PROJECT 1.1: DETECTION AND ATTRIBUTION OF CHANGES TO WEATHER SYSTEMS AND LARGE SCALE CIRCULATION DRIVERS

Principal Investigators

Carsten Segerlund Frederiksen, Bureau of Meteorology, Centre for Australian Weather and Climate Research, PO Box 1289, Melbourne, Victoria, 3001

Phone: 03 9669 4566; Email: c.frederiksen@bom.gov.au

Jorgen Segerlund Frederiksen, CSIRO Marine and Atmospheric Research, Centre for Australian Weather and Climate Research, Private Bag 1, Aspendale, Victoria, 3195, Phone: 03 92394683; Email: jorgen.frederiksen@bom.gov.au

Meelis Zidikheri, Bureau of Meteorology, Centre for Australian Weather and Climate Research, PO Box 1289, Melbourne, Victoria, 3001

Phone: 03 9669 4427; Email: m.zidikheri@bom.gov.au

Milestone 1.1.1: Report on observed changes in mean SH climate and high frequency systems affecting WA

Completed 31/12/2009

This milestone has been completed and was reported on extensively in the IOCI3 Report 1.

Milestone 1.1.2: Report on simulated changes in mean SH climate and transients under observed anthropogenic forcing

Completed 31/12/2009

This milestone has been completed and was reported on extensively in the IOCI3 Report 1.

Milestone 1.1.3: Report on observed changes in low frequency weather systems affecting WA in both observations and models

Completed 31/12/2010

This milestone has been completed and was reported on extensively in the IOCI3 Report 2.

Milestone 1.1.4: Report on possible projected changes in SH circulation and WA weather systems under future IPCC scenarios

Completed 31/12/2010

This milestone has been completed and was reported on extensively in the IOCI3 Report 2.

Milestone 1.1.5: Formulation, development and documentation of an inverse modelling technique for attribution studies

This milestone was reported on extensively in IOCI3 Report 3. In particular, that report detailed the formulation and development of two inverse modelling techniques for systematically attributing climate change by directly calculating the anomalous climate forcing responsible. These methods included an iterative approach and a more computationally efficient method based on a statistical dynamical closure model. Both methods calculate the anomalous forcing directly from the dynamical equations for a given observed climatic response. The methods are documented in Zidikheri and Frederiksen (2011) (see publications below).

Milestone 1.1.6: Report identifying a "fingerprint" of climate change forcing of observed changes in SH circulation and WA weather systems

Here, we present an overview of the application of the methodology to understand those factors that caused the observed changes in the Southern Hemisphere (SH) winter atmospheric circulation and thermal structure, and associated with the observed changes in the mid-latitude weather systems affecting SWWA rainfall. In particular, we identify the anomalous forcing function which is responsible and can be considered a “fingerprint” of the climate change forcing. We also identify the impact of the weather systems on the mean climate of the SH circulation and thermal structure, and how this has changed over the last half of the twentieth century.

In a previous report (IOCI3 Report 3), we presented, as part of Milestone 1.1.5, results identifying the anomalous forcing function associated with changes in the vertically average zonal (east-west) winds between the periods (1949-1968) and (1975-1994). Here, we will focus on the anomalous forcing function associated with changes in the thermal structure of the SH atmosphere between these same two periods.

Key research findings

Determining the causes of the changing climate during the last half century and the likely projections into the 21st century is of great importance for policy development. To attribute these causes one needs to disentangle the anthropogenic (i.e. due to human influence) component from natural internal variability on various time scales. Particular external forcing agents of import for climate change include greenhouse gases, aerosols, and changes in solar radiation, volcanic activity as well as changes in surface albedo, roughness and evaporation due to land use.

