Indian Ocean Climate Initiative

Informed Adaptation

Indian Ocean Climate Initiative Stage 2: Report of Phase 1 Activity

July 2003 – Dec 2004

Establishing the methodological foundations of Stage 2 and updating regional interpretations from global climate modelling

Editors
Brian Ryan and Pandora Hope
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The Indian Ocean Climate Initiative (IOCI) is a partnership of the State, CSIRO and the Australian Bureau of Meteorology formed by the Western Australian Government to support informed decision making on climate variability and change in Western Australia.

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1) Foreword

Climate change and variability are profoundly important issues in southwestern Australia. Observed climate shifts over recent decades are over-turning traditional bases of both seasonal and long term decision-making of climate affected sectors.

The recent changes in regional climate regime, particularly those relating to rainfall decrease, have caused heavy impacts on some sectors. Although impacts and responses have varied widely until now, change issues will ultimately affect a broad spectrum of society, directly or indirectly. People in sectors that have been unaffected to date need to be alert and consider their vulnerability.

The region's climate issues are an inter-play of natural variability and anthropogenically forced change. Some of the most critical climate regime shifts which have occurred in our region are larger than have been simulated in climate models forced with recent changes in greenhouse gas concentrations. This is a source of serious concern and added uncertainty for many decision makers.

Study of cause is important to forecasting future climate conditions, particularly in respect to the observed rainfall change. This last phase of the Indian Ocean Climate Initiative (IOCI) research has strengthened the view that anthropogenic factors, most particularly greenhouse gas concentrations, have contributed to the observed change.

To sustain our region's social, economic and environmental prosperity, informed judgements on issues relating to climate are necessary. Both climate and climate science are evolving rapidly and a need to keep pace with such developments will continue throughout the 21st century. Surprises will be inevitable, but alertness, supported by on-going regional science and interpretation, will be a key to avoiding shocks and to exploiting opportunity.

The second five year stage of IOCI research has taken several important steps in both support objectives and in scientific approach.

In support terms, IOCI's Stage 2 program is designed to actively relate to key State strategies. This role includes very specific linkages to the adaptive stream of the State Greenhouse Strategy and the current front-line issues of the State Water Strategy. Within the constraint of a limited budget, Stage 2 will increase IOCI's interpretation and communication of climate information in keeping with decision priorities.

In research terms the Stage 2 program has been designed to strategically pursue three key themes: *Current Climate Regimes*; *Climate Change*; and *Climate Prediction*. The program, which commenced in July 2003, is a five year research strategy in three approximately equal phases. These phases are designed to progress from developing foundations and tools to applying these developments to the key research questions.

The Stage 2 program is pursuing current state-of-art methodologies and approaches, both physical and statistical, to achieve its support goals. A key directional thrust underlying this program is to employ these technologies in the study of broad synoptic conditions and changes. This stratagem is viewed as the most robust approach available for further study of variability and change and for attempts at attributing primary cause to observed variability and change phenomena.

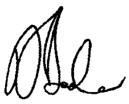
Phase 1, reported herein, is the foundation phase of the Stage 2 program. New ways of looking at the description of regional synoptics and techniques for measuring, analysing and modelling their trends and perturbations have been developed. These tools will be used systematically in following activity to form bridges between observation, modelling, projection, and downscaling of future regional climate variables. Along the way, as in this report, the study of techniques and synoptics will yield direct insights into climatic regime shifts and events which are impacting on our economy, environment and life-style.

This document presents a summary of progress on Phase 1. It reports successes, some non-successes, and some related activities and emerging opportunities in developing the tools for the next phases of research. A solid foundation for work on the next phases is demonstrated.

Concurrent with its reporting of progress on the research strategy, the document also presents developing insights and interpretive material. Included specifically in support of the State Greenhouse Strategy and Water Strategy are up-to-date regionalised projections of trends associated with global warming.

The southwestern region of Australia is an important frontline area in national climate adaptation. The products of IOCI, together with the parallel initiatives that are stimulated by the IOCI activity, are of national as well as regional significance. They represent a substantial achievement for a very modestly funded research program.

This report, in conjunction with other IOCI products, is commended to decision-makers and researchers alike, at regional, state and national levels. IOCI and its partners will take steps to make elements of this work widely accessible.



Brian Sadler PSM FTSE
Chairman, Indian Ocean Climate Initiative Panel

2) Overview

Stage 2 of the IOCI core research strategy aims to:

- systematically investigate changes and causes of change in the climatic patterns of southwest Western Australia (SWWA);
- investigate climate variability;
- help decision-making to adapt to climate change and climate variability.

The research program addressing the strategy is built around a framework of three interacting themes:

- Current climate regimes;
- Climate change projections;
- Short-term climate predictions.

The Stage 2 work program consists of two phases with a planned mid-term report to the state partners on the outcomes of Phase 1 prior to the commencement of Phase 2 of the research strategy.

This report of Phase 1 activity presents three theme summaries that:

- report on the projects and their scientific findings;
- discuss the achievement Phase 1 targets;
- document the scientific basis for Phase 2.

More detailed reports on the individual projects in Phase 1 are provided as separate documents (Theme 1, Theme 2 and Theme 3) and are available at http://www.ioci.org.au/publications/reports.html.

Key messages

The activity report highlights the following key messages for policy decision makers concerning changes to the climate baseline and the impact of greenhouse forcing on future climate baselines:

- IOCI (2002) concluded that “Most likely, both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease” and that “Other local factors, such as land-use changes in the southwest…seem unlikely to be major factors in the rainfall decrease, but may be secondary contributors”;
- Although conclusive detection and attribution of climate change in an area the size of the southwest is challenging, especially for rainfall, the work thus far in Stage 2 has, if anything, strengthened the conclusions from Stage 1;
- In Stage 2, IOCI applied more emphasis to investigating and downscaling large scale changes in atmospheric circulation. There is now stronger evidence that the rainfall decline is associated with such large scale changes and that these are at least partly driven by anthropogenic changes, most particularly the enhanced greenhouse effect. Research also indicates the statistical possibility that such changes could occur through natural variability;
- The latest suite of climate change simulations show that greenhouse gas radiative forcing does not fully explain the observed trend in rainfall over the most recent period and IOCI retains the opinion that it is most likely that both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease;

- Because of the geographic scale of the influences, IOCI remains of the opinion that other local anthropogenic factors such as land-use change in SWWA are unlikely to be the primary cause of the observed change. No conclusive position has been reached on whether ozone depletion has contributed to the rainfall decline;
- The latest suite of climate change simulations also show that even with the most optimistic emission scenarios, SWWA is projected to be drier and warmer later this century with increasing probability of 'dry everywhere' winter weather patterns and decreasing probability of 'wet west and central' weather patterns;
- Recent winters in SWWA have been particularly dry. Coupling this situation with the expectation of further rainfall decline and the past experience of a step decrease, has given rise to legitimate local concerns that the region may be in the throes of another step decrease. It is to be hoped that the additional scientific insights now being developed will help quicker identification of such an event (or indeed of some natural recovery towards past regimes). However, there is insufficient statistical and synoptic evidence, at this stage, to support or reject this inference. Regular review appears desirable.

Key findings of a more specific nature in understanding of SWWA climate

All three themes have delivered important insights and understanding of the climate of the SWWA that include:

- Insights into how the large-scale circulation was different before and after the mid-1970s. The likelihood of conditions conducive to storms over the region has reduced and concomitant with this, the frequency of synoptic types associated with southwest rainfall has decreased;
- Confirmation from recent model studies of the assessment in the Stage 1 report that most likely both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease;
- An assessment that land cover changes may be contributing to a rainfall decrease but are unlikely to be responsible for the changes in large-scale circulation which accompanied the observed decline;
- New projections for inland regions of SWWA under SRES emission scenarios which indicate:
  - a warming during the summer-half of the year of between +0.5 and +2.1°C by 2030 and between +1.0 and +6.5°C by 2070;
  - a warming during the winter-half of the year of between +0.5 and +2.0°C by 2030 and between +1.0 and +5.5°C by 2070.
- Projected rainfall changes for the SRES emission scenarios which are between –2% and –20% by 2030 and between –5% and –60% by 2070 for SWWA during the winter-half of the year;
- Projected changes of potential evaporation under the SRES scenarios of up to +10% by 2030 and by up to about +30% by 2070 for SWWA during the winter-half of the year;
- Statistical downscaling of rainfall in models using complementary techniques developed by CSIRO and BMRC show consistent climate change projections both from the CCAM and the MK3 CGCM (a 15% decrease by mid-century for the relatively extreme A2 scenario);

- There is a significant drying trend under projections using the 450 ppm and 550 ppm stabilisation emission scenarios;
- Some tentative findings from investigations of extreme daily rainfall with a prototype spatial statistical model. These preliminary results indicate that, over the Avon catchment region during winter:
  - for events with a return period of 5 years there has been an increase to the north and a decrease to the south;
  - for events with a return period of 25 years there has been an increase throughout the northwest and a decrease in the southeast.

New methodologies to investigate change and seasonal prediction in the next phase

The strategic goals of Stage 2 have required the application of new methodologies that have potential to enhance forward projection via modelling of large scale effects:

- The development of synoptic classifications using self organising maps;
- A methodology to analyse the large-scale changes to the weather systems since 1970;
- Improved procedures for selecting atmospheric predictors for statistical downscaling;
- Improved methodology for the statistical downscaling of rainfall amounts;
- A methodology to analyse synoptic events that lead to extreme rainfall;
- Early development of hybrid tools linking physical and statistical models as a new approach to seasonal forecasting.

New scientific challenges or opportunities

- Changes in sea ice have been identified as a possible driver of rainfall change in the 1970s. If confirmed this could result in opportunity for model refinement;
- It has become apparent, when using CCAM to dynamically downscale results from large-scale climate models, that the influence of the large-scale upper-level wind fields should be included;
- Skilfully predicting SWWA winter rainfall from as early as April 1 does not look feasible using the CSIRO GCM in seasonal hindcast mode. A new approach is being considered.

The partners would like to acknowledge the support of Julie Siedses in the preparation of this report. Thanks are also given to Robin Ryan and Simon Torok for their assistance in editing the report.

