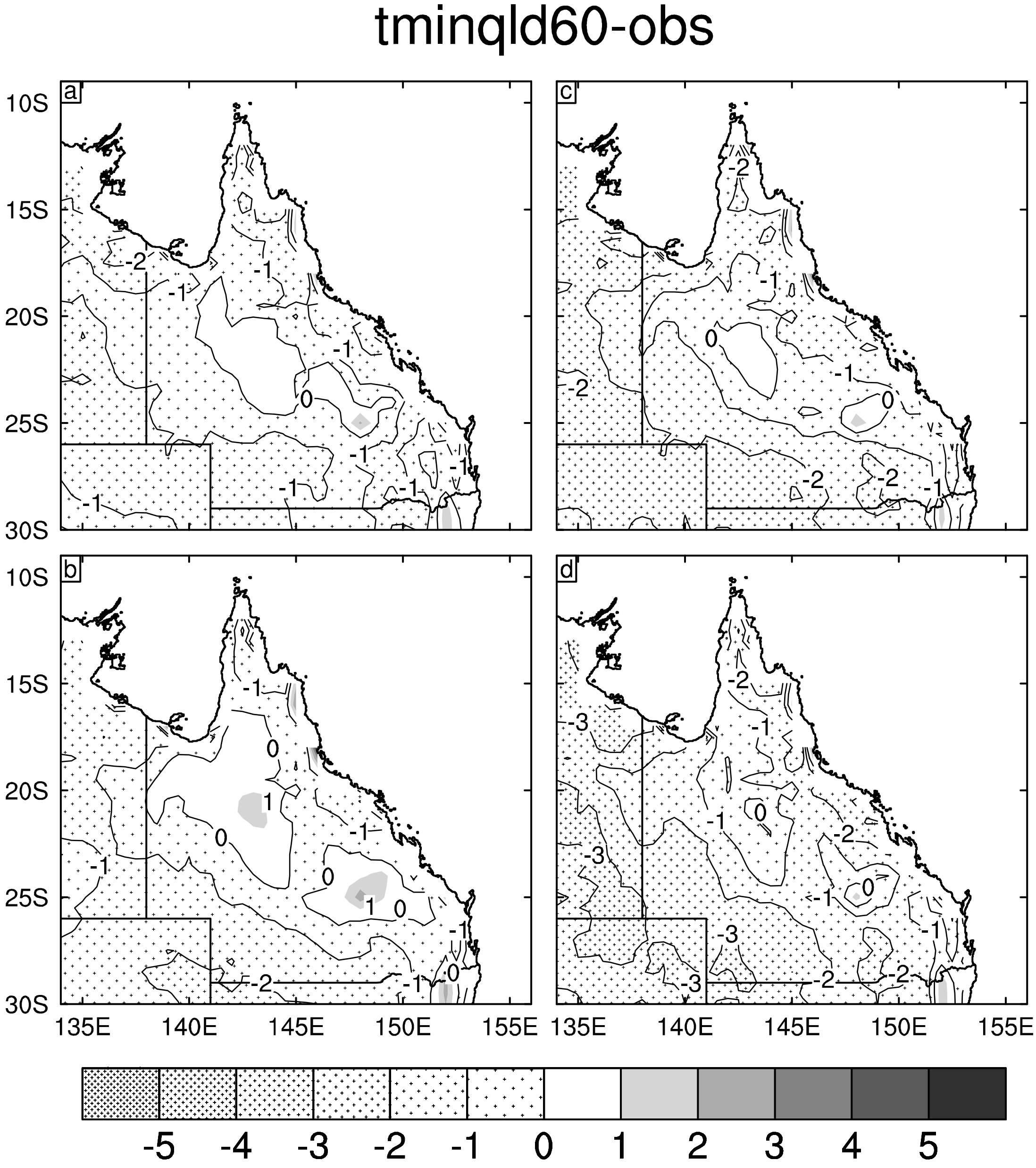


Figure 3.19. The same as Fig. 3.17 but for difference, Mark 4 minus observations.

For maximum temperature, a slightly different picture emerges (Figs. 3.20-3.22). The Mark 4 model simulates rather warmer than observed average maximum temperatures for all seasons in a band from the Gulf of Carpentaria down the eastern highlands. This bias is most pronounced in summer (Fig. 3.22(a)) and least visible in winter (Fig. 3.22(b)). Analysis shows that in this region the Mark 4 model is simulating less cloud cover than present in the observations. There also may be some impact on the surface temperature from the representation of bare soil processes included in the model. Both of these aspects are being investigated. The results presented here are very encouraging and indicate the advantages of fine resolution simulations.

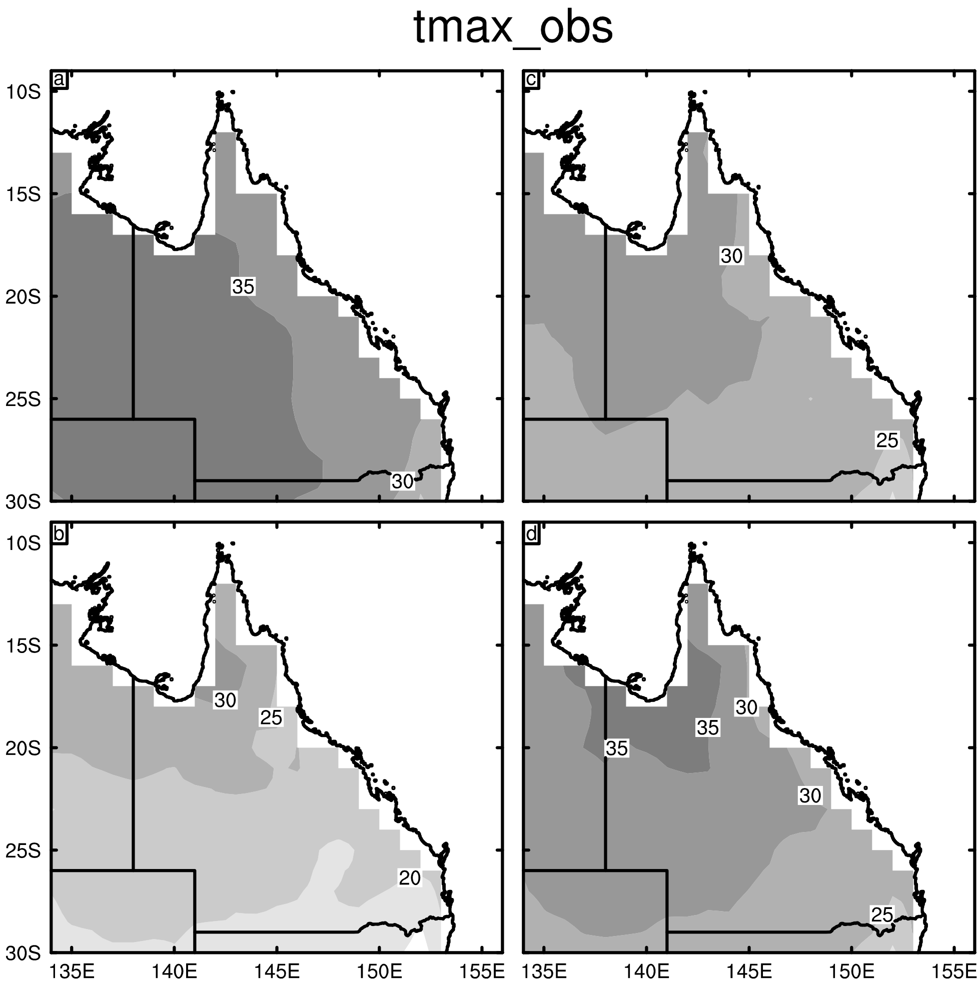


Figure 3.20. The same as Fig. 3.14 but for average maximum screen temperatures.

