EXECUTIVE SUMMARY

This report marks the conclusion of the second phase of Stage 3 of the Indian Ocean Climate Initiative (IOCI 3). It is comprised of nine parts, with each part corresponding to a research project within the Initiative. The research outcomes support a number of broad conclusions that may be summarised as follows:

Project 1.1 Detection and Attribution of Changes to Weather Systems and Large Scale Circulation Drivers.

- Twentieth century changes in Southern Hemisphere low frequency weather systems that affect Western Australia during July have been studied using a global two-level primitive equation instability model. Focus has been on changes in mid-latitude blocking, Northwest Cloudband (NWCB) disturbances, Intra-seasonal Oscillation (ISO) modes, and high latitude modes.
- Results show that the leading NWCB modes crossing Western Australia have increased their growth rates by ~25% in the time interval (1975-94) compared with (1949-68), and by ~45% in the time interval (1997-2006) compared with (1949-68). These modes consist of wave trains of high and low pressure anomalies that originate in the Indian Ocean and propagate eastward over Australia and into the South Pacific, and have maximum impact on rainfall over central Western Australia.
- The greater potential for development of the NWCB weather systems has been shown to be associated with continuing increases in the percentage change in July rainfall over central Western Australia since the mid-1970s.
- The leading intra-seasonal oscillation modes also consist of propagating wave trains of pressure anomalies extending again from the central Indian Ocean across central and northern Western Australia and affecting rainfall over these regions. Their growth rates have increased by about 30% and their periodicity has reduced from ~60 days to ~25 days since the mid-1970s.
- There has also been a decrease in the growth rate and development of mid-latitude atmospheric blocking by up to ~19%. What impact these changes might have had on Western Australia climate is being investigated.

- The properties of the high latitude, or Antarctic, modes, such as for example the southern annular mode (SAM) show little systematic change in their structure or growth rate, suggesting that these have little relevance to the changing climate of Western Australia during the 20th century.
- Further evaluation of the CMIP3 coupled models and atmosphere-only models from the Climate of the 20th Century (C20C) Project, suggest that the inability of many of the coupled models to reproduce the observed changes in the Phillips Instability criterion is most likely due to problems with the oceans or the coupling between the ocean and atmosphere in these models.
- The relationship between changes in the Phillips criterion, which is related directly to storm formation, and changes in winter rainfall during the twentieth century and the extent to which climate models capture them, has also been studied. In particular, we have investigated possible linear trends in the Phillips criterion and rainfall, and the decadal variations about these trends, to try to elucidate the roles of anthropogenic forcing and internal variability.
- Over the last 50 years of the 20th century, observed trends in the Phillips instability criterion are about -0.12 ms^{-1} per year upstream and over SW Western Australia and highly statistically significant; corresponding rainfall trends over SW Western Australia are about -0.4mm/month per year, and also highly significant. This suggests that a 1 ms^{-1} reduction in Phillips criterion is associated approximately with a 6mm/month reduction in rainfall over SW Western Australia.
- The "better" CMIP3 models that are able to reproduce the correct sign of the observed change and trend in the Phillips criterion and rainfall have about half the trend in both cases.
- Model projections for (2001-2100) for the "better" models under the SRES scenarios with increasing anthropogenic CO_2 gas forcing show trends in the Phillips criterion and rainfall similar to those during the 20th century. Keeping in mind that they are about half the observed trends, this suggests that we are likely to see similar or larger reductions in SW Western Australia rainfall over the next fifty years as occurred over the previous fifty years, with further similar reductions over the subsequent fifty years.

- An analysis of trends in model "commit" runs (with constant anthropogenic CO_2 gas forcing of about 365 ppm) over the 2001-2100 period shows no significant trends in the Phillips criterion, indicating that the trends are the result of the prescribed anthropogenic CO_2 gas forcing

Project 1.2 South-West Western Australia's Regional Surface Climate and Weather Systems.

