Indian Ocean Climate Initiative

Informed Adaptation

Indian Ocean Climate Initiative Stage 2:

Report of Phase 2 Activity
January 2005 - June 2006

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

Editors
Brian Ryan and Pandora Hope
October 2006

Government of Western Australia

Australian Government
Bureau of Meteorology

CSIRO

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

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Obituary

It is with deep sadness that we acknowledge the passing of our colleague and friend Brian Ryan on 20 October 2006.

Brian, co-editor of this report, was a very active member of the IOCI Panel throughout Stage 2. Since early 2005 he served as the first point of contact for the State members of the Panel. Brian's passion for communicating the science was clear, and his representation of both the Bureau of Meteorology and CSIRO was generous and fair. Brian had worked tirelessly on the research plan for Stage 3 of the Initiative, ensuring that the proposed research would lead to tangible benefits for the State.

His presence and guiding hand are missed.

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Contents

Foreword

The first explicit risk management responses for adaptation to climate change in south-west Western Australia were taken, in 1988, by water managers who based forward planning on a scenario of gradual decline in rainfall from 1970 to 2040 caused by global warming from the Enhanced Greenhouse Effect. Prompted by studies for the Greenhouse '87 conference and low rainfalls dating from the early 70s, this was a highly contentious decision at the time. The institutional decision environment of 1988 was highly sceptical in respect to these matters and for various reasons was largely disinterested in, or even hostile to, proposals for adaptation to ongoing long term climate change. However a research program was initiated to determine possible associations between the ENSO phenomenon, the impacts of which were becoming increasingly recognised in Eastern Australia, and climate changes observed in the south-west region.

No apparent association with ENSO was revealed, but in 1993 Allan and Haylock reported circulatory changes associated with the observed winter rainfall decrease. In December 1996, almost a decade after water managers had adopted the scenario of gradual winter rainfall decline, a water sector workshop concluded that a significant step decrease of south-west rainfall had actually occurred in the early to mid 1970s and had reduced rainfall to levels not expected until around 2040 under the assumed trend. The workshop proposed that such a shift had to be considered in water planning as more representative of present and future climatic regimes than was the former assumption of gradual rainfall decline. However, the public decision environment of the time remained sceptical on climate change and, in the absence of specific evidence, water managers were unable to attribute cause for the apparent regime shift. The issue, nonetheless, was highly critical to reliability of water supplies and a period of massive water source augmentation was begun using decision scenarios reflecting markedly diminished present and future inflows.

Concurrently, national climate science was delivering some promise in probabilistic inter- and intra-seasonal forecasting based on sea temperature observations. The identified opportunities were most strongly associated with the eastern seaboard and near-term effects of El Nino linkages on climate variability. WA managers were keen to see if such techniques could be profitably deployed in south-west Western Australia, possibly linked to cyclic phases affecting the Indian Ocean.

In this general decision environment the Indian Ocean Climate Initiative (IOCI) was formed in 1998. Its mission was to enhance regional climate knowledge and understanding in support of adaptive decision-making. Some research and investigation of climate variability and change in WA was being conducted at that time within government agencies but the efforts mostly lacked strategic focus and coordination. The research emphasis, chosen by the State partners for the first Stage of the IOCI program, was towards climate variability, rather than study of climate change per se. However, the Stage 1 Report[1], issued in 2002, reinforced the view that the rainfall decrease was associated with changes in global atmospheric circulation and noted that these changes had broad similarities with modelled predictions of enhanced greenhouse conditions.

By 2002, adaptive management to climate change impacts, dominated by rainfall decline, was more strongly recognised within the IOCI partnership as its current, front-line decision issue. Altered stream-flows, the most evident manifestations of these impacts, were a surrogate measure of much wider environmental stresses, including those observed in native woodlands and coastal plain wetlands. Even for those decision-makers whose dominant interest had been inter-seasonal forecasting, the start-point for risk management now needed to be an assessment of the baseline variability and risk associated with altered climatology. Consequently, IOCI Stage 2 was set on a primary course of establishing and then applying more powerful tools of climate analysis to define, explain and project change and attendant variability. Methods, emphasising large scale atmospheric processes, were developed and applied to south-west climate studies which would provide a more robust insight to local trends and causes. Stage 2 affirmed

1. *Climate variability and change in south west Western Australia, IOCI Sept 2002*

strongly that the primary causes of observed change in south-west Western Australia were large scale regional and global phenomena. Stage 2 also provided much more substantive evidence that the Enhanced Greenhouse Effect was a primary, if not the only significant, cause of rainfall decrease.

In 2006, the State is considering embarking on a Stage 3 IOCI research program in a different decision environment. Nationally and internationally there is compelling evidence for the here-and-now significance of climate change due to the Enhanced Greenhouse Effect. A workshop convened in late 2005 by IOCI demonstrated and helped mobilise a wider sectoral interest in adaptive management issues in WA decision circles. Active interest by bodies such as the Chamber of Commerce and Industry has led to calls for a wider scope of investigation, with movement into issues of extreme events in the north-west. Also widening concern has been expressed that more attention needs to be given to coastal matters and IOCI is exploring collaborations with bodies such as the WA Marine Science Institution.

There is also another circumstance at the potential start of Stage 3 which is a reminder of how actively these issues must be followed in a risk management sense. The south-west winter of 2006 has been the worst since regional settlement began. Its start was typical (in a worst case sense) of the last quarter century of rainfall decrease where poor early season (MJJ) rainfalls have been almost universal. This event compounds concerns and questions, raised particularly by water managers, as to whether possible further significant rainfall decrease has occurred in the very dry run of recent years. IOCI research strongly confirms that the risk of these failed south-west winters has been increased by climate change of the last quarter century. However, it is still too early to be scientifically conclusive on the extent of base-line change in recent years. Ultimately water managers and other decision-makers must formulate their own risk management responses reflecting the risk structure of their sectors and the best science available at the time. These dynamics in the climate situation and in scientific observation and prediction emphasise how science, monitoring and risk management will need to continue moving forward collaboratively in the relatively more uncertain world of climate change adaptation.

This report of IOCI Stage 2 is in summary form. Stage 2 has been shortened with the intention of moving forward into a more comprehensive third Stage. However the report contains important developments and questions for active consideration by researchers and decision-makers alike. More substantive reporting and debate of some initiatives herein is proposed under specific initiatives for an IOCI Stage 3.

Brian Sadler
Chairman Indian Ocean Climate Initiative Panel, Stage 1&2

Executive summary

Changes in weather systems and investigation of their cause

A significant component of Stage 2 has been work characterising changes in large weather systems with the potential for then investigating causes of their trend by climate modelling. This approach is important. It moves investigation further back towards the root cause of change than say direct study of rainfall. The approach is also relatively robust because it works at the scale in which climate models operate and it is amenable to physical interpretation.

This report presents objective descriptions of observed large scale changes in pressure systems and storm tracks, and in the incidence of wet and dry weather, which explain rainfall reductions of the general scale experienced in south-west Western Australia (SWWA). Possible secondary local influences such as land clearing are not discounted.

Observed aspects of changes in the large scale winter weather systems that bring rain to SWWA include:

- a decrease since the mid 1970s in the number of weather patterns that bring wet conditions accompanied by an increase in the number of weather patterns that bring dry conditions;
- the reduction in the number of wet weather patterns crossing SWWA in June and July has contributed to 50 per cent of the rainfall decline in the mid 1970s;
- a reduction of 20 per cent in the strength of the upper level winds has lead to a reduction in the likelihood of storm development over SWWA compared to the pre 1970s.

The collective evidence of Stage 1 and Stage 2 coupled with the broader evidence of national and international science has increased confidence in attributing the causes of climate change that has taken place in SWWA:

- It is unlikely that the observed warming is a result of natural fluctuations in the climate,
- It is likely that the natural fluctuations inherent in the climate system and changes in greenhouse gas concentrations have contributed to the observed rainfall decline in south-west Western Australia and
- The role of land cover changes is unlikely to be a major factor in the reduction of the rainfall in south-west Western Australia but must be recognised as one possible secondary contributor.

Risk, uncertainty and confidence in climate change projections

There are three reasons for the range of uncertainty associated with climate projections.

The first uncertainty is natural internal variability (in the form of a statistical risk) which arises because of the chaos exhibited by the climate system. A real world climate sequence may be represented by a 'trend' component overlaid by a component of random variation. 'Perfect' climate projection would therefore include projection of the trend/change and of variability about the trend (a forecast of risk). Climate models behave similarly and no two model climate runs will be identical. In order to detect and estimate a modelled trend/change many simulations (ensembles) are required so that the natural internal climate variability can be filtered out of the signal and the underlying trends isolated. To address this uncertainty, the IOCI Stage 2 studies, when resources allowed, used ensembles of models and simulations.