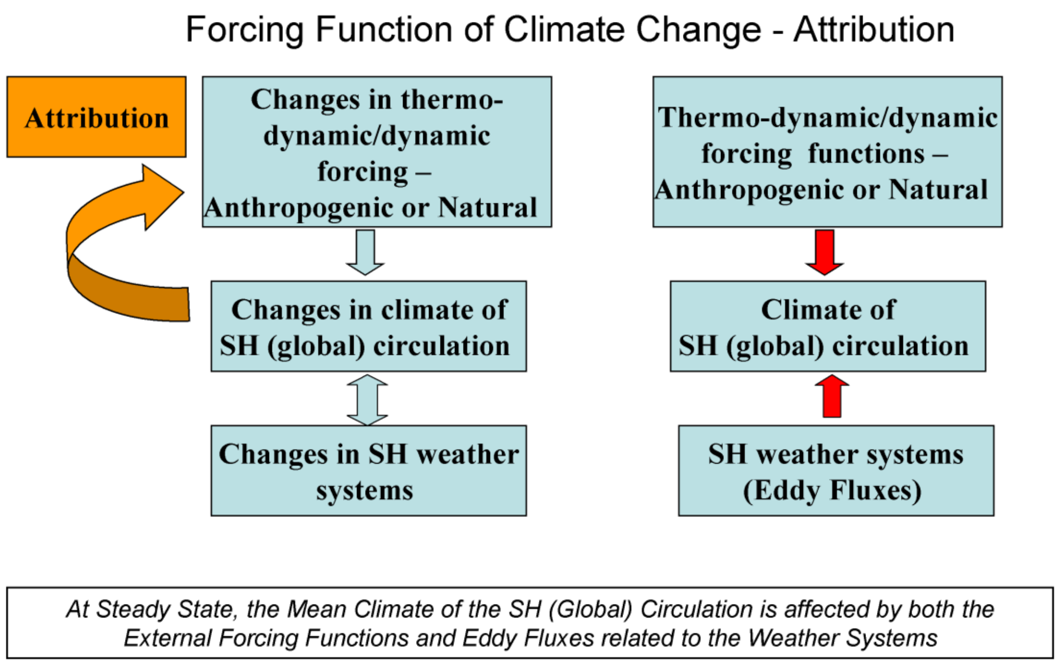

Figure 1: Schematic showing relationship (left panel) between changes in the climate of the atmospheric circulation, changes in weather systems and changes in external forcing on the climate system. Also shown (right panel)

Figure 1 shows a simple schematic of the relationship between changes in the climate of the atmospheric circulation and thermal structure, the changes in weather systems and the changes in the external forcing (left panel). Changes in the external forcing, whether natural or anthropogenic, will in general cause changes in the mean climate of the SH circulation, which in turn will affect the weather systems that can develop in the new climate. However, the weather systems will also impact, or feedback onto, the mean climate. Thus, at steady state, the mean climate is affected by both the external forcing and the weather systems (through the associated eddy fluxes) (see the right panel). That is, in order to determine the forcing function, we also need to estimate the contribution of the weather systems on the mean climate. The two methods of Zidikheri and Frederiksen (2011) parameterize the effects of the weather systems and consequently allow the forcing function to be estimated.

Their first scheme uses iterative methods of calculating the anomalous forcing responsible for the changed circulation between two time periods. The iterative scheme successfully reconstructs the anomalous forcing functions but is computationally intensive since many climate simulations may be required for convergence. A second scheme, which is based on statistical dynamical closure theory, obtains the forcing by an inverse method that is more computationally efficient. The two schemes provide cross checks and both have been applied to determine the anomalous temperature forcings responsible for the changes in the Southern Hemisphere circulation during the second half of the 20th century.