- The data quality from rainfall recording stations formerly noted for their high-quality and long-term records have been re-assessed. Some stations with long-term, high-quality data have had reductions in quality in recent years for a range of reasons, including the consolidation of farms. This information has fed into Project 1.4.
- Annual average rainfall declined in south-west Western Australia in the late 1960s and has not recovered since. A further shift to lower rainfall was identified at approximately the year 2000. The early decline was associated with a decrease in the number of days on which a winter deep low pressure system influenced the region. The recent decline was not associated with a continuing decrease in the number of deep low pressure systems, but rather had a strong contribution from an increase in the number of days when a high pressure system influences the region. New, improved datasets do not alter this picture.
- Recent years have also seen extremely high values of winter mean sea-level pressure over SW Western Australia. Both the increased pressures and increased daily occurrence of high pressure systems are as projected for the end of this century by climate models forced with increasing levels of atmospheric greenhouse gases. The magnitudes of the changes expressed by most models suggest that the recent high values might be expected to continue and possibly amplify.
- The recent large decline in rainfall in the late 1960s in May to July has persisted and expanded spatially. Both trends and percentage change were analysed to explore this signal. Trends reveal that regions where rainfall did not decline in the late 1960s are now seeing a decline in early winter, whilst the percentage change also suggested a strengthening signal in regions already

drying (the far south-west and wheatbelt), a signal that is not so clear using trend analysis.

- The interannual variability in the far south-west continues to decline. Trends in the 95th percentile rainfall were generally weak, except along the south coast since 1970 and at Manjimup since 1950. The signal at Manjimup which shows a weakening of the decreasing trend in the extreme rainfall between the 1950-2007 period and the 1970-2007 period supports the findings in Milestone 1.2.1 that recent declines are not associated with a further decrease in the daily occurrence of deep low pressure systems. The stronger trends remain when a more robust statistical technique to calculate the trends was used.
- In the summer half year there were minimal trends from both 1950 and 1970 except inland and along the south coast where increases were seen in both totals and, as summer rainfall is dominated by extreme events, extremes.
- Analysis of 'standard' seasons was found to potentially 'hide' important information, as found by the analysis of the spring and 'late winter' (August to October) trends. There were only weak trends from 1950, but some stronger trends from 1970 in late winter; increases at Manjimup and Nyerilup and decreases at Peppermint Grove. The map of spring trends showed decreases everywhere. Examining the decadal variability by month revealed that rainfall in August and September had been increasing, but decreasing in October and November.
- A new array (self-organising map) of weather 'types' was developed to explore summer rainfall variability. It included fewer types and a measure of lower atmospheric humidity was included. There was little distinction in the amount or spatial distribution of rainfall associated with each different type. Higher rainfall events, that defined the spatial pattern, were associated with tropical low pressure systems or cyclones. The timing of the occurrence of rainfall associated with these did not align with any particular weather type.
- Summer maximum temperatures display cooling trends over the last 50 years across the south-west. A self-organising map was developed to explore temperature variations. The spatial distribution of maximum temperature associated with each synoptic type was quite distinct. This is being explored further to better understand the observed cooling trend.

Project 1.3 Quantification of the Limits of Seasonal Predictability of Western Australia Rainfall and Surface Temperature.

Milestone 1.3.1 and Milestone 1.3.2 have been completed.

Project 1.4 Regionally Specific Climate Data and Monitoring for the North-West and South-West to Support the Understanding of Past, Present and Future Climate.

