EXECUTIVE SUMMARY

This report marks the conclusion of the third phase of Stage 3 of the Indian Ocean Climate Initiative (IOCI 3). It consists 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

Milestone 1.1.4 has been completed and Milestone 1.1.5 is due for completion on 31/12/2011.

- Two inverse climate models for climate change attribution have been developed and applied.
- The climate driving pattern obtained by both methods suggests that a combination of global (longitudinally invariant) and local effects are responsible for the observed climate change.
- Future work will involve the use of more complicated models.

Project 1.2: South-west Western Australia's Regional Surface Climate and Weather Systems

Milestone 1.2.3 was completed on 31/12/2010.

- Summer maximum temperatures display cooling trends over the last 60 years in the eastern reaches of South-West Western Australia (SWWA).
- This cooling is associated with an increase in the daily occurrence of synoptic types associated with cool conditions, higher pressures in the Indian Ocean and the high phase of the Southern Annular Mode (SAM).
- The upward trend in summer SAM is projected to flatten in coming decades, which might mean a rapid shift to warmer summer conditions in this part of the south-west.
- These summer associations are not so strong in the west of the south-west.

Progress on Milestones 1.2.4 and 1.2.5

- The Self-Organising Map (SOM) was deemed to be the best tool to use to explore weather systems and their impact in spring and autumn.
- 'Spring' was extended to August to December to explore the question of how weather systems impact late larval-stage lobsters (puerulus) settlement rates.
- The 'spring' SOM was expanded to 5x7 types and the corresponding low-level wind anomalies were explored. Preliminary results suggest one type in particular was prevalent during the low puerulus return year of 2008.
- Autumn SOM of 4x5 types. Types that occur more commonly in May are associated with more emphatically dry or wet conditions across SWWA.
- Preliminary analysis reveals that the occurrence of dry types drives May rainfall variability more so than the occurrence of wet types.

Project 1.3: Quantification of the Limits of Seasonal Predictability of WA Rainfall and Surface Temperature

All Milestone reports have been completed and submitted.

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

Milestone 1.4.1 has been completed

- A combination of empirical and analytical methods has led to the definition of a high quality daily rainfall network consisting of 157 stations. These stations have a very high completeness of precipitation entries and have a small level of gross error (determined by statistical and empirical tests).
- In addition to *single stations*, 12 composites were created where (a) a single station with a sufficiently complete record was not found or (b) a station passed all other tests but was recently closed.
- The record studied included all entries in years up to and including 2008.

Milestone 1.4.2 has been completed

- A beta version of the homogenised data set was completed in December 2010 and updated in June 2011 and was reviewed by a number of climate scientists at the Bureau. The completion of the beta version has identified a number of issues but it is expected that these will be able to be resolved without undue difficulty.
- As a result of the intense public scrutiny of temperature data in Australia and elsewhere (including a court case involving the equivalent data set in New Zealand), an external review of the data set was undertaken prior to its public release. The review involved a number of international experts and took place in August 2011. The review report was received by the Bureau of Meteorology in early September.
- A series of six reports was prepared for the external review. The temperature data set is documented under the *ACORN-SAT analysis and results document: Report 3a for the Independent Peer Review of the ACORN-SAT data-set*. This report has not yet been made public at the time of writing but is available to support IOCI activities.
- A full public release of the data set and associated documentation is scheduled for early 2012. This should not preclude the earlier use of the data in IOCI-associated analyses, once the issues identified above are resolved.

Milestones 1.4.3, 1.4.5 and 1.4.6 were completed on 31/12/2010, and work for Milestones 1.4.4, 1,4,7 and 1.4.8 is ongoing and on schedule.

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

- CSIRO Mk3.6 GCM runs suggest that anthropogenic aerosols have delayed the response of atmospheric circulation and rainfall to increasing greenhouse gases (GHGs) in the Indo-Pacific region, including north-western Australia. However, aerosol emissions are projected to fall rapidly in the next few decades, suggesting that the effects of increasing GHGs will be augmented by the decreasing effects of aerosols.
- There are several uncertainties regarding our results including the strength modelled anthropogenic aerosol forcing and the dependence on a single climate model.