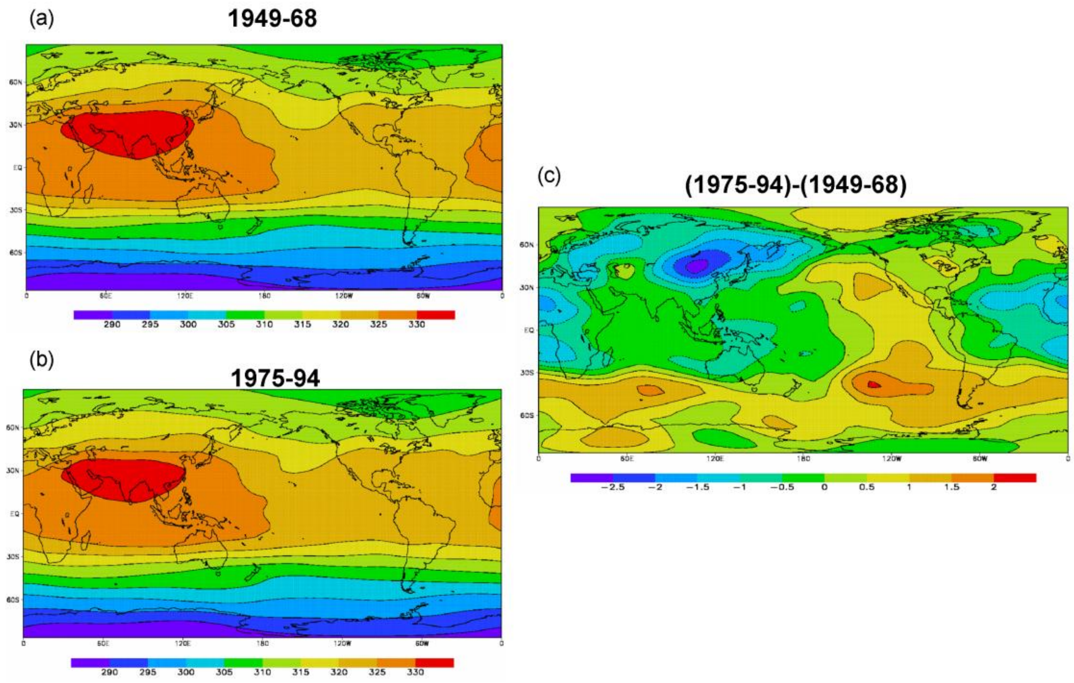

Figure 2: The vertically average July atmospheric potential temperature (degree Kelvin) for (a) 1949 to 1968 and (b) 1975 to 1994, and (c) the differences (1975-1994) minus (1949-1968).

Figure 2 shows the vertically averaged atmospheric potential temperature for the periods (a) (1949-1968) and (b) (1975-1994) during July, as well (c) the differences in temperature between the periods. From this, we can see that the atmospheric temperature is relatively warmer in a zonal band between 30S and 60S in the latter period. North of this band and over Australia and the Indian Ocean the temperature is cooler, in the latter period. These changes in the atmospheric temperature mean that the meridional (equator to pole) temperature gradient upstream (i.e. to the west) of Australia has reduced between the two periods. In earlier reports, we have shown that this has resulted in a dramatic reduction in the strength of the subtropical (near 30S) jet stream maximum wind speed over this region and a subsequent reduction in the development of mid-latitude storms that are responsible for rain over SWWA.

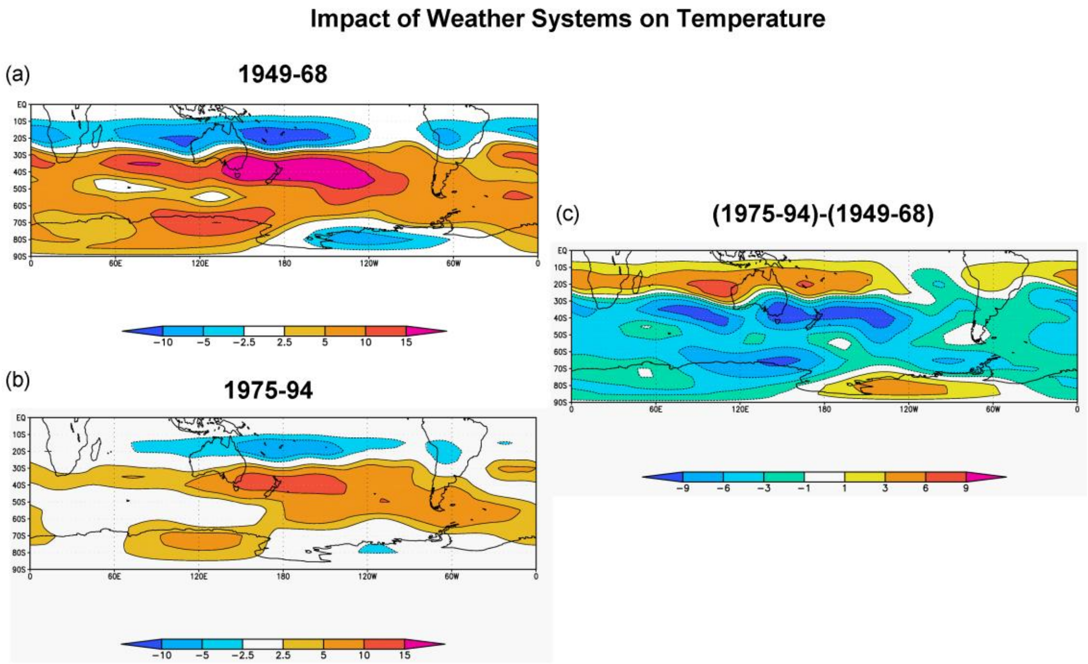

Figure 3: The impact of weather systems on the vertically averaged atmospheric potential temperature for (a) 1949 to 1968 and (b) 1975 to 1994, and the anomalous impact for the differences (1975-1994) minus (1949-1968). Units are degree Kelvin.

