symposium



presenters' abstract papers

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Climate change and frost in South West Western Australia

Dr Tom Lyons, Murdoch University



The effects of climate change are expected to have a huge impact on Western Australia's marine and terrestrial ecosystems and our environment.

Organisations, institutions and agencies are carrying out a range of research activities which are directly relevant to climate change and its impacts.

This symposium is a showcase of some of those research achievements, providing an outline of preliminary findings and suggestions of the pathways we need to take to ensure a sustainable future.





The Western Australian Marine Science Institution, The University of Western Australia, CSIRO, the Australian Meteorological and Oceanographic Society, the Bureau of Meteorology and Landgate have sponsored *A changing climate: Western Australia in focus* to provide a snapshot of the importance of research and communicate its value to society.

Dr Peter Rogers

Chairman

Western Australian Marine Science Institution



Current and projected climate change in Western Australia

Bryson C. Bates

Theme Leader, CSIRO Climate Adaptation Flagship Chief Research Scientist, CSIRO Division of Marine and Atmospheric Research

Climate change presents a challenge to Western Australia.

It is widely accepted, based on analyses of data from the last few decades, that rainfall has decreased in the South West and increased in the North West.

The rainfall decline in the South West has been studied extensively under the auspices of the Indian Ocean Climate Initiative (IOCI). The first stage of IOCI was launched in November 1997 and was comprised of partners from several State agencies, the Bureau of Meteorology and CSIRO.

The objectives of the Initiative were to improve understanding of climate variability at interannual and multidecadal scales and to enable operational seasonal forecasts with sufficient skill to inform decision making across a wide variety of sectors. Stage 3 of the Initiative (launched in 2008) is committed to establishing and maintaining state-of-the-art and regionally-specific knowledge of past and projected climate trends in the State.

For the first time, the economically important North West region is a major focus of the research program.

The three research themes of IOCI Stage 3 are:

- Baselines, Predictability of Western Australia Climate and Attribution of Climate Change;
- Current and Future Climate of the North West, including Extreme Events; and
- Very-High Resolution Climate Change Projections for the South West.

This presentation will provide a brief overview of the research achievements of IOCI since its inception and an introduction to the research programme for IOCI Stage 3. It will also demonstrate the benefits obtained by collaboration across a wide range of disciplines. Some thoughts will be offered on key research areas that remain to be explored.

Bryson Bates

Bryson Bates was Director of CSIRO's Climate Program between 2004 and 2006, and served as a lead author for the second, third and fourth assessment reports of the Intergovernmental Panel on Climate Change (IPCC). He was a convening lead author for the IPCC's Technical Paper on Water and Climate Change.

He received a certificate of recognition for his contribution to the 2007 Nobel Peace
Prize awarded jointly to the IPCC and Al Gore. His research interests include
hydroclimatic extremes, analysis and simulation of non-stationarity in hydroclimatic time series,
downscaling numerical climate model simulations, and the effects of climate forcing on rivers.

He is an editor for the international journal Climate Research and an invited member of the Steering Committee for International Meetings on Statistical Climatology, the Surface Water Committee of the American Geophysical Union, and the Expert Groups on a) Scenarios and b) Climate Change and Water, for the UN's World Water Assessment Program. He is also a member of the Expert Advisory Board for the European Union's WATer and global CHange (WATCH) Project.

Contact: Dr Bryson Bates

CSIRO Climate Adaptation Flagship

Private Bag 5

Wembley, Western Australia 6913 AUSTRALIA

Email: Bryson.Bates@csiro.au

Best practice in climate change adaptation policy

Steve Waller

Director, Office of Climate Change Department of Environment and Conservation, Western Australia

The Western Australian Government has committed to a number of climate change policies including the development of a Climate Change Adaptation Strategy that will also address mitigation issues.

This presentation will cover some of the current climate change projects that the Department of Environment and Conservation (DEC) through the Office of Climate Change are pursuing which pave the way for the new Strategy, It will then focus on answering the question 'what could a best practice adaptation strategy look like?', followed by a discussion of how marine science more generally can support, and be supported by, future climate change policy.

Government climate change commitment – a new strategy in development

The Government has committed to taking "several immediate steps to prepare our State for the potential effects of climate change and the move toward a less-carbon intensive economy."

The Liberal Plan for Environmental Sustainability and Water Management (2008) sets out a number of these commitments, including to: "Work with industry, scientists, local government and conservation groups to develop a Climate Change Adaptation Strategy covering each major sector of Western Australian industry as well as urban planning agencies and state water and energy utilities."

It is timely to be revising and renewing the State's responses to climate change. The climate policy environment is changing rapidly with the Commonwealth Government committing to the introduction of emissions trading by 2010, and the next round of climate change international negotiations coming to a climax in Copenhagen later this year. In addition the latest climate science and projections of climate change impacts are sobering. They underline the importance of taking urgent action to both reduce greenhouse gas emissions and to adapt to the unavoidable impacts of climate change.

DEC is currently developing the framework for the Climate Change Adaptation Strategy including the design of an appropriate public consultation process. This presentation will not attempt to pre-empt that strategy development process, but will consider the 'best practice in the field'.

Current climate change projects

DEC has been active in developing various projects on climate change science, adaptation and mitigation which will pave the way for the new Strategy. These projects include:

- the Indian Ocean Climate Initiative Stage 3 (IOCI 3);
- Carbon Accounting frameworks;
- a Low Emissions Energy Development Fund (LEED);
- a longitudinal study into Western Australians' attitudes and behaviours with respect to climate change;
 and
- Climate Change in Local Government.

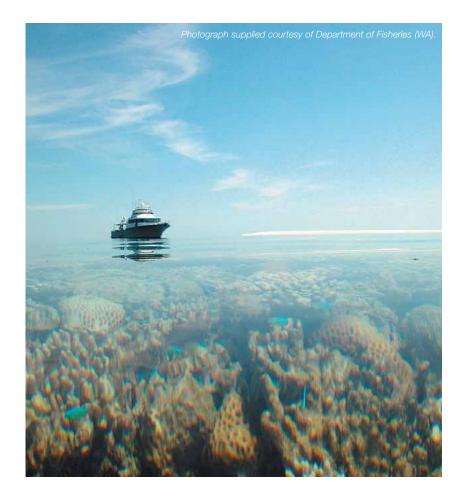
What would a best practice adaptation strategy look like?

Observations about what best practice climate change adaptation strategies could achieve will be provided. These include:

• Reflect that current thinking in this discipline is recognising it is now essential to take urgent action to reduce greenhouse gas emissions (mitigation) and to adapt to observed and future unavoidable climate change impacts. In addition there is a growing recognition that future tasks of mitigation and adaptation cannot be considered and developed in isolation but need to be integrated. While in many cases mitigation efforts can help reduce vulnerability to climate change impacts and therefore aid adaptation, there are some mitigation measures that might have perverse impacts on adaptation efforts. Similarly adaptation efforts can have either synergistic or perverse impacts on mitigation efforts. Therefore the development of mitigation and adaptation policies need to be coordinated to optimise the synergies

- where appropriate and manage or avoid the potential perverse impacts. There are two elements to climate change policy integration; the coordination of mitigation and adaptation policy and the incorporation or the 'mainstreaming' of climate change policy into policy and operational management. In future climate policies might include programs and policies that facilitate the incorporation of climate change adaptation considerations into all government activities.
- Clarify the roles for different levels of Government with regards to adaptation. Potential roles for the State Government might be in building adaptive capacity and implementing adaptation actions. The former could include identifying public communication strategies, knowledge infrastructure, advisory services, and skills training that might be needed to support adaptation efforts and establishing appropriate programs to meet those needs. Implementing adaptation actions could include delivering adaptation projects where the Government has a clear role, for example in investing in adaptation measures that are public good in nature and supporting innovation, research and development into adaptation technologies.
- Identify the needs and priorities required to develop the knowledge infrastructure needed for effective
 adaptation. This would include climate science and projections, adaptation science, and social and
 economic data needed, and the tools and resources to support risk assessments, vulnerability
 assessments, and the development of private, local and regional adaptation strategies.
- Support the implementation of integrated regional vulnerability assessments that are cross-disciplinary
 and cross-sectoral in nature and that embrace systems thinking. Such assessments could in turn
 support the development of adaptation strategies at a regional scale. Regional scale strategies could be
 favoured in the recognition that they allow regional conditions, impacts and adaptive capacities to be
 appropriately taken into account in their development.
- Develop a thorough public consultation process, which is reviewed regularly. Such a process would have a long-term timeframe, yet be flexible enough to adjust, where appropriate, to new knowledge, emerging climate science, evolving circumstances and any learnings from an adaptive management approach.
- Take advantage of the insights that a resilience approach to adaptation can provide. Resilience is based on complex systems studies, takes a dynamic view, and examines the adaptive capacity of socioecological systems together with the characteristics that can make them more resilient. It is also concerned with the implications of adaptation actions for other non-targeted elements of the system, possibly at different but linked scales from the one on which the action was focused. It emphasises the importance of preparation for surprises and system renewal, and the possibility of transformational change.





How marine science can support, and be supported by, future climate policy

The final part of this presentation will discuss some of the ways that future marine science research programs might be able to support future climate policies and programs, and how those policies and programs may in turn support marine science. Here are some observations:

Coordination

Climate change is a multi-dimensional, multi-disciplinary problem that crosses the full range of sectors and stakeholders in our State. Adapting to climate change successfully will require significant contributions from a range of science disciplines. The provision of climate change science is currently fragmented between research providers, and requires better coordination of research activities to avoid overlap, duplication and important knowledge gaps.

Coordinating the climate change science effort so that it joins up to provide a meaningful and effective framework is a key challenge for policy makers. WAMSI clearly has a role in coordination with respect to marine science. Nationally, there are a number of initiatives that have coordination roles including the National Climate Change Adaptation Facility, the National Adaptation Research Plans and Adaptation Research Networks that it is establishing. A mechanism to coordinate and promote information exchange between researchers more broadly in Western Australia is sorely needed. DEC has established an interdepartmental group to consider the direction of government sponsored climate science across State Government agencies. It is also exploring the idea of establishing a Climate Change Science Alliance, to help with Government-sponsored climate change science coordination across the State. Improved coordination will help to support the business case for the future investment in marine science.

Mainstreaming climate change into science

There is also the question about how climate change considerations are incorporated into the broader range of marine science projects and programs into the future. While there is often an acknowledgment of the importance of climate change, it is still not well embedded in strategic thinking. This needs to change; science can't continue to operate as if it was in a climate change vacuum. We need to consider how we can mainstream these climate change considerations into science research programs more generally.

Meeting stakeholder adaptation needs

There is a need for future marine climate science to meet the needs of stakeholders and marine science users. Western Australia has a head start here with the role and work of WAMSI. There is still a need however to ensure that 'Stakeholder Needs Analyses' are undertaken to inform the design of future research programs. The need to manage climate change impacts brings in a new, broad range, of stakeholders that haven't previously been heavily involved in marine science and not all of whom are science-based. In addition, marine scientists themselves have a need for reliable climate change projections to inform their research and this should be incorporated into future State and national climate change science research plans.

Making research findings accessible

The results of marine science research relevant to climate change adaptation need to be physically and intellectually accessible for the stakeholders who are likely to use them. In other words the presentation of the research and results need to be appropriate for target audiences.