The second uncertainty arises from the errors due to limitations in modelling a perfect representation of the climate system. All international models used in the IOCI projections for 2030 outlined below have been evaluated so as to select only those that more accurately model the major features of the climate of SWWA. Downscaling methods (statistical or dynamical) can assist in reducing this type of uncertainty.

The third area of uncertainty is in the assumed future greenhouse gas emission profiles used in the modelling studies. A range of scenarios is commonly used to represent a range of plausible international scenarios. These scenarios are diverse but do not diverge greatly over the next 25 years.

Climate change projections for 2030

There is now increased confidence in how the temperature and rainfall in SWWA will change under different greenhouse scenarios. The Stage 2 IOCI projections used up to nine international models. Two emission scenarios were downscaled to the regional and rain gauge scale. Results for 2030, directly from the models or downscaled, indicate that:

- all emission scenarios indicate a rise in temperatures in all seasons and a decrease in winter rainfall for SWWA by 2030;
- the projected winter rainfall results suggest that rainfall may fall by as much as 20 per cent relative to the 1960-1990 baseline level;
- the results of 'downscaling', using a range of models and two scenarios based on data from 30 SWWA rainfall stations, suggest that rainfall may fall by as much as 19 per cent relative to the 1960-1990 baseline level;
- the results of 'downscaling', based on data from the same 30 SWWA stations, suggests that the number of winter rain days will reduce by up to 17 per cent and this corresponds with the predicted decrease in wet weather patterns and predicted increase in dry weather patterns; and
- hydrological sensitivity studies indicate that by 2030 the catchments across SWWA can expect decreases in runoff ranging from 5 per cent to 40 per cent relative to 1990.

With the availability of increased numbers of model simulations from the IPCC Fourth Assessment model archive further enhancements and separation of risks and uncertainties associated with the climate projections can be expected. In particular, analyses of ensembles to best filter variability from underlying trends and centrally weighting model differences should be possible for different emission scenarios.

Seasonal prediction and climate baselines

IOCI has evaluated some new methodologies for short term climate prediction and concluded that:

- there are no current seasonal prediction schemes utilising climate models that have the necessary skill for operationally reliable seasonal forecasting for SWWA;
- future work should focus on a rigorously theoretical assessment of the predictive skill of statistical and dynamical seasonal forecasts as they apply to WA;
- the seasonal prediction studies highlight the need for developing robust climate baselines that take account of climate change;
- a tool for forecasting the onset of winter rainfall for the SWWA has demonstrated some promise in a proof of concept study;
- tools have been developed to synthesise the output from observed and modelled climate data using empirical (statistical) models. However further applications for seasonal prediction to WA is dependent on progress on improving the seasonal predictability of climate models; and
- the new tools to study the spatial modelling of rainfall extremes have potentially significant applications to hydrological studies.

Looking forward

The IOCI Stage 2 program has provided outcomes for decision support and capacity building in Western Australia. Climate science gaps, identified by State partners in IOCI workshops as needing to be addressed in an IOCI Stage 3 core climate science program are:

- baseline, predictability and attribution of climate change studies extended across the whole of the state and for all seasons;
- understanding the current and future climate of the north-west of WA; and
- scenarios of climate change for sector impact and vulnerability studies.

IOCI Stage 3 would draw heavily on extensive international modelling studies carried out as part of the IPCC Fourth Assessment report. As well as drawing upon the Bureau of Meteorology and CSIRO climate and climate change research portfolios.

1. Overview

The objectives of the IOCI Stage 2 core research strategy were to:

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

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

- current climate regimes;
- climate change projections; and
- short-term climate projections.

The IOCI Stage 2 work program comprised of two phases with the planned Phase 1 mid-term report released at the "Living with our changing climate" seminar and workshop held in August 2005. Phase 1 concluded in December 2004, at which time the outcomes from Phase 2 were discussed, the deliverables for Phase 2 were re-assessed and a revised set of deliverables for the three themes approved by the IOCI Panel. See Tables 1-3 in the IOCI Stage 2 Phase 1 Report (Ryan and Hope, 2005).

This IOCI Stage 2 Phase 2 Report presents:

- key findings from IOCI Stage 2;
- three theme summaries:
  - reporting on the projects and their scientific findings and
  - interpreting the scientific findings in terms of key messages for the State partners;
- future climate research directions identified by the "Living with our changing climate" workshop;
- a bibliography of:
  - references in the report and
  - other references relevant to IOCI objectives; and
- an appendix of acronyms and glossary of terms used in the report.

Key findings from IOCI Stage 2 (with reference to the Stage 2 research agreement)

1. **The synoptic drivers of the climate of SWWA have changed.**
   - On average, in 1976-2003, compared to 1958-1975, there has been a marked decrease in the frequency of synoptic troughs (in June and July) associated with wet conditions while the frequency of high pressure patterns over the continent associated with dry conditions in SWWA has increased. This is consistent with the IOCI Stage 1 statistical downscaling findings that May-October frequency of wet weather patterns across the central western and central areas of SWWA decreased in the period 1958 to 1975 and has remained stationary and the frequency of dry weather patterns increased abruptly in the mid 1970s and continues to increase. (2.1.1)
   - The reduction in the number of deep troughs crossing SWWA in June and July contributed to 50 per cent of the rainfall decline in the mid 1970s. (2.1.1)
   - The 1975-1994 period, on average, displays a 20 per cent reduction in the strength of the subtropical jet over Australia and an associated reduction in the likelihood of storm development over SWWA compared to the earlier 1949-1968 period. (2.1.2)

2. **There is increased confidence in the causes of the recent climate change in SWWA.**
   - It is likely that natural fluctuations inherent in the coupled atmosphere ocean system and the greenhouse effect have both contributed to the observed rainfall decline in SWWA. (2.2.3)
   - It is unlikely that the observed warming is a result of natural variability alone. (2.2.3)
   - There is no modelling evidence to link the changes in sea ice extent to rainfall changes in SWWA. (2.2.1)

- The role of land cover is unlikely to be a major factor in the reduction of the rainfall in the SWWA but must be recognised as one of the possible secondary contributors. (2.3.2)

3. **There is increased confidence in how the climate of the south-west will change under enhanced greenhouse scenarios.**
   - All coupled climate models analysed and all emission scenarios indicated a rise in temperatures in all seasons and decreases in winter rainfall for the SWWA by 2030. The projected decline in winter rainfall is a consistently evident trend under a wide range of scenarios, including one with very little increase in emission levels from the present. The upper limit of the projected decline is about -20 per cent below the 1960 – 1990 baseline by 2030. It is not possible to be more precise because of the uncertainties associated with different emission scenarios and different model responses. It must also be understood that the actual run of rain event outcomes from now to 2030 will include an unpredictable stochastic component overlying any mean trend. (Phase 1 report and Themes 3.1.1, 3.3.3)
   - Statistical downscaling of a range of models and emission scenarios yield consistent results relative to the 1960-1990 baseline. (3.1.2)
     - Changes to median winter half-year (MJJASO) rainfall totals from a range of models and emission scenarios for 30 SWWA stations range from -19 per cent to 0 per cent by about 2030, -27 per cent to -1 per cent by about 2050 and from -34 per cent to -5 per cent by about 2085, depending on station, model and emissions scenario.
     - Changes to median winter half-year (MJJASO) rain day frequency for 30 SWWA stations range from -17 per cent to 0 per cent by about 2030, -24 per cent to -1 per cent by about 2050 and from -30 per cent to -3 per cent by about 2085, depending on station, model and emissions scenario.
   - Analyses of observed trends provide a third method for estimating future rainfall trends and for the 2030 predicted global warming these rainfall trends are consistent with the results from climate model rainfall projections. (3.1.3)
   - IOCI is now in a position to further examine the robustness of these conclusions by evaluating model projections of key synoptic conditions which drive rainfall outcomes. (2.2.2, 3.1.2 and 3.3.2)
   - Hydrological sensitivity studies indicate that by 2030 the catchments across SWWA can expect decreases in runoff ranging from 5 per cent to 40 per cent (relative to 1990) for a global warming of 0.85oC. (3.3.3)

4. **An evaluation of some new methodologies for short term climate prediction.**
   - There are no current climate model seasonal prediction schemes that have the necessary skill in forecasting predictors suitable for statistical downscaling. (4.2.2)
   - A tool for forecasting the onset of winter rainfall has demonstrated some promise in a proof-of-concept study. (4.1.1)
   - Spatial modelling of rainfall extremes has been extended to the whole south-west. Whilst no significant forecast skill has been found with the predictors studied to date, the method can be used to make inferences at ungauged sites. This has potentially significant applications to hydrological studies in WA. (4.1.2.)
   - A change point analysis of heavy rainfall events at five rainfall stations in SWWA from 1930-1965 to 1966-2001 suggests a change in extremes directionally consistent with the decrease of average rainfall. The analysis shows a uniform increase in return periods for rainfall greater than 30 mm and less than 80 mm. In four out of five cases this increase is for all rainfall amounts greater than 30 mm. (4.1.2)

- The value associated with the skill of existing prediction schemes is questionable. An assessment of value for wheat farming within SWWA indicated that relatively high values of skill are required in order to add value. (4.2.1)
- Tools have been developed to synthesise physical and empirical models. Further applications for seasonal prediction to WA are dependent on progress in modelling the WA climate processes and a review of practical potentialities. (4.1.3)

5. **Key climate science priorities identified by State agencies to underpin adaptation strategies (5.3)**

   Priorities for a Stage 3 core IOCI program were developed in a workshop/meeting held in April 2006 to identify the core climate science focus for IOCI Stage 3 and the outcomes that would be sought for decision support and capacity building in WA. The priorities listed in this proposal are based on the outcomes of these consultations and are as follows:

   - baselines, predictability of WA climate and attribution of climate change across all seasons;
   - current and future climate of the north-west, including extremes; and
   - scenarios of climate change for sector impact and vulnerability studies.

