Strategic Research Fund for the Marine Environment (SRFME)

Interim final report June 2005

Edited by John K. Keesing and John N. Heine CSIRO Marine and Atmospheric Research

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CONTENTS

CHAPTER 7

CHAPTER 8

EXECUTIVE SUMMARY

The Strategic Research Fund for the Marine Environment (SRFME) is a 6-year (2001-2006), $20 million joint venture between CSIRO and the Western Australia Government. SRFME has the following as its mission:

SRFME will enhance Western Australia's marine research capability and capacity, deliver strategic research outcomes of benefit to Western Australia and enhance collaboration among marine researchers in Western Australia.

SRFME was established with the following high-level goals:

- Build capability and capacity in marine science in Western Australia
- Facilitate strong collaboration among the Western Australian marine science community
- Conduct fundamental and strategic research that is of benefit to Western Australia and Australia

With these goals and focus in mind, SRFME has invested in strategic research on the Western Australian marine environment in a way which enhances capability and capacity for marine science, encourages collaboration amongst the Western Australian research community and delivers strategic research outcomes which will have long-term benefits to the state.

This report completed in June 2005 is an *interim* report aimed at presenting SRFME's achievements to date to its members, stakeholders and collaborators. Much of the work presented here is still in progress and will be completed over the coming year with a *final* report for SRFME anticipated in June 2006. Even then much of the work that has been initiated by SRFME will be ongoing. This is a product of both the nature of strategic scientific research and strong and enduring collaborative partnerships that have been developed as a result of SRFME.

By any measure, SRFME has achieved or is achieving its goals and has set a new benchmark in establishing collaborative research partnerships.

With regard to building capability and capacity in marine science in Western Australia, SRFME has achieved its goal by growing CSIRO's marine research capacity in Western Australia from just 4 scientific and support staff in 2001 to over 25 in 2005. These staff have been relocated or recruited to its Floreat laboratories where they have formed part of a critical mass of over 300 staff within CSIRO's Centre for Environment and Life Sciences. A strong partnership developed between SRFME and CSIRO's Wealth from Oceans Flagship has also ensured strong links between SRFME researchers in WA and those elsewhere in CSIRO working towards Wealth from Oceans ambitious national and international goals in climate science and operational oceanography.

Capability and capacity have also been further developed in Western Australia through SRFME's Postgraduate Scholarship program and the SRFME Collaborative Projects program. SRFME has 13 PhD students at four Western Australian Universities who have strongly supported the program through co-investing in stipends and operating funds and providing supervision. Many of the SRFME students participate in SRFME Core Projects and are co-supervised by staff from CSIRO and other commonwealth and state research and management agencies. SRFME has also created capability and capacity through the recruitment of 6 postdoctoral researchers at Western Australian Universities as part of its $2 million investment in the SRFME Collaborative Projects.

In terms of facilitating collaboration, SRFME has brought about a range of strong multidisciplinary collaborations to its research programs. Research described in this report outlines the involvement of ten research organisations in SRFME projects with the vast majority of projects having collaborations amongst multiple organisations. In particular the SRFME Core projects and the Jurien Bay Collaborative projects comprise large multidisciplinary teams and include postdoctoral fellows and PhD students in the projects. Through these large multidisciplinary research projects SRFME researchers have also secured a large number of national facility sea days aboard the Southern Surveyor enhancing these collaborations.

Lastly, SRFME is meeting its goal to conduct fundamental and strategic research that is of benefit to Western Australia and Australia through all of its programs. The highlights of this work are outlined in this *interim* report. Chapter 1 sets out the background to the establishment of SRFME, how it is managed and how its research portfolio was developed. Chapter 2 provides summary reports on each of the SRFME PhD scholarship projects, Chapters 3 and 4 outline the SRFME Collaborative Projects and State Linkage Projects respectively and Chapters 5, 6 and 7 provide overviews and detail in some parts of the large SRFME Core Projects: Biophysical Oceanography, Coastal Ecosystems and Biodiversity and Integrated Modelling. Over the coming year much of this work will be completed and find its way into PhD theses, technical reports and the primary literature and the data, models and tools developed during SRFME will become available to researchers and NRM managers. An example of these tools, DIVE (Data Interrogation and Visualisation Environment) is included in this report on the CD included.

CHAPTER 1

1.1 About SRFME

1.1.1 Role and Purpose of SRFME

SRFME is a 6-year (2001-2006), $20 million joint venture between CSIRO and the Western Australia Government. The State Government is represented in the joint venture by the principal agencies involved in marine resource development and conservation: Department of Fisheries, Department of Conservation and Land Management, Department of Environment, Department of Industry and Resources, and Office of Science and Innovation.

SRFME was established with the following high-level goals:

- Build capability and capacity in marine science in Western Australia (in particular through re-establishing CSIRO's marine research capacity in Western Australia and a postgraduate fellowship program)
- Facilitate strong collaboration among the Western Australian marine science community
- Conduct fundamental and strategic research that is of benefit to Western Australia and Australia

The most important characteristic of SRFME is that it has been established to invest in and carry out "strategic" research rather than "applied" or "tactical" research. A strategic approach allows us to gain a broad understanding of the WA marine ecosystem and in particular how it functions and varies over time.

With these goals and focus in mind, SRFME has invested in strategic research on the Western Australian marine environment in a way which enhances capability and capacity for marine science, encourages collaboration amongst the Western Australian research community and delivers strategic research outcomes which will have long- term benefits to the state.

As a result of this foundation SRFME adopted the following as its mission:

SRFME will enhance Western Australia's marine research capability and capacity, deliver strategic research outcomes of benefit to Western Australia and enhance collaboration among marine researchers in Western Australia.

1.1.2 Background to SRFME

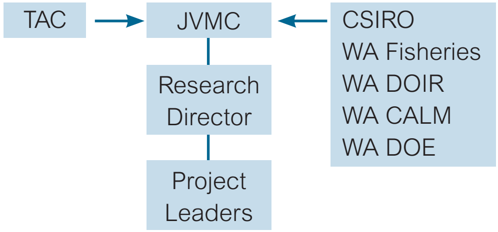
In July 1998 CSIRO Marine Research (CMR) approached the Western Australian Government and began a dialogue aimed towards strengthening CMR's presence in Western Australia. The State government formed the Marine Research Taskforce, which conducted a two-day workshop in October 1998 to identify the State's marine science priorities. The workshop involved over ninety representatives from peak industry bodies, research, academic and training institutions, community bodies and state and federal government agencies.

A major outcome of the workshop was a strong identification of the need for strategic research to support decision making for ecologically sustainable development and conservation in the marine environment. Additionally, the limited funding available to support such research was identified as a major constraint. In June 1999, the outcomes of the workshop were handed to the Coordination Committee on Science and Technology (CCST) by the Marine Research Taskforce for implementation and the CCST established a Marine Science Working Group to work with CMR to develop a solution to this funding situation.

In January 2000, the Western Australia Government agreed to jointly establish and manage the Strategic Research Fund for the Marine Environment (SRFME) with CSIRO Marine Research. In July 2000, following the Western Australian Government's endorsement of the structural and administrative arrangements for the fund, a Joint Venture Management Committee was established with the immediate task of negotiating the Joint Venture Agreement. This Joint Venture Agreement was entered into on 4 January 2001 pledging $10 million from each of the joint venture partners over six years.

1.2 Structure and Governance of SRFME

SRFME is managed by a Joint Venture Management Committee (JVMC) made up of the joint venture partners. There is also a SRFME Technical Advisory Committee (TAC) with members having a high level of technical expertise in marine science also drawn from the joint venture partners.



1.2.1 SRFME Joint Venture Management Committee

The Joint Venture Management Committee (JVMC) comprises senior executives from each of the Departments of Premier and Cabinet, Department of Conservation and Land Management, Department of Fisheries, Department of Environment, Department of Industry and Resources, and the Office of Science and Innovation; and the CSIRO Chief and Deputy Chief, Marine and Atmospheric Research. The role of the JVMC is to set the strategic direction for SRFME, approve the research portfolio and project investments, oversee the operations of SRFME and monitor its performance.

Joint Venture Management Committee (JVMC) Members

DR SUE MEEK (Chair) (2001-2002)	Head, Science and Technology, Department of Commerce and Trade
DR BRUCE HOBBS (Chairman) (2003-present)	Chief Scientist and Executive Director, Office of Science & Innovation, Dept of Premier & Cabinet
DR CHRIS SIMPSON	Manager, Department of Marine Conservation, Conservation & Land Management
DR PAUL VOGEL (2001-2002)	Department of Environment and Water Catchment Protection.
DR RAY MASINI (2003-present)	Manager of Marine Management & Protection, Dept of Environment
MR PETER MILLINGTON	Director of Fish Management Services, Department of Fisheries WA
MR RICHARD CRADDOCK	General Manager, Safety & Environment, Petroleum Division, Department of Industry and Resources
DR NAN BRAY (2001-02)	Chief of Marine Research, CSIRO
DR TONY HAYMET (2003-present)	Chief of Marine and Atmospheric Research, CSIRO
DR PAUL WELLINGS (2001)	Deputy Chief Executive, CSIRO
DR IAN POINER (2001-04) MR TIM MOLTMANN (2004 to present)	Deputy Chief, Research, Marine Research, CSIRO Deputy Chief, Business, Marine and Atmospheric Research, CSIRO
DR JOHN KEESING	Research Director, SRFME
MS LINDA PENNY (Observer)	Senior Policy Officer, Office of Science & Innovation, Dept of Premier & Cabinet
MS LUCY KAY (Secretary)	PA to the Research Director, SRFME

1.2.2 SRFME Technical Advisory Committee

This committee comprises the Project Leaders and technical experts from the relevant State Government agencies and CSIRO, and is chaired by the SRFME Research Director. The role of the TAC is to provide technical scientific advice to the JVMC and to review of project proposals.

Technical Advisory Committee (TAC) Members

DR JOHN KEESING (Chairman)	Research Director, SRFME
DR ALAN BUTLER (2001-2002)	SRFME Project Leader, CMAR
DR PETER THOMPSON (2001-2002)	SRFME Project Leader, CMAR
DR PETER CRAIG	SRFME Project Leader, CMAR
DR RUSS BABCOCK	SRFME Project Leader, CMAR
DR TONY KOSLOW	SRFME Project Leader, CMAR
DR PETER THOMPSON	Principal Research Scientist, CMAR
DR JIM PENN	Director, Fisheries Research, Department of Fisheries, WA
DR DES MILLS	Principal Environmental Officer, Department of Environment
DR NICK D'ADAMO	A/Manager Senior Oceanographer, Marine Conservation Branch, Dept of Conversation & Land Management
MR GRAHAM COBBY (2001-03)	Manager, Safety & Environment, Department of Industry and Resources
MS KIM ANDERSON (2003 to present)	Manager, Safety & Environment, Department of Industry and Resources

1.2.3 SRFME Research Director and Project Leaders

The day to day management of the SRFME Joint Venture is carried out by the SRFME Research Director who reports to the JVMC. Project Leaders are responsible for the conduct of projects funded by SRFME and report on the performance of those projects through the SRFME Research Director to the SRFME JVMC.

1.3 The SRFME Framework and Research Portfolio Structure

1.3.1 The SRFME Framework

Research carried out through funding from SRFME has been focussed within a framework of priorities developed by the CSIRO together with Western Australian government researchers, marine resource managers and academics. This framework was developed over a two-year period during the planning period leading up to the beginning of SRFME.

The SRFME Framework consisted of two components; a framework of priority research outcome areas and a framework of relative emphases.

The five areas in the framework of priority research outcome areas were:

1. **Broad scale oceanography** – where the aim is to develop enhanced understanding of Indian Ocean oceanographic processes, which may lead to benefits in greater understanding of:
   - fisheries recruitment processes
   - climate variability and rainfall prediction
   - slope and deep ocean currents
   - regional interconnectedness
   - continental shelf circulation characteristics

2. **Continental shelf and coastal processes** – these studies should lead to an improved understanding of the marine ecosystem providing a number of benefits in relation to:
   - sustainable management of areas of high productivity
   - regional interconnectedness with relevance to MPAs
   - fisheries recruitment processes
   - catchment-related impacts
   - cumulative impacts of human activity

3. **Living marine resource inventories** – this priority area acknowledges the importance of biodiversity studies and will provide increased information about:
   - broad scale benthic habitats and marine flora and fauna distributions
   - surrogates for measuring biodiversity which can lead to benefits in:
   - managing impacts in multiple use environments
   - site selection for aquaculture or industry development
   - fine scale mapping of areas of specific interest; and to,
   - assist with identification of marine protected areas

4. **Baseline monitoring and defining natural variability of ecosystem function and change over time** – will be important in order to:

   - develop or identify appropriate natural variability parameters/ indicators which are representative of key values or processes

   - design and implementation of cost-effective systems to monitor these parameters in areas representative of undisturbed ecosystems and bioregions in the state

5. **Planning tools for Ecologically Sustainable Development** – improved decision-making for agencies will be facilitated by the planned strategic research which will form the basis for the development of user-friendly and reliable management and decision-making tools.

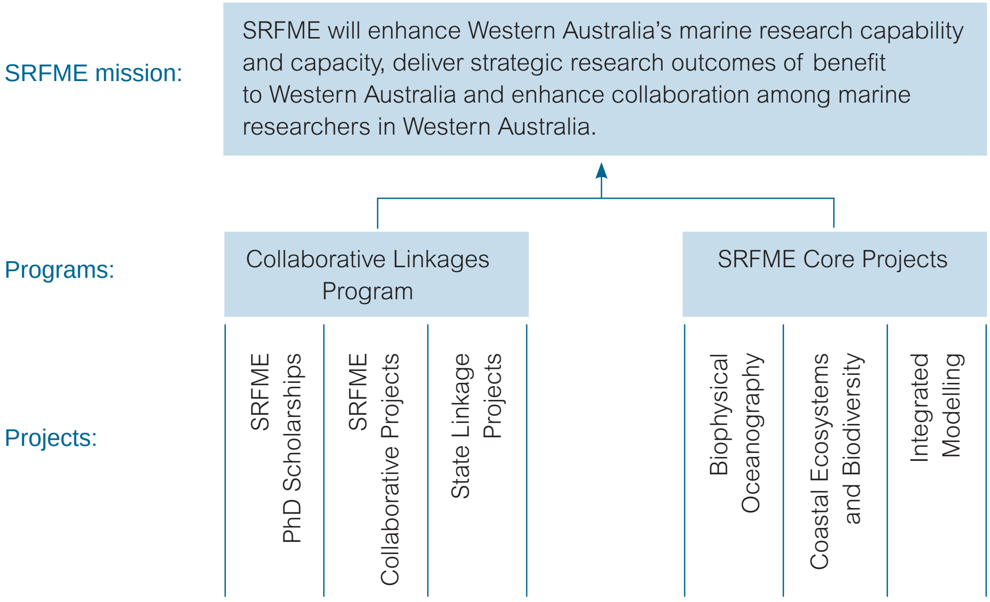
The framework of relative emphases consisted of the following:

- A relative emphasis between the five priority research outcome areas favouring Biological Inventory/Baselines (50-70%), Continental Shelf and Coastal Processes (10-30%), Broadscale Oceanography (5-15%) and Management Tools (5-15%)
- A geographic emphasis favouring the south coast through to the Gascoyne for Biological Inventory, Baselines and research on Continental Shelf and Coastal Processes
- A relative emphasis extending seaward from the coastline that favoured about 50% of the effort in coastal waters less than 50 m deep, 30% on the continental shelf and 20% offshore
- A relative emphasis along "measurement-understanding–prediction" continuum which favoured a predictive focus on projects with a primarily physical focus and an emphasis favouring measurement or new observations for primarily biological projects. Understanding physical and biological processes was given equal emphasis.
- A relative emphasis favouring physical studies on pelagic ecosystems and biological studies on benthic ecosystems.

It is within this framework that the SRFME research portfolio was developed.

1.3.2 SRFME Research Portfolio Structure

SRFME's research portfolio is structured around a Collaborative Linkages Program and Core Projects Program, which each have three projects or schemes.



1.4 Collaborative Linkages Program

The SRFME Collaborative Linkages Program seeks to build on existing research activities in Western Australia and to complement the SRFME Core Projects in ways which strengthen the breadth (both scientifically and geographically) of research outcomes from SRFME. The following are the main components of the collaborative linkages program.

1.4.1 SRFME PhD Scholarships

The SRFME Research Portfolio provides for the award of scholarships for full time postgraduate research leading to the award of a PhD by research at one of Western Australia's four publicly funded universities. The SRFME PhD Scholarship scheme has had the objective of strengthening and broadening the outcomes from SRFME Core projects, engaging the marine research capacity of WA Universities in SRFME and encouraging collaboration between Universities and scientists/managers in Commonwealth and State Government agencies.

The PhD scholarship scheme involves SRFME and WA Universities co-investing in 15 PhD stipends and operating funds. SRFME's investment into the scheme is about $650,000 over three and a half years. Many of the students who are carrying out the work towards a PhD degree are co-supervised by CSIRO scientists and staff from other commonwealth and state research and management agencies.

SRFME has held three annual symposia where the SRFME PhD Scholars present results on the progress of their projects.

1.4.2 SRFME Collaborative Research Projects

The other major component of the Collaborative Linkages Program is the SRFME Collaborative Research Projects scheme which is investing about $2 million in projects which tackle interdisciplinary projects in a collaborative way and add to the realization of capacity building goals of SRFME by providing opportunities for the appointment of Post-doctoral scientists.

Among the objectives of the SRFME Collaborative Research Projects were to address the gaps in the JVMC Framework not addressed by the Core SRFME Projects, leverage greater funding and research capacity for the SRFME research portfolio and to strongly engage with state and commonwealth research organisations, WA Universities and the private sector.

1.4.3 State Linkage Projects

The final component of the SRFME Collaborative Program is the State Linkage Projects scheme. SRFME is investing $200,000 in this scheme with the objective of enabling WA State Government agencies to engage actively in SRFME through small projects which link new or existing initiatives to other parts of the SRFME Research Portfolio.

1.5 SRFME Core Projects

The largest components of SRFME are the SRFME Core Projects. These were established to enable SRFME to achieve its principal objective which was to deliver an enhanced marine research capability to Western Australia through re-establishing CSIRO's marine research capability in Western Australia by relocating and recruiting 20 CSIRO marine research staff to Western Australia and by funding the capacity to carry out research by both CSIRO and other Western Australia research providers.

1.5.1 Development of the SRFME Core Projects

Core Project outlines were developed by CSIRO and considered by the Technical Advisory Committee. Projects developed were to be non-sectoral with research outcomes directed primarily at ensuring the strategic information requirements of the Western Australian Government were met. Projects were not to be developed for which existing dedicated funding mechanisms were not in place or where the research would be more appropriately funded by other funding mechanisms. Additionally, it was determined that projects chosen must meet three criteria approved by the WA Government. These were that projects must be of high priority to the Western Australian Government *and* of high priority to CSIRO *and* best undertaken through a local CSIRO presence in WA. Through an iterative process spanning the period from July 2000 to May 2001, the projects were refined to an extent that they were broadly consistent with the strategic priorities for the WA Government priorities within the SRFME framework and delivered a strong CSIRO research capability into Western Australia which complements rather than duplicates existing capability. The process of developing Core Projects was completed on 22 May 2001. The resulting three SRFME Core projects as a combined package have a total indicative cost of $15.385 million over the six years.

1.5.2 Biophysical Oceanography Core Project

The Biophysical Oceanography project seeks to characterise the continental and shelf/slope pelagic ecosystem off south-western Western Australia: its productivity and dynamics, and the physical, chemical and biological factors driving spatial and temporal variability.

1.5.3 Coastal Ecosystems and Biodiversity Core Project

The Coastal Ecosystems and Biodiversity project was established to characterise the coastal benthic ecosystems of south-western Western Australia, with a particular focus on benthic reef ecosystems, their productivity and dynamics, and the physical, chemical and biological factors driving variability on a range of spatial and temporal scales.

1.5.4 Integrated Modelling Core Project

The Integrated Modelling project was developed with the objective of working closely with the other SRFME Core Projects to provide quantitative descriptions of the Western Australian and shelf ecosystems that will assist environmental managers to predict and monitor natural and human induced change.

CHAPTER 2

2. COLLABORATIVE LINKAGES PROGRAM: PhD PROJECTS

2.1 SRFME PhD Scholarship Program

The objective of this program is to deliver strategic research outcomes and capacity building through postgraduate training. A total of $650,000 has been awarded to the funding of fifteen scholarships, which started in 2002 and 2003, and of these, thirteen scholars are currently enrolled, including two at Curtin University, two at Edith Cowan University, three at Murdoch University, and six at the University of Western Australia. Each student has at least one CSIRO staff member as a supervisor.

Three SRFME scholar symposia have been held at the Floreat Laboratories of CSIRO, in June 2003, 2004, and 2005. To date, one PhD thesis has been submitted, by Nisse Goldberg at the University of Western Australia. The remainder of the students plan to submit their theses from mid 2005 to mid 2006.

2.2 SRFME PhD Projects, Students, and Affiliations

1. The development and validation of algorithms for remotely sensing case II waters. Wojciech Klonowski, Curtin University.
2. Remotely sensing seasonal and interannual oceanic primary production for WA waters. Leon Majewski, Curtin University.
3. Morphological responses of seagrass meadows to light limitation and their application to environmental quality criteria. Catherine Collier, Edith Cowan University.
4. The role of detached macrophytes for fish production & biodiversity in coastal ecosystems. Karen Crawley, Edith Cowan University.
5. Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia. Barbara Muhling, Murdoch University.
6. Comparisons of benthic macroinvertebrate communities in marine environments and nearby estuaries in south-western Australia. Michelle Wildsmith, Murdoch University.
7. Uncertainty associated with alternative ecosystem representations. Sara Belmont, Murdoch University.
8. Temporal and spatial variation of sediment composition, redox potential and benthic photosynthesis in semi-enclosed coastal embayments subject to different catchment loading regimes. Alicia Loveless, University of Western Australia.
9. Biogeochemical processes in seagrass sediments. Kieryn Kilminster, University of Western Australia.
10. The influence of microphytobenthos on nitrogen cycling in sediments. Hugh Forehead, University of Western Australia.
11. Use of surrogates for the rapid assessment of marine biodiversity. Nisse Goldberg, University of Western Australia.
12. Physical and chemical forcing of primary production in shallow coastal waters off southwestern WA. Florence Verspecht, University of Western Australia.
13. The Biophysical Oceanography off Western Australia: Microzooplankton. Harriet Paterson, University of Western Australia.
14. Enhancing zooplankton and micronekton biomass estimation and size and species classification based on acoustic remote sensing. Chris Van Etten, Curtin University (withdrawn).
15. Investigation of the cycling of trace metals and metalloids as contaminants in WA coastal ecosystems. Yi Yuan, Murdoch University (withdrawn).

2.3 PhD Scholars Reports

2.3.1 The Development and Validation of Algorithms for Remotely Sensing Case II Waters

Wojciech Klonowski
Department of Applied Physics
Curtin University of Technology

Supervisors:
Mervyn Lynch, Brendan McGann, Peter Fearns, Lesley Clementson, Arnold Dekker

Introduction

Coastal embayments and estuaries are important ecosystems containing a number of critical habitats and resources that are important for sustaining fisheries and ecosystem health. Although there has been a wealth of new knowledge generated over the last decade about these ecosystems, the spatial and temporal patterns of biological and physical processes are not fully mapped or understood. Remotely sensed data offer a unique perspective on these processes because of the synoptic view over time and quantitative algorithms that can be used to extract geophysical and biophysical information from them.

Aims/Objectives:

1. To develop and validate a coastal water reflectance model that will permit the simultaneous retrieval of the concentrations of in-water constituents (Chl-a, CDOM, SS), water column depth as well as the composition of the seafloor, from remotely sensed data.

a) A coastal water reflectance model that incorporates the reflectance spectra of 3 common bottom types, found off WA coastal waters, was developed based on the work of Lee *et al*, 1999. In their work, they have demonstrated that their model can retrieve water column parameters and depth to a relatively high accuracy. However, a requirement of their model is that the spectral shape of the sea bottom is required and only sandy bottom environments were studied. The question is can this model approach be used to retrieve the contributions of more than one bottom type, namely sand, seagrass and brown algae, and hence generate a bottom classification map? The validity of the model with the inclusion of the 3 bottom types has been explored in this PhD research and the results are summarised below.

b) A large database of remote-sensing reflectance spectra corresponding to various water depths, bottom reflectance spectra and water column properties was constructed. The reflectance spectra were generated using the Hydrolight radiative transfer numerical model, which provides an exact solution of the radiative transfer equation for a given input. The 3-bottom component model was then applied to each generated reflectance spectrum incorporating the Levenburg-Marquardt optimisation scheme. The scheme involves adjusting the model parameters until the difference between the model and Hydrolight reflectance curve reaches a minimum. Comparison between the model-retrieved bottom coefficients for sand, seagrass and brown algae and the Hydrolight input coefficients show very promising results. Figure 1a) shows that for a bottom input spectra of sand the 3-bottom component model retrieves B_{Sand} coefficient values near to the Hydrolight input value (0.098) and values of zero for $B_{Seagrass}$ and $B_{Brown\ Algae}$ coefficients. Similarly, figure 1b) shows that for a bottom input spectra of seagrass the model retrieves $B_{Seagrass}$ coefficient values near the input value of 0.0106 and B_{Sand} and $B_{Brown\ Algae}$ coefficients near zero and Figure 1c) shows that for a bottom input spectra of brown algae the model retrieves $B_{Brown\ Algae}$ coefficient values near the input value of 0.0095 and B_{Sand} and $B_{Seagrass}$ coefficient values close to zero. These results demonstrate the ability of the 3-bottom component model to retrieve appropriate contributions of the bottom coefficients for a given bottom type.

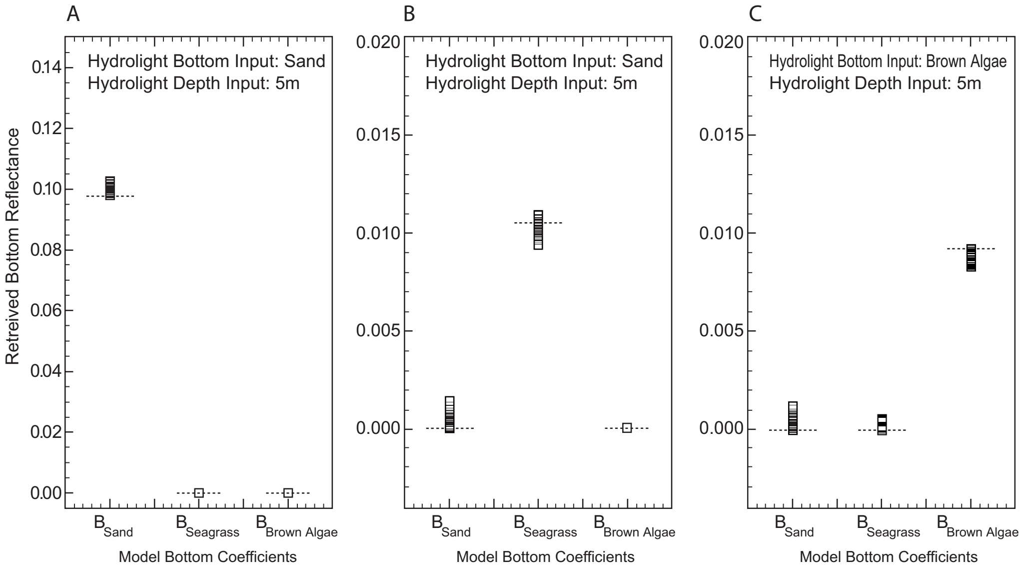


Figure 1. Model retrieved bottom coefficients, B_{Sand}, $B_{Seagrass}$ and $B_{Brown\ Algae}$ for Hydrolight bottom input spectra, a) sand, b) seagrass and c) brown algae.

2. Acquire *in situ* hyperspectral data from SRFME field programs to permit the testing of the 3-bottom component model.

a) The 3-bottom component model was applied to field measured above-water remote sensing reflectance spectra and comparisons of model-retrieved depth and Chl-a concentration with *in situ* measurements were made. Comparison between model-retrieved depth and *in situ* measured depth showed very close agreement with each other. The mean difference in depth was 7.6% for selected coastal water stations. Comparison between model-retrieved Chl-a and *in situ* Chl-a measurements also agreed well with each other. The mean difference in Chl-a concentration was 11.1%. Unfortunately, there were no measurements of bottom type for the stations sampled during the field campaigns and therefore validation of the retrieved bottom coefficients were not able to be undertaken. However, the model does seem to work well for the estimation of Chl-a concentration and water depth without any knowledge of the type of bottom cover present.

3. Apply the 3-bottom component model to appropriate satellite/aircraft data sets and compare the retrieved products to the in situ data.

a) Two flight lines of HyMap (HyVista Corporation) imagery of Jurien Bay were captured on 23rd of April 2004 to study the possibility of bottom type retrieval from shallow, coastal waters. The 3-bottom component model was applied to a small section of the image scene covering the “scientific reference zone”. The retrieved bottom coefficients of sand, seagrass and brown algae were used to generate a 3-bottom type classification map (figure 2a).

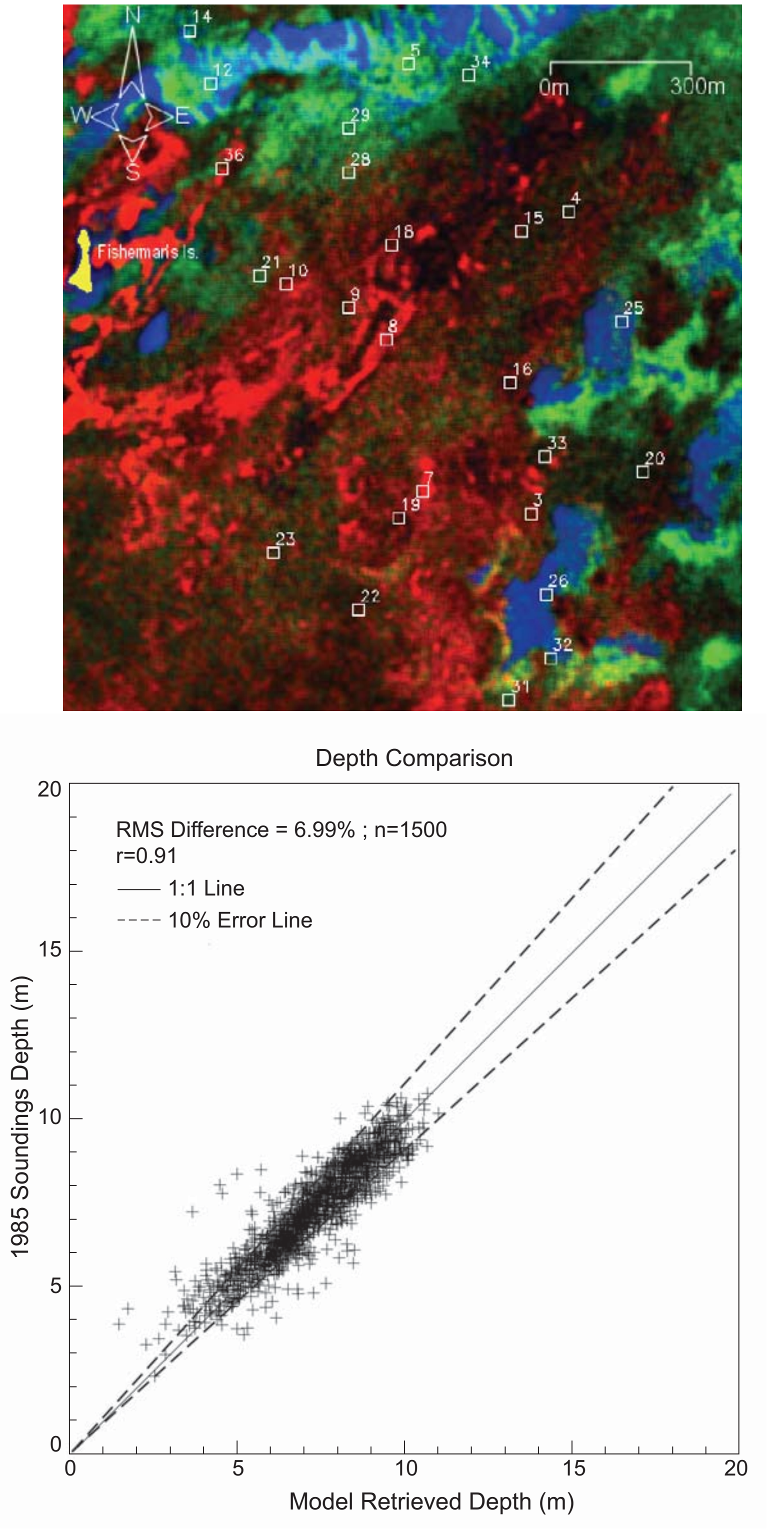


Figure 2. a) A high-resolution bottom type classification image of the "scientific reference zone" generated from model-retrieved bottom coefficients. Blue pixels represent areas of sand, green represents seagrass and red represents brown algae. Locations of the 36 ground-truthing stations are marked out as squares. b) A scatter plot of the model-retrieved depth over the "scientific reference zone" compared with hydro-acoustic soundings.

a) A historical hydro-acoustic data set of bathymetry was used to validate the model-retrieved depth. The scatter plot in figure 2b shows that depth retrieval capabilities of the model work well for the selected region. The mean difference in depth was calculated to be 6.99%.

b) To study the validity of the generated bottom type classification image a SRFME field campaign was undertaken whereby video drops over 36 sites within the image scene (figure 2a) were deployed to identify the bottom composition. The locations of the image pixels corresponding to the field sites were extracted and their colour was compared to the bottom composition identified with the video data. Blue pixels corresponded to sandy bottom environments, green pixels were associated with mainly seagrass with some stations containing a small proportion of sand. Red pixels were associated with dense cover of *Ecklonia* and *Sargassum* species of brown algae. Dark green pixels were associated with mixtures of seagrass and bare reef. Dark red pixels were associated with mixtures of seagrass and brown algae.

These results are promising and demonstrate the ability of the 3-bottom component model for providing bottom classification maps of sand, seagrass and brown algae, which are of interest to end users such and coastal water managers and environmental scientists.

Summary/Conclusion

A shallow water reflectance model that incorporates 3 bottom type spectra, typical of WA coastal waters, was developed during this PhD research. The model retrieval capabilities of bottom type were tested with a synthetic reflectance data set. The results indicate that the model has the ability to select the appropriate bottom type cover (sand, seagrass or brown algae) up to water column depths of 15m. The model was then tested with field data collected during the SRFME field campaigns. The model-retrieved depth and Chl-a concentration agreed very well with the *in situ* measured data. Comparison with the absorption and backscattering properties of the water column will be made once all the results from the water sample analysis are complete and made available.

The model was then applied to HyMap reflectance data collected over Jurien Bay coastal waters. The model-retrieved bottom coefficients were used to generate a bottom type classification map of sand, seagrass and brown algae. A SRFME ground truthing exercise was undertaken to validate the classification image. Comparison between *in situ* determined bottom type cover and model generated bottom type classification correlate well with each other, especially for dense cover of sand, seagrass and brown algae. The accuracy of the retrieved water column depth was evaluated by comparing historical hydro-acoustic soundings with the model-retrieved depth. The results indicate that the model is capable of estimating water column depth, accurate to around 10% up to depths of 15m.

These results are very promising and show potential for the routine mapping and monitoring of sea floor composition and bathymetry over coastal western Australian waters.