3) Summary Report[1] for Theme 1: Current climate regimes

How is climate changing, what is causing it to change, and what is the current climate baseline?

Contributing Authors: Pandora Hope, Neville Nicholls, Lynda Chambers, Carsten Frederiksen, Jorgen Frederiksen, Wenju Cai, Ge Shi, Mark Collier, Bertrand Timbal, Ian Smith, Scott Power

The aim of Theme 1 is to investigate the nature and causes of the recent rainfall decrease in SWWA. A detailed examination of the large-scale drivers of climate variability and change in the Southern Hemisphere will facilitate this investigation. It builds on the research in IOCI Stage 1, which concluded that: "Most likely, both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease".

The research addresses what was identified, in IOCI 2002, as the "major scientific challenge", namely to "determine the relative influences of natural variability and the enhanced greenhouse effect in causing the recent decrease in rainfall". Until this is resolved it will be difficult to produce confident projections of future rainfall in the southwest.

This stream also addresses the question of how much other global anthropogenic changes (e.g. land-use changes or ozone depletion) may have contributed to the rainfall decrease and also, where easily addressed, the impact of local changes to the environment (e.g. land-use changes or air pollution). Only those factors likely to have had a substantial impact on the recent climate changes are considered. This question is also addressed in the Report for Theme 2.

The primary output targets for the first phase of this theme were:

- Methods to produce time series of synoptic events affecting the southwest;
- CSIRO Mk3 CGCM results dynamically downscaled to regional scales and also statistically downscaled to individual station points for the period 1960s to the present in order to facilitate a detailed comparison between simulated and observed climate. The results of this output are presented as part of Theme 2;
- Documentation of the changes in large scale atmospheric circulation in the 1970s;
- Analysis of the Mk3 CGCM simulation without greenhouse forcing to identify the indicators of natural decadal variability in the model.

The three projects within this theme, for completion during Phase 1, were:

- Project 1.1: Develop methods to identify the changes in synoptic events affecting southwest rainfall;
- Project 1.2: Determine the mid-1970s changes in the mean Southern Hemisphere (SH) circulation;
- Project 1.3: Assess the role of multi-decadal variability by analysing the results from a climate model run for several hundred years under present-day conditions.

Progress in each of these projects is summarised below, along with a discussion of other related work. More comprehensive descriptions of each project are given in the Theme 1 report.

[1]The Theme 1 Technical Report is available from: http://www.ioci.org.au

3.1 Summary of progress on core activity, July 2003 – December 2004

3.1.1 Project 1.1: Develop methods to identify the changes in synoptic events affecting southwest rainfall

This part of the study will develop objective techniques to determine the number and intensity of various synoptic events using historical synoptic analyses and synoptic observations, and will relate them to southwest rainfall and other climate variables to determine the relative importance of the various events in the region.

A computer-assisted technique has been used to cluster synoptic patterns of sea-level pressure into types and to assess how the frequency of each type changes through time. The composite of rainfall on days corresponding to each synoptic type shows wet conditions linked to deep troughs and dry conditions linked to high pressure, with a continuum in between. A domain ranging from 90 to 130°E and 15 to 50°S was found to capture the variability associated with systems affecting rainfall in the southwest. *Synoptic types associated with wet conditions have decreased in frequency since the mid-1970s*. Analysis of the results when upper level data are included, and the link between the synoptic types and features such as northwest cloudbands, will form the basis of further work.

Backward air parcel trajectories can describe the source region of moisture and distinguish between different types of synoptic systems. Trajectories were calculated using reanalysis data from rainfall events (a discussion on the value of the reanalyses in studies such as this is given in the Theme 1 report). The weighted difference between the trajectory density maps for 1948–1975 and 1976–2003 shows that the *preferred direction of approach is from further south in the latter period*. The features driving these shifts need further consideration and analysis.

The direction of station wind during rain-days at Wandering, Perth Airport and Cape Leeuwin was assessed. At Wandering and Perth Airport the wind was mostly from the north during rain-days in June and July. Furthermore, the amount of rainfall on these occasions far exceeded the rainfall totals when the wind came from any other direction. Rainfall associated with winds from the north and northeast has decreased since the 1970s at both these stations. At Perth Airport, the rainfall associated with winds from the east (predominantly from the northeast) has decreased markedly in June from the 1944–1959 average. This confirms that synoptic systems associated with surface winds from the northeast have contributed to the rainfall decline.

3.1.2 Project 1.2: Determine the mid-1970s changes in the mean Southern Hemisphere circulation

This project will examine the mean circulation before and after the mid-1970s decrease in rainfall in the southwest. These will be compared with different model circulations associated with anthropogenic climate change due to increasing greenhouse gases and other composition changes associated with human activity.

The Southern Hemisphere (SH) winter (MJJ) climates for the periods 1949–1968 and 1975–1994, using the reanalyses, have been compared. There are significant differences between the two periods. *Most noticeable is a reduction of 20% in the peak strength of the SH subtropical jet stream*. The jet stream is a region of strong upper level winds that often dictates the track of weather systems. The thermal structure of the SH atmosphere has also changed with a significant warming south of 30°S, tending to reduce the equator-pole temperature gradient. Such changes would be expected to have a significant effect on the stability of the SH circulation, and hence on the nature of the SH large-scale weather systems.

An analysis of the impact of these observed SH winter climate changes on the nature of the dominant SH weather 'modes' (or preferred configurations of the atmosphere) was conducted, with particular emphasis on the modes associated with storm tracks. A primitive equation instability model was used to identify the important weather modes in each period. Overall, the changes in the SH winter climate since the mid-1970s have led to a *reduction in the likelihood of the development of large-scale weather systems over SWWA (frontal passages and low pressure systems).* The dominant weather mode in the early period exerts most impact over SWWA, but in a corresponding mode in the later period, the region of most impact has moved over eastern Australia.

It is clear from this initial study that there have been large changes in the weather modes associated with large-scale weather systems in the SH between the two periods, and that these are associated with changes in the atmospheric circulation. We still have to evaluate the effects of the observed changes in the SH climate on other modes of variability that also affect Australian rainfall (e.g. northwest cloudband modes, the Southern Annular Mode). But we suspect that the changes in the modes associated with the storm track are probably the most important.

3.1.3 Project 1.3: Assess the role of multi-decadal variability by analysing the results from a climate model run for several hundred years under present-day conditions

This component of the project aims to identify drivers of multi-decadal variability which are independent of greenhouse forcing. The CSIRO Mark 3 climate model has been used to provide an unforced simulation of present-day climate, which represents a 'control' simulation against which other climate experiments can be compared.

The CSIRO Mark 3 coupled model, covering a multi-century (500 year) period, was run under 'control' conditions (i.e. without the effect of an enhanced greenhouse effect or other anthropogenic influences). *The winter rainfall over SWWA shows significant decadal and inter-decadal fluctuations, including multi-decadal-long drying trends at a rate similar to or greater than that observed. Thus, the amplitude of winter rainfall decrease resulting from multi-decadal 'natural' variability could be comparable to what has been observed since the late 1960s*.

The modelled multi-decadal rainfall fluctuations in the southwest are related to variations in the main pattern of variability in sea-level pressure in the SH – the Southern Annular Mode (SAM). Higher values of the SAM have high pressure across southern Australian latitudes and low pressure further south, while lower SAM values correspond to lower pressures across Australian latitudes. On multi-decadal time-scales, high values of the SAM correspond with low rainfall values in the southwest. Attributing the southwest rainfall decline to a specific cause is not a trivial task, as various forcings such as ozone depletion or the enhanced greenhouse effect may cause a positive trend in the SAM.

The results from this project suggest that both greenhouse forcing and multi-decadal natural variability may have combined to generate the observed drying trend in SWWA, further strengthening the conclusion of IOCI Stage 1.

3.2 Other related work by BMRC and CSIRO and in the literature

3.2.1 Has there been another shift?

There is a question as to whether or not, in recent years, rainfall (and thus streamflow) may have decreased further.

Bates et al. (2004) have extended an earlier report to IOCI (Bates et al., 2001) in an attempt to determine if there has been a further rainfall decline. The earlier work considered the winter half years (May to October) in the period 1958–1998; while the recent report considers 1958–2003. Again a stochastic downscaling model (the nonhomogeneous hidden Markov model, NHMM) was used to examine the relationship between multi-site rainfall and regional atmospheric circulation. No reprieve is shown from the extended dry period over the last few decades; in fact, the drying appears to have extended inland. The break points found in the late 1960s and mid-1970s have not changed with the inclusion of data since 1998, and the probability series for the weather state corresponding to dry conditions across SWWA continues to show an increasing trend.

Extending the work, by linking the southwest rainfall with large-scale features via nonlinear statistical methods, suggests possible changes through the mid-1990s in the relationship of Indian Ocean sea surface temperatures and Perth mean sea level pressure (PMSLP) with southwest average rainfall. PMSLP in particular seems to be having a largely negative effect on rainfall subsequent to 1997.

A simple way of assessing whether there has been another shift is by examining the time series of average SWWA rainfall. Figure 1 is a time series of winter (May–July) SWWA rainfall (southwest of a line between 30˚S, 115˚E and 35˚S, 120˚E – calculated from the National Climate Centre web site (http://www.bom.gov.au/silo/products/cli_chg). Horizontal lines indicate the means for the periods 1990–1975 and 1976–2004. The sharp drop in rainfall in the mid-1970s is clearly shown. *The mean of the last four years is lower again. However, it is too early to determine whether this is a new climate 'baseline'*. For example, the rainfall totals over the last four years are similar to other four year periods, (e.g. around 1970). Thus the rainfall over the last four years is not substantially different from the past few decades.