A key component in the priority setting was project synergy with the new climate component of the Western Australian Marine Science Institution.

The priorities were developed to extend the knowledge base from IOCI Stage 2 by increasing understanding of the drivers of climate change in Western Australia and to provide regionally specific scenarios with reduced uncertainty. Specifically, IOCI Stage 3 will draw heavily on the extensive international modelling studies carried out as part of the IPCC Fourth Assessment report. A major new aspect of the expanded IOCI Stage 3 is an extension of the study area to the north-west of Western Australia.

2. Summary Report for Theme 1: Current climate regimes

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

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Following the completion of the Stage 2 Phase 1 report the milestones for Theme 1 were adjusted. The summary report addresses the revised milestones with the new projects specifically identified.

2.1 Summary of progress on core activity, Jan 2005 – June 2006

2.1.1 Complete the development of a climatology of synoptic systems. Link synoptic systems with surface features. (BMRC)

In the Phase 1 report, several methods to capture the full climatology of the synoptic systems influencing SWWA were described. After further testing, with a range of new data, (lower level winds, upper level geopotential heights or moisture), the self-organising map (SOM) of 20 synoptic types based on June and July NCEP/NCAR reanalyses mean sea-level pressure (MSLP) was decided to be used. This SOM captured the synoptic patterns anticipated a *priori* from a knowledge of the weather systems that influence SWWA. Limiting the data required to create this SOM to just MSLP allows for easy application to climate model output.

Using these 20 synoptic types, links with observed June and July rainfall across SWWA were described, and expected patterns were shown. These included widespread, heavy rainfall associated with deep troughs crossing the region, dry conditions under regions of high pressure, wet conditions along the west coast when a trough was positioned just off-shore, and wet conditions along the south coast when a trough was positioned south of SWWA. The time-series associated with each of these synoptic types and the corresponding SWWA rainfall totals indicate that a decrease in the number of deep troughs over the region contributed about 50% to the rainfall decline (Hope et al. 2006)

Links between the 20 synoptic types and the wind measured at Wandering were also considered. The results of this analysis added another layer of information about how the surface conditions behave for each synoptic type in the NCEP/NCAR reanalyses. Wandering was chosen because it has continuous wind measurements for the full period, it is right in the heart of the observed rainfall decline and is some distance away from coastal influences. The results reinforce the findings in the Phase 1 report, that rainfall is generally associated with wind from the north and north west. This is true for the synoptic types with deep troughs over the region associated with wide-spread rainfall. Dry synoptic types are associated with winds from the dry inland. These results add further credence to the veracity of the synoptic types in the NCEP/NCAR reanalyses MSLP SOM and are consistent with the statistical downscaling rainfall pattern and weather state time series (IOCI, 2002).

Preliminary work by Telcik (2001) suggests that north-west cloud bands are not closely linked to rainfall in the south-west. Thus, other work, on future rainfall variations from climate models (3.3.2) took precedence over further study of the links between the range of synoptic types and north-west cloudbands.

2.1.2 Determine changes in storm tracks under climate change in CSIRO Mk3 simulations (BMRC/CSIRO)

The Southern Hemisphere atmospheric conditions at 2081-2100 from two simulations of the CSIRO Mk3 model were compared. One simulation was run with unvarying, pre-industrial, forcing, while the other was forced with increasing greenhouse gases following the SRES A2 emissions scenario. The differences highlighted how the Southern Hemisphere climate will most likely respond to future anthropogenic forcing. The changes are qualitatively similar in the Australian region to the observed changes in the NCEP/NCAR reanalyses ([1975 to 1994] compared to [1949 to 1968]) that were largely responsible for the changes in the southern hemisphere storm tracks that affected SWWA (see Phase 1 Report). For example, the 500hPa geopotential height is greater under climate change over SWWA, as was the case when comparing [1975 to 1994] to [1949 to 1968], which is suggestive of either fewer deep troughs crossing the region, or a greater proportion of high pressure systems. Changes in atmospheric stability also resemble those seen in the observations (reanalyses), with more stable conditions over southern Australia and less stable conditions further southward. The similarities are particularly strong in the SWWA region. Thus, the changes between simulations at the end of this century (2081-2100), with and without enhanced levels of greenhouse gases are similar in signature to the changes around the mid 1970s, particularly in the vicinity of the south west. This similarity adds more weight to the suggestion that the large-scale circulation shift, observed around the 1970s, may have been driven, at least in part, by increasing greenhouse gas concentrations and these circulation changes have contributed as drivers of the rainfall increase.

These results provide excellent guidance to the potential changes in the storm tracks in this region under climate change, however, this study will be continued and the effect of these changes on the modelled storm tracks will be examined directly.

2.2 Progress on new projects

2.2.1 Changes in sea ice (CSIRO)

The hypothesis that changes in Antarctic sea ice could help explain the decline in rainfall and changes to atmospheric circulation around 1970 was tested using the results from experiments with the CSIRO Mk3 climate model. The study looked at the simulated changes between a model run with fixed sea ice cover and model runs with prescribed increases and decreases in sea ice cover. The findings indicated that, although changes in sea ice cover can have an impact on the circulation and rainfall patterns at high latitudes, they are insufficient to perturb the circulation and rainfall at mid-latitudes, particularly over SWWA. There was no model evidence that changes in sea ice extent as large as plus or minus 20 per cent can explain the observed changes in southern hemisphere MSLP and winter (JJA) rainfall changes over SWWA. As a result, it is unlikely, based on the current generation of models, that the sea ice changes prior to 1970 could cause the observed pressure and rainfall changes in SWWA.

2.2.2 Comparison of synoptic events simulated by the high resolution CSIRO Conformal Cubic Atmospheric Model (CCAM) and observed events (BMRC/CSIRO)

A comparison has been performed of the distribution of synoptic patterns within the CCAM simulation of present day Australian climate and those derived from an analysis of the NCEP/NCAR reanalyses. A self-organising map (SOM) was used to assess the distribution of synoptic types. The range of synoptic types represented in the SOM based on CCAM MSLP is reasonably similar to the distribution in the SOM produced with NCEP/NCAR reanalyses. The 12-hourly CCAM MSLP was also assigned to each synoptic type in the reanalyses SOM, and there were fewer occurrences of conditions with a deep trough across SWWA, but more occurrences of situations with minimal disturbance across the region. The differences were not extreme, indicating that, although differences do exist in the circulation in CCAM and the reanalyses, they both capture the known range of synoptic systems.

Furthermore, the synoptic types that are associated with wet conditions over SWWA behave similarly within the CCAM simulations as in the NCEP data, indicating that not only does CCAM reflect the appropriate range of systems, but the changes in the frequency of those systems over time are also aligned with changes observed in the reanalyses. Correspondingly, statistical downscaling of CCAM reproduces the observed interannual variability and mid-1970s change in rainfall.

2.2.3 Synthesis of climate change detection and attribution studies relevant to SWWA (BMRC)

Note: The full report is available at http://www.ioci.org.au

A review was completed that synthesised all recently published climate change detection and attribution studies relative to SWWA (Nicholls, 2006). It demonstrates that the understanding of climate change has advanced somewhat since IOCI (2002).

Based on this recent work, it is reasonable to conclude, as was done in IOCI (2002), that the warming in the south-west[2] is likely the result of human actions, specifically the enhanced greenhouse effect.

It still seems likely that the mid 1970s decline in winter rainfall was the result of the enhanced greenhouse effect and natural variability, but that land use change could also have contributed. There may also be some contribution from changes in the Southern Annular Mode, which is influenced by changes in concentrations of greenhouse gases but may also respond to other aspects of the climate system. However, the continuation of the dry phase, and new studies, tend to support the conclusion that natural variability alone seems unlikely to have been the sole cause of the decline. A major advance has been our improved understanding of the circulation changes and shifts in local synoptic systems that are intimately linked to the rainfall decline. Further studies attributing the causes of these synoptic changes are necessary, if we are to provide a more conclusive attribution for the rainfall decrease.