Intended Thesis Submission Date: 24 September 2005

Conference Presentations

Conference	Location	Date	Abstract Title
AMSA	Fremantle	10-12 Jul 02	"The Development and Validation of Algorithms for Remotely Sensing Case II Waters"
AMOS	UWA	10-12 Feb 03	"Hyperspectral Remote Sensing of Western Australian Coastal Waters"
SPIE	San Diego	3-8 Aug 03	"Hyperspectral Remote Sensing of Western Australian Coastal Waters"
ARSPC	Fremantle	18-21 Oct 04	"Characterisation of Seagrass Beds using HyMap Imagery"
OO	Fremantle	25-29 Oct 04	"Bottom Type Classification using Hyperspectral Imagery"

AMSA – Australian Marine Sciences Association
AMOS – Australian Meteorological and Oceanographic Society
SPIE – The International Society for Optical Engineering
ARSPC – Australian Remote Sensing and Photogrammetry Conference
OO – Ocean Optics

Publications

SPIE	"Hyperspectral Remote Sensing of Western Australian Coastal Waters"
ARSPC	"Characterisation of Seagrass Beds using HyMap Imagery"
OO	"Bottom Type Classification using Hyperspectral Imagery"

2.3.2 Remotely Sensing Seasonal and Interannual Oceanic Primary Production for Western Australian Waters

Leon John Majewski
Department of Applied Physics
School of Applied Science
Curtin University of Technology

Supervisors: Mervyn J. Lynch (Curtin), Brendan T. McGann (Curtin)
Peter R.C.S. Fearns (CSIRO MR, SRFME)
Lesley A. Clementson (CSIRO MR, SRFME)
Arnold G. Dekker (CSIRO L&W)

Introduction

Our knowledge of phytoplankton production in the southeast Indian Ocean near Western Australia is limited by the very few measurements of carbon uptake made in this area over the last 50 years. This data set is not sufficient to form an understanding of the seasonal or interannual variability present in production, a key variable in current global biogeochemical models.

Remote sensing provides a means of obtaining environmental data sets such as sea surface temperature and chlorophyll *a* concentration at high spatial and temporal resolution (Figure 3). These and other high resolution data sets can be manipulated to form an estimate of primary production. To achieve an understanding of the variability of production and possible flow on effects, algorithms applicable to the area of interest must be devised and validated.

Aims and major findings

The development of a remotely sensed phytoplankton primary production algorithm for application to southeast Indian Ocean waters near Western Australia is the primary goal of this research. The validity of certain remotely sensed ocean products has been assessed through the use of optical and biological measurements obtained during field experiments along the SRFME Two Rocks transect and other miscellaneous voyages.

1. The MODIS and SeaWiFS normalised water-leaving radiance and surface chlorophyll *a* products have been found to be within 10-20% of *in situ* measurements for offshore stations (Figure 4). Deviations from this range have been observed under poor measurement conditions.
2. Estimates of photosynthetically active biomass within the water column have been shown to be within 20-30% for offshore stations in the presence of a chlorophyll a maximum below the remotely observable depth.

The optical properties of phytoplankton are directly related to photosynthetic efficiency and thus to production. Measurements of phytoplankton specific absorption (a key optical property) have been made along the Two Rocks transect.

3. A model to estimate phytoplankton specific spectral absorption has been implemented (Figure 5).
4. These absorption spectra have been included in hyperspectral models that are applied to field data to yield inherent optical properties.

A model of phytoplankton production based on water column optical properties has been developed, but further improvements are expected.

5. This preliminary model has been expanded to the remote sensing case, where little is known of physiological variables.
6. Remotely sensed estimates of production do not yet fully represent the variability observed during the field program.

Summary and conclusions

To achieve the goals of this research, aspects of the biological and bio-optical oceanography of the southeast Indian Ocean have been investigated through a series of field experiments and by obtaining remotely sensed data sets. One of the main achievements of these field experiments is the validation of remotely sensed ocean products, especially estimates of water-leaving radiance, surface chlorophyll a concentration and estimated phytoplankton biomass. This has been achieved through the deployment of a hyperspectral profiling radiometer and HPLC analysis of discrete water samples at a series of locations along the Two Rocks Transect and a number of other locations in Western Australia.

Various non-spectral, depth integrated, remote sensing production models have been developed using data collected from regions with physical and biological characteristics different to those observed during the series of field experiments. These depth integrated models are generally based on phytoplankton biomass (as expressed as concentration of chlorophyll *a*), some physiological rate (e.g. the maximum rate of carbon uptake) and a set of empirically determined coefficients. The empirical nature of these algorithms limits their applicability to the location in which they were devised.

Spectrally resolved algorithms reduce the number of empirically determined coefficients and as such provide a more generally applicable method for estimating production. Algorithms have been developed to estimate water column optical properties (including absorption and backscattering coefficients) from the remotely sensed water-leaving radiance at a number of wavelengths. The absorption coefficient can be separated into various components, including that part due to phytoplankton. Knowledge of the phytoplankton specific absorption coefficient allows an estimate of the energy absorbed by phytoplankton throughout the euphotic zone to be developed. If the quantum efficiency of production is known (or can be estimated) an estimate of production can be obtained.

Models of phytoplankton absorption and quantum efficiency have been implemented to provide a spectral, depth resolved, model of primary production. Model output has been compared to field measurements and displays general agreement. However, the variability within measurements of primary production is yet to be fully captured using this approach. A complete analysis of the SRFME Two Rocks transect data set is being undertaken to expose possible sources of variability for inclusion in the model.

The final model will be applied to the historical data record of ocean colour data (1997-present) to produce accurate synoptic maps of phytoplankton production for the southeast Indian Ocean, thereby achieving the goal outlined in the original research project proposal.

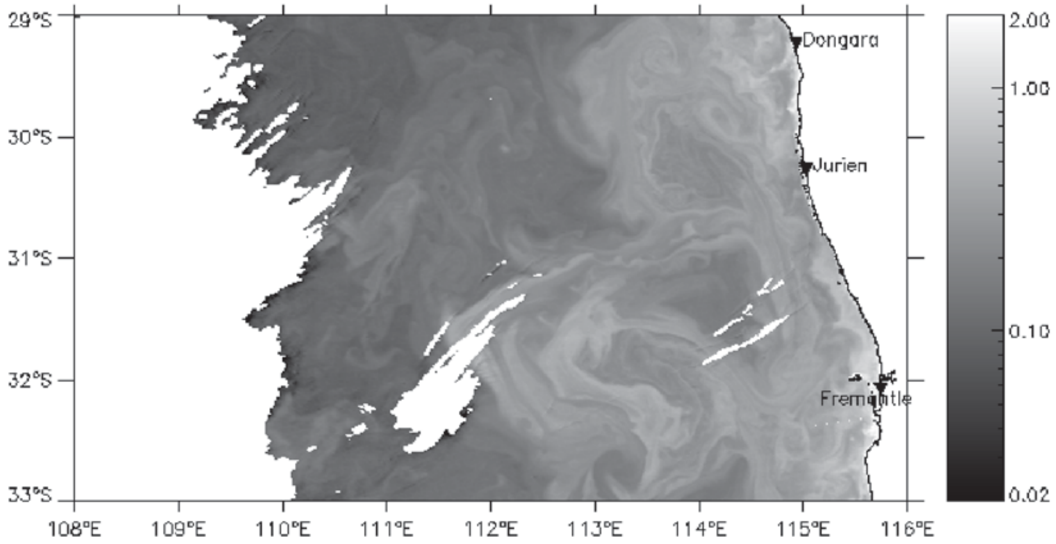


Figure 3. This image of the MODIS surface chlorophyll ***a*** product (mg m^{-3}), from the 19th June 2003, provides an example of the spatial variability encountered in the southeast Indian Ocean near Western Australia and the fine details that are able to be resolved within MODIS imagery. Note the log scale and that masked (white) pixels are either land or cloud.

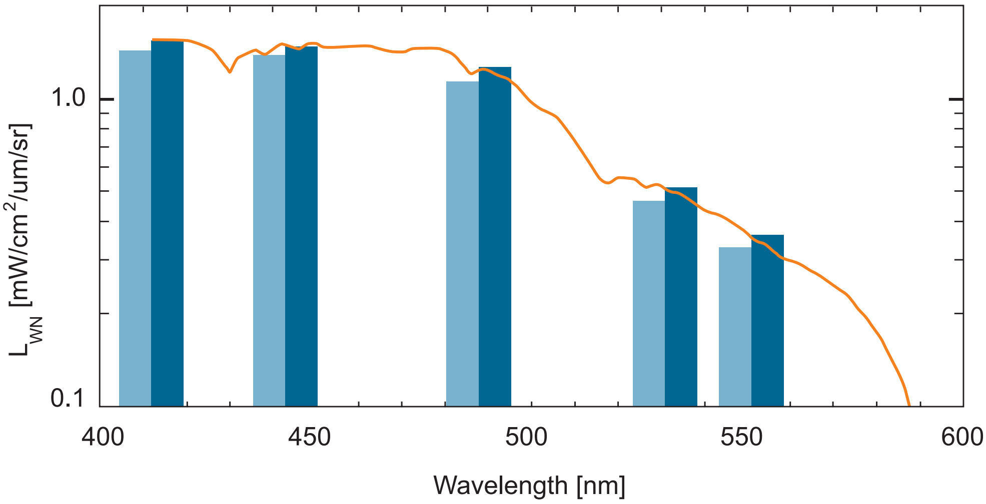


Figure 4. Comparison of MODIS-Aqua normalised water-leaving radiances (L_{WN}, aqua coloured bars) with hyperspectral (red line) and simulated MODIS values (orange bars) at a deep water site (Station E; 31.9°S, 114.9°E) on the 25th January 2004. Under good conditions, MODIS and *in situ* measurements of L_{WN} are within 10-20%.

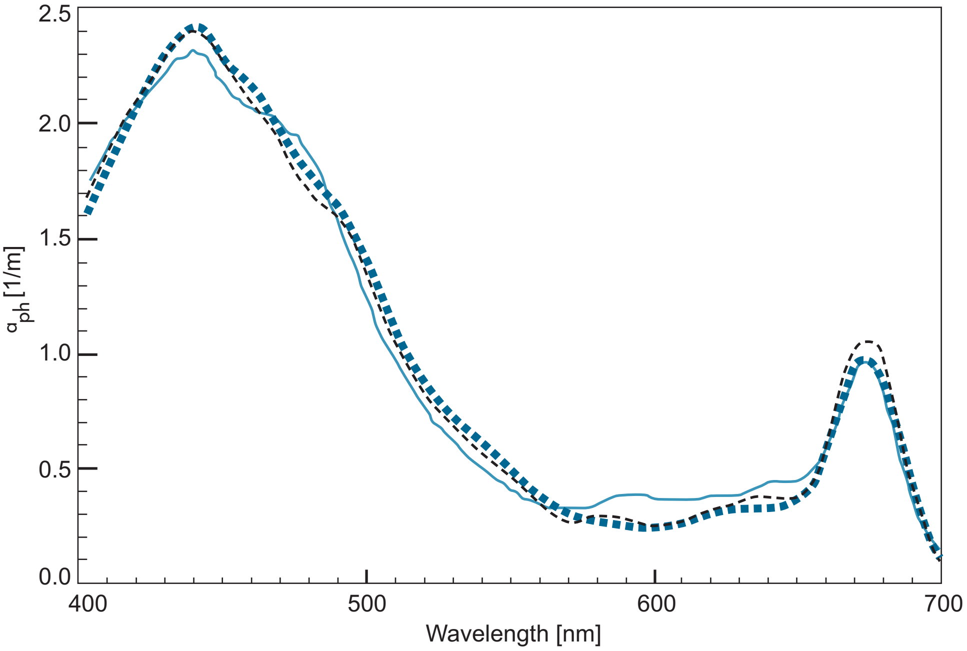


Figure 5. Comparison of a measured phytoplankton absorption spectrum (black line) with modelled (blue and yellow symbols) data. The reconstruction of the peaks at 440nm and 678nm is encouraging.

Indended date to submit thesis for examination: 15 August 2005

Conference Contributions

Majewski, L.J., W.M. Klonowski, P.R.C.S. Fearns, L.A. Clementson, and M.J. Lynch, 2004, *Ocean colour product validation in Western Australian Waters*, in Ocean Optics XVII, SPIE, Fremantle.

Lynch, M.J., and **L.J. Majewski**, 2004, *The role of ocean colour products in bioregion classification schemes*, in Ocean Optics XVII, SPIE, Fremantle.

Klonowski, W.M., **L.J. Majewski**, and P.R.C.S. Fearns, 2004, *Bottom type classification using hyperspectral imagery*, in Ocean Optics XVII, SPIE, Fremantle.

Clementson, L.A., P.R.C.S. Fearns, **L.J. Majewski**, W.M. Klonowski, and T. Harriden, 2004, *Seasonal effects in the inherent optical properties of Western Australian coastal waters: Impacts on the validation of ocean colour sensors in this region*, in Ocean Optics XVII, SPIE, Fremantle.

Slivkoff, M., W.M. Klonowski, L. Clementson, M.J. Lynch, and **L.J. Majewski**, 2004, *Detection of potentially harmful algae using an above-water hyperspectral radiometer in the Swan River estuarine system*, in Ocean Optics XVII, SPIE, Fremantle.

Majewski, L.J., M.J. Lynch, B.T. McGann, P.R.C.S. Fearns, and L.A. Clementson, 2004, *Remotely sensing seasonal and interannual oceanic primary production for WA waters*, in 3rd SRFME Symposium, Floreat.

Majewski, L.J., W.M. Klonowski, P.R.C.S. Fearns, L. Clementson, and M.J. Lynch, 2004, *Validation of remotely sensed ocean colour products in Western Australian waters*, in ASLO Ocean Research Conference, Honolulu.

Majewski, L.J., 2003, *MODIS Bioregion Classification*, in WA MODIS Science Applications Team Meeting, Floreat.

Majewski, L.J., P. Hick, I. Tapley, and J. Forward, 2003, *Evaluation of MODIS data for aquaculture in the Kimberley*, in WA MODIS Science Applications Team Meeting, Floreat.

Majewski, L.J., M.J. Lynch, B.T. McGann, P.R.C.S. Fearns, L.A. Clementson, A. Dekker, S. Pesant, and A. Waite, 2003, *Remotely sensing seasonal and interannual oceanic primary production for WA waters*, in 1st SRFME Symposium, Floreat.

Majewski, L.J., 2003, *MODIS Ocean Processing*, in Australian MODIS Users Group Meeting, Floreat.

Majewski, L.J., M.J. Lynch, B.T. McGann, L.A. Clementson, A. Dekker, and S. Pesant, 2003, *Remotely sensing the primary production of WA waters*, in AMOS-2003, AMOS, Perth.

Majewski, L.J., 2002, *Generation of Level 2 products from MODIS DB data, in Australian MODIS Users Group Meeting*, Canberra.

Majewski, L.J., and M.J. Lynch, 2002, *Remotely sensing seasonal and interannual oceanic primary production for WA waters*, in AMSA-2002, AMSA, Fremantle.

Publications

No refereed publications to date.

2.3.3 Seagrass Responses to Light Availability: A Mechanistic Approach

Catherine Collier
Faculty of Computing, Health and Science
School of Natural Sciences, Edith Cowan University

Supervisors: Assoc. Prof. Paul Lavery, Dr Ray Masini, Assoc. Prof. Peter Ralph

Introduction

Seagrasses are demonstrably sensitive to changes in their environment (Walker and McComb 1992). When subjected to reduced light availability, seagrasses may demonstrate a range of responses at the physiological or morphological level and if reduced light availability is sustained will eventually lead to seagrass loss (Longstaff *et al*. 1999). Worldwide, a range of potential indicators have been identified for a number of species, however, a large gap remains in the understanding of why species demonstrate such broad responses that cannot be applied globally to other species. The locally dominant species, *Posidonia sinuosa*, has slow growth rates and a poor capacity to recover following loss (Fitzpatrick and Kirkman 1995) therefore the processes enabling their tolerance to reduced light is crucial to enable their survival. Knowledge of these mechanisms is central to the positive identification of reliable monitoring tools that identify an effect of light reduction.

Aims/objectives

1. Explore a range of *P. sinuosa* attributes (both physiological and morphological) down a depth gradient in order to infer seagrass responses to long-term light availability and to describe natural depth-related variability.

2. Monitor the rate and sequence of *P. sinuosa* responses to reduced light availability and monitor recovery following return to ambient light conditions.

3. Trace the movement of carbon (in terms of direction and distance) through seagrass plants in both natural and reduced light conditions to identify the importance of this process as a mechanism for seagrass maintenance in response to reduced light availability.

4. Assess the appropriateness of currently employed seagrass indicators of light availability and derive (if appropriate) a suite of complementary indicators for use in monitoring programs.

Major Findings

1. Experiment 1 Depth gradient analysis

The first research phase examined a range of physiological and morphological parameters down a depth gradient in Cockburn Sound and Warnbro Sound. Shoot density and biomass exhibited the greatest differences between the depths sampled and conformed to *a priori* expectations (Fig 6A). Productivity and morphological parameters such as canopy height and leaf width demonstrated far more complex differences as the differences observed were dependant on sampling time (Fig 6B). Some physiological parameters examined showed seasonal differences but little difference between depths (Fig 6C). Of the pigments analysed, antheraxanthin (a product of the photoprotective mechanism), was reduced in winter but there was no significant difference between depths. Total Chlorophyll concentration and chlorophyll *a*/*b* ratio as well as a number of the PAM fluorometry parameters showed no consistent pattern between depths, being dependant on a combination of site and season sampled (Fig. 6D). This study highlighted that shoot density is the parameter most consistently affected by depth for *P. sinuosa*. This mechanism may allow persistence of this species at deeper sites by reducing respiratory load and increasing light penetration through the canopy.

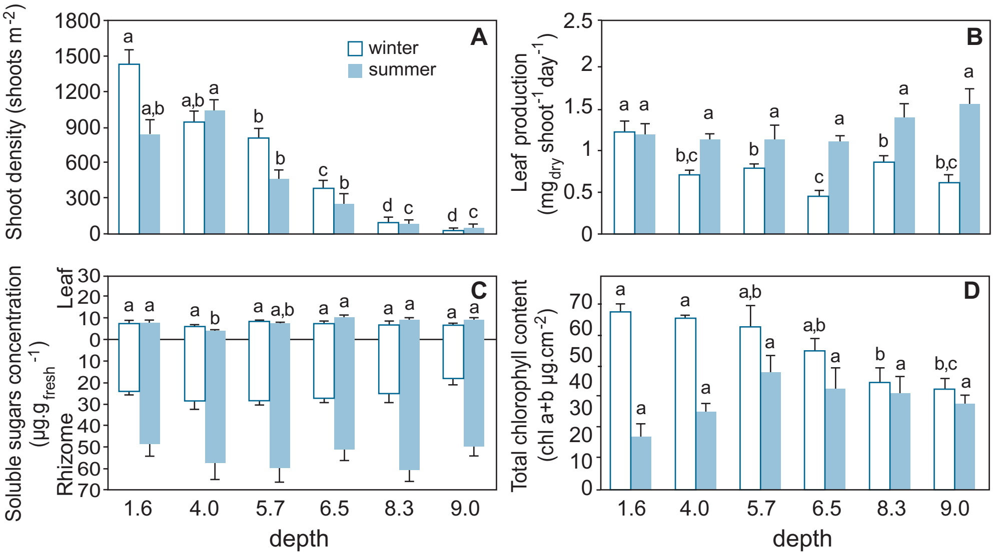


Figure 6: Shoot density (A), leaf productivity (B), soluble sugar concentration in leaf and rhizome material (C) and total chlorophyll content (D) at 6 depths at North Garden Island in winter 2002 and summer 2002-2003. n=12 (A) and n=6 (B-D) ±SE.

2. Shading

In situ shadings (light (receiving ~81% of control), moderate (~30%) and heavy (~6%)) were applied at 2 different depths in Cockburn Sound in early spring 2003. Within 106 days of shading a significant reduction in shoot density occurred in the moderate and heavy treatments (Fig 7A). Continued decline in these treatments resulted in shoot densities after 196 days that were 38% (moderate) and 6% (heavy) of the control. At the shoot level, the meadow-scale response (thinning) acted to offset changes in the light environment, resulting in comparable absolute light levels at the bottom of the canopy. Leaf production again remained unaffected by light reduction (Fig 7B). After 2 weeks (and on a number of future sampling occasions) a typical “shade response” was observed in the heavy shade treatment for example a reduced relative maximum electron transport rate (rETRmax) (Fig 7C). Overall, however, the response of these parameters was inconsistent throughout the shading period. Chlorophyll concentration was not significantly affected by light reduction. In the rhizome, carbohydrates were reduced (probably to supplement growth and respiration) in all treatments at around the time shoots were lost, after 106 days (Fig. 7D). However, soon after shoot loss and canopy thinning recovery of the carbohydrates began in the light and moderate treatments.

There was no recovery of shoot density following removal of the shade screens. Productivity has remained equal between all treatments. For the PAM fluorometry parameters, a reversal of the pattern earlier described, occurred. ETRmax increased and alpha reduced in the moderate and heavy shade treatments. As there was no detectable differences in chlorophyll concentration it is hypothesised that these PAM differences result from the more open canopy structure in the impacted sites where light availability was now measurably higher at the bottom of the canopy. These data indicate that some shoot-scale responses occur (carbohydrates and PAM) but generally they provide further indication that for *P. sinuosa*, shoot-scale responses to light availability are less pronounced and consistent than meadow-scale responses, a finding consistent with our earlier field observations for this species.

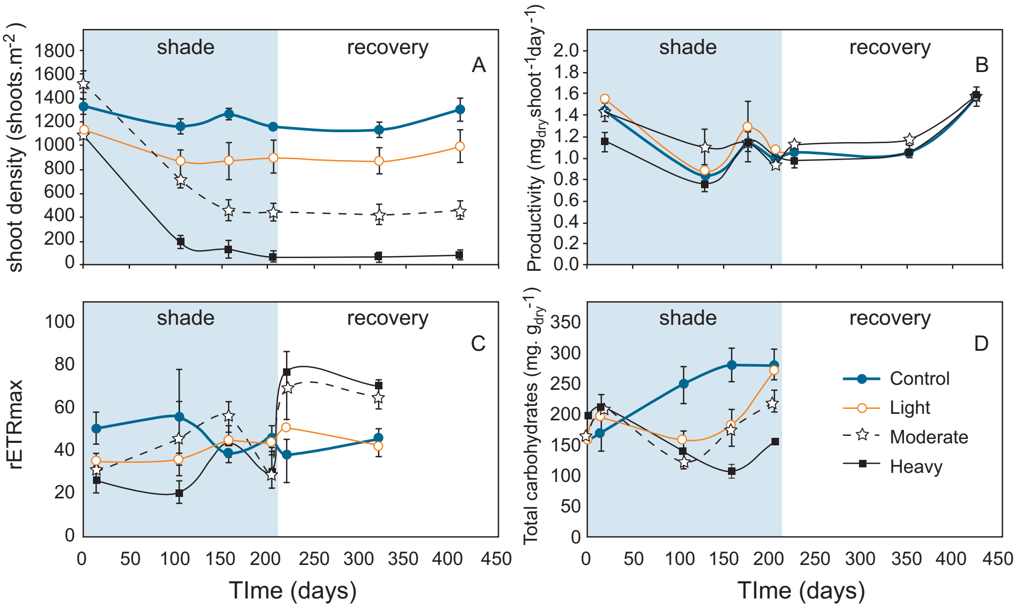


Figure 7: Shoot density (A), leaf production (B), rETRmax (C) and rhizome carbohydrates (D) at North Garden Island in response to shading. n = 4 ± SE

3. Carbon and nitrogen translocation

The role of nutrient transfer from mature leaves to support young growing leaves and the impact of reduced light availability on this process was investigated. In December 2004, *P. sinuosa* shoots in both ambient and shade were selected for those with one mature leaf and one growing leaf less than 10cm long. The oldest leaf was covered with a plastic bag and sealed at the base. A solution of $NaH^{13}CO_3$ and $^{15}NH_4^+$ enriched in the stable, heavy isotope of carbon and nitrogen was added to the bag and allowed to uptake. After 2 hours the majority of ^{13}C was found in the mature leaf (91%) followed by the rhizome (~8%) and the youngest leaf (~1%) (Fig 8A and 8B) and for nitrogen, 96%, 3% and 1% respectively (not shown).

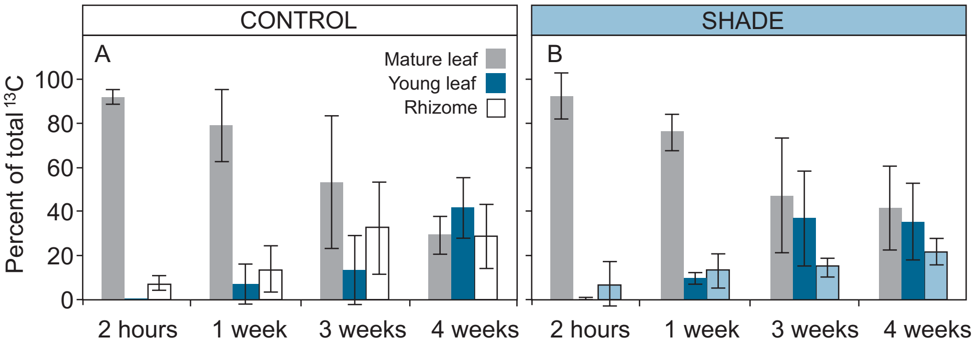


Figure 8: Percentage of the total shoot ^{13}C mass within the mature leaf, young leaf and adjacent rhizome, in control (A) and shaded treatment (B) throughout the 4 week experiment. n=4, ± SE.

Although the total mass of isotope in the shoot did not reduce over time, the percentage of ^{13}C and to a lesser degree, ^{15}N, in the youngest leaf and the rhizome continued to increase while decreasing in the oldest leaf. After 4 weeks the percentage of the ^{13}C in each leaf and rhizome segment was approximately equal and for nitrogen was 60-75%, 20-30% and 6-7% in the mature leaf, youngest leaf and rhizome respectively. These results indicate that within a shoot, the transfer of carbon, and to a lesser degree nitrogen, from the oldest to the youngest leaf may be an important process for subsidizing growth requirements of the young leaf.

In order to determine whether preferential distribution of nutrients to certain shoots occurs and may play a role in the persistence of these shoots during light reduction, translocation of carbon and nitrogen between shoots on a rhizome was measured. In January 2005 a whole shoot was sealed in a bag and again exposed to a solution of $NaH^{13}CO_3$ and $^{15}NH_4^+$ for 4 hours. After 1, 2 and 4 weeks, the whole seagrass plant was collected from the apical shoot, including all branches back to the 9th branch. Preliminary findings indicate that translocation of carbon along the rhizome is unlikely to be a significant process in ambient or light reduced conditions. Some nitrogen translocation occurs, however, particularly towards the apical shoot.

Summary and conclusions

The requirement for effective tools to monitor *P. sinuosa* and avoid light related loss is highlighted by the rapid loss and very slow recovery observed following shading. The most consistently responsive parameter to light reduction is the currently employed monitoring parameter, shoot density. Reduced shoot density results in greater light penetration and reduced respiratory load and is probably the dominant mechanism allowing seagrass persistence in reduced light conditions. Some response of carbohydrates and PAM parameters indicates potential for their application as monitoring tools. However, recovery of carbohydrates during shading, inconsistent PAM data and spatial variability suggests potential confusion in their application. A broader investigation targeting spatial and temporal variability will determine whether the establishment of base-line values is feasible for these parameters. Translocation of carbon and nitrogen between shoots does not appear to be a fundamental mechanism for shoot maintenance. However, reduction of carbohydrates in the rhizome during shading indicates that stores of carbohydrates may be re-mobilised during these times. Within an individual shoot, however, nutrient recycling is probably important under ambient conditions. Nonetheless, within-shoot cycling of nutrients is unaffected by shading and again is unlikely to be an important process in prolonging shoot life during periods of light reduction.

Intended date to submit thesis for examination: December 2005

Conferences attended

International Seagrass Biology Workshop (ISBW5) 2002, Ensenada, Mexico; SRFME Symposium 1; AMSA July 2003 Brisbane, Australia; SRFME Symposium 2; AMSA WA Student workshop, June 2004; ISBW6 2004, Townsville, Australia

Awards

SRFME 2003 Award for presentation; SRFME 2004 Award for presentation; International Seagrass Biology Workshop (ISBW) 2004 Excellence award

2.3.4 The Role of Detached Macrophyte Accumulations for Fish Production and Biodiversity in Coastal Ecosystems

Karen Crawley
School of Natural Sciences, Edith Cowan University

Supervisors: Dr Glenn Hyndes (ECU) and Dr Julia Phillips (CSIRO)

Introduction

Accumulations of detached macrophytes within nearshore surf-zones and on beaches are commonly referred to as wrack. Detached macrophytes can be an important source of food and habitat for juveniles of some fish species, and their invertebrate prey. In south-western Australia, wrack comprises a mixture of seagrasses and macoalgae. The broad objective of this study was to investigate further the links between detached macrophytes, invertebrate fauna and fish in terms of food supply and habitat. In particular, to determine the role of different types of wrack (i.e. seagrass, brown, red and green algae) as a habitat and food source for fish and their invertebrate prey in nearshore waters. The influence of different volumes of surf-zone wrack on fish abundance and composition and the potential contribution of wrack detritus to offshore regions were also investigated.

Aims/objectives

Invertebrate research

- **Aim:** To determine the habitat preference of *Allorchestes compressa* for different types of macrophytes through a series of laboratory and field experiments.

The focus of my invertebrate research is on the semi-aquatic amphipod *Allorchestes compressa*, which in Western Australia constitutes more than 90% of the macroinvertebrate fauna and is one of the main prey of juvenile fish in wrack habitats. A habitat preference experiment using different types of detached macrophytes in tanks was carried out. Results revealed that *A. compressa* prefers seagrass (*Posidonia* and *Amphibolis*) as a habitat under laboratory conditions. To test which type of macrophyte *A. compressa* uses as a habitat in the field with the presence of fish predators, an experiment was carried out with different types of detached macrophytes contained in cages in surf-zone wrack at Two Rocks and Shoalwater Bay. In contrast to tank trials, *A. compressa* showed a strong preference for either brown algae, red algae or a mixture of different types of plants over seagrass as a habitat in the field (Figure 9).

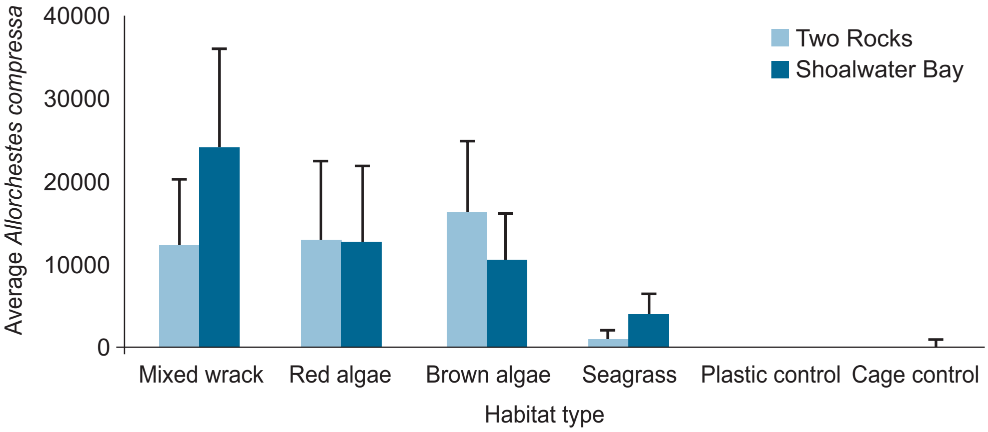


Figure 9: Average abundance of *Allorchestes compressa* (± S.E.) in different caged habitat types.

- **Aim:** To determine the feeding preference of *Allorchestes compressa* for different types of macrophytes, and the plant type(s) that contributes most to the detached macrophyte – amphipod – fish food chain in neashore regions in south-western Australia.

A feeding preference experiment offering different species of detached macrophytes to *A. compressa* over four days was carried out in the laboratory. Results revealed that *A. compressa* preferred brown algae (*Ecklonia* and *Sargassum*) over other detached macrophyte types as food. While *Allorchestes compressa* shows a preference for feeding on brown algae, it may be that other types of wrack are assimilated. To investigate which types of wrack *A. compressa* consumes and assimilates, samples of detached macrophytes, *A. compressa* and 3 fish predators (sea trumpeter, yellow-eye mullet and cobbler) were collected at 3 sites (Two Rocks, Hillarys and Shoalwater Bay) for biomarker analysis. The samples were analysed for stable isotopes (δ^{13}C, δ^{15}N and δ^{34}S), as well as fatty acids and lipid classes. Results of stable isotope analysis revealed that *A. compressa* feeds on macroalgae rather than seagrass, with fatty acid analysis revealing that the consumers (amphipods and fish) are most similar in fatty acid composition to brown algae *Ecklonia* and *Sargassum* (Figure 10) and therefore brown algae are likely to contribute more to the food chain than other types of macroalgae. The stable isotope values (δ^{13}C and δ^{15}N) of *A. compressa* after consuming different plant types were also investigated under controlled conditions to determine the expected enrichment between *A. compressa* and different types of wrack (both fresh and decomposed plant material) over 3 weeks. Plant material and amphipods were subsampled weekly to determine how these signatures change over time.

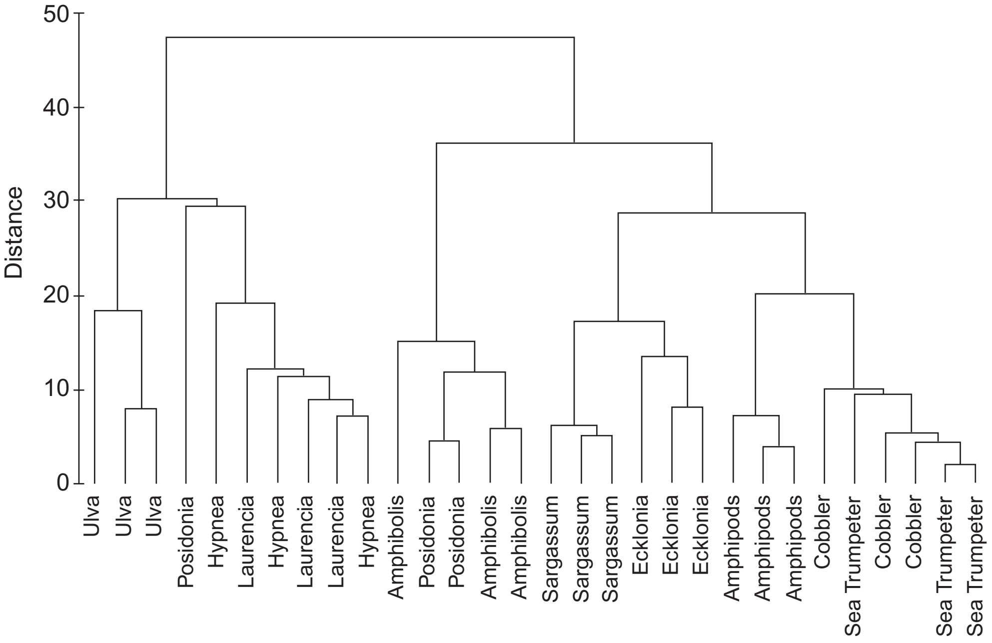


Figure 10: Cluster analysis of the mean relative abundance of fatty acids for seven macrophyte species, amphipods and 2 fish species from 3 nearshore sites.

Fish research

- **Aim:** To determine the influence of different volumes of surf-zone wrack on fish abundance and composition in surf zones of southwestern Australia.