In order to calculate the forcing function associated with the change in atmospheric temperature depicted in Figure 2, it is necessary first to estimate the impact of the weather systems on the climate of the atmospheric temperature. Figure 3 shows this impact on the 500hPa atmospheric temperature for the two periods, as well as their differences. Figures 3(a) and (b) show that the impact of the weather systems is to reduce the temperature over the tropics (i.e. north of about 30S) and increase the temperature poleward of 30S. That is, the role of the weather systems, or eddies, is to reduce the meridional temperature gradients seen in Figures 2(a) and (b). In other words, the role of the weather systems is effectively to attempt to mix and equalize the temperature of the atmosphere. Comparing Figures 3(a) and (b), we can see that the temperature anomalies have much larger amplitudes in the earlier period; this is also indicated by the differences in their impact (Figure 3(c)). This is also consistent with the observations from our earlier IOCI3 reports that mid-latitude storms near 30S are less likely to form in the latter period.

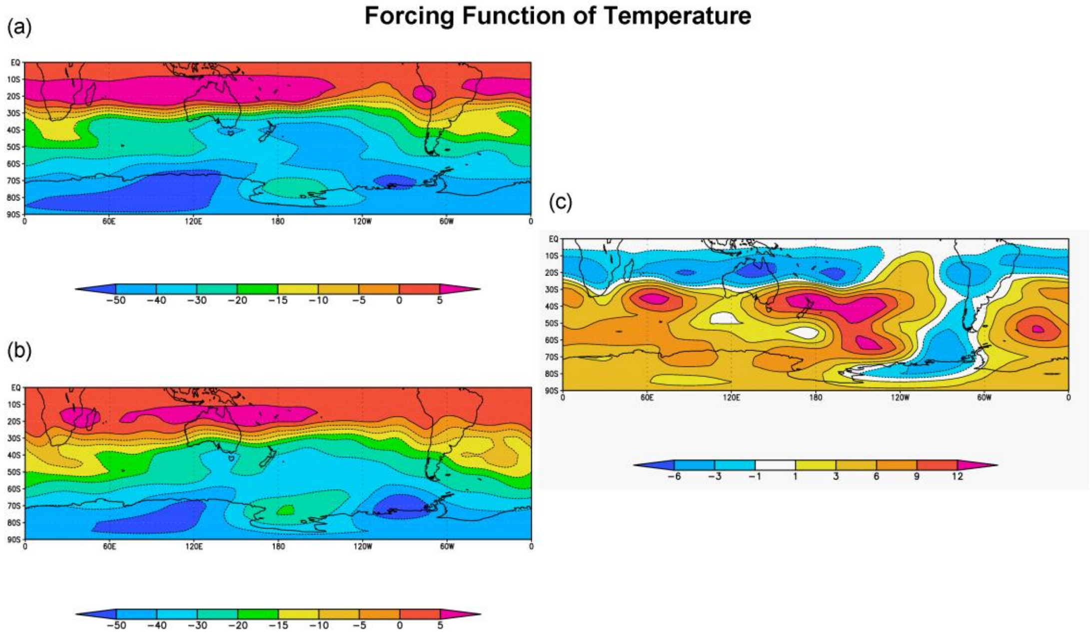

Figure 4: The forcing function of the vertically averaged atmospheric potential temperature for the periods (a) 1949 to 1968 and (b) 1975 to 1994, and the anomalous forcing for the difference act of weather systems on the vertically averaged atmospheric potential temperature for (a) 1949 to 1968 and (b) 1975 to 1994, and the anomalous impact for the differences (1975-1994) minus (1949-1968). Units are degree Kelvin.

Figure 4 shows the anomalous 500 hPa temperature forcing function associated with the changed temperature (Figure 2) and, by implication, the circulation (refer to our earlier reports) between the July periods (1949-1968) and (1975-1994). Firstly, Figure 4(a) and (b) show that the forcing function in each period acts to enhance the equator to pole temperature gradient, indicated by positive temperature anomalies in the tropics/subtropics and negative anomalies at high latitudes. It is also seen, from Figure 4(c), that the Southern Hemisphere temperature and circulation changes have been driven by largely zonally symmetric temperature forcing anomalies that enhance warming tendencies in the mid to high latitudes with reductions in the tropics and subtropics. This has reduced the meridional temperature gradients over mid latitude regions such as those over southern Australia and SWWA in particular. In turn, this has reduced the instability of the Southern Hemisphere atmosphere in the mid latitude regions, has reduced the intensity of storm formation and has reduced the rainfall as discussed in earlier reports.