2.3 Summary of related work by BMRC and CSIRO and in the literature

2.3.1 Link between Southern Annular Mode and WA rainfall in CSIRO Mk3 (CSIRO)

The observed links between Perth mean sea level pressure and SWWA winter (JJA) rainfall have been well documented but a link between rainfall and mean sea level pressure on the large scale is also manifest. Li et al. (2005a) demonstrated this link with dominant patterns of global tropical and sub-tropical MSLP, but links with the Southern Hemisphere hemispheric pattern in mid and high latitude MSLP, known as the 'annular mode' have also been found (e.g. Meneghini et al. 2006). The winter trend from 1958-2000 in an index of the annular mode is small but positive (Marshall 2003). Lower pressures at 65°S and higher pressures at 40°S are evident as the annular mode strengthens (and its index is higher). Results from the CSIRO Mk3 model also show links between WA rainfall and the annular mode, with SWWA winter rainfall decreasing, but inland WA winter rainfall increasing as the annular mode strengthens. This model result adds weight to the evidence that large scale changes in the circulation contributed to the observed rainfall decline in SWWA in the mid-1970s.

2.3.2 New simulations assessing how land-cover change might influence SWWA rainfall (BMRC)

In the Phase 1 report, results from simulations with a regional scale climate model suggested that reduced tree cover in SWWA would result in decreased rainfall (Pitman et al. 2004). There were some limitations in that study, such as little influence from antecedent conditions, since an ensemble of results from only one month (July) was considered. Timbal and Arblaster (2006) addressed some of the limitations in the Pitman et al. (2004) study by using a global climate model with a full seasonal cycle coupled with a statistical downscaling technique. They found a similar result to Pitman et al. (2004), with drying occurring over SWWA. Limitations on the Timbal and Arblaster (2006) study include having only a small ensemble of model simulations available and that the land cover change was extreme. The land cover change imposed in both Pitman et al. (2004) and Timbal and Arblaster (2006) was different from observed;

2. *Temperatures, both day-time and night-time, have increased gradually but substantially over the last 50 years, particularly in winter and autumn. See: http://www.bom.gov.au/silo/products/cli_chg/*

Timbal and Arblaster (2006) modified an area four times greater than observed, while Pitman et al. (2004) imposed the observed changes abruptly. Both these differences from observed changes in land cover are a result of the limitations imposed by the nature of each style of modelling study (for example, the grid size in the climate model used by Timbal and Arblaster (2006) was large, therefore the area of the changes is also large). However, the concurrence in the results from these two studies adds further credence to the likelihood that land cover change in SWWA has contributed to the observed rainfall changes.

2.3.3 Recent trends in SWWA winter rainfall. (BMRC)

The question of whether or not, in recent years, rainfall (and thus streamflow) may have experienced another step-drop since the 1970s was addressed in the Phase 1 report and it was concluded that it is *too early to determine whether this [2001-2004 period] is a new climate "baseline".*

No new statistically significant shift can be found in the data unless the 2001-2004 dry conditions persist for about 10 more years. The linear trend from 1975 to 2005 has been flat, but more recent anomalies are increasingly negative. The disastrously dry winter in 2006 has added to the extremity of this dry run. The early winter (MJJ) totals for 2006 were the lowest on record while the 10-year average (1995-2006) value was also the lowest on record.

Statistically, there are still not enough years to infer or define a new statistically significant climate baseline. However, the future projections of drier conditions (e.g. 3.3.2) suggest that these dry sequences do need to be factored into risk management decisions with greater probability than is inferred by the historic record and that wet sequences such as in the middle of the twentieth century are inferred as having decreasing probability.

Late winter (August, September and October) totals have displayed a slight upward trend since 1975.

2.3.4 Paleoclimate studies

Instrumental climate records in Australia are short, of the order of 100 years. As future climate research will have more emphasis on the impact of climate changes, it is important to appreciate the full spectrum of historical climate variability and how the natural system responded to past climate changes. IOCI has a palaeoclimate sub-committee. The palaeoclimate sub-committee has drafted a preliminary review of literature relevant to the past climate of WA, encompassing many of the different methods of estimating past climate trends. They have also developed a draft investment plan for palaeoclimate research. This includes accessing funding for further dendro-chronology, coral, palaeo-hydrology, speleothem and sediment core studies.

Dr Treble of the Australian National University is currently funded by a Land and Water Australia grant to reconstruct long proxy rainfall records for southwest WA. This research is providing a unique, high resolution rainfall record for SWWA extending back 1000 years using the geochemistry of speleothems (cave stalagmites). Such a long-term record will quantify the region's natural climate variability and provide a baseline against which contemporary rainfall changes can be compared. The records will also be used to calibrate global circulation models used to assess the vulnerability of water supplies to projected anthropogenic climate change.

To date, four suitable speleothems have been collected from the Augusta and Yanchep regions. These speleothems were actively growing when collected and range in total age span from 400 to 8000 years, determined by radionuclide dating. Construction of the proxy rainfall records have begun using oxygen isotopes and various trace elements which were determined in a previous study to be rainfall sensitive. Understanding these geochemical signals is being further advanced by a detailed cave drip water monitoring program.

2.4 Key findings from Theme 1

The following findings were taken from the core work planned for Phase 2:

- A range of approaches to classify synoptic types and study changes in large scale atmospheric systems have given consistent insights to observed rainfall decreases and provide IOCI with generally robust tools for improved investigation of present and future change.
- Observed rainfall and surface winds match these synoptic classifications in ways that would be physically expected.
- A quantitative assessment of the time-series of these synoptic types and their associated rainfall indicates that about 50 per cent of the mid-1970s rainfall decline was caused by fewer deep troughs crossing SWWA.
- Analyses verify that the CSIRO Mk3 climate model reproduces the observed link between SWWA winter (JJA) rainfall and MSLP on an interannual time scale and simulates a long-term change in rainfall and atmospheric circulation that is consistent with observations.
- Because of the similarity between the simulated and observed relationship between SWWA winter (JJA) rainfall and large scale circulation changes, the CSIRO Mk3 coarse scale climate change projections for SWWA can be treated with increased confidence. Analysis of rainfall from eight models that submitted results for the IPCC Fourth Assessment Report (3.3.2) shows that SWWA is a region where all models are consistent, and they all show a decline in rainfall late in the twentieth century.
- Analyses also verify that the high resolution CCAM model can capture the expected winter (JJA) circulation features influencing SWWA, including their variation over time.
- Modelled changes in sea ice extent as large as plus or minus 20 per cent do not explain the observed changes in Southern Hemisphere MSLP and winter (JJA) rainfall changes over SWWA.

2.5 Climate insights from Theme 1

- It is increasingly unlikely that the observed warming in SWWA is the result of natural variability.
- The results from the above projects 2.1.2 and 2.3.1 verify that the CSIRO Mk3 climate model reproduces the observed link between rainfall and MSLP on an interannual time scale and simulates a long-term change in rainfall and atmospheric circulation that is consistent with observations. Consequently, this adds confidence to the climate change projections from this model since it is important that climate models not only be able to simulate rainfall changes, but also be able to simulate rainfall changes for the correct reasons.
- Further consistencies are beginning to emerge between synoptic changes which explain a significant component of observed rainfall decline and the modelled atmospheric response to anthropogenic forcing.

3. Summary Report for Theme 2: Climate change

How will future climate be affected by the greenhouse signature?

Contributing authors:
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Following the completion of the Stage 2 Phase 1 report the milestones for Theme 2 were revised. The summary report addresses the revised milestones with the new projects specifically identified.

Climate models are the major tool used to answer the questions posed in this theme. One of the aims of analysing the results of climate model simulations is to estimate future scenarios, and to explain recent climatic changes which are due to increases in greenhouse gases. To adequately interpret climate model results, and attribute them to relevant forcing, an understanding of the forcing and limitations of both the climate system and climate model simulations is required.

The Earth's climate and the modelled climate are both forced by a range of factors. These are termed 'natural' and 'anthropogenic' (or 'human induced'). Natural forcing can be both 'external' and 'internal', while anthropogenic forcing is generally only external. External forces include variability in solar radiation, volcanic eruptions, changes in the Earth's atmospheric chemistry (e.g. greenhouse gases or stratospheric ozone), atmospheric particulates, and land-cover change. 'Internal' forces arise from various feedbacks and interactions within the climate system itself. Some of the external forces on climate are natural – for example: solar variations and volcanic eruptions, while many large changes in greenhouse gases, stratospheric ozone, particulates and land-cover can be ascribed to human activity (anthropogenic forcing). The term 'natural variability' is sometimes also used to describe internal variability (see Glossary), but it will not be used in that context in this report.