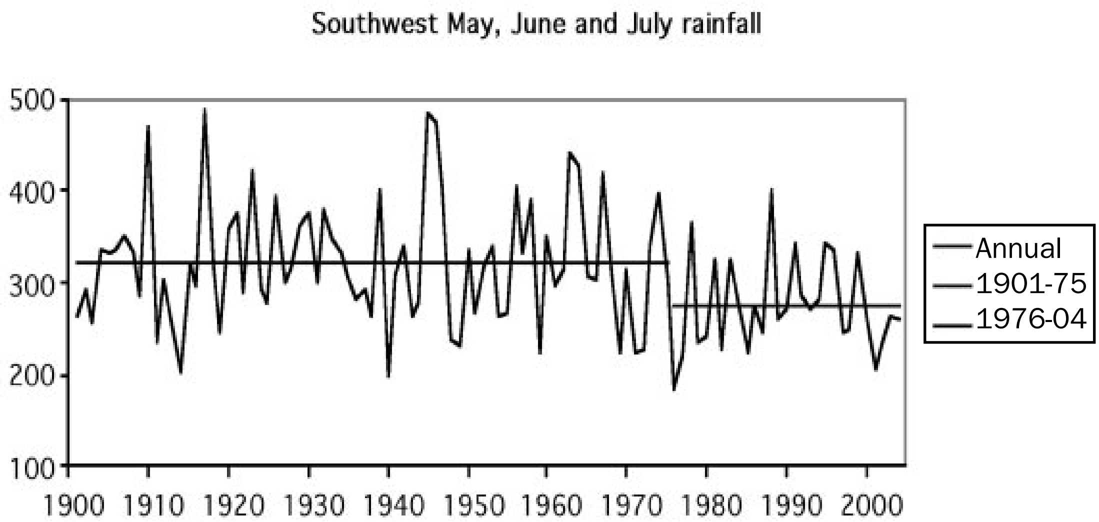


Figure 1. Time series of SWWA winter (MJJ) rainfall. The means for the periods (1900–1974), (1975–2000) and (2001–2004) are represented by the horizontal lines.

References

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- Bates, B.C., Charles, S.P. and Campbell, E.P. (2004). Early recognition of changes to climate regime: Are there any signs of further rainfall decline? Indian Ocean Climate Initiative Panel Meeting No. 18, May 10, 2004.

3.2.2 Analogous synoptic situations

Bertrand Timbal (BMRC) applied a statistical method, based on the idea of identifying analogous synoptic situations, to study the observed rainfall trends in the southwest. The method was developed by relating patterns of atmospheric fields (predictors) to station rainfall (predictands), for both rain occurrences and daily rain amounts. The method was first tested using reanalyses data to select analogues. In a cross-validated sense, the method was able to reproduce the rainfall trend observed during the past 50 years. The choice of predictor had an important impact on the results: mean sea level pressure and vertically integrated precipitable water were both important in explaining the observed local rainfall trend.

The method was then applied to simulations of future climate conditions. Results suggest a continuation and worsening of the drying trend over the southwest. The main differences between the observed changes in rainfall and the projections with enhanced greenhouse forcing are that the projected rainfall decrease also occurs in spring as well as winter and that the area with reduced rainfall is larger (Timbal 2004).

In a second study (Timbal et al. 2005), the technique was applied to two ensembles of simulations of the late 20th century, one with natural forcing only (such as solar forcing and large volcanic eruptions) while in the second ensemble anthropogenic atmospheric forcing (including the enhanced greenhouse effect and changes in ozone and sulfates) were added to the natural forcings. *Only the downscaling of model simulations with the full forcing resembles the observed drying trend.* These results give the clearest indication yet that anthropogenic forcing might have played a role in the drying of SWWA. Some ambiguities remain: *the modelled decline is only about one half of the observational estimate* and the timing differs from the observations.

References

- Timbal, B. (2004). Southwest Australia past and future rainfall trends. Climate Research, 26, 233–249.
- Timbal, B., Arblaster, J.M., Power, S. (2005). Attribution of the late 20th century rainfall decline in Southwest Australia. (Pers. Comm.)

3.2.3 Utility of reanalysis products

Pandora Hope (BMRC), in response to a request at IOCIP19, examined the utility of the various reanalysis products in detecting and attributing climate change in the Australian region, drawing heavily on work by Ian Watterson (CSIRO Atmospheric Research). *The major conclusion is that the reanalysis products can be relied upon for diagnosing circulation changes (although there will be some doubts in some regions, especially for the early years when data were sparse), but they would be of little use for diagnosing rainfall and other more model-dependent variables.*

3.2.4 Changes in sea ice

Ian Smith (CSIRO) has been considering whether changes in sea ice (either total area or northern most extent) might explain the timing of the rainfall decrease in the SWWA (both the fact that the decline is particularly in early winter, and occurred in the mid-1970s). The seasonality and year of the rainfall decrease is not captured well by climate models forced by observed sea surface temperatures (and sea ice), but sea ice observations were limited prior to satellites in the late 1970s. Curran et al. (2003) suggest that decreases in Antarctic sea-ice extent occurred between 1950 and 1972 south of Western Australia. If such a large reduction in sea ice did occur at that time, a link to the rainfall decline may provide answers to these questions. For example, the years of the sea ice reductions approximately coincide with those of the rainfall reduction. The satellite-based sea ice record suggests that very little change has occurred subsequently. The seasonal cycle of sea ice extent has a minimum in January and a maximum in August so that any reductions in extent might be expected to have their greatest impact in winter. There are theoretical reasons and climate model experiments which indicate that a reduction in sea ice extent can cause a poleward shift in the general circulation. It is conceivable that such a shift took place, giving rise to a shift in the tracks of rain-bearing systems and therefore a decline in winter rainfall at lower latitudes. The fact that climate model simulations fail to reproduce the rainfall decline could be a consequence of relatively poor sea ice and sea surface temperature boundary conditions prescribed in the models prior to 1973. Finally, there is a statistically significant link (correlation coefficient $r = +0.49$) between southwest May–October rainfall and the average May–October sea ice extent (as derived from satellite measurements) over the period 1973–2003. While this link could imply that sea ice is a driver of the rainfall decline, it is also possible that a third factor is driving both, and further analysis is required to better define cause and effect.

The changes in sea ice extent may offer an explanation for the timing and the location of the rainfall decline. It will require model experiments to determine whether the change in sea ice extent could have resulted from greenhouse warming, natural variability or a combination of the two processes.

References

- Curran, M. A. J. van Ommen, T.D., Morgan, V I., Phillips, K L., Palmer, A.S. (2003). Ice Core Evidence for Antarctic Sea Ice Decline since the 1950s. Science, 302, 1203–1206.

3.2.5 Link between rainfall and inflow

The decline in annual southwest stream-flow is much larger than the decline in southwest annual rainfall. This is broadly consistent with normal (non-linear) hydrological responses and with the particular absence of 'wet years'. However, is some of the large stream-flow decline due to enhanced evapotranspiration driven by regional surface warming over the past century? If it is, then even if rainfall returns to the higher levels experienced in the first half of the last century, inflow might remain low. Scott Power's (BMRC) preliminary statistical analysis of observational records indicates that the stream-flow decline is, in fact, almost entirely due to reduced rainfall and to the non-linear relationship between stream-flow and rainfall in the region that leads to a larger reduction in inflow for any decrease in rainfall. The retention of subsurface moisture in at least part of the catchment also leads to a small amount of memory in the system from year to year. In any given year over the past three decades the stream-flow decline was exacerbated by the absence of any large inflow events in preceding years. *While increased temperature in the region (as a surrogate for transpiration) is linked to reduced inflow, the magnitude of the effect has been very small.*

The study area was all the land between 110–118°E and 31–35°S, and the 1972–2001 decline was compared with the long-term average from 1911–1971.

3.2.6 The possible influence of land cover change (LCC) on the climate of the southwest

Andrew Pitman, Gemma Narisma and colleagues from Macquarie University (Pitman et al., 2004) have used several high-resolution models to investigate the likely influence of land-use changes since European settlement on southwestern Australian climate. *The models simulated a decrease in rainfall approximately equivalent to that observed in the past few decades*. The warming simulated by the models ranged between zero and 50% of that observed over the second half of the 20th century. They also discussed some points raised in IOCI (2002) as arguments against LCC having been a dominant influence on the rainfall decline in the southwest, namely that:

- The observed decline in rainfall was associated with a near-hemispheric pattern of change in atmospheric circulation. Such a large-scale pattern seems unlikely to be the result of local changes in land use. *There still seems to be no reason why local LCC could induce the near-hemispheric circulation change noted in IOCI (2002) as being associated with the rainfall decline* (and further discussed in Project 1.2 above);
- Pitman et al. (2004) compared simulated climate with land use prior to European settlement, and climate simulated with late 20th century land use. However, the observed decline in rainfall commenced in the 1970s, well after land clearing had begun. Pitman et al. (2004), however, point out that a non-linear response to a linear change in forcing is feasible. (Note from the Department of Agriculture: the rate of land clearing in Western Australia has not been linear, with a rapid increase in the 1950s and 1960s)
- IOCI (2002) also pointed out that the rainfall decline was observed in areas somewhat removed from the area of LCC. Pitman et al. (2004) demonstrate, however, that LCC could produce regional changes that could account for such changes outside the immediate area of LCC.

References

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- Indian Ocean Climate Initiative, (2002). Climate variability and change in south west Western Australia. c/Department of Environment WA. ISBN 1-920687-03-3.