- More work is required to explore the mechanism that relates to north-western Australian rainfall changes, both in models and observations. The individual runs that comprise our 10-member ensembles show large internal variability, suggesting that an unambiguous attribution of rainfall trends in the North-West may be difficult to achieve.
- Better understanding of the effects of aerosols on the Hadley (north-south) circulation as opposed to the Walker (east-west) circulation is required. Our current analysis suggests that the effect on the Walker circulation may be more crucial in the Australian region.
- Due to the unexpected delay in the Queensland-funded Mk3.6 CMIP5 project, on which Project 2.1 depends, this report is based on provisional results, rather than from our CMIP5 submission as originally planned. For our final report on Project 2.1 (in 2012), we intend to analyse the revised simulations in more detail than has been possible with the current set of runs.

Project 2.2: Tropical Cyclones in the North-West

Milestones 2.2.1 and 2.2.2 were completed on 31/12/2009.

Milestone 2.2.2 was completed on 31/12/2010 – the research paper is undergoing revision after submission to the international journal *Monthly Weather Review*.

Milestones 2.2.4 and 2.2.5 were completed on 31/12/2010 – papers have been submitted to *Journal of Climate* and *Geophysical Research Letters*.

Work on Milestone 2.2.6 is ongoing and on schedule.

- There is no evidence for a detected trend in the intensity of tropical cyclones in our region.
- Although global climate models do consistently project an increase in intensity of tropical cyclones in a warmer climate, this is a global-scale result and projections for particular regions, (e.g. the Southern Indian Ocean) are still highly uncertain and not consistent from model to model.
- Other issues addressed include whether a threshold sea temperature for tropical cyclone development occurs in individual cases, and whether there has been any trend detected in the value of the threshold. Results show that the existence of a threshold temperature is most apparent when the sea temperature over the 48 hours preceding development is considered. There is a shift towards a higher mean temperature at which development occurs by approximately 0.2 degrees °C; but it is not statistically significant.
- Tropical cyclones move to lower sea surface temperatures after they develop. There is a poleward shift in the point of maximum intensity or lowest central pressure for cyclones that form at higher sea temperatures at the early stage of their lifecycle.
- Tropical cyclones are a major contributor to wet season total rainfall over North West Western Australia. Further work is being done to determine the spatial structure of this contribution and the degree of inland penetration.

Project 2.3: Statistical Downscaling for the North-West

- The historical runs of these five GCMs (1961-2000) were downscaled to assess similarities between Reanalysis and GCM downscaled weather states (types) and station rainfall trends.
- The Reanalysis downscaled weather states and long-term station rainfall trends for the Kimberley region summer half-year (Nov-Apr) are not reproduced in the

GCM downscaled results for the 1960-2000 period. This may be due to the role of natural climate variability and/or inadequate representation of the impact of aerosols in the climate model simulations.

- There is a better match between the Reanalysis and GCM downscaled weather state and station rainfall trends for the Pilbara region during the winter half-year, although the strong Reanalysis downscaled trends are not fully captured.
- The multi-site daily rainfall stochastic downscaling model (NHMM) has been combined with a stochastic weather generator to generate at-site daily maximum and minimum temperature conditional on NHMM simulated daily weather-state and wet/dry status sequences. An important advance afforded by this implementation is the ability to generate stochastic sequences of temperature reflecting the changes in distribution as indicated by the projections.
- Extraction and processing of the large-scale predictor fields for the selected GCMs and corresponding CCAM future climate projections is being completed.
- Completion of Milestones 2.3.6 and 2.3.7 will result in the provision of 100 stochastic realisations of daily rainfall and maximum and minimum temperature for each of the five GCMs and corresponding CCAM runs selected, for the periods as noted above. Discussions on how best to disseminate this large amount of data to State Agencies should commence to allow the opportunity for feedback from those who plan to use this resource.