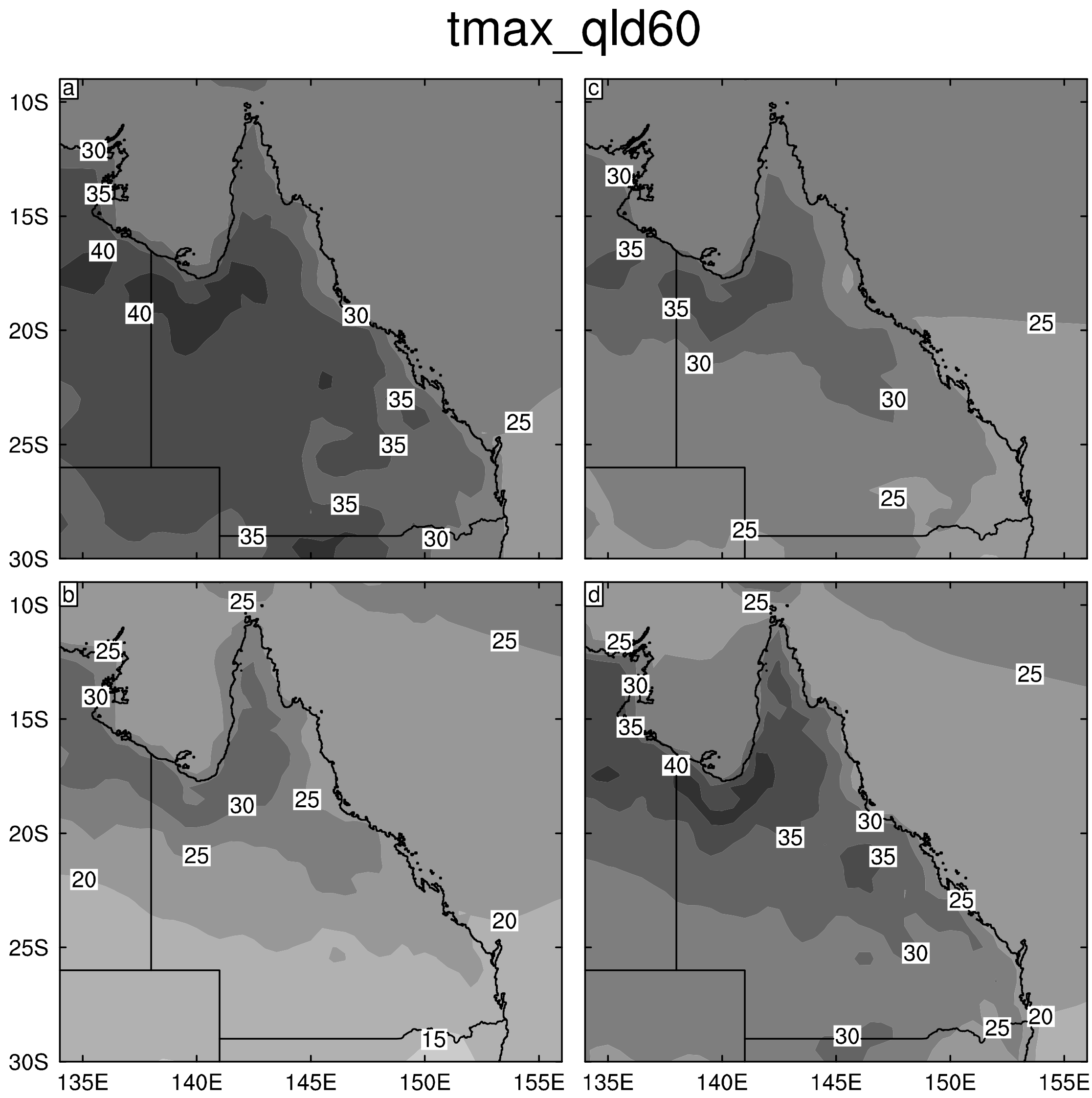


Figure 3.21. The same as Fig. 3.20 but for the Mark 4 simulation.

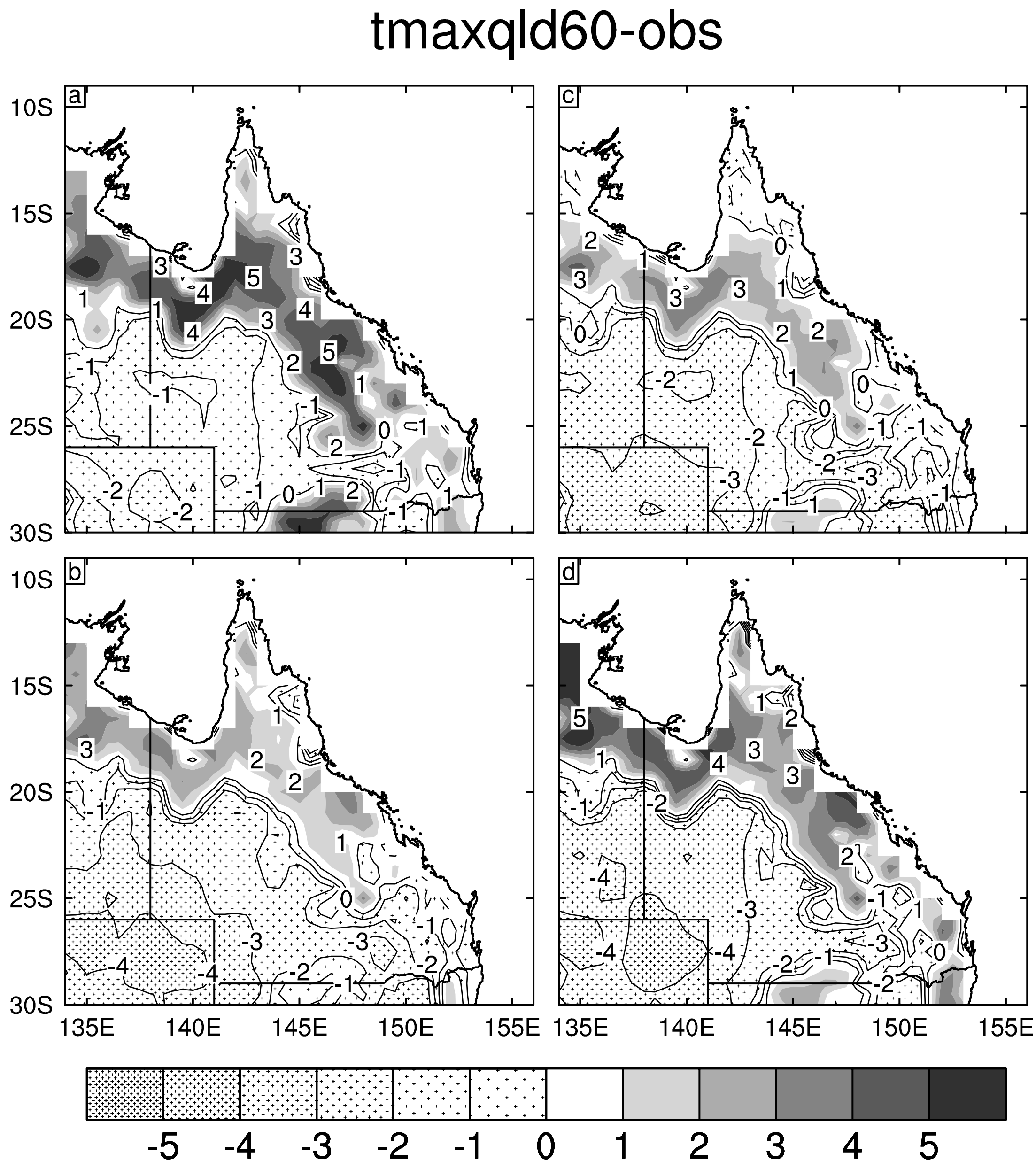


Figure 3.22. The same as Fig. 3.20, but for the difference, Mark 4 minus observed. Contour interval is 1 degree C.

3.3.2.2 Simulated changes in temperature under enhanced greenhouse conditions

Changes in screen temperature over Queensland under enhanced greenhouse conditions in the Mark 4 simulation were calculated. The temperature difference between the 30 year average, centred on 1990, and the 30 year average, centred on 2050, was calculated. The results (Fig. 3.23) may be compared with the warmings for Mark 3 shown in Fig. 3.7. In all seasons, Mark 4 warms up faster than does Mark 3. For instance, in summer, when Mark 3 gives warmings of 0-1.2^{o}C, Mark 4 shows warmings of 0.5-2.0^{o}C.