System of long-term reference sites

There is a need for system of long-term monitoring reference sites to help us understand the natural variability of marine ecosystems at local and regional scales and to be able to help isolate and identify regional and global trends that are due to climate change. Such a system will assist in understanding what level of observed impacts on marine ecosystems can be attributed to climate change including the comparison of observed impacts against the projections from climate models. There will be significant implications for marine reserve design from generating this kind of knowledge. A system of reference sites would also assist in better developing our understanding of cause and effect pathways and tolerance limits for climate change impacts on species and ecosystems.

Timely responses to emerging climate science

We need to be able respond to rapidly emerging climate science in a timely manner where that may be necessary. It will be a challenge for all of us, but particularly challenging for research institutions and programs that are not designed to be nimble. Scientists have a crucial role to play in helping society understand what the important results are, which ones to act on, and when.

Similarly, longer term marine research programs need to incorporate governance and funding mechanisms that are capable of adaptive management, where research findings can have a quick feedback loop into the direction and resources of future research programs.

Steve Waller

Mr Waller is Director of the Office of Climate Change which sits within Western Australia's Department of Environment and Conservation.

His appointment in 2007 followed a 25-year career in environmental management in the resources extraction sector.

He has held professional positions in the climate change and greenhouse portfolios since 1997, most recently as the Greenhouse Opportunity Manager for Woodside Energy Limited in Perth, Western Australia.

Contributions to national and international forums have covered a range of climate change-related issues. These include renewable energy, bio energy, offsets and emissions trading and greenhouse emission monitoring, verification, management and economics.

He has been a member of the Commonwealth Government's Greenhouse Challenge Program's Partnership Committee, the International Petroleum Industries Environment and Conservation Committee and the International Emissions Trading Association as well as other industry representative bodies.

Mr Waller holds degrees in Biological and Chemical Sciences and an MBA from the Australian Graduate School of Management.

Contact: Steve Waller

Western Australian Office of Climate Change

Level 4, 168 St Georges Terrace

Perth, Western Australia 6000 AUSTRALIA

Email: steve.waller@dec.wa.gov.au



Changes in Southern Hemisphere storm tracks during the twentieth century

Jorgen S. Frederiksen¹, Carsten S. Frederiksen² and Stacey L. Osbrough¹

- 1. Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia
- 2. Centre for Australian Weather and Climate Research, Bureau of Meteorology, Docklands, Victoria, Australia



Introduction

The changes in Southern Hemisphere winter storm track modes during the 20th century have been studied based on reanalysed observations and on data from climate models incorporating anthropogenic forcings.

Storm track instability modes based on reanalyses show a dramatic reduction in growth rate post-1975. This reduction in the intensity of cyclogenesis has continued to the present time for storm track modes that cross Australia and is associated with the observed decrease in rainfall in southern Australia. We have examined the ability of a number of climate models with anthropogenic forcing including increasing greenhouse gas concentrations to replicate the changes in transient weather systems during the 20th century.

In this paper we focus on Australian models including the CSIRO Mark 3.0 and 3.5 coupled models and the ACCESS atmospheric model with prescribed sea surface temperatures (SSTs). We also consider the UKMO HadGem1 coupled model that has a similar atmospheric component to the ACCESS model. The coupled models are not able to capture the storm track changes. However, the leading storm track mode crossing Australia, using data from ACCESS model simulations with prescribed SSTs, has a structure that is remarkably similar to those based on reanalyses. Furthermore, the growth rate of the ACCESS leading storm track mode is in closer agreement with growth rates for storm track modes based on reanalyses.

Changes in the Southern Hemisphere circulation

The global Southern Hemisphere (SH) winter climates for the periods 1949-1968 and 1975-1994, using the National Centres for Environmental Prediction (NCEP) reanalyses, have been compared and there are significant differences between the two periods. Most noticeable is a reduction of about 20 per cent in the peak strength of the SH subtropical jet stream (Figure 1).

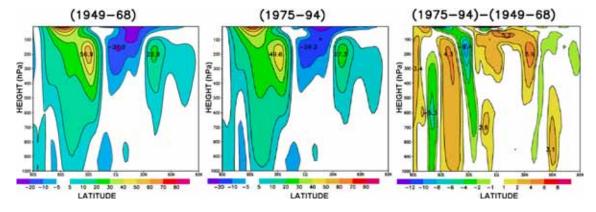


Figure 1: Vertical cross-section of the SH zonal wind (ms-1) averaged over 100E-130E longitude for the periods (left) 1949-1968, (middle) 1975-1994 and (right) their difference.

Figure 1 shows the height (in pressure units) and latitudinal cross-section of the SH zonal wind, averaged over 100E-130E longitude. In both periods, there is a maximum in the zonal wind strength in the subtropics (near 30S) at about the 200hPa pressure level. In the later period, there is a reduction of about 10ms-1 in this maximum. This is directly associated with changes in the Hadley circulation in the Southern Hemisphere. There have also been substantial changes in the Walker circulation with increased upper level wind

divergence in the eastern tropical Pacific in the latter period. The thermal structure of the SH atmosphere has also changed with a significant warming south of 30S, tending to reduce the equator-pole temperature gradient (not shown). Such changes would be expected to have a significant effect on the stability of the SH circulation and hence on the nature of the SH storms, which have a major impact on South West Western Australia (SWWA), and other modes of weather variability. In fact, the SH atmosphere has generally become less unstable in those regions associated with the generation of mid-latitude storms.

Changes in storm track modes from reanalyses

An analysis, of the impact of these observed SH winter climate changes on the nature of the dominant SH weather modes, was conducted, with particular emphasis on the storm track modes. Here, we have used the primitive equation instability model described in Frederiksen and Frederiksen (2005, 2007) to identify the dominant unstable weather modes in each period. In the earlier period, the fastest growing weather mode is a SH storm mode which affects southern Australia, and has largest impact over SWWA (Figure 2). This mode consists of a series of eastward propagating troughs (blue shading) and ridges (red shading), and is shown in the top panel of Figure 2 at a particular instance. As the troughs and ridges move eastward they amplify to reach a maximum in preferred regions.

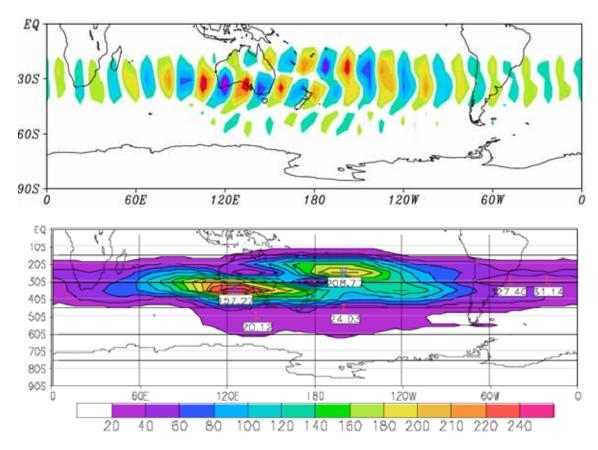


Figure 2: The fastest growing storm mode, mode 1, for the period 1949-1968. Shown in top panel are the 250 hPa troughs (blue) and ridges (red) of the streamfunction at a particular instance and in bottom panel the corresponding amplitude for the storm track. Units are relative

The bottom panel of Figure 2 shows the storm track associated with this mode and indicates that its largest impact (red shading) is over south-western Australia. By contrast, in the latter period between 1975 and 1994, the dominant SH storm mode has a different horizontal structure. In particular, this weather mode effectively bypasses SWWA and has maximum impact in the central south Pacific (not shown). There are, however, other subdominant weather modes (mode 9 in Figure 3, top panel), with a similar structure and frequency to the dominant mode from the earlier period, but their growth rates have been reduced 33 per cent or more, as shown in Table 1. This is consistent with the observed reduction in rainfall over southern Australia, and in particular, SWWA. Also, their largest impact has shifted to be over eastern Australia (Figure 3

top panel). The bottom panel of Figure 3 shows the corresponding storm track mode (mode 12) for the recent period 1997-2006. We note from Table 1 that compared with the results for 1949-1968 there has been a further reduction in the growth rate (by 37 per cent).

Storm track modes from climate models

We have examined storm track modes in Australian climate models including the CSIRO Mark 3.0 and 3.5 coupled ocean-atmosphere models and the ACCESS atmospheric model with prescribed SSTs. We have also considered the HadGem1 coupled model that has a similar atmospheric component to the ACCESS model. The top panel of Figure 4 shows mode 4, the leading storm track mode crossing southern Australia, using data from the CSIRO Mark 3.0 coupled model run with pre-industrial forcing. We note that the peak of the leading storm track mode occurs over the southern Atlantic rather than over southern Australia. The same failing occurs with other fast growing storm track modes. As seen from table 1, the correlation with

Basic State	Mode	Correlation with	Growth Rate,	Change in
		Mode 1	\mathbf{w}_{i}	w _i
1949-68 NCEP	1	1.0000	0.423 day ⁻¹	0.0%
1975-94 NCEP	9	0.9148	0.282 day ⁻¹	-33.5%
1997-2006 NCEP	12	0.8960	0.266 day ⁻¹	-37.1%
Pre Indust CSIRO 3.0	4	0.5435	0.293 day ⁻¹	-30.7%
Pre Indust HadGem1	11	0.5770	0.336 day ⁻¹	-20.6%
1980-99 HadGem1	2	0.7995	0.481 day⁻¹	+13.7%
1980-99 ACCESS	2	0.9013	0.367 day-1	-13.3%

 Table 1:
 Properties of leading storm track modes crossing southern Australia.

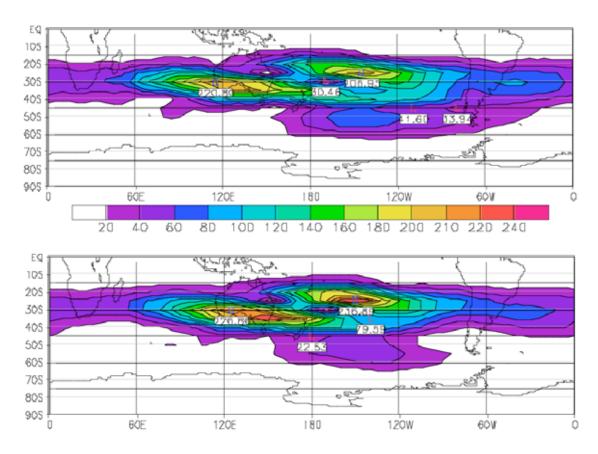


Figure 3: As in bottom panel of Figure 2 for mode 4 for 1975-1994 (top panel) and mode 12 for 1997-2006 (bottom panel).

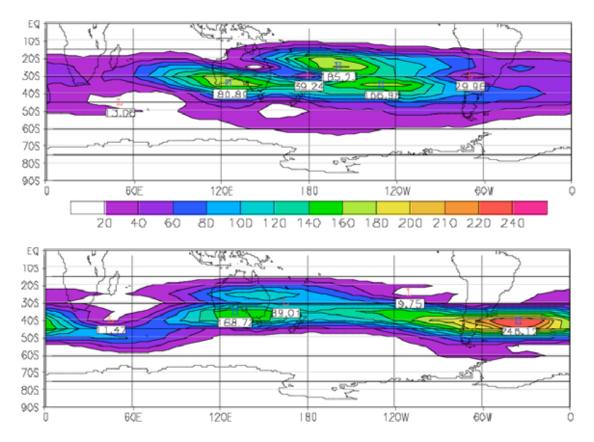


Figure 4: As in bottom panel of Figure 2 for mode 9 for CSIRO Mark 3.0 model run with pre-industrial forcing (top panel) and mode 2 for 1980-2000 with ACCESS model (bottom panel).

mode 1 for 1949-1968 is poor at 0.54 and its growth rate is too low. These deficiencies also apply to the CSIRO Mark 3.5 model. For the HadGem1 coupled model with pre-industrial forcing the structure of the storm track is again poor with maximum amplitude over the south-west Pacific. Again, correlation with mode 1 for 1949-1968 is low at 0.57 and its growth rate is low.