The largely zonally symmetric anomalous temperature forcing pattern (Figure 4), or "finger print", is seen to be consistent with anomalous forcing due largely to increasing greenhouse gases and is also consistent with the predictions of skilful climate models during the 20th and 21st century (see earlier reports and publications). When forced by the radiative effects of increasing greenhouse gas concentrations, models such as the Miroc high and medium resolution coupled climate models obtain very similar changes in the Southern Hemisphere temperature and circulation, including baroclinic instability and southern Australian rainfall, as in the observations (Frederiksen et al. 2010, 2011a, b). Further, their projections into the 21st century, when forced by increasing anthropogenic gases under SRESB1, SRESA1B and SRESA2 scenarios, show a continuing of the trends seen in the second half of the 20th century.

Milestone 1.1.7: Dissemination of the attribution of observed changes in WA weather systems

The research carried out for this project have been documented in a series of eleven peer-reviewed papers (see publications below) and four IOCI3 Reports, including the current one. Copies of these have been placed on the IOCI3 web-page and can be accessed by stakeholder members at:

http://www.ioci.org.au/members/19-stage-3-research-reports.html.

The work has also been presented at numerous national and international conferences and workshops, including the four annual IOCI3 workshops. Conference presentations for 2011/2012 are listed below; earlier ones are listed in IOCI3 Reports 1 to 3 (see IOCI3 webpage). These presentations include an opening address at the "WA 21st Century Challenge Forum" held at CSIRO Floreat in October 2011, and an invited talk to the "Southeast Australian Climate Initiative (SEACI) Workshop" in Canberra during July 2011. There was also a CSIRO Media Press Release that resulted from a number of presentations at the

"International Union of Geodesy and Geophysics (IUGG) General Assembly" meeting held in Melbourne during July 2011. The press release gained national and international attention for the research that we have conducted for this project. This research is also presented in the IOCI3 technical synthesis report, which will be a public document. An entire chapter of this report is devoted to the results, providing compreshensive coverage in a format that is, in the main, accessible to a non-expert audience.

List of Publications

Frederiksen, J.S. and C.S. Frederiksen, 2011: *Twentieth century winter changes in Southern Hemisphere synoptic weather modes.* Adv. Meteorol., Article ID 353829, 16pp, (2011), doi:10.1155/2011/353829.

C.S. Frederiksen, J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Observed and projected changes in the annual cycle of southern hemisphere mid-latitude storm formation.* Modsim11, 2719-2725, (2011). http://www.mssanz.org.au/modsim09/F5/frederiksen_2.pdf

J.S. Frederiksen, C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2011: *Changes in southern hemisphere rainfall, circulation and weather systems.* Modsim11, 2712-2718, (2011). http://www.mssanz.org.au/modsim09/F5/frederiksen.pdf

Zidikheri, M.J. and J. S. Frederiksen, 2011: *Inverse methods for attribution of climate change*, ANZIAM J., 52, C823-C836..

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

http://anziamj.austms.org.au/ojs/index.php/ANZIAMJ/article/view/3892

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, **3**, 170-188.

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.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson, and S.L. Osbrough, 2010a: *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., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2010b: *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.

Frederiksen, C.S., J.S. Frederiksen and J.M. Sisson, 2009: *Simulation of twentieth century atmospheric circulation changes over Australia.* 18th World IMACS/MODSIM Congress, Cairns, Australia, 13-17 July, 2009, 2555-2561, http://www.mssanz.org.au/modsim09/G1/frederiksen_c.pdf

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, 2562-2568, http://www.mssanz.org.au/modsim09/G1/frederiksen_j.pdf

Frederiksen, J.S. and C.S. Frederiksen, 2007: *Interdecadal changes in southern hemisphere winter storm track modes.* Tellus. **52A**, 599-617.

Frederiksen, J.S. and C.S. Frederiksen, 2005: *Decadal changes in southern hemisphere wintercyclogenesis.* CSIRO Marine and Atmospheric Research Paper No. 002, 35pps.

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

Frederiksen, J.S., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2012: *Changes and projections in the annual cycle of Southern Hemisphere weather systems.* 10th International Conference on Southern Hemisphere Meteorology and Oceanography Noumea, New-Caledonia, 23 - 27 April 2012. p5.

Frederiksen, J.S., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2012: *Changes in Southern Hemisphere Jet-streams and Weather Systems*. AMOS 18th Annual conference, University of New South Wales, Australia, 31 January -3 February, 2012, p 195-196.