The results can also be expressed as changes per degree of global warming; in other words, the calculated Mark 4 screen temperature differences between these two periods are divided by the average global warming of the Mark 4 model between these two periods. Since the Mark 4 model is “nudged” by the Mark 3 model, the average global warming in the two models is very similar. Under enhanced greenhouse conditions (Fig. 3.24), average screen temperature increases per degree of global warming show values of up to 3^{o}C per degree of global warming in spring (Fig. 3.24(e)). These contrast with rather smaller increases per degree of global warming simulated for the combination of DARLAM at a resolution of 60 km nested within the Mark 2 GCM (see Walsh et al. (2001), Fig. 2.5). The global warming of the Mark 3 model itself is relatively slow in the early part of the 21st century and becomes more rapid towards the end of the century (not shown). Because of this slow global warming and the more rapid response of the land regions of Mark 4, the increase in temperature over the land regions of Australia per degree of global warming is large. Similar results are seen for maximum and minimum temperature (not shown).

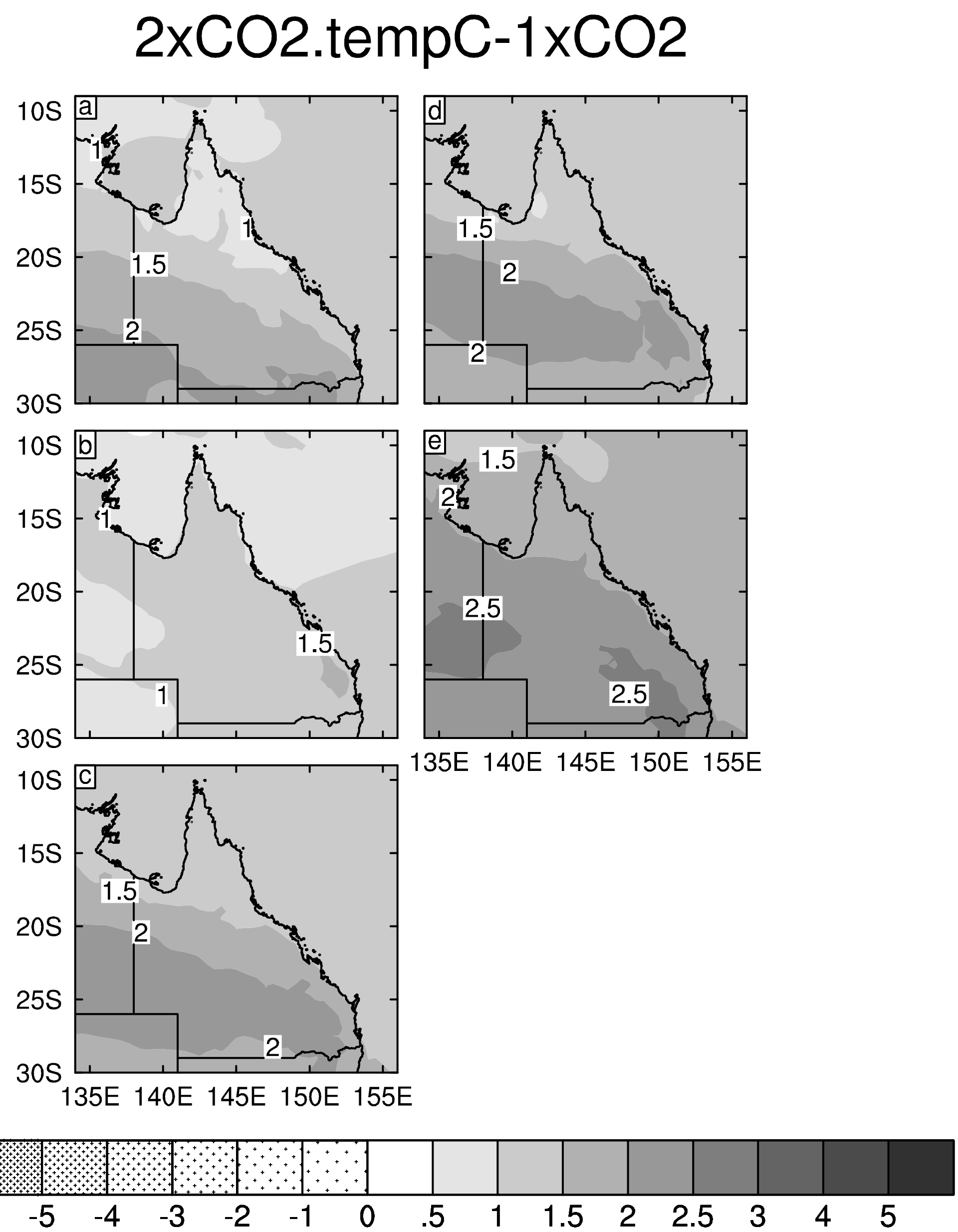


Figure 3.23. Change in average screen temperature for Mark 4 model, difference of 2050 minus 1990, for (a) Dec.- Feb.; (b) June-Aug.; (c) annual average; (d) March-May; and (e) Sept.-Nov. Contour interval is 0.5 degrees.

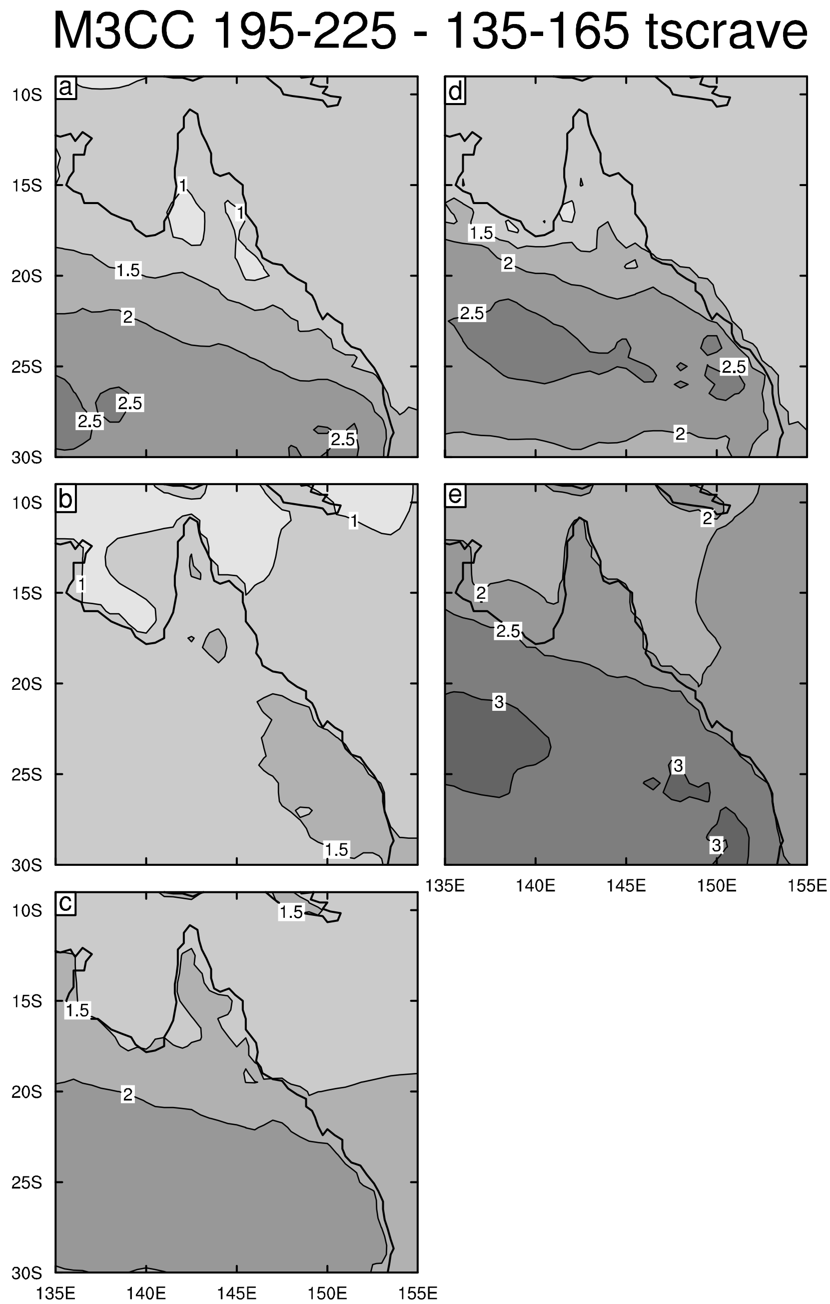


Figure 3.24. The same as Fig. 3.23 except changes per degree of global warming.