Project 2.4: Physical-Statistical Modelling of Extreme Weather Events

- The selection of high-quality stations is now complete (Milestone 2.4.1).
- Using output from a regional climate model adds information to the spatial modelling of extreme rainfall, making it potentially useful in regions for which data is sparse (e.g. NWWA).
- Our method of fast variable selection has been used to identify potential drivers of extreme rainfall at individual stations in NWWA. Many of the variables, such as sea-level pressures and components of wind, are consistent with other studies. In the next step, we will be using some of these variables in the spatio-temporal model.
- Hot spells in SWWA appear to be related to the weakening Southwest Australian Circulation (SWAC) index.
- A new mechanism that describes the variability and increasing trend of summer rainfall over Northwest Western Australian has been found.
- A report on seasonal forecasting skill is under preparation for internal review, and a report documenting changes in the frequency and region of occurrence of tropical cyclone-like vortices has been submitted.
- Collation of datasets of global climate model and regional climate model projections of temperature is underway.

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

- Extraction of large-scale predictor fields from the five selected GCMs and the corresponding CSIRO Cubic Conformal Atmospheric Model (CCAM) is continuing.

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

- A report documenting current work on predictors of extreme rainfall was submitted in October 2010 (Milestone 3.2.1).
- There is evidence of a decrease in extreme rainfall over SWWA, and that this decrease may be related to the decline in inflow to Perth dams. The various climatic drivers that we have investigated so far do not show a relationship with the changes in extreme rainfall. Seasonal estimates of dam inflow could be used to estimate seasonal extreme rainfall.
- Climate drivers do not appear to be useful in estimating rainfall extremes at a seasonal scale.
- Work on the amalgamation of daily rainfall and pluviometer data sets and the derivation/calculation of site dependent covariates (e.g., distance from coast, height above sea level) is ongoing.
- Dissemination of climate change scenarios for seasonal extreme rainfall as regional maps has commenced.
- A report on very-high resolution climate change projections for the south west of WA has been submitted.

The third year of IOCI 3 has 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

Abbs, D., 2010: The Impact of Climate Change on the Climatology of Tropical Cyclones in the Australian Region. Technical Report. 16 pp

Bates, B.C., Chandler R.E., Charles S.P., Campbell E.P., 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 Resour. Res.*, 46, W00H02, DOI:10.1029/2010WR009509.

Braganza, K., S. Power, B. Trewin, J. Arblaster, B. Timbal, P. Hope, C. Frederiksen, and J. McBride, 2011: Update on the state of the climate, long-term trends and associated causes. In: *Climate science update: A report to the 2011 Garnaut Review. CAWCR Technical Report 36*.T. D. Keenan and H. A. Cleugh, Eds., The Centre for Australian Weather and Climate Research, 107 pp.

Chandler, R.E., Bates, B.C. and Charles, S.P., 2011, Rainfall trends in southwest Western Australia. In: *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences* R.E. Chandler and E.M. Scott (eds), John Wiley & Sons, Ltd, Chichester, UK. doi: 10.1002/9781119991571.ch8.

Dare, R.A. and J.L. McBride. Sea Surface Temperature response to tropical cyclones. submitted to Monthly Weather review. Fully funded by IOCI.

Dare, R.A. and J.L. McBride. The Threshold Sea Surface Temperature Condition for Tropical Cyclogenesis. Submitted to Journal of Climate. Fully funded by IOCI

Feng, J., J. Li, and Y. Li, 2010: A monsoon-like Southwest Australian circulation and its relation with rainfall in Southwest Western Australia. *Journal of Climate* 23, 1334-1353.

Feng, J., J. Li, and Y. Li, 2010: Is there a relationship between the SAM and Southwest Western Australian winter rainfall? *Journal of Climate* 23, 6082- 6088.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, 2011: *Australian Winter Circulation and Rainfall Changes and Projections.* Int. Journal of Climate Change Strategies and Management, Paper 4, Vol. 3, Issue 2.

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.* International Journal of Climate Change: Impacts and Responses, 2, 143-162.