The bottom panel of Figure 4 shows mode 2, the fastest growing storm track mode crossing southern Australia in the ACCESS atmospheric model with prescribed SSTs for the period 1980-1999. It has a similar structure to the leading storm track modes during the second half of the twentieth century (Figures 3 and 4). From Table 1 we note that the correlation with mode 1 for 1949-1968 is 0.9, which is similar to the results for the reanalyses for the periods 1975-1994 and 1997-2006. We also see that its growth rate is reduced compared with the period 1949-1968 in the reanalyses but somewhat larger than for the later periods. Table 1 also shows the results for the HadGem1 coupled model for the period 1980-1999. We see that the correlation with mode 1 for 1949-1968 reanalyses is less than for the ACCESS model but still quite reasonable at 0.8. However, the growth rate is much too large compared with the reanalyses for the twentieth century.

Summary and conclusions

There has been approximately a 20 per cent reduction in SWWA rainfall, a 20 per cent reduction in peak jet stream strength and about 30 per cent reduction in growth rates of leading SH storm track modes crossing Australia since the mid 1970s. These changes have continued and spread to south-east Australia during the period 1997-2006. The structures of leading winter storm track modes crossing Australia are very similar during the 20th century. A primary cause of the rainfall reduction over SWWA since 1975 is the reduction in the intensity of cyclogenesis and the southward deflection of some storms. Many climate models have difficulty in capturing the detailed structure of the Southern Hemisphere circulation and transient weather systems and their changes during the 20th century. A summary of the performance of the CSIRO, UKMO and ACCESS models has been presented. The structure of the leading SH winter storm track mode crossing Australia, using data from the ACCESS AMIP run, is in very good agreement with results from reanalysed observations and its growth rate is reasonable.

A changing climate: Western Australia in focus

Acknowledgments

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Contact: Dr Jorgen Frederiksen

CSIRO

Aspendale, Victoria, AUSTRALIA Email: Jorgen.Frederiksen@csiro.au

Effect of tropical and subtropical Indian Ocean dipoles in driving precipitation around Indian Ocean rim countries

Matthew England

Professor Matthew H. England, Caroline C. Ummenhofer, Alexander Sen Gupta Climate Change Research Centre University of New South Wales

Motivation

The importance of the Indian Ocean sea surface temperature (SST) anomalies in modulating regional climate has recently received increasing recognition. Surface variability has been implicated in widespread changes to precipitation around Indian Ocean rim countries, including East Africa, India, Indonesia, and Australia. Non-uniform warming of the Indian Ocean has recently been described (e.g., Alory et al. 2007, Ihara et al. 2008) and characteristics of the dominant mode of tropical Indian Ocean variability are suggested to be changing (Abram et al. 2008). These factors highlight the need for a better understanding of the mechanisms by which Indian Ocean variability modulates regional rainfall. This has major implications for seasonal rainfall forecasting and will ultimately aid in improvements to water and agricultural management.

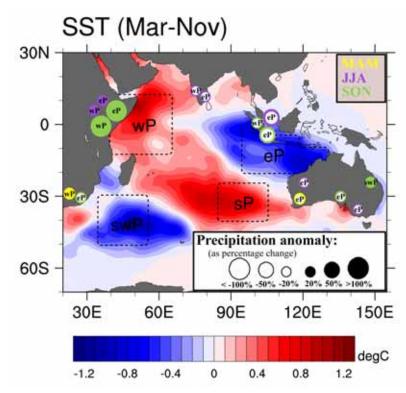


Figure 1: Schematic of Indian Ocean SST anomalies on precipitation in Indian Ocean rim countries in AGCM simulations for the March-May (MAM), June-Aug. (JJA) and Sep.-Nov. (SON) seasons. The SST anomalies (°C) are shown as the average over the March-Nov. months. Specific regions ('poles') of SST anomalies, characteristic of various tropical and subtropical Indian Ocean dipoles, are employed in the AGCM experiments, with the poles indicated by the dashed boxes. The anomalous rainfall associated with these regions of SST anomalies is shown by circles around the Indian Ocean rim countries. Filled (empty) circles denote an increase (decrease) in precipitation (as percentage change), with the size of the circle reflecting the magnitude of change and the color of the circle the season.

Results

In a series of atmospheric general circulation model experiments, the potential impact of Indian Ocean SST anomalies in modulating low- to mid-latitude precipitation around the Indian Ocean-rim countries is examined (Ummenhofer et al. 2008, 2009a,b). SST anomalies closely resembling a leading mode of Indian Ocean variability with features of both tropical and subtropical Indian Ocean dipoles induce a basin-wide reorganisation of the atmospheric circulation. This induces significant changes to precipitation distributions over the surrounding landmasses (Fig. 1).

This work quantifies the relative contribution of regional SST anomalies associated with various characteristic tropical and subtropical Indian Ocean SST poles, both individually and in combination, to these precipitation changes. The role of these poles and the associated meridional gradients are assessed in modulating the strength and position of the Walker circulation. Furthermore, the mechanisms behind the modulation of precipitation over the adjacent landmasses are investigated via changes to the large-scale circulation, the thermal properties of the atmosphere, moisture flux advection, and the strength of the Walker circulation.

Precipitation over southern and western regions of Australia is modulated by variations in the meridional temperature gradients in the eastern tropical/subtropical Indian Ocean by affecting thermal winds and moisture flux as well as baroclinicity over the region (Ummenhofer et al. 2008, 2009b). The relative importance of regional Indian Ocean SST anomalies is assessed for precipitation around Australia. Implications for seasonal forecasting in connection with the evolution of Indian Ocean SST anomalies in characteristic regions are also discussed.

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Contact: Professor Matthew England

Ph: +61-2-9385-7065 Fax: +61-2-9385-7123

Email: M.England@unsw.edu.au

Web www.maths.unsw.edu.au/~matthew CCRC Web: www.ccrc.unsw.edu.au

Caroline C. Ummenhofer, Climate Change Research Centre, University of New South Wales, Kensington NSW 2052 AUSTRALIA Email: c.ummenhofer@unsw.edu.au

Alexander Sen Gupta Climate Change Research Centre, University of New South Wales NSW 2052 AUSTRALIA

Tropical cyclones off North West Australia in a changing climate: method and validation

Stan Stroud Woodside Energy Ltd

Study driver

Woodside is interested in future return period wave heights off North West Australia (figure 1) out to 2060 for management of its offshore oil and gas producing facilities; and air temperatures as affecting its air-cooled liquefied natural gas (LNG) plants located on the coastline.

Tropical cyclones (TCs) off North West Australia control return period wave heights. Return period wave heights are derived universally using the calibrated storm wind and wave hindcast method, utilising either historical or synthetic TC tracks. Consequently, to quantify future return period wave heights, future storm tracks are required to allow modelling of the wind and wave-fields and subsequent determination of return period quantities. The use of qualitative information such as changes of storm intensity categories or storm occurrence rates does not lead to information that allows quantitative assessment required for the engineering design process, where changes in return period wave height are required.

In view of this, it was decided to run a climate model to generate future tropical cyclone storm tracks. The process involved testing the model against the historical period between 1970 and 2000.

Climate model

Future TC storm tracks were supplied by Professor Lance Leslie, for the region of interest off North West Australia, from climate model runs using the Oklahoma University (OU) suite of atmospheric (non-flux corrected) global climate models (GCMs), coupled to the MOM3 ocean circulation model, for the IPCC A1B scenario. The OU CGM includes other sub-models such as terrain, soil moisture (nine layers) and ice.

The model results were sent to Perth for analyses and comparison with historical tropical cyclone storm tracks, air temperatures, rainfall and other indicators such as shear and vorticity.

Climate model and grid details.

The OU suite of six ensemble climate models consisted of two numeric and three sets of (cloud) physics schemes. These models are most similar to those of the British Met Office GCM.

They were run on an approximate 25 km (0.2 degree) fine scale grid as required to allow tropical cyclone formation, covering a 40 degree by 40 degree region, 90–130 deg E, zero–40 deg S. Outside of this region, the grid graded by 5 per cent per grid point to a grid size if some 160 km (1.5 deg). Beyond this, the grid size was kept at 1.5 deg. Use of the variable grid allowed for two-way energy transfer.

Model spin-up and IPCC scenario

Each ensemble was spun up for 30 years to represent conditions at 1 January 1970. The 'Control' (CTRL) or present day suite of six ensembles, used the measured CO2e for the period 1970–2000, then the CO2e was held constant out to 2100. The EGHG runs used six ensembles with the measured CO2e 1970–2000. Beyond 2005 the IPCC A1B scenario CO2e levels were used. Between 2000 and 2005 the measured and IPCC A1B CO2e levels were merged so that no sharp discontinuities existed.

Data were saved each six hours at all grid points for the 12 models and at all model levels (including the soil model).

TC track extraction, and estimation of central pressures

Tropical cyclone track locations were identified for the model ensemble closest to the mean in each decade. An inverted Holland pressure field model was fitted to the grid point modelled pressures along the storm tracks, to estimate the storm central pressures. This resulted in storm tracks for the control (CTRL) and EGHG for the 1970–2060 period.

Study schedule

The above modelling was undertaken in 2006. Storm tracks were extracted in 2007 to September 2008. Storm track quality checking and subsequent tropical cyclone wave modelling were undertaken between October 2008 and January 2009. As at March 2009, the database (binary point files) are being culled and rewritten as netCDF gridded files at each six hour saved time step, at selected model layer levels.

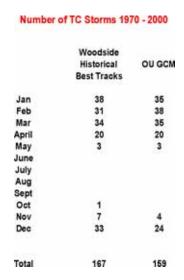
Storm numbers, control period 1970/71–1999/00 seasons

Storm numbers from the historical records and CTRL modelling (total and by month) compare remarkably well (table 1). The total number of storms by tropical cyclone season is shown in figure 2. Both the short term (two year) and longer occurrence rates show skill.

To investigate the inter-annual and inter-decadal variability, an additional case was run, but with volcanic ash removed.

Additional investigation is in progress to demonstrate that the shear increases in the future for the offshore region adjacent to the Pilbara.

At the time that this modelling was undertaken, the IPCC scenario did not account for the larger than expected atmospheric pollutants over the tropics from China and India.



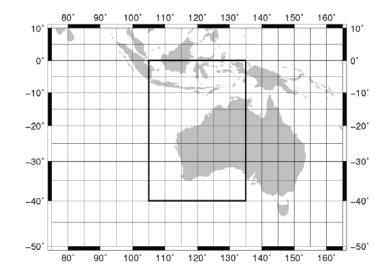


Table 1: Historical and modelled TC storm numbers entering the region 105 – 135 E, 0 – 40 S.

Figure 1: Region of interest for tropical cyclones affecting NW Australia.

Storm start positions - historical and CTRL

Storm start points, are defined at the location where the pressure on the tracks first attain a pressure of 995 hPa. Figure 3 shows start positions for historical and the modelled CTRL storms. The start positions agree well for November to May and overall, except for April where the CTRL modelled storms start slightly more to the south than the historical storms.