Rainfall

The Mark 4 simulation of average annual precipitation is particularly good (Figs. 3.25-3.27; observations are from Jeffreys et al., 2001). In general, the observed spatial patterns are well-simulated and the biases are mostly less than 100 mm in most places, with a few exceptions such as the Gulf region in summer. This represents a considerable improvement on the simulations reported on in Walsh et al. (2001) where the DARLAM model anomalies were sometimes in excess of 200 mm per season. The improvement is due to the increased resolution of Mark 4 that enhances the underlying climatology of the driving Mark 3 simulation.

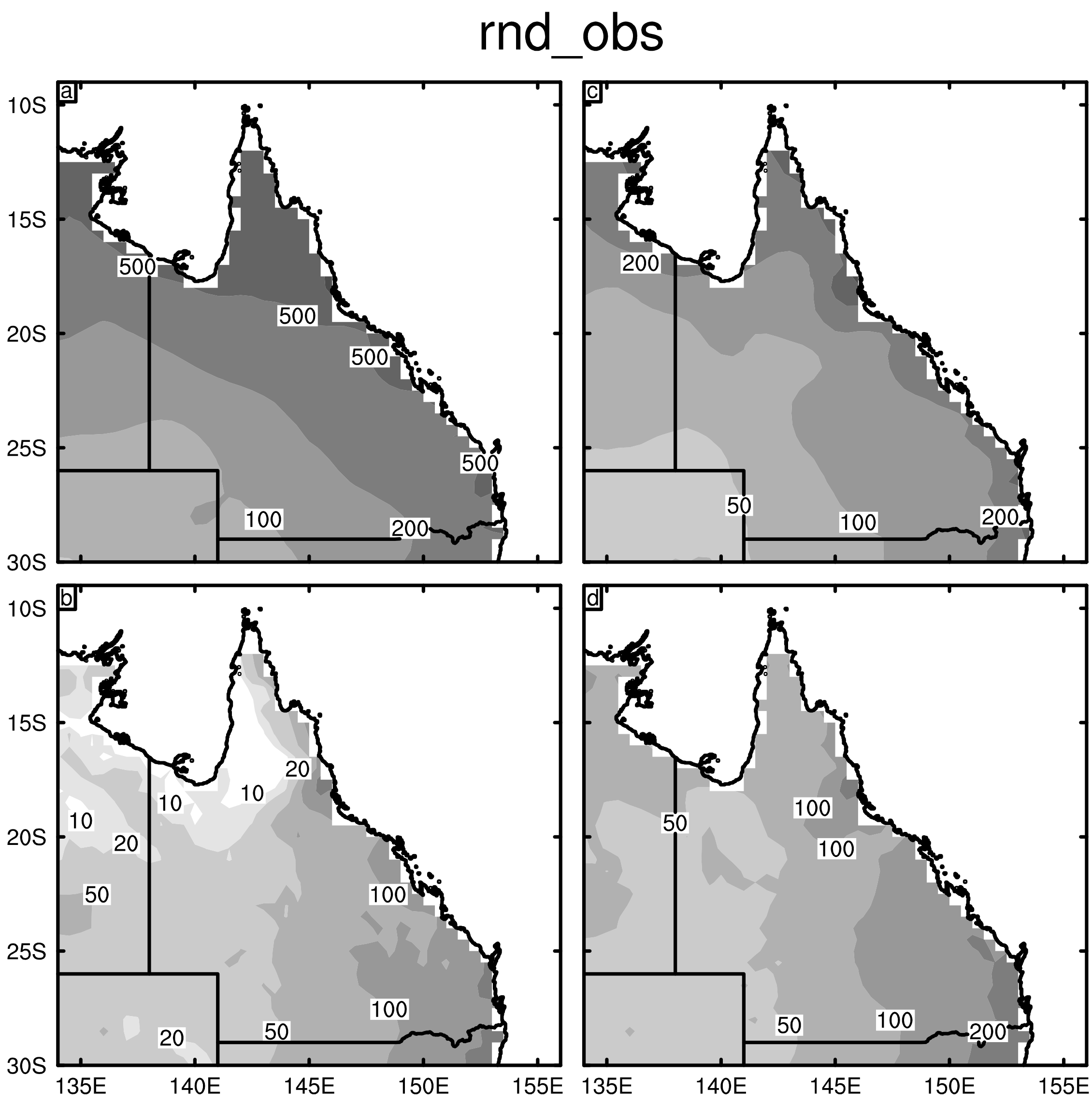


Figure 3.25. Observations of Queensland rainfall per season, in mm: (a) summer (Dec.-Feb.); (b) winter (June-Aug.); (c) autumn (Mar.-May); and (d) spring (Sept.-Nov.). Derived from Jeffrey et al. (2001).