Frederiksen, J.S. and C.S. Frederiksen, 2011: *Role of dynamical modes in changing Southern Hemisphere climate.* ANZIAM J. 52, C72-C88.

Frederiksen, J.S. and C.S. Frederiksen, 2011: *Twentieth century winter changes in Southern Hemisphere synoptic weather modes.* Advances in Meteorology, (submitted).

Frederiksen, J.S., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2010: *Causes of changing Southern Hemispheric weather systems.* GH2009 book, CSIRO publication. "Managing Climate Change", Chapter 8, 85-98, Eds. Imogen Jubb, Paul Holper and Wenju Cai, CSIRO Publishing.

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, I. Jubb, P. Holper, and W. Cai, Eds., CSIRO Publishing.

Jovanovic B, Collins D, Braganza K, Collins D and DA Jones, 2010. A high-quality monthly total cloud amount dataset for Australia. Climatic Change, published online.

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: 10.1038/ngeo779.(multi-institution paper: McBride and Ramsay contributions funded by IOCI)

Lin, Z., and Y. Li, 2011: Remote influence of the tropical Atlantic on the variability and trend in North West Australia summer rainfall. *Journal of Climate* (Submitted). Manuscript ID: EP11510

M. M. P. B. Fuentes and D. Abbs, 2010: Effects of projected changes in tropical cyclone frequency on sea turtles. *Marine Ecology Progress Series*, 412, 283–292, doi: 10.3354/meps08678

McBride, J.L, H.A. Ramsay and M. B. Richman. Trend Analyses of Globally Consistent satellite-based estimates of tropical cyclone intensity. Submitted to Geophysical research Letters (Fully funded by IOCI. Submitted during 2011).

Phatak, A., Bates, B.C. and Charles, S.P. Statistical downscaling using sparse variable selection methods. *Environ. Model. & Software* (accepted 8 May 2011).

Rex Lau and Y. Li, 2011: A Markov model of the hot spell activities. *Monthly Weather Review* (In preparation).

Rotstayn, L. D., S. J. Jeffrey, J. I. Syktus, M. A. Collier, S. M. Dravitzki, A. C. Hirst, and K. K. Wong (2011), Have anthropogenic aerosols delayed greenhouse gas-induced changes in Indo-Pacific regional circulation and rainfall?, Atmos. Sci. Lett., submitted.

Trewin, B. and Vermont, H. 2010. Changes in the frequency of record temperatures in Australia, 1957-2009. Aust. Met. Oceanogr. J., 60, 113-119.

Y. Kuleshov, L. Qi, D. Jones, R. Fawcett, F. Chane-Ming, J. McBride and H. Ramsay, 2010: On Developing a Tropical Cyclone Archive and Climatology for the South Indian and South Pacific Oceans. In*, Indian Ocean Tropical Cyclones and Climate Change*, 4, 189-197, DOI: 10.1007/978-90-481-3109-9_23 Springer,

Netherlands. Indian Ocean and the South Pacific Ocean*. J. Geophys. Res.* 115, D1, D01101, 0148-0227 (Paper with members of the Bureau of Meteorology National Climate Centre. McBride and Ramsay contributions funded by IOCI).

Y. Kuleshov, 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. (Paper with members of the Bureau of Meteorology National Climate Centre. McBride and Ramsay contributions funded by IOCI)

Zidikheri, M.J. and J. S. Frederiksen, 2011: *Inverse methods for attribution of climate change*, ANZIAM J., (submitted).

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

Abbs, D, *Tropical cyclones – methods to analyse changes in frequency and intensity for the Australia-Pacific region*. Greenhouse 2011, Cairns, 4-8 April, 2011.

Charles SP, Fu GB (2011) *Statistical downscaling predictor selection assessment* [abstract accepted, paper in preparation] MODSIM 2011, Perth, December 2011.