Zidikheri, M. J., J. S. Frederiksen , and C. S. Frederiksen, 2012: *Attribution and projections of changes in southern hemisphere storm tracks.* AMOS 18th Annual conference, University of New South Wales, Australia, 31 January -3 February, 2012, p 193.

Frederiksen, C.S., J. S. Frederiksen , J. M. Sisson and S. L. Osbrough, 2012: *Changes and Projections in the Annual Cycle of Southern Hemisphere Baroclinicity for Storm Formation.* AMOS 18th Annual conference, University of New South Wales, Australia, 31 January -3 February, 2012, p 192.

Frederiksen, J.S., 2012: *Dynamics and predictability of climate variability and change.* Aksel Wiin-Nielsen Symposium, 92nd American Meteorological Society Annual Meeting, New Orleans, USA, 22-26 January, 2012, paper 204071.

Frederiksen, J.S., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2012: *Attribution and projection of Southern Hemisphere climate change*. 92nd American Meteorological Society Annual Meeting, New Orleans, USA, 22-26 January, 2012, paper 204322.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Observed and projected changes in the annual cycle of southern hemisphere mid-latitude storm formation*. 19th International Congress on Modelling and Simulation, Perth, Australia 12-16 December 2011.

Frederiksen, J.S., C.S. Frederiksen, S.L. Osbrough and J.M. Sisson, 2011: *Changes in southern hemisphere rainfall, circulation and weather systems*. 19th International Congress on Modelling and Simulation, Perth, Australia 12-16 December 2011.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: O*bserved and projected changes in the Southern Hemisphere circulation, weather systems and WA winter rainfall.* IOCI Stage 3 workshop, 5-6 December, 2011, Perth, WA.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Detection and attribution of changes to weather systems and large scale circulation drivers (Project 1.1).* IOCI Stage 3 workshop, 5-6 December, 2011, Perth, WA.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Advances in understanding drivers of climate drying.* WA 21st Century Climate Challenges Forum “What’s happening in climate-related research for agriculture in Western

Australia: An update for researchers, industry leaders, and government". CSIRO Floreat, WA, 27th October, 2011.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Observed changes and projections in Southern Hemisphere weather systems and climate.* SEACI Workshop, 20 July 2011, CSIRO Corporate, Canberra, ACT.

Zidikheri, M.J. and J.S. Frederiksen, 2011: *An inverse method for determining climate forcing from climate data.* IUGG, 28 June - 7 July, 2011, Melbourne, Australia, p 87.

Frederiksen, J.S. and C.S. Frederiksen, 2011: *Decadal Changes in Southern Hemisphere Subtropical Jet and Weather Modes.* IUGG, 28 June -7 July, 2011, Melbourne, Australia, p 84.

Frederiksen, C.S., J.S. Frederiksen, J.M. Sisson and S.L. Osbrough, 2011: *Winter Changes and Projections in Southern Hemisphere Circulation and Australian Rainfall.* IUGG 2011, 28 June -7 July, 2011, Melbourne, Australia, p 106.

Theme and Project Number: 1.1 **Principal Investigator(s):** C. Frederiksen

To be Completed for First Annual Report, and Included in Subsequent Annual Reports		To be Completed for First Annual Report and Updated in Subsequent Annual Reports	
Milestone description	Target completion date	Progress against milestone (1- 3 dot points)	Recommended changes to research plan (1- 3 dot points)
1.1.1 Report on observed changes in mean SH climate and high frequency systems affecting WA	31/12/2009	Completed (see IOCI3 Report 1.)	N/A
1.1.2 Report on simulated changes in mean SH climate and transients under observed anthropogenic forcing	31/12/2009	Completed (see IOCI Report 1.)	N/A
1.1.3 Report on observed changes in low frequency weather systems affecting WA in both observations and models	31/12/2010	Completed (see IOCI Report 2.)	N/A
1.1.4 Report on possible projected changes in SH circulation and WA weather systems under future IPCC scenarios	31/12/2010	Completed (see IOCI Report 2.)	N/A
1.1.5 Formulation, development and documentation of an inverse modelling technique for attribution studies	31/12/2011	Completed (see IOCI Report 3.)	N/A

1.1.6 Report identifying a "fingerprint" of climate change forcing of observed changes in SH circulation and WA weather systems	31/12/2011	Completed (see also IOCI Report 3.)	N/A
1.1.7 Dissemination of the attribution of observed changes in WA weather systems	31/12/2011	Completed	N/A