CSIRO Wealth from Oceans Flagship Fellowship
"SOUTHERN OCEAN TELECONNECTIONS TO AUSTRALIAN CLIMATE"
Professor Matthew England
Final Report

Executive summary

The goal of the CSIRO Flagship Fellowship was to explore the role of the Southern Ocean in forcing Australian climate, particularly via the Southern Annular Mode (SAM). The Southern Annular Mode is the leading mode of climate variability over the Southern Ocean, manifesting as a circumpolar pressure oscillation between Antarctica and southern midlatitudes.

The study aimed to: (1) Examine the dynamics of interannual to decadal climate variability in the Southern Ocean, particularly that associated with the Southern Annular Mode, and (2) Identify teleconnections between the Southern Ocean and Australian climate extremes, particularly regional rainfall.

Extended integrations of global climate models were analysed to determine the variability in upper-ocean circulation, water-mass properties (especially sea surface temperature (SST) and heat content), sea-ice, and atmospheric variables linked to the Southern Annular Mode. Observational data have also been compared to the model-simulated SAM variability where possible.

The teleconnection between the SAM and variability in Australian regional rainfall was examined. This was assessed using coupled models and observational data sets and reanalyses. An ongoing research project is analysing how low-frequency variations in the strength and location of the polar front jet translate to significant climate anomalies over Australia (e.g., drought and heavy rainfall seasons).

The main conclusions from the project to date are

1. The Southern Annular Mode forces an organized circumpolar response in ocean circulation, SST, mixed layer depth and sea-ice
2. The sea surface temperature response is significant due to a conspiring of ocean circulation effects and air-sea heat fluxes
3. A link between the Southern Annular Mode and Australian rainfall is apparent in southwest WA, Tasmania, and parts of Victoria and SA
4. The atmosphere appears to respond to Southern Ocean SST and sea-ice variations by prolonging phases of the Southern Annular Mode

This six-month project has seeded several new studies that will be undertaken in collaboration with CSIRO colleagues ("Response of the Southern Annular Mode to climate change"; "Dynamics of the Southern Annular Mode – Australian rainfall teleconnection"). In addition, a study of mode and intermediate water ventilation rates is being completed with co-CI Steve Rintoul. An international workshop on the Southern Annular Mode will be held in Sydney in November co-chaired by Matthew England (UNSW) and Wenju Cai (CSIRO MAR).

Research projects

Stage 1: "Southern Annular Mode climate variability"

Extended integrations of a global climate model were analysed to determine the variability in upper-ocean circulation, water-mass properties (especially heat content), sea-ice, and atmospheric variables (particularly atmospheric moisture transport) linked to the Southern Annular Mode. The models that have been assessed include the NCAR CCSM 3.0 and CSIRO Mk3 multi-century natural variability simulations run with constant atmospheric CO_2. Momentum and property budgets were employed to elucidate the dominant processes controlling the magnitude of ocean-atmosphere variations driven by the Southern Annular Mode. Variables analysed include atmospheric conditions (e.g., air temperature, cloud cover, precipitation, winds, sea-level pressure), sea-ice extent and thickness, air-sea property fluxes, ocean circulation and ocean hydrography. Observational data have also been compared to the model-simulated SAM variability where possible.

Stage 2: "Teleconnection of the Southern Annular Mode to Australian climate"

The objective of Stage 2 was to identify teleconnections between the SAM and extremes/trends in Australian climate. This has been assessed using coupled models and observational data sets and reanalyses. Of particular interest was how low-frequency variations in the strength and location of the polar front jet translate to significant climate anomalies over Australia (e.g., drought and heavy rainfall seasons). To address this we used EOFs, regressions, composite statistics and analyses of correlation and coherence to identify the nature of time-space connectivity between the SAM and Australian climate extremes. Analysed properties included precipitation, surface air temperature, SST, evaporation, cloud cover, air pressure, air humidity, soil moisture, and wind speed/direction. Regressions were also formed for surface ocean currents and air-sea property fluxes. In ongoing work, composite means and standard deviations are being formed for extreme drought events over regions of southern Australia. An analysis is being undertaken of the climate dynamics operating during these periods of anomalously low rainfall. The degree of uncertainty, or incoherence, of the climate teleconnection will be assessed using the standard deviation of composite properties. This analysis will give some initial idea of the predictability of southern climate extremes controlled by the SAM.