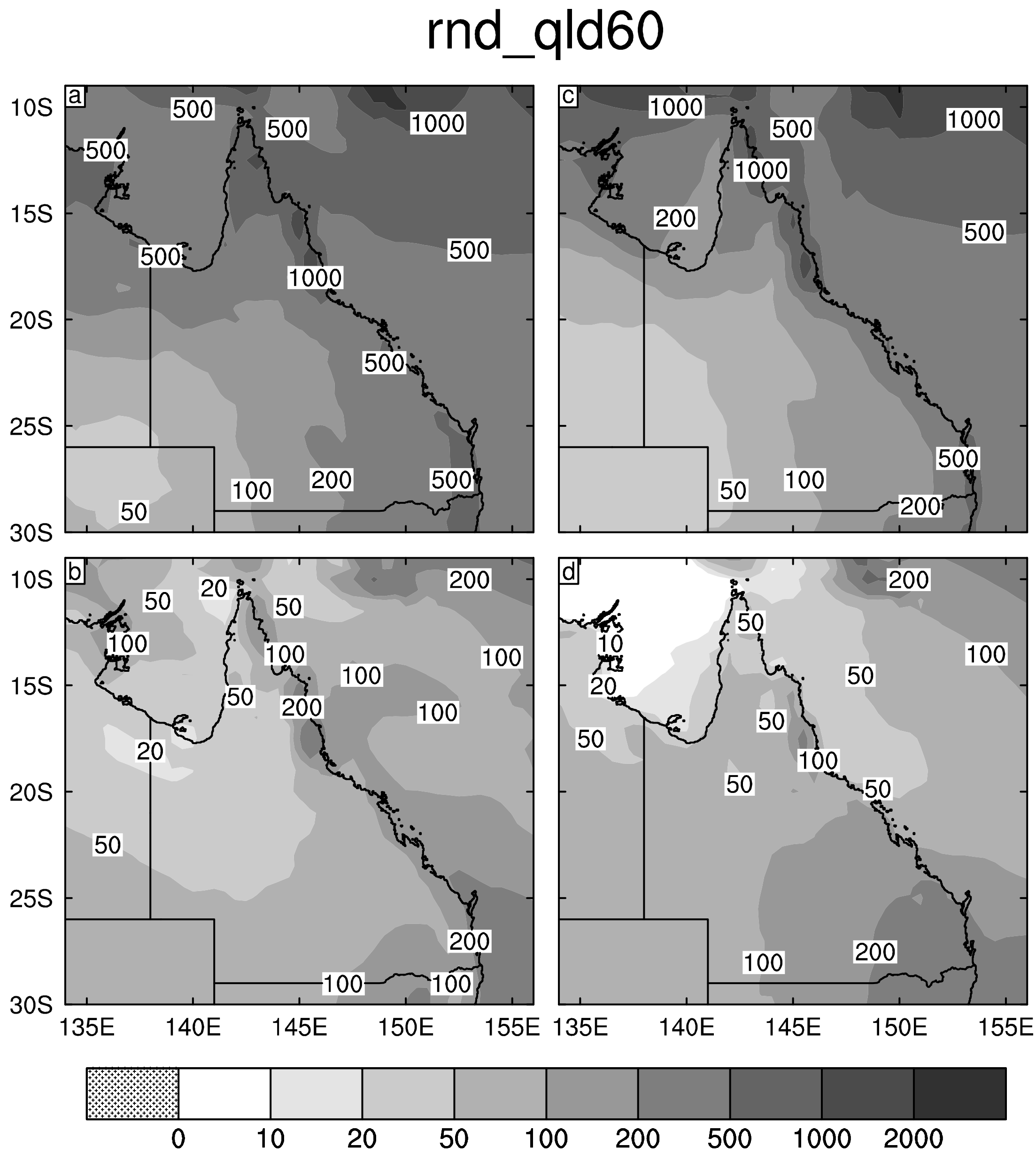


Figure 3.26. The same as Fig. 3.25 but for the Mark 4 simulation.

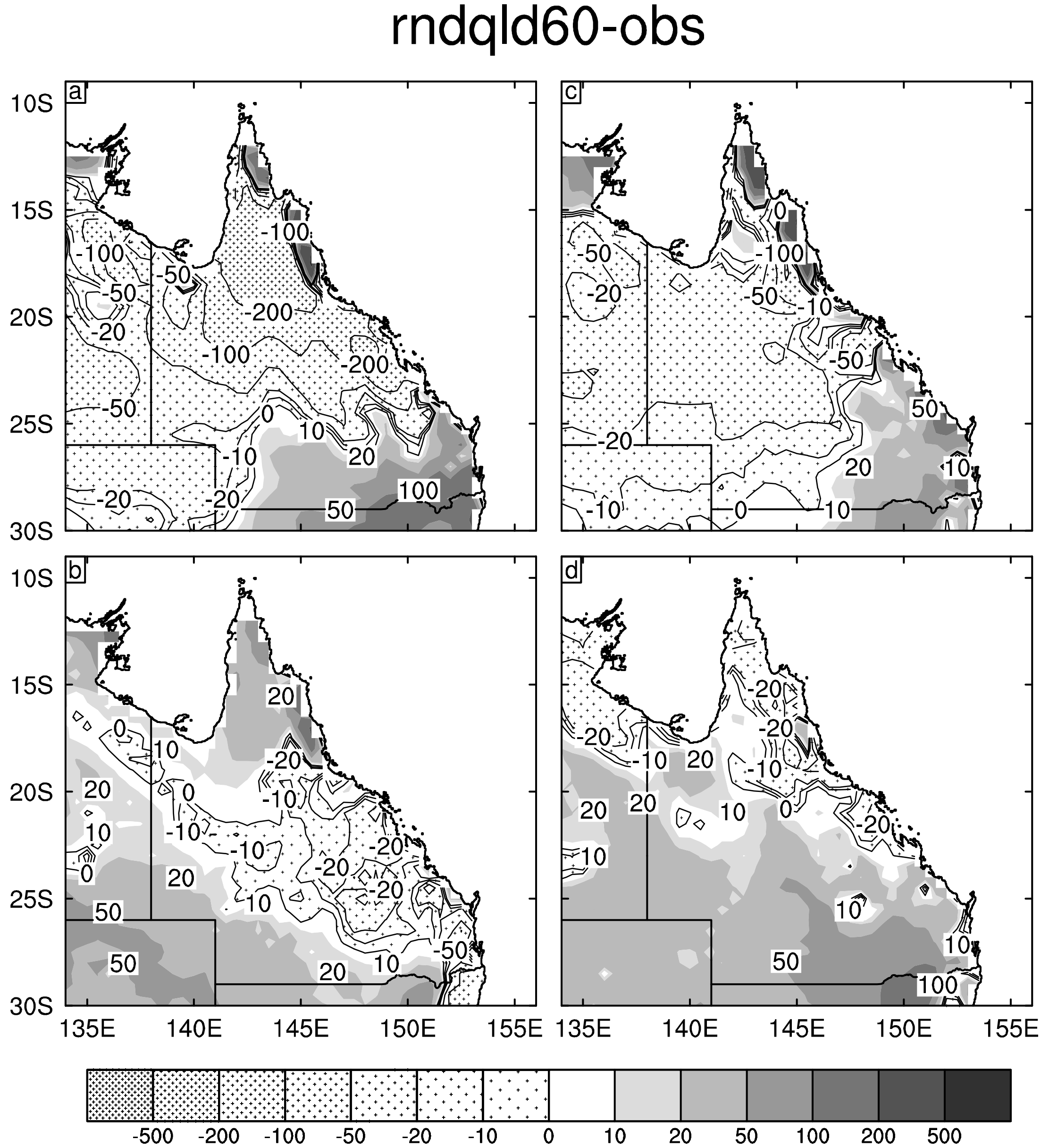


Figure 3.27. The same as Fig. 3.25 except difference, Mark 4 minus observed.

3.3.2.3 Simulated changes in rainfall under enhanced greenhouse conditions

Changes in rainfall are shown in Fig. 3.28, with changes expressed in percent per degree of global warming in Fig. 3.29. In general, the pattern appears fairly noisy, with substantial differences in trends evident across various regions of the state. Slight increases are simulated over the north of the State in summer and in the southwest, but most of the state could be characterised as little changed (that is, less than 20% increase or decrease per degree of global warming). In autumn, mostly decreases or no change is simulated, with an area tending towards increase in the southwest. The winter simulation is characterised by an area of increases in the centre of the state, and little change elsewhere. This pattern is somewhat different from that of the climate change scenarios of Fig. 2.2. The spring simulation gives mostly little change, whereas the scenarios for this month suggest a tendency towards decreases in rainfall.

For the annual mean (Fig. 3.26c), rainfall changes are relatively small, with only small regions in the north predicting increases of more than 20%.

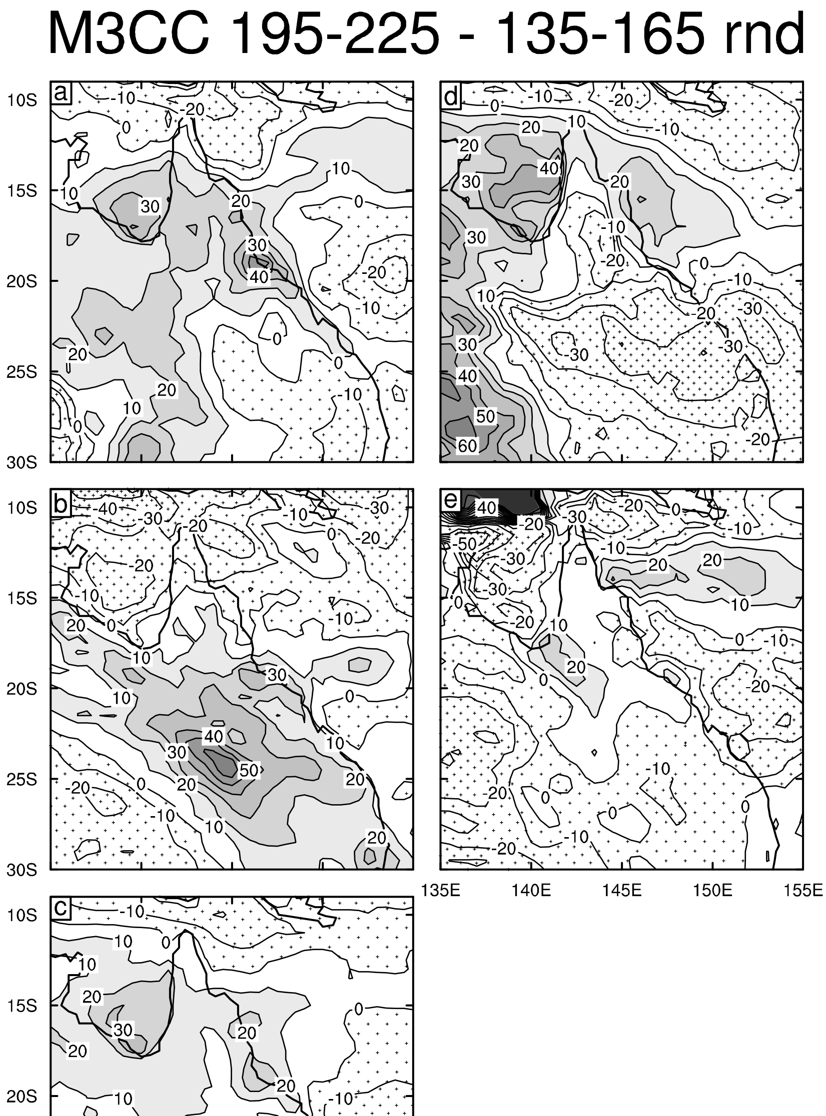


Figure 3.28. The same as Fig. 3.23, except for rainfall changes in mm.