3.3 Key findings from Theme 1

The following findings were gleaned from the core work planned for Phase 1:

- *Synoptic types associated with wet conditions in the southwest have decreased in frequency since the mid-1970s (3.1.1);*
- *The preferred direction of approach for winds associated with rain events is further south since the mid-1970s (3.1.1);*
- *There has been a 20% reduction in the strength of the subtropical jet over Australia. There is an associated reduction in the likelihood of synoptic disturbances developing over the southwest since the early 1970s (3.1.2);*
- *A long integration of a CSIRO coupled climate model has demonstrated that the rainfall decrease is not outside the range of natural variability (i.e., it may be the result of natural variations, but see below) (3.1.3).*

These additional findings were collated from other research, and further research conducted by both BMRC and CSIRO (some initiated in response to requests from IOCIP):

- *Although concern has been expressed that rainfall may have decreased again in recent years it is far too early to suggest we have reached a new 'baseline' (3.2.1);*
- *Statistically downscaled model projections of rainfall from a GCM forced with observed data from the last 50 years only simulate a rainfall decline when anthropogenic atmospheric forcings (ozone, aerosols and greenhouse gases) are included, but even so the decline is less than observed (3.2.2);*
- *Reanalyses (a major tool for studying climate change and variability) appear to be useful for diagnosing circulation changes but are little use for examining rainfall changes directly. This supports the approach adopted in Theme 1 to concentrate on diagnosing changes in synoptic activity to assist in the attribution of causes of rainfall changes (3.2.3);*
- *Increased temperatures appear to have contributed little to the large decline in stream-flow in the southwest, which is dominated by the decline in rainfall (3.2.5);*
- *Model studies indicate that land cover changes may be contributing to the rainfall decrease. However, the inability of land cover changes to cause large-scale circulation changes such as those discussed in the results from the core work above indicates that land-use changes could only be a supplementary cause of the rainfall decrease (3.2.6).*

3.4 Key messages from Theme 1

- *IOCI (2002) concluded that "Most likely, both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease" and that "Other local factors, such as land-use changes in the southwest…seem unlikely to be major factors in the rainfall decrease, but may be secondary contributors". The work completed thus far in Theme 1, Stage 2 of IOCI, along with the review of related work, confirm the conclusions at the end of Stage 1, and extend our understanding of the drivers of the rainfall decline in the southwest;*
- *The large-scale synoptic changes are consistent with the drying in SWWA, providing further evidence that the rainfall decline is linked with large-scale global circulation changes;*
- *It is feasible that the drying trend could have been the result of unforced climate variability;*
- *However, at least part of the observed decline in rainfall is consistent with the modelled effect of anthropogenic forcing;*
- *Changes in land cover may also have contributed to the rainfall decline.*

Although conclusive detection and attribution of climate change in an area the size of the southwest is challenging, especially for rainfall, the work thus far in Stage 2 has, if anything, strengthened the conclusions from Stage 1. There is now stronger evidence that the rainfall decline is at least partly driven by anthropogenic changes.

3.5 Climate insights from Theme 1

The apparent sudden change in sea ice extent south of Western Australia discussed by Ian Smith suggests a possible explanation for the suddenness of the rainfall decrease and its restriction to winter. However, this possible link does not shed light on whether the sudden rainfall decrease was due to natural variability or a large-scale change, possibly caused by the enhanced greenhouse effect.

Attribution of the forcing of multi-decadal atmospheric natural variability has been linked to the oceans. However, this needs further analysis. Decreasing levels of stratospheric ozone (particularly in summer) can also lead to the climate persisting in one 'state'.

3.6 Project Targets – achievements and exceptions

P1.1: Develop methods to identify the changes in synoptic events affecting SWWA rainfall.

- A number of methods have been tested for defining southwest synoptic types;
- A neural network technique that produces a 'map' of different synoptic types shows promise. The development of the map with surface data is complete, and time-series have been analysed (P1.4). Further development of the method, with upper air data, is expected to give improvements;
- Rainfall is linked to surface winds from the north sector at Perth and Wandering.

P1.2: Determine the mid-1970s changes in the mean Southern Hemisphere circulation.

- A method to draw out the major atmospheric modes linked with the development of weather systems highlights a 30 % reduction in their strength and an eastward shift in their region of strongest influence, away from the southwest;
- The method will be applied to CSIRO Mk3 CGCM output from 1960 to 2100.

P1.3: Assess the role of multi-decadal variability by analysing the results from a climate model run for several hundred years under present-day conditions.

- Phase 1 further confirms that natural variability can produce rainfall declines such as that seen in the southwest;
- Multi-decadal variability in the model rainfall links well with variability in the major mode of variability in model sea-level pressure. Potential drivers of this mode have been considered.

3.7 Basis for Phase 2

3.7.1 Opportunities and issues

P2.3: Comparison with observations.

- The analysis of observed synoptic events completed under Project 1.1 will be extended to an analysis of simulated synoptic events in the new CCAM results.

P1.6: Determine transient dynamical instabilities.

- P1.6 will be done during Phase 2. This is before returning to the question of what anomalous climate forcing factors were associated with the mid-1970s changes in the circulation (P1.5) for Phase 3.

P1.5: Anomalous climate forces associated with mid-1970s change.

- Testing of the sea ice/winter rainfall hypothesis can be further pursued in the next phase by correlating southwest monthly and seasonal rainfall with monthly and seasonal sea ice concentrations over the period 1973 to present;
- A review of recent studies of the detection and attribution of climate change relevant to the southwest has been proposed.

3.7.2 Readiness for Phase 2

- Method for producing the time-series of synoptic types is established;
- Method for determining the transient dynamical instabilities is established;
- The possibility was established that multi-decadal dry periods, of the scale observed, could result from natural variability; the project is complete, and will not continue into Phase 2.

THEME 1 PHASE 2 proposed timelines

Partners		
CAR	Sea ice analysis. (3)	
BMRC	Comparison of synoptic events as simulated with CCAM and observed. (3)	
	Completion of synoptic typing method.	Link synoptic type time-series with surface winds and circulation features such as northwest cloudbands.
	Application of methodology for determining transient dynamical instabilities to Mk3 output. Investigate changes into the future.	
	Synthesis of detection and attribution of climate change studies relevant to SWWA. (3)	
	January 2005 to June 2005	**July 2005 to June 2006**

(3) New

4) Summary Report[2] for Theme 2: Climate Change

How will future climate be affected by the greenhouse signature?

Contributing Authors: Brian Ryan, Ian Smith, John McGregor, Steve Charles, Bryson Bates, Ramasamy Suppiah, Ian Watterson, and Paul Durack

The aim of Theme 2 is to undertake strategic research to investigate the relative influence of the enhanced greenhouse effect on the rainfall decrease since the late 1960s and to address possible changes to rainfall and other important climate elements over the coming decades.

The primary output targets for Phase 1 were:

- Daily values for climate variables (e.g. rainfall, temperature) as simulated by the CSIRO Mk3 CGCM for the period 1960 to the present and the period 2015–2045;
- The CSIRO Mk3 CGCM results dynamically downscaled to regional scales and also statistically downscaled to individual station points for the period 1960 to the present in order to facilitate a detailed comparison between simulated and observed climate as part of Theme 1;

[2]The Theme 2 Technical Report is available from: http://www.ioci.org.au

- An analysis of the model results to make a judgement on the extent to which greenhouse forcing has influenced regional weather systems and the observed rainfall decrease in SWWA;
- Advice to State Partners supporting any regional impact assessments with state-of-the-art climate change interpretations for SWWA.

There are five projects that relate to Theme 2 for completion in Phase 1. The first four projects also form part of Theme 1 because they relate to the results of climate model experiments that simulate the effect of greenhouse gases over the last 40 years. These are:

- Project 2.1: Dynamical downscaling;
- Project 2.2: Statistical downscaling;
- Project 2.3: Comparison with observations;
- Project 2.4: Assessment of the role of enhanced greenhouse gases.

The fifth project relates to the analysis of climate model experiments which simulate the effect of enhanced greenhouse gases over the next 100 years:

- Project 2.5: Synthesis of global model results for key climate variables.

In this segment of the report we also report progress from the CSIRO Water for a Healthy Country climate project planned for integration into IOCI research findings during Phase 3:

- Project 2.12: Integration of outcomes from IOCI and the CSIRO Flagship Program 'Water for a Healthy Country'.

Progress in each of these projects is summarised below. More comprehensive descriptions of each project are given in the Theme 2 report.

4.1 Summary of progress, July 2003 – December 2004

4.1.1 Project 2.1 and Project 2.3: Dynamical downscaling and Comparison with observations

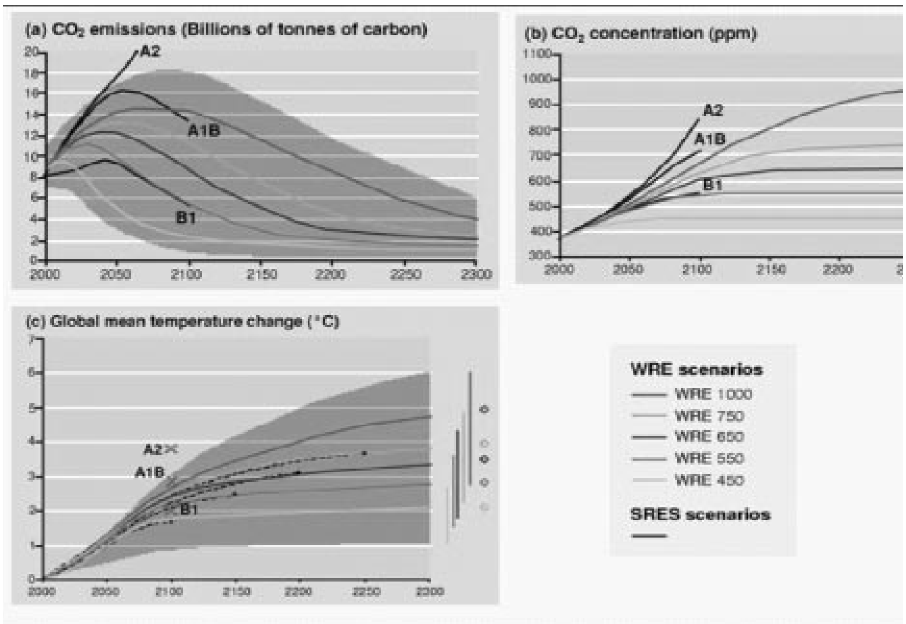
A major objective in Phase 1 was to downscale, using the Conformal-Cubic Atmospheric Model (CCAM), the results of the CSIRO Mk3 CGCM simulations for the period 1960–2000 in order to facilitate a detailed comparison between observed and modelled synoptic events.

Whereas the Mk3 CGCM results (A2 emissions scenario, see Box 1) indicate a drying trend for SWWA rainfall (Project 2.5) over the 40-year period, the dynamically downscaled results from CCAM yielded no such trend. Consequently, in order to provide a firmer basis for comparing observed rainfall and synoptic events, within both the current and future climate, work has been focused on better understanding and resolving this discrepancy.