Storm tracks out to 2060

Figures 4 and 5 show modelled CTRL and EGHG storm tracks for the period 2000 to 2060. No significant differences are noted.

Rainfall

As a matter of interest a point of data in the Perth region was extracted. The six hourly total rainfalls for the period between 1970 and 2080 were summed on an annual basis and are compared with the Perth Bureau of Meteorology annual averages to 2008. The inter-annual variability and the trend agree without adjustment (figure 6). It is noted that the present annual rainfall decrease appears to have started about 1950.

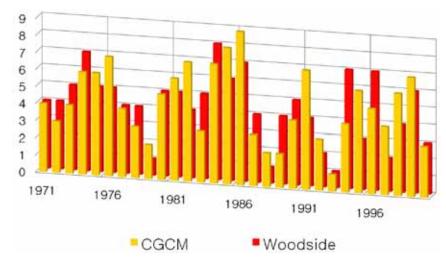


Figure 2: 2 Historical (red) and CTRL (orange) modelled storm numbers by TC season 1970/71 to 1999/2000.

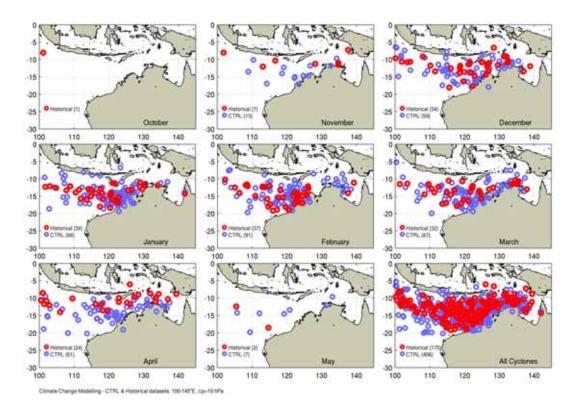


Figure 3: Storm start positions for TCs entering the region of interest, historical (red) and CTRL modelling (blue), by month and season 1970 – 2000.

Acknowledgments

The climate modelling study design and modelling, and tropical cyclone storm track extractions were undertaken by Professor Lance Leslie at Oklahoma University. Comparisons of model output with the historical records have been undertaken by Stan Stroud and Bruce Buckley.

Contact: Stan Stroud

Principal Metocean Engineer and Team Leader

Woodside Energy Ltd

GPO Box D188, Perth, Western Australia 6840 AUSTRALIA

Ph: +61 8 9348 4900

Email: STAN.STROUD@woodside.com.au

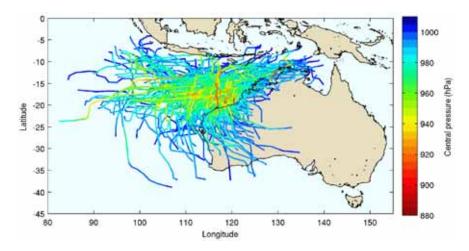


Figure 4: Modelled CTRL tropical cyclone storm tracks 2000 – 2060, for the region of interest.

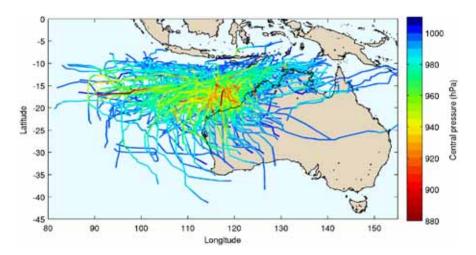


Figure 5: Modelled EGHG tropical cyclone storm tracks 2000 – 2060, for the region of interest

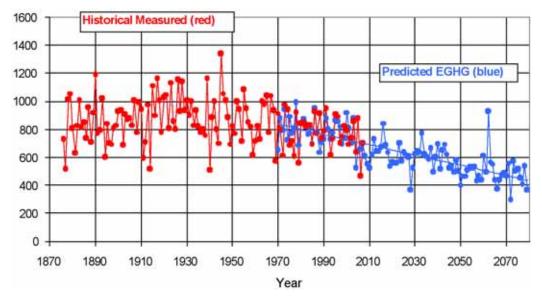


Figure 6: Measured and OU-GCM modelled IPCC A1B annual rainfall, Perth (115.87°E,-31.92°S), from the 25 km grid.



Photograph courtesy of Western Australian Museum/Clay Bryce

Climate change impacts on coastal systems in Western Australia

Charitha Pattiaratchi

School of Environmental Systems Engineering, The University of Western Australia, Nedlands, WA 6009, Australia

Coastal ecosystems and communities around the world are widely recognised to be vulnerable to rising sea levels and other climate-change impacts, as documented in the various assessment reports of the Intergovernmental Panel on Climate Change (IPCC). In this paper, I will examine two contrasting impacts on coastal systems in Western Australia: (1) impacts of sea-level rise on coastal stability and flooding; and (2) the possibility of coral bleaching on Ningaloo reef due to warming temperatures.

Charitha

South-western Australia experiences a micro-tidal range (~0.5m) and therefore small changes in mean sea level have a large influence on the coastal response and stability. Fremantle tide data have shown that the mean sea level has increased almost 20 cm at a rate of 1.54 mm per annum since 1897 (Figure 1). This represents 20 per cent of the maximum water level range at Fremantle. The rise in sea level has been attributed to thermal expansion of the oceans due to increased warming. From 1991, an acceleration of the rate of sea level rise has been observed at Fremantle, a rate of 5 mm per annum - a rate more than three times the trend over the previous 100 years. This resulted in Fremantle recording maximum sea levels in 2003 and 2004. Climate change has also been associated with an apparent increase in storminess determined from storm surge records. These changes have indicated the requirement for revision of design criteria (e.g. return periods) for the design of coastal structures and prevention of coastal flooding. Thus, similar to coastal regions around the world, Western Australia is vulnerable to climate change impacts at the shoreline arising from changes to the wind climate, frequency and magnitude of storm surges and mean sea level rise. Changes to wind fields have the potential to influence the wind wave climate and the generation of storm surges. The combined effects of an altered wind wave climate and the magnitude and frequency of storm surges together with relative sea level rise would have important implications for coastal stability and vulnerability.

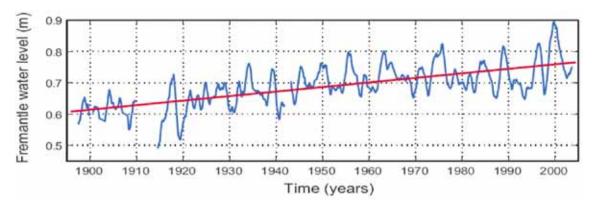


Figure 1: Time series of Fremantle sea level (one year running mean) with the linear trend of 1.54 mm per annum superimposed in red.

Ningaloo Reef is the third largest fringing coral reef in the world with a length of ~290 km extending from Red Bluff in the south to the northern reaches of the North West Cape. It is one of the few large coral reef systems located along an open ocean, especially along an eastern margin of a major ocean basin. Eastern ocean margins are generally highly productive ecosystems supporting high primary productivity and large pelagic finfish stocks, due to large scale wind-driven coastal upwelling. The exception to this rule is off the Western Australian coast where the presence of the Leeuwin current suppresses large-scale upwelling and provides an oligotrophic, warm-water environment conducive to the maintenance of coral reefs. Recent studies have shown that under strong southerly winds, particularly during the summer months, localised upwelling occurs along particular sections of the Western Australia coastline including the continental shelf region adjacent to Ningaloo Reef, thereby generating the so-called colder Ningaloo Current (Figure 2).

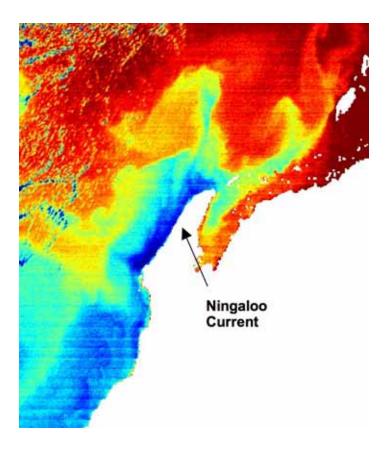


Figure 2: Sea surface temperature image obtained on 19 January 2007 after a period of sustained strong winds showing the colder water adjacent to Ningaloo reef.

Higher ocean temperatures, particularly during La Nina episodes, have resulted in mass bleaching of many of the world's coral reefs. For example, during the 1997-98 La Nina event, mass bleaching is estimated to have caused over 90 per cent coral mortality to 16 per cent of the world's coral reefs. However, extensive coral bleaching has not been observed on Ningaloo Reef even though mass bleaching events have been observed in coral reef systems located to the north of Ningaloo. In this paper, we argue that the absence of coral bleaching on Ningaloo Reef could be due to the oceanographic regime along the continental shelf which, during the summer months, is susceptible to wind-driven upwelling events. These events typically make water temperatures adjacent to the reef to be 2-3° Celsius lower than offshore waters thus 'insulating' the reef from higher temperatures. Thus wind driven upwelling has an 'insulating' effect on the reef and it is unlikely that coral bleaching due to temperature effects will occur at Ningaloo reef under a warming ocean.

Contact: Professor Charitha Pattiaratchi

Australian National Leader for

Coastal Oceanography

School of Environmental Systems Engineering

Mailstop MO 15

The University of Western Australia 35 Stirling Highway, Crawley, Western Australia 6009 AUSTRALIA

Ph: +61 8 6488 3179

Email: Pattiaratchi@sese.uwa.edu.au



Photograph courtesy of The University of Western Australia.

Projection of ocean acidification in the Australian region and its effect on the coral reefs and other marine organisms

R. J. Matear

Centre for Australian Weather and Climate Research (CAWCR). A partnership between CSIRO and the Bureau of Meteorology

Background information on ocean acidification

Our anthropogenic CO_2 emissions are increasing the CO_2 level in the atmosphere and causing an increase in oceanic CO_2 as the oceans absorb some of our emissions. Over the past decade the oceans have absorbed about 30 per cent of our emissions (McNeil et al., 2003). The oceanic uptake of anthropogenic CO_2 is good in that it is reducing global warming by reducing the atmospheric CO_2 level. However, the uptake of the CO_2 by the ocean is altering the chemistry of the oceans. As CO_2 enters the ocean it undergoes the following equilibrium reactions:

$$CO_2 + H_2O \iff H_2CO_3 \iff HCO_3^- + H^+ \iff CO_2^{2^-} + 2H^+$$
 (1)

where the addition of ${\rm CO_2}$ will increase the total carbon content of the water, alter the concentration of the carbon species (i.e. all terms in equation 1 that contain C), and alter the H^+ concentration. Throughout my talk, I will use three parameters – change in total dissolved inorganic carbon (DIC) concentration, pH, and the ${\rm CaCO_3}$ saturation state of seawater (Ω) – to describe how the oceanic uptake of ${\rm CO_2}$ is altering the ocean carbon chemistry. The following is a brief definition of these three parameters.

The DIC concentration provides a measure of the total amount of inorganic carbon dissolved in the ocean. The oceans contain a huge quantity of DIC (\approx 38,000 GtC) which dwarfs the total carbon in the atmosphere (\approx 780 GtC), terrestrial biosphere (\approx 2000 Gt C) and organic carbon in the oceans (\approx 1000 Gt C). Since preindustrial times, the DIC concentration of the surface ocean has increased by about 2.5 per cent.