Other ongoing projects related to the Fellowship:

- A case study of interannual Tasmanian rainfall extremes and possible links to the Southern Annular Mode (CIs England, Hill)
- Mode and Intermediate Water ventilation pathways and time-scales in a high resolution global ocean model (CIs Sen Gupta, Rintoul and England)
- A study of the role of SST forcing in the maintenance and/or attenuation of variations/trends in the Southern Annular Mode (CIs Sen Gupta, Rintoul and England)
- Diagnosis of Antarctic Bottom Water formation and its variability in the CSIRO coupled climate model (CIs England and Santoso)

Scientific outcomes

Analysis of the coupled ocean-atmosphere-ice response to variations in the Southern Annular Mode (SAM) in the NCAR Community Coupled Climate Model has been submitted to the Journal of Climate (Sen Gupta and England, 2006). The model shows considerable skill in capturing the predominantly zonally symmetric SAM while regional deviations between model and observation SAM winds go a long way in explaining the generally small differences between simulated and observed SAM responses in the ocean and sea-ice systems. Vacillations in the position and the strength of the circumpolar winds and the ensuing variations in advection of heat and moisture result in a dynamic and thermodynamic forcing of the ocean and sea-ice, summarized below in Fig. 1. Both meridional and zonal components of ocean circulation are modified through Ekman transport which in turn leads to anomalous surface convergences and divergences that strongly affect the meridional overturning circulation, and potentially the pathways of intermediate water ventilation.

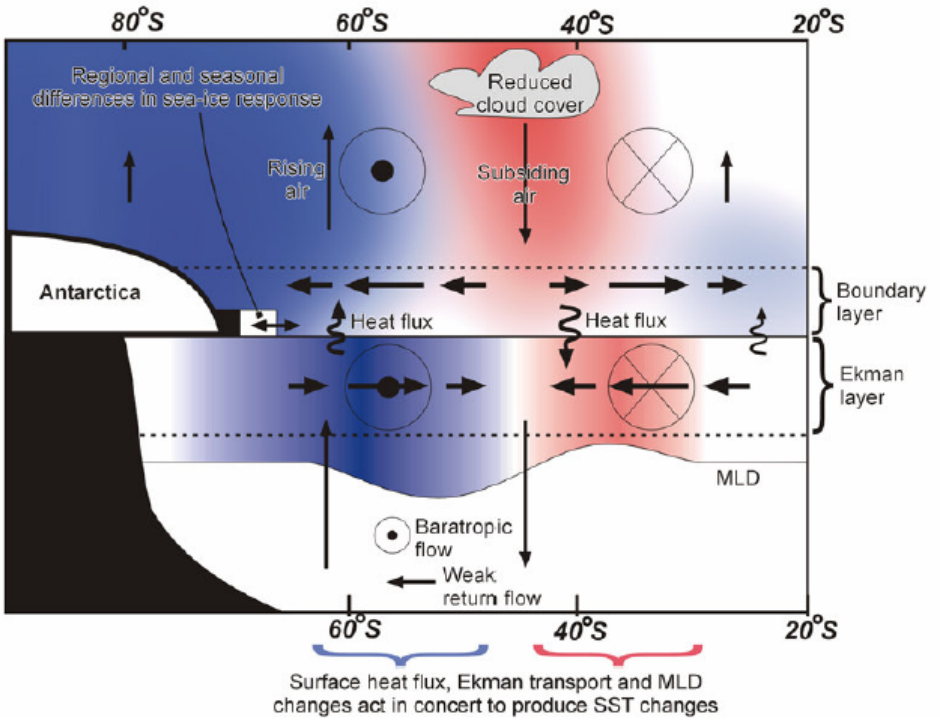

Figure 1. *Schematic representation of the climate system response to a positive phase of the SAM. The schematic of circulation, properties and fluxes for the negative phase of the SAM exhibits the same patterns as displayed above, only with reversed directions of circulation and the opposite sign for property anomalies and fluxes (from Sen Gupta and England, 2006).*