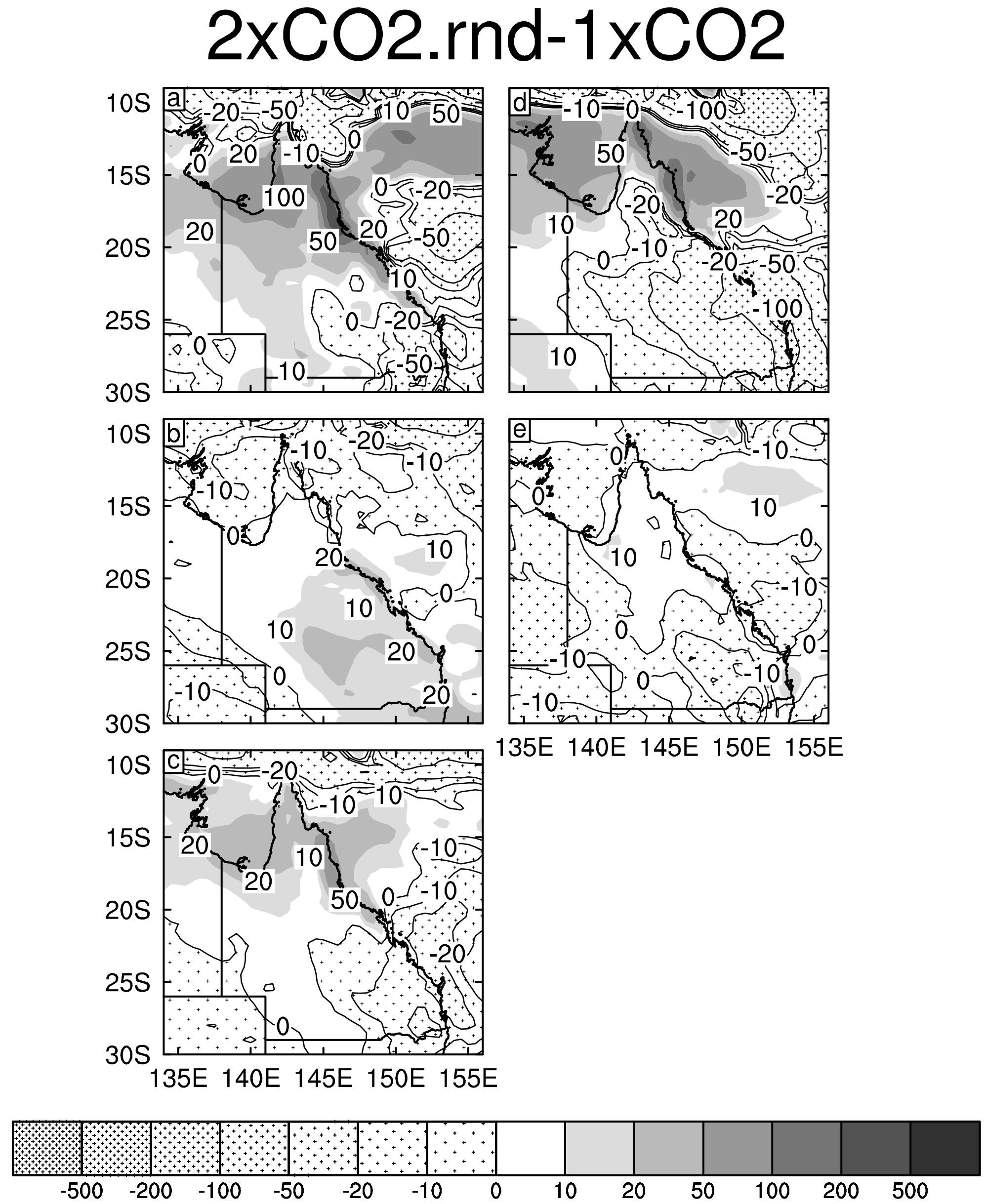


Figure 3.29. The same as Fig. 3.28 except changes in percent per degree of global warming.

3.4 Summary

The Mark 3 global climate model has a generally good simulation of rainfall over Australia, with an excellent simulation of the seasonal variation of Queensland rainfall and a good simulation of its characteristic year-to-year variability. By 2050, Mark 3 predicts temperature increases over Queensland that are towards the low end of most model projections of temperature change, as documented in the climate change scenarios produced by CSIRO (2001). In Mark 3, Queensland average rainfall is projected to change little, with a tendency towards slightly wetter conditions. The model does not substantially drift towards a more El Niño-like average state under enhanced greenhouse conditions, as do the majority of current climate models.

The Mark 4 variable-resolution climate model was "nudged" by the Mark 3 global model to create a new high-resolution simulation over Queensland. Mark 4 has a good simulation of air temperature over Queensland and an excellent simulation of rainfall. There are some biases in the model's simulation of maximum air temperature in the north of the State that need to be investigated. Under enhanced greenhouse conditions, the Mark 4 model warms up over Australia considerably faster than the Mark 3 GCM. Rainfall changes simulated by the Mark 4 model tend to be noisier than those generated by the Mark 3 global model, because of Mark 4's higher spatial resolution. Annual average rainfall over Queensland is projected to change little by Mark 4.

Because of the high quality of its rainfall simulation, the predictions of the Mark 4 model will form an important part of any newly constructed rainfall change scenario for Queensland. Most importantly, further analysis of this simulation will aid in establishing a robust prediction of the direction of rainfall change over the different regions of the State.

4 Tropical Cyclones and Climate Change (Milestone 2.4.2)

4.1 Introduction

Considerable progress has been achieved in the past few years in our understanding of the effect of climate change on tropical cyclones. It would be fair to say that as little as five years ago, nothing genuinely concrete was known regarding this issue, despite some preliminary attempts to address it. Since then, the science has advanced to the point where IPCC (2001) considers that increases in tropical cyclone intensities are "likely, over some areas" (IPCC, 2001 defines "likely" as a 66-90% chance). This statement has been based in part on work that has been completed as part of this consultancy (Walsh and Ryan, 2000).

4.2 Current Understanding

Giorgi et al. (2001) details current understanding of this issue. Their conclusions, and those of this consultancy, are briefly summarized here:

- Little change in the regions of tropical cyclone formation is expected.
- Changes in numbers could be significant in some regions, mostly tied to possible changes in the behaviour of ENSO. A trend that is seen in a number of GCM simulations, to a more "El Niño-like climate" in a warmer world, may lead to tropical cyclone formation that is more similar to that seen in El Niño years than that in the current average climate, but this change has not yet been properly calculated.
- There is an emerging consensus that maximum tropical cyclone intensities (i.e. wind speeds) are likely to increase by 5 to 10%. This will be accompanied by increases in peak precipitation rates of 20 to 30%.
- There is no convincing evidence yet that tropical cyclones will travel further poleward than they currently do.