The pH of seawater is defined by the H⁺ ion concentration: $pH = -log_{10}[H^+]$ or more commonly thought of as a measurement of acidity. As the ocean absorbs the CO₂, the pH will decline and the ocean will become more acidic. Ocean model simulations with an IS92a atmospheric CO₂ scenario predicts a pH drop of 0.4 units by the year 2100 and a further decline of 0.7 by the year 2300 (Caldeira and Wickett, 2003). The decline in pH over the next several centuries may result in the lowest surface ocean pH for the past 300 million years, with the possible exception of those resulting from rare, extreme events such as bolide impacts.

The Ω value defines the chemical stability of calcium carbonate in seawater. In the oceans, one generally finds two different mineral phases of calcium carbonate produced by marine biota – aragonite and calcite. It is common to present Ω values for both aragonite and calcite, and from this you would observe that $\Omega_{aragonite}$ is always less than $\Omega_{calcite}$ because aragonite is less stable than calcite in seawater. The key point in using Ω is that it provides both a measure of how stable calcium carbonate is and how much energy is required by marine biota to form calcium carbonate. With rising CO_2 , Ω will decline.

Biological impact of ocean acidification

Increasing CO_2 concentrations in the surface ocean via anthropogenic CO_2 uptake could have three potential biological effects.

First, it will increase the total carbon content of the seawater, which may directly impact the ability of marine phytoplankton to grow. A recent study suggested that increased carbon uptake by phytoplankton will occur under elevated CO_2 conditions (Riebesell et al., 2007). However, at present there is no clear consensus on how phytoplankton will respond to increasing CO_2 levels since other studies show negative, positive and no response to a CO_2 increase. It is expected that the phytoplankton response to increased CO_2 will be very species dependent.

Second, the acidification (lowering of pH) may adversely impact marine biota's metabolic processes (Raven, 2005). A decrease in environmental pH will alter the acid-base balance within the cells of marine organisms. Marine organisms regulate intercellular pH by the metabolic interconversion of acids and bases, the passive

chemical buffering of intra- and extra-cellular fluids, and the active ion transport (Walsh and Milligan, 1989). Experiments to determine the likely response of marine organisms to pH changes have explored large changes in pH (greater than a 1 unit decline) under laboratory conditions (Engel et al., 2005). Little is known on what the gradual long-term effects of pH lowering will be on marine organisms.

Third, the increase in oceanic CO_2 will decrease the surface ocean calcium carbonate saturation state (Ω) . Laboratory experiments have shown some species of corals and calcifying phytoplankton (Gattuso et al., 1998; Langdon et al., 2000) are highly sensitive to changes in Ω . Model projections with the IS92A atmospheric CO_2 scenario predicts up to a 30 per cent decline in calcification by 2100 due to a decline in Ω (Kleypas et al., 1999). Recent work suggest that high latitude oceans are particularly susceptible to a decline in Ω to a point where the surface seawater would be corrosive to calcium carbonate (McNeil and Matear, 2008; Orr et al., 2005). This extreme environmental change may pose a substantial risk to the future survival of calcifying organisms in this environment.

Summary

We have identified three mechanisms whereby the marine organisms inhabiting Australian waters may be impacted by ocean acidification. Unfortunately, we lack critical understanding to adequately address the first two mechanisms. For the third mechanism, we know that rising CO_2 levels in the ocean will reduce the ability of biological organisms to calcify with the possibility in the near future that the surface seawater will become corrosive to calcium carbonate formed by marine biota. But, it is not clear what the wider ecosystem consequences of these changes will be.

Key outstanding questions to address are:

How will marine organisms and ecosystems deal with the acidification changes projected for this century? What are the adaptive capacity of marine organisms and ecosystems to ocean acidification? Is there a clear tipping point beyond which irreversible changes to the marine ecosystems will occur? How will the biological impact of ocean acidification combine with other stresses to impact marine ecosystems?

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Contact: Dr Richard Matear

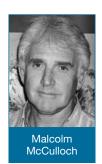
CSIRO Marine and Atmospheric

GPO Box 1538

Hobart, Tasmania 7001 AUSTRALIA Email: richard.matear@csiro.au

Coral reefs and climate change: challenges for Western Australia

Malcolm T. McCulloch Research School of Earth Sciences The Australian National University ARC Coral Reef Centre of Excellence



Coral reef ecosystems are highly sensitive to climate and environmental change. Rapidly increasing CO_2 emissions will result in a doubling of atmospheric levels by later this century. This is not only causing global warming and associated coral bleaching, but is also directly changing the chemistry of the world's surface oceans by ocean acidification. This in turn is reducing the oceans carbonate-ion concentration upon which coral calcification is dependent. Rising sea levels are also affecting coral reefs, but still at a relatively benign level relative to those anticipated from catastrophic melting of the major polar ice sheets. Local human impacts on the marine environment are also placing many reefs at risk. Land-use changes in river catchments, wetlands, and estuaries, together with increased agriculture and growing urbanisation of coastal zones, is leading to increased supplies of sediment and nutrients to many inshore coral reefs. Degradation of water quality is also invariably accompanied by other pressures from human activities, such as trawling and overfishing, which collectively can lead to a phase shift from coral to algal dominated reefs.

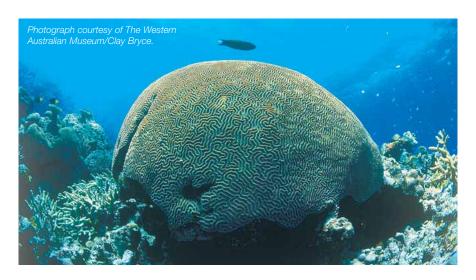
How are the coral reefs of Western Australia responding to the combined impacts of climate and local environmental change? Although quantitative data is lacking, it is presumed that the reefs of Western Australia are in relatively unaffected by local impacts. The major exceptions are Rowley Shoals, Scott, and Ashmore reefs that have been subject to extensive overfishing from our Indonesian neighbours. The near-shore reefs of the North West shelf, Ningaloo Reef, and the higher latitude Houtman Abrolhos Islands, may however still be largely unaffected from overfishing and are subject to minimal river runoff. However terrestrial inputs from tidal action and aerial deposition from desertification are largely undetermined.

The impacts of climate change are even more uncertain. Coral bleaching in 1998 was particularly severe at Scott Reef and presumably adjacent reef systems, but the potentially wider impacts of this and more recent bleaching events are poorly known. Like most of the world's reefs the effects of ocean acidification on carbonate-ion concentration and hence coral calcification are also yet to be determined. The coral reefs of Western Australia provide a unique opportunity to examine the role of global warming and ocean acidification over a large latitudinal gradient, and importantly, with the complexities of local anthropogenic affects being minimal. Such quantitative, scientifically-based data on the impacts of CO_2 induced climate change is urgently needed to constrain critical thresholds for the sustainability of coral reefs, both locally and globally.

Contact: Professor Malcolm McCulloch

The Australian National University Canberra ACT 0200, AUSTRALIA

Email: Malcolm.McCulloch@anu.edu.au



Climate change and coral reef habitat: implications for fish

Shaun Wilson
Senior Research Scientist
Marine Science Program
Department of Environment and Conservation, Western Australia



On coral reefs the most tangible impacts of climate change are on the reef building scleractinian corals. Increased frequency of warm water events, outbreaks of disease, severe tropical storms and acidification of marine waters are all attributable to climate change and have already contributed to extensive decline in corals globally. A recent synopsis of coral reef status estimates that 19 per cent of the world's coral reefs have been lost and 15 per cent of existing reef area will be seriously threatened in the next 10 to 20 years (Wilkinson 2008). Extensive coral loss leads to shifts in the composition of benthic communities and, in some circumstances, phase shifts to algal dominated communities. As reef fauna are often closely associated with habitat any change in existing conditions will ultimately have an impact on their distribution and abundance patterns.

Perhaps the most widely studied reef associated fauna are the fishes. This group has important economical value to both tourist and fishery industries, while some species, such as the herbivores, have key functional roles within the reef system. A meta-analysis of 17 studies that monitored fish abundance and coral cover, both before and after habitat disturbances that resulted in >10 per cent coral decline, was used to assess fish response to coral loss at species and functional levels (Wilson et al. 2006). Declines in abundance of fish were observed primarily among those species that either feed upon, or shelter within, live coral (Fig. 1). In contrast, abundance of species that feed on the epilithic algal matrix (EAM), such as the parrotfish (F. Scaridae) and surgeonfish (F. Acanthuridae), tended to increase. However, within this group the response was highly variable, and there were no species that consistently increased in abundance after habitat disturbance.

Even among the obligate coral feeding fish there is considerable variation in the extent of population decline in response to coral loss. Variation in response to disturbance can be partially explained by differences in feeding specialisation among fish. For example, the Chevron butterflyfish (*Chaetodon trifascialis*), feed almost exclusively on a single coral species, whilst others like the melon butterflyfish (*Chaetodon trifasciatus*) feed on >50 corals species. The highly specialised corallivores consistently decline in abundance and are the most severely affected by coral loss, yet abundance of those species with a generalised coral diet may be unaffected (Pratchett et al. 2008). Similarly, abundance of fish species that inhabit a certain type or species of coral are more likely to decline in abundance than those that shelter within a range of coral types and habitats (Munday 2004, Wilson et al. 2008a). It is these highly specialised coral dependant species that are at the greatest risk of local extinction due to climate change.

It is also notable that abundance of some species with no apparent reliance on live coral can decline following coral loss. This may relate to the type of disturbance. For example, when coral mortality is caused by bleaching the coral skeleton remains intact and can contribute to the structural complexity of the reef for several years after the bleaching event. Conversely, tropical storms can cause both high coral mortality and loss of structural complexity. Consequently storms can have a much greater impact on the fish community than bleaching, as many reef fish are reliant on structural complexity created by coral skeletons for shelter. However, erosion and collapse of skeletons following bleaching events will result in a broader impact to fish communities. Thus, although the immediate effect of coral bleaching is restricted to the few fish species that feed or shelter on coral, the number of species affected over time will increase as reef complexity is lost (Graham et al. 2006).

Importantly, a loss of structural complexity will have its greatest impact on small fish. This includes small bodied species and juveniles of large species. A comparison of the size distribution of fish before and after coral bleaching events in the Seychelles and Fiji demonstrated that the total number of small fish declined several years after bleaching, when the structural complexity of the reef had collapsed (Graham et al. 2007, Wilson et al. 2008b). This has serious implications for reef recovery and reef fisheries, as many species targeted by fishers, or with critical functional roles, recruit directly to reefs. If juvenile abundance of these species declines due to loss of structural complexity, replenishment of these stocks may be impaired (Graham et al. 2007). Furthermore, it is apparent that many reef fish recruit directly to live coral, even when the adults do not feed or shelter within coral (Jones et al. 2004, Feary et al. 2007). It is difficult to tease apart the relative

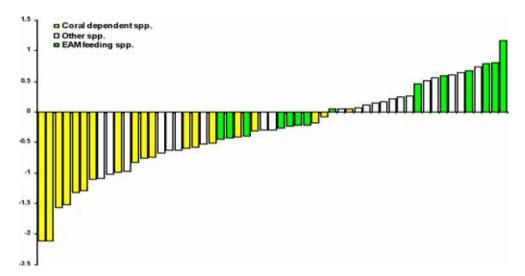


Figure 1: Response of 55 fish species to coral decline. Response is calculated as the change in fish abundance divided by the change in coral cover and standardised by survey area. Each response is the mean value calculated from four or more independent studies. EAM species includes herbivores and detritivores. Figure modified from Wilson et al. 2006.

importance of live coral and structural complexity loss on recruitment of juvenile fish; however it is clear that both processes will have a detrimental effect on abundance of juvenile fish and thus on future fish stocks.