Fish were sampled using a 21 metre seine net in nearshore areas containing high, medium or low levels of wrack, as well as in bare sand areas at both Hillarys and Shoalwater Bay. Data analysis was carried out for the field data using MDS ordinations and Analysis of Variance (ANOVA). Generally, fish abundance and biomass increased as the volume of wrack increased (Figure 11). The types of fish also differed between volumes. In areas of bare sand, or low amounts of wrack, bait species were common. In mid and high levels of wrack, species such as sea trumpeter and cobbler were common.

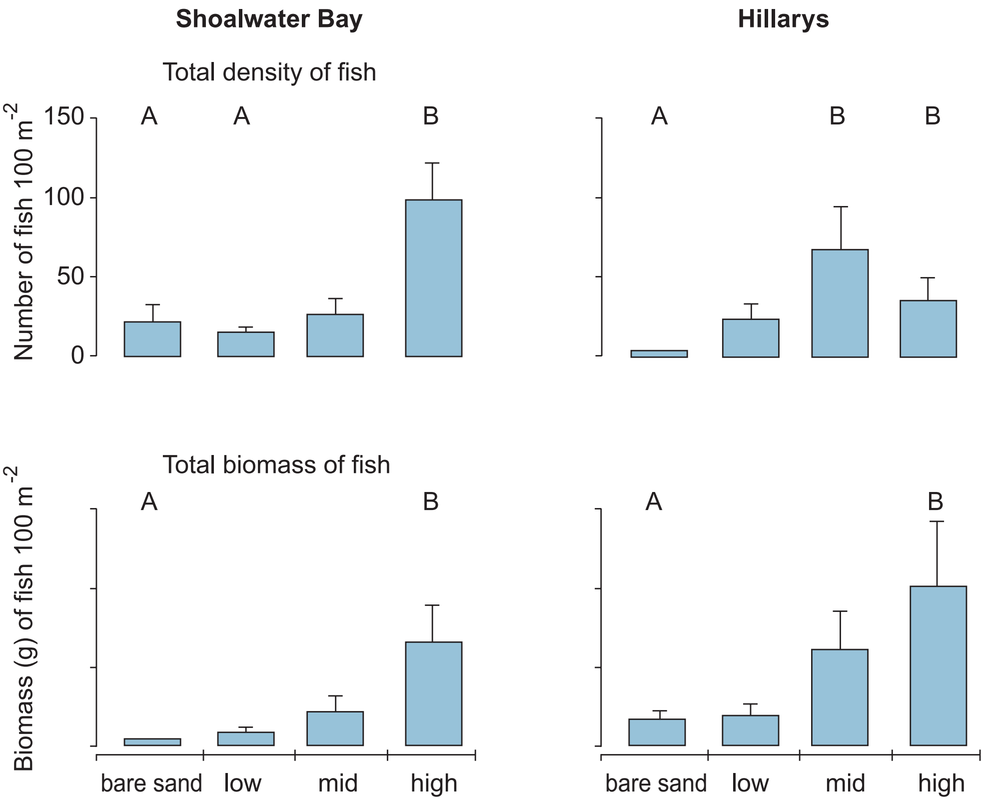


Figure 11: Mean (+SE) density and biomass of fish found in bare sand, low, mid and high wrack volumes at Shoalwater and Hillarys. Different letters denote volume categories that are significantly different (*P*<0.05).

- **Aim:** To test whether the two dominant fish in beaches containing wrack, namely cobbler (*Cnidoglanis macrocephalus*) and sea trumpeter (*Pelsartia humeralis*), show a preference for different types of detached macrophytes as a habitat.

A habitat preference experiment was conducted in a series of outdoor aquaria. Different types of macrophytes (i.e. seagrass only, brown algae only and a mixture of both types) were placed at either end of aquaria and the number of fish in each plant type recorded at the end of each trial. Data analysis, using a non-parametric goodness of fit binomial test, showed that neither sea trumpeter nor cobbler had a clear preference for different types of macrophytes.

Sediment/offshore wrack samples

- **Aim:** To determine whether detached macrophytes could provide an important carbon and nutrient source in offshore regions of south-western Australia.

In August 2003 and January 2004, I collected a set of sediment samples while onboard RV Southern Surveyor along the CSIRO Two Rocks transect from 15 to 360 metres depth. The samples were sent to CSIRO in Hobart for analysis to determine whether traces of broken down detached macrophyte material has bound up with the sediments and can be detected. The samples are yet to be analysed.

Summary and Conclusions

Results of this study have shown that different types of detached macrophytes are important for the amphipod *Allorchestes compressa*, which uses different types of plants as food or habitat. *A. compressa* shows a strong preference for feeding on brown algae, with this plant type contributing more than other macrophyte types to the detached macrophyte – amphipod – fish food chain in nearshore areas. In terms of shelter, brown and red algae and mixed wrack are important in providing a habitat for *A. compressa*. For fish, the volume, rather than the type, of wrack present in surf-zones has a strong influence on fish assemblages. Dense wrack accumulations are an important habitat for some fish species, particularly juvenile cobbler and sea trumpeter and could be critical for productivity and biodiversity in nearshore areas. Removal of wrack could have a detrimental impact on some fish species and their invertebrate prey, which rely on wrack for food and shelter.

Intended thesis submission date: 1 October 2005

Awards received

1) September 2004: Australian Society of Fish Biology, John Glover Travel Award.

2) March 2004: Dame Mary Gilmore Award offered by The Karrakatta Club (Perth) in conjunction with Edith Cowan University.

3) June 2003: 1st Symposium of the SRFME Postgraduates Scholarship Program
   – third prize from CSIRO for the best student oral presentation
   – best presentation related to fisheries management from ASFB

Professional development courses

- April 2002 : Seminar Presentation and Public Speaking Course through ECU
- June 2002: Australian Red Cross Senior First Aid Certificate
- February 2004: Macroalgae Identification Workshop run by Dr John Huisman at Murdoch University as part of the Australian Marine Science Association
- July 2004: Multivariate Statistics Workshop using PRIMER v6 (Plymouth Routine in Marine Ecological Research) and PERMANOVA, with some univariate statistics
- March 2005: Four wheel drive training course (2 days) through Adventure Out

Conferences / presentations

- March 2005 – Rockingham/Kwinana/Mandurah Naturaliste Club. Oral presentation.
- November 2004 – Seagrass monitoring volunteer group, Rockingham. Oral presentation.
- September 2004 – Australian Society of Fish Biology Conference (Adelaide). Oral presentation "The importance of volume and type of wrack on nearshore fish assemblages".
- June 2004 – 2nd SRFME Postgraduates Symposium (CSIRO, Perth). Oral presentation "The importance of volume and type of wrack on nearshore fish assemblages".
- March 2004 – The Karrakatta Club (Perth). Oral presentation "The importance of wrack in nearshore areas".
- July 2003 – Australian Marine Science Association Conference (Brisbane). Oral presentation "The role of different types of detached macrophytes for *Allorchestes compressa*, a surf-zone inhabiting amphipod".
- June 2003 – 1st SRFME Postgraduates Symposium (CSIRO, Perth). Oral presentation "The role of detached macrophytes for nearshore fish production and biodiversity".

Publications

"The influence of different volumes and types of detached macrophytes on fish community structure in surf zones of sandy beaches in south-western Australia" (submitted).

2.3.5 Ichthyoplankton Assemblage Structure in Coastal, Shelf and Slope Waters off South-western Australia

Barbara Muhling
School of Environmental Science
Division of Science and Engineering, Murdoch University

Supervisors: Dr Lynnath Beckley (Murdoch), Dr Tony Koslow (CSIRO)

Project aims

1) To document ichthyoplankton (larval fish) assemblages in coastal, shelf and slope waters off Western Australia

The SRFME biophysical oceanography program, of which this project is a component, has involved regular sampling for a period of three years (2002 to 2004), along a transect of five stations running offshore from the town of Two Rocks. All stations were sampled on a quarterly basis, and the three inshore stations were sampled monthly. Larval fish were collected by using oblique bongo net tows to 150m in deep water, or otherwise to within 10m of the sea-bed. Depth-stratified and night-time samples were also collected on two voyages on the RV *Southern Surveyor*, in August 2003 and January 2004.

All plankton samples have been sorted to remove larval fish, with the exception of the depth-stratified and night-time samples, and the larvae from sorted samples have been identified up to October 2004. Initial analysis involves a simple calculation of larval densities per m^3 of seawater. This shows the changes in larval fish densities over time at each station. Data for the three inshore stations (A-C) for the three year voyage period are shown in Figure 12. Sea surface temperature data from concurrent CTD casts are also presented, to show the variability across the transect between seasons, and between years.

Station A (18m), the closest inshore, shows the clearest seasonal trend, with higher larval fish densities in summer, and the lowest in winter. Both stations B (40m) and C (100m) were dominated by inter-annual variability, with high densities of larvae in the spring and summer of 2004. This was most likely to due to inter-annual variations in regional oceanography, in particular, the strength and timing of the Leeuwin and Capes Currents.

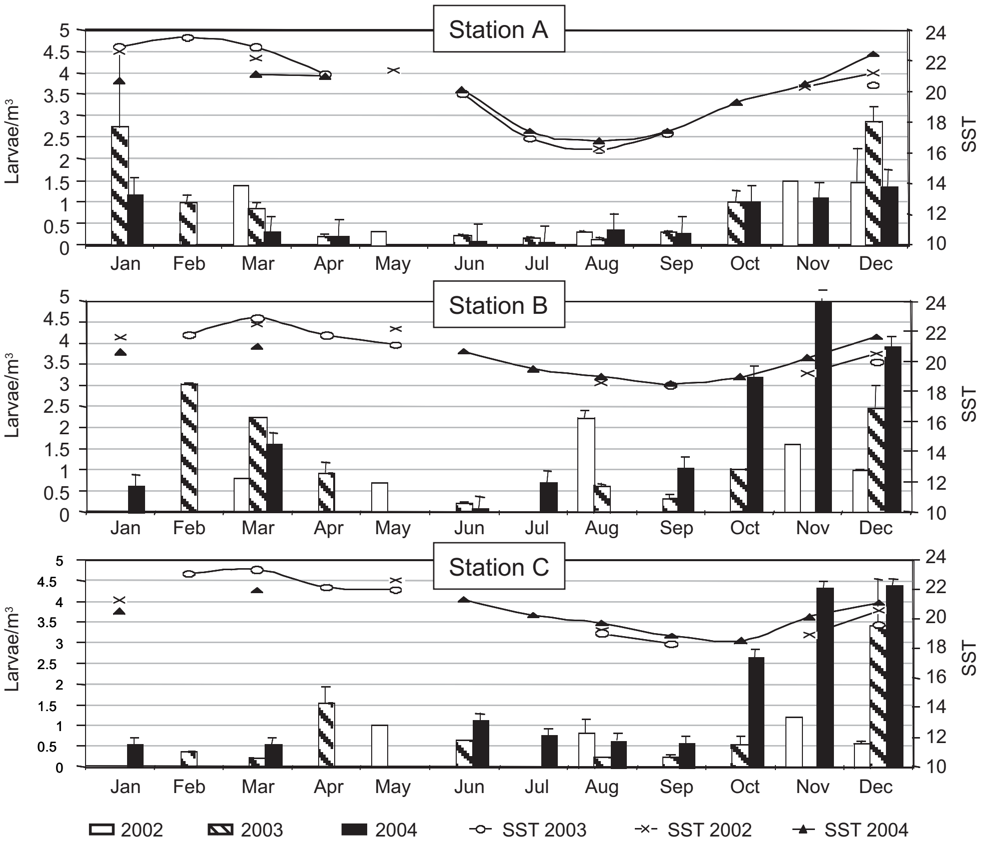


Figure 12: Larval fish density per m^3 of seawater at stations A (18m), B (40m) and C (100m), 2002 to 2004. Sea surface temperature is also shown.

2) To document the seasonal and inter-annual changes in these assemblages

Once the larval fishes in the samples have been identified, species matrices within and between stations and years can be analysed to determine trends and similarities between assemblages, using multivariate analytical packages such as PRIMER. One of the possible outputs from PRIMER is a cluster analysis, where samples are grouped based on the similarity of their species assemblages. A cluster analysis of larval fish assemblages from August 2002 to September 2004 is shown in Figure 13.

Assemblages divide into the broad groups of offshore, shelf and inshore samples, with these groups further split into smaller clusters as shown. These groupings are generally composed of samples from different seasons, for example, the shelf assemblage may be further divided into an autumn/winter shelf assemblage, a summer/autumn shelf assemblage, and a spring/summer assemblage. These distinctions are a result of both the spawning biology of fish species, and of the changing oceanography, and productivity patterns throughout the year. The investigation of these linkages will provide a clearer picture of the forces driving ichthyoplankton assemblages, and this encompasses the third major aim of the project.

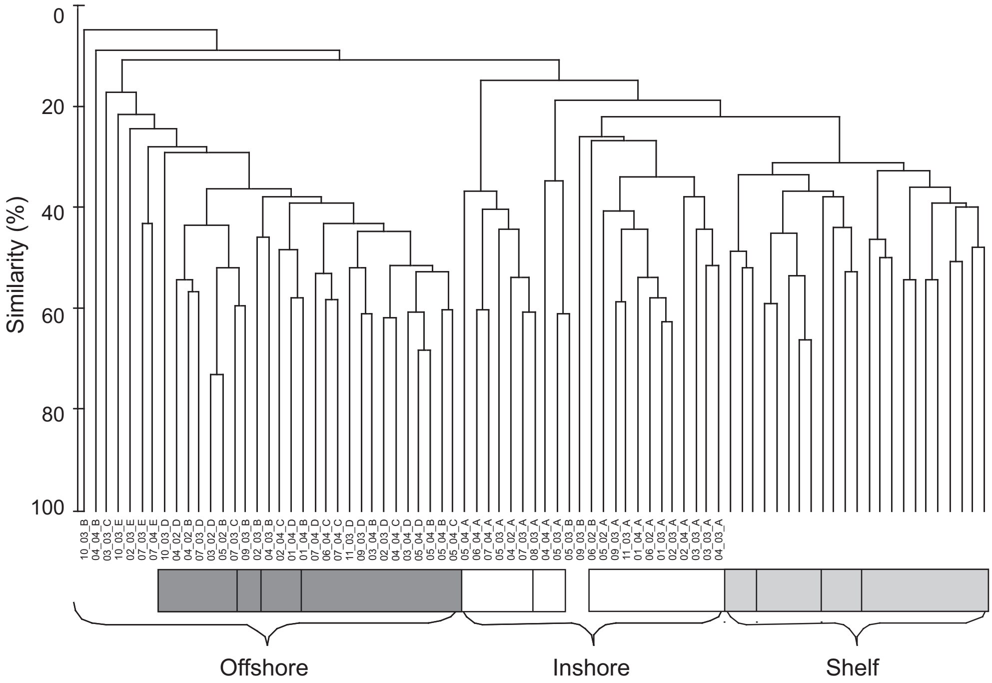


Figure 13: Cluster analysis of ichthyoplankton assemblage structure: August 2002 to September 2004

3) To examine the links between larval fish assemblages, and regional oceanography

This section of the project is progressing, as oceanographic and productivity data are collated and analysed. Ichthyoplankton assemblages may be structured by a number of oceanographic and biophysical conditions and events. These may potentially include water mass movements, such as those relating to the strength and position of the Leeuwin and Capes Currents, the intrusion of oceanic water to coastal areas, or the export of coastal water to offshore areas. These broad scale features, along with climatological conditions around the time of sampling, will affect components of the local environment, such as the spatial distribution and magnitude of primary productivity in the water column, the presence of small areas of localized upwelling, and the existence of suitable food organisms for larval fish. When this information is related to the spawning and behavioural biology of species, conclusions may be drawn on the processes which are driving assemblages, and the sources of inter-seasonal and inter-annual variability between them.

4) To compare ichthyoplankton assemblages between two meso-scale Leeuwin Current eddies

This aspect of the project was investigated during a multi-disciplinary voyage on the RV *Southern Surveyor*, which took place over a period of 23 days in October 2003. Two eddies were examined: one warm core downwelling and one cold core upwelling. The aims of the voyage were to compare the physical and biological dynamics of the two eddies, and to investigate their role as both a transport mechanism for coastal primary production and larvae, and as a modifier of the biological environment in which fish and other larvae exist.

Data analysis for this part of the project is now complete, and a manuscript is being prepared for submission to a special issue of *Deep Sea Research*, devoted to results from the voyage.

Summary and Conclusions

In summary, the project is proceeding according to schedule, with analysis of samples nearly complete, and data analyses well underway. The remainder of 2005 will be occupied with the completion of the statistical analysis of ichthyoplankton assemblages, and the incorporation of biophysical factors into the interpretation of assemblage structure. Night-time and depth-stratified samples collected from the two *Southern Surveyor* voyages will be analysed, in order to investigate small scale variability across the transect. Chapters of the thesis will also be completed, in order to conclude the project by January 2006. Dr Pliar Olivar will also be visiting from Spain later in 2005, to assist with the identification of oceanic larvae from both the SRFME transect and the eddies voyage.

Project start date: January 2003

Thesis will be submitted: January 2006

Conferences attended

Muhling, BM, Beckley, LE and Koslow, JA, (2004) *"Ichthyoplankton assemblage structure in coastal, shelf and slope waters off Western Australia"*, oral presentation, AMSA national conference, Hobart, Tasmania.

Muhling, BM, and Beckley, LE, (2004) *"Ichthyoplankton in Two Meso-scale Leeuwin Current Eddies: Preliminary Results"*, oral presentation, AMSA national conference, Hobart, Tasmania.

Muhling, BM, Beckley, LE and Koslow, JA, (2003) *"Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia"*, poster presentation, 2nd State Coastal Conference, Geraldton, Western Australia.

Other presentations

Muhling, BM, Beckley, LE and Koslow, JA, (2004) *"Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia"*, oral presentation, SRFME Student Symposium, CSIRO Laboratories, Floreat, Western Australia.

Muhling, BM, Beckley, LE and Koslow, JA, (2004) *"Ichthyoplankton assemblage structure in coastal, shelf and slope waters off Western Australia"*, oral presentation, AMSA student workshop, Rottnest Island, Western Australia.

Muhling, BM, Beckley, LE and Koslow, JA, (2003) *"Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia"*, oral presentation, SRFME Student Symposium, CSIRO Laboratories, Floreat, Western Australia.

Muhling, BM, Beckley, LE and Koslow, JA, (2003) *"Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia"*, oral presentation, AMSA student workshop, Rottnest Island, Western Australia.

2.3.6 Comparisons Between Benthic Macroinvertebrate Assemblages in Estuarine and Nearshore Marine Habitats

Michelle Wildsmith
Division of Science and Engineering
School of Biological Sciences, Murdoch University

Supervisors:
Dr F.J. Valesini, Prof. I.C. Potter (Murdoch University), Dr Russ Babcock (CSIRO)

Introduction

The nearshore marine and estuarine environments of south-western Australia comprise a range of different habitats, which can be distinguished on the basis of a suite of environmental characteristics. Differences among such habitats are thus likely to be reflected in differences in the compositions of their benthic macroinvertebrate assemblages. A thorough exploration of the ways in which these assemblages vary amongst habitats and the rigorous statistical analyses of faunal-habitat relationships depend firstly on the habitats having been distinguished on the basis of sound quantitative data and then on the ability to match statistically those data with quantitative data on species composition.

Aims

1. To compare benthic macroinvertebrate assemblages in different nearshore marine habitats on the lower west coast of Australia

Benthic macroinvertebrates were sampled seasonally in the subtidal and upper and lower swash zones at two sites in each of six nearshore habitat types on the lower west coast of Australia. The habitat types, which differed mainly in the extent of their exposure to wave activity and whether sea grass and/or nearshore reefs were present, had been distinguished quantitatively using values for a suite of seven statistically-selected enduring environmental characteristics (Valesini *et al*. 2003). The core samples yielded 121 species representing eight phyla, among which the Polychaeta, Malacostraca and Bivalvia were the most speciose classes, contributing ~ 38, 23 and 10%, respectively, to the total number of individuals. The total number of species and mean density of macroinvertebrates at the most protected habitat type (1), i.e. 70 and 209.2 individuals 0.1 m^{-2}, respectively, were far greater than in any other habitat type. Habitat type influenced species composition to a greater extent than either zone or season. Furthermore, the extents of the differences among the species compositions of the six habitat types statistically matched the extents of the differences among the values for the suite of enduring environmental characteristics that distinguished each of those habitat types. Overall, the species composition at habitat type 1 was the most distinct, containing five abundant species of polychaetes that were adapted to deposit-feeding in calm waters with high levels of organic material and which were rare in all other habitat types. In contrast, the fauna at the most exposed habitat type was characterized by four crustacean species and a species of bivalve and polychaete, whose mobility and tough external surface facilitated their survival and feeding in turbulent waters. The zonal differences in faunal compositions among habitat types were greatest in the case of the subtidal zone. The faunal compositions differed among zones and seasons only at the most protected habitat type.

The results of this part of my study have been completed as a chapter for my thesis and accepted for publication in the *Journal of the Marine Biological Association of the United Kingdom* (volume 85, 2005). The data were also presented in a seminar at the 52nd Annual Meeting of the North American Benthological Society, for which I received excellent feedback from world authorities in my area of research. The sampling techniques and statistical approaches developed in this study will be of great value for my estuarine studies.

2. Comparisons between benthic macroinvertebrate assemblages in nearshore habitats in the Swan-Canning Estuary

Environmental data (e.g. depth data, aerial photographs and location and volumetric output of main drains) was sourced and used to generate information on 18 different variables for one hundred sites in the lower, middle and upper regions of the Swan-Canning estuary. These variables included modified effective fetch distances in 9 different directions, distance to the two meter depth contour, distance to the nearest drain outlet and the average slope and percentage contributions of bare substrate, vegetated substrate (seagrass and macroalgae), rock, snags, reeds and bivalve beds to the substrate located within a 100m arc from the center point on the shore at each site.

In order to generate information on the contributions of the various types of substrate at each of the sites, aerial photographs were classified using the GIS program Idrisi Kilimanjaro v14. The data for these 18 variables were then used to classify the one hundred sites into different habitat types with the use of the SIMPROF module in the PRIMER v 6 statistical package.

Sampling of benthic macroinvertebrates in the shallow subtidal regions at pairs of sites representing eight of the habitats that were classified in the Swan estuary commenced in January 2005 and will continue seasonally until November 2005. The subsequent data will be used to investigate the extents to which the benthic macroinvertebrate fauna differ among habitat types and seasons in the Swan-Canning estuary and whether any such differences match those in the environmental variables that were used to distinguish those habitat types.

3. To compare recent and historical data on benthic macroinvertebrate assemblages in the basins of the Swan-Canning and Peel Harvey estuaries

Seasonal sampling and processing of benthic macroinvertebrates at four sites in both the Swan-Canning and Peel-Harvey estuaries were undertaken seasonally between winter of 2003 and winter of 2004. The samples have been processed and the results of this study are being compared with those recorded by Rose (1994) at the same sites in 1986/87 in order to elucidate the extent to which the benthic macroinvertebrate fauna in each estuary has undergone long term changes in composition and whether any such changes can be related to differences in the environmental conditions of those estuaries. Particular emphasis is being placed on determining how biotic variables, such as density, diversity and species composition in the middle estuary have changed as a result of a marked reduction in eutrophication. A first draft of this chapter will be completed by June 2005.

Summary and Conclusions

The marine component of my study has been completed and published in an international journal. Classification of the habitats in the Swan Estuary has also been completed and sampling of the resident benthic macrofaunal assemblages in 8 of those habitats has commenced. The fieldwork will be completed in November 2005 and a first draft of this component of the study will be completed by June 2006. A comparison between current and historical data on the benthic macrofaunal assemblies in the basins of the Swan and Peel-Harvey estuaries is underway and will be completed by June 2005.

Intended date for thesis submission: August 2006

Conference attended: Annual Meeting of the North American Benthological Society, Vancouver 2004 (presented marine component of my work).

Course Attended: Introduction to Geographical Information Systems (GIS), Murdoch University.

Publication (in press):

Wildsmith, M.D., Potter, I.C., Valesini, F.J. and Platell, M.E. (2005). Do the assemblages of benthic macroinvertebrates in nearshore waters of Western Australia vary among habitat types, zones and seasons? *Journal of the Marine Biological Association of the United Kingdom*, 85, 4787/1-16.

2.3.7 Uncertainty Associated with Marine Ecosystem Models

Sara Belmont-Kleingeld
Murdoch University

Supervisors: Murdoch - Dr Norm Hall (Centre for Fish and Fisheries Research)
Dr Graeme Hocking (Mathematics and Statistics)

Note: Sara has been on maternity leave for 9 months, so her most
recent progress report, dated April 2004, is included here.

Nature and Aims of the Thesis

This thesis uses a multidisciplinary approach combining mathematics, computer simulation and biological theory to produce a numerical model to represent a marine ecosystem. The aim of the study is to identify and simulate physical and biological factors that have a significant impact on marine ecosystems. The simulation model will be used to explore the range of model predictions based on the uncertainty in the model structure and parameter values. This study is being conducted in association with CSIRO Marine Research, forming part of the Strategic Research Fund for the Marine Environment program.

Achievements: January 2003 – April 2004

I spent a considerable amount of time developing and programming an ecosystem model based on a study conducted by the Perth Coastal Waters Study (Lord & Hillman 1995). Model development included the identification of a set of mathematical equations to describe the environmental and biological processes within a marine ecosystem. These equations were programmed into C++ along with a 4th order Runge-Kutta scheme to numerically solve the equations.

Cockburn Sound was selected as the study site due to the availability of fisheries, biological and environmental data. The initial model represented only a small subset of processes within an ecosystem, including a couple of environmental variables and some benthic processes. The model was run numerous times in order to investigate the effect of changes to some parameters values. The investigation revealed issues with model stability relating to unbounded population sizes. This finding indicates the model equations require a specific term containing a population “carrying capacity” in order to eliminate the occurrence of exponential growth or decay in the model output.

The next phase of the research plan was to modify and expand the initial model to include more species, in particular, those that exist higher up the food web. Fisheries catch and effort data dating back to the mid 1970s were analysed to determine the commercially significant species found within Cockburn Sound. These species were aggregated into functional groups based on size, diet, predation and method used for fishing. The following food web diagram shows the groups identified and the relationships that exist between each group (an arrow leading into a group indicates that species requires or preys on the group the arrow has come from).

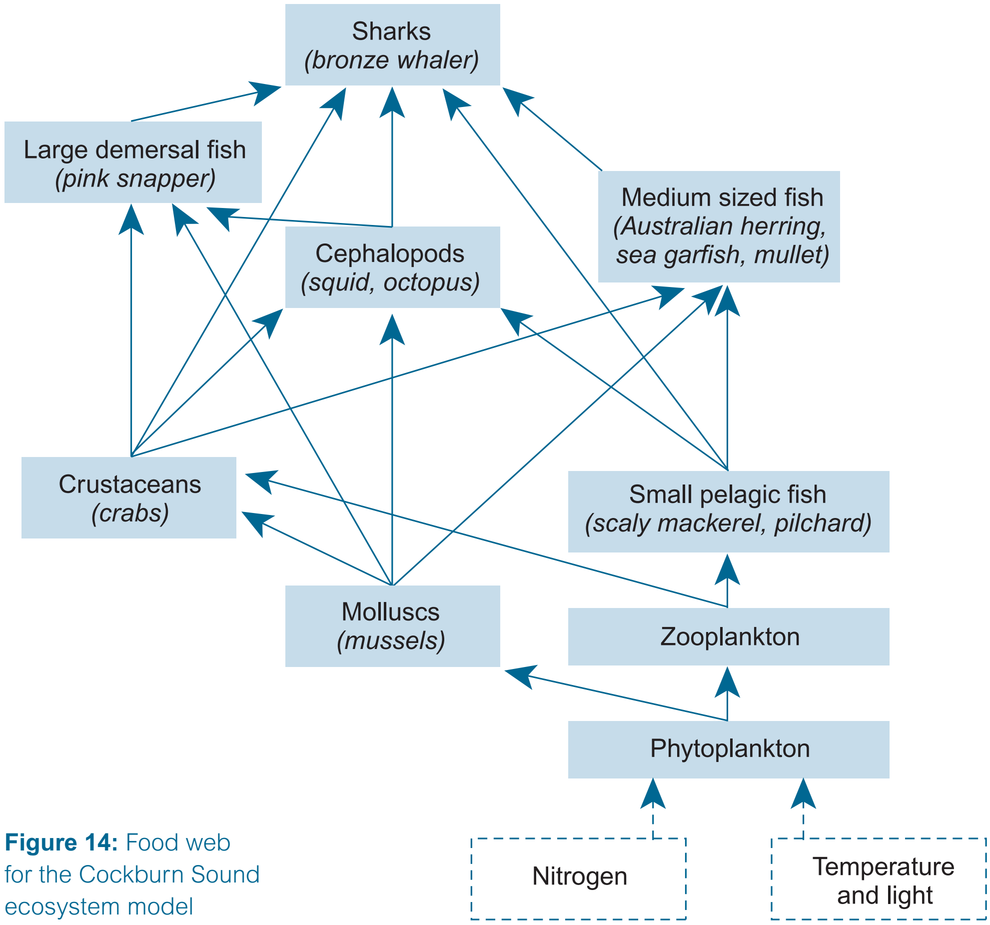


Figure 14: Food web for the Cockburn Sound ecosystem model

The current model reflects this food web structure and has the following attributes:

- Data input
  - – Environmental variables – temperature and light (values calculated using the sine curves described in Masini & van Senden 1995)
  - – Nitrogen (values input from data file, data derived from Bastyan, Paling & Wilson 1994 and Pearce, Helleren & Marinelli 2000)
- Phytoplankton and zooplankton populations calculated on a daily time step
- Fish, mollusc and crustacean populations calculated on a monthly time step. General equation for the biomass of species P:

$$\frac{dP}{dt} = (r + D \times \frac{\alpha \times \mathrm{Pr}\,ey}{D \times P + \alpha \times \mathrm{Pr}\,ey} \times AssimEff - M - F - \mathrm{Pr}\,edation - \frac{P}{CC})P$$

where

r = intrinsic growth rate
D = food demand (consumption rate per biomass)
α = availability of prey species
Pr *ey* = biomass of prey
AssimEff = assimilation efficiency (fraction of food converted to biomass)
M = natural mortality
F = fishing rate where F=Effort x Catchability
CC = carrying capacity

A difficulty arising in the development of an ecosystem model is how to determine the parameter values for each species for the general equation described above. For some of the biological parameters, ranges of values can be found in the literature. For the values not readily found in the literature, it is necessary to make certain assumptions in order to derive a particular value or range of values to be used as input parameters.

The primary aim of this study is to explore the uncertainty that arises in model output due to the manner in which the parameters are derived. I am currently carrying out a sensitivity analysis to determine which of the parameters has the greatest influence on the model output. This is done be varying each parameter by a prescribed relative amount then observing its effect on the long term forecast for each species. From this analysis, I will shortlist the most significant parameters and these will form the basis for an uncertainty analysis.

Drafts of three thesis chapters have been written. The first is an introductory chapter describing the need for this study. The second chapter is a detailed literature review including a historical timeline of the development of fishery stock assessment techniques and the current methods in use. The beginning of a third chapter contains a description of the study region, Cockburn Sound.

Future Work

Model uncertainty is defined as the unpredictable difference between model output and what is happening in the real world. An uncertainty analysis begins with determining the variables that contribute most significantly to the final model prediction (sensitivity analysis) then a technique known as “ensemble modelling” will be used to investigate the uncertainty. This involves constructing a density function for each parameter identified in the sensitivity analysis to reflect the likelihood they will take on some value within a possible range. These values will be propagated through the model to generate probability distributions of predicted output values. The derived probability distributions will then be used to make inferences about the probability of obtaining certain desired states of the fishery over a long period of time. With this knowledge of uncertainty, the final milestone of the project will be to consider how to manage fisheries based on the information predicted by the model.

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2.3.8 Coastal Groundwater Discharge and Nutrient Supply in a Semi-enclosed Marine Basin

Alicia Loveless
Centre for Water Research
University of Western Australia, Crawley WA 6009

Supervisor: Dr Carolyn Oldham

Introduction

Direct groundwater discharge may be a significant source of nutrients to surface waters, particularly in oligotrophic marine systems and "water poor" regions that experience periods of limited surface runoff. In coastal basins that are partially enclosed, the mixing and dilution of discharged groundwater is restricted compared to open sections of the coastline. Groundwater contaminants are therefore potentially available to primary producers for longer time scales. Understanding the interactions between hydrogeology and oceanography in coastal regions will aid in discerning the transport and fate of groundwater nutrients, and its role in coastal productivity.

Objectives

This project examines seasonal dynamics of submarine groundwater discharge in a complex coastal aquifer. The project intersects hydrogeology and oceanography, and investigates the magnitude of groundwater discharge, biogeochemical processing of groundwater nutrients prior to discharge, and transport of groundwater in the marine surface waters. New methodologies are applied to achieve these outcomes, and the significance of the work is enhanced by the contaminated nature of the regional groundwater and the impacts of the contaminants on the naturally oligotrophic Cockburn Sound.

Cockburn Sound is one example of coastal contamination by groundwater discharge, which can occur anywhere in the world where there is coastal development above an unconfined aquifer. The effects of groundwater contaminants in marine waters have been recognised in Cherrystone Inlet, Florida Keys and Waquiot Bay (Reay *et al*. 1992; Corbett *et al*. 2000; Charette *et al*. 2001). Further understanding of the magnitude and dynamics of groundwater and nutrient contaminant fluxes may help toward future remediation and management strategies.

Geochemical techniques are applied to achieve three research aims:

1. Obtain a regional estimate of groundwater discharge and groundwater nitrogen input;

2. Track the fate of groundwater in surface waters;

3. Examine pre-discharge processing of nutrients in the groundwater/marine mixing zone.

Approach

The Cockburn Sound superficial groundwater aquifers consist of a layer of sand underlain by a porous limestone layer. Dense saline ocean water sinks into the surface aquifer and intrudes up to kilometers inland, just as a salt wedge does in a surface water estuary. Fresh groundwater flows along its hydraulic gradient to discharge at the coast, flowing over the top of the intruded seawater. Sea level changes, wave and tidal pumping drive marine water into the aquifer at the shoreline, creating a pre-discharge mixing zone of marine and freshwater.

A confining layer between the sand and limestone aquifer often separates the two groundwater sources, and it is expected that the different groundwater bodies will discharge at different locations. Fractures in the confining layer, and subcropping of the limestone through to the benthic surface will create regions of focused discharge from such features which have been identified in Cockburn Sound (Burnett *et al*. 2004).

Geochemical tracers are useful in estimating groundwater discharge to coastal areas as a detailed knowledge of regional hydrogeology and geological heterogeneities is not required. Radium is one naturally occurring earth element that is used to trace and measure groundwater flux. Radium is generated from the radioactive decay of thorium bound in soil particles. With seawater intrusion, the radium atoms are out-competed by seawater ions for charged sites on sediments, and are freely dissolved in solution. The radium is advected out with mean groundwater flow. There are four radioactive isotopes of radium with a range of half-lives (Table 1), and these features make this element a very useful geochemical tracer of water fluxes across a range of timescales. Thus, hidden submarine aquifer heterogeneity is incorporated into the groundwater estimate by the radium technique.