A heat budget analysis demonstrates a conspiring of oceanic meridional heat advection, surface heat fluxes and changes in mixed-layer-depth, which act in phase to imprint a strong circumpolar SAM signature onto sea surface temperatures (SST) while, other oceanic processes, including vertical advection, are shown to play only a minor role in contrast to previous suggestions. Lagged correlations show that although the SAM is mainly controlled by internal atmospheric mechanisms, the thermal inertia of the ocean re-imprints the SAM signature back to surface air temperatures (SAT) on timescales longer than the initial atmospheric signal. Sea-ice variability is well explained by a combination of atmospheric and ocean dynamic and thermodynamic forcing, and by an albedo feedback mechanism that allows ice extent anomalies to persist for many months. Non zonally-symmetric components to the SAM winds, particularly in the region surrounding the Antarctic Peninsula, have important effects for other climate variables.

A link between the Southern Annular Mode and Australian rainfall is apparent in southwest WA, Tasmania, and parts of Victoria and SA (see Fig. 2 below). An extended analysis was performed for Tasmanian rainfall. Westerly winds of the circumpolar trough were found to shift south (north) during the positive (negative) phase of the SAM. A similar annular pattern and north-south shift was seen in sea level pressure (SLP), outgoing longwave radiation (OLR) and precipitation. During years of anomalous positive SAM there is an enhanced OLR anomaly over Tasmania, confirming that during this phase of the SAM conditions across Tasmania are less conducive to precipitation.

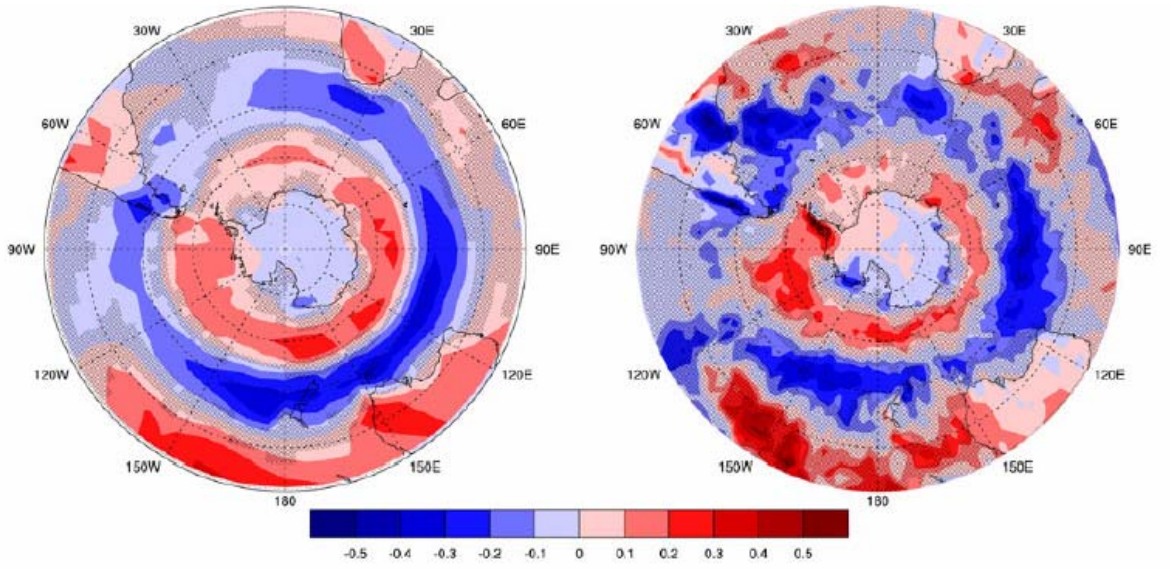

Figure 2. *Regressed total precipitation (mm per day) for the NCAR CCSM model (left) and the ECMWF reanalyses (right). Crosshatching indicates areas where confidence levels are below 95% (90%) for simulation (observation). Apparent is a signature of decreased rainfall over regions of southern Australia, especially southwest WA and Tasmania, during a positive phase of the SAM. This may have implications for climate change as the SAM is undergoing a sustained multi-decadal positive trend due to increased greenhouse gases.*