D. J. Abbs, S. L. Lavender, K.J.E. Walsh and A. S. Rafter: *Dynamically downscaled simulations of Australian region tropical cyclones – a multi-model approach for the Australian region*. 3rd International Summit on Hurricanes and Climate Change. Rhodes, Greece. 27 June-1 July, 2011.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, *Changes and projections in southern Australian winter rainfall and circulation.* Australia-New Zealand Climate Forum 2010 Conference, Hobart, Tasmania, Australia, 12-15 October, 2010.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, *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.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, *Observed Changes and Projections in Southern Hemisphere Mid-latitude Storm, Rainfall and Circulation,* European Geosciences Union (EGU) General Assembly, Vienna, Austria, 3-8 April, 2011.

Frederiksen, J.S. and C.S. Frederiksen, *Changes in Southern Hemisphere climate and weather systems during the 20th century.* Australia-New Zealand Climate Forum 2010 Conference, Hobart, Tasmania, Australia, 12-15 October, 2010.

Frederiksen, J.S. and C.S. Frederiksen, *Role of dynamical modes in changing Southern Hemisphere climate.* The 15th Biennial Computational Techniques and Applications Conference, Sydney, Australia, 28 November – 1 December, 2010.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, *Changes and projections in southern hemisphere climate and weather systems.* 19th Australian Institute of Physics Congress, Melbourne, Australia, Session 1D: Meteorology, Oceanography, Environmental Physics & Climate Change, 5-9 December, 2010

Hope, P. and C.J. Ganter, *South west Western Australia summer temperature cooling trend*. Australia and New Zealand Climate Forum, Hobart, 2011

Li Y., and R. Katz, *Statistical modelling hot spells in southwest Western Australia.* Proc. Joint Conference of the New Zealand Meteorology Society and the Australian

Meteorological and Oceanographic Society, 100. Wellington, New Zealand, 9-11 Feb, 2011.

M. Marinelli, K. Braganza, D. Collins, D. Jones, S. Maguire, 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.

M. Marinelli, K. Braganza, D. Collins, D. Jones, S. Maguire, 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 11th International Meeting on Statistical Climatology, 12-16 July 2010.

M. Marinelli, K. Braganza, D. Collins, D. Jones, S. Maguire, 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*. Australia New Zealand Climate Forum. Hobart, 12 October 2010.

Palmer M.J. et al., (2010). *Spatial-Temporal Modelling of Extreme Rainfall*. Poster at an Interdisciplinary Workshop, held at the Banff International Research Station on Extreme Events in Climate and Weather, sponsored by SAMSI, August 2010.

Rafter, A and D. Abbs: *Tropical Cyclones - Methods To Analyse Changes In Frequency And Intensity For The Australia-Pacific Region*. IUGG 2011, Melbourne. 28 June-7 July 2011.

Rafter, A. and D. Abbs, High resolution dynamical downscaling of model-based tropical cyclones. Proc. Joint Conference of the New Zealand Meteorology Society and the Australian Meteorological and Oceanographic Society, 100. Wellington, New Zealand, 9-11 Feb, 2011.

Rotstayn, L. D . *Different forcings: land cover, greenhouse gases, ozone and aerosols*, CMIP5 Science Workshop, Melbourne, April 2011.

Rotstayn, L. D . *The CSIRO Mk3.6 GCM: An Australian Contribution to CMIP5,* Australia - New Zealand Climate Forum, Hobart, October 2010.

S. L. Lavender, M. Chattopadhyay and D. J Abbs, *Contribution of tropical cyclones to rainfall and extreme rainfall: Observations and GCMs.* 3rd International Summit on Hurricanes and Climate Change. Rhodes, Greece. 27 June-1 July, 2011.

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.

Zidikheri, M.J. and J.S. Frederiksen, 2010: *Inverse method for attribution of climate change*. The 15th Biennial Computational Techniques and Applications Conference, Sydney, Australia, 28th November – 1st December, 2010.

Zidikheri, M.J., Frederiksen, J.S., and Frederiksen, C.S., 2011: *Attribution of Southern Hemisphere climate change and projections.* Greenhouse 2011 Conference, Cairns, Australia, 4th – 8th April, 2011.

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