- The high quality daily rainfall network has been expanded from 40 stations to 213 single and composite daily reporting stations. There has been a particular increase in the north-west of the state, where previously there were very few high-quality stations.
- A purpose built web area attached to the Bureau of Meteorology's Climate Change Tracker has been built to make available the new rainfall and temperature high-quality datasets to State stakeholders. This web site uses the OpenLayers platform, which allows innovative site navigation and provides users with other relevant information, such as roads, rivers, elevation and place names and a dynamical way.
- Dr Marco Marinelli has been recruited to provide an enhanced local capacity in climate analysis and monitoring and to liaise with State stakeholders.
- New very high-resolution analyses of rainfall, temperature and vapour pressure have been developed and made available to IOCI researchers. Early analyses have revealed that the rainfall decline in the south-west has been more severe than earlier estimates have suggested, with particularly strong drying trends at higher elevations and in the far south-west corner. In the coming months further customisation of these analyses will be pursued under IOCI to support more robust climate analyses for Western Australia including the north-west.
- A high-quality cloud data set with 33 stations in Western Australia has been completed, and made available through the IOCI data portal. Analysis of this data has revealed a decline in winter cloudiness since the 1950s which has become particularly marked since the early 1980s. Summer cloud cover has tended to increase about the north coast and in inland parts where rainfall has also shown an increase.

Project 2.1 Observed and Modelled Climate of the North-West.

- In collaboration with the Queensland Climate Change Centre of Excellence, a set (ensemble) of coupled atmosphere-ocean runs for the CSIRO Mk3.6 climate model have been carried out for the period 1851 to 2005.
- Preliminary analysis of these runs has yielded some support for the hypothesis that anthropogenic aerosols have contributed to the observed rainfall increase in the north-west region of Western Australia. However, the largest modelled trends occur in the first half of the 20th Century rather than the second half when aerosol emissions are higher.
- There are large differences between the simulations produced by individual ensemble members
- The impact of the Asian aerosols on Australian rainfall appears to be more limited than the impact of all anthropogenic aerosols.

Project 2.2 Tropical Cyclones in the North-West.

- The IOCI research activities marked the first time the researchers had focussed their attention on Tropical Cyclones in the Southern Indian Ocean. Research in the first year has concentrated on gaining familiarity with the tropical cyclone data set in the region and on investigating whether there are trends. It is well documented that the sea surface temperatures during the cyclone season have increased over the past 25 years by approximately half a degree C. It is important to determine whether there has been an increase in tropical cyclone activity in response to this climate signal. That first year's research resulted in contributions to a number of publications and the development of an improved forecast model for tropical cyclone activity on the 1-3 weeks ahead time-window. The following dot points describe results obtained to-date during 2010.
- We have documented the response of the upper oceans to tropical cyclones through compositing on a 0.5^{o} by 0.5^{o} latitude-longitude grid the anomalies of sea surface temperature before and after tropical cyclone passage. Two primary variables have been defined as measures of the sea surface temperature response: sea surface temperature reduction, and sea surface temperature recovery time. This work is important for the understanding of

tropical cyclone impacts on the circulation of the Indian Ocean region. It is also important for climate change studies. The study provides evidence that tropical cyclones can have a major impact on the heat balance of the underlying oceans.

- Data sets and software have been developed to study the relationships between tropical cyclogenesis and cyclone intensity in the north-west as a function of the underlying sea surface temperature.
- Software has also been developed and data prepared for the assessment of the contribution of tropical cyclones to north-west Western Australia climatological rainfall.
- Work is progressing on a "State of Knowledge" report which will draw on original and recent research on three themes: a) the tropical cyclone database; b) tropical cyclone climatology and dynamics in the region; c) projections for north-west Western Australia tropical cyclones under climate change. Extensive material has been gathered for all three and a report will be prepared by end 2010.

Project 2.3 Statistical Downscaling for the North-West:

- Screening of daily rainfall data has led to the selection of nine and ten high quality stations in the Kimberley and Pilbara regions of the north-west, respectively.
- Statistical downscaling models for the Kimberley and Pilbara regions have been fitted and tested.
- The observed rainfall trends in the Kimberley and Pilbara regions can be reproduced by the downscaling model.
- Five climate models have been found to reproduce the historical probability distributions of the atmospheric variables (predictors) used by the downscaling model.

Project 2.4 Physical-Statistical Modelling of Extreme Weather Events.

- Additional rainfall data has been obtained from the Department of Agriculture and Food for sites in the north-west and south-west, and the time periods covered by these records assessed.