Based on predicted changes to habitat composition and structure, the long term effects of climate change on coral reef fish will be a shift towards communities dominated by species currently considered as diet or habitat generalists, and a decline in specialised coral feeders and dwellers. A loss of structural complexity and poor recruitment associated with loss of juvenile habitat will expand the impact of climate change to a broader range of species and could ultimately reduce the diversity of reef fish assemblages.

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Contact: Dr Shaun Wilson

Tropical Marine Scientist Marine Science Program

Department of Environment and Conservation

Locked Bag 104

Bentley Delivery Centre, Western Australia 6983 AUSTRALIA

Ph: +61 8 9219 9806

Email: shaun.wilson@dec.wa.gov.au

Historical perspectives from corals on a changing climate

Janice M. Lough
Australian Institute of Marine Science

Significant coral reef ecosystems occur along Australia's tropical west and east coasts.

These coastal oceans have already experienced significant warming as a regional consequence of global climate change (Lough 2008a). Although global warming has been and is projected to be greater at high compared to low latitudes and greater in continental interiors compared to the oceans, shallow-water tropical coral reef ecosystems are already showing responses to the relatively modest warming observed to date. Evidence from the Great Barrier Reef (GBR) along the east coast demonstrates both the sensitivity and vulnerability of the many components that make up coral reef ecosystems to a changing climate (Johnson and Marshall 2007).

Warmer water temperatures have already increased the frequency of mass coral bleaching events (where the coral animals lose their symbiotic algae) and are also associated with more outbreaks of coral diseases. Weakening of the coral reef structure will be a more insidious effect of changing ocean chemistry as the oceans continue to absorb part of the extra carbon dioxide humans are injecting into the atmosphere. More intense tropical cyclones will increase localised destruction of reefs and more extreme rainfall will result in more low salinity waters affecting coral reefs (Lough 2008b). Changes in ocean circulation patterns, although poorly constrained at present, will significantly affect the connectivity of reefs and the dynamics of larval supplies (Monday et al., 2009). This is likely to be of particular significance for the more widely scattered reefs of Australia's west coast compared to the GBR.

Understanding past climate and environmental variability is fundamental to understanding their causes and for detecting the nature and significance of current changes. Instrumental observations of coral reef environments are relatively short for such purposes. Fortunately, coral reefs contain their own history books



Figure 1: Large Porites bommie on the Great Barrier Reef (Photo credit: Eric Matson, AIMS).



Figure 2: X-ray positive print of coral core collected by AIMS in 2008 from Tantabiddi on the Ningaloo Reef tract showing annual density bands.

with some massive corals growing to be several metres in height (Figure 1) and containing annual bands similar to tree rings. These bands are revealed when slices of coral are X-rayed (Figure 2) and provide the chronological basis for obtaining a range of proxy climate and environmental records from the corals.

There are no perfect sources of proxy climate and environmental information, each record (whether from tree rings, ice cores or corals) is biased by error terms that are unrelated to environmental conditions (Jones et al. 2009). One way to reduce these uncertainties in reconstructing the past is to combine records from multiple samples (replication). This approach has allowed the development of a robust reconstruction of riverflow/rainfall onto the GBR back to the early 17th century using luminescent lines in nearshore corals (Figure 3; Lough 2007). This reconstruction shows that although average rainfall does not appear to have changed over past centuries, there has been a recent increase in the intensity of extremes. Similarly, an analysis of multiple coral growth records has provided evidence of a recent and rapid slowing of growth rates on the GBR (De'ath et al., 2009). Although the exact causes of this decline, which appears to be unprecedented in at least the past 400 years, are not known it is a sign of a changing environment for coral growth that may well be linked to both increased thermal stress and ocean acidification.

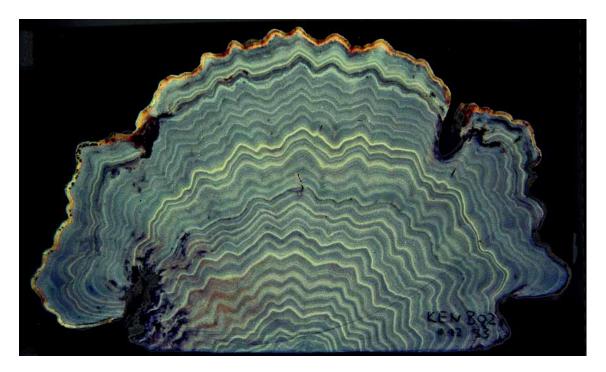


Figure 3: Coral slice from northern Great Barrier Reef under UV light showing luminescent lines which record past river flood events.

A variety of records obtained from long-lived massive corals, extending over the past several centuries, have provided the historical perspectives necessary to determine the unusual nature of recent changes on the GBR. Obtaining similar historical perspectives from massive corals of Western Australian corals reefs is a current focus of AlMS' research. Several coral cores were collected from Thevenard, Tantabidii and Bundeggi in October 2008 and preliminary processing is underway (Figures 2 and 4). Multiple coral cores from a range of reefs will, however, be necessary to build a history of Western Australian marine climate changes comparable to that of the east coast.



Figure 4: Coral slice from Bundeggi on the Ningaloo Reef tract (collected by AIMS in 2008) under UV light.

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Contact: Dr Janice M. Lough

Australian Institute of Marine Science (AIMS) PMB 3, Townsville MC, Queensland, AUSTRALIA

Email: j.lough@aims.gov.au

www.aims.gov.au



Photograph courtesy of Western Australian Museum/Clay Bryce.

Physical environmental changes off the Western Australian coasts and the potential impacts on marine ecosystems

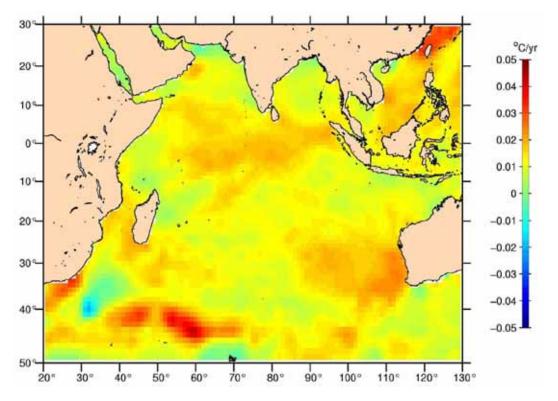
Dr Ming Feng

CSIRO Marine and Atmospheric Research

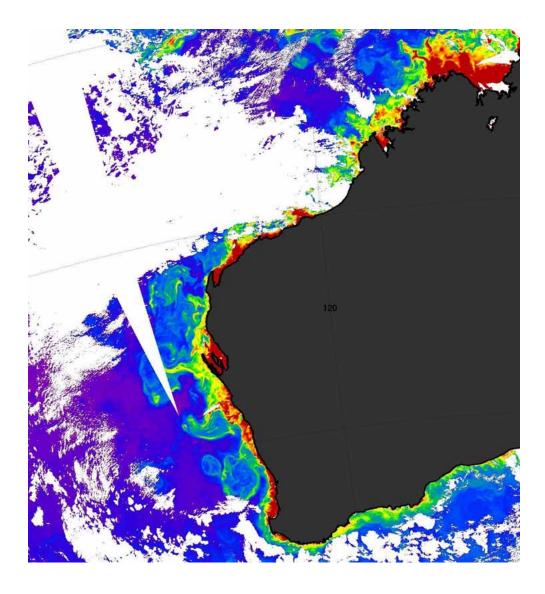
Ocean circulation off the west coast of Australia is dominated by the anomalous, poleward-flowing eastern boundary current, the Leeuwin Current. Interannual and decadal variations of the Leeuwin Current, as well as the Indonesian Throughflow off the north-west coast of Australia, are to a large extent a response to the large scale climate variability of the Indo-Pacific Ocean. The Leeuwin Current is strong during the La Niña years when the trade winds in the Pacific are strengthened, while it is weak during the El Niño years when the trade winds are weakened.

The Leeuwin Current has a profound influence on marine ecosystems off the Western Australian coast. The existence of the Leeuwin Current deepens the thermocline and nitracline off the west coast and therefore suppresses upwelling and productivity on the continental shelf off Western Australia. However, there are relatively large invertebrate populations off the coast. The Leeuwin Current is also responsible for the existence of coral reefs as far south as 29°S and the presence of tropical species along the west and south coasts. The Leeuwin Current and the mesoscale eddies are important in alongshore connectivity and cross-shelf exchanges off the west coast.

The long term changes in the tropical oceans may also influence the marine environments off the Western Australian coasts. The weakening trade winds in the Pacific since the 1970s have induced shallow thermocline (nitracline) depth anomalies off the north-west to west coasts. A global numerical model simulation suggests that the transport of the Leeuwin Current has reduced. Research also shows that the strength of the Indonesian Throughflow may have weakened since 1970s. Shallow nitracline implies higher primary production off the west coast, especially between Ningaloo Reef and Shark Bay, where episodic upwelling during the summer season is important for the marine ecosystem. A weakened Leeuwin Current may imply reduced alongshore connectivity and cross-shelf exchange.



From Pearce and Feng (2007): Warming trends in the Indian Ocean since 1950.



In recent decades an increased warming rate of SST has been observed in the tropical Indian Ocean and in the Leeuwin Current region off the west coast of Australia. It has also been shown that there are seasonal variations in the warming trend off the west coast of Australia, with most of the temperature increase occurring in the austral autumn-winter while little or no increase in the austral spring-summer. The increase in ocean temperature and shift in seasonal cycle of the physical environment may also influence the biological activities off the coast.

The long term changes in the Southern Ocean has induced a poleward shift of the frontal structures off the south-west coast, as well as the reduction of winter storm activity off the coast, resulting in the reduction of early winter rainfall. The changes in the Southern Ocean may have affected the wave climate off the coasts of Western Australia, which needs further examination using numerical models.

Marine ecosystems and fisheries recruitments off the coasts are sensitive to the changes of the physical environment, especially the Leeuwin Current. In order to improve the ability to manage the marine ecosystem off the west coast of Australia, climate model results are being downscaled onto the continental shelves in WAMSI, which will be used to examine the changes of the physical environment in the Leeuwin Current system under the future climate.

Contact: Dr Ming Feng

CSIRO Research Scientist

Private Bag 5

Wembley, Western Australia 6913 AUSTRALIA

Ph: +61 8 9333 6512 Email: Ming.feng@csiro.au

The effect of climate change on fisheries in Western Australia

Nick Caputi and Rod Lenanton

Western Australian Fisheries and Marine Research Laboratories Department of Fisheries, Western Australia



One of the areas of greatest increase in surface sea temperatures (SST) (0.02°C per year) in the Indian Ocean over the last 50 years occurs off the lower west coast of Australia; an area dominated by the Leeuwin Current. Water temperature trends at a number of coastal sites since the early 1970s: two rock lobster puerulus (post larval stage) monitoring sites in shallow water (<5m); four sites from a monitoring program onboard rock lobster vessels that provide bottom water temperature (<36 m); an environmental monitoring site at Rottnest (0-50m depth) and two global SST datasets show that there was a strong seasonal variation in the historic increases in temperature off the lower west coast of Australia with most of the increases (0.02-0.035°C per year) focused only on four to six months over the austral autumn-winter with little or no increase (<0.01°C per year) apparent in the austral spring-summer period. These increases are also apparent after taking into account the interannual variation in the strength of the Leeuwin Current. The warming trend results in a change to the seasonal temperature cycle over the decades with a delay in the peak in the temperature cycle during autumn between the 1950s and 2000s of about 10-20 days. A delay in the timing of the minimum temperature is also apparent at Rottnest from August-September to October.