Table 1.
Radium half lives and parent decay series

Series	**Parent**	**Daughter**	**Half life**
^{236}U	^{228}Th	^{224}Ra	3.66 day
^{235}U	^{227}Th	^{223}Ra	11.4 day
^{236}U	^{232}Th	^{228}Ra	5.75 yr
^{238}U	^{230}Th	^{226}Ra	1600 yr

The ratio of the short-lived ^{224}Ra to long lived ^{228}Ra radium isotopes are used to calculate surface water residence time (Equation 1) (Moore 2000; Charette *et al*. 2001; Kelly and Moran 2002). Due to the long decay time (1600 y), a change in the activity ^{226}Ra from the groundwater (GW) to Cockburn Sound surface water (CS) will be due to dilution and mixing of groundwater with surface waters. Changes in ^{224}Ra will occur due to decay and dilution. The relative change in the ratios of the short and long isotopes from groundwater to marine water therefore calculates the water residence time, τ, in Cockburn Sound (CS), according to the decay constant λ of ^{224}Ra ($t_{1/2}^{-1}$= 0.1894).

$$\left(\frac{^{224}\mathrm{Ra}}{^{228}\mathrm{Ra}}\right)_{\mathrm{CS}} = \left(\frac{^{224}\mathrm{Ra}}{^{228}\mathrm{Ra}}\right)_{\mathrm{GW}} e^{-\lambda_{224}\tau} \tag{1}$$

A radium mass balance is used to calculate an excess of ^{226}Ra activity in the Sound ($^{226}\mathrm{Ra}_{\mathrm{U}}$) that is not accounted for by end-member sources (sediments, suspended (SS), and benthic (B), and oceanic sources of ^{226}Ra (O)) (Equation 2). The marine activities are corrected for the total volume of the Sound (V), and the benthic sediments are extended to the total benthic surface area (A). The residence time τ accounts for loss ^{226}Ra in the Sound waters due to mixing with nearby coastal waters.

$$^{226}\mathrm{Ra}_{\mathrm{u}} = \frac{\left(^{226}\mathrm{Ra}_{\mathrm{CS}} - {}^{226}\mathrm{Ra}_{\mathrm{O}} - {}^{226}\mathrm{Ra}_{\mathrm{SS}}\right)\mathrm{V}}{\tau} - {}^{226}\mathrm{Ra}_{\mathrm{S}} \times \mathrm{A} \tag{2}$$

This excess $^{226}\mathrm{Ra}_{\mathrm{U}}$ is attributed to groundwater. SGD is calculated using this flux (m^{3} day^{-1}) and the mean activity in groundwater ^{226}Ra of the sand and limestone aquifer (mBq m^{-3}) (Equation 3).

$$^{226}\mathrm{Ra}_{\mathrm{u}} = \frac{\left(^{226}\mathrm{Ra}_{\mathrm{CS}} - {}^{226}\mathrm{Ra}_{\mathrm{O}} - {}^{226}\mathrm{Ra}_{\mathrm{SS}}\right)\mathrm{V}}{\tau} - {}^{226}\mathrm{Ra}_{\mathrm{S}} \times \mathrm{A} \tag{3}$$

Methods & Results

Pilot Study

A pilot study was conducted in Northern Harbour in March 2003 to test the radium activities and validate the mass-balance approach used to achieve the first project aim. The results of the pilot study demonstrated the usefulness of radio-isotope tracers. ^{224}Ra in groundwater is relatively high, at around 50 mBq/L. At the shoreline of the harbour, where groundwater is expected to be discharging, this activity decreases by an order of magnitude to ~ 4 mBq/L. Across the harbour the activity continues to decrease by one mBq, and reaches a constant value in Jervoise Bay of 1.83 mBq/L. ^{226}Ra also displays relatively high activity of ~ 20 mBq/Lin the groundwater, and decreases also by an order of magnitude to ~ 2 mBq/L, and further decreases to ~ 1.8 mBq/L in external waters.

Residence time of the water in Northern Harbour can be calculated from the amount of decay exhibited by the ^{224}Ra across sampling stations in the surface waters. As it has a short half-life, the decrease of ^{224}Ra across and out of the Harbour is due to radioactive decay as well as dilution of the groundwater in the surface water. The long lived isotope ^{226}Ra is used to account for dilution: The decay rate of ^{226}Ra is orders of magnitude longer than the flushing time of the surface waters, thus a reduction in ^{226}Ra activity in the Harbour is only due to dilution of the groundwater with marine water. This change in ^{226}Ra is used to correct for the dilution of the short-lived isotope, and the remaining decrease in ^{224}Ra is due to radioactive decay. The time taken for the groundwater ^{224}Ra to decay by that amount is calculated from the decay rate, and represents the transport time of the sample in the Harbour. Thus by calculating the decay of ^{224}Ra from the shoreline of the Harbour to Jervoise Bay, a residence time of water in the Harbour was calculated.

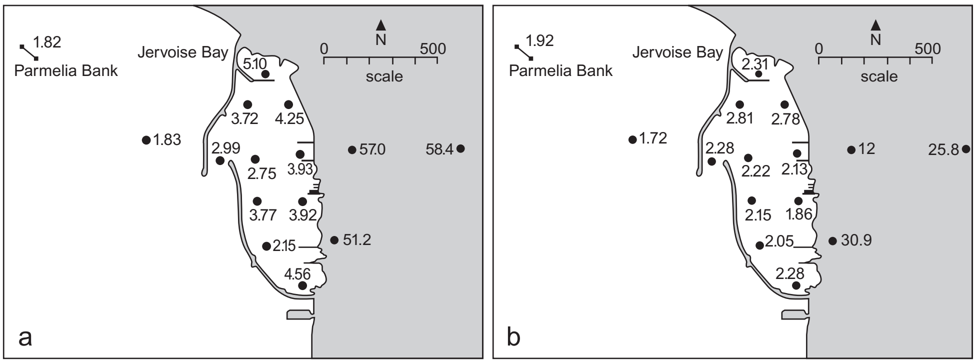

Figure 15: Radium isotope activities in surface water and inland monitoring wells at Northern Harbour, Cockburn Sound. a) Activity of long lived ^{226}Ra, $t_{1/2}$ = 1600 years. b) Activity of shortlived ^{224}Ra, $t_{1/2}$ = 3.6 days. Activities are in units of mBq/L.

The decreases in ^{226}Ra from the aquifer to the surface water is due to dilution of groundwaters with marine water in the harbour. Change in ^{224}Ra is due to dilution plus decay. The relatively constant ^{226}Ra activity across the harbour, Figure 15b, indicates that the harbour is evenly mixed, with the activity of ^{224}Ra decreasing from shoreline to harbour mouth. Using the ^{226}Ra to account for mixing the change in ^{224}Ra just due to decay is this line. Using Equation 3, a residence time of 2.2 days is calculated from mean activities, or 3.2 days from the shoreline to the mouth. This value is in agreement with 2.8-3 days summer exchange of harbour waters with Jervoise Bay calculated from HAMSOM modeling to estimate (Wright 2000).

At the time of sampling, a residence time of 2.8 – 3.2 days for water in the harbour was calculated from Equation 1. An excess of 8.41×10^8 mBq/L of ^{226}Ra was contained in Northern Harbour that cannot be accounted for by other sources. Using Equation 3, this method estimates a volume 36.7 m^3 of groundwater entering the harbour per day.

Estimates of groundwater discharge

The radium residence time and mass balance equations (Equations 1-3) are employed in a sampling array across Cockburn Sound basin and groundwater monitoring bores to estimate groundwater flux to the marine waters. Sampling was conducted at the locations marked in Figure 15 and groundwater stations at four times across a year to examine seasonality of the flux.

Using Equations 1-3 and the mean activities of radium in groundwater and surface waters (Table 2) an estimate of groundwater discharge is calculated (Table 3).

Table 2.
Radium mass balance results for Cockburn Sound, December 2003.

CS Mean Activity ^{226}Ra (mBq/L)	1.71
GW Mean Activity ^{226}Ra (mBq/L)	7.01
Ocean ^{226}Ra (mBq/L)	0.14
Sediments (mBq/m^2)	$0.7 \times 10^{-3} + 7 \times 10^{-5}$

Table 3.
Radium mass balance results for Cockburn Sound, December 2003.

τ (days)	Excess ^{226}Ra (mBq/L)	Discharge (m^3/day)
29	1.91×10^7	1.37×10^3

This estimation of groundwater discharge in Cockburn Sound is in progress. All results are in progress. There is not enough space in this report to present nutrient and radium data from September 2003, March 2004 and July 2004. Error analysis of the data and Equations 1-3 is not presented. Further work currently taking place is the splitting of the radium mass balance result into two models according to the transmissivity of the two different aquifer layers and the variability of radium levels between the two aquifers. This work is in preparation of publication under the title "A two-layer radium model to estimate seasonal patterns of groundwater discharge into a semi-enclosed coastal basin."

Mixing of groundwater in marine waters

A seasonal study of radium concentrations in marine surface water was conducted in September and December (2003), March and July (2004). Sample locations are presented in Figure 15. Plotting the two short-lived radium isotopes relative to each other at each location reveals mixing and transport of the groundwater in surface waters on the timescale of the isotope half-lives. During September, all sampling stations exhibited low activities of ^{224}Ra and ^{223}Ra, indicating that groundwater radium is well mixed across the Sound on the timescale of 3 - 11 days. In December there was a separation radium activity at the different sampling locations. By March, the separation of the sample sites represented different masses of water circulating within the Sound. The furthest offshore sample (CS1) was lowest in radium, suggesting no nearby source of groundwater. Along shore were higher activities of radium, indicating less decay and therefore a recent and nearby groundwater source. The interior of Sound (CS6, CS8 and CS9) exhibit low activities, signifying that the water in this part of the Sound is largely diluted by low-activity marine water or that the groundwater radium has decayed with distance from the groundwater source.

Current work is being carried out on modeling Cockburn Sound ocean circulation using wind data at the times of sampling. A HAMSOM oceanographic model for Cockburn Sound, developed at the Centre for Water Research, indicates surface water currents in the sound, with a particle tracking ability. Reverse particle tracking is currently being developed for the sampling locations, to determine the trajectory of particles arriving at the sampling locations over 10 days prior to the sampling period. These results are being prepared for publication, under the title: "Short-lived radium isotopes as markers of groundwater movement and mixing in surface waters" and is expected to be submitted during May 2005.

Discharge biogeochemistry

The validity of using inland bore nutrient concentrations to estimate nutrient flux to the coast was tested. In the processes of discharge, groundwater flows horizontally through an aquifer and may encounter changing physico-chemical conditions. Varying mineralogy, microbiology, pH and aerobic status, for example, introduce potential for biogeochemical processing. In the subterranean groundwater/marine water mixing zone, nutrients and contaminants may be diluted along the groundwater flow pathway. A process-based understanding of the groundwater source will assist future preventative decision-making relating to contaminated groundwater discharge.

A two kilometer inshore groundwater transect has been built perpendicular to the shoreline at James Point. Two pre-existing clusters of multi-level bores on the site of BP, aligned normal to the flow, are sampled as typical inland bores. Five clusters of beach piezometers have been installed to depths of 1, 3 and 5m below the water table to continue the transect in the beach-face. Figure 16 illustrates the transect profile of the beach face, water table at the time of sampling, beach piezometers and two wells in one of the BP well clusters. The pre-discharge marine and fresh groundwaters of the superficial Safety Bay Sand aquifer were sampled to examine any horizontal changes in nutrient levels.

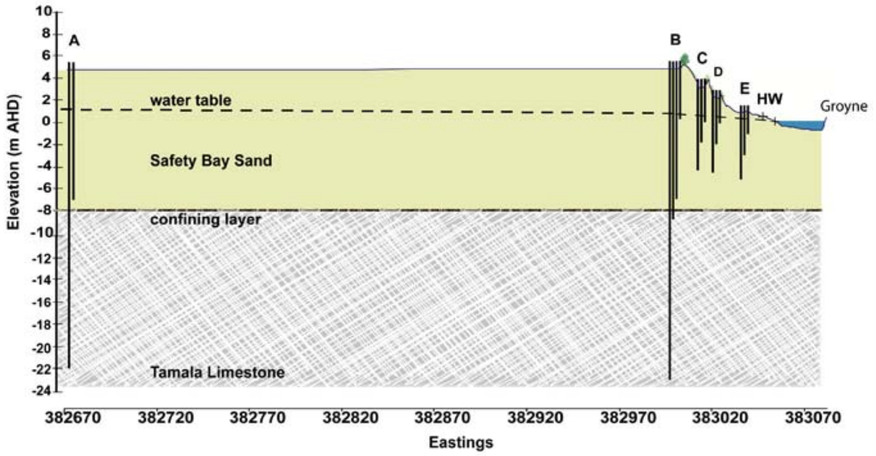

Figure 16: Beach profile and sampling wells located on beach face of James Point.

The suite of chemical species sampled along the transect indicated that a high degree of nutrient processing is occurring in the surface aquifer immediately prior to discharge. A distinct mixing region of fresh and marine water was identified at a depth to 5m below the beach surface, with a salinity gradient of very fresh water (0.1 ppt salinity) above seawater (36 ppt). This work is in current preparation for submission for publication at the end of April 2005, under the title "Pre-discharge biogeochemical cycling of groundwater nutrients in a sandy beachface."

Summary

The three aims of this project convene from different angles to achieve a process-based knowledge of groundwater nutrient supply to coastal waters. This study considers three stages of groundwater discharge:

– pre-discharge mixing, dilution and biogeochemical processing
– regional discharge and seasonal variability
– surface transport, dilution and biological nutrient uptake

A number of approaches and scales are used, and comparisons will be made between the estimate of groundwater nutrient discharge from these geochemical techniques with past discharge estimates.

Intended thesis submission date: 20 January 2006

2.3.9 Biogeochemistry of Seagrass Sediments

Kieryn Kilminster
School of Plant Biology
Faculty of Natural and Agricultural Sciences, University of Western Australia

Supervisors: Prof. Di Walker (Plant Biology, UWA)
Prof. John Raven (University of Dundee, Scotland)
Dr Peter Thompson (CSIRO, Hobart)

Introduction

Seagrass meadows are dynamic and productive environments. Interactions within seagrass habitats between seagrasses, epiphytic algae, benthic microalgae, sedimentary bacteria, and a large diversity of protists and invertebrates, are complex and often not well understood. Seagrasses manipulate sediment characteristics by detritus accumulation (Van Mooy & Keil 2002), support of benthic invertebrates (Sheridan & Livingston 1983), root oxygen loss (Connell *et al*. 1999), dissolved organic matter exuded from roots during photosynthesis (Penhale & Smith Jr. 1977) and demand for nutrients (Moriarty & Boon 1989). These processes may influence the fluxes of nitrogen (N) and phosphorus (P), and the subsequent availability of nutrients to the seagrass. Western Australia has some of the most extensive seagrass meadows in the world, with a large diversity of species represented. Many of these species are unique to Australia (Kirkman & Walker 1989). Understanding the processes maintaining seagrass nutrition is particularly pertinent for coastal waters of Western Australia where residual nutrient concentrations in water columns are low.

Specific Aims and Major Findings

1. Does organic matter enrichment of sediment benefit the seagrass?

Halophila ovalis acquired nutrients following the addition of either particulate organic matter (POM) or dissolved organic matter (DOM). Seagrass leaf P concentrations increased following organic matter addition (Table 4). There was a linear relationship for nitrogen *versus* phosphorus concentrations in roots and rhizomes but not for leaves. Below-ground nutrient concentrations may better demonstrate inherent differences between species of seagrass, yet for determining response to eutrophication leaf concentrations are a more effective measure of seagrass nutrient status. The nutrient content of *H. ovalis* was manipulated by sediment OM enrichment in this study, yet remained in the centre of the range typical of seagrasses worldwide (Fig. 17).

Table 4.
Seagrass tissue nutrient concentrations (mean n=8, ± SE) for pooled POM and DOM enriched samples. Concentrations displayed as % wt to simplify comparison to published critical nutrient values. Control data (no organic enrichment) is displayed first and data in parentheses is for highest organic matter enrichment treatments (i.e. 12 g POM or 5.2 g DOM).

Plant Part	[N] % by wt	[P] % by wt
Leaf	2.0 ± 0.1 (2.3 ± 0.1)	0.205 ± 0.009 (0.267 ± 0.009)
Rhizome	0.97 ± 0.07 (0.99 ± 0.04)	0.15 ± 0.02 (0.155 ± 0.009)
Root	0.94 ± 0.09 (0.94 ± 0.08)	0.105 ± 0.009 (0.12 ± 0.02)

Addition of organic matter (OM) to *Halophila ovalis* cores resulted in a general decrease in plant production (Fig. 18). Seagrass exposed to more DOM produced larger leaves and more above ground biomass relative to below ground biomass. Addition of OM may have caused an increase in below ground sulphide concentrations. Response of *Halophila ovalis* producing bigger leaves and more above-ground biomass relative to below-ground biomass may be interpreted as the plant increasing oxygenation of sediment via higher photosynthetic rate.

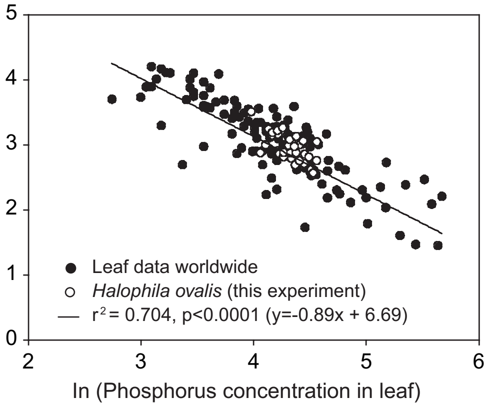

Figure 17: Plot of [P] in seagrass leaf tissue versus atomic N:P ratio (in transformed) for *Halophila ovalis* from this experiment (DOM and POM) comparted to data for eight genera of seagrass worldwide.

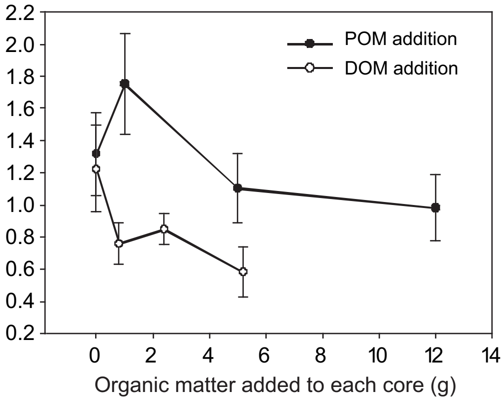

Figure 18: Biomass production of *Halophila ovalis* decreased overall for additions of either particulate organic matter (POM) or dissolved organic matter (DOM) (mean ± 1SE, n=4).

Porewater nutrient concentration data shows that P, removed to a relatively greater extent than is N, was translocated to the leaves. Data on the timescale of the utilization of N+P by *Halophila ovalis* demonstrates that the plants are initially able to benefit from a pulse of organic matter. The greater biomass of the seagrass initially relative to the microalgae and bacteria enables the seagrass to compete better for the increased pulse in nutrients. After a few days, competition from microalgae and from bacteria reduces the nutritional benefit seen by the plant.

2. Does the seagrass sediment of Western Australia support similar numbers of bacteria as other sites world wide? Does this vary with seagrass species or site?

Numbers of bacteria enumerated from Western Australian seagrasses were 10 – 100 times less than values for other seagrasses published worldwide. *Halophila ovalis* showed the highest number of attached bacteria (~1×10^7 CFU g^{-1} dry weight root), followed by *Posidonia sinuosa* and *Amphibolis antarctica* (both ~4-5×10^6 CFU g^{-1} dry weight of root). The significant difference in the number of bacteria enumerated from *H. ovalis* ($p < 0.01$) when compared to the number of bacteria enumerated from either *P. sinuosa* or *A. antarctica*, could be indicative of either season (autumn *vs*. spring) or environment (estuary *vs*. oceanic).

3. Is the stable isotope signature of sedimentary bacteria more strongly coupled to seagrass in a pristine, oligotrophic site than a site with more allochthonous inputs? Is age of seagrass critical in the establishment of microbial communities in seagrass sediment?

Samples have been collected from two sites in Albany (Fig. 19) and are awaiting analysis for the $\delta^{13}C$ of PLFAs. In Oyster Harbour, sediment was collected from seagrass transplant sites of known age (1 yr, 3 yr and 10 yr). In Two Peoples Bay, clump size was used as a surrogate for age.

4. Does light reduction also impact seagrass ability to acquire nutrients?

A laboratory experiment was run to assess the impact on the nutrient cycling of *Halophila ovalis* following light reduction. Nutrient analyses are incomplete at present; however the productivity of *H. ovalis* showed the expected decline with light reduction.

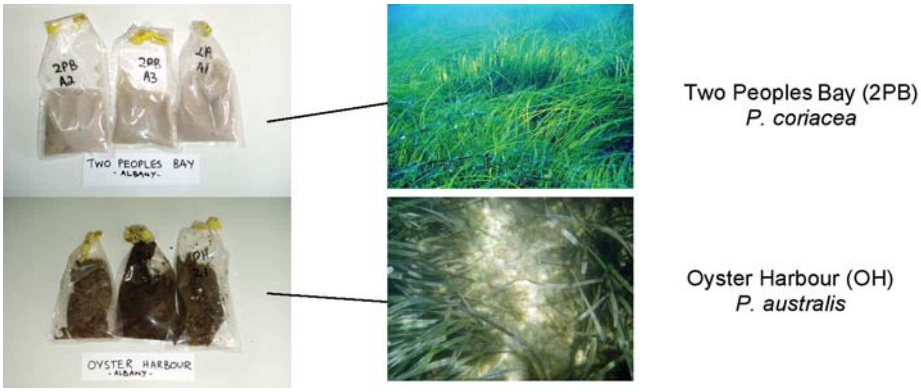

Figure 19: Contrasting sediment types from two sites in Albany

Summary and Conclusions

Seagrasses do benefit nutritionally from inputs of organic matter, however the reduction of growth seen across the experiments suggest that there is a fine balance between inputs of organic matter and supply of oxygen to the sediments. In oxygen-poor sediment, bacterial decomposition utilizes sulphate as the electron acceptor producing increased concentrations of sulphide in the sediment. As has been seen in other work, increases in sulphide can directly inhibit seagrass production (Koch & Erskine 2001). This work establishes that there should be equal environmental concern for pollution by either inorganic nutrients or organic matter inputs. Continued inputs of organic matter will favour microalgal and bacterial production rather than seagrass production, and most likely lead to reduced water quality. This outcome also seems likely for chronic low level inorganic enrichment of water systems where epiphytic algae will out-compete seagrass for inorganic nutrients, thus leading to a chronic organic matter increase to the sediment as the epiphytic algae turn over.

A low population of sedimentary bacteria was found associated with roots of several species of seagrass from south-western Australia highlighting how little is known about the interaction and importance of heterotrophic bacteria in nutrient regeneration in oligotrophic environments.

It is expected that outcomes of the incomplete experiments will further demonstrate that seagrass manipulated sediment changes do influence nutrient regimes especially in environments with typically low nutrient resources.

Intended thesis submission date: December 2005

Conferences: International Society for Plant Anaerobiosis (ISPA) Sept 2004 (poster), SEAGRASS 2004 –Sept 2004 (Oral), GRDC Root and soil biology Workshop - Nov 2003 (Poster)

Courses: Microsensor Workshop (Jan 2004), Thesis writing workshop (Nov 2004), CMM microscopy courses (2003) – SEM, ESEM, EMPA, TEM, BTEM

Awards: Travel award towards travel to attend GRDC Workshop in Canberra

Publications

Kilminster, K.L., Walker, D.I., Raven, J.A., 2004. Few sedimentary bacteria attached to seagrass roots in south-western Australia. (Submitted to *Aquatic Microbial Ecology*, March 2004)

Kilminster, K.L., Walker, D.I., Thompson, P.A., Raven, J.A., 2004. Amendment of seagrass sediment with organic matter: growth and nutrient response of *Halophila ovalis*, in culture. (In preparation)

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Koch MS, Erskine JM (2001) Sulfide as a phytotoxin to the tropical seagrass *Thalassia testudinum*: interactions with light, salinity and temperature. *J Exp Mar Biol Ecol* 266:81-95

Moriarty DJW, Boon PI (1989) Interactions of seagrasses with sediment and water. In: Larkum AWD, McComb AJ, Shepherd SA (eds) Biology of Seagrasses. Elsevier Science Publishing Company Inc, New York, p 500-535

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2.3.10 The Influence of Benthic Microalgae on Nitrogen Cycling in Western Australia

Hugh Forehead
Botany/Centre for Water Research,
Plant Biology/Engineering, University of Western Australia

Supervisors: Gary Kendrick, Peter Thompson, Anya Waite

Introduction

Benthic microalgae (BMA) can affect nutrient cycling in a number of ways: by assimilation of nutrients, modulation of bacterial processes by photosynthetic oxygen release, decay of the algae leading to release of labile organic carbon and fixing of nitrogen gas by blue-green algae. The extent of these effects is dependent on the microalgal biomass and community composition. The communities of benthic microalgae are strongly affected by wave and current disturbance and sediments are exposed to widely varying regimes of such disturbance by the geography of the WA coastline. My research has examined the ways in which the sediment communities are affected by physical disturbance by waves and currents, by seasons, nutrient enrichment and how in turn the communities affect various nitrogen fluxes (dissolved inorganic nutrient (DIN) exchanges, denitrification and N_2 fixing). My approach has been a combination of surveys of sites with different degrees of wave exposure, and of *in situ* manipulations by disturbing, sheltering and enriching sediments. Fluxes are measured by ex-situ incubations at UWA and sediment biota (benthic microalgae and associated organisms) are measured by a range of biomarkers and other sediment characteristics in Hobart at CSIRO Marine Research.

Major findings of each aim

A. To determine whether long-term shelter of sediments decreases the capacity of the sediments to retain dissolved inorganic nitrogen.

Study areas were Hillary's Boat Harbour, Two Rocks Boat Harbour, Mangles Bay and Jervoise Bay. Sediments at paired sites in each area outside (exposed) and within (sheltered) artificial structures (sea walls) were compared for sediment properties and fluxes.

Diatoms dominated the sediment community at all locations, implying that despite an oligotrophic water column, the sediment's BMA communities were not limited by N.

Bacterial biomarkers also represented a major fraction of the lipid profiles and correlated strongly with microalgal markers; implying that BMA were the main source of labile organic matter in these systems.

Organic C concentration and C:N ratio were greater at sheltered than at exposed sites.

Levels of net primary production and community respiration were greater inside than outside sea walls.

Denitrification rates were greater inside than outside Northern Harbour, but the pattern was reversed at Mangles Bay.

DIN fluxes increased into the sediments with sheltered areas, NH_4^+ comprised the majority of N fluxes.

Sediments appear to be net sinks of N, uptake is generally higher inside than outside sea walls.

B. To examine changes in sediment communities and N cycling with seasons.

Using the same sites within Cockburn Sound as for study A, measurements were made in winter and summer.

N_2 fixation was not detectable in winter, and comprised less than 10% of summer time N fluxes.

Denitrification was a smaller flux than N_2 fixation and occurred at similar rates in winter and summer.

BMA and bacteria biomass and measured fluxes were less in winter than in summer.

C. To examine the effect of depth on sediment communities and N cycling.

At the north of Cockburn Sound, 3 transects down Parmelia Bank were measured at 4 depths, from 1.5m to 14m deep.

The sediments at the 3 lower depths (4m, 8m and 14m) were not significantly different in terms of community composition or flux rates.

The 1.5m sites had sediments with no visible color to suggest algal colonisation (deeper sites had areas of golden brown sand, due to BMA), and coarse grain size, consistent with frequent resuspension by currents and waves. Biomarker analyses revealed lower biomass of algae and heterotrophs. Flux rates were also smallest at the shallow sites.

D. To determine whether short-term enrichment and/or shelter increases the proportion of cyanophytes in the BMA community and increases N_2 fixing activity.

Plots in 7m depth, south of Woodman Point were treated in one of 3 ways: either left open (control) enclosed (E) or enclosed and enriched with PO_4^- (E+E). The experiment ran over 10 days, plots were sampled at the beginning and end.

Enclosing the sediments resulted in an increase in BMA biomass.

There was a small BMA community shift in the enclosures; there was an increase in cyanophytes in all enclosures and a small decrease in the proportion of chlorophytes in the enriched enclosures. Diatoms increased as a proportion of the community in all treatments over the experiment.

There was an increase in bacterial biomass concurrent with the increase in BMA.

There was no measurable N_2 fixation before or after the experiment, even though it was measured in similar sediments nearby.

E. To determine if simulated sediment resuspension decreases BMA biomass and sediment nutrient fluxes.

16 plots on the south side of Woodman Point were sampled, then either raked or left undisturbed. A second raking was done after 2 days, then the sediments were sampled a second time and measurements taken.

Community biomass and the magnitude of sediment fluxes were decreased in raked plots relative to control plots.

Denitrification rates were low, at the limits of detection.

N_2 fixation was not detectable before or after the experiment.

Summary and Conclusions

BMA do play an important role in the coastal ecosystems studied: as a sink for nutrients under conditions of water column stability, and as a source when sediments are resuspended.

BMA provide high levels of primary productivity through efficient recycling of nutrients within the sediments. This is likely to have implications for the support of higher trophic levels, such as grazing fish.

BMA are not light limited at depths of up to 14m; which includes large areas of sediment around the WA coastline.

Denitrification and N_2 fixation are rarely significant N fluxes in these systems.

Disturbance of the sediments is important in influencing the biomass, composition and functioning of the sediment communities. Hence the degree of exposure to, and temporal frequency of current and wave activity must be taken into account when attempting to model sediment processes.

Intended date to submit thesis for examination: 11 September 2005

Awards received, professional development courses attended, conferences attended, or presentations given.

Attended Sediment biogeochemistry conference, SCU, Lismore, NSW, 2002

Presented oral paper at the Phycological Society of America 2003 Annual Meeting at Gleneden Beach, Oregon, USA

Awarded the Hoshaw Award at the PSA meeting

Seminar in MSE seminar series, 2004, CWR, UWA, Perth, 2004

Oral presentation at SRFME student symposium, 2004

Oral presentation at Biotechnology and Environmental Applications of Microalgae meeting at Monash University, 2005

Gas safety course at CSIRO Marine Research, 2004

Scientific writing course at CSIRO Marine Research, 2003

Report writing course at CSIRO Marine Research, 2003

Multivariate statistical analysis course at Newport, Oregon, USA, 2003

3 day workshop on fluorescence measuring techniques for microalgae, Monash University, Melbourne, 2005

2.3.11 Ecological and Historical Processes Maintaining Macroalgal Diversity in the Recherche Archipelago, Western Australia

Nisse Goldberg
School of Plant Biology, University of Western Australia

Supervisors: Gary Kendrick, Di Walker, Alan Butler

Introduction

The macroalgal flora of southern Australia is among the richest globally. Records of macroalgal distributions and abundances remain incomplete because of the length and remoteness of the south coast. This thesis provides a comprehensive description of the diverse subtidal flora found in the Recherche Archipelago (RA), links patterns of diversity to potential surrogates, to dispersal potential, and to interspecific interactions. In addition, contemporary diversity in the RA was assessed in context with biogeography.

Aim 1: Characterize the systematics and distribution of the macroalgae in the Recherche Archipelago, Western Australia

Over 250 species were recorded in the RA, of which 42 had range extensions, with the new species *Sargassum kendrickii* described (Goldberg and Huisman 2004; Goldberg and Kendrick 2005) (Figs. 20, 21). In addition, one rhodolith bed was sampled in Esperance Bay. The number of nongeniculate coralline species consisted of at least three of the following genera: *Melobesiodeae, Mastophoroideae, Lithothamnion, Hydrolithon*, and *Sporolithon*. The structure of subtidal reef assemblages consisted of a diverse canopy and understory layer. Diversity and distribution of canopy and understory species differed with wave exposure and depth (Goldberg and Kendrick 2004). For example, fucoid canopy species were more abundant in depths <10 m and understory species *Osmundaria prolifera* and *Botryocladia sonderi* were more abundant in depths 10-20 m. Macroalgal diversity showed no consistent temporal variation, particularly between austral spring and autumn. Assemblages were characterized with high species turnover, with each species present in only 15% of the sampled quadrats, and with numerous species fertile in spring and autumn. Successful recruitment despite continual physical disturbance from Southern Ocean storms may ensure high species diversity.

Figure 20: *Sargassum kendrickii*.
Scale = 3 cm.

Figure 21: Detail of receptacles.
Scale = 2mm

Aim 2: Identify surrogates for macroalgal diversity in the Recherche Archipelago, Western Australia

To minimize sampling effort in future surveys in the RA, the ability of potential surrogates- higher taxonomic levels and dominant taxa- to predict species diversity was investigated. Patterns in species diversity were retained with species richness data (Fig. 22a, b), indicating species turnover and not necessarily relative abundance can accurately characterize macroalgal diversity. Success of dominant-taxa surrogates was dependent on island location (Fig. 22c, d). Where differences in exposure were presumably greatest, the dominance of *Ecklonia* and other canopy taxa successfully predicted species diversity at the genus level, particularly in depths 10 m and greater. Genera of dominant taxa did not capture species-level patterns of diversity at inshore islands as well as at offshore islands. Sampling effort would be reduced if collecting richness data in species-rich macroalgal assemblages such as those found in temperate Australia.

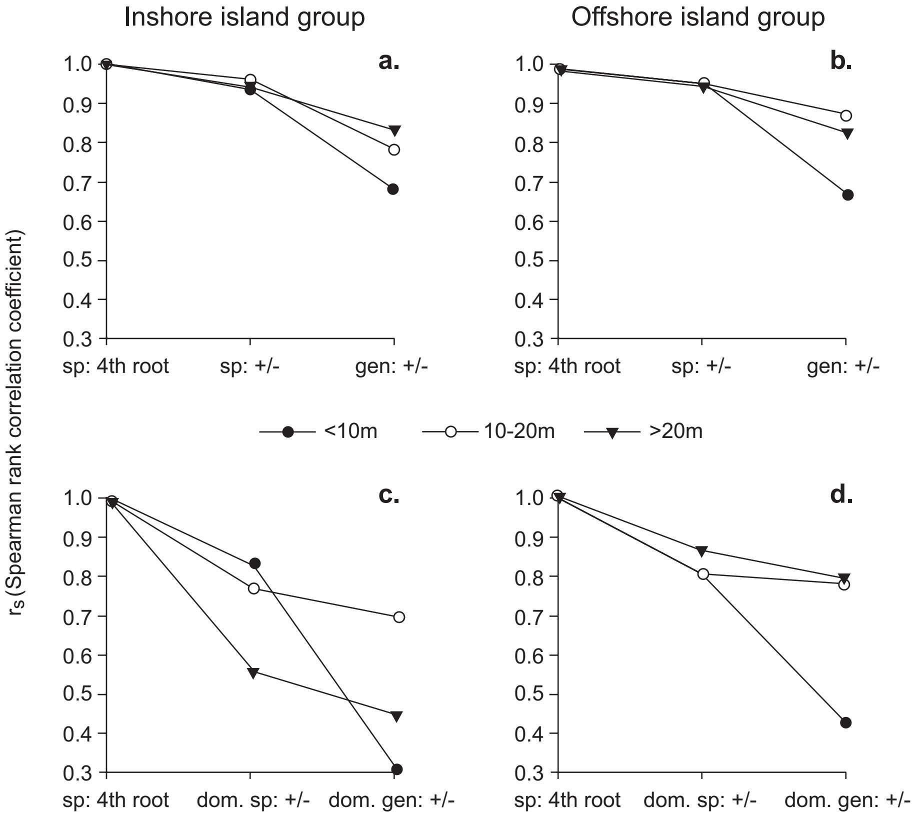

Figure 22: Correlation (modified Spearman rank) between similarity matrices of species diversity[a] and surrogates at inshore and offshore islands in three depth strata. Surrogates: a.,b. species and genus presence/absence (+/-) data[b]; c,d. dominant (dom.) species-level and genus-level +/- data[b]. n = 36- 0.25 m^2 quadrats per depth stratum within each island group. *P* = 0.001 for all tests. [a]Diversity data were 4th root transformed. [b]Diversity data were transformed to +/- data.