A series of simulations using the Mk3 AGCM showed that simply prescribing observed SSTs over the period 1960–2000 as a lower boundary condition did not yield results for variability or trends in rainfall which were comparable with observations (this extra work was performed by Jozef Syktus and Ian Watterson). This was also the case when the CCAM model was used to dynamically downscale the results. Furthermore, simulations conducted with the CCAM model alone, also forced by observed SSTs and far-field winds, yielded similar results. However, simulations in which CCAM was forced by observed SSTs and nudged by observed (NCEP) upper level winds, did reproduce many of the observed features of SWWA winter rainfall. This result effectively demonstrated that feeding information about the large-scale winds into the CCAM simulations leads to quite accurate representations of the rainfall. It also demonstrated the need to nudge CCAM with the simulated upper level winds when dynamically downscaling future climate simulations from a CGCM, such as Mk3. Thus, dynamical downscaling within the CCAM A2 run will need to be repeated. Completion is expected early in Phase 2.

A CCAM simulation forced by observed SSTs and nudged by the observed winds is able to simulate the observed inter annual variability in rainfall. As a consequence the CCAM down-scaled runs in Mk3 CGCM will be re-designed.

A reason why information about the large-scale winds may be as important as the SSTs in atmospherically-forced climate simulations (such as CCAM) is that the upper level wind structure is linked to the mid-latitude horizontal temperature gradient. At high latitudes, where sea surface temperature (SST) and sea ice coverage observations have been sparse, changes to the mid-latitude temperature gradient may not have been accurately diagnosed. As a consequence, errors in the upper-level winds may have occurred in the climate simulations forced by NCEP SSTs since these may not accurately represent the high latitude SSTs and sea ice changes that occurred prior to the 1970s (when satellite observations increased the reliability of the SSTs and sea ice reconstructions). Preliminary results with the CSIRO Mk3 AGCM suggest that an increase (of +20%) in average sea ice extent can lead to increases in winter rainfall over SWWA. This result is consistent with the hypothesis that larger sea ice extents prior to the 1970s were linked to the higher SWWA winter rainfall regime. A more comprehensive analysis of this result, together with a rigorous examination of the results from an ensemble of such experiments, will be required as a means of confirming that sea ice changes are a factor in the observed rainfall decline. This analysis will also focus on the effects on the atmospheric circulation patterns, including the position and strength of the upper level winds as addressed in Theme 1 (Project 1.5).



Box 1: Emissions, concentrations and temperature changes corresponding to different stabilisation levels for CO2 concentrations (IPCC 2001).

Reference

- IPCC. (2001). Climate change 2001: the scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change, ed. J.T. Houghton, Y.Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, Cambridge University Press, Cambridge and New York.
- IPCC. (2001). Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change, ed. J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White, Cambridge University Press, Cambridge and New York, 881 pp.

4.1.2 Project 2.2: Statistical downscaling

Statistical downscaling of both the Mk3 CGCM and the CCAM results has been performed using the existing techniques developed under IOCI Stage 1.

Statistical downscaling (SD) is the only method capable of producing projections at the ‘point’ scale (e.g. rain gauge) required by many impacts models (e.g. water resources, agricultural production, ecosystem function). Statistically downscaled winter (May–October) rainfall has been produced for a 30-station network in SWWA using daily output from the Mk3 CGCM A2 run and the associated CCAM run nested within the Mk3CGCM run (note that this will be repeated in Phase 2, see report for Projects 2.1 and 2.3). The SD model uses the following atmospheric predictors: MSLP, north-south gradient in MSLP, and dew-point temperature depression at 850 hPa. This was done for two 30 year time-slices, centred on 1990 (i.e. current climate) and 2050 (i.e. mid-21st century projection).

The key findings from an intercomparison of the CCAM and SD results show that:

- *The CCAM model nested in the Mk3 CGCM A2 emission scenario provides a much better representation of the observed mean winter rainfall than the coarser resolution Mk3 CGCM. However it does not reproduce the correct frequency of wet days nor the correct distribution of daily rainfall amounts of the observed rain gauge records. Hence the need for the SD model*
- *Consistent climate change projections are obtained when driving the SD model with either the Mk3 CGCM or CCAM atmospheric predictors*
- *The projected mid-21st century SWWA winter rainfall decreases by approximately 15% (averaged across the 30 stations) relative to current rainfall when the results from the Mk3 CGCM and nested CCAM A2 runs are statistically downscaled.*

4.1.3 Project 2.4: Assessment of the role of enhanced greenhouse gases

The degree of similarity between the observed and modelled climate changes over the past several decades provides a basis for judging the role of enhanced greenhouse gases in the observed rainfall decline.

Theme 1 demonstrated that the control Mk3 CGCM simulation (pre-industrial CO_2 concentration of 330ppm) generated naturally occurring drying sequences over SWWA of the order of 20%.

The analysis of nine international models provides estimates of changes to both temperature and rainfall due to enhanced greenhouse conditions for the period 1990–2005 relative to the period 1960–1990. While small, the contribution to May–October temperature is estimated to be a change of between +0.13° and +0.16°C, while the contribution to

May–October rainfall is estimated to change by –2.6% and –1.3%. The observed change in rainfall over the period is estimated to be close to –10%. *These modelled rainfall decreases are far less than observed*. This may mean that the effect of enhanced greenhouse gases over this time period is insufficient to explain the decline and that other factors are more important. Alternatively, it could also mean that the models may be underestimating the real effect on rainfall.

A key message from the latest set of Mk3 CGCM simulations using both the control and transient simulations confirm the conclusions from IOCI Phase 1 that both natural variability and greenhouse gas radiative forcing of the atmosphere are likely to be the main contributors to the current decrease in rainfall over the SWWA, but separating these two signals is very difficult.

4.1.4 Project 2.5: Synthesis of global model results for key climate variables

The interim results from global and regional climate model analyses and comparison with observations and their implications will be synthesised and reported to state partners.

The Mk3 CGCM has been run for three emission scenarios (A2, A1B and B1) as part of the Australian input into the IPCC Fourth Assessment Report (Box 1). The scenarios represented depict a range of Special Report on Emissions Scenarios (SRES) CO_2 concentrations increasing from the current concentrations of 360 ppm to 850 ppm and the Wigley, Richels and Edmonds (WRE) stabilisation scenarios of 720 ppm and 550 ppm by 2100. Daily variables have been saved from these runs so that climate variables can be statistically and dynamically downscaled. Note that dynamical and statistical downscaling of these runs will be performed under Phase 2.

The analysis of 9 international models provides estimates of changes to both temperature and rainfall due to enhanced greenhouse conditions for the period 1990 to 2005 relative to the period 1960 to 1990. While small, the contribution to May–October temperature is estimated to be a change of between +0.13o and +0.16°C, while the contribution to May-October rainfall is estimated to change by -2.6% and -0.22%. The observed change in rainfall over the period is estimated to be close to -10%. *These rainfall modelled decreases are far less than observed*. This may mean that the effect of enhanced greenhouse gases over this time period is insufficient to explain the decline and that other factors are more important. Alternatively, it could also mean that the models may be underestimating the real effect on rainfall.

Temperature and rainfall projections are given for the years 2030 and 2070 based on SRES emission scenarios and also for stabilised emissions scenarios at 450 and 550 ppm. The new projections for the SWWA region indicate an increase in temperature and a decrease in rainfall under enhanced greenhouse conditions. *Projections for inland regions show a warming of between +0.5 and +2.1°C by 2030 and between +1.0 and +6.5°C by 2070 during the summer-half of the year (November-April) for SRES emission scenarios. During the winter-half of the year (May-October), increases in temperature are projected to reach between +0.5 and +2.0°C by 2030 and between +1.0 and +5.5°C by 2070*. Southern coastal regions show relatively less warming. Relatively smaller increases are projected under the stabilised scenarios for 550 and 450 ppm.

Projected rainfall changes for the SRES emission scenarios show up as between –2% and –20% by 2030 and between –5% and –60% by 2070 for SWWA during the winter-half of the year. The magnitudes of the decreases are smaller for the stabilised emission scenarios. The pattern of rainfall changes during the summer-half of the year is less consistent, with decreases and increases, particularly in the inland regions. Even under the most optimistic stabilised emissions scenarios, significant rainfall decreases are projected for 2030.

Potential evaporation is projected to change, by up to +10% by 2030, and by up to about +30% by 2070 for the SRES scenarios during the winter-half of the year. The projected increases are lower relatively for the stabilised scenarios. Note that only seven out of the 19 available sets of model results were used to construct these projections.

The latest suite of climate change simulations show that even with the most optimistic emission scenarios SWWA is projected to be drier and warmer later this century.

Table 1. Projected changes in SWWA climate variables under SRES Scenarios

Winter half			
	2005	**2030**	**2070**
Temperature	+0.13 to +0.16°C	+0.5 to +2.0°C	+1.0 to +5.5°C
Rainfall	-0.22% to -2.6%	–2% to –20%	–5% to –60%
Potential Evaporation		+1% to +10%	+3% to +31%
Summer half			
Temperature		+0.5 to +2.1°C	+1.0 to +6.5°C
Rainfall		–15% to +5%	–50% to +15%
Potential Evaporation		+1% to +7%	+3% to +24%

4.1.5 Project 2.12: Integration of outcomes from IOCI and the CSIRO Flagship Program 'Water for a Healthy Country'

A new methodology, using non-linear techniques, has been developed to represent the spatial distribution of extreme events. This methodology has been developed using observed data for extreme rainfall events in the Avon catchment and will be applied to the output from the existing Mk3 CGCM runs and the associated dynamical downscaling runs with CCAM to be undertaken in Phase 2. The aim is to examine the change in spatial distribution of extreme events in future climates.

4.2 Other related work conducted by BMRC and CSIRO

Ian Watterson has analysed the ensemble of simulations from the Mk3 AGCM with specified SSTs over the period 1950–2002 (carried out by Jozef Syktus at QDNRM). Some of the resultant findings have been discussed in section 2.1 of this report.