There has also been a weakening of westerly winds in winter and an increase in the frequency of El Niño events that affects the strength of the Leeuwin Current. The long-term trend on the strength of the Leeuwin Current based on modelling data indicates a weakening trend. The strength of the Leeuwin Current has been identified as a key factor associated with changing abundance of a number of key invertebrate and scalefish species harvested by on-shelf commercial fisheries off the Western Australian coast. Therefore any trends in the Leeuwin Current can have significant impact on a number of commercial and recreational fisheries in Western Australia.



The western rock lobster fishery is the only species where larvae are primarily distributed in the area of the influence of the Leeuwin Current and its offshore eddies. It has a long time series of about 40 years of biological data which makes it useful to examine trends that may be affected by changing climate patterns. Environmental factors, such as the Leeuwin Current and westerly winds in late winter/spring, significantly affect puerulus settlement of the western rock lobster fishery of Western Australia. Increasing water temperatures over 30-35 years may have resulted in a decrease in size at maturity and size of migrating lobsters from shallow to deep water, an increase in abundance of undersize and legal size lobsters in deep water relative to shallow water and a shift in catch to deep water. The size of the migrating lobsters is related to the water temperature about the time of puerulus settlement (about four years previously). The climate change effects may also influencepuerulus settlement, catchability, females moulting from setose to non-setose, timing of moults and peak catch rates. Climate change models project that the warming trend will continue so these biological trends may continue. The changes may have negative (increasing frequency of El Niño events) or positive (increasing water temperature) implications on the fishery.

For other species, the Leeuwin Current is a significant factor affecting recruitment but other factors also appear to affect the abundance. The strength of the Leeuwin Current appears to have a positive relationship for Shark Bay king prawns and whitebait, but a negative relationship with scallops in Shark Bay and Abrolhos, west coast Australian salmon, south coast pilchards and tailor. Tailor recruitment was positively correlated with salinity, which is believed to be influenced by higher on-shelf evaporation in years of weak Leeuwin Current, together with higher salinity waters associated with the on-shelf northward flowing Capes Current. In years of stronger Leeuwin Current transport on the south coast, there is a greater recruitment and settlement of juvenile Australian herring east of the Great Australian Bight, while in years of weaker current, there was a stronger pulse of juveniles collected from the western Bight nursery areas. While dhufish recruitment also appears to be positively influenced by the strength of the Capes Current which flows northward primarily in the summer period, it is also positively correlated with salinity. Thus the documented trend of increasing salinity in waters off the Western Australian coast during the last 50 years may also have contributed to the changing abundance of a number of scalefish species harvested by on-shelf fisheries. The identification of climate change effects on the environmental factors that affect fisheries means that these changes need to be taken into account in the stock assessments, and ultimately the management of these fisheries.

Contact: Dr Nick Caputi

Supervising Scientist (Invertebrates)

Western Australian Fisheries and Marine Research Laboratories

Department of Fisheries PO Box 20 North Beach,

Western Australia 6920 AUSTRALIA

Ph: +61 8 9203 0165 Fax: +61 8 9203 0199 Mob: 0417 920 451

Email: Nick.Caputi@fish.wa.gov.au

Climate change effects on kelp forest ecosystems

Russ Babcock

Senior Principal Research Scientist CSIRO Marine and Atmospheric Research

Mechanisms through which climate change may affect coastal marine ecosystems in temperate Australia are numerous, including temperature, waves and storms, solar radiation, terrestrial runoff and pH. These physical factors interact with each other and with the life history and ecology of marine ecosystems making prediction of the ecological effects of climate change a challenging task.

Temperature is a principal shaper of the abundance and distribution of coastal marine life such as intertidal fauna and seaweeds, kelp on subtidal reefs and seagrasses. Fluctuations in species abundances and community composition have been linked to variations in temperature while range shifts associated with ocean warming are documented from other temperate coastal ecosystems. Direct evidence of range shifts of coastal benthic species in Australia is still rare, probably reflecting the scarcity of data from Australia, but there is indirect evidence that climate change has already influenced coastal marine life in Australia including giant kelp and other brown algae in Tasmania.

Temperature may work in synergy with changes in nutrients to affect marine algae. The giant kelp *Macrocystis* is particularly sensitive to rising temperatures and reduced nutrients, partly due to its position in the water column, and partly due to its limited nitrate storage capacity.



Changes to kelp forests can be caused indirectly by temperature change, such as where larvae of warm water urchin species may be able to colonize new areas as temperature rises. In Tasmania large areas of kelp forest have now been converted into barren rock habitats following warming that has allowed the urchin *Centrostephanus* to colonise Tasmanian shores. Similar range shifts in urchin populations have been documented in Japan.

Storms also cause significant damage to temperate ecosystems, for example in kelp forests, by the removal of habitat forming kelps and associated fauna and as with coral reefs there is the potential for these storms to produce synergistic effects in combination with other environmental factors that are likely to occur as part of global climate change. Marine animal and plant communities are structured by wave exposure and current velocity and species tolerant of high energy hydrodynamic forces dominate at high wave exposed sites. An increase in the size of waves and the frequency of storms with climate change will mimic current spatial variation in wave exposure and may result in a significant reduction in algal and seagrass production or a shift in community composition in areas that are affected. For example, the large fucoid alga *Carpophyllum flexuosum* is characteristic of calm conditions and is now common in areas of north eastern New Zealand where it was once virtually absent. This range expansion coincides with a significant decrease in storm frequency and intensity in this part of New Zealand over the past 30 years related to decadal scale climate variation.

Intertidal and subtidal algae and seagrasses will generally be susceptible to changes in solar irradiance. Upper depth limits of many species in these groups may deepen or grow shallower with increased or decreased levels of UVR respectively. Early life stages may be may be more susceptible to UVR than mature plants, thus regulating depth limits of adults. For example, the upper depth limit of some kelp species is determined by susceptibility of their zoospores to UVR or early post-settlement stages (gametophytes or embryonic sporophytes) to PAR. Plants produce UV-absorbing compounds found predominantly in the epidermis and there is some capacity for adaptation in certain species. Levels of UVR blocking pigment in certain tropical seagrasses increase when plants are grown at higher irradiance.

 ${\rm CO_2}$ and pH levels in seawater have been shown to affect the growth of kelps, but these effects may be highly species specific, with positive responses in some species and negative responses in others. The potential impacts of ${\rm CO_2}$ changes on marine ecosystems are further complicated by the fact that the nutritional qualities of kelps may be altered by ${\rm CO_2}$ and UV therefore there is significant potential for flow-on trophic effects to other parts of the ecosystem.

Light penetration may be affected by runoff from land and is an important factor limiting the distribution of marine macroalgae, both in Australia and elsewhere. Changes in turbidity associated with climate related changes in rainfall may degrade kelp communities by generally decreasing the light penetration and depth ranges of macroalgal species. The ability of kelp to compete with algal turfs may be reduced by coastal runoff turfs may benefit from the interaction between sediment and nutrients. Kelp forests may also be affected indirectly by terrestrial runoff. Where populations of grazing urchins were killed by a freshwater pulse, kelp forests rapidly re-colonised the affected reefs. However, the re-establishment of urchin barrens was almost equally rapid. Recruitment of grazers such as urchins or abalone is reduced by sediment or sedimentation, probably resulting in a longer-term reduction in grazing pressure that can have large-scale effects of the structure of kelp forests.

In Western Australia kelp forests are an important part of many coastal habitats, providing the foundations of a highly productive ecosystem. The task of predicting how they will be affected by climate change provides and illustration of the levels of complexity and the current uncertainty around these predictions. The main kelp in the ecosystem, *Ecklonia radiata*, may grow more quickly with increased temperatures, but in higher temperature environments kelp forests appear to be less able to recover after disturbances. Changes in weather patterns may interact temperature effects. Increased storminess as a result of climate change may result in an accelerated decline in kelp forest density and the range of *Ecklonia* because of higher rates of kelp forest disturbance. Predictions of changes in wave climate around South West Western Australia are currently uncertain. Other global climate models predict an increase in production in south west Western Australia with further predicted flow-ons to increased *Ecklonia* productivity. Human systems may find it difficult to adapt to climate change without the ability to predict how systems are likely to change.

Contact: Dr Russ Babcock

Senior principal research scientist, CSIRO

Private Bag 5

Wembley, Western Australia 6913 AUSTRALIA

Ph: +61 8 9333 6200 Email: Russ.Babcock@csiro.au

Climate change and biodiversity: complexity and uncertainty

Colin Yates* and Richard McKellar

Science Division

Department of Environment and Conservation, Western Australia

Managing climate change impacts on biodiversity values such as endangered species and uncommon ecosystems is challenging. Biological systems, from individuals to ecosystems, generally respond to environmental changes in a non-linear fashion. Climate change adds a further degree of complexity, especially given its pervasive and fundamental influence on biological and ecological processes. The additional effects of climate change will also exacerbate many current stressors, such as fire, as well as causing unprecedented, additional stress in its own right.

Western Australia's Department of Environment and Conservation (DEC) is responsible for managing biodiversity values in some of Australia's most biologically rich areas and some of its most remote regions. That some regions are only now being surveyed indicates the challenges of identifying priorities for climate vulnerability research, and the management challenges such as identifying species and communities which should be listed and which should receive priority management. DEC's research and biodiversity management staff have developed a research framework that acknowledges complexity and sparse knowledge but defines research projects and outcomes which are relevant to management priorities. The utility of this approach will be demonstrated through the findings of recent research undertaken as part of a collaboration with the South African National Biodiversity Institute.

* Presenting author

Contact: Dr Colin Yates

Manager Biodiversity and Climate Change

Science Division, Department of Environment and Conservation, Western Australia

17 Dick Perry Avenue, Technology Park, Western Precinct

Kensinston, Western Australia 6151 AUSTRALIA

Ph: + 61 8 9334 0489

Email: colin.yates@dec.wa.gov.au



Photograph courtesy of the Department of Environment and Conservation, Western Australia.

Marine birds as bio-indicators of changes in ocean climate off Western Australia

J.N. Dunlop¹ and C.A. Surman²

- 1. Conservation Council of Western Australia
- 2. Halfmoon Biosciences, Denmark

Seabirds by definition are marine animals. They are particularly useful as bio-indicators of trophic conditions within marine ecosystems because:

- Most are higher order predators near the apex of marine food-chains and therefore integrate the biophysical processes operating in those ecosystems.
- They are **colonial nesters** (mostly on islands), predictable in location and time facilitating the repeated sampling necessary for monitoring programs.
- They are **central-place foragers**, when breeding, with different species having specific foraging ranges. This provides opportunities to monitor changes on a range of spatial scales from 10¹ to 10⁴ km².
- Different species occupy a range of marine ecosystems from estuarine to coastal, continental shelf to oceanic. Information of changes in different marine ecosystems can therefore be monitored from one focal location.
- The high energy demands associated with rearing young lead to marked variations in reproductive output. Breeding performance is a robust indicator of prevailing, within-season, oceanographic and trophic conditions.