The climate system is stochastic. The observed rainfall record represents one realisation of possible outcomes comprising some underlying trend signal and an overlying noise of random variation. The noise can only be filtered out of the record when the record is of sufficient length to statistically isolate the underlying trend.

Climate model simulations also exhibit stochastic behaviour. In order to detect a greenhouse signal in model studies, an ensemble of many simulations can help to filter out the internal climate variability from the signal and the underlying trends can be isolated. To produce such an ensemble, different realisations of the model climate system can be achieved by using different climate models or starting each simulation from a subtly different starting point. The variability between simulations reflects the 'internal' variability of the climate system.

A high-quality model would reproduce the underlying trend and the statistical distribution of the overlying variability in the observed record but could not replicate the particular run of events actually realised in the observed record. Thus, as models improve in their capacity to simulate the current climate, our confidence in their results increases, but an ensemble will still help to differentiate the underlying internal variability from the trend.

At shorter time scales the greenhouse signal can be swamped in models and the observed record by the noise from internal climate variability. At the longer time scales of projection scenarios the trend from the greenhouse signal becomes stronger but the uncertainty associated with emission scenarios becomes more important. Consequently, there will always be a region of uncertainty associated with any climate change projections. Where resources allow, uncertainty is minimised in this theme by the use of ensembles. In some cases downscaling is used to minimise the uncertainties.

3.1 Summary of progress on core activity, January 2005 – June 2006

3.1.1 Dynamical downscaling of the results from large-scale climate models (CSIRO)

The CSIRO Conformal Cubic Atmospheric Model (CCAM) was used to dynamically downscale (i.e. directly simulate at a finer scale) the results of a single run of the larger scale CSIRO Mk3 climate model for both the late twentieth century and for later this century. The aim was to provide more detail at the regional scale, particularly where surface topography affects local climate. In the case of

CCAM, the grid resolution was 60 km compared to approximately 200 km for Mk3. The only external forcing in these experiments were enhanced greenhouse gases, and changes in aerosols and ozone (the SRES A2 scenario). Dynamical downscaling can reduce uncertainties, however, its heightened computing requirements make downscaled ensembles impractical at this stage.

The simulated results for the late twentieth century (1961-1990) were compared with observations. The results for SWWA winter (JJA) rainfall, while more detailed than the Mk3 results, do not explain the full magnitude of the relatively large decreases observed around 1970. While only one realisation was performed, this result is consistent with results using the larger scale models – namely, that the observed rainfall changes cannot be explained solely by greenhouse gas forcing.

The CCAM results for the period 2071-2100 under the SRES A2 scenario indicate rainfall decreases of about -20 per cent (relative to 1961-1990) for SWWA. This is consistent with the results from Mk3 and all other climate models used in the IPCC Fourth Assessment Report.

The CCAM simulation for winter (JJA) rainfall based on the SRES A1B scenario, which has lower emission levels than A2, indicates a reasonably linear climate response to emission levels. In general, the magnitude of the rainfall changes over Australia for later this century (as with warming), are less in the A1B simulation than in the A2 simulation.

3.1.2 Statistical downscaling of large-scale climate model outputs (CSIRO)

Statistical downscaling provides a means of interpreting large-scale model information at station or point scales. This information can be more useful than grid scale information for some applications.

A set of results from a range of climate models and emissions scenarios has been statistically downscaled to a network of 30 stations across SWWA for the winter half-year (MJJASO). Although still reasonably small, the set of projections is much larger than originally envisioned due to re-direction of effort and beneficial co-investment from AGO and GRDC projects. The models used are the CSIRO Mk3, CSIRO CCAM, the Hadley Centre HadAM3P and the Max Planck ECHAM4. Greater confidence could be gained if this study were expanded in the future to include downscaling of more models, simulations and, particularly, more emissions scenarios.

Although results indicate that some climate models are more responsive to greenhouse gas forcing than others, there is broad consistency between the downscaled results from different models. The magnitude of downscaled drying was strongly related to the emissions profiles of the scenarios, i.e. the greater the emissions the greater the projected circulation changes and hence the greater the downscaled rainfall reductions.

The percentage decreases in rainfall totals for both scenarios are slightly larger than the decreases in rain day frequency. For both rainfall totals and rain day frequencies, the projected 90th percentile changes are (slightly) less than the projected median changes across the range of models and scenarios.

Summarising across all stations, models, and emissions scenarios, the downscaled changes can have a wide range. The range is greater than at just one site because each of the 30 stations considered in this analysis can have a different local response to the large-scale forcing. The change in median rainfall totals range from -19 per cent to 0 per cent by about 2030, -27 per cent to -1 per cent by about 2050 and from -34 per cent to -5 per cent by about 2085 . The corresponding changes to median rain day frequency range from -17% to 0 per cent by about 2030, -24 per cent to -1 per cent by about 2050 and from -30 per cent to -3 per cent by about 2085, again depending on station, model and emissions scenario.

The relative contribution of uncertainty from the different models, emissions scenarios and stations to these ranges of projected change was assessed. For example, for the -19 per cent to 0 per cent change in median rainfall totals by 2030, the inter-model uncertainty is the greatest. Assuming we have more confidence in the CSIRO models, then leaving out the ECHAM model, which is more sensitive, reduces this range to -11 per cent to 0 per cent. The range across emissions scenarios is the next largest contributor of uncertainty. For five scenarios modelled by the CSIRO Mk3 GCM (SRES A2, B2, B1, A1B and 'committed', which is holding GHG concentrations at current levels), the range is -8 per cent to 0 per cent. For individual stations, the range across these five scenarios decreases further, the smallest being -5 per cent to -3 per cent for Wongan Hills and the largest -7 per cent to -1 per cent for Kojunup. Similar analyses can be undertaken for changes in rain day frequency and for later periods. The uncertainty across the scenarios becomes larger for the later periods, for example Wongan Hills' range increases to -17 per cent to -2 per cent and Kojunup's to -18 per cent to -2 per cent for 2050.

The results of downscaling can easily be employed in impact studies. Impacts studies at single sites were undertaken in two joint studies with the Department of Agriculture and Food (to investigate changes to crop yields in the WA Wheatbelt) and the Department of Water (to investigate projected changes to runoff in Perth's surface water catchments (Berti *et al*. 2004; Kitsios *et al*. 2006; Charles *et al*. 2006)).

3.1.3 Simulated daily rainfall distributions – current and future (CSIRO)

Extreme daily rainfall amounts over Australia for the period 1961-1990 as simulated by the CSIRO Mk2, Mk3 and CCAM models have been analysed and compared with high resolution gridded daily data based on observations. The aim was to assess whether the models can realistically simulate the distribution of rainfall amounts in addition to simply simulating the means. One measure of this ability is how well the very high rainfall amounts (extremes) are simulated. Extreme rainfall in the context of this study is defined as the top 10 per cent of the rainfall days.

The observed gridded data were averaged onto the same grid as the models to ensure that the extremes referred to similar spatial scales. Of the three models, the high-resolution CCAM results yielded the best depiction of the observed gridded extreme rainfall. The coarser Mk3 model yields a similar pattern of results to CCAM while the coarsest model, Mk2, yields the poorest results. The CCAM results for the future period 2071-2100 relative to 1961-1990 indicate that extremes tend to increase over land, even when the mean decreases.

The significant outcome from this analysis is that it is difficult to identify a robust signal for the SWWA region and further sophisticated statistical analysis such as those discussed in Theme 3 are required in order to better identify the nature and magnitude of any changes due to greenhouse forcing.

3.2 Progress on new projects

3.2.1 Mk3 sea ice analysis (see Theme 1 report)

3.2.2 Comparison of synoptic events as simulated with CCAM and observed (see Theme 1 report)

3.3 Summary of related work by BMRC and CSIRO and in the literature

3.3.1 An analysis of recent rainfall trends and implications for expected changes by 2030 (CSIRO)

Most model-based projections of future changes to SWWA winter rainfall by the year 2030 typically lie within the range -22 per cent to 0 per cent (CSIRO, 2001, 2002; IOCI, 2002; Whetton et al, 2005) and this is consistent with the range of changes projected for 2030 derived from the latest CSIRO Mk3 and CCAM raw rainfall results, and the statistically downscaled results from several models.

An independent statistical method for estimating future rainfall changes is to analyse observed trends over the past few decades, assume that these may reflect the true effects of global warming, and use these to extrapolate forward in time. This is feasible since global warming has been well under way for several decades and it is logical to expect that the effects on rainfall may be starting to emerge as a signal above the noise. Linear regression between SWWA winter half-year (MJJASO) rainfall and global average temperature over the past 50 years yields a linear regression coefficient that indicates that rainfall decreases as temperature increases. Using this coefficient provides an indication of the magnitude of the decreases that might occur due to global anthropogenic warming only (greenhouse gases plus aerosols). Note this analysis does not take any account of land clearing. If warming reaches +0.6 to +1.0 degrees by 2030 then the median decrease is estimated to lie between -8 per cent to -14 per cent. This is consistent with the current model-based projections.