Aim 3: Link patterns of diversity with dispersal potential of macroalgae

To investigate if algal diversity was maintained from within island reef assemblages, dispersal potential, as measured by presence of recruits of resident species was estimated with increasing distance from subtidal reefs. Dispersal shadows of canopy taxa (up to 50 m away from subtidal reefs) were found to be narrower than for understory taxa (up to 500 m away from subtidal reefs). Diversity in the RA may be maintained via dispersal within island reefs for canopy species and among island reefs for many understory species (Goldberg *et al*. 2004).

Aim 4: Link patterns of diversity with interspecific interactions

The effects of canopy and understory layers on macroalgal recruitment and vegetative recolonization were compared between depths where canopy and understory species were most abundant. Recruits of canopy Sargassaceae were more abundant in the presence of canopy layers in depths <10 m, and in cleared areas for recruits of canopy Cystoseiraceae. Understory species *Osmundaria prolifera* and *Botryocladia sonderi* recruited in the presence and absence of understory and canopy layers, and were more abundant in depths 10-20 m. Depth-associated factors may control species distributions more than the presence of canopy or understory layers.

Aim 5: Assess contemporary diversity in context with biogeography

To investigate if local and/or regional processes drive contemporary patterns of species diversity in the RA, macroalgal floras were compared between the RA and temperate Australia. In addition, species diversity was compared among three island groups in the RA. The flora of the RA was continental in origin, and similar to that of the south coast. High species turnover was common within island groups, a pattern that has been documented elsewhere along the south coast. High regional species richness in temperate Australia influenced the flora in the Recherche Archipelago, with little indication of ecological processes depressing diversity at the local scale.

Summary and Conclusions

The macroalgal flora of the Recherche Archipelago was characteristic of the flora of the southern coast of Australia. Subtidal macroalgal assemblages were similar to assemblages found east of the Great Australian Bight. Patterns in macroalgal diversity in the Recherche Archipelago were presumably related to past speciation events and shared biogeography along the southern coast of Australia. In addition, diversity may be maintained via coexistence of species that share niche characteristics. The structure of subtidal macroalgal assemblages consisted of two layers: a locally-maintained, diverse, and abundant canopy layer; and an understory layer that was species-rich. Understory species, with their widespread distributions contributed to high species diversity for macroalgae across the southern coast of Australia.

Date thesis was submitted for examination: February 17, 2005

Awards

Australasian Society of Phycology and Aquatic Botany, Phycological Society of America and the University of Western Australia travel awards, August 2004; Australian Institute of Nuclear Science and Engineering research awards, December 2004, 2005; Australian Marine Sciences Association grant to attend International Marine Biological Workshop held in Esperance, Western Australia, February 2003; Australian Marine Sciences Association travel award, July 2003; Strategic Research Fund for the Marine Environment best paper awards, June 2003 and 2004.

Professional development courses attended

"Detecting multivariate changes in biological assemblages: Experimental design and analysis", June to July 2004.

"The PVCR's ARC Grant Workshop for Graduate Research Students", January 2005.

Conferences attended/presentations given

Phycological Society of America, 2004; Strategic Research Fund for the Marine Environment Symposium, 2003, 2004; Australian Marine Sciences Association, 2003; Australasian Society for Phycology and Aquatic Botany, 2002 and 2004.

Publications

Book chapters

Goldberg, N.A., Huisman, J.M. 2005. First record of tetrasporangia in *Herposiphoniella plurisegmenta* Womersley (Rhodomelaceae: Rhodophyta). In: *The marine flora and fauna of Esperance, Western Australia*. Wells, F.E., Kendrick, G. A., Walker, D.I. (Eds.), W.A. Museum, Perth (Accepted April 2004, in press).

Goldberg, N.A., Kendrick, G.A. 2005. A catalogue of the marine plants found in the western islands of the Recherche Archipelago (Western Australia, Australia), with notes on their distribution in relation to island location, depth, and exposure to wave energy. In: *The marine flora and fauna of Esperance, Western Australia*. Wells, F.E., Kendrick, G. A., Walker, D.I. (Eds.), W.A. Museum, Perth (Accepted April 2004, in press).

Journal articles

Goldberg, N.A., Kendrick, G.A., Walker, D.I. 2005. Do surrogates describe patterns in marine macroalgal diversity in the Recherche Archipelago, temperate Australia? *Aquatic Conserv: Mar. Freshw. Ecosyst*. (in press).

Goldberg, N.A., Huisman, J.M. 2004. *Sargassum kendrickii* (Fucales, Phaeophyceae) a new species of subgenus *Phyllotrichia* from southern Australia. *Botanica Marina* 47:424-430.

Goldberg, N.A., Kendrick, G.A., Heine, J.N. 2004. Highway or country road: Algal recruitment with distance from an island reef. *Journal of the Marine Biological Association of the United Kingdom* 84:879-882.

Goldberg, N.A., Kendrick, G.A. 2004. Effects of island groups, depth, and exposure to ocean waves on subtidal macroalgal assemblages in the Recherche Archipelago, Western Australia. *Journal of Phycology* 40:631-641.

Kendrick, G.A., Harvey, E.S., Wernberg, T., Harman, N., Goldberg, N. 2003. The role of disturbance in maintaining diversity of benthic macroalgal assemblages in southwestern Australia. *The Japanese Journal of Phycology* 51:5-9.

2.3.12 Diurnal Fluctuations in Primary Production in Shallow Waters off South-western Australia

Florence Verspecht
Centre for Water Research, University of Western Australia

Supervisors: Dr Anya Waite, Professor Charitha Pattiaratchi & Dr Peter Thompson

Outline of Research Project

Research into aspects of the variability of marine production on a spectrum of spatial and temporal scales has highlighted the lack of understanding of planktonic responses at the smaller, higher frequency scales of perturbation. Here, the physical processes controlling diurnal fluctuations in primary production are investigated and the biological effects of wind-driven mixing in the oligotrophic waters off south-western Australia are characterized. The coast of Western Australia experiences a diel cycle of mixing and stratification, recorded in various other field studies including Wilson Inlet, Whitfords Lagoon and Cockburn Sound. Stratification and vertical mixing affect the movement of phytoplankton through the water column, and consequently the irradiances they experience. Previous studies have shown that neither stabilization nor destabilization of the water column favours production and that frequent alternation in the physical stability of the water column is conducive to enhancing primary production. Phytoplankton responses differ according to the intensity and persistence of this mechanical energy input. The aim of this study is to determine whether local wind-mixing augments the potential for production in the nearshore zone through varying of the light and nutrient climate that phytoplankton experience. Experiments have thus been conducted in the lagoonal waters off the south-west coast to characterize the physical stability of the water column, biological response and nutrient status for three sites with varying exposures. High frequency time-series were obtained during summer and winter for chlorophyll *a*, fluorescence, dissolved oxygen, temperature, conductivity, light and current data. Primary production was estimated through carbon uptake experiments with one hour *in situ* incubations and photosynthetic efficiency was estimated using high frequency pulse amplitude modulated (PAM) fluorescence measurements. Preliminary results will be discussed in the context of a highly dynamic coupled biophysical environment.

Aims

1. Characterise the diurnal stratification/mixing cycle and determine whether this cycle enhances the potential for production using pulse amplitude fluorometry.

In order to physically characterise the mixing and stratification cycle, vertical profiles of conductivity, temperature and depth (CTD) were taken at 20-minute intervals for two days at each site during summer and winter. Density plots were created for each data set and from this the potential energy anomaly was calculated for the water column. The potential energy anomaly is an indication of the level of stratification and the higher the value (ϕ), the greater the stratification. The potential energy anomaly is found to increase during the day (with increased solar heating) and then decrease with wind mixing (sea breeze) in the afternoon (Figure 23) for all sites during summer. Winter results have also shown this dynamic diurnal cycle to a lesser extent.

The non-dimensional Richardson number (Ri) will then be used to determine the presence of active turbulence. The Richardson number is calculated by dividing the static stability number (N^2) by the vertical current shear $(dU/dz)^2$, where $N^2=(g/\rho)(d\rho/dz)$. A larger Ri indicates the presence of stratification. The CTD profiles provide the density values with depth for N^2 and current measurements were obtained using an acoustic doppler current profiler (ADCP).

Rapid light curves (RLC) have been constructed using a pulse amplitude modulated fluorometer (PAM) and these will be used to determine if the instantaneous electron transport rate and yield are correlated to the physical stratification and mixing cycle. The slopes and maximums of the RLC's show how well the phytoplankton were producing at that instant in time at that depth. In addition to the PAM curves, photosynthesis-irradiance (PI) curves will be plotted using production values obtained through carbon uptake experiments that were conducted on the second day at each site every 2 hours. Samples were incubated in situ with ^{14}C for an hour and filtered to obtain a carbon uptake value for each depth and PI curve.

Using the physical results from the CTD profiles and ADCP time-series to obtain potential energy anomaly and Richardson numbers, and correlating these with the biological PAM and ^{14}C production results will show whether the stratification and mixing cycle is enhancing the potential of the water column for phytoplankton production.

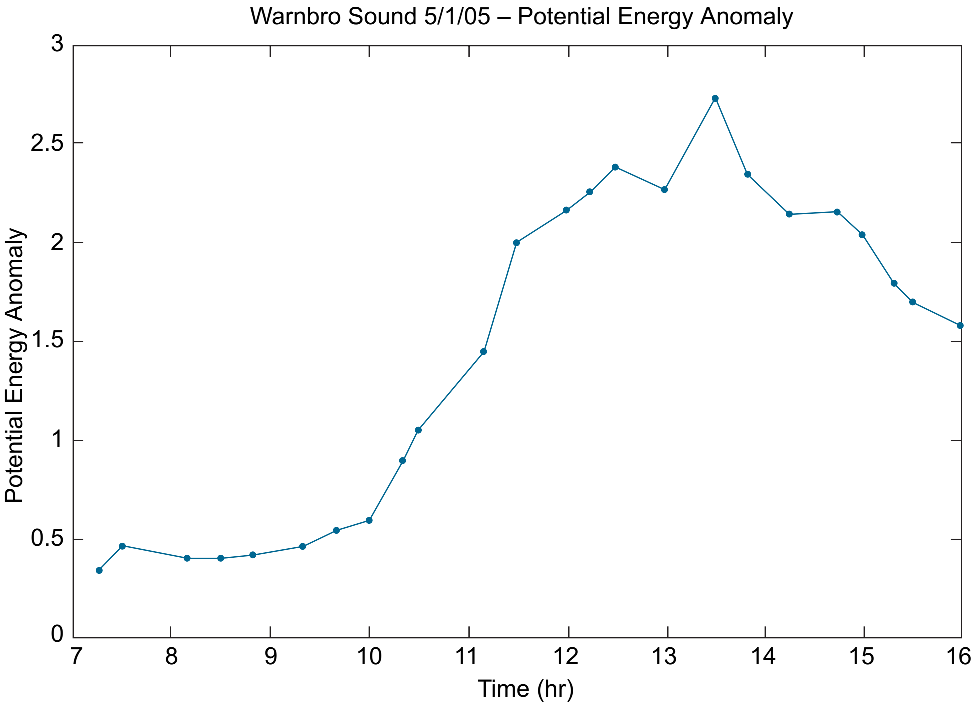

Figure 23: Potential energy anomaly with time plot for Warnbro Sound 5/1/05

2. Determine whether diurnal fluctuations in chlorophyll *a* and primary production are significant with respect to fluctuations between sites and seasons.

Preliminary results indicate that the fluctuations on a diurnal scale are of the same order of magnitude as the fluctuations on a seasonal scale. Winter chlorophyll *a* concentrations are shown to be higher than summer chlorophyll *a* concentrations. The 'calm' autumn season will be sampled during April and May, 2005. This will complete all seasons experienced along the Western Australian coastline.

The most enclosed site sampled (Mangles Bay) has shown to have the strongest diurnal cycle and the highest chlorophyll a concentrations. The lowest concentrations and diurnal signal was found at the most exposed site, Warnbro Sound.

3. Elucidate diurnal fluctuation patterns in the nutrient status of the water column and determine whether this is correlated to chlorophyll a and primary production.

Nutrient samples were collected every hour for 0, 5 and 9m each day at all sites. This data will be correlated with electron transport rate and yields from the PAM and with primary production values from the carbon uptake experiments. The hypothesis that wind mixing and storms make nutrients available to phytoplankton and consequently enhance production is being investigated.

Intended date to submit thesis for examination: February, 2006

Workshops and Conferences attended

BEAM Research Network Postgraduate Workshop: This was attended in Melbourne (February 2005) to learn more about applications of microalgae. Topics discussed included PAM fluorometry, culturing and phytoplankton photosynthesis. An experiment using PAM to investigate nutrient induced fluorescence transients (NIFTS) was conducted involving all the student participants and will be published in the near future.

Indian Ocean Marine Environmental Conference (IOMEC): This was attended in Perth (February 2005) and work from this research was presented during the Primary Production session. During the conference I was involved in the organizing committee and helped with registrations and general organizational tasks.

Publications

A conference paper was presented at the Indian Ocean Marine Environmental Conference (IOMEC) in February 2005 entitled ‘Diurnal fluctuations in primary production in shallow waters off south-western Australia’.

2.3.13 An Investigation of Spatial and Temporal Variations in the Abundance and Species Composition of Microzooplankton and Their Growth and Grazing Rates off Western Australia

Harriet Paterson
School of Animal Biology
Faculty of Natural and Agricultural Sciences, University of Western Australia

Supervisors: Brenton Knott, Tony Koslow, Anya Waite

Abstract

Assessment of the microzooplankton assemblage and their impact on phytoplankton was quantified using samples collected from the “Two Rocks” transect on the lower west coast of Western Australia. In depth studies of marine microzooplankton have not been made in this region previously. This investigation was undertaken as a component of the Biophysical Project, a core project within the Strategic Research Fund for the Marine Environment (SRFME). The microzooplankton was highly variable in terms of it community, abundance and impact on phytoplankton. The abundance of microzooplankton varied from an average of 2000 cell l^{-1}, with blooms reaching 10 000 cell l^{-1} inshore during the first autumn bloom of each year. The impact of grazing varied from 0 to 100 % of phytoplankton production with the greatest impact occurring offshore, indicating that the microbial food web is the dominant pathway offshore and the classic food web influences the fate of production inshore.

Aims/objectives

The objectives of this study were to:

1 Characterise the microzooplankton assemblage, its temporal and spatial variability and the influence of environmental forcing.

2 Quantitatively assess the herbivory of microzooplankton on phytoplankton both temporally and spatially.

3 Develop a conceptual food-web model of plankton less than 200 μm.

Results

Objective 1: Investigate the microzooplankton assemblage, its temporal and spatial variability and the influence of environmental forcing.

Samples were collected from 3 sources. The primary source was from the "Two Rocks" transect as part of the biophysical monthly sampling program. Additional samples were collected from a cruise that covered the region from the Abrolhos Islands south to the Capes region and from of two eddies approximately 300 NM West North West from Perth. From each sampling location approximately 850 ml of seawater were collected from the surface and deep chlorophyll *a* maximum, fixed in 10% acid Lugols and stored prior to examination by microscopy.

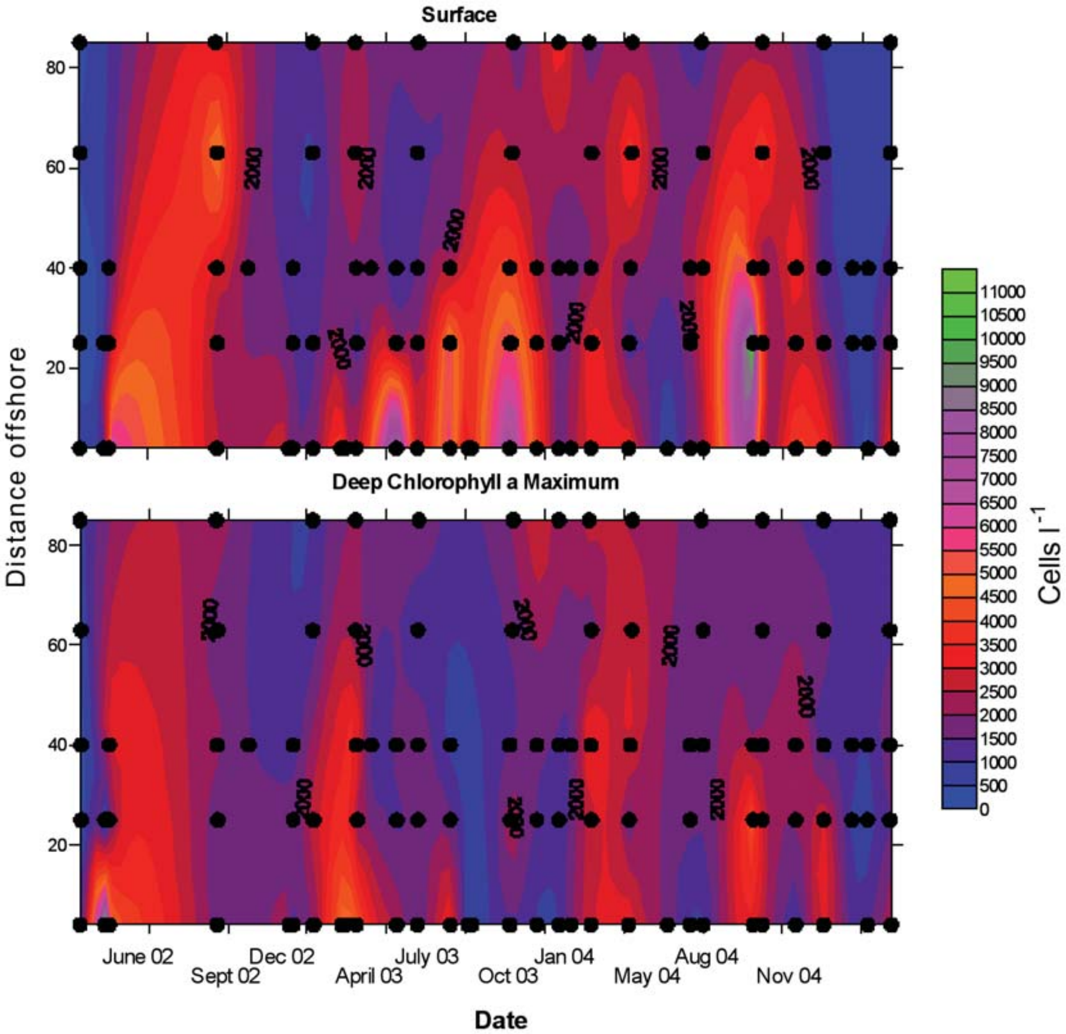

Figure 24: Microzooplankton abundance from February 2002 – December 2004 on the Two Rocks transect.

In total 300 samples have been examined by microscopy, from which abundance, bio-volume and carbon contribution of the major groups were calculated. Ciliates numerically dominate the assemblages; however heterotrophic dinoflagellates may occasionally dominate, and are generally present in high numbers. In keeping with other oligotrophic areas the average abundance of microzooplankton is approximately 2000 cells l^{-1}. Variability at the offshore stations (1000 m depth) is minimal compared to the inshore stations (15 m depth). The inshore station has the greatest blooms of up to 10 000 cell l^{-1} during autumn with smaller blooms during the remainder of the winter. Sustained lower abundances were found during summer. Species specific abundances followed the seasonal patterns of the assemblage as a whole. The only species to have a spatial niche was the tintinnid *Metacyclis* sp. which occurred at the inshore station (15 m depth) and occasionally at the inner shelf station (40 m depth).

Objective 2: Investigate the herbivory of microzooplankton on phytoplankton both temporally and spatially.

Investigations into the herbivory of microzooplankton on phytoplankton were concentrated on quarterly cruises on the “Two Rocks” transect, although experiments were also conducted during the Eddies cruise in October 2003. These experiments were based on the dilution method (Landry and Hassett 1982). These results again reveal a highly dynamic environment.

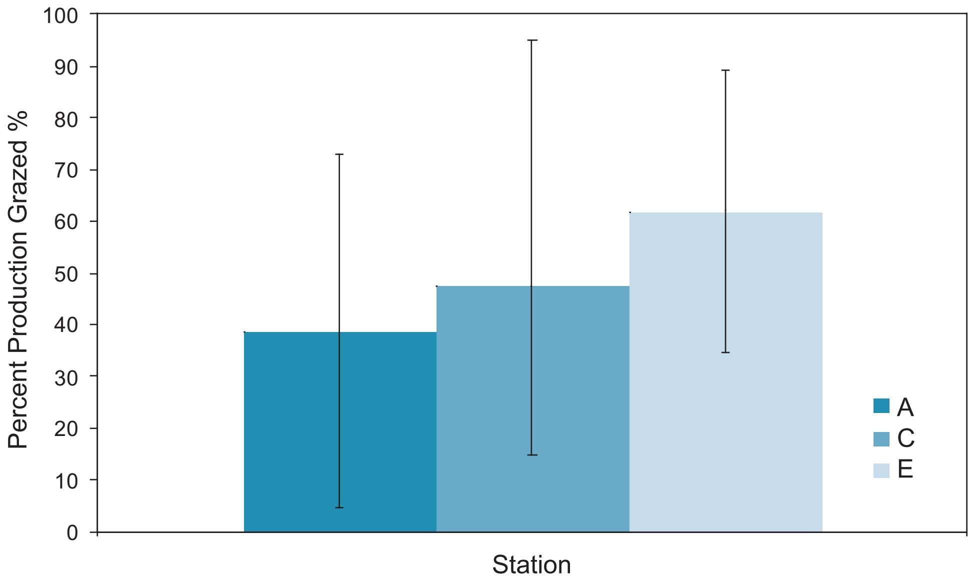

Figure 25: Percentage of primary production grazed by microzooplankton

Figure 25 shows an increasing trend in the percentage of primary production grazed by microzooplankton further offshore, although there is no significant difference between sites. Each experimental site was characterized by a high degree of variability in rate of grazing; however, the variability was greatest inshore where half the experiments resulted in no grazing. The inshore station is likely to be influenced by terrestrial inputs, and mixing from the sea bed, leading to a greater potential for eutrophic conditions. Under these circumstances this station may support large cells such as diatoms and subsequently the classic food web. Further offshore small phytoplankton cells dominate the phytoplankton assemblage due to their ability to obtain nutrient more efficiently from a nutrient poor environment, out-competing larger cells, thus making the microbial food web more important.

Objective 3: Develop a conceptual food-web model of plankton less than 200 µm for the Two Rocks transect.

The development of a conceptual food web aims to answer the question of “How many tropic transfers are there within the micro – planktonic food web”. This question is of particular interest in light of the findings of the Landry and Calbet (2004) summary paper which finds that four trophic transfers within the microzooplankton fraction reduces the ability of primary production to support larger organisms.

Intended date to submit thesis for examination: November/December 2005

Awards:
SRFME Student Symposium 2003 – Best abstract
SRFME Student Symposium 2004 – 2nd presentation

Symposia:
Third International Symposium on Zooplankton in Spain, May 2003
SRFME Student Symposium 2003
SRFME Student Symposium 2004
AMSA 2004

References

Landry M. R., Calbet A (2004) Microzooplankton Production in the Oceans. *Ices Journal of Marine Science* 61:501-507

Landry M. R., Hassett R. P. (1982) Estimating the Grazing Impact of Marine Micro-zooplankton. *Marine Biology* 67:283-288

3. Collaborative linkages program: collaborative projects

3.1 SRFME Collaborative Projects

The objective of this program is to deliver strategic research outcomes, capacity building and new and/or strengthened research collaboration among Universities, other research providers and government agencies. A total of $1.99 million has been committed to the funding of eight collaborative projects within SRFME, to universities and institutions including the University of Western Australia, Edith Cowan University, Murdoch University, and the WA Museum.

One SRFME collaborative projects symposium was held at the Floreat Laboratories of CSIRO, in June 2004.

3.2 SRFME Collaborative Projects, PI's, and Affiliations

Project Title	Principal	Principal Investigators	Co-Invesigators
Interaction of Coastal Currents, Phytoplankton Dynamics and Trophic Transfer in the Coastal Waters of Western Australia	Dr Anya Waite – UWA	Dr Anya Waite – UWA Dr Peter Thompson – CSIRO Dr Luke Twomey – UWA Dr Dan Gaughan – WA Fisheries	Dr Michael Borowitzka – Murdoch A Prof Mervyn Lynch – Curtin
Spatial Patterns in Sessile Benthic Sponge and Ascidian Communities of the Recherche Archilpelago	Dr Gary Kendrick – UWA	Dr Gary Kendrick – UWA Dr Jane Fromont – WA Museum Dr Justin McDonald – UWA	Dr Euan Harvey – UWA Dr Chris Simpson – CALM
Understanding the Natural Variability of Currents Along the Western Australian coastline	Prof Charitha Pattiaratchi – UWA	Prof Charitha Pattiaratchi – UWA Dr Yun Li – CSIRO Dr Ming Feng – CSIRO	Dr Gary Meyers – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: Trophodynamics	Dr Glen Hyndes – ECU	Dr Glen Hyndes – ECU	Dr Mat Vanderclift – CSIRO Dr Russ Babcock – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster	Dr Glen Hyndes – ECU	Dr Glen Hyndes – ECU	Dr Russ Babcock – CSIRO Dr Mat Vanderclift – CSIRO
Ecophysiology of Benthic Primary Producers	Dr Paul Lavery – ECU	Dr Paul Lavery – ECU	Dr Russ Babcock – CSIRO
Biodiversity of Marine Fauna on the Central West Coast	Dr Fred Wells – WA Museum	Dr Fred Wells – WA Museum	Dr Russ Babcock – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: The Fish Communities and Main Fish Populations of the Jurien Bay Marine Park	Professor Ian Potter – Murdoch University	Professor Ian Potter David Fairclough – Murdoch University	Dr Russ Babcock – CSIRO

3.3 Collaborative Project Reports

3.3.1 Interaction of Coastal Currents, Phytoplankton Dynamics and Trophic Transfer in the Coastal Waters of Western Australia.

Dr Anya Waite (PI)
School of Water Research, University of Western Australia, Crawley WA 6009
waite@cwr.uwa.edu.au Ph. 6488 3082

Dr Peter Thompson (PI)
CSIRO Marine Research, Hobart, TAS
Peter.A.Thompson@csiro.au

Dr Luke Twomey (PI)
School of Water Research, University of Western Australia, Crawley WA 6009
twomey@cwr.uwa.edu.au Ph. 9360 2589

Dr Dan Gaughan (PI)
Department of Fisheries, Government of Western Australia,
Western Australian Marine Research Laboratories, POB 20 North Beach WA 6920
dgaughan@fish.wa.gov.au Ph. 9246 8444

Dr Michael Borowitzka (Co-PI)
School of Biological Science and Biotechnology, Murdoch University,
South Street, Murdoch, WA 6150
borowitz@possum.murdoch.edu.au Ph. 9360 2333

Assoc. Prof. Mervyn Lynch (Co-PI)
Head, Remote Sensing and Satellite Research Group, School of Applied Science,
Curtin University of Technology, PO Box U1987, Perth WA 6845
m.lynch@exchange.curtin.edu.au Ph. 9266 7540

Report

Project Aims

- To determine the extent to which new upwelled nitrate associated with the interaction between nearshore and continental-shelf currents in coastal waters near Esperance fuels phytoplankton productivity and trophic transfer to finfish and shellfish larvae.
- To determine whether N-fixation occurs in the Esperance region, and if so, to estimate its possible contribution to the growth of larval fish and shellfish.
- To develop an understanding of the link between primary productivity and the spatial and/or temporal distribution of larval *Sardinops sargax* in coastal waters between Albany and Esperance.
- In a comparative study, to map the larval abundance & health, and ecosystem structure of two eddies off the west coast of WA: a downwelling ("death-trap") eddy, possibly dominated by N-fixation, and an upwelling ("nursery") eddy, possibly dominated by upwelled nitrate.

Expected Outcomes

- Detailed understanding of the links between upwelling, phytoplankton nutrient requirements, and ecosystem structure off Esperance and in the eddy system off WA's west coast.
- Enhanced understanding of the links between primary productivity and fish population dynamics.
- Enhanced understanding of regional dynamics impacting the fisheries resources of WA.
- Improved ability to manage future commercial/industrial development.
- Estimate of the possible contribution to fish production made by N-fixing cyanobacteria, essentially short-circuiting the need for upwelled nutrients during non-upwelling periods.

Field Sampling Summary

Fisheries Sampling

9th July – 17th July 2003 (Albany to Hopetoun)
1st – 15th March 2004 (Hopetoun to Esperance)
11th – 17th July 2004 (Cape Naturaliste to Perth)

Scientific Objectives

- To test field equipment and observe the test site.
- To examine the vertical structure of salinity, temperature and fluorescence across the continental shelf break.
- To measure phytoplankton biomass, productivity and nitrogen uptake relative to nutrient availability.
- To measure spatial variability of phytoplankton biomass in surface waters.
- To collect particulate organic matter (POM) at various size fractions to examine the isotopic signatures various trophic levels.

Results

- Several major faults were encountered with the field equipment on the first cruise. These faults were rectified and new equipment was purchased to withstand the adverse weather conditions and high seas experienced on the south coast.
- CTD profiles were collected during each cruise.
- Surface water samples were collected for phytoplankton biomass, productivity and taxonomic analyses. When weather conditions permitted, samples were collected from the chlorophyll maximum depth (70-90m).
- The surface chlorophyll profiling equipment (DUDES) was severely damaged on the first cruise in high seas.
- Planktonic samples were collected and size fractionated for POM analysis.
- A PAM fluorometer was used to measure primary production.
- Nitrogen uptake incubators were used on each day to assist in the calculation of simulated *in situ* N uptake.

Summary

Due to the high seas, adverse weather conditions and equipment malfunction, the first fisheries field trip had low to moderate success. The trip was successful in providing base line data of phytoplankton composition and biomass, nutrients in the surface waters and some data on the vertical structure of salinity, temperature and fluorescence in the region. The trip was useful in highlighting the difficulties encountered in coastal oceanography and helped to highlight the weaknesses in our sampling techniques. We have since purchased more robust equipment and organised to use the CSIRO Seabird CTD to obtain more comprehensive profiles.

Despite poor weather, the second field trip had moderate to high success. The full complement of biological samples were collected, however the trip was hampered by failure of the DUDEs surface profiler and 4 days of corrupt CTD data.

Sea conditions were generally moderate to rough on the third cruise, however we were successful in collecting surface and deep chlorophyll maximum samples across the shelf-break, in an area where there is a paucity of biological oceanographic data. We obtained a comprehensive set of CTD casts to enable a good assessment of the spatial (north to south, on-shore to shelf-break and vertical) structure of the physical and biological characteristics in the region. The calculation of nutrient profiles and N uptake rates await water chemistry analysis. These samples are currently being processed. Chlorophyll extraction and POM analyses have been completed.

Albany Trench Sampling

February 2004, September 2004, October 2004, November 2004,
December 2004, January 2005, February 2005.

Scientific Objectives

- To test day trip field sampling regime and observe characteristics of the major field transect.
- To examine the vertical structure of salinity, temperature and fluorescence across the continental shelf break adjacent to the Albany trench.
- To measure phytoplankton biomass, productivity and nitrogen uptake relative to nutrient availability.
- To collect particulate organic matter (POM) at various size fractions to examine the isotopic signatures various trophic levels.

Results

- We sampled 7 sites, including 3 major sites for biological sample collection. A charter boat was taken across the continental shelf break to an area where the depth exceeded 500m.
- The CSIRO Seabird CTD was used to collect depth profiles of salinity, temperature, depth and fluorescence at sites.
- Surface and chlorophyll maximum water samples were collected for phytoplankton biomass, productivity, nitrogen uptake and taxonomic analyses at 3 major sites on each transect.
- Planktonic samples were collected and size fractionated for POM analysis at 3 major sites on each transect.

Summary

The day trips have been highly successful. All of the major objectives have been fulfilled and the full complement of physical, chemical and biological sampling was completed. The charter boat operators were extremely helpful and enthusiastic about the research program and were eager to continue throughout the course of the SRFME collaborative project.

We are currently conducting laboratory analyses of the samples collected during the first 12 months of intensive field sampling, and planning the next intensive summer field program during 2005/06 to characterise summer upwelling at the Albany trench.

Voyage Summary RV Southern Surveyor SS08/2003

Meso-Scale Eddies off Southwestern Australia:
Death-Traps or Nurseries for Fisheries Recruitment?

Objectives

The voyage objective was to study, in detail, both a cyclonic eddy and an anticylonic eddy off WA, and more specifically:

- To measure nutrient concentration gradients inside and outside the eddies and to estimate their fluxes;
- To estimate the rate and extent of 1^{ary} and 2^{ndary} production inside and outside the eddies;
- To estimate the contribution of nitrogen fixation to total primary production inside and outside the eddies;
- To determine the abundance of larvae inside and outside the eddies;
- To measure the downward flux of organic matter in the two eddies.

Results

All desired measurements were made within both Eddies, except that 1) loss of contact with the sediment trap buoy limited the number of sediment trap deployments in Eddy C (the second eddy studied) to a single long deployment rather than many short deployments, and 2) the SeaSoar mapping was occasionally interrupted by technical failure and in that case was replaced with CTD drops along the same eddy transect.

We put forward the following hypotheses:

1. Nutrient pumping, enhanced production and suppression of N-fixation occur in the cyclonic eddy

We already have clear evidence that nutrient pumping in Eddy C (the cyclonic eddy) was quite different than we expected in 1. We will possibly disprove this hypothesis. The cyclonic eddy was capped by a layer of temperate water, limiting the upwelling signature in the temperature and salinity field to a small upward-pointing cone in the centre of the eddy. Associated with this cone was a spherical high-fluorescence signature suggesting phytoplankton growth (and therefore nutrient upwelling and/or particle accumulation) in the immediate vicinity of the upwelling. However, we saw no evidence of large-scale upwelling, and it is unlikely that the deep upwelling we saw could impact surface nitrogen fixation.

2. Fish larvae and rock lobster phyllosoma are preferentially
aggregated within the anticyclonic eddy

Very cursory preliminary evidence suggests that larvae avoided the very low-nutrient anti-cyclonic eddy. Daytime catches of larvae were low and fish larvae appeared to remain below the eddy until night, when they rose into it. A very limited number of lobster larvae were observed.

3. The nutritional status of larvae is highest in the cyclonic eddy compared
to the surrounding waters and to the anticyclonic eddy

Preliminary observations suggest the anticyclonic eddy may have contained more biomass than the cyclonic eddy, and the cyclonic eddy was dominated by a large grazing population of salps, which may have decimated the biomass. If the cyclonic eddy consisted of a relatively self-contained mass of water (which does not discount the possibility of internal currents that may yet aggregate particles), the dominance by salps may represent the end of a succession of the plankton community, which had a finite reserve of nutrients.

4. The downward flux of organic matter is highest in the cyclonic eddy

This hypothesis was disproved. Both primary production and the downward flux of organic matter were highest in the anticyclonic eddy, by 2 – 4 X (Eddy B, Table 1).

Summary

In general, we consider Voyage 08/2003 to have been highly successful. The EZNet and the SeaSoar were crucial to this success. Despite being high-maintenance instruments, and occasionally failing, they allowed us to sample in ways otherwise impossible. The EZNet provided stratified sampling for the zooplankton and fish teams. The SeaSoar illuminated key oceanographic features and provided data that generated exceptional excitement and formed the basis for novel insights in this study. Other than the difficulty with some of the instrument deployment and retrieval from the stern of the Southern Surveyor, the ship itself was well equipped for the voyage, and generally well-run.