4.3 Key findings for Theme 2

- *A CCAM model simulation forced by observed SSTs and nudged by the observed upper level winds is able to simulate the observed inter annual variability in rainfall. As a consequence the CCAM climate down-scaling in MK3 CGCM simulations will be re-designed (4.1.1);*

- *The CCAM model, when nested in the Mk3 CGCM for the A2 emission scenario, provides a much better representation of the observed mean rainfall (1975–2005) than does the coarser resolution Mk3 model. However, it does not reproduce the correct frequency of wet days nor the daily amounts of the observed rain gauge records (4.1.2);*
- *Consistent climate change projections are obtained when driving the statistical downscaling model with either the Mk3 CGCM or CCAM atmospheric predictors (4.1.2);*
- *Based on the downscaled CCAM run the projected mid-21st century SWWA winter rainfall decreases by approximately 15% (averaged across the 30 stations) relative to current rainfall (note that this is in the range of the new projections based on nine models) (4.1.2);*
- *Based on the results of nine international models, the change in the winter half-year (May–October) rainfall over recent time due to enhanced greenhouse gases indicates a decline, but far less than observed (4.1.3);*
- *New projections for inland regions show a warming for the winter half-year of between +0.5 and +2.0°C by 2030 and between +1.0 and +5.5°C by 2070 for SRES emission scenarios. During the summer half- year (November to April), increases in temperature are projected to reach between +0.5 and +2.1°C by 2030 and between +1.0 and +6.5°C by 2070 (4.1.4);*
- *Projected rainfall changes for the SRES emission scenarios show up as between –2% and –20% by 2030 and between –5% and –60% by 2070 for SWWA during the winter half-year (4.1.4);*
- *Potential evaporation for the winter half-year is projected to change by up to +10% by 2030 and by up to about +30% by 2070 for the SRES scenarios (4.1.4).*

4.4 Key messages from Theme 2

- *The latest set of Mk3 CGCM simulations using both the control and transient simulations confirm both natural variability and greenhouse gas radiative forcing of the atmosphere are likely to be the main contributors to the rainfall decline;*
- *The latest suite of climate change simulations show that the effect of enhanced greenhouse gases over recent decades underestimates the observed trend in rainfall;*
- *The latest suite of climate change simulations show that even with the most optimistic emission scenarios, SWWA is projected to be drier and warmer later this century.*

4.5 Climate insights from Theme 2

- *Dynamical downscaling using the CCAM model yields better simulations of SWWA mean rainfall than do coarser resolution climate models;*
- *Statistical downscaling is still required to realistically simulate the frequency of wet-days or daily amounts;*
- *Atmospheric models (including high resolution dynamical downscaling models such as CCAM) when forced by observed SSTs alone do not reproduce observed inter-annual variability nor the observed decrease in SWWA winter rainfall;*
- *The use of upper level wind nudging within CCAM overcomes the foregoing problem and indicates a more appropriate method to use when dynamically downscaling future climate;*
- *Sea ice changes (as opposed to SSTs) may be responsible for the changes in large-scale meteorological systems which have accompanied the observed decline in SWWA winter rainfall.*

4.6 Project targets – achievements and exceptions

P2.1: Dynamical downscaling

- CCAM has been used to downscale the results from the Mk3 CGCM A2 run for both the present day and future climate. However, the downscaling will need to be repeated using upper level wind nudging;
- Dynamical downscaling of the Hadley Centre climate model simulation was not attempted because higher priority was given to demonstrating that CCAM could downscale the seasonal variability when forced by NCEP analyses;
- A possible link between sea ice changes and SWWA climate has been identified and will be analysed in a series of sensitivity experiments (Phase 2).

P2.2: Statistical downscaling (SD)

- SD has been used to downscale the Mk3 CGCM A2 results and the associated CCAM results. These yield consistent projections of changes in rainfall that may occur at rain gauge sites;
- Application of SD to the Mk3 CGCM A1B and B1 results will take place in Phase 2;
- SD will also be applied to the new CCAM results for all 3 of these scenarios, also to take place in Phase 2.

P2.3: Comparison with observations

- The new CCAM results for rainfall (based on nudging of NCEP upper level winds) compare favourably with observations. Detailed comparison of synoptic events within these results will be made during Phase 2.

P2.4: Assessment of the role of enhanced greenhouse gases

- According to the new scenarios, the changes to SWWA winter rainfall over the past few decades due to enhanced greenhouse gases is less than that what has been observed.

P2.5: Analysis of climate model experiments

- The new scenarios provide a range of uncertainty in the temperature, rainfall and evaporation changes to be expected later this century.

4.7 Basis for Phase 2

4.7.1 Opportunities and issues

P2.3: Comparison with observations

- The analysis of observed synoptic events completed under Project 1.1 will be extended to an analysis of simulated synoptic events in the new CCAM results.

P2.6: Dynamical downscaling of Mk3 CGCM results

- Dynamical downscaling with CCAM of the Mk3 CGCM A2 run will need to be repeated using nudging of the (Mk3 CGCM) upper level winds. While this is judged to be the more appropriate approach, it is unclear how much difference it will make to the results obtained to date (P2.2);
- The same method will be used for dynamical downscaling of the Mk3 CGCM results for the A1B and B1 scenarios. This item replaces the planned downscaling of the Hadley Centre model results.

P2.7: Statistical downscaling of both Mk3 CGCM and CCAM results

- Statistical downscaling of the new CCAM results from the Mk3 CGCM A2 run will be compared with the results obtained in Phase 1 (P2.2);
- Statistical downscaling will be performed on the Mk3 CGCM results for the A1B and B1 scenarios;
- It will also be performed on the CCAM results for these scenarios.

P2.8: Reliability of projected changes

- The consistency of the projections obtained using both dynamical and statistical downscaling techniques will be assessed in Phase 2.

P2.9: Climate change scenarios

- The downscaled projections from the Mk3 CGCM results for the 3 emission scenarios will provide a basis for generating climate change scenarios, one of which is a stabilisation scenario.

P2.12: Water for a Healthy Country

- Changes in extreme events in the Avon catchment will be estimated using the results from Mk3 CGCM and the new CCAM results available in Phase 2;
- Statistically downscaled results for both current and future climate will be used as inputs into a model of the Gnangara Mound.

4.7.2 Readiness for Phase 2

- The Mk3 CGCM results for the three emission scenarios are available;
- The appropriate method for dynamical downscaling has been identified;
- The statistical downscaling technique is established;
- Methods for analysing simulated synoptic events are established;
- Methods for analysing rainfall extremes are established;
- A new project to test the influence of Antarctic sea ice has commenced.

THEME2 PHASE 2 proposed timelines

Partners		
CAR	Mk3 Sea ice analysis (3) New CCAM A2 run completed (3)	CCAM 2 other scenarios completed (2)
CLW	SD of CCAM A2 (3)	SD of 2 other scenarios from Mk3 and CCAM (2)
BMRC	Comparison of synoptic events as simulated with CCAM and observed (3)	
CMIS	Analysis of extremes in model outputs (current and future). Extension of study region (1)	
	January 2005 to June 2005	**July 2005 to June 2006**

(1) Extension of HC work (AVON) (2) Replaces Hadley model output (3) New

5) Summary report[3] for Theme 3: Short-term Climate Prediction

What are the opportunities for climate prediction, and how can we develop and use these productively?

Contributing Authors: Santosh Aryal, Bryson Bates, Eddy Campbell, Steve Charles, Yun Li, Mark Palmer, Neil Viney

5.1 Summary of progress, July 2003 – December 2004

The aim of Theme 3 is to investigate how well seasonal climate in SWWA can be predicted and to assess the suitability and utility of new forecasting techniques in application settings. The emphasis of the work undertaken in Theme 3 was to couple physical modelling with statistical modelling for forecasting, and to examine the potential benefits versus statistically- or physically-based forecasting alone. The questions addressed under this theme were:

- Using statistical, dynamical and statistical-physical forecasts, what levels of predictive skill are obtainable for lead times of interest to State Agencies?
- Does the use of 'now' variables increase predictive skill compared to statistical schemes using only lagged variables?
- Do hybrid methods offer a way to develop forecast models for particular applications of interest to State Partners?

There were six projects undertaken in Stage 1:

- P3.1: Improved procedures for selecting atmospheric predictors for statistical downscaling schemes;
- P3.2: Improved rainfall amount simulations generated by the statistical downscaling model;
- P3.3: Processed atmospheric fields from hindcasts produced by CAR and IRI for Climate Prediction (USA);
- P 3.4: Analysis of synoptic events that lead to rainfall extremes;
- P 4.1: Development of a hybrid model of factors influencing SWWA rainfall;
- P4.2: Customised nonlinear data mining tools.

The first two projects relate to development of the CLW stochastic downscaling model, which provides a means to relate global climate model results to local scales of concern to decision makers. Project 3.3 examined the predictability of 6 month forecasts for SWWA from COCA2 seasonal hindcasts. Project 3.4 focused on extreme climate events, and links with activities in the Water for a Healthy Country Flagship project. Project 4.1 was concerned with new methods to couple physical and statistical models together, ideally to extract the benefits of both approaches to derive probability forecasts. A key issue in climate prediction is the identification of good predictors of future climate. Project 4.2 was designed to bring together a range of contemporary tools from the statistical literature, known as nonlinear data mining, and to make them more available within the climate community.

5.1.1 P 3.1: Improved procedures for selecting atmospheric predictors for statistical downscaling schemes

This project aims to improve the statistical downscaling results by looking for better links between the large scale atmospheric fields and daily rainfall at the point scale.

[3]The Theme 3 Technical Report is available from: http://www.ioci.org.au

Activities have been initiated in two main areas. The first uses ideas from machine learning, which is concerned with making predictions when large numbers of potential predictors are available. Machine learning ideas have already found uses in IOCI work, such as the bridging project using boosting undertaken by CMIS between IOCI Stage I and IOCI Stage 2. Progress is well advanced on machine learning through international collaborations, although it is too early to report results. It is also planned to conduct a local study using this technique. The second main area essentially uses mathematical techniques to approximate the downscaling model. The key here is that predictor selection is easier for the approximation, and therefore variations on conventional methods can be used. A research plan for the mathematical approximation technique has been developed and work on this has commenced. The Australian Greenhouse Office has recently provided funding on predictor selection, so more resources will be available in Phase 2.

IOCI has also benefited from a GRDC project that uses statistically downscaled rainfall projections to drive crop yield models. *It has investigated a larger set of potential predictors and found evidence that 700 hPa moisture fields offer improved performance over the current SWWA model using 850 hPa level data*.

5.1.2 Project 3.2: Improved rainfall amount simulations generated by the statistical downscaling model

This project aims to develop techniques which can improve the rainfall amount simulations.