3.3.2 How has the frequency of different synoptic types changed in simulations of the future under different scenarios, and what are the future projections of direct-model-output rainfall? (BMRC)

Future conditions from a suite of state-of-the-art national and international climate model simulations, made available for analysis for the upcoming IPCC Fourth Assessment Report, were assessed over SWWA (Hope 2006). Two emission scenarios were considered, bracketing the range of possible future scenarios (SRES B1 and A2: lower and upper level emissions respectively). By about 2050 most models displayed fewer troughs, and the response was even greater by 2100. One climate model investigated displayed a different response, but it is accepted that that model has known errors (Karoly, pers. comm.). However, all models showed decreases in rainfall for the periods 1976-2000[3], 2045-2065 and 2081-2100 compared to the twentieth century (1901-2000). These results are consistent with the shifts in frequency of the synoptic types. For all climate models, the conditions at the end of this century will be drier than those at present under the SRES A2 emissions scenario.

3.3.3 Estimating the impacts of anthropogenic climate change on Western Australia's runoff using a hydrological sensitivity model (CSIRO)

Jones and Durack (2005) developed a simple model to represent the sensitivity of catchments to climate change and used this model to scope the range of possible changes to annual mean runoff from Victorian catchments in 2030 and 2070. This model has now been applied to 16 river catchments across SWWA.

The outputs of nine climate models were used to explore the complete range of regional changes in precipitation and potential evaporation. The climate change patterns derived from climate model output were scaled to represent local change per degree of global warming. This procedure eliminates the individual climate sensitivities of different GCMs allowing the comparison of regional patterns and the subsequent construction of projected ranges of regional change utilising the full range of projected global warming. The GCMs show that in SWWA rainfall increases dominate over the summer but decreases in rainfall dominate over autumn (MAM) winter (JJA) and spring (SON).

The hydrological sensitivity study shows that by 2030 the catchments across SWWA can expect decreases in runoff ranging from 5 per cent to 40 per cent for a global warming of 0.85oC. If the full range of global warming is considered based on the SRES scenarios, the worst possible case for almost all catchments exceeds a 50 per cent reduction from the 1990 stream values.[4]

3. *This difference was calculated: (1976-2000)-(1901-1975)/(1901-2000)*

4. *Note that, since it is now 2006, much of this shift may already have occurred. The graph at http://www.watercorporation.com.au/D/dams_streamflow.cfm indicates greatly reduced streamflow since 2001 compared to 1990 values.*

3.4 Key findings for Theme 2

The effects on Australian climate, over time, of prescribed anthropogenic changes have been simulated by the a range of national and international models and been dynamically downscaled using the CSIRO CCAM model. The observed trends over the twentieth century are not reproduced in full because it is believed that they may by influenced by internal variability. However, the results for later this century are dominated by the anthropogenic signals. The raw climate model results, the dynamically downscaled results and statistically downscaled results indicate some level of certainty with regard to the sign of the projections.

- Deep troughs, associated with heavy rainfall across SWWA decrease in number in climate model simulations of the future, and greater decreases are associated with increasing levels of greenhouse gas levels (later in the century, and in scenarios with higher emissions). SWWA rainfall taken directly from the models shows a corresponding decline.
- The statistical downscaling of a range of model results yields consistent results. Strong forcing, such as the A2 scenario, results in projected winter half-year rainfall decreases of up to 19 per cent by 2030, 27 per cent by 2050 and 34 per cent by 2085. Moderate forcing. e.g. A1B, produces approximately half this change by mid-century and low forcing, e.g. B1, only small reductions.
- The statistical downscaling analyses show that the reduced rainfall will be associated with a decrease in the number of wet synoptic patterns and an increase in the number of dry synoptic weather patterns.
- Analyses of observed trends provide an alternative method for estimating future trends. These indicate that an increase in global average temperatures may be associated with a decrease in SWWA winter half-year (MJJASO) rainfall. If global average temperatures increase by between +0.6 and +1.0 degrees by 2030, then it is estimated that the median decrease could be between -8 per cent and -14 per cent respectively. These are consistent with the results from models, dynamical downscaling and statistical downscaling.
- By 2030, the typical decreases in runoff from the 1990 stream values could range from -5 per cent to -40 per cent for a global warming of 0.85˚C. A key message is that all runoff regions in the SWWA face a similar risk from climate change.

3.5 Climate insights from Theme 2

- The latest model results indicate continuing consensus for a decrease in SWWA winter rainfall by 2030 and for later this century.
- A large component in the uncertainty associated with the projected anthropogenic rainfall decreases is likely to depend on uncertainties in the emission scenarios and also the uncertainty in the responses from different models. As a consequence there are limits to the extent that the range of global warming (and therefore regional warming) at various times into the future can be narrowed.
- The climate model response to changes in emissions is quite sensitive and hence projected declines in SWWA winter half-year rainfall obtained directly from the climate models and from statistical downscaling show that lowering of future global emission profiles significantly dampen the circulation changes that cause the projected rainfall decline.
- The projected rainfall changes (3.3.2) and projected changes in temperature and potential evaporation (Phase 1 report) would be expected to have a compounding adverse effect on soil moisture, surface runoff, water supply and water demand.

4. Summary Report for Theme 3: Short-term climate prediction

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

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Following the completion of the Stage 2 Phase 1 report the milestones for Theme 3 were revised. The summary report addresses the revised milestones with the new projects identified.

4.1 Summary of progress on core activity, January 2005–June 2006

4.1.1 Project 3.5: Mining climate data sets for potential predictors (CSIRO)

This project was concerned with methods to identify potentially predictive relationships in climate data sets, (termed 'nonlinear data mining'). The method provides a capacity to build forecast models using very large sets of potential predictors without making restrictive assumptions. It is worth noting that such methods can be used to find relationships that may or may not make physical sense. It is crucial therefore that their performance be judged on their capacity to make sound predictions on independent data sets. So long as this is done there is confidence that only physically reasonable relationships will be identified. The philosophy is to use established software tools with suitable amendments. The statistical software e.g. partial least-squares, multivariate adaptive regression, splines and random forests described in this project is available from: http://cran.au.r-project.org/. Software customised for the case study described below may be obtained by emailing Eddy Campbell at: eddy.campbell@csiro.au.

A case study was undertaken to develop predictive rules for the onset of winter rainfall (Firth et al. 2005). Soil moisture levels were used rather than rainfall directly as this gives a more useful indication of the potential impact on crop growth, for example. Seasons were classified as early season (April), mid-season (May) or late season (June). Five south-west towns were used for the study: Corrigin, Merredin, Geraldton, Wongan Hills and Lake Grace.

Potential predictors for rainfall onset season used in the study were Indian Ocean sea surface temperatures, Perth mean sea-level pressure and the southern oscillation index for the period 1949-1999. Using these predictors, the case study was able to predict the onset of winter rainfall in the SWWA with a success rate of approximately 80 per cent. The important regions lie in the Southern Indian Ocean.

Before this case study can be expanded to general use, the method needs to be benchmarked against current operational procedures for producing seasonal outlooks. In addition, a more detailed investigation of potential predictors is desirable.

For end users the information derived using this approach can be delivered in a variety of ways. Perhaps most useful is the possibility of providing probabilities for each rainfall onset season, allowing risk-based judgments to be made.

4.1.2 Project 4.5: Predicting SWWA spatial rainfall extremes. (CSIRO)

This project was concerned with developing and applying models for climate extremes, with a focus on rainfall at this stage. A prototype model was developed as part of Phase 1, and was applied to rainfall data for the Avon river catchment. This model has now been more fully developed and the analysis has been extended to the rest of SWWA.

The results found, using the statistical extremes model, are strongly dependent on the skill of predictors, whether they be observed or derived from a dynamical model (see section 4.1.3). As discussed in section 4.2.1, on seasonal time scales, climate models have little skill over SWWA in winter. In addition, there were no predictors found with predictive skill, so the methodology has not been applied to seasonal forecasting.

An alternative perspective is provided by change point analyses, to examine the presence of climate shifts in the extreme rainfall records of a collection of rainfall stations. Return periods for the winter half-year (May to October) daily rainfall amounts exceeding 30 mm were investigated (Li et al. 2005b). A representative sample of five southwest Western Australian rainfall stations was selected. In four out of five cases a uniform (for all return periods) increase in return periods was found within the range of the observed data for the 1966-2001 period compared to the earlier 1930-65 period. This implies a decrease in heavy rainfall events. In the remaining case the decrease is only for rainfall amounts less than 80 mm (and greater than 30 mm). These changes appear to be associated with changes in the Southern Annular Mode, which is consistent with other studies.