Voyage Summary RV Southern Surveyor SS09/2003

Continental Shelf Processes between Cape Leeuwin
and the Abrolhos Islands during the Summer.

Scientific Objectives

- To identify the physical and biological processes of the Capes Current, which flows along the south-west Australian continental shelf during summer and its extension to the region to the north of Rottnest Island terminating at the Abrolhos Islands.
- To define the role of the onshore geostrophic flow from the West Australian Current to the Leeuwin Current.
- To define the effects of topographic features of the Capes Current.
- Subsurface Chlorophyll Maximum (SCM) – determine if there is a consistent SCM on the shelf and under the Leeuwin Current, and the spatial extent of this feature between Abrolhos Islands and Cape Leeuwin.
- To assess onshore-offshore and alongshore patterns in the abundance, diversity and species composition of the zooplankton community.

Biological Oceanography Objectives

- To assess the spatial variability of phytoplankton biomass and to document species composition between Cape Leeuwin and the Abrolhos Islands.
- To measure primary productivity of the subsurface chlorophyll maximum (SCM) and determine its significance in driving the trophodynamics cross-shelf biological communities.
- To estimate nitrogen uptake in surface and in the SCM and determine whether the phytoplankton community is fuelled by nutrients recycled in the water column (NH_4) or through delivery of “new” nitrogen (NO_3) via upwelling.
- To examine the rate of nitrogen fixation in the coastal phytoplankton community and to determine whether or not atmospheric N contributes significantly to phytoplankton production.

Biological Oceanography Results

- Size fractionated chlorophyll extraction was conducted at the surface and SCM at three major sites on each transect. Preliminary results suggest that the majority of phytoplankton biomass is tied up in the <5 µm fraction.
- Size fractionated productivity measurements were conducted on phytoplankton collected at 5 depths in the photic zone of water column.
- Nitrate and ammonium uptake rates were conducted on surface and SCM samples collected at three major sites on each transect. The samples are currently being processed.
- Nitrogen fixation was conducted on surface and SCM samples collected at three major sites on each transect. These samples are also currently being processed.

Summary

The trip was considered very successful. The productivity data collected by Florence Verspecht (CWR PhD student) will fill large gaps in the current level of understanding of coastal phytoplankton dynamics in Western Australia. Additionally, the measurement of N fixation by Vanessa Pez (CWR honours student) will provide estimates of N fixation that have not previously been quantified in these waters. These data promise to provide important insight into the processes which control biological productivity and distribution of fisheries in this region.

Intended Date of Completion: 30th of September 2006

List of Students, Personnel, Awards, Conference Attendance and Presentations

Students
Vanessa Pez (Completed - 1st Class Honours)
Tim Malseed (Completed – 2A Honours)
Florence Verspecht (Continuing – PhD)
Elis Smedley (Continuing – Honours)

Personnel
Kim Brooks (Field and Lab Technician)
Geoff Bastyan (Field Technician)

Conference Attendance and Presentations

Australian Marine Science Association (AMSA) 2004

At the Australian Marine Science Association annual conference held in Hobart, July 2004, Drs Anya Waite and Stéphane Pesant organised a special session on Biological and physical oceanography off Western Australia and Mesoscale Eddies off Western Australia: Deserts and oases in an oligotrophic ocean. The session was organised to present the results from the Eddies Cruise (SS08/03) and the South Coast Survey (SS09/03) and to encourage discussion amongst our colleagues and peers. A highlight of the special session was the plenary presentation by Dr. R. Bidigare, biological oceanographer from the University of Hawaii. Dr. Bidigare also reviewed our project and participated in a workshop with key investigators discussing the preliminary outcomes of our work in the global context. Dr. Bidigare was highly complimentary of the project as a whole, and commended especially the excellent broad coverage of numerous important aspects of biological oceanography under the constraints of a modest budget. A list of the presentations that were directly associated with the current project are below:

Pattiaratchi *et al*. – Physical Oceanography off WA, Twomey *et al*. – Nutrient Limitation off WA., Pesant *et al*. – A size-fractionated approach to pelagic ecosystems off WA., Bidigare – Overview of mesoscale eddy features globally., Waite – Eddy Cruise Overview., Feng *et al*. – Physics of the Eddies., Pesant *et al*. – Phytoplankton component: DIC & DIN uptake., Thompson *et al*. – Phytoplankton component: HPLC & PAM, Holl *et al*. – Phytoplankton component: N-fixation., Paterson *et al*. – Microzooplankton component., Muhling *et al*. – Fish Larvae component : Ichthyoplankton in two meso-scale Leeuwin Current eddies: preliminary results., Waite *et al*. – Reconstructing the food webs: Isotopic signature approach., Pesant – SeaSoar Transects., Patterson *et al*. – Microplankton abundance., Pesant *et al*. – Pvs.I experiments Centre Station Eddy B., Thompson *et al*. – PAM experiments Centre Station Eddy B., Holl *et al*. – N-uptake experiments Centre Station Eddy B.

Indian Ocean Marine Environmental Conference (IOMEC) Linking Science, Engineering and Management 14 – 18 February 2005 – Perth, Western Australia
Lynnath E. Beckley, Barbara A. Muhling and Anya M. Waite. Primary production and fish larvae in two eddies.

Southern African Marine Science Symposium – Durban, July 2005 – Invited plenary
Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite
Leeuwin Current meso-scale eddies: death traps or saviours in the oligotrophic eastern Indian Ocean?

Indo-Pacific Fish Conference – Taipei May 2005
Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite
Meso-scale Leeuwin Current eddies: oceanographic history and ichthyoplankton assemblages

International larval fish conference – Barcelona July 2005
Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite
Ichthyoplankton assemblages and primary production in meso-scale eddies associated with the Leeuwin Current, eastern Indian Ocean.

Publications

Theses

Two completed final year projects contributed to the project, both filed at the Centre for Water Research (Malseed, 2004, and Pez, 2004).

Journal Publications:

In late 2004, Dr Anya Waite was invited by John Milliman (editor of Deep Sea Research) to contribute a special edition on the Leeuwin Current and its eddies. Dr Waite has submitted a tentative list of 8-10 papers. The deadline for manuscript submission is December 1st 2005. The majority of the manuscripts will be derived from the Eddies cruise SS09/03, with invited contributions from the SW coast cruise SS09/03.

3.3.2 Spatial Patterns in Sessile Benthic Sponge and Ascidian Communities of the Recherche Archipelago

Dr Justin I. McDonald[1], Dr Jane Fromont[2] , and Dr Gary Kendrick[1]

[1] School of Plant Biology, Faculty of Natural & Agricultural Sciences,
University of Western Australia, 35 Stirling Highway, Crawley 6009 Western Australia

[2] Department of Aquatic Zoology, Western Australian Museum,
Kew Street, Welshpool, Western Australia

Introduction

The southwestern region of Western Australia is a relatively pristine environment of great diversity with high levels of endemism recognised in some groups of crustaceans and molluscs (Morgan & Wells, 1991). It is estimated that at least 60 percent of the Australian sponge fauna is undescribed, with the Demosponge fauna of temperate southwestern Western Australia being the most poorly known of all (Hooper & Lévi, 1994). Presently our knowledge of the sponge and ascidian fauna of the southwest is from a limited number of papers, most of which were published more than half a century ago (e.g. Lamarck, 1813-1814; Bowerbank, 1876; Lendenfeld, 1888). None of these early studies examined the fauna in the Esperance region and many of the publications only document fauna as far south as Albany. Indeed most of the historical collections were conducted in metropolitan waters (Cockburn Sound, Fremantle, Cottesloe and Rottnest Island). Poore (1995) has recorded high levels of endemic species in southern temperate regions of Australia and suggests that it is in the south that the majority of 'native' marine fauna resides. Yet for much of the temperate marine benthic fauna nothing is known of their distribution patterns or levels of endemism.

A recent 'biological survey of the major benthic habitats of the south coast' conducted by Colman (1997) in the Fitzgerald Biosphere Reserve identified 102 different sponges. Of this number, however, only one was identified to species level. The lack of taxonomic detail illustrates the importance of the present study in the Recherche Archipelago. There is an urgent need to correctly describe and quantify the sponge and ascidian communities. This study addresses the critical need for correct taxonomic identifications and statistically sound quantitative sampling of the sessile benthic communities from the Recherche Archipelago, and indeed the entire southwestern Australian region.

Study sites

In October 2002 fauna were collected from horizontal substrata at five islands: Black, Thomas, Woody, Figure of Eight, Mondrain Island. Habitats were sampled at sheltered and exposed sites, and at a range of depths: waters 0-10m, 10-20 m, and waters 20-25 m depth, with equal numbers of quadrats taken from each exposure and depth. As a result of the 2002 collections the sampling design was modified to capture habitats associated with vertical substrata in addition to the horizontal substrata. However, the addition of vertical substrata to the design effectively doubled the sampling and processing effort, and it was therefore decided that sampling would only occur at a single depth (10-20 m (15 m). The 15 m depth was chosen as species diversity and numbers were greatest at this depth. This new sampling regime commenced at Figure of Eight and Mondrain Islands. In October 2003 the final field trip sampled the more remote islands: Mart Group, Twin Peaks and Middle Island. These islands were sampled at sheltered and exposed sites, at the single depth of 15m but sampled horizontal and vertical substrata.

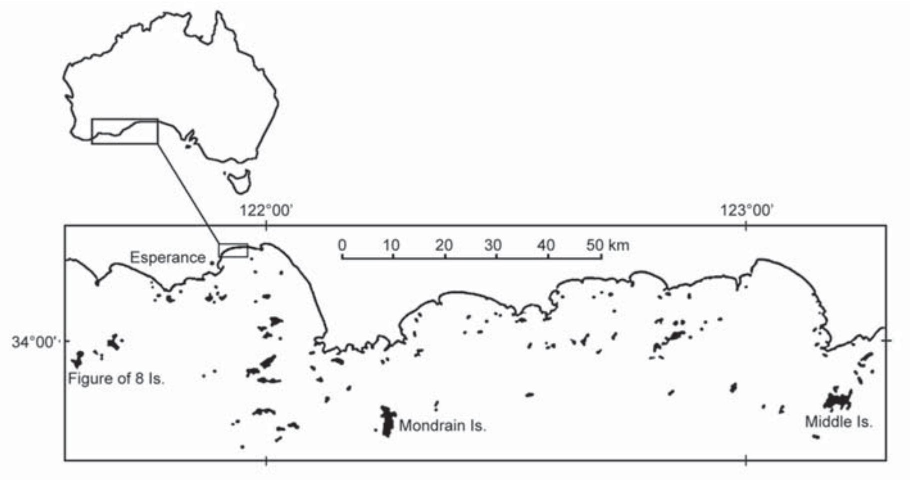

Figure 26: Map of the Recherche Archipelago study sites.

Aims/objectives

The primary goal of the proposed research is to provide a biological inventory of sessile benthic communities within the Recherche Archipelago and quantitatively identify the spatial patterns that exist within these communities. Within this goal there are three specific aims:

Aim 1. Describe the distribution and abundance of the sponge and ascidian dominated communities from the Recherche Archipelago

Major findings of Aim 1:

Of the six phyla examined in this study, the sponges were the dominant taxa. Sponges represented approximately 72% of all fauna collected, bryozoans 10%, ascidians and sea-stars 7%, and hydroids and corals both 2%.

A total of 644 individual Demosponges were collected, representing 11 of the 15 orders of Demospongiae currently recognised. Demosponge orders were dominated by the Poecilosclerida and the Dictyoceratida, which in combination made up approximately 60% of the sponges identified to date. Sponges were consistently the most abundant organisms recorded for each island. No patterns in sponge community composition (using a full assemblage at order level) were associated with any of the factors tested (exposure, depth or substrata orientation). There were no significant differences in the number of sponges collected among exposures, depths or substratum orientation for the Chondrosidae, Dictyoceratida, Hadromerida or the Halichondrida. The Astrophorida had significantly more individuals in exposed sites and significantly more on vertical substrata (Figure 27). The Dendroceratida also had significantly more individuals on vertical than on horizontal substrata. The Haplosclerida showed significant differences associated with increasing depth, with significantly more individuals at 20+ m depth. The Poecilosclerida had significantly fewer individuals with increasing depth, with more individuals in <10 m depth (Figure 28). The Poecilosclerida also had had significantly more individuals in exposed than sheltered sites.

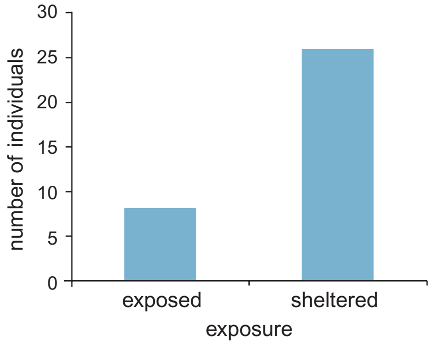

Figure 27: Number of Astrophorida individuals recorded from exposed and sheltered sites (all islands (n=310 quadrats).

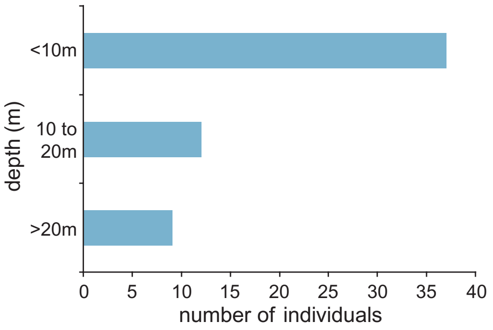

Figure 28: Decrease in the number of Poecilosclerid sponges with increasing depth.

Ascidian faunal structure differed at the island (kilometre scale; ANOSIM global R value: 0.32) (Figure 29) and regional scales (10-100 km; ANOSIM global R: 0.167).

There was no pattern in benthic assemblages associated with exposure (sheltered/ exposed)(global R value: -0.014) nor with substratum orientation (horizontal/ vertical) (global R value: 0.063).

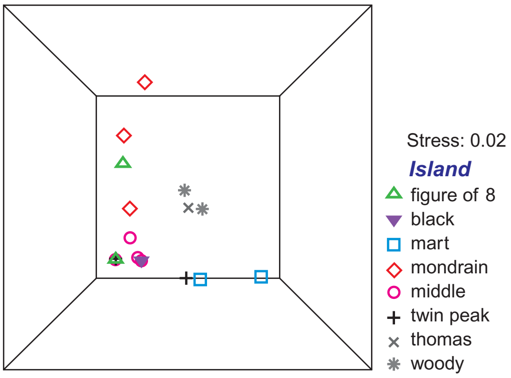

Figure 29: A two dimensional nMDS plot showing the pattern in ascidian assemblage across islands (100's m – km).

Ascidians were present in all three depth regimes sampled, however only one species, *Pyura gibbosa*, was recorded in all three depths. Ascidian fauna was numerically dominated by representatives of *Clavelina ostrearium* and *Herdmaina grandis*, which in combination made up approximately 69% of the ascidians recorded. *Herdmania grandis* showed a significant change with depth, individuals were completely absent at depths greater than 20 m (chi^2 10.7; chi^2 critical 5.99). *Clavelina ostrearium* and *Pyura spinifera* had the converse pattern no individuals present in shallow waters <10 m deep (chi^2 7.42 and 7 respectively; chi^2 critical 5.99). The undescribed ascidian fauna consists mainly of colonial species, the majority of which are Didemnid species. The introduced pest *Ciona intestinalis* was recorded in Bandy Creek Harbour but was not observed at any of the sites targeted in this study.

Aim 2. Compile a taxonomic database of specimens collected during this study

Major findings of Aim 2:

A web-site has been constructed as part of the FRDC Recherche project and can be accessed from the http address below. This site has a page on the sponge and ascidian communities of the Recherche Archipelago (http://marine.uwa.edu.au/recherche).

A web-based site specifically on the SRFME based research is currently under development. The site will outline the nature of the research and its primary findings. A menu page will list the fauna available for further examination. Users will then be able to select a desired subject e.g. seastars, and will be transferred to a seastar menu where they can browse a collection of thumbnail images. They then select the thumbnail image they are interested in and are provided with taxonomic and ecological information pertinent to that species. The database will be incorporated in FaunaBase on the website of the Western Australian Museum (WAM) (www.museum.wa.gov.au/FaunaBase), and will be accessible via this public interface and using web links from the UWA website. Note that an enormous number of species were collected and cannot all be processed during the scope of this study. As such only the most abundant species from each group will be available to web users.

Aim 3. Provide a comprehensive voucher collection of sponge, ascidian and associated macro invertebrate species from the region

Major findings of Aim 3:

A comprehensive collection of sponge and ascidians has been collected through this study. The collection is very extensive, with 409 species of sponge, 11 species of ascidian, 12 species of seastar, 16 species of hydroid and over 100 species of bryozoan. Once all data processing has finalised the material will be deposited at WAM.

Discussion

The objectives of the study were to investigate the sessile benthic sponge and ascidian communities of the Recherche Archipelago and determine if there were any patterns associated with islands, exposure, depth, or substratum orientation.

Sponges were the dominant fauna and were highly diverse, being recorded from every island, exposure, depth and substrata orientation. There was considerable variation in the numbers of animals and the species richness among islands with no significant relationship evident between these factors recorded at any island. This suggests a fragmented distribution of sponge orders across all sites sampled.

Sponge composition using order level data differed with islands examined. Thomas and Middle Islands had individuals from nine orders, while Black and Twin Peak had only five orders present. There was, however, no difference in sponge composition between exposures indicating that orders were not exposure specific and occurred at both sheltered and exposed sites. There was a significant difference in the number of sponges, but not assemblage structure, associated with horizontal and vertical substrata.

The lack of differences in sponge assemblage structure among exposures, depths or orientation of substrata indicated that the distribution of sponge orders were not specific to these categories. This was evident in orders such as the Poecilosclerida, which occurred at every island, exposure, depth and orientation. The absence of pattern may, however, be related to the use of high taxonomic (order) level data masking any lower taxonomic variation present at family or genus levels. For groups such as sponges which require considerable time and effort in processing for identification, it may be that lower taxonomic level species data would be required to identify any assemblage level patterns that may exist.

Univariate examination of individual orders revealed that the sponges were dominated by the orders Poecilosclerida and the Dictyoceratida, which combined made up approximately 60% of the sponges identified to date. The Poecilosclerida are one of the most species rich orders in the Demospongiae (akin to the Phaeophyta in the algal realm) and consequently it is not surprising that they were recorded in every island, exposure, depth and orientation, dominating the sponge fauna of the Recherche Archipelago. Despite the cosmopolitan nature of the Poecilosclerida, they exhibited distinct preferences for exposure and depth, with significantly more individuals recorded from exposed sites and shallow depths (< 10 m). Several other sponge orders such as the Astrophorida, Haplosclerida and Dendroceratida showed significant differences in abundance associated with exposure, depth or substratum orientation, indicating a distinct preference in these orders for a particular habitat.

The ascidian fauna identified to date was dominated by six species of solitary ascidia belonging to three families, the Cionidae, the Clavelinidae and the Pyuridae. Many samples are still to be identified and consist mainly of colonial ascidians belonging to the family Didemnidae. The species described in this study are common throughout much of Australia's southern temperate waters. See McDonald (2004) in References for more details of this group.

Ascidian faunal structure differed at the island scale. These differences in assemblage structure require further investigation, however they are likely to be linked to differences in environmental variables such as nutrient content of the surrounding water column. As with the sponge assemblages there was no pattern in ascidian assemblages associated with exposure nor with substratum orientation, indicating that these animals are more influenced by larger landscape scale environmental factors such as nutrient availability than smaller habitat specific attributes.

Ascidians were present in all three depth regimes sampled, however only one species, *Pyura gibbosa*, was recorded in all three depths. Multivariate analysis divided the sites based upon their species compliment. The species *Clavelina ostrearium* was completely absent from shallow waters less than 10 m deep. This species has a soft gelatinous head situated upon a short flexible stalk. It is this soft structure that may restrict this species to the calmer waters greater than 10 m deep where they are less likely to be negatively influenced by wave action. The habitat and anatomy (thin test) of *C. ostrearium* may make it vulnerable to UV damage as with *Corella inflata*. The thicker test of *H. grandis* and the darker opaque tests of the Pyurid species may provide protection from UV damage.

Conclusions

The data in this report provides valuable baseline data on the distribution of benthic invertebrates within the Recherche Archipelago. Furthermore it provides data on the distribution patterns in these fauna and sponge morphologies across a range of spatial scales.

The results of this study raise several questions. Are the spatial patterns recorded in sponge and ascidian communities determined by larval behaviour and morphology, physically mediated patterns in recruitment or are there distinct physiologically parameters of each species that restrict them to depths? Larval behaviour is proposed to be one of the primary determinants of species distribution. Direct observations on the settlement and mortality of larvae would be the most accurate way to measure depth preference, however given the difficulties of such a study the approach used in this study of recording adult presence/absence indicates a distinct pattern of distribution that provides the basis for further investigation.

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Conferences attended, or presentations given

McDonald J.I. (2004) Sponge and ascidian communities of the Recherche Archipelago CSIRO Strategic Research Fund for the Marine Environment Symposium, Perth.

McDonald J.I. (2004) Sponge and ascidian communities of the Recherche Archipelago Department of Conservation & Land Management (Marine Division) Lecture series, Fremantle, Western Australia.

Publications and/or outcomes to date

McDonald J.I. (2004) The invasive pest species *Ciona intestinalis* (Linnaeus, 1767) reported in a harbour in southern Western Australia – *Marine Pollution Bulletin* 49: 868-870.

McDonald J.I. (2005). Solitary Ascidiacea from shallow waters of the Recherche Archipelago, Western Australia. – accepted – International Marine Biology Workshop Proceedings.

McDonald J.I. (2005). Asteroidea from shallow waters of the Recherche Archipelago, Western Australia – accepted – International Marine Biology Workshop Proceedings

Kendrick, G., Harvey, E., McDonald, J., Wells, F. & Walker, D. (2005) Introduction to the marine biology of the Archipelago of the Recherche Western Australia – accepted – International Marine Biology Workshop Proceedings

Popular Science Publications

Landscope (2004) Vision Splendid (provided scientific information and photographic imagery)

Landscope (2004) Researching the Recherche (provided scientific information and photographic imagery)

Ecos November-December (2004) Treasure Islands – The Recherche Archipelago's underwater riches (provided scientific information and photographic imagery)

Threatened species of Western Australia (2004) (provided scientific information and photographic imagery)

Tracks Magazine of the Western Australian Museum (2004) Esperance marine life under the microscope (provided photographic imagery)

Helix magazine (2005) article and educational poster (provided scientific information and photographic imagery)

Reports

Kendrick, G.K., Harvey, E.S., McDonald. J.I., *et al*., (2004) *Characterising the fish habitats of the Recherche Archipelago: Final Research Report.* Report to Fisheries Research and Development Committee

McDonald. J.I., and Fromont, J. (2004) *Sponge and ascidian communities of the Recherche Archipelago 3*. Report to CSIRO Strategic Research Fund for the Marine Environment

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3.3.3 Understanding the Natural Variability of Currents Along the Western Australian Coastline

Principal Investigator and Co-PI's

Alexis Berthot and Charitha Pattiaratchi
Centre for Water Research
The University of Western Australia

Ming Feng and Gary Meyers, CSIRO Marine Research

Yun Li and Eddy Campbell, CSIRO Division of Mathematical and Information Sciences

Introduction

Western Australia experiences a strong inter-annual variability in climate and oceanic conditions. For example, annual mean sea levels and rainfall in south-western Australia exhibit significant inter-annual variability. Some of this natural variability may be related to the El Niño Southern Oscillation (ENSO) phenomenon, often represented by the Southern Oscillation Index (SOI). In the case of sea level, the relationship between SOI and sea level varies over time. From 1989 to 1998, the sea level and SOI signals were virtually identical in relative amplitude and phase, with a 1 unit change in SOI representing a 13 mm change in mean sea level. The relationship is less clear when the analysis is conducted over the period 1966 to 1996 and extension of this analysis to the full 100-year Fremantle sea level database produces a relatively poor relationship between sea level and SOI (Figure 30). In particular, the period 1920 to 1940 has a very poor correlation between SOI and mean annual sea level and this period corresponds to a period where the SOI was almost invariant but experienced the highest changes in mean water level over the past 100 years. This indicates processes other than the SOI signal is contributing to the variability in mean sea level. The above example with respect to sea level highlights the variability that is experienced in the oceanic conditions off Western Australia. Two hypotheses on the cause of non-ENSO variability are: a change in climatic conditions (e.g. weather patterns, wind field, rainfall) over the eastern Indian Ocean; or a change in internal structure of the western Pacific Ocean transmitted to WA by the coastal and equatorial wave guides. These conditions will appear locally, in particular, through the behaviour of the Leeuwin Current, wind driven near-shore and continental shelf currents, incident wave climate and river run-off and groundwater inflows to the ocean (due to variability in rainfall). This project aims to quantify the natural variability of the oceanic circulation off Western Australia through the analysis of long-term data sets such as Fremantle sea level, surface and subsurface temperature in the Indian Ocean and sea surface variability from satellite altimeter. Results of the study are directly relevant to managers charged with establishing a network of marine protected areas, management of fish stocks and environmental protection as well as other researchers in the marine environment dealing with field data studying both the physical and ecological systems. Knowledge of the natural variability of the physical environment that on most cases is responsible for the ecological response (both pelagic and benthic) is crucial for management.

Based on above, the objectives of this project are to develop:

- an enhanced understanding of the natural variability of the nearshore and continental shelf current systems and oceanic properties off south-western Australia
- advanced statistical methods to the detection of climate change signals
- regional climate change scenarios for circulation off Western Australia

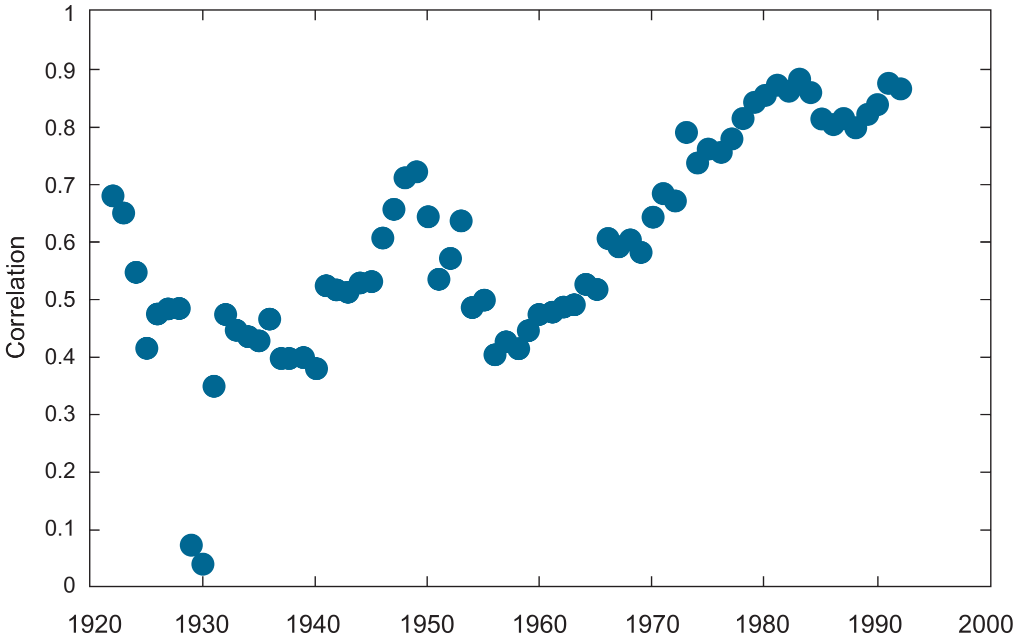

Figure 30: Correlation between annual mean SOI and Fremantle sea level using a 19-year moving window

Aims/objectives

- Enhanced understanding of the natural variability of the nearshore and continental shelf current systems and oceanic properties off south-western Australia and to include the core SRFME observations and modelling efforts into the long-term variability context
- Development and application of advanced statistical methods to the detection of climate change signals
- Development of regional climate change scenarios for shelf circulation

Current Status

The project is in its first phase, and A. Berthot has been recently appointed for the position of Post-Doctoral fellow. This report presents preliminary results that combine work undertaken by the principal investigators (prior to this appointment) using the Fremantle sea level records and more recent results from the author. This paper focus on the first theme of this project (i.e. understanding of the variability of the nearshore and continental shelf current systems and oceanic properties) and presents some of the responses of the local Western Australia ocean system to larger global climate system.

Over the last century, the signature of the sea surface temperature (SST) of the oceans has varied significantly according to climatic changes on the earth. The global ocean surface temperature has been fairly stable at the beginning of this century followed by an increase of 0.2 ºC between 1910 and 1940. It has remained stable over a period from 1940 to 1970 before gradually rising by 0.5 ºC to the present day. The Indian Ocean has generally followed the same trend as the global sea surface temperature with an average of 0.1-0.2 ºC warmer. (Figure 31). These periods of increasing and stable Indian Ocean SST, represent periods where the circulation off Western Australia may have varied, and need to be investigated.

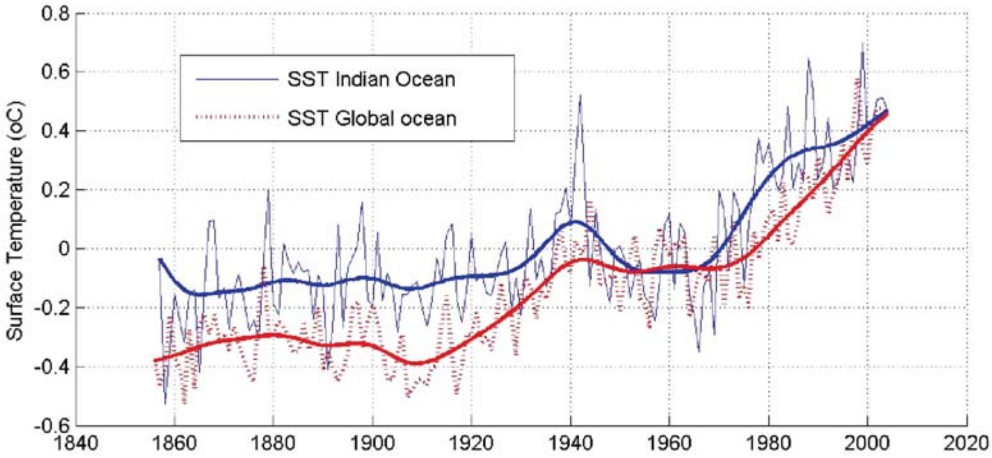

Figure 31: Time series of annual global Sea Surface Temperature (SST) and annual SST of the Indian Ocean (in ºC). The heavy lines are smoothed time series using a 19-year Hanning filter.

Fremantle Sea Level Variability

The sea level has been recorded continuously at Fremantle since 1897 and forms the longest sea level data record, not only in Australia, but also in the southern hemisphere. In view of the fact that the sea level variability is an excellent proxy for the variability in ocean parameters, this is very fortuitous and will become the primary data set for analysis. For example, recent work by Feng *et al*. (2003) have shown that there is a quasi-linear relationship between the volume transport of the Leeuwin Current at 32ºS (the latitude of Perth) and Fremantle sea level: here it was shown that one centimeter change in mean sea level variation corresponded to a 0.13 Sv ($=10^6$ $m^3 s^{-1}$) change in volume transport of the Leeuwin Current. Hence, the sea level variability directly corresponds to the volume transport, i.e. the strength, of the Leeuwin Current.

Examination of the complete sea level record, indicates, that in agreement with the global sea level rise (see Church *et al*., 2004), there is a linear trend of sea level increase of 1.54 mm per annum reflecting the increase in global surface temperature (Figure 32). If the linear trend is removed from the annual sea level record (Figure 33), it is clear that although overall there has been an increasing trend, there have been periods where the mean sea level variability changed: From 1900 to 1917 there was a decrease in mean water level whilst between 1917 and 1952 there has been an increase and decreasing trends with a period of between 10 to 14 years. Between 1952 and 1991, there has been a decreasing trend, with an increase in the rate of water level decrease since the 1976-77 El Niño. Decrease of sea level trend between 1976 and 1991 is attributed to the higher frequency of El Niño events during this period. However, since 1991, the annual sea level has increased at a rate of 5 mm per annum, a rate more than 3 times the trend over the previous 100 years. During this latter period, there is a linear correlation between the southern oscillation index (SOI) and the Fremantle sea level with a 1 unit change in SOI representing a 13 mm change in mean sea level.

Linear and non-linear (MARS) models were used to predict the observed low-frequency mean sea level changes using the low-pass filtered SOI (Figure 34). It is shown that over two time periods: (1) between mid-1930’s and early 1950’s; and, (2) between,mid-1970’s and mid-1990’s, the low-frequency variations of the mean annual Fremantle sea level may be predicted using the low-pass filtered SOI but at other times there is no correlation between the low-frequency variations of the SOI and mean sea level. We will examine the surface and sub-surface (XBT) ocean temperature to examine this variability.

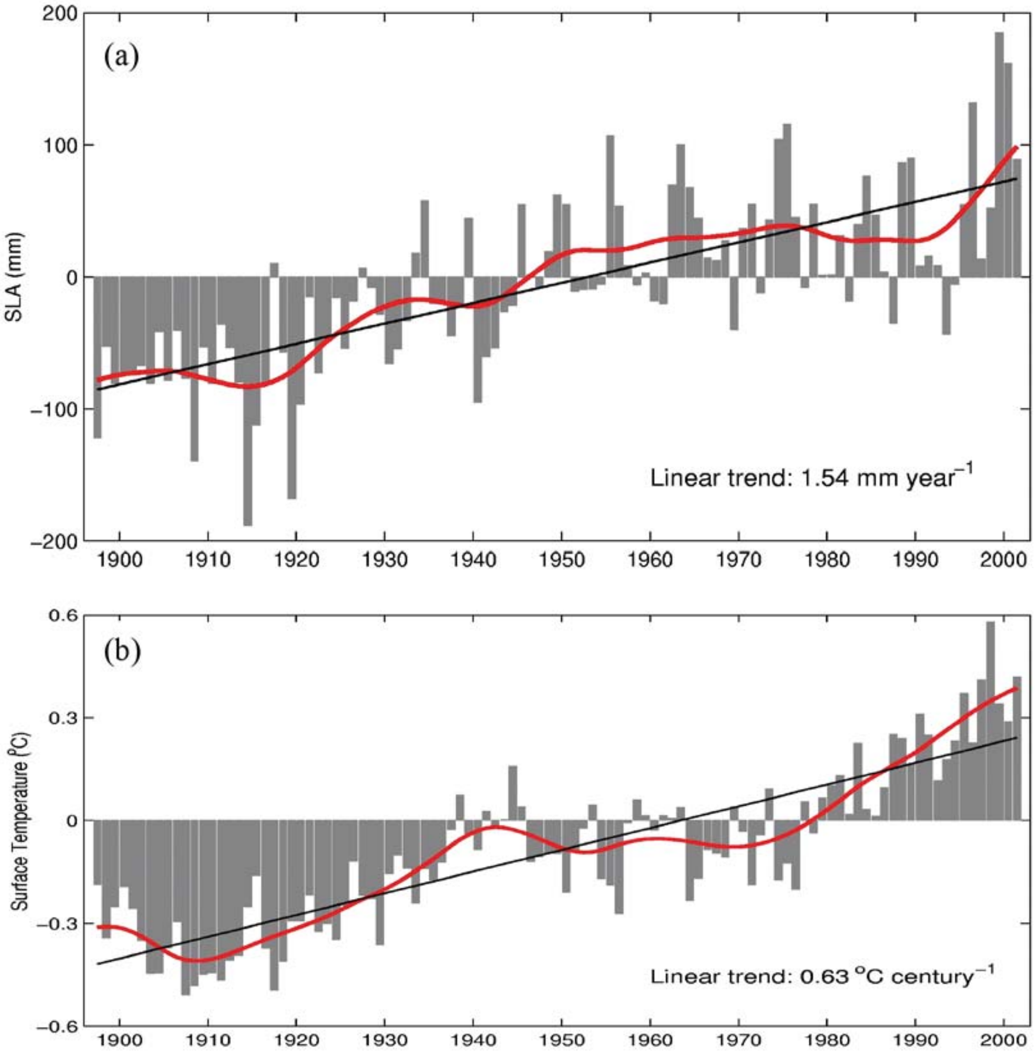

Figure 32: Time series of (a) annual Fremantle level and (b) annual global surface temperature. The linear trend in each of the time series is shown as well as a 5-year moving average.