Little change in the typical regions of formation implies no extension southward of the current formation region, which extends from the far north of the State to near the Tropic of Capricorn. After formation, tropical cyclones can travel quite far south of these latitudes, occasionally affecting the Gold Coast and even the north island of New Zealand, but there is yet no convincing evidence that climate change will lead to cyclones retaining their intensity further south than they currently do, despite some studies that have examined this issue (Walsh and Katzfey, 2000).

An unresolved issue is whether changes in ENSO will cause changes in tropical cyclone numbers in the Queensland region. Cubasch et al. (2001) conclude that the majority of GCM projections indicate a future climate that is more El Niño-like, with central and eastern equatorial Pacific temperatures warming faster than the western equatorial Pacific. This is accompanied by a corresponding eastward shift in mean precipitation. Given the teleconnections to cyclone activity, this should also lead to an eastward shift in tropical cyclone formation away from the Queensland coast, and the simulations of Nguyen and Walsh (2001) indeed found some support for this argument. The difficulty in properly estimating the effect on numbers of tropical cyclones hitting the Queensland coast is that the actual size of this effect is currently poorly quantified because the models need to be improved. However, McInnes et al. (2000) estimated that to negate the combined impact of increases in tropical cyclone intensity and higher sea level on the changes in the storm surge climatology of the Cairns region, the number of tropical cyclones would have to decrease by a factor of three, which seems very large.

4.3 Analysis of high-resolution simulations of tropical cyclones

One way of better quantifying the interrelationships between climate change, ENSO and tropical cyclones is to improve on the work of Nguyen and Walsh (2001) by using a higher-resolution tropical cyclone model. Preliminary results of this new study were reported in Walsh et al. (2001). Additional results are presented here, using DARLAM at 30 km horizontal resolution implemented over the domain shown in Fig. 4.1. This extends slightly further north than the domain shown in Walsh et al. (2001), because the edges of the 30-km resolution domain are forced by a coarser-resolution 125-km domain, and so near the edges of the 30-km domain, tropical cyclones are less intense and thus harder to detect. This was suppressing formation in the northern part of the domain compared to that observed in reality, so here the domain boundary was moved northwards.

An important point to note is that unlike previous simulations, tropical cyclone-like vortices in this version of DARLAM were detected if their maximum wind speeds were above the actual observed threshold for real tropical cyclones of 17 m s^{-1}. In previous coarser-resolution climate simulations, the detection threshold was set rather lower to compensate for the lower horizontal resolution, which makes the simulated tropical cyclones less intense.

With the change of northern boundary, simulated formation improves (Fig. 4.2). Under enhanced greenhouse conditions (roughly corresponding to 2060-2090), formation does not change very much. To examine the issue of whether tropical cyclones are likely to track further south in a warmer world, we plot the simulated occurrence, or the number of tropical cyclone days that occur in a latitude band (Fig. 4.3). The model simulates slightly too much tropical cyclone occurrence in the band from 15^oS-20^oS, but there does not appear to be a strong consistent increase in cyclone occurrence under $3xCO_2$ conditions south of 25^oS. Therefore this simulation does not support the idea that tropical cyclone occurrence will increase substantially in the southern coastal regions of Queensland.

This simulation is also of high enough horizontal resolution to examine the issue of whether tropical cyclones will increase in intensity in a warmer world. The simulated intensity distributions for current climate and $3xCO_2$ conditions are shown in Fig. 4.4. In this Figure there is some simulated increase in the number of tropical cyclone days of wind speeds higher than 30 ms^{-1} in a warmer world. This result is not inconsistent with the conclusions reached in IPCC (2001). Note, though, that the simulated intensities of tropical cyclones in this model are rather lower than the observed intensities, which would be improved by finer resolution. Studies have shown that to simulate most characteristics of a tropical cyclone, including their intensities, horizontal resolutions approaching 5 km would be necessary (e.g. Liu et al., 1997).

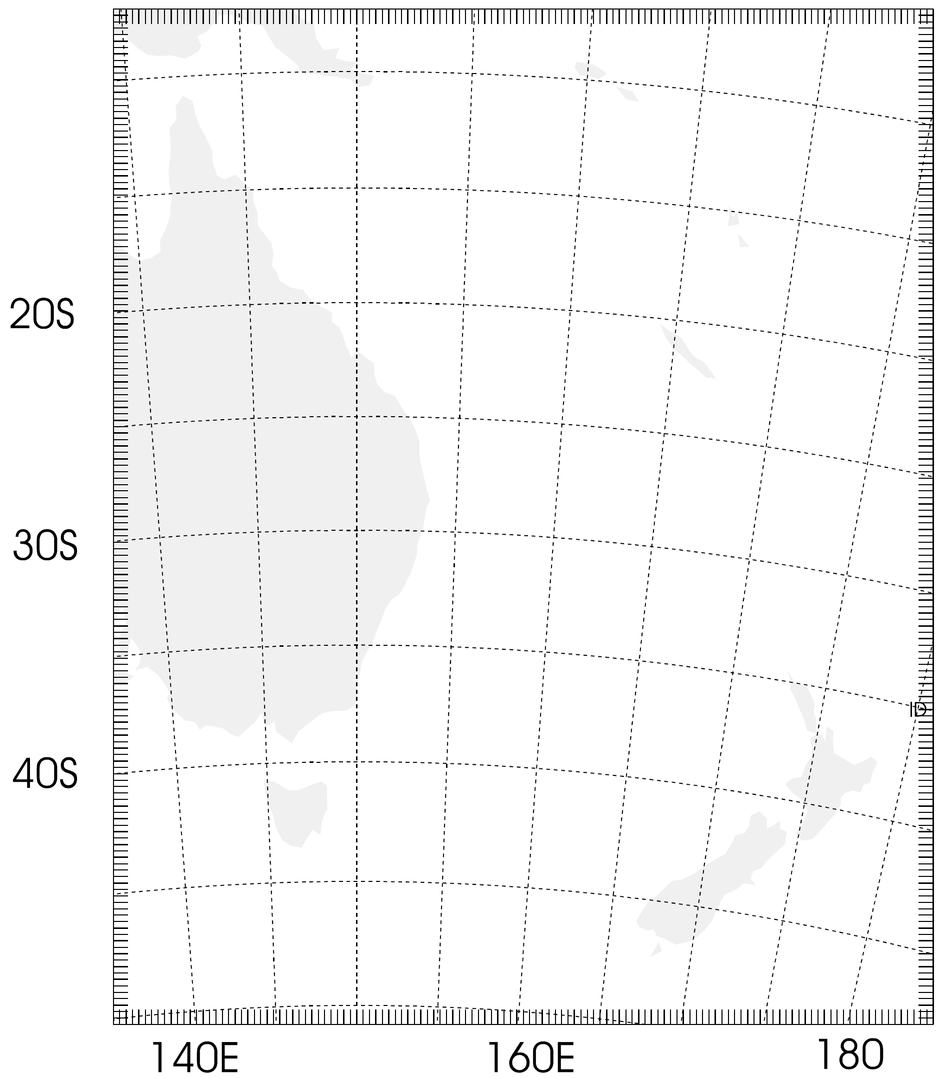


Figure 4.1. Domain of 30-km horizontal resolution tropical cyclone simulations.

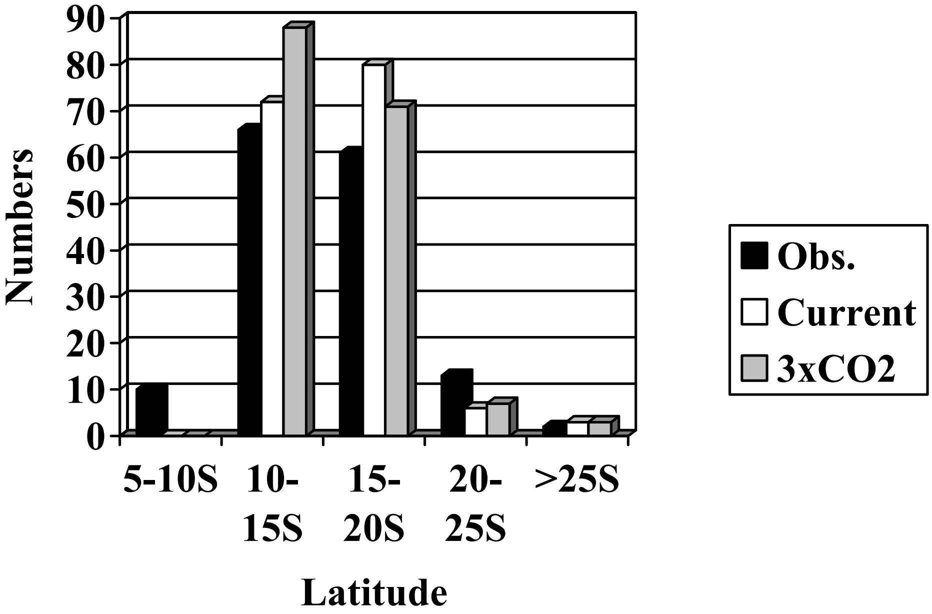


Figure 4.2. Simulated versus observed January-March tropical cyclone formation by latitude band, for the observations (black bars), current climate (white bars) and the $3xCO_2$ simulation (grey bars).