- Data from rainfall stations in the Northern Territory but near to the Western Australian border have been acquired.
- Because high quality rainfall data sets are spatially sparse in the north-west,
- Results obtained from the use of a sparse regression method known as RaVE (**R**apid **Va**riable **E**limination) continue to indicate that it can generate parsimonious atmospheric predictor sets for downscaling models that are both sensible and interpretable.
- Point process and aggregated Markov chain models for temperature extremes have been developed.
- There is an upward trend in hot days in the north-west corner of south-west Western Australia and no trend or downward trends in the south-west corner. This appears to be due to an upward trend in the south-west Western Australia Circulation index.

Project 3.1 Statistically-Downscaled Projections for the South-West.

- An assessment of the performance of 25 global climate models has revealed that some models perform consistently better than others.
- The statistical downscaling model has been successfully extended so that it can now simulate rainfall occurrence and amounts concurrently.
- A stochastic weather generation model for daily maximum and minimum temperature has been implemented.

Project 3.2 Climate Extremes: Potential Forecast Skill and Climate Change Scenarios.

- The amalgamation of daily rainfall and pluviometer data sets and the calculation of site dependent covariates have commenced.
- The statistics of extreme rainfall are dependent on the generating mechanism (synoptic type).
- It is permissible to use simple models for rainfall extremes over the full range of durations of interest (five minutes to three days).

The second 12 months of IOCI 3 have been productive. The research output produced so far inspires optimism that the Initiative will continue to lead to new knowledge and

skills that will in turn provide valuable economic and social benefits for the north-west and south-west regions of Western Australia.

List of Publications

Bates, B.C., Chandler RE, Charles SP, Campbell EP, 2010, Assessment of apparent non-stationarity in time series of annual inflow, daily precipitation and atmospheric circulation indices: A case study from southwest Western Australia, *Water Resources Research*, revised version submitted.

Fawcett, R., Trewin B. and Jones D. 2010. On Emerging Droughts. *Bull. of the Aust. Meteor. and Ocean. Soc*., 23, 28-36.

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Frederiksen, J.S., C.S. Frederiksen and S.L. Osbrough, 2009, *Modelling of changes in Southern Hemisphere weather systems during the 20th century.* 18th World IMACS/MODSIM Congress, Cairns, Australia, 13-17 July, 2009. *Modsim09*, 2562-2568. (http://www.mssanz.org.au/modsim09/G1/frederiksen_j.pdf)

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Fu, G., Viney NR, Charles SP, Liu JR, 2010, Long-term temporal variation of extreme rainfall events in Australia: 1910–2006, *Journal of Hydrometeorology*, In press, DOI: 10.1175/2010JHM1204.1

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Fu, G.B., Viney NR, Charles SP, 2010, Evaluation of various root transformations of daily precipitation amounts fitted with a normal distribution for Australia, *Theoretical and Applied Climatology*, 99, 229–238.

Hope, P. and C.J. Ganter, 2010: Recent and projected rainfall trends in south-west Australia and the associated shifts in weather systems. In: Book of Proceedings from Greenhouse 2009 Conference. CSIRO publishing. in press.

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Knutson, Thomas R., J McBride, J Chan, K A Emanuel, G Holland, C Landsea, Isaac Held, J Kossin, A K Srivastava, and M Sugi, March 2010: Tropical cyclones and climate change. Nature Geoscience, 3, doi:doi:10.1038/ngeo779.

Kuleshov, Y., R. Fawcett, L. Qi, B. Trewin, D. Jones, J. McBride and H. Ramsay: 2010, Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean. J. Geophys. Res. 115, D1, D01101, 0148-0227.

Li, Y., Lau, R. and C. Liu, 2010, On the large-scale circulations and their linkages to temperature extreme events over southwest Western Australia, (*in preparation*).
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Trewin, B. and Vermont, H. 2010. Changes in the frequency of record temperatures in Australia, 1957-2009. *Aust. Met. Oceanogr. J.*, 60, 113-119.