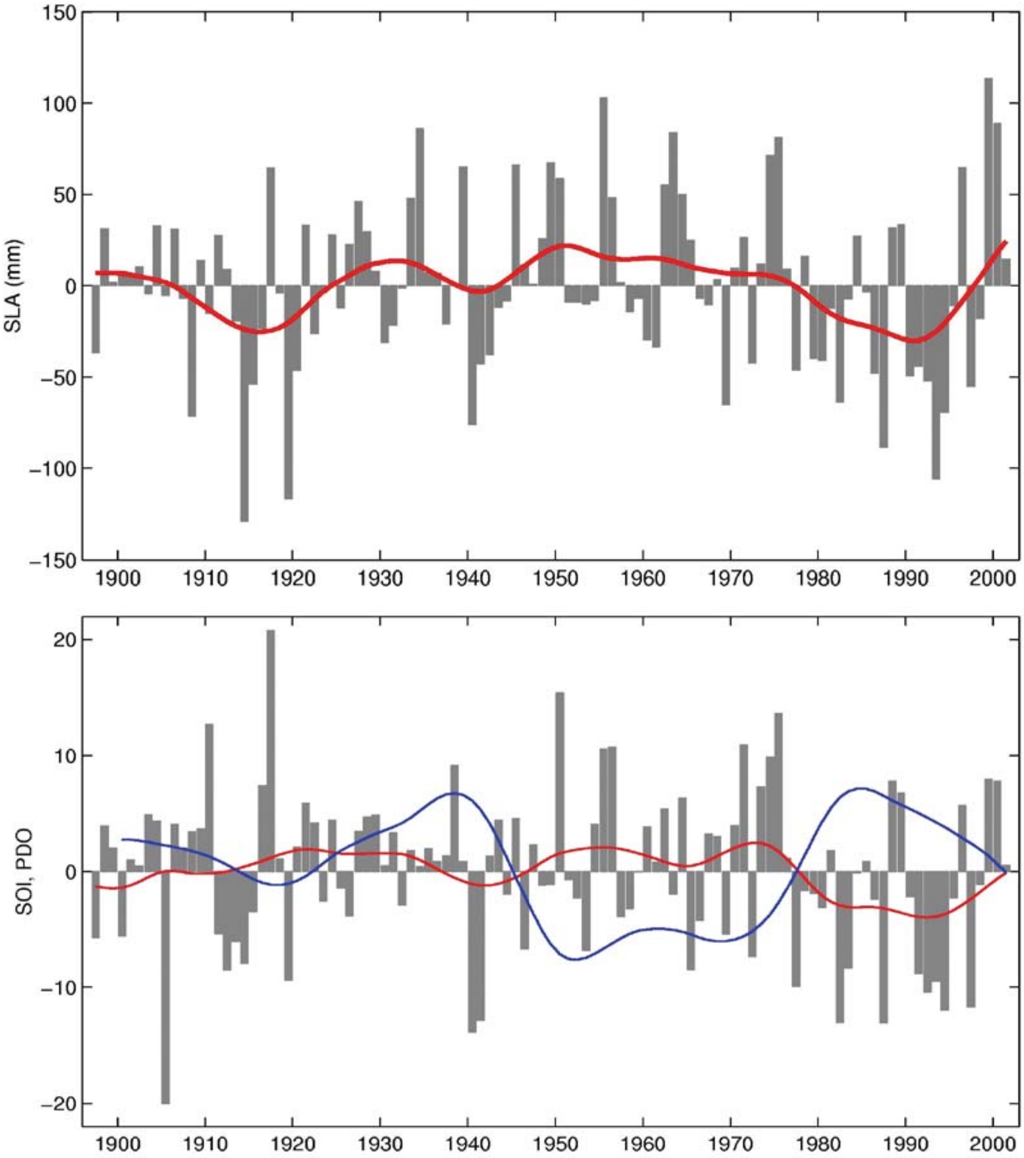

Figure 33: Time series of (a) annual Fremantle level, with the linear trend removed; and, (b) Southern Oscillation Index and the Pacific Decadal Oscillation (PDO).

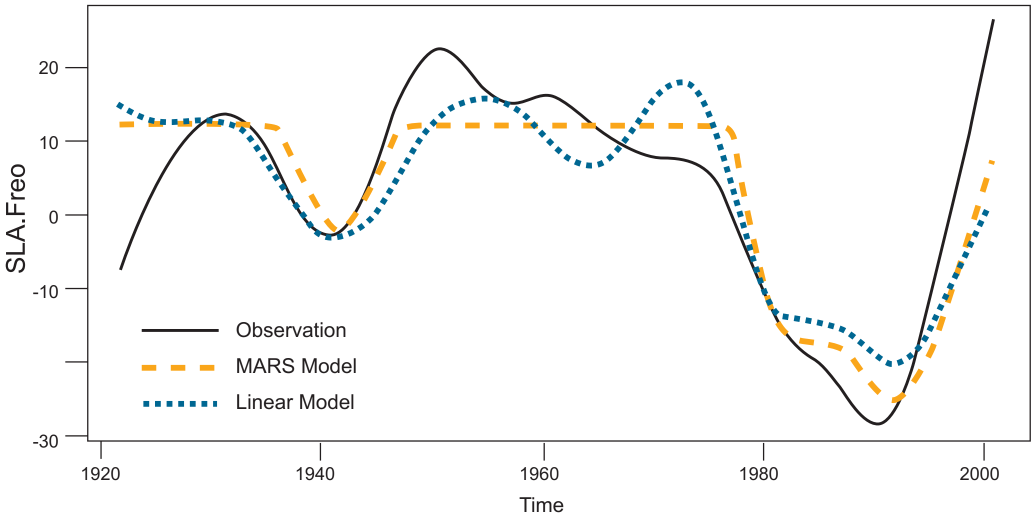

Figure 34: Comparison of results of linear and non-linear (MARS) predictive model for mean annual Fremantle sea level using the SOI.

Indian Ocean Dipole

In addition to the El Niño/Southern Oscillation (ENSO), the recently discovered Indian Ocean Dipole (IOD; Saji *et al*. 1999) is another important manifestation of the tropical Air-Sea interaction present in the Indian Ocean. It is defined as the sea surface temperature anomaly difference between the tropical western Indian Ocean and the tropical southeastern Indian Ocean (Figure 35). Its physical existence has been demonstrated and it has been shown that IOD events may exist independently of ENSO and correlation between El Niño/La Niña events and IOD events is generally low (Rao *et al*. 2002, Ashok *et al*. 2003). The Dipole mode is characterized by a low sea surface temperature off Sumatra and high sea surface temperatures in the Western Indian Ocean, with accompanying wind and precipitation anomalies, its impact on the southern part of the Indian Ocean and more specifically on the oceanic currents off Western Australian has still to be discussed. However recent work by Ashok et al (2003) has shown that IOD has significant negative partial correlation with the rainfall over the western and southern regions of Australia. Strong positive (or negative) IOD events are determined by considering the annual mean Dipole Mode Index amplitudes greater than one standard deviation (Rao *et al*., 2002). Correlation between the Indian Ocean Dipole and the Fremantle Sea Level, i.e. strength of the Leeuwin Current has not yet been established. Nevertheless, preliminary results show that strong negative IOD event (positive IOD event) are associated with high Fremantle Sea Level Anomaly (low Fremantle Sea Level Anomaly) particularly during the last 50 years (Figure 36). The effect of the Indian Ocean dipole on the ocean circulation present off Western Australia needs further investigation, e.g. to determine statistical correlation over the last century as well as physical explanation for the linkages between atmospheric patterns observed over the tropical Indian Ocean and the currents variability off Western Australia.

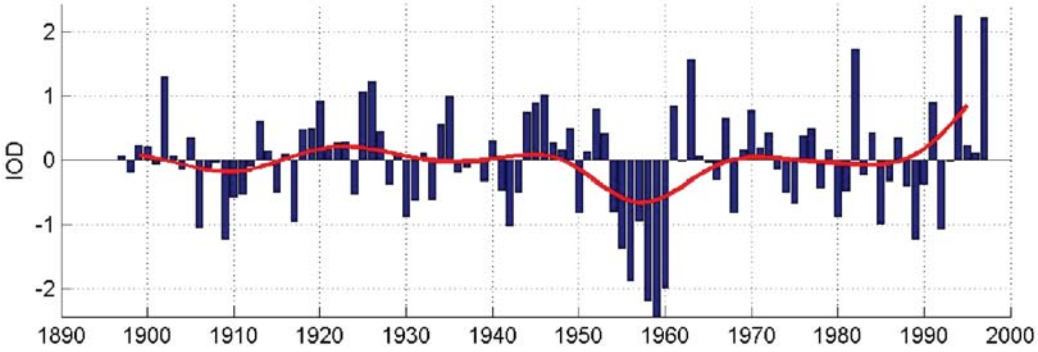

Figure 35: Time series of the Indian Ocean Dipole Mode Index.
The heavy lines are smoothed time series using a 19-year Hanning filter.

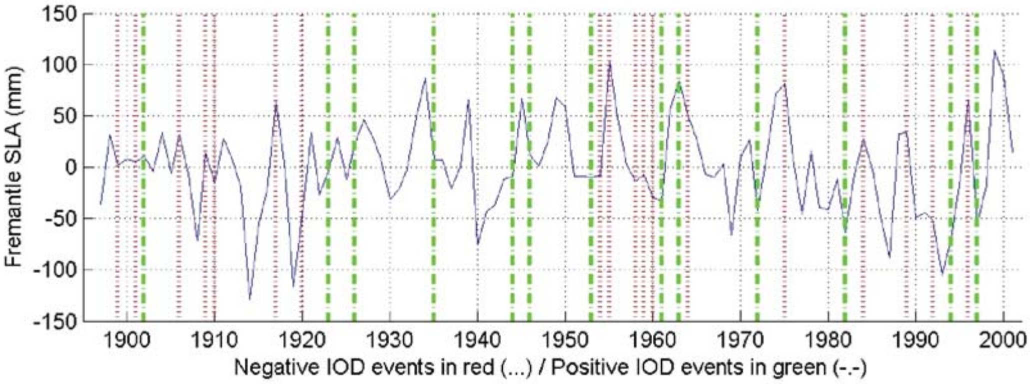

Figure 36: Annual mean detrended Fremantle Sea Level Anomaly (SLA).Vertical dashed green line (dotted red line) represent strong positive IOD events (negative IOD events), determined from Rao *et al*. (2002).

Wind Forcing

Along the eastern ocean boundary off Western Australia the prevailing winds are predominantly equatorward like most of subtropical eastern ocean boundaries, however, the Leeuwin current flows poleward along the coast of Western Australia. There is general agreement that the Leeuwin Current is generated by a meridional pressure gradient, which overwhelms the opposing equatorward windstress. The Leeuwin Current is weaker during the summer months as it encounters a cool wind driven equatorward coastal countercurrent, running close inshore (Godfrey & Ridgway, 1985). However, Batteen *et al*. (1992) showed using numerical model results that near the northernmost part of the Western Australian coastline, winds have offshore and equatorward component; hence their effect according to Ekman theory, increases the strength of the poleward flow in to the prevailing wind. Nevertheless a comparison of their model results with LUCIE observations showed that the effect of the winds is less significant than the NW shelf waters.

In this study we considered a wind index calculated by averaging the component of the wind over a box bounded by latitudes 35 ºS -21 ºS and longitude 105 ºE -115 ºE (wind at 10m, obtained from NCEP re-analysis). The zonal and meridional components of the wind averaged over the box and over the summer (October-March) and winter period (April to September) are presented in Figure 37a and 37b. During the last 50 years, consistently with general wind circulation patterns over subtropical oceans, the meridional wind is directed equatorward and the zonal wind direction is variable over the winter months but easterly during summer months. The variations of the summer zonal wind index appeared to be correlated with the Fremantle Sea level, with strong (weak) summer zonal wind generally followed by a high (low) Fremantle Sea Level, which by extension indicate a strong (weak) Leeuwin current (Figure 37c). In this case, Ekman transport as well as local atmospheric variation of the sea level pressure may have an influence in the Fremantle sea level variation. Further investigation of the long term variability of the synoptic wind and associated sea level pressure variability in the southern Indian Ocean, and their implications for the Leeuwin current is needed.

Summary & Conclusions:

- Between mid-1930's and early 1950's; and between mid-1970's and mid-1990's, the low-frequency variations of the mean annual Fremantle sea level may be predicted using the low-pass filtered SOI.
- Strong negative (positive) Indian Ocean Dipole event appeared to be associated with high (low) Fremantle Sea Level Anomaly.
- Over the last 50 years, summer zonal wind index off Western Australian coastline appeared to be correlated with the Fremantle Sea level. Strong (weak) summer zonal wind is generally followed by a high (weak) Fremantle Sea Level.

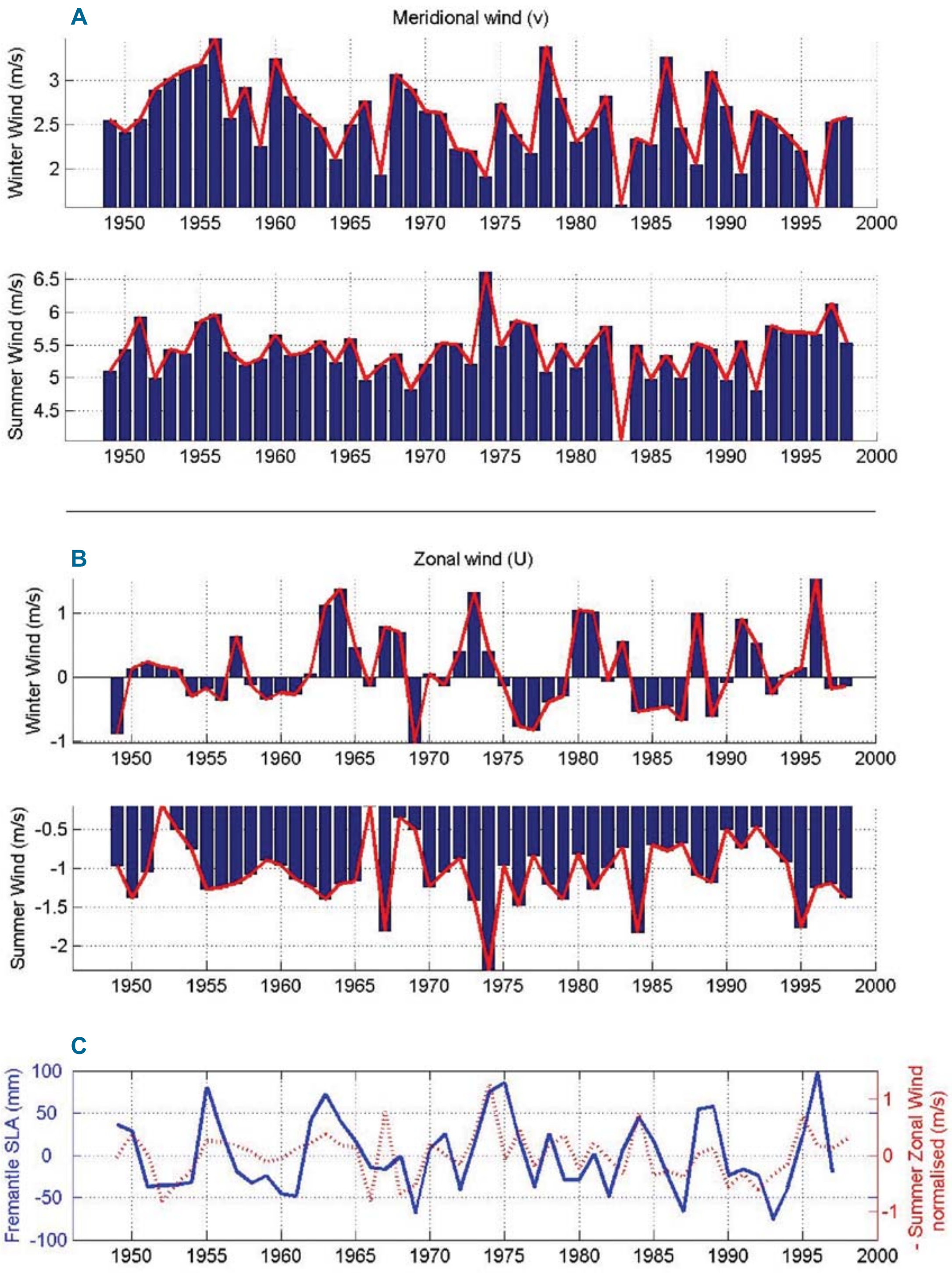

Figure 37: Time series of the yearly seasonal average of the meridional (a) and zonal wind index (b). The meridional (zonal) wind index is calculated as an average of the meridional (zonal) wind at 10m, over 35 ºS -21 ºS ,105 ºE -115 ºE region. c) Time series of the annual mean detrended Fremantle Sea Level Anomaly and of the normalized summer zonal wind index.

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'Sea level variability in south-western Australia', IOCIP meeting, 10/5/04. CSIRO, Floreat, WA, 2004.

List of publications and/or outcomes to date

As the project start was delayed due to problems associated with recruiting a post-doctoral fellow – there are no publications or outputs at this stage.

3.3.4 Ecological Interactions in Coastal Marine Ecosystems: Trophodynamics

Principal Investigator
Dr Glenn Hyndes
Senior Lecturer
School of Natural Sciences, Edith Cowan University, 100 Joondalup Drive, JOONDALUP WA 6027
Phone: 6304 5798 Fax: 6304 5509 Email: g.hyndes@ecu.edu.au

Co investigator
Dr Mat Vanderklift
Research Scientist
CSIRO Marine Research, Underwood Ave, Floreat WA 6014
Phone: 9333 6536 Fax: 9333 6555 Email: mat.vanderklift@csiro.au

Dr Russ Babcock
Senior Research Scientist
CSIRO Marine Research, Underwood Ave, Floreat WA 6014
Phone: 9333 6535 Fax: 9333 6555 Email: russ.babcock@csiro.au

Note: This project has just commenced, and has no results to report as of this date.

Project Description

Background

A three-year program to investigate ecological interactions in midwest coastal reef communities will be built around the Jurien Bay Marine Park (Figure 38), using multiple-use management zones within the park as large scale manipulations of predator abundance. This focus will give the program an emphasis that distinguishes it from core SRFME projects and takes advantage of the unique opportunities developing in the midwest area. Two groups of predators, finfish and spiny lobster, are of primary interest and the zoning of the park, into areas subject to all kinds of fishing, lobster fishing only, and no-take restrictions, will facilitate the understanding of their respective ecological roles.

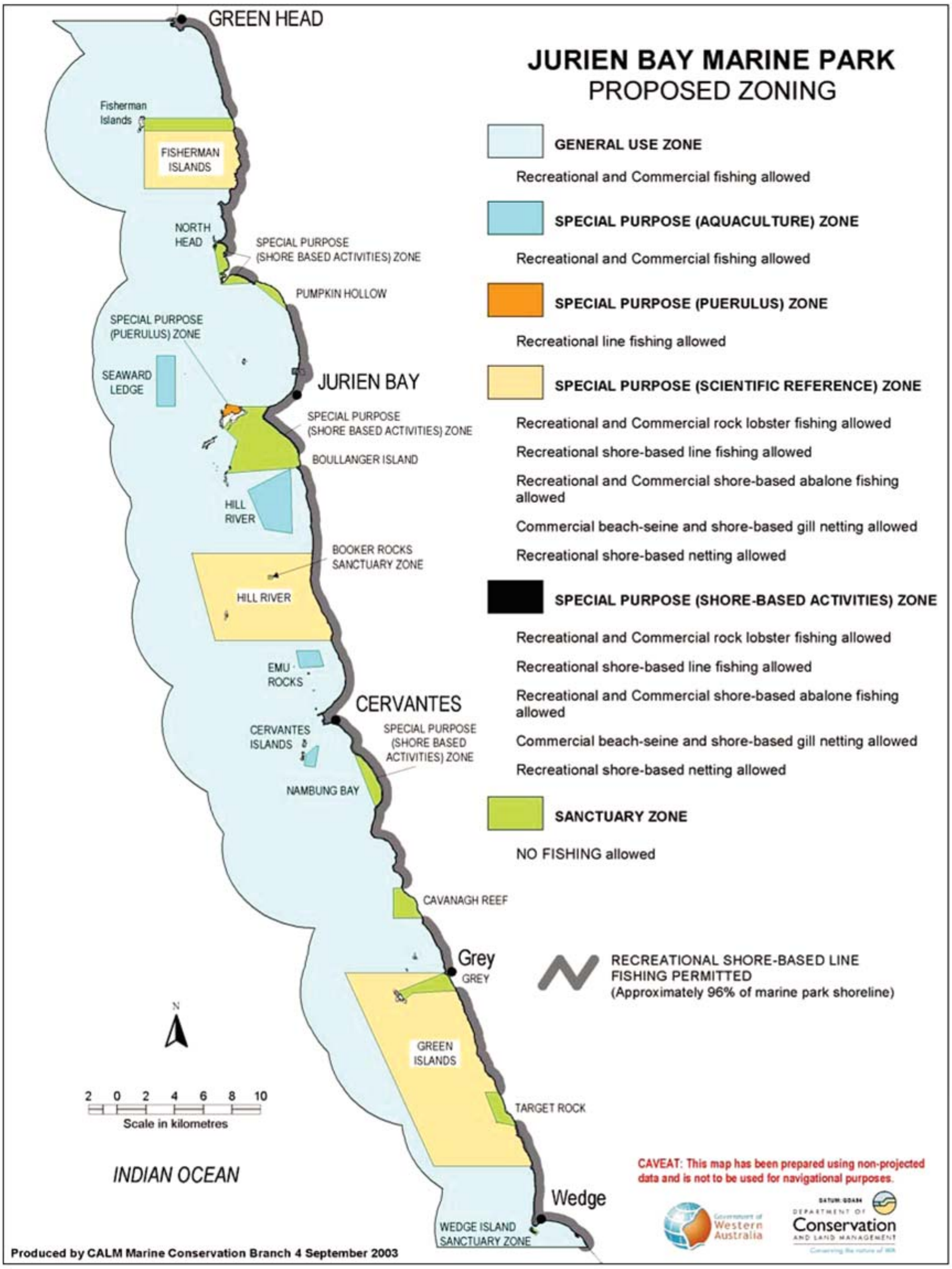

Figure 38: Map showing draft management zoning of the Jurien Bay Marine Park

Outline

The key research/management questions that exist in the context of Ecological Interactions in the Midwest are as follows:

- What are the trophic linkages of exploited species to other ecosystem components?
- What are the pathways of transport of organic matter and nutrients between habitats and across the shelf?
- How do exploited species in particular utilize the range of available coastal shallow water habitats (e.g. foraging in seagrass, sheltering on reefs)?
- What are the potential trophic (indirect) effects of variations in predator density?
- What is the relative importance of any anthropogenic variation in ecological interactions relative to natural variability at the habitat, seasonal and interannual levels (e.g. can we detect indirect ecological effects of fishing against the background of natural variability)?
- How will populations of exploited predatory species respond to marine park protection (i.e. what are the direct effects of fishing)?

The goals outlined above can be achieved through an integrated research program involving state institutions, Universities and CSIRO. In order to maximize the information gained in the Midwest region, studies of ecological interactions can usefully be divided into the following sub-sections. These do not map directly onto the goals above, rather they provide a more practical framework through which to plan the research program.

1. Habitat characterization and benthic community biodiversity studies.
2. Studies of major predator groups – finfish
3. Studies of major predator groups – rock lobster
4. Trophodynamic studies.

Ultimately this suite of studies will allow reasonably detailed quantitative models of Midwest coastal ecosystems to be developed, through the input of underpinning data, as well as through an iterative process of validation and observation. Such models are currently being developed as part of SRFME core objectives and should begin coming online around the time that the Midwest Collaborative program is being completed.

Trophodynamic studies

Trophodynamic studies undertaken as part of the program will mesh with other proposed and ongoing studies to provide a much better understanding of the flow of energy and nutrients at a range of spatial scales, from the small scale between habitats to larger cross-shelf scales. Studies on the dietary composition through gut content analyses of fish have traditionally been used to examine food webs and trophic linkages in aquatic ecosystems. However, such an approach rarely considers the ultimate source of energy and provides limited information on the interactions between the various primary producers and consumers in an ecosystem. Analyses of gut contents often provides only a snapshot of the diet of fish at a particular time, when the food consumed by fish often varies considerably over time (hours, days, seasons), during the life cycle of the fish (juveniles to adults) and among habitats (e.g. Werner and Gilliam 1984, Hyndes *et al.* 1997). Furthermore, different food types are digested at different rates, whereby hard-shelled prey can often be over-represented in gut-content analyses due to their recognisable fragments remaining in the guts for longer periods. In addition, the pharyngeal grinding of food by certain fish species renders the different food types consumed by these species indistinguishable.

Recently, researchers have recognised stable isotope techniques as a useful tool to identify and trace food/energy sources in coastal ecosystems (e.g. Kitting *et al*. 1984, Peterson and Fry 1987, Newell *et al*. 1995, Loneragan *et al*. 1997, Jennings *et al*. 1997, Pinnegar and Polunin 2000). This approach allows the linkages between fish and the various food sources in the coastal environment to be determined through measuring the natural isotopic ratios, typically $^{13}C/^{12}C$ and $^{15}N/^{14}N$, in the different primary producers and consumers. Since ^{13}C exhibits only slight enrichment in tissue from primary producers to the various consumer levels, $^{13}C/^{12}C$ typically is considered useful for tracing the source material in the food web (Peterson and Fry 1987). In comparison, ^{15}N displays a stepwise enrichment of approximately 3‰ between primary producer and each of the different consumer levels. The measurement of $^{15}N/^{14}N$ ratios has therefore been used to provide an estimate of the number of trophic levels in the food web (e.g. Fry and Quinones 1994). The combination of these isotopes provides a useful tool to examine the linkages among the various food sources and consumers in coastal environments and thereby provide an indication of the importance of different environments to major consumers.

Many important floral and faunal components of habitats are highly mobile, travelling large distances from one habitat to another. This transport includes the supply of drift algae or seagrass, as well as movements of reef-associated predators into other habitats to feed, or as part of seasonal foraging, ontogenetic or reproductive movements. By quantifying the abundance and origin of drift material, and by modeling the transport of algal and detrital particles we will begin to quantify the ecological linkages between habitats. Movement studies of key predatory species will provide information on the relative importance of different habitats for feeding and foraging. Biomarkers, particularly stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$), will be used to validate and calibrate the relative magnitude of energy flows within the system, as well as the potential for habitat-related and ontogenetic differences in trophic relationships of key species such as lobster.

Need

Part of the rationale for basing SRFME collaborative projects in the Midwest relates to opportunities presented by the Jurien Bay Marine Park, however it will take some time for differences in predator abundance to develop and for the park to reach its potential as a useful tool for ecological research. Nevertheless it is important for studies to commence as soon as possible, for two reasons. Firstly, the convincing demonstration of any direct or indirect effects of fishing revealed by changes of fishing pressure in the park will rely on a BACI design. Therefore we must act now to begin collecting all the necessary baseline data. Secondly, important information relating to trophic structure of coastal communities and how it varies among habitats as well as seasonally and interannually, can be collected now and will be a vital part of interpreting and potentially predicting any changes in ecological interactions that emerge as a result of park zoning. Trophodynamic studies undertaken as part of the program will mesh with other proposed and ongoing studies to provide a much better understanding of the flow of energy and nutrients at a range of spatial scales, from the small scale between habitats to larger cross-shelf scales. An understanding of habitat variability is also essential for the stratification of baseline sampling designs. A conceptual diagram of the processes and patterns to be investigated is provided in Figure 39.

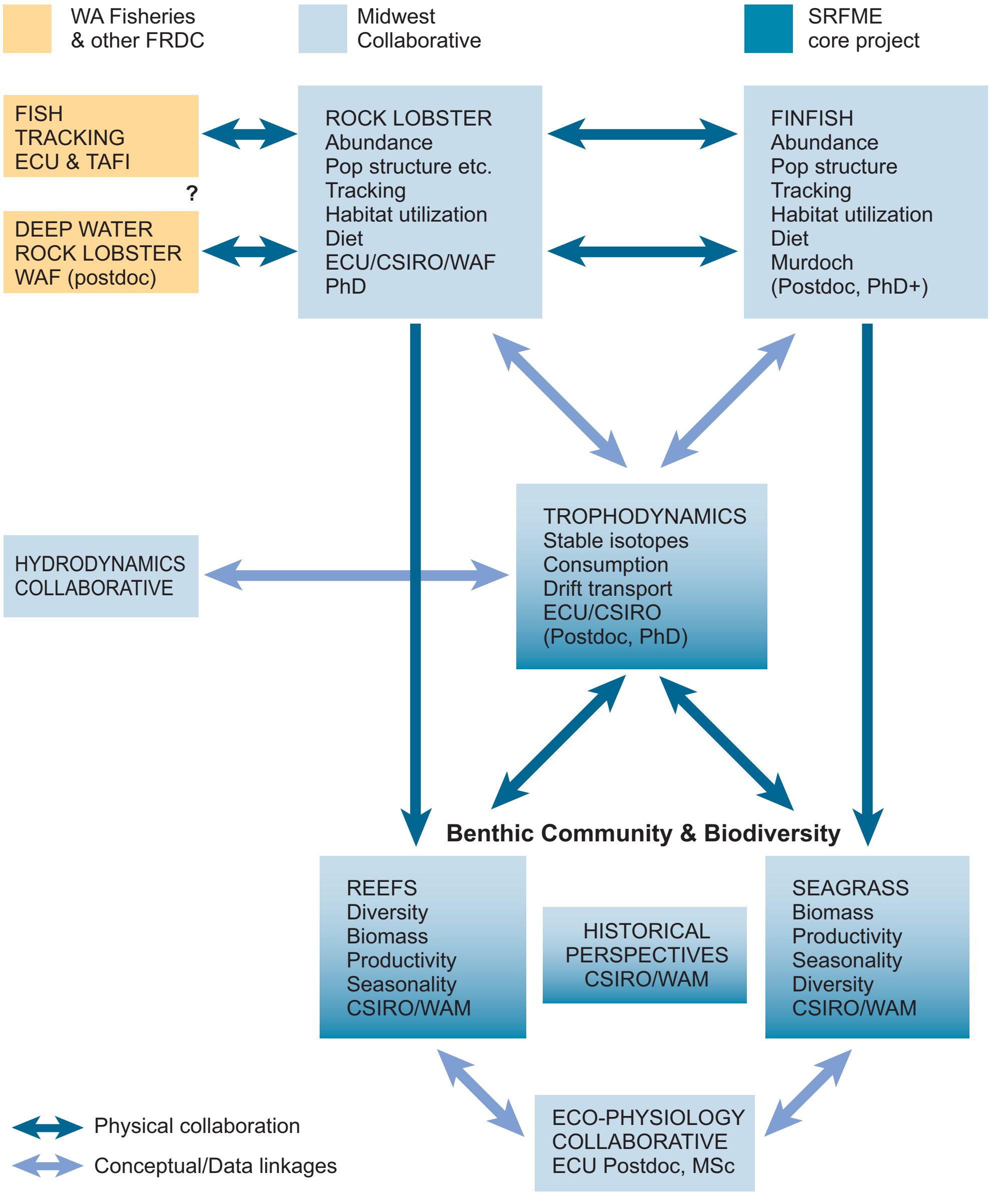

Figure 39: Midwest Collaborative Study Ecological interactions. The diagram indicates the main thematic components of the study, key institutional involvements, and their potential inter-relationships.

Objectives

The broad aim of this study is to examine the trophic linkages of different habitats within a coastal marine environment. This broad aim will be achieved through investigating the following specific objectives.

1. To determine the source of primary production that drives the food web for major consumers in a coastal marine environment using biomarker techniques;
2. To determine the spatial and temporal variability in the source of production for major consumers in a coastal marine environment; and
3. To determine the movement patterns of detached reef algae and seagrass into adjacent coastal marine habitats.

Outputs and Extension

The main objective of the outputs and extension plan is to provide regular updates on the progress of the study to the funding body and stakeholders, and finally provide coastal managers with information pertaining to the linkages between different habitats within a marine mid-west coastal marine environment.

Information arising from the study will be disseminated through scientific publications, reports and presentations. Progress reports will regularly be provided to SRFME and a final report will summarise the overall findings. Scientific Publications will be submitted to appropriate peer-reviewed journals. Seminars will be presented at SRFME Symposia, relevant national and international conferences, and where deemed necessary, interest groups. A web site will be constructed and continually updated to inform stakeholders of new results.

Planned Outcomes

The specific study will provide outputs into the degree of spatial and temporal links among different broad habitats within the Jurien Bay Marine Park, which will allow managers to assess whether the size of current management zones within the marine park are adequate. Furthermore, in combination with the compilation of data from the other related projects within the programme, will help establish baseline data on the biodiversity and ecology of Jurien Bay Marine Park. Such base-line data is essential for any future assessment of the effectiveness of management zones in the newly established Jurien Bay Marine Park, and allow for adaptive management of the marine park.

Methods

The study will be split into two main subcomponents; (1) biomarker analyses; and (2) movement and biomass of wrack.

Biomarkers (Stable isotopes)

Examining the diets of consumers has traditionally been used as a mechanism to study food webs in marine systems. However, dietary studies can underestimate the importance of some organisms to the food web due to their rapid digestion. Furthermore, dietary studies do not provide information on whether particular organisms are assimilated. It is therefore difficult to trace the origins of nutrients and energy using dietary approaches. Measurements of natural $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotopic ratios have been shown to be a useful tool for identifying and tracing the source of carbon and nitrogen in aquatic food webs (e.g. Kitting *et al*. 1984, Thresher *et al*. 1992, Newell *et al*. 1995, Loneragan *et al*. 1997, Marguillier *et al*. 1997). When an organism assimilates carbon and nitrogen from a source it either assimilates the isotopes indiscriminately, or displays a preference for one isotope (the fractionation ratio) for both carbon and nitrogen, thereby acquiring $\delta^{13}C$ and $\delta^{15}N$ that reflect the source. With the use of mixing models (e.g. Phillips & Gregg 2003), the $\delta^{13}C$ and $\delta^{15}N$ values of an organism can be used to infer the source of carbon and nitrogen it has assimilated, provided that the $\delta^{13}C$ and $\delta^{15}N$ ratios of all possible sources are known and differ to each other.

This component of the study will be split into two sections. The first phase of the study will examine the stable isotope signatures of a range of primary producers and consumers in a range of habitats in different regions of Jurien Bay. This part of the study will provide broad information on the flow of energy and nutrients in the food web of Jurien Bay. In other words, it will provide data on the contribution of the major primary producers to the food web of this marine system, and whether there are trophic linkages among different habitats. The second phase of the study will examine the spatial patterns in the influence of primary producers in unvegetated habitats and the extent to which primary producers from reefs and seagrass meadows influence the food web of unvegetated areas with increasing distance from those plant dominated habitats.