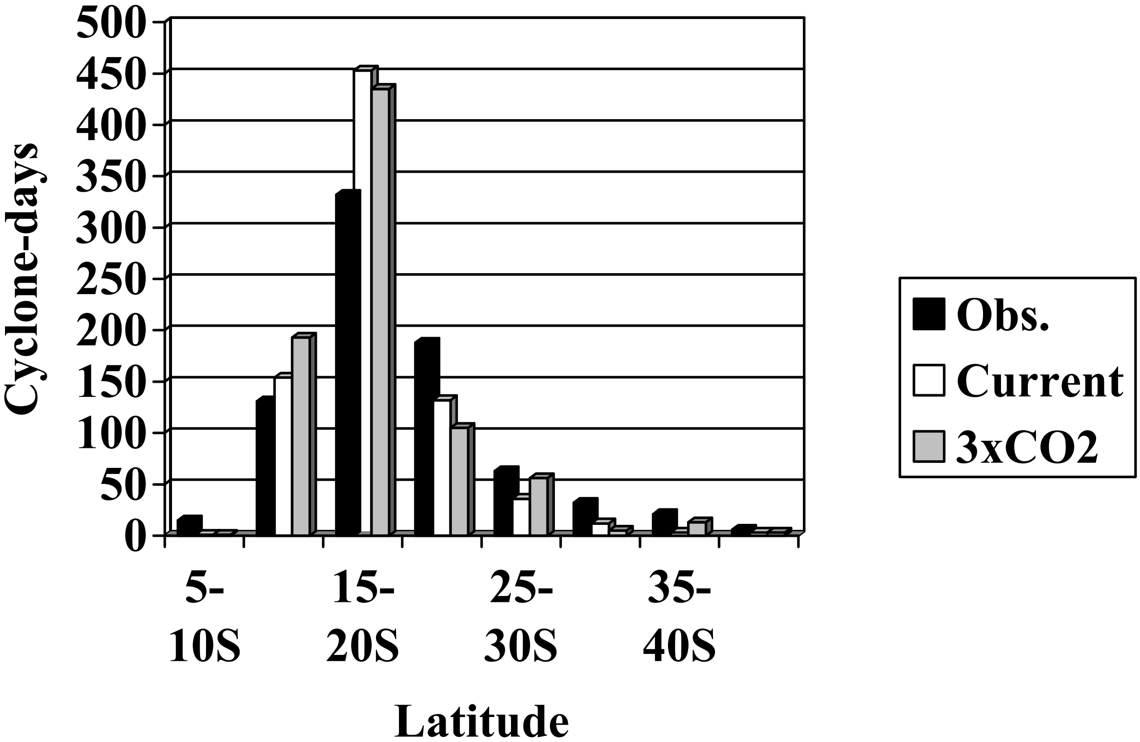


Figure 4.3. The same as Fig. 4.2 but for cyclone occurrence.

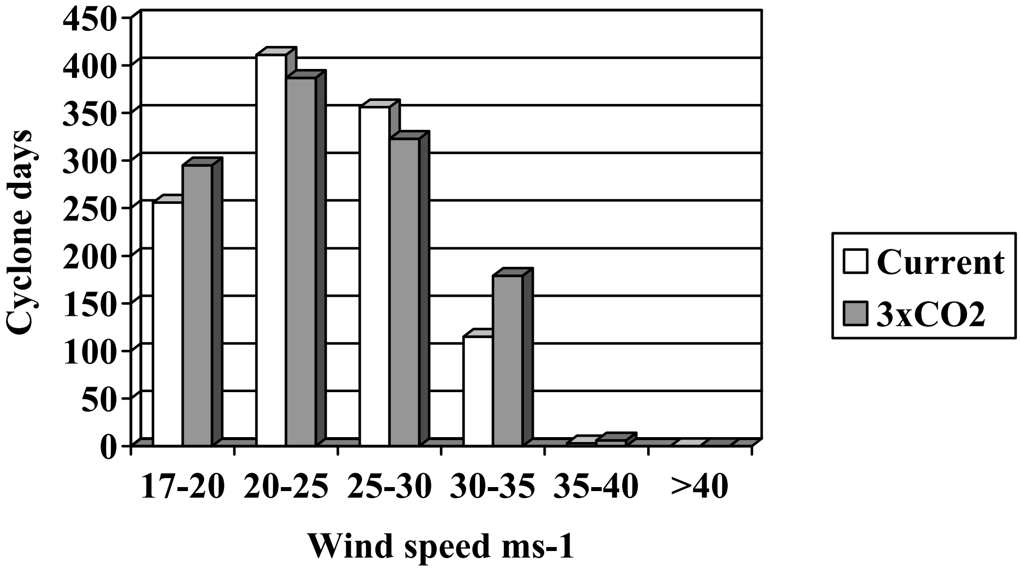


Figure 4.4. Distribution of simulated tropical cyclone wind speeds in the current climate (white bars) and in $3xCO_2$ conditions (grey bars).

In summary, the latest simulations for the Queensland region are consistent with increases in maximum tropical cyclone intensities, but do not provide convincing evidence of any southward extension of their typical tracks in the Queensland region. Simulations at even finer resolution are required to address these issues.

5 Future Work

Considerable progress has been made during the four-year period of this consultancy. It was realized at the commencement of the contract that one of the main focuses of the work would be on improvement of the existing climate models, as this was the only way that answers were likely to be found to questions such as the effect of climate change on Queensland rainfall, for instance. With the development of the Mark 3 climate model, it appears that robust answers to this question now appear to be in sight. Further model development is envisaged, however, as it is fair to say that while current climate models now have a reasonable simulation of the general characteristics of ENSO, they still do not simulate all of the characteristics of ENSO in detail. For instance, most state-of-the-art climate models generate a region of anomalously cool water along the equator that is not observed.

Nevertheless, model development has now proceeded to the point where some answers can be given to questions regarding the impacts of climate change on infrastructure and the environment. In regions of tropical Queensland, there may need to be some further consideration of the impact of increases in tropical cyclone wind speeds and rainfall rates on the design standards of infrastructure. There will likely be changes in tropical forest environments. A general decrease in soil moisture in Queensland in a warmer world will have implications for agriculture. Some beneficial effects of increased atmospheric carbon dioxide concentrations are likely for some agricultural sectors. There are many other questions on the impacts of climate change that need to be resolved.

Crucial questions that remain to be answered include a robust estimate of the direction of rainfall change in the various regions of Queensland, rather than the ranges supplied so far, and the resulting impact on water resources; the interaction between the effects of climate change and the large decadal variability in rainfall that is experienced in Queensland; and whether tropical cyclone numbers will change significantly off the coast of Queensland in a warmer world. The effort to apply to results of climate model experiments to the assessment of climate impacts will become increasingly important as the science of climate change progresses.

Not all of the answers to the effects of climate change will be available at the same time. Because of the inevitable uncertainty in future greenhouse gas emissions, projections of climate change impacts will always be accompanied by a range of predictions. Thus managing climate change is about managing risk. The value of climate change studies is that by reducing the range of uncertainty they can minimize the costs of under- or over-adaptation to the effects of climate change.

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