List of IOCI-Related Presentations at National and International Conferences, Symposia and Workshops

Presentations to Interdepartmental Climate Change Policy sub-Committee - on IOCI Stage 3 - overview and progress, 31 July 2009

Bates, B.C., *Overview and Progress of Stage 3*.

Marinelli, M., *Project 1.4 – Regionally Specific Climate Data and Monitoring for the North-West and South-West to Support the Understanding of Past, Present and Future Climate*.

Charles, S.P., *Project 2.3 – Statistical Downscaling for the North-West*.

Charles, S.P., *Project 3.1 – Statistically Downscaled Climate Change Projections for the South-West*.

Palmer, M., *Project 2.4 – Physical-Statistical Modelling of Extreme Events*.

Palmer, M., *Project 3.2 – Climate Extremes: Potential Forecast Skill and Climate Change Scenarios*.

2nd IOCI Annual Workshop, Perth, 26-27 October 2009.

Bates, B.C., *Overview of IOCI Stage 3*.

Frederiksen, C.S., *Detection and Attribution*.

Ganter, C., *Regional Climate and Weather Systems*.

Frederiksen, C.S., *Limits of Seasonal Predictability* .

Marinelli, M., *Regionally Specific Climate Data and Monitoring for WA*.

Rotstayn, L. *The CSIRO mk3.6 GCM: Simulation of Rainfall in Australia's North West*.

McBride, J., *Tropical Cyclones in the North West*.

Charles, S.P., *Statistical Downscaling for the North West*.

Abbs, D., *Dynamical Downscaling of Tropical Cyclones for the North West*.

Charles, S.P., *Statistically Downscaled Climate Change Projections for the South West*.

Palmer, M. *Rainfall Extremes: Potential Forecast Skill and Climate Change Scenarios for the South West*.

Other

Bates, B.C., *Introduction to Climate Change Science*, invited presentation, University of Western Australia Business School, Perth, 29 September 2009.

Bates, B.C., *Global Warming and its Likely Impact on the Great Southern*, invited presentation, Carbon Pollution Reduction Scheme, Mount Barker, 7 October 2009.

Bates, B.C., *Adaptation under Climate Uncertainty: Challenges and Opportunities*, keynote address, 32nd Hydrology and Water Resources Symposium, 1 December 2009.

Bates, B.C., *Climate Change: Menace, Myth or Conspiracy*, invited presentation, Western Australian Wetlands Conference, Perth, 2 February 2010.

Bates, B.C., *Climate Change Science*, invited presentation, Peel Climate Change Adaptation Summit, Mundijong, Perth, 12 March 2010.

Bates, B.C., *Global Climate Change Predictions and Local Impacts*, invited presentation, Western Suburbs Regional Organisation of Councils (WESROC) Climate Change Information Forum, Bold Park, 17 March 2010.

Bates, B.C., R. Chandler, R., S.P. Charles, and E.P. Campbell, *Assessment of Apparent Non-Stationarity in Hydroclimatic Series: A Case Study from Western Australia*, invited presentation, Burges Symposium, Seattle, Washington, 25 March 2010.

Bates, B.C., *Capacity, Resources and Barriers; and the Communication Tools Needed*, DCCEE Climate Extremes Workshop, Melbourne, 10 May 2010.

Bates, B.C., *Managing Water Resources under Climate Uncertainty: Challenges and Opportunities*, 2010 Climate Adaptation Futures Conference, Gold Coast, Queensland, 30 June 2010.