The Southern Annular Mode influences Tasmanian precipitation distributions via SLP and wind anomalies. The zonal winds and SLP patterns of extreme rainfall years over Tasmania coincide with the positive and negative phases of the SAM (see Fig. 3 below). More detailed analyses were performed dividing the state into western and eastern regions, due to its distinctive east-west topographic and rainfall gradients. Sea surface temperatures (SSTs) were found to have little influence over rainfall in the western districts of Tasmania and were instead forced by local atmospheric fluctuations associated with the Southern Annular Mode. The SST anomalies for extreme rainfall years over western Tasmania were colder during wet years and warmer during dry years, indicating local atmospheric forcing of the oceans. The SST anomalies during extreme dry/wet years over eastern Tasmania indicate an additional ENSO influence beyond that projected by the SAM. In summary the phase and intensity of the SAM impacts on precipitation across both western and eastern Tasmania, whereas the influence of ENSO is only detected over parts of eastern Tasmania.

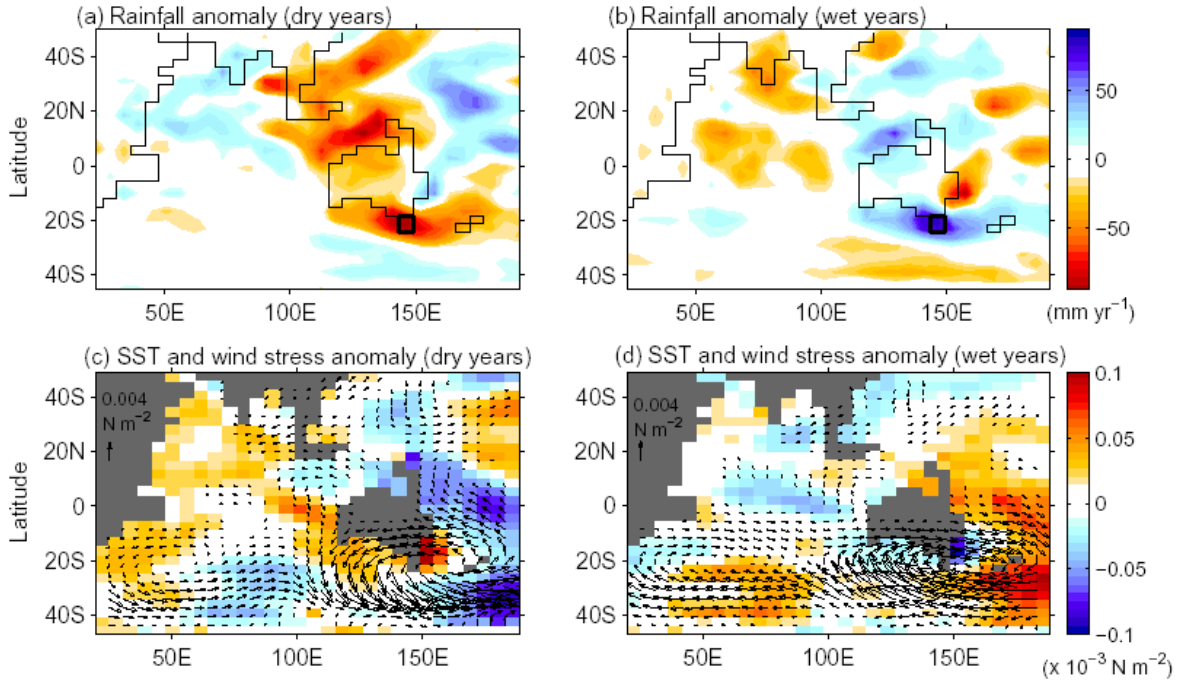

Figure 3. *Composite maps of (a-b) rainfall anomaly, and (c-d) SST anomalies overlaid on vector wind stress anomalies during dry and wet years in the CSIRO Mk2 coupled climate model. The box in (a-b) marks the region in the model corresponding to Tasmania where the anomalous rainfall years are defined.*

Future activities

The CSIRO Flagship Fellowship has seeded a number of new studies (see below). While I am funded as an ARC Federation Fellow over the next five years, I am presently exploring possibilities for an ongoing formal link to CSIRO Marine and Atmospheric Research and the *Wealth from Oceans* program.