- Pelagic seabirds have conservative life histories, e.g. strongly philopatric, long-lived delayed maturity, low capacity for increase and rest years. Changes in population size and/or distribution reflect trends in marine ecosystems and not short-term spikes.
- A curious mixture of tropical and temperate cool-water species share breeding islands off central and South West Western Australia due to the presence of the Leeuwin Current. Changes in seabird community composition and structure are potential indicator of shifts in ocean climate.
- They are **visible and 'popular' subjects for observation** increasing the potential for participation in monitoring programs.
- There is, for central west and South West Western Australia, a useful historical record of breeding distribution dating back to the colonial period.

Significant changes have been observed in the distribution and abundance of at least eight tropical seabird species populations off south-western Australia since 1900, south of the Houtman Abrolhos Islands. The observed changes have involved a southward shift in breeding distribution or the rapid growth of colonies located on or beyond their previous limits. The rate of change appears to have accelerated over the last three decades of the 20th century.

A study of one 'frontier colony' that encompassed its entire establishment period was used as a framework for a 'demographic transition model' extrapolated to other frontier colonies. A wide range of historical observations together with more detailed recent studies have been brought together to propose a general hypothesis to explain the observed changes in tropical seabird population dynamics in the region. The increased frequency of the *El Nino* and its negative impact on food availability appears to have been a major driver of the population dynamics in tropical pelagic species in the region.

Since 2000 however the relationship between the ENSO, the Leeuwin Current and breeding success in the tropical pelagic seabird species has broken down. Increasing years of poor breeding performance (particularly at the Abrolhos) are being recorded outside *El Nino* periods. This has been accompanied by a significant seasonal delay in the onset of breeding in the four tropical pelagic tern species. Based on our seabird observations we postulate that a regime shift has occurred in offshore and oceanic planktonic foodchains off central Western Australia in recent years.

Contact: Dr J.N. Dunlop

Biodiversity Conservation Officer

Conservation Council of Western Australia

2 Delhi Street

West Perth, Western Australia 6005 AUSTRALIA

Ph: +61 8 94207266 Fax: + 61 8 94207273 Email: tern@git.com.au www.conservationwa.asn.au



Photograph supplied courtesy of CSIRO

Improved climate data and monitoring for Western Australia to support the understanding of past, present and future climate

Marco Marinelli 1,2,

Karl Braganza¹, Dean Collins¹, David Jones¹, Catherine Ganter^{1,3}, Pandora Hope³, Glenn Cook²

- 1. National Climate Centre, Bureau of Meteorology, Melbourne 3001
- 2. West Australian Regional Office, Bureau of Meteorology, Perth, 6872
- 3. CAWCR, Bureau of Meteorology, Melbourne 3001

Recent, observed climate change in Western Australia has been well documented. Specifically, significant rainfall declines have occurred in South West Western Australia during autumn and winter since the mid 1970s. In the North West of the state, significant increases in summertime rainfall have more recently been observed, with changes in the South West. Climate change in Western Australia is still very much an area of active research, particularly changes in the North West.

An important component of the third stage of IOCI will be the improvement of historic climate data for Western Australia. The study regions for IOCI 3 are characterised by diverse climates and often sparse meteorological networks. In addition, these networks have undergone large changes over the past century (for example a marked expansion during the early and mid 20th century). Significant effort is required to develop datasets that can form a sound basis for analyses of observations (e.g., trend and change point detection), model validation, adaptation studies and downscaling.

The National Climate Centre (NCC), at the Bureau of Meteorology, plans to prepare a range of improved climate datasets for Western Australia. These include high-quality daily rainfall data, extended high-quality temperature data, surface solar-radiation and cloud data and tropical cyclone data. These datasets will be developed with the specific aim of supporting IOCI 3 research, and will include sector relevant climatologies and trend analyses.

The NCC plans to apply rigorous scientific methods to the development and extension of these climate datasets. In particular, records will be analysed to remove non-climate inhomogeneities. Work has begun on the improvement of daily rainfall records that extend back to 1900. High quality daily rainfall observations are essential for properly characterising climate change at finer spatial and temporal scales, such as for the analysis of streamflow or rainfall frequency distributions. Such observations are also an important component of downscaling techniques (that have been developed as part of IOCI Stages 1 and 2) aimed at predicting future rainfall changes. Special focus will be given to the North West of Western Australia, where currently there is not a single station that contributes to the NCC, daily, high-quality rainfall network.

Contact: Dr Marco Marinelli

Bureau of Meteorology

PO Box 1370 West Perth, Western Australia 6872 AUSTRALIA

Ph: +61 8 9263 2214 Email: M.Marinelli@bom.gov.au

A cloud climatology for Western Australia

Mervyn Lynch¹, Helen Chedzey² and W Paul Menzel²

- 1. University of Wisconsin, Madison, Wisconsin, USA
- 2. Curtin University of Technology, Perth, Western Australia

The frequency of occurrence of upper tropospheric clouds has been extracted from NOAA/HIRS polar orbiting satellite data from 1979 onwards using CO_2 slicing (Wylie et al, 2005) to infer cloud amount and height. A regional study over Western Australia has been compared with decadal rainfall from the 1980s through the 1990s.

HIRS cloud observations since the early 1980s

Since 1979, High Resolution Infrared Sounder (HIRS) measurements have found clouds most frequently in two locations; (1) the ITCZ in the deep tropics where trade winds converge and (2) the middle to high latitude storm belts where low pressure systems and their fronts occur. Figure 1 (left) shows the global average of the frequency of detection for all clouds found in HIRS data since 1979. The decadal average cloud cover has not changed appreciably from the 1980s to the 1990s. Figure 1 (right) shows that the globally averaged frequency of cloud detection (excluding the poles where cloud detection is less certain) has stayed relatively constant at 75 per cent; there are seasonal fluctuations but no general trends. High clouds in the upper troposphere (above 6 km) are found in roughly one third of the HIRS measurements; a small increasing trend of ~ 2 per cent per decade is evident representing a modest increase of thermally trapping high thin ice clouds that are possibly contributing to global warming.

The time series reported here were taken from the NOAA satellites in the 2 am/pm orbit; data gaps in the 8 am/pm orbit precluded their inclusion. Measurements were adjusted for orbit drift and the increase in atmospheric CO_2 (Wylie et al, 2005). Anomalous sensors were removed from the data record; subsequent reprocessing of the HIRS data is attempting to account for sensor to sensor differences in spectral response functions.

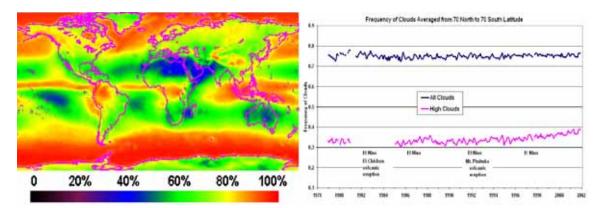


Figure 1: (left) Frequency of all clouds found in HIRS data since 1979. (right) The monthly average frequency of clouds and high clouds (above 6 km) from 70 S to 70 N from 1979 to 2002.

Regional results for Western Australia

The importance of rain bands and their location over population and agricultural centres has prompted a regional study into decadal changes. The two data sets used in the Western Australian regional study were the HIRS cloud frequency data recorded between 1985 and 2001 and the Global Precipitation Climatology Project (GPCP) data (Adler et al., 2003) for the matching time period. The GPCP Version 2 Combined Precipitation Data set is the amalgam of data from over 6000 rain gauge stations, sounding observations and satellite measurements. Total cloud cover over Western Australia is found to be 58 per cent, well below the global average. Earlier work has suggested that rain is primarily associated with thicker mid- to upper-level clouds (effective emissivity greater than 75 per cent and cloud top pressure less than 700 hPa). The average percentage of occurrence of this type of cloud over Western Australia is 11 per cent. Kimberley and Pilbara regions of Western Australia record their highest rainfall during Southern Hemisphere summer months (December-January-February). The remainder of the state experiences more rainfall during Southern Hemisphere winter months (June-July-August). The JJA percentage change in cloud cover from 1980s

(1985 to 1993) to the 1990s (1994 to 2001) is charted in Figure 2 (left); the associated percentage change in the rainfall is found in Figure 2 (right). It is apparent in Figure 2 (right) that the rain has shifted in a northeasterly direction over time, leaving the southwestern regions of Western Australia with a reduction in rainfall of between 20-30 per cent (approximately 0.3 mm/day). Figure 2 (left) shows that the location of potential rain-producing clouds has shifted in a consistent manner. Ongoing investigations into MODIS (Moderate resolution Imaging Spectroradiometer) data will provide added cloud microphysical products such as cloud phase, optical thickness and effective radius for further classification of Western Australian regional rain clouds.

Conclusions

Clouds were found in 75 per cent of HIRS global observations since 1979 (high clouds in 33 per cent); latitudinal cloud cover follows the sun. The two decade trend in HIRS reveals modest 2 per cent per decade increase in high clouds. It was necessary in this study to mitigate the effects of orbit drift, $\rm CO_2$ increase, and satellite to satellite differences. In Western Australia, clouds were found in 58 per cent of the HIRS observations; a northeastward shift in the cloud cover evident in the HIRS data from the 1980s to the 1990s was associated with a corresponding change in the rainbands observed in GPCP data. Algorithm adjustments for low level inversions, stratospheric intrusions, and discrimination between water and ice clouds are showing promise in tests with MODIS data (Menzel et al, 2008); these adjustments will be included in the reprocessing of the complete HIRS archive. Merging with the higher spatial resolution AVHRR (Advanced Very High Resolution Radiometer) data is also being investigated.

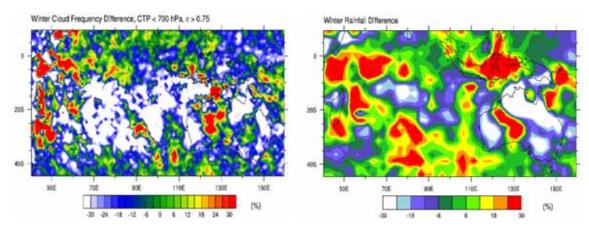


Figure 2: (left) Percentage change in frequency of HIRS cloud observations in June-July-August (1990s minus 1980s) for clouds with effective emissivity greater than 75 per cent and cloud top pressure less than 700 hPa. (right) Percentage change in GPCP rainfall (1990s minus 1980s).

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Contact: Professor Mervyn Lynch

Head of Remote Sensing and Applied Physics

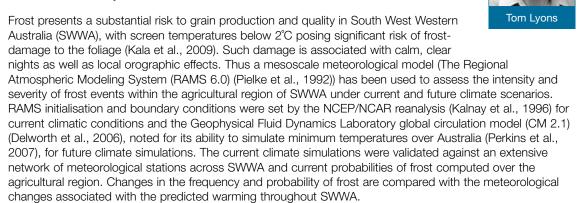
Curtin University of Technology,

GPO Box U1987 Perth, Western Australia 6845 AUSTRALIA

Ph: +61 8 9266 7540 Email: M.Lynch@curtin.edu.au

Climate change and frost in South West Western Australia

Dr Tom Lyons *Murdoch University*





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Contact: Dr Tom Lyons

Professor of Environmental Science

School of Environmental Science, Murdoch University Murdoch, Western Australia 6150 AUSTRALIA

Ph: +61 8 9360 2413 Fax: +61 8 9360 6788 Email: T.lyons@murdoch.edu.au