Campbell, E., "Modelling of extreme rainfall" CSIRO CAF Science Symposium, Melbourne, February, 2010

Campbell, E., "Modelling of Extremes" CSIRO CAF theme meeting, Melbourne, March, 2010

Campbell, E., "Modelling of Extremes" DCCEE meeting on extremes, BoM Melbourne, May, 2010

Campbell, E., "Spatial-Temporal Modelling of Extreme Rainfall" Poster at 25th International Workshop on Statistical Modelling, Glasgow, July, 2010

Campbell, E., "Spatial-Temporal Modelling of Extreme Rainfall" Presentation at 11th International Conference on Statistical Climatology, Edinburgh, July, 2010

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Frederiksen, C.S., S. Grainger and X. Zheng, 2009: Australian rainfall variability and predictability : the relative importance of slow and intraseasonal processes. GWEX 2009: 6th International Scientific Conference on the Global Energy and Water Cycle, 24-28 August 2009, Melbourne, Australia.

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Frederiksen, J.S.,C.S. Frederiksen and S.L. Osbrough, 2009: Decadal Shifts in Weather Systems Affecting Southern Australia. GWEX 2009: 6th International Scientific Conference on the Global Energy and Water Cycle, 24-28 August 2009, Melbourne, Australia.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, 2010: Changes and Projections in Australian Winter Rainfall and Circulation: Anthropogenic forcing and internal variability. 2nd International Climate Change Conference, Qld. Univ., Queensland, 8-11 July, 2010.

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Marinelli, M. , K. Braganza, D. Collins, D. Jones, D. Maquire, C. Ganter, P. Hope and G. Cook. 2010. Improved Climate Data and Monitoring for Western Australia to Support the Understanding of Past, Present and Future Climate. Presentation to the 17th AMOS National Conference, Canberra, 27-29 January, 2010.

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Marinelli, M. , K. Braganza, D. Collins, D. Jones, D. Maquire, C. Ganter, P. Hope and G. Cook. 2010. Improved Climate Data and Monitoring for Western Australia to Support the Understanding of Past, Present and Future Climate. Poster presentation to the 11th International Meeting on Statistical Climatology, Edinburgh, Scotland, 12-16 July, 2010.

McBride, John L. “Climate Change Impacts on Tropical Cyclones — the Current State of Knowledge, 14th Australasian Wind Engineering Society Workshop, Canberra 5-6 August, 2010 (Invited/Keynote Presentation).

Phatak, A., Chan, C., and H. Kiiveri, 2010: Fast variable selection for extreme values. Proceedings of International Environmental Modelling and Software Society (iEMSs)2010 International Congress on Environmental Modelling and Software, Fifth Biennial Meeting, Ottawa, Canada

Rotstayn, L., “Aerosols and tropical Australian Climate Change”: Workshop on climate change simulations for CMIP5 (IPCC AR5) and the data requirements for Queensland and the wet tropical regions, Port Douglas, July, 2009.

Rotstayn, L., “Anthropogenic aerosols and Southern Hemisphere climate change: a modelling perspective”: GEWEX-ILEAPS Joint Conference, Melbourne, August, 2009.

Rotstayn, L., “Australian rainfall changes and the four-legged dog”: Theme 1155 Pathways to Adaptation Forum, Lancefield, March, 2010.

Rotstayn, L., “Coordinated Climate Change Experiments for AR5 including CSIRO’s contribution”: Workshop on climate change simulations for CMIP5 (IPCC AR5)

and the data requirements for Queensland and the wet tropical regions, Port Douglas, July, 2009.

Rotstayn, L., "The CSIRO Mk3.6 GCM, CMIP5 and the four-legged dog": formal seminar, CSIRO Marine and Atmospheric Research, Melbourne, October, 2009.

Rotstayn, L., "The CSIRO Mk3.6 GCM: Simulation of Rainfall in Australia's North West": IOCI3 Annual Workshop, Perth, October, 2009.

Trewin, B. and H. Vermont 2010. Temporal Distribution of Record Temperatures in Australia through the 1957-2007 Period. 17th AMOS National Conference, Canberra, 27-29 January, 2010.

Trewin, B., 2010. New indices for monitoring changes in heatwaves and extended cold spells. 11th International Meeting on Statistical Climatology, Edinburgh, 12-16 July, 2010.

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