Approaches for improving simulations of rainfall amounts include extending the current rainfall amount module to simulate rainfall amounts as a function of a set of atmospheric predictors, as well as rainfall occurrence at neighbouring stations. These predictors are in addition to those used to define the weather state sequences. A modified algorithm for re-sampling daily rainfall amounts, which better describes rainfall amounts distributions by using the gamma distribution, has been developed and tested. Although improvement in performance is not consistent across all stations, in many cases better reproduction of inter-annual variability and daily probability density functions are evident for the model using the gamma distribution. This improved model will be more comprehensively tested in Phase 2.

International collaborators have developed a version of the NHMM statistical downscaling model that models weather states as a function of rainfall amounts directly. The code for this new version has been obtained and testing on SWWA data has commenced.

5.1.3 Project 3.3: Processed atmospheric fields from hindcasts produced by CAR and IRI for Climate Prediction (USA)

This project aims to demonstrate the potential skill of dynamical seasonal forecasting schemes by downscaling the simulated atmospheric fields.

A hindcast is a retrospective forecast by a model based on a priori information, i.e. it represents a forecast made after the event. If it is applied to independent data, the model skill is a true measure of forecast skill. The COCA2 model (based on the CSIRO Mk3 CGCMI) has been used to generate rainfall hindcasts from April 1 start dates for each year over the period 1980–2003 and these have been compared with observed winter (June to August) amounts. *These did not demonstrate any significant skill. In addition, statistically downscaled winter rainfall hindcasts based on the daily data produced from these hindcasts were found to be inferior to those produced from the previous COCA1 model*. However, the COCA1 results only referred to a relatively small sample of 7 years (1996–2002).

The COCA2 rainfall hindcasts from the July 1 start dates were also compared to the observed late winter (July to October) amounts but again demonstrated no significant skill.

These results refer to the skill of just a single seasonal prediction model and it remains unclear as to how other models may perform. Consequently, it is planned to analyse the existing hindcast data sets from several other models. The DEMETER set comprises the results from several European seasonal prediction models and is available for analysis. It has been decided that accessing this data set may be more efficient than accessing the IRI data set.

In addition, the analyses will also make use of any further hindcast data produced by the newly improved COCA2 model and also the Bureau of Meteorology POAMA model. These are expected to become available at some time during 2005. The new version of the COCA2 model will incorporate several features including the effect of greenhouse gas forcing over the period 1950 to the present.

Note that a complete and comprehensive hindcast study requires an ensemble of forecasts from the same model. With the DEMETER set it is impossible to distinguish how much of the spread in the hindcast results from use of different models and how much of the spread results from the natural variability in the climate system. The first test for the DEMETER set is to confirm that the observed climate realisations lie within the range of realisations generated by the ensemble of models.

5.1.4 Project 3.4: Analysis of synoptic events that lead to rainfall extremes

This project aims to seek greater capacity to develop outlooks for extreme events (defined to be occasions of relatively infrequent large daily rainfall totals).

This project is carried out under the CSIRO Water for a Healthy Country Flagship Program and may be of interest to State partners. The study region adopted as an initial case study is the Avon catchment, which coincides with interests of the Water for a Healthy Country Flagship project. A requirement of the project is to capture relatively fine spatial detail in the landscape, and make projections under scenarios for future climate change. The strategy adopted is to develop a statistical model to capture the fine spatial detail, forced by predictors selected using available data. Candidate predictors include the Antarctic Oscillation Index, ENSO measures etc. These predictors can be derived from climate models under various scenarios of climate change, enabling future extremes scenarios for the Avon catchment to be derived.

The work to date has focused on developing a clean data rainfall set and developing a prototype spatial model. Exploratory analysis of rainfall data in the catchment has established clear spatial patterns, so a spatial model can be expected to have greater predictive power than modelling individual sites separately. Statistical considerations have been used to identify a set of extreme events from the rainfall record, and further work is required to identify common synoptic features. A prototype spatial model has been developed, and used to commence a search for predictors of extreme events. Some tentative findings to date show that for the Avon catchment region during winter:

- *For events with an average recurrence interval of five years there has been an increase in associated extreme rainfall to the north and a decrease to the south;*
- *For events with a an average recurrence interval of 25 years there has been an increase in associated rainfall throughout the northwest, which may perhaps be linked to cloud band activity. This has been accompanied by a mild decrease to the southeast.*

Once fully operational the spatial model will also allow us to make inferences at ungauged locations, thus providing inputs for other applications such as groundwater models. A key output will be probabilistic forecasts of extreme events.

5.1.5 Project 4.1: Development of a hybrid model of factors influencing SWWA rainfall

This project investigates methodologies to essentially couple together physical and statistical models to provide more effective forecasts.

Two major approaches to hybrid modelling have been investigated. The first involves forcing a statistical model for rainfall using a physical model of some kind. As a first step, NCEP reanalysis data have been used as a proxy for modelled data to examine potential predictability. *This shows that the hybrid approach has greater predictive skill than NCEP alone*. The next stage will involve the use of model data from CSIRO Atmospheric Research.

In the second approach, a fully integrated physical-statistical conceptual model for ENSO has been developed to show how such a model would work. This indicates how probability forecasts may be derived, and what can be learned about uncertain parameters. An interesting finding is that forecast uncertainty does not behave as expected from a purely statistical scheme, since uncertainty does not necessarily increase with how far ahead in time the forecast is. Uncertainty is also a function of the underlying physics, so forecasts can be distinctly nonlinear. Another way to think of this is that the statistical model is being constrained to be physically reasonable, thereby eliminating some uncertainty.

The results of this project so far indicate that hybrid methods have much potential. What is required now is a focused application for which conceptual models can at least be used to capture some relevant physical knowledge.

5.1.6 Projects 4.2: Customised nonlinear data mining tools

This project seeks to make these tools available in a form suitable for climate applications.

Data mining tools are very useful for identifying patterns in data, which may be investigated to determine if there is a reasonable physical basis. Climate variables can be sought that are important in their own right, or are important in combination with other variables. For any patterns found it is very important that the physical basis be considered because in large, complicated data sets it is certain that spurious relationships can occur which will impede predictability.

It is also possible to design tools that are physically-inspired, ideally guaranteeing that any patterns found will have a physical basis. An example is provided by so-called threshold models, developed in IOCI Phase I. Climate processes can be nonlinear in the sense that they behave differently depending on which regime is currently in force. A good example is SWWA rainfall. A research tool was developed to identify the number of regimes, their boundaries, and the key variables within each regime. Work has been undertaken in this project to bring the software together for use by others.

As part of this project, methods have been investigated for identifying key interactions in a data set, then tested on climate data with good results. Rapid screening of very large sets of potential predictors, using a technique from the machine learning literature known as boosting, has also been tested. This tool is currently being optimised for functional use.

5.2 Key findings for Theme 3

- *There is evidence that statistical downscaling of the 700 hPa level moisture offers improved performance over the current SWWA model which uses 850 hPa level data (5.1.1)*
- *The COCA2 has model was unable to skilfully predict SWWA winter rainfall (1980–2003) when started from April 1. The statistically downscaled predictions based on the daily output data also did not demonstrate significant skill (5.1.3);*
- *For events with an average recurrence interval of five years there has been an increase in associated extreme rainfall to the north and a decrease to the south (5.1.4);*
- *For events with a an average recurrence interval of 25 years there has been an increase in associated rainfall throughout the northwest, which may perhaps be linked to cloud band activity. This has been accompanied by a mild decrease to the southeast (5.1.4);*
- *The hybrid approach has greater predictive skill than NCEP alone (5.1.5);*
- *The development of a prototype spatial model for extreme events will allow inferences to be made about ungauged locations and provide inputs for other applications such as groundwater models (5.1.4).*

5.3 Key messages from Theme 3

- Skilfully predicting SWWA winter rainfall from as early as April 1 does not look feasible using COCA2.

5.4 Project targets – achievements and exceptions

- An improved rainfall amounts model for statistical downscaling has been developed and tested;
- There is clear evidence that ‘now’ variables obtained from models combined with nonlinear statistical models of rainfall have greater predictive skill than nonlinear statistical models alone;
- A hybrid modelling framework has been developed, with two variants examined. One has been applied to SWWA rainfall with very promising results;
- Nonlinear data mining tools are now being used almost routinely to assist in climate predictor selection.

5.5 Basis for Phase 2

5.5.1 Opportunities and issues

- Further work on seasonal prediction will be delayed until CSIRO has obtained the DEMETER (European) set of hind casts (July 2005). At the time of writing the research plan it had been intended to use the IRI hindcasts as well as COCA2. However, the emergence of the DEMETER database (http://www.ecmwf.int/research/demeter) offers a second and far more powerful alternative. DEMETER is a multi-model ensemble system whereas the IRI provides an ensemble of hindcasts for one model only;
- The time delay of 6 months while the DEMETER data are being obtained should be redirected to examine the issue of the impact of sea ice on model predictability (Theme 2);
- For feed-back hybrid modelling to be successful it will be necessary to define a key application using partner input, and to assign a multi-disciplinary team to develop a compelling case study. Physical processes driving SWWA rainfall are too little understood at this stage;

- Work on feed-forward hybrid forecasting will continue when seasonal prediction work recommences.

5.5.2 Readiness for Phase 2

- P3.5: Work is ready to commence on the implementation of nonlinear mining tools as software for wider dissemination;
- P4.3: Downscaling of hindcasts and assessments of predictive skill and lead times will recommence after DEMETER data sets become available (July 2005);
- P4.4: The predictive skill of the various methods listed above will be compared against the so-called naïve forecasts based on mean regional and station climatology. Commencement of this work is dependent on the skill of the ensemble seasonal hindcasts (new COCA2, POAMA, DEMETER) for SWWA. Project structure was defined in July 2005;
- P4.5: Work is ready to commence on extending the extreme rainfall analysis to the prediction of spatial extremes in SWWA;
- P4.6: The development of tools to speed development of hybrid forecasting model application has already commenced.