Broad trophic study

We propose to undertake detailed analyses of stable isotope signatures for rock lobster and selected finfish species with a view to gaining a better understanding of, not only how trophic relations vary among species, but also whether they vary ontogenetically due to changes in diet of individuals of increasing size. Habitat use may also vary ontogenetically, therefore we will explore variation in trophic signature between habitats and the possibility that isotopic signatures may be the result of the interaction between size and habitat.

The study will concentrate on collecting samples of consumers [finfish (e.g. Pink snapper) and major invertebrates (e.g. Western rock lobster)] from a range of dominant habitats in Jurien Bay, as well as collecting dominant primary producers (seagrasses and seagrass epiphytes, reef macroalgae, phytoplankton and benthic micro-algae) from the region. Since detritus is likely to form a major link in the food web, samples of different fractions of detritus will be collected to determine its composition in different regions of Jurien Bay.

Fish and invertebrates will be collected from reef, seagrass and unvegetated habitats in three regions of Jurien Bay using trawls or gill nets or by spearing. Where possible, this project will link into the dietary studies by MU, but additional samples may be required for the collection of adequate sample sizes. White flesh will be removed for stable isotope analyses. Macro-invertebrates will be collected through dive collections or coring. Flesh samples will be removed and stored for stable isotope analyses. Where invertebrates are too small to remove sufficient flesh, individuals will be pooled as one sample. Samples of live algae will be collected from reefs, and seagrass and epiphytic algae will be collected from seagrass meadows adjacent to reefs. Plants will be removed of any epiphytic material.

At least three replicate samples will be collected for each organism from each habitat and region. For major consumers, attempts will be made to collect samples from different size groups to examine ontogenetic shifts in stable isotope signatures. Since diets may vary seasonally, samples will be collected during two times of the year (summer/autumn and winter/spring).

Since $\delta^{13}C$ and $\delta^{15}N$ values among primary producers can be similar, alternative biomarkers may be required to allow differentiation of primary producers as sources for consumers. Sulphur isotopes have been shown to be useful to distinguish between benthic and pelagic food webs. For this reason, we will analyse sulphur isotope for target key benthic and pelagic species for these analyses.

All samples will be processed for $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios using an ANCA-NT/20-20 stable isotope ratio mass spectrometer at ECU. The $\delta^{13}C$ and $\delta^{15}N$ values will subsequently be calculated and compared using a multiple-source mixing model (e.g. Phillips and Gregg 2003). For targeted species, samples will be processed for sulphur and sent to other facilities for analyses.

Many studies have used the assumption that $\delta^{13}C$ displays minimal enrichment while $\delta^{15}N$ displays a stepwise enrichment (3-5 ‰) between different trophic groups. However, this can be highly variable among different organisms, particularly for $\delta^{15}N$ (Ponsard & Vanderklift 2002). Interpretation of stable isotope data requires information on the enrichment of both $\delta^{13}C$ and $\delta^{15}N$ through the various trophic steps. However, there is limited information available on enrichment of these isotopes for the organisms that will be examined in this study. We therefore propose to carry out a series of experiments to examine the trophic enrichment of $\delta^{13}C$ and $\delta^{15}N$ and sulphur exhibited by some major consumers.

Selected invertebrates will be placed in aquaria and provided with food for which the $\delta^{13}C$ and $\delta^{15}N$ values are known. Consumers will be kept in the aquaria for up to two months to ensure that SI signatures derived from their existing diet has been replaced by that derived from their new diet. At the end of the experiments, consumers will be removed from the aquaria, euthanased and flesh removed for SI analyses. Differences between the $\delta^{13}C$ and $\delta^{15}N$ values will indicate the level of enrichment (or depletion). For fish and large macro-invertebrates, the turnover of $\delta^{13}C$ and $\delta^{15}N$ in the flesh is likely to occur over an extensive timeframe, thereby limiting any opportunity to carry out aquaria experiments to examine enrichment in these organisms. We therefore propose to collaborate with personnel at the TAFE Maritime Centre, where fish are being reared in captivity. We will examine the $\delta^{13}C$ and $\delta^{15}N$ of a suite of fish species (e.g. Pink snapper, Black bream and Dhufish) and their food source.

Spatial influence

As previously noted, trophic studies using stable isotopes are useful when the SI signatures of the various primary producers are widely disparate. Current work at ECU (G. Hyndes and P. Lavery) is showing that the seagrasses *Posidonia* spp. and *Amphibolis* spp. have highly enriched $\delta^{13}C$ values relative to algal species. However, the SI signatures of brown, red and green algae are relatively similar to each other, making it difficult to distinguish these groups as potential sources. The second phase of the stable isotope study will therefore attempt to fill some of the gaps that have become event from the broad stable isotope study. Potentially, by the end of Phase 1, we will not have a clear understanding of the principal sources of C and N in unvegetated areas that are adjacent to reefs and seagrass meadows, yet the transport of material from these other major benthic habitats is likely to provide significant production into these unvegetated areas.

The second phase of the study (year 2) is likely to focus on examining the change in stable isotope signatures in the benthic infauna and epibenthic fauna in unvegetated areas with increasing distance away from seagrass meadows and reefs. A current study by Mat Vanderklift is examining the hypothesis that $\delta^{13}C$ in seagrass fauna should change gradually with distance from reef, reflecting the gradual change in the relative importance of reef-derived macroalgae and seagrass. The proposed study will expand on this hypothesis by examining the hypothesis that $\delta^{13}C$ in fauna associated with unvegetated areas should change gradually with distance from reef and seagrass meadows, resulting from a shift in the relative importance of reef-derived macroalgae and seagrass.

Artificially enriching either the $\delta^{13}C$ or $\delta^{15}N$ of some of the major primary producers may be required to provide a clear demarcation of the SI signatures of those sources that will allow SI signatures to be tracked along transects away from reefs or seagrass meadows. Alternatively, other biomarkers, such as sulphur, fatty acids or amino acids, may be required to fulfill this task. Results from current preliminary work at CSIRO and ECU will be used to help direct and refine this part of the project.

Movement and biomass of wrack

Accumulations of wrack are a prominent feature of the coastline of south-western Australia. Algae from reefs and seagrasses and their associated epiphytic material become dislodged, particularly during winter storms, and are transported into adjacent habitats. It has been estimated that approximately 20% of production from reefs and seagrass meadows passes through the nearshore regions (Hansen 1984), where it has been shown to provide important habitats for a range of invertebrates and finfish species (Robertson & Lenanton 1984, Lenanton *et al*. 1981). Currently, a SRFME PhD study at ECU (K. Crawley) is further examining the importance of this wrack material to the habitat structure and trophic dynamics of nearshore waters in the Perth metropolitan region. This study is showing that fish species have a clear preference for particular volumes and types of wrack and that prey species have a clear preference for brown algae as a food source.

We propose to examine the movement patterns of wrack from reef and seagrass meadows into subtidal, unvegetated areas in Jurien Bay. The transport of this material is likely to contribute significantly to secondary production in these areas. We will also examine the biomass and composition of wrack material in these areas. This will be achieved through:

- Stratified random design using towed video transects, and ground truthing using large quadrats to quantify the volume/biomass of different wrack types in different regions during different times of the year. Sampling will be conducted over at least four (seasonal) sampling occasions.
- Tracking of wrack using either acoustic tags and receivers for tracking the movement of wrack, or using conventional tags or colour-dyed plant material and towed video transects to record presence of “tagged” material in adjacent unvegetated areas. The acoustic tagging approach will be dependent on the success of additional proposals to gain funds for this part of the study.

Performance Indicators

1. Results describe the major source(s) of primary production that contribute(s) to the production of major consumers, including economically important finfish species and western rock lobster.
2. Results describe the spatial and temporal variability in the relative contribution of primary producers to the production of major consumers.
3. Results describe the movement patterns of detached reef algae and seagrass among broad habitats.

MILESTONES

31 May 2005: Postdoctoral Fellow and Research Assistant appointed. Sampling protocol and locations finalised. Collection of stable isotope samples for first season completed.

30 November 2005: Processing and analyses of stable isotope samples for first season completed. Preliminary studies on isotope enrichment completed. Collection of stable isotope samples for second season completed.

31 May 2006: Processing and analyses of stable isotope samples for second season completed. Sampling design and methods finalized for second phase of the stable isotope study.

30 November 2006: Processing of stable isotope samples for the second phase of the stable isotope study completed. Survey of wrack in different habitats completed.

31 May 2007: Analyses of stable isotope samples for the second phase of the stable isotope study completed.

30 November 2007: If acoustic tagging studies of wrack are possible, collection of movement patterns of wrack through acoustic tagging will be completed. Final analyses of stable isotope and wrack data completed. Draft report completed.

Project Staff Justification

The Postdoctoral Fellow (to be appointed) will be responsible for the extensive field and laboratory program, and run the projects on a day to day basis, as well as contributing to the supervision of students involved. A casual Research Assistant (to be appointed) is required for field support, laboratory processing and maintenance of equipment. The Principal Investigator (Glenn Hyndes) will be responsible for the overall management and coordination of the project supervised, as well as supervision of the Postdoctoral Fellow, Research Assistant and students. Co-investigators (Mat Vanderklift and Russ Babcock) will provide intellectual input into the project and help with the supervision of students involved in the project.

3.3.5 Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster

Principal Investigator
Dr Glenn Hyndes
Senior Lecturer
School of Natural Sciences, Edith Cowan University, 100 Joondalup Drive, JOONDALUP WA 6027
Phone: 6304 5798 Fax: 6304 5509 Email: g.hyndes@ecu.edu.au

Co Investigator
Dr Russ Babcock
Senior Research Scientist
CSIRO Marine Research, Underwood Ave, Floreat WA 6014
Phone: 9333 6535 Fax: 9333 6555 Email: russ.babcock@csiro.au

Dr Mat Vanderklift
Research Scientist
CSIRO Marine Research, Underwood Ave, Floreat WA 6014
Phone: 9333 6536 Fax: 9333 6555 Email: mat.vanderklift@csiro.au

Note: This project has just commenced, and has no results to report as of this date.

Project Description

Background

A three-year program to investigate ecological interactions in midwest coastal reef communities will be built around the Jurien Bay Marine Park (see Figure 38, previous section, trophodynamics), using multiple-use management zones within the park as large scale manipulations of predator abundance. This focus will give the program an emphasis that distinguishes it from core SRFME projects and takes advantage of the unique opportunities developing in the midwest area. Two groups of predators, finfish and spiny lobster, are of primary interest and the zoning of the park, into areas subject to all kinds of fishing, lobster fishing only, and no-take restrictions, will facilitate the understanding of their respective ecological roles.

Outline

The key research/management questions that exist in the context of Ecological Interactions in the Midwest are as follows:

- What are the trophic linkages of exploited species to other ecosystem components?
- What are the pathways of transport of organic matter and nutrients between habitats and across the shelf?
- How do exploited species in particular utilize the range of available coastal shallow water habitats (e.g. foraging in seagrass, sheltering on reefs)?
- What are the potential trophic (indirect) effects of variations in predator density?
- What is the relative importance of any anthropogenic variation in ecological interactions relative to natural variability at the habitat, seasonal and interannual levels (e.g. can we detect indirect ecological effects of fishing against the background of natural variability)?
- How will populations of exploited predatory species respond to marine park protection (i.e. what are the direct effects of fishing)?

The goals outlined above can be achieved through an integrated research program involving state institutions, Universities and CSIRO. In order to maximize the information gained in the Midwest region, studies of ecological interactions can usefully be divided into the following sub-sections. These do not map directly onto the goals above, rather they provide a more practical framework through which to plan the research program.

1. Habitat characterization and benthic community biodiversity studies.
2. Studies of major predator groups – finfish
3. Studies of major predator groups – rock lobster
4. Trophodynamic studies.

Ultimately this suite of studies will allow reasonably detailed quantitative models of Midwest coastal ecosystems to be developed, through the input of underpinning data, as well as through an iterative process of validation and observation. Such models are currently being developed as part of SRFME core objectives and should begin coming online around the time that the Midwest Collaborative program is being completed.

Studies of major predator groups – rock lobster

The Western Australian rock lobster *Panulirus cygnus* is the dominant invertebrate predator in coastal and shelf ecosystems between Northwest Cape and Cape Leeuwin. As such it is likely to have an important role in the dynamics of these ecosystems. Because of ontogenetic changes in the spatial distribution of western rock lobster these dynamics are likely to be complex, and interactions with a large commercial fishery have the potential to add further layers of complexity. Puerulus settle on shallow coastal reefs, where they spend the first months of their lives solitary and sheltering in small crevices in limestone reefs during the day and foraging at night in algal turf and seagrass habitats. As they grow the young lobsters become less solitary and move into larger caves and crevices on deeper reefs where they shelter during the day. Less is known about the foraging and feeding of lobsters and the range of habitats that they use at this stage, which lasts until about the age of 4 years when many of the lobsters undertake long distance migration into deeper waters (>30m), well off the coastal reef systems. It is at around this time that the lobsters reach legal size and enter the fishery.

Gaps in our knowledge of rock lobster ecology in shallow waters relate primarily to two areas: habitat use and feeding; and population structure. Our understanding of how lobsters use deeper reefs, sandy areas, and seagrass habitats such as *Posidonia* meadows with respect to shelter and foraging, and the principal prey of lobsters in these habitats, is not complete. We know that lobsters of different sizes tend to be found in different habitats but it is unclear how the population structure of lobsters in shallow water may have changed as a result of fishing. Anecdotal historical reports describe large rock lobster as being present or common in shallow reef systems in the past, yet such individuals are now very rare in shallow coastal reef systems. Consequently, the historical role of rock lobsters in shallow coastal ecosystems (and the indirect effects of fishing on ecosystem structure and function) is difficult to assess.

In order to effectively study or to demonstrate the potential role of predation by rock lobster on coastal benthic communities, we require populations of lobsters with differing population structures and that vary over a range of population densities. The reason for this is simple. For example, we may design caging experiments to exclude lobsters but if they are not present, the exclusion will make little difference to the experimental results. This may be especially relevant to determining the influence of larger rock lobsters. One way of gaining access to such populations of lobsters is to use fished and unfished areas. Such areas are currently being established at Jurien and are potentially extremely useful experimental tools. However, it is not clear whether strong contrasts in lobster density or population structure will develop. Studies of rock lobster populations in other parts of the world have shown, using no-take marine protected areas (MPAs), that there are significant changes to population structure and also to total biomass inside these areas relative to fished areas (Kelly *et al* 1999, Edgar and Barrett 1999, Lafferty and Kushner 2000), but such changes are not observed universally, possibly because either they lack suitable habitat (Mayfield *et al* 2000) or, where species are highly mobile, MPA boundaries fragment suitable habitat (Acosta 2001). Since most *P. cygnus* reach legal size and move into deeper water at the age of around 4 years, and most of the Sanctuaries within the Jurien Marine Park are located in relatively shallow waters, it may be that there is little if any detectable effect of fishing on shallow water populations.

Developing an understanding of the variation in density and population structure of rock lobsters, and its resulting consequences, is intimately related to ontogenetic shifts in habitat utilization. Broadly speaking lobsters settle on inshore reefs as puerulus and live in inshore areas until approximately the age of 4 yrs at which time they move into deeper shelf waters. Whether there are finer scale habitat preferences of lobsters within this framework is not clear. For example, is there an incremental shift of lobsters from coastal and lagoon reefs to offshore reefs as they grow older, and do lobsters prefer particular reef habitats? Also, vital to understanding the interactions of rock lobsters with benthic assemblages is the collection of data on how diet may vary with lobster size. Finally we need to know how lobsters use their habitat and the extent to which they move from one to another.

Need

Part of the rationale for basing SRFME collaborative projects in the Midwest relates to opportunities presented by the Jurien Bay Marine Park, however it will take some time for differences in predator abundance to develop and for the park to reach its potential as a useful tool for ecological research. Nevertheless it is important for studies to commence as soon as possible, for two reasons. Firstly, the convincing demonstration of any direct or indirect effects of fishing revealed by changes of fishing pressure in the park will rely on a BACI design. Therefore, we must act now to begin collecting all the necessary baseline data. Secondly, important information relating to trophic structure of coastal communities and how it varies among habitats as well as seasonally and interannually, can be collected now and will be a vital part of interpreting and potentially predicting any changes in ecological interactions that emerge as a result of park zoning. Given the high economic value of Western rock lobster and the greater emphasis on ecological effects of fishing through the EPB act, it is imperative that we gain a greater understanding of the impact of removal of rock lobster on the broader ecosystem. This study will mesh with other proposed and ongoing studies to provide a much better understanding of the movement of lobster and the flow of energy and nutrients at a range of spatial scales, from the small scale between habitats to larger cross-shelf scales. A conceptual diagram of the processes and patterns to be investigated is provided in Figure 39 (see previous section, trophodynamics).

Objectives

The broad aim of this study is to determine the habitat use and trophic links of Western rock lobster in the mid-west region. This broad aim will be achieved through investigating the following specific objectives.

1. Determine the densities and size structure of western rock lobster in a range of different benthic habitats;
2. Determine the movement patterns of western rock lobster between reefs and foraging habitats;
3. Investigate dietary changes of western rock lobster with changes in size, habitat use and season; and
4. Provide baseline data that will allow the success of sanctuary zones in terms of increasing lobster abundance to be assessed in the future.

Outputs and Extension

The main objective of the outputs and extension plan is to provide regular updates on the progress of the study to the funding body and stakeholders, and finally provide coastal managers with information pertaining to the linkages between different habitats within a marine mid-west coastal marine environment.

Information arising from the study will be disseminated through scientific publications, reports and presentations. Progress reports will regularly be provided to SRFME and a final report will summarise the overall findings. Scientific Publications will be submitted to appropriate peer-reviewed journals. Seminars will be presented at SRFME Symposia, relevant national and international conferences, and where deemed necessary, interest groups. A web site will be constructed and continually updated to inform stakeholders of new results.

Planned Outcomes

The study will provide descriptions of abundance, population structure, diet, home range and seasonal movement patterns of rock lobster in Jurien Bay Marine Park, thereby providing information on the temporal and spatial habitat utilization and population structure of western rock lobster and any ontogenetic, temporal and spatial shifts in its diets. The study will provide a sound basis for understanding trophic relations at higher levels and will lay the groundwork for understanding what, if any, are the direct and indirect effects of fishing on coastal ecosystems. Furthermore, in combination with the compilation of data from the other related projects within the program, this study will help establish baseline data on the biodiversity and ecology of Jurien Bay Marine Park. Such base-line data is essential for assessing whether the size of current management zones within the marine park are adequate, and for future assessment of the effectiveness of management zones in the newly established Jurien Bay Marine Park.

Methods

Lobster density and population structure will be measured twice yearly in October/November and June/July on reefs less than 20 m depth. Potentially a third sampling season will be included, in January/February, to better document any changes in shallow water populations related to the “whites” migration. The reefs studied will be stratified according to habitat type, reef depth and cross-shelf location to account for physical habitat variability. In addition the population studies will be stratified with respect to levels of protection from fishing pressure, and include sanctuary zones, zones open only to commercial rock lobster fishing, and zones open to all kinds of fishing. Reef size, size of sanctuary and distance from sanctuary will be factored into analyses as co-variates. Sampling will concentrate across these locations in two regions (e.g. Jurien and Green Head). The sampling philosophy is to study these areas within the Jurien Bay Marine Park intensively, rather than study all the zones in the park extensively. Portions of the core survey will be conducted in collaboration with CSIRO Marine Research as required to complete or extend the design as required.

Adult and sub-adult lobsters will be censused by divers using 50 x 5 m transects deployed parallel to the reef slope over reef habitat. Within each strata there will be two sites, and six transects per site. The Carapace Length (CL) of all lobsters seen within transects will be estimated visually by trained and pre-calibrated divers (MacDiarmid 1991) and the sex of all lobsters determined to provide data on sex ratios. Moult stage will be recorded, as will any damage to lobsters (e.g. broken antennae, missing legs). Data, including general habitat type, will be recorded in 5m blocks to enable subsequent spatial analysis. Surveys of juvenile lobsters (< 40 mm CL) will be conducted at the same sites using 5 x 1 m transects, following methods similar to those employed in previous studies in the region (e.g. Edgar 1981), including nocturnal surveys.

Lobster diet will be directly determined from the gut contents of lobsters collected by divers within 1 hour of sunrise. Collections will be made throughout the year, with approximately equal samples from three seasons, coinciding with population surveys. Data will be collected from the entire available size range of lobsters, and sampling will take place within all of the strata sampled in the population surveys. Lobsters will be put on ice immediately after collection, gut contents dissected within 3 hours, and preserved in 70% ethanol. Contents will be identified to the lowest possible taxonomic level, classified according to trophic level, and quantified using image analysis of relative abundance.

Lobster movements will be assessed across a range of spatial scales using several techniques. Standard Capture-Mark-Recapture using “spaghetti” tags inserted ventrally between the tail and carapace will be used to attempt to capture some information from the commercial and recreational fisheries. A subset of these animals will be tagged using colour coded tags placed around the base of the antennae and will allow for medium term re-sighting and identification of lobsters by divers. This method allows animals to be individually identified without handling and has proven useful in assessing levels of site fidelity over periods of 6-12 months. These data will be supplemented with direct observations of nocturnal lobster foraging behaviour where possible.

Approximately 20 lobsters will be tagged using acoustic tags (VEMCO VR2) attached dorsally to the carapace using cable ties. This will allow larger scale movements of animals to be tracked with an accuracy of approximately ±100 m (Egli and Babcock *in press*) using an array of at least 24 receivers that will cover an area approximately 19 km^2. In particular, 3+ and 4+ year class animals will be targeted post-moulting in November and December as "whites". Most will be expected to take part in offshore migrations and may be picked up by offshore acoustic arrays (Chubb *et al*. WAFish FRDC proposal), however some may remain in near-shore waters and establish long-term residence there (in the absence of fishing mortality). Therefore, in order to establish whether some animals remain resident on coastal reefs, the tracking will be done in a sanctuary zone, most likely the large zone immediately to the south of Jurien and focused around the Booka Reef area.

Performance Indicators

1. Results clearly describe the habitat utilization of western rock lobster in the reef/seagrass habitat complex in take and no-take zones of Jurien Bay.
2. Results clearly describe the movement patterns of western rock lobster among reefs and between reefs and foraging habitats.
3. Results clearly describe the dietary changes of western rock lobster associated with change in size, habitat and season.

MILESTONES

31 May 2005: Sampling protocol and locations finalised. Collection of density and population structure data for the first season. Collection of gut samples for the first season completed.

30 November 2005: Collection of density and population structure data and gut samples for the second season completed. Processing of gut samples for first season completed.

31 May 2006: Collection of density and population structure data for the third season completed. Processing of gut samples for second season completed.

30 November 2006: Collection of density and population structure data for the fourth season completed. Tagging studies initiated.

31 May 2007: Tagging studies completed. Preliminary analyses of density and population structure and dietary data completed.

30 November 2007: Final analyses of density and population structure and dietary data completed. Draft report completed.

Project Staff Justification

The postgraduate student (Lachlan MacArthur) will be responsible for the extensive field and laboratory program, and run the projects on a day to day basis. A casual Research Assistant (to be appointed) is required for field support, laboratory processing and maintenance of equipment. The Principal Investigator (Glenn Hyndes) will be responsible for the overall management and coordination of the project, as well as the supervision of the postgraduate student. Co-investigators (Russ Babcock and Mat Vanderklift) will provide intellectual input into the project and co- supervise the student.

3.3.6 Ecophysiology of Benthic Primary Producers

Principal Investigator

Associate Professor Paul Lavery, School of Natural Sciences, Edith Cowan University
Dr Russ Babcock, Marine Research, CSIRO
Dr Ray Masini, Department of Environment (WA)

Introduction

Light is probably the single most important environmental factor controlling coastal benthic primary productivity. A broad range of coastal and marine developments can lead directly or indirectly to a reduction in PAR availability at the seabed. In this context, the understanding of light and its co-variates as a driver of ecosystem structure is of fundamental importance for the management of the State's marine environment.

Robust and ecologically meaningful indicators of sub-lethal environmental stress must underpin such management. Sound science to inform the development of these indicators and their associated criteria is therefore critical to achieving sustainability in Western Australia. The objectives of this research program are to fill gaps in our understanding of how ecosystems respond to variation in light, in order to improve our ability to understand variations in habitat structure at the ecosystem level and to assess and manage impacts associated with human use of these systems.

Key benthic habitats along the central west coast for which scientific research is required are primarily seagrass meadows and macroalgal reefs. There are particular gaps in the understanding of the effects of light stress on *Amphibolis* species (*A. antarctica* and *A. griffithii*). In the context of allowing the correct balance to be struck between protecting the environment without unnecessarily constraining development, quantitative assessments of the degree of light reduction that can be sustained without irreversible or long term damage are urgently required.

Only by conducting controlled and replicated field experiments that involve the manipulation of known factors are we able to limit the relative contribution of potentially confounding factors to the research outcomes. To this end a single experimental design has been developed to address a range of reduced light scenarios. The research project involves the establishment of treatment and control sites to determine the effect of reduced PAR and the timing and duration of light reduction on Amphibolis species.

Aims/objectives

1. To determine the effect different intensities, durations and timing of PAR reductions on *Amphibolis* ecosystems; and

2. To determine the subsequent patterns of recovery.

Major findings

The project was initiated in November 2004, but was preceded by pilot research. The pilot research addressed the question of the effect of a high intensity, short-term reduction in PAR on *Amphibolis* ecosystems. Replicate plots of *A. griffithii* meadow were subjected to either 89.9% (treatment) or 0% (control) reduction in incoming PAR for three months and variables monitored over that period and a subsequent one month recovery period.

Shoot and leaf density & biomass

Total leaf biomass displayed marginal increases over time in the control plots, but declined significantly in shaded plots (Fig 40). After 106 days, the shaded plots had about one-third the leaf biomass of unshaded plots (150 ± 38 g m^{-2} and 452 ± 103 g m^{-2}, respectively). Leaf biomass increased in the shaded plots following removal of the shade screens and was not different to the controls after 42 days. The reduction in leaf biomass in the shaded plots was due to a loss of leaves that appeared to be distributed over all leaf clusters, with the number of leaves per cluster showing a similar response to leaves per stem: at day 106 there was an average of 1.9 leaves per cluster in the shaded plots compared to 3.1 leaves per cluster in the control plots. Over 106 days, cluster density declined from 3075 to 1825 clusters per m^{-2} in shaded plots, but remained between 2575 – 3675 clusters per m^2 throughout the period in the control plots. A sharp recovery in leaf cluster density was evident in the shaded plots following removal of shading; 42 days later there was no difference between the previously shaded and the control plots.

Stem density and biomass

Stem biomass and stem density in both treatment and control plots remained relatively stable and ranged from approximately 250 – 400 g DWper m^2 and 250 – 400 stems per m^2 throughout, respectively (Fig 41). Maximum and average canopy heights also remained relatively stable over time (30 – 58 cm) with average heights of 25 – 38 cm.

Below ground biomass

Root, rhizome and detrital biomass remained stable throughout the study with little difference between treatments and control. Only root biomass showed a significant treatment affect.

Epiphyte biomass

Epiphyte dry weights declined in the shaded plots (Fig 42). After 42 days epiphyte biomass was less than half that in the control plots (211 ± 122 and 476 ± 200 g m^{-2}, respectively) and after 106 days was about 20% of the control (92 ± 82 versus 500 ± 29 g m^{-2}).

Leaf Extension

Leaf extension in control plots was constant over the experimental period, at about 0.6 mm leaf $^{-1}$ day $^{-1}$ but in the treatment plots decreased to approximately one half and one third of this after 66 and 106 days of shading, respectively (Fig 42). The differences between control and shaded plots were no longer significant 42 days following shade removal. Similarly, areal leaf production, the product of leaf density and leaf extension rates, was significantly affected by treatment.

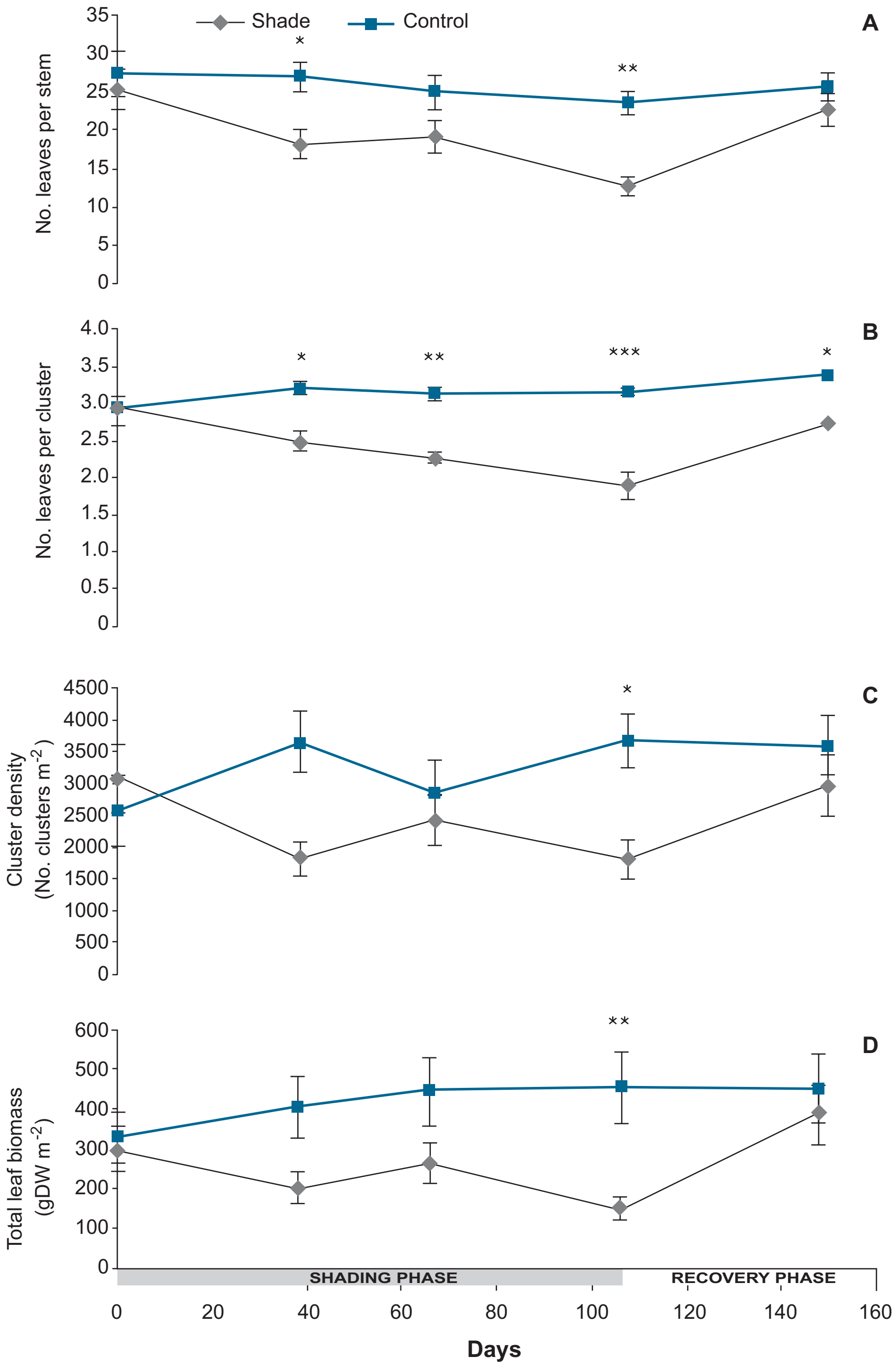

Figure 40: Leaf and leaf cluster responses in the seagrass *Amphibolis griffithii* during both the shading and recovery phases of the study A) number of leaves per stem, B) number of leaves per cluster, C) areal leaf cluster density, D) total leaf biomass (n=4 ±SE). Values significantly different between control and treatment at each time indicated by * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).

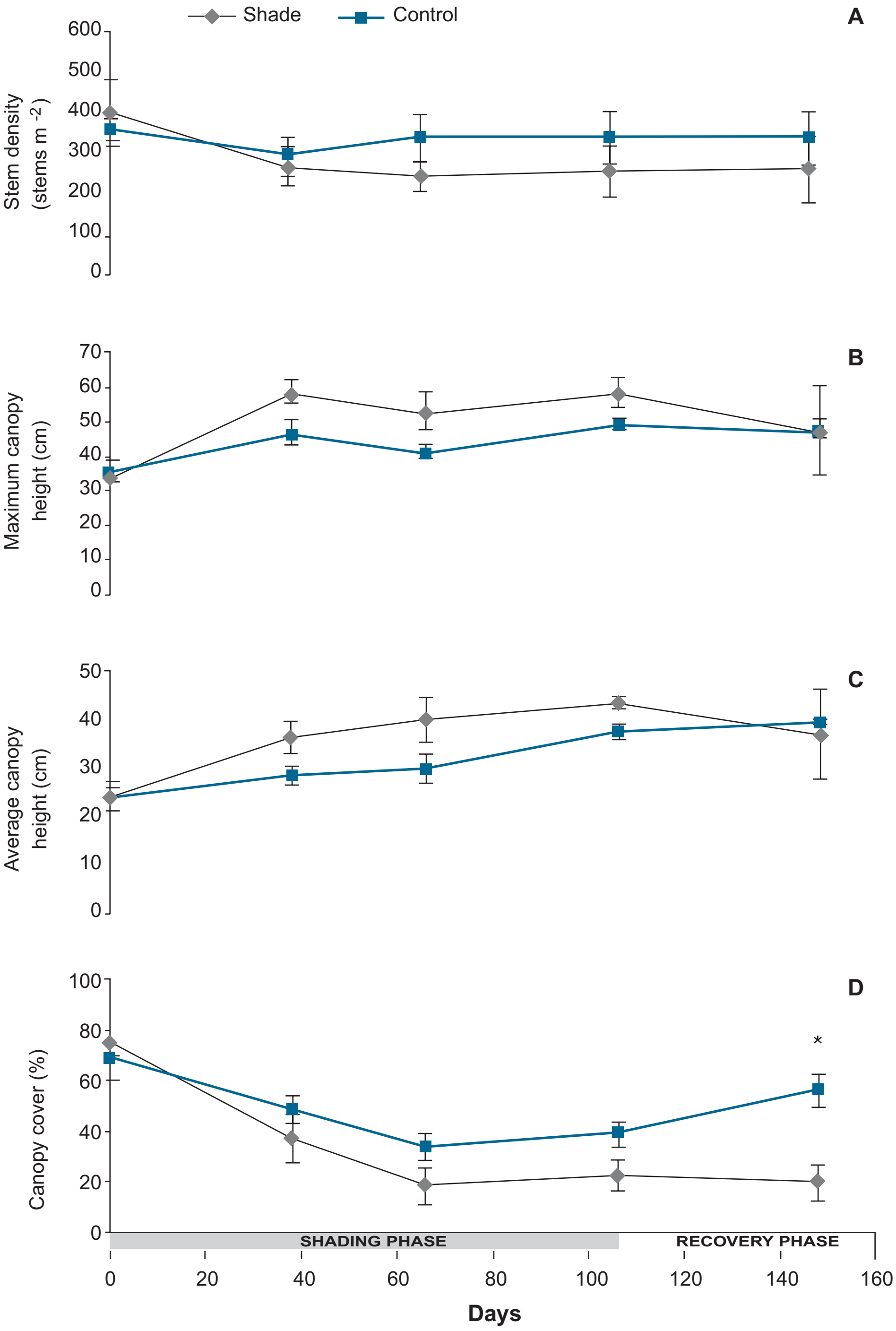