Ongoing WfO – UNSW research projects seeded by the Fellowship:

- A case study of interannual Tasmanian rainfall extremes and possible links to the Southern Annular Mode (CIs England, Hill)
- Mode and Intermediate Water ventilation pathways and time-scales in a high resolution global ocean model (CIs Sen Gupta, Rintoul and England)
- A study of the role of SST forcing in the maintenance and/or attenuation of variations/trends in the Southern Annular Mode (CIs Sen Gupta, Rintoul and England)
- Diagnosis of Antarctic Bottom Water formation and its variability in the CSIRO coupled climate model (CIs England and Santoso)
- A study of water-mass transformation rates in the Southern Ocean (CIs Rintoul, England, Le Sommer, and Treguier [IFREMER]).

Future projects will involve joint collaborations and the co-supervision of PhD projects (e.g., PhD student Caroline Ummenhofer is working with Peter MacIntosh on Australian rainfall extremes/trends). I have four new Postdoctoral Research Fellows commencing in 2006, and one of these, Dr. Julien Le Sommer from IFREMER, will work in collaboration with Steve Rintoul and myself on a project to study water-mass transformation rates in the Southern Ocean. Hence, while the Flagship Fellowship only ran for six months, years of joint research is anticipated between the UNSW climate research group and CSIRO MAR.

Some other medium term goals include (1) The development of useful indices - akin to the Southern Oscillation Index for El Niño - that relate Southern Ocean atmospheric processes to Australian rainfall with lead-times of months, (2) Improved understanding of the predictability of Australian climate extremes originating over the Southern Ocean.

Finally, an international workshop on the dynamics, stability and impacts of the Southern Annular Mode is being planned for November 2006 (co-convened by Matthew England, Wenju Cai, and David Thompson [Thompson TBC]). We anticipate up to 50 participants, with a mix of national and international delegates.

APPENDICES

(i) Publications resulting from Flagship Fellowship as at March 2006

England, M.H., and K. Hill, 2006: Interannual rainfall extremes over Tasmania linked to the Southern Annular Mode. *J. Climate*, in preparation.

Sen Gupta, A., and M.H. England, 2006: Coupled ocean-atmosphere-ice response to variations in the Southern Annular Mode. *J. Climate*, in press.

Sen Gupta, A., M.H. England, and S. Rintoul, 2006: Evaluation of interior circulation in a high resolution global ocean model, Part II: Mode and Intermediate Waters, *J. Phys. Oceanogr.*, to be submitted.

Santoso, A., and M.H. England, 2006: Antarctic Bottom Water circulation and variability in a coupled climate model. *J. Phys. Oceanogr.*, in preparation.

(ii) Staff involved in the Flagship Fellowship project

Lead Investigators:

Matthew England (UNSW)

Steve Rintoul (CSIRO MAR)

Co-investigators:

Tony Hirst (CSIRO MAR)

Siobhan O'Farrell (CSIRO MAR)

Anne-Marie Treguier (IFREMER, France)

Research Students:

Alex Sen Gupta (PhD, UNSW)

Agus Santoso (PhD, UNSW)

Khalia Hill (Hons I, UNSW)

(iii) Copy of financial statement

	$ 2005-06	$ 2005-06	$ 2005-06
REVENUE	**Budget**	**Actual**	**Variance**
Contribution from the FCF	72,612	72,612	0
Applicant Contribution	0	0	0
Total Revenue	**72,612**	**72,612**	**0**
EXPENSES			
Labour Costs (England)	60,254	60,254	0
Travel (England to Hobart)	3,491	3,491	0
Operating (Teaching Relief)	8,867	8,867	0
Depn. on Specialised Equipment	0	0	0
Specialised Services	0	0	0
Indirect Costs	0	0	0
Total Expenses	**72,612**	**72,612**	**0**
Surplus/(Deficit)	**0**	**0**	**0**