The development of the model has made good progress. Available rainfall data (B. Fuller, pers. comm.) revealed station records of different lengths, and/or containing missing observations, and the spatial extremes model has been extended so that such data can be included directly, greatly increasing the method's applicability and ease of use. The model can handle rainfall data of multiple durations simultaneously, such as sub-daily, daily and longer durations. The model now includes geographic information, to incorporate the effects of orographic features for example. In some cases this reveals complex patterns of spatial variability. The spatial model is able to infer intensity-frequency-duration characteristics at ungauged sites, and provide error bounds. This provides a particular opportunity for hydrological studies in WA seeking to make inferences at ungauged sites. Furthermore, it is now technically easier to calculate intensity-frequency-duration curves in a practical application.

Results show that extreme rainfall is much more uniform in its spatial distribution during summer than in winter, however the proportion of variance explained has been found to be low in all cases. This supports the general consensus that forecast skill in SWWA is low at this time.

4.1.3 Project 4.6: Tools to speed development of hybrid forecasting models in particular applications (CSIRO).

The term 'hybrid models' means models comprised of both physical and empirical components. The most radical perhaps is based on hierarchical modelling approaches in Bayesian statistics, which integrates uncertainty measures with modelling of physical and observation processes in physical systems. This approach is explored with a case study that describes the software architectures and approaches to make these models easier to develop and apply in future (Campbell, 2005).

An alternative hybrid approach is to use modelled data with suitably flexible statistical modelling techniques. The rationale is as follows. Climate models have strong capabilities in reproducing broad scale climate features, such as pressure patterns, but are not able to model rainfall in particular with sufficient skill to provide useful seasonal outlooks. It has been shown in previous IOCI work that modelled data for air pressure and other variables can be combined using contemporary statistical tools to produce good models for rainfall. In this framework a climate model produces forecasts from a set of climate variables, which are combined statistically to produce an outlook for rainfall. In the second approach the statistical technique used is semi-automatic in its operation to make the approach easy to perform.

As a first step, simplified dynamical and empirical models were brought together to extract the best from both. Simplified dynamical models or more conceptual models can be used to incorporate physics with empirical models to form a class of so-called physical-statistical models. Using this approach, Campbell (2005) found that forecast lead times can be significantly longer than using empirical models alone. The combined model can also be used to improve our understanding of climate dynamics, as it provides a framework to use data to learn about climate processes that are less well understood. The technology is now at a point where it can be taken up by end-users for application development.

Developing hybrid models using full climate model outputs will constitute the next step, however, this technology is still immature and will require a peer-reviewed case study before further progress can be made.

4.2 Progress on new projects

4.2.1 Analysis of DEMETER data (CSIRO)

The hindcast rainfall results spanning up to 44 years (1958 to 2001) from four seasonal prediction models from the DEMETER set of seven models were assessed. In several, statistical forecast schemes were also analysed. In each case, rainfall predictions for the wheat growing season (May to October) were used to modify theoretical fertiliser and date-of-sowing management decisions for simulated crops within the wheatbelt of SWWA. While there is some low level of skill at predicting winter half-year (MJJASO) rainfall, the level of most systems is not enough to add value to wheat farming on clay soils in SWWA. Only two systems appear skilful enough to potentially add value over and above a fixed, optimum fertilizer strategy. However, these findings are based on a maximum of only 44 hindcast years and may not be applicable in the long-term. In the case of loamy soils, no forecast system has enough skill to add value. The same general result is found for wetter sites. i.e. the more reliable the rainfall the more skilful a forecast system must be in order to improve farmers' returns.

The SOI phase system performed worst in these assessments. The combining of model forecasts into multi-model forecasts did not lead to any improvement. The GESS statistical forecast system as developed by the WA Department of Agriculture and Food performed better than the SOI phase system. Further work is needed to assess whether this system can add value.

4.2.2 Statistical downscaling of DEMETER hindcasts. (CSIRO)

Mean sea-level pressure (MSLP) is an important component of the CSIRO statistical downscaling technique for SWWA rainfall. It was evaluated in the DEMETER hindcasts, and found to provide no useful skill to predictions. Poor reproduction of interannual variability is particularly evident. The poor performance of DEMETER hindcasts preclude their use in the CSIRO statistical downscaling model for SWWA winter rainfall, as MSLP is a key predictor. Recent international experience has also highlighted the poor performance of DEMETER hindcasts (Benito Garcia-Morales and Dubus, 2006). They concluded that overall the DEMETER hindcasts did not improve on climatology. This result is consistent with the lack of skill exhibited by the CSIRO Mk2 and Mk3 forecast models.

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

4.3.1 Further data mining studies (CSIRO)

CSIRO has been exploring a diverse range of automatic procedures for selecting predictors capable of improving forecasts. A number of separate studies have been undertaken to explore this issue. Important atmospheric and oceanic variables that influence SWWA winter rainfall have been identified (15 atmospheric and oceanic contemporaneous variables and their one to six month lags) from a large number of potential predictors. A range of new nonlinear tools have also been adapted to explore factors influencing apparent shifts in rainfall regime in SWWA.

4.3.2 Inter-comparison of downscaling methods (CSIRO)

Downscaling is a key strategic activity in climatology and a study has been commenced examining techniques for selecting good predictors in downscaling studies. In this activity NCEP/NCAR reanalyses data were used to provide broad scale information, which was then downscaled to fine scale rainfall information. A method called 'partial least squares' (PLS) was used, which provides semi-automatic predictor selection, which is a significant benefit over most other downscaling procedures. This method performs reasonably well at simulating JJA regional-scale rainfall for SWWA. It may be that the PLS method could be combined with other downscaling methods as a predictor selection tool, yielding a new class of improved downscaling techniques.

Significant predictive skill was found with this approach. However further exploration of the technique is needed to test its operational value. Some limitations include the considerable variability in skill when simulating small-scale (i.e. grid point) rainfall, and the dependence of the method on the performance of GCMs in forecasting key climate variables. The evidence at this stage is that GCMs are not yet sufficiently accurate for seasonal prediction over SWWA.

4.4 Key findings for Theme 3

- The level of skill of dynamical seasonal prediction schemes at predicting SWWA winter rainfall is relatively low. The evidence suggests it is unlikely to be any greater than that achieved by relatively simple statistical-based schemes.
- The value associated with the skill of existing prediction schemes is questionable. An assessment of value for wheat farming within SWWA indicated that relatively high values of skill are required in order to add value.
- A tool for forecasting the onset of winter rainfall has demonstrated some promise in a proof of concept study.
- The previous work on spatial modelling of rainfall extremes has been extended to the whole southwest. Whilst no significant forecast skill has been found with the predictors studied to date, the method can be used to make inferences at ungauged sites. This offers a solution to a significant problem for hydrological studies in WA.
- A change point analysis from [1930-65] to [1966-2001] of heavy rainfall events at five rainfall stations in SWWA shows a uniform increase in return periods for rainfall greater than 30 mm and less than 80 mm. In four out of five cases this increase is for all rainfall amounts greater than 30 mm.
- Tools have been developed to synthesise physical and empirical models. Further applications for seasonal prediction for WA are dependent on progress in modelling the WA climate processes.
- The interannual variability of MSLP, a key predictor for statistical downscaling, is not reproduced by any of the climate models in the DEMETER hindcast ensemble database.

4.5 Climate insights from Theme 3

- There are no current climate model seasonal prediction schemes that have the necessary skill in forecasting predictors suitable for statistical downscaling.

4.6 Project exceptions

4.6.1 Assess improvements in interannual rainfall reproduction and at-site rainfall distributions of NHMMs that use predictors selected based on the new machine-learning methodologies.

An automated, objective methodology for selecting optimum sets of atmospheric predictors for NHMM stochastic downscaling models is not currently available. However, lack of in-house research capability in machine-learning and redirection of international collaborators research focus has meant that research has not progressed as originally envisioned.

4.6.2 Application of techniques to latest COCA2/POAMA3/ seasonal hindcasts

This was not progressed due to the cessation of COCA2 as a seasonal forecast tool and the fact that POAMA3 does not yet provide reliable data sets suitable for downscaling.

5. IOCI Stage 3 Planning

5.1 "Living with our changing climate" workshop recommendations

The IOCI Seminar and Workshop 'Living with our changing climate' held in August 2005 laid the foundation for the proposed climate research programs of Stage 3. The workshop found that the sectoral climate science requirements broadly fell into the following themes:

- good data sets from meteorological observations and associated output from climate models;
- science to provide information for tactical decision making (seasonal to five years);
- science to provide information for strategic decision making (five to 20 years);
- science to inform policy decision making; and
- communication strategies and initiatives.