THEME3 PHASE 2 proposed timelines

Partners		
CLW	Assess improvements in interannual rainfall reproduction and at-site rainfall distributions of NHMMs that use predictors selected based on the new machine-learning methodologies.	Downscale DEMETER hindcasts for SWWA winter for all years available and compare with observed at-site rainfalls.
CMIS	Analysis of extremes in model outputs (current and future). This is an extension of the HC study region (Avon) into the southwest.	Application of techniques to latest COCA2/POAMA3/ seasonal hindcasts
CAR	Download of DEMETER data (3)	Analysis of DEMETER data (3)
	January 2005 to June 2005	**July 2005 to June 2006**

(3) New

6) Appendix

6.1 Acronyms

3DVAR+FGAT	3-Dimensional VARiational method + First Guess at Analysis Time
AGO	Australian Greenhouse Office
AOI	Antarctic Oscillation Index
BMRC	Bureau of Meteorology Research Centre
BoM	Bureau of Meteorology
CAR	CSIRO Atmospheric Research
CCAM	CSIRO conformal-cubic atmospheric model
CLW	CSIRO Land and Water
CMIS	CSIRO Mathematical and Information Sciences
COCA2	CSIRO MK3 CGCM use in seasonal forecast mode (supersedes the earlier version, COCA1)
CRU	Climatic Research Unit, http://www.cru.uea.ac.uk/cru/data/
CSIRO	Commonwealth Scientific and Industrial Research Organization
DEMETER	Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction (E.U.)
ECMWF	European Centre for Medium-range Weather Forecasts
ENSO	El Nino Southern Oscillation
EOF	Empirical Orthogonal Function (dominant modes of ERA15
ECMWF	Re-Analysis (15 years)
ERA40	ECMWF Re-Analysis (40 years) variability)
GCM	General Circulation Model OR Global Climate Model
GRDC	Grains Research and Development Council
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory model
IOCI	Indian Ocean Climate Initiative
IOCIP	Indian Ocean Climate Initiative Panel
IPCC	Inter-governmental Panel on Climate Change
IRI	International Research Institute for Climate Research
LCC	Land Cover Change
Mk3 AGCM	CSIRO Mark 3 Atmospheric General Circulation Model
Mk3 CGCM	CSIRO Mark 3 Coupled General Circulation Model
MSLP	Mean Sea Level Pressure
NCAR	National Center for Atmospheric Research (U.S.)
NCEP	National Centers for Environmental Prediction (U.S.)
NCEP-DOE reanalysis 2	NCEP-Department of Energy reanalysis 2 (update of NCEP/NCAR reanalysis)
NH	Northern Hemisphere

NHMM	Nonhomogeneous Hidden Markov Model
PMSLP	Perth Mean Sea Level Pressure
POAMA	Predictive Ocean Atmosphere Model for Australia
ppm	Parts Per Million
SAM	Southern Annular Mode (also Antarctic Oscillation)
SD	Statistical Downscaling
SH	Southern Hemisphere
SOM	Self Organising Map
SRES	Special Report on Emissions Scenarios (from IPCC, 2001)
SST	Sea Surface Temperature
SWWA	Southwest Western Australia
TOVS	TIROS (Television, Infra-red Observation Satellite) Operational Vertical Sounder
WRE	Wigley, Richels and Edmonds

6.2 Glossary of Terms

(Based in part on the Synthesis Report of the Intergovernmental Panel on Climate Change, 2001)

700/850 hPa level moisture fields
Refers to the pattern of water vapour amount in the atmosphere at levels well above the surface. These amounts are usually indicated by values for relative humidity or mixing ratio.

Antarctic Oscillation (also Southern Annular Mode) Index (AOI)
A measure of the contrasting mean sea level pressure anomalies at mid- and high-southern latitudes. The AOI has exhibited an increase over recent years corresponding to relatively high mean sea level pressures over southern Australia.

Anthropogenic Forcing
The forcing imposed in climate model simulations from human influenced change. This includes increasing levels of some greenhouse gases (e.g. carbon dioxide and methane), aerosols and changes in ozone. It may also include land cover change.

Climate
Climate is the sum or synthesis of all the weather recorded over a long period of time. It tells us the average or most common conditions, or extremes, or counts of events, or frequencies. These relevant quantities are most often surface variables such as temperature, precipitation, and wind.

Climate adaptation
Climate adaptation is a continuous process adjusting to stresses and risks relating to current, or future, climate. It involves both deliberate adjustment by society in order to moderate harm (reduce vulnerability) and exploit opportunity and spontaneous adjustment by natural systems.

Climate baseline
The baseline is any datum against which change is measured. It might be a 'current baseline', in which case it represents observable, present-day conditions. Alternative interpretations of the baseline conditions can give rise to different thresholds being set by decision-makers.

Climate change
Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity.

Climate hazard
Climate hazards are the climatic sources of vulnerability and impact.

Climate model
A numerical representation of the *climate system* based on the physical, chemical, and biological properties of its components, their interactions and *feedback* processes, and accounting for all or some of its known properties. Coupled General Circulation Models (CGCMs) provide a comprehensive representation of the climate system. Climate models are applied, as a research tool, to study and simulate the climate, and also for operational purposes, including monthly, seasonal, and interannular climate predictions.

Climate prediction
A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g. at seasonal, inter-annual, or long-term time-scales).

Climate projection
A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based on simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend on the emission/concentration/radiative forcing scenario used, which is based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

Climate scenario
A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A 'climate change scenario' is the difference between a climate scenario and the current climate.

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and human-induced forcings such as the changing composition of the atmosphere and land-use change.

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Climate vulnerability
Climate vulnerability is the potential to be harmed by climate change (a function of hazard, exposure and sensitivity or resilience).

Downscaling
Statistical or dynamical methods of deriving finer regional detail of climate parameters from regional or global climate models.

Emissions scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships.

Ensemble
In seasonal (and weather) forecasting, models are often repeatedly run forward in time, on each occasion with slightly different initial conditions. The various results are referred to as an ensemble set of results. The mean of the results is referred to as the ensemble mean. If the results are similar, the forecast can be described as 'certain', otherwise a mixed set of results can be described as 'uncertain'.

Gamma distribution
A theoretical shape which often provides a good fit to the frequency distribution ('probability density function') of rainfall amounts.

Greenhouse effect
Greenhouse gases effectively absorb infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Thus greenhouse gases trap otherwise escaping heat within the surface-troposphere system. This is called the 'natural greenhouse effect'. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is the 'enhanced greenhouse effect'.

Hindcasts
A hindcast is a retrospective forecast by a model based on a priori information.

Impact assessment
The practice of identifying and evaluating the detrimental and beneficial consequences of *climate change* on natural and *human systems*.

Impacts
Impacts are the actual consequences of climate change on natural and human systems over an observed period. They are a manifestation of residual vulnerability and spontaneous adjustment.

Indirect aerosol effect
Aerosols may lead to an indirect radiative forcing of the climate system through acting as condensation nuclei or modifying the optical properties and lifetime of clouds.

IPCC Fourth Assessment Report
The fourth assessment of the Intergovernmental Panel on Climate Change, due out in 2007. The IPCC Third Assessment Report was published in 2001 (IPCC, 2001).

Land-use change
Land-use change is a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system, and may thus have an impact on climate, locally or globally.

Natural forcing
The forcing imposed in climate model simulations due to natural changes such as variations in solar input and the effects of volcanic eruptions. See Anthropogenic forcing.

Natural variability
This term has two meanings:

1) The variability of the climate system due to natural forcing (see above) but excluding anthropogenic forcing.
2) The 'unforced' variability of the climate. This can refer to climate model simulations with no external (anthropogenic or natural) forcing.

Non-linear
Linear relationships are such that a particular increase/decrease in one variable (e.g. x) always causes the same change (increase/decrease) in another variable (e.g. y) no matter what the value of x or y. In non-linear relationships (e.g. $y=x^2$) the change in y can depend on the value of x. The use of thresholds also defines non-linear relationships.

Now variables (as distinct from 'lagged' variables)
Usually refers to variables which can be used to predict, simultaneously, another variable (e.g. rainfall). Lagged variables can be used to predict another variable ahead in time.

Potential evaporation
The amount of surface evaporation that would occur if there were an unlimited water supply. This is often linked to the 'pan' evaporation, the method by which evaporation measurements are usually taken, where the decrease in water level in a large 'pan' is measured daily.

Probability density function
Describes the frequency of occurrence of events (such as rainfall amounts).

Reanalyses
Global gridded datasets of many atmospheric variables produced by assimilating surface, air and remotely-sensed observations into a recent global forecast model. The same version of the model is used to produce many years of data.

Self Organising Maps (SOM)
A method for clustering synoptic maps into a limited number of types.

Southern Annular Mode (SAM)
The southern annular mode is the dominant pattern of non-seasonal tropospheric circulation variations south of 20°S, and it is characterised by pressure anomalies of one sign centred in the Antarctic and anomalies of the opposite sign centred about 40–50°S.

SRES scenarios
SRES scenarios are emissions scenarios developed by Nakicenovic et al. (2000) and used, among others, as a basis for the climate projections in the IPCC Third Assessment Report (IPCC, 2001). There are four families of scenarios:

- **A1** – future world of very rapid economic growth, global population peaks in mid-century and declines thereafter, with the rapid introduction of new and more efficient technologies.
- **A2** – Heterogeneous world with self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic growth is primarily regionally oriented and per capita economic growth and technological change is fragmented.
- **B1** – A convergent world with the same global population profile as A1 but with global solutions that emphasise economic, social and environmental sustainability.
- **B2** – A world that focuses on local and regional solutions to economic, social and environmental sustainability. It has continuously growing global population that is less than A2 and intermediate economic development but less rapid and more diverse that B1.

Statistical Downscaling (SD)
Relating weather variables (usually daily precipitation amounts) at a site to large scale atmospheric variables.

Synoptic types
To represent the climatology of synoptic systems (as portrayed on weather maps in the news, which are maps of mean sea-level pressure), the more common systems were determined and termed the ‘synoptic types’.

Vulnerability
The degree to which a system is susceptible to, or unable to cope with, adverse effects of *climate change*, including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its *sensitivity*, and its *adaptive capacity*.

Residual vulnerability
Residual vulnerability is the net potential to be harmed that remains at any time after particular adaptive responses.

Weather states
See Synoptic types. (The method for determining weather states differs to that used to determine synoptic types.)

WRE profiles
The carbon dioxide concentration *profiles* leading to stabilisation defined by Wigley, Richels, and Edmonds (1996) whose initials provide the acronym. For any given stabilisation level, these profiles span a wide range of possibilities.

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