The sector specific science requirements were broadly classified into the biophysical science frame works and socio-economic frame works.

5.2 IOCI planning workshop

CSIRO and the Bureau of Meteorology convened meetings in December 2005 and March 2006 to outline a work program that addressed the sectoral needs identified in the August workshop while recognising that the capacity to deliver outcomes was dependent on the funded budget.

The aim of this workshop was to assemble advice from State stakeholders which would assist the IOCI Executive Officer and Office of Science and Innovation (OSI) to decide strategic goals, negotiate programs and establish governance for the next Stage of IOCI to begin in July 2006.

Priority objective:

Identify priority selections of research questions and deliverables to guide the IOCI Executive in negotiating a new core research agreement.

Other objectives:

Identify deliverables to guide the Executive in:

- scoping the integrated IOCI program;
- establishing a collaborative information and communication arrangement covering terrestrial, coastal and marine aspects of climate; and
- establishing priorities for the proposed research fund.

Identify appropriate principles for governance and collaboration.

Following the workshop the science partners participating in the workshop and the key State Agencies affirmed on 26 and 27 April respectively that the priorities identified for the core science program should form the basis of the new IOCI Stage 3 core science proposal.

5.3 IOCI Stage 3 core science priorities

Priorities for a Stage 3 core IOCI program were developed in a workshop/meeting held in April 2006 to identify the core climate science focus for IOCI Stage 3 and the outcomes that would be sought for decision support and capacity building in WA. The priorities in this proposal are based on the outcomes of these consultations.

The climate science focus developed by these workshops has been interpreted in three key themes for the core research program. These are:

- baselines, predictability of WA climate and attribution of climate change across all seasons;
- current and future climate of north-west, including extremes; and
- scenarios of climate change for sector impact and vulnerability studies.

The workshops recognised that a science support and capacity building program was a fundamental expectation of Stage 3. This element would, of necessity, develop progressively in response to opportunity and need through specifically negotiated activities and projects. Deliverables identified at the workshop include:

- state-of-knowledge reviews of:
  - climate baselines for the north-west;
  - coastal impacts of climate change for WA; and
  - seasonal prediction for WA.
- regionally specific climate data and observations to support impact and vulnerability studies;
- WA agencies have access to CSIRO/BoM scientists for state-of-the-art-advice about climate science and applications;
- building WA expertise in climate change.

Of these deliverables the state-of-knowledge reviews were seen as being of up-front importance. The reviews would serve two roles. They would be direction setting elements at the start of the *core research program* and valuable policy support products for delivery to the *science support program*. It was seen that these reviews would result in the issue by the IOCI 'Panel' of several information bulletins of the style produced in IOCI Stage 2.

The workshop also noted the need for IOCI to establish synergies with the Western Australian Marine Science Institution (WAMSI) and to be co-ordinated with the adaptation and vulnerability studies undertaken as part of Action 5.5 of the State Greenhouse Strategy.

6. Communication

To be found at
http://www.ioci.org.au/publications/bulletins.html

6.1 IOCI Reports

Ryan, B. and Hope, P., 2005: Indian Ocean Climate Initiative Stage 2: Report of Phase 1 Activity. July 2003-Dec 2004 40pp.

Dracup, M., McKellar, R. and Ryan, B., 2005: Living with our climate change: Report of workshop, 17 August 2005.

6.2 IOCI Bulletins

Bulletin No. 1, 23 May 2003
Bulletin No. 2, 21 August 2003
Bulletin No. 3, 5 December 2003
Bulletin No. 4, 15 May 2004
Bulletin No. 5, 17 August 2004
Bulletin No. 6, 15 August 2005

6.3 Climate Notes Series 1

Note 1:
How our climate has changed – Introduction,
Compiled by Brian Sadler (IOCI)

Note 2:
How our temperatures have changed,
Compiled by John Cramb (Bureau of Meteorology, Perth)

Note 3:
How our sea temperature has changed,
Compiled by Ming Feng, Gary Meyers, John Church, CSIRO

Note 4:
How our winter atmospheric circulation has changed,
Compiled by Ian Smith (CSIRO) and Pandora Hope (BMRC)

Note 5:
How our rainfall has changed – The south-west,
Compiled by Pandora Hope (BMRC) and Ian Foster (Dept Ag)

Note 6:
How extreme south-west rainfalls have changed,
Compiled by: John Ruprecht (Dept Environment); Yun Li and Eddy Campbell, CSIRO; Pandora Hope (BMRC)

Note 7:
How our river flows have changed,
Compiled by: Mark Pearcey (DoE) and Colin Terry (Water Corporation)

Note 8:
How our groundwater has changed,
Compiled by Philip Commander and Ed Hauck, DoE

Note 9:
How our regional sea level has changed,
Compiled by Charitha Pattiaratchi and Matthew Eliot, Centre for Water Research, UWA

Note 10:
Variability in the Leeuwin Current,
Compiled by Charitha Pattiaratchi (Centre for Water Research, UWA)

Note 11:
How salinity has changed,
Compiled by Don McFarlane (CSIRO) and John Ruprecht (DoE)

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8. Appendix

8.1 Acronyms

AGO	Australian Greenhouse Office
BoM	Bureau of Meteorology
BMRC	Bureau of Meteorology Research Centre
CAR	CSIRO Atmospheric Research
CLW	CSIRO Land and Water
COCA2	CSIRO MK3 CGCM use in seasonal forecast mode (supersedes the earlier version, COCA1)
CSIRO	Commonwealth Scientific and Industrial Research Organization
CCAM	CSIRO conformal-cubic atmospheric model
CMIS	CSIRO Mathematical and Information Sciences
CRU	Climatic Research Unit, http://www.cru.uea.ac.uk/cru/data/
DEMETER	Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction (E.U.)
DLL	Dynamic Link Libraries
ECMWF	European Centre for Medium-range Weather Forecasts
ECHAM4	Max Plank GCM
ENSO	El Nino Southern Oscillation
EOF	Empirical Orthogonal Function (dominant modes of variability)
GCM	General Circulation Model OR Global Climate Model
GRDC	Grains Research and Development Council
HadAM3P	Hadley Centre GCM
IOCI	Indian Ocean Climate Initiative
IPCC	Inter-governmental Panel on Climate Change
LCC	Land Cover Change
Mk3 CGCM	CSIRO Coupled General Circulation Model
Mk3 AGCM	CSIRO Atmospheric General Circulation Model
MSLP	Mean Sea Level Pressure
NCAR	National Center for Atmospheric Research (U.S.)
NCEP	National Centers for Environmental Prediction (U.S.)
NHMM	Nonhomogeneous Hidden Markov Model
NH	Northern Hemisphere
POAMA	Predictive Ocean Atmosphere Model for Australia
PMSLP	Perth Mean Sea Level Pressure
PPL	Partial Least Squares
ppm	Parts Per Million
SH	Southern Hemisphere
SOM	Self Organising Map
SRES	Special Report on Emissions Scenarios (from IPCC report, 2001)
SST	Sea Surface Temperature
SAM	Southern Annular Mode (also Antarctic Oscillation)
SD	Statistical Downscaling
SOM	Self Organising Map
SWWA	South-west Western Australia
WRE	Wigley, Richels and Edmonds

8.2 Glossary of terms

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

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, but 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 upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socio-economic and technological developments that may or may not be realized, 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.

Early winter

May, June and July

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, or studies of climate change, 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”. An ensemble can also be achieved from a set of simulations from a number of different models.

External forcing

Forcing ‘external’ to the climate system, for example, solar variability, volcanic eruptions, marked changes in levels of atmospheric constituents such as greenhouse gases and land cover change. See ‘internal forcing’.

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.

Internal forcing

Internal forces on the climate system arise from various feedbacks and interactions within the climate system itself. See 'external forcing'.

IPCC Fourth Assessment Report

The fourth assessment of the Inter-governmental Panel on Climate Change, due out in 2007. The IPCC Third Assessment Report was published in 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.

Late winter

August, September and October

Mid winter

June and July

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 Organizing 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 20S, and it is characterized by pressure anomalies of one sign centred in the Antarctic and anomalies of the opposite sign centred about 40-50S.

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, 2001a). There are four families of scenarios

- **A1** – future world of very rapid economic growth, global population the 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 region converge very slowly which results in continuously increasing population. Economic growth is primarily regionally orientated 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 emphasize economic, social and environmental sustainability.
- **B2** – A world that focuses on local and regional solutions to economic, social and environmental sustainability. It has continuously 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 the site to large scale atmospheric variables.

Synoptic types

To represent the climatology of synoptic systems (like the weather maps on the television news - maps of mean sea-level pressure) the more common types 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).

inter half-year

May, June, July, August, September and October

WRE profiles

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

8.3 IPCC References

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2007007 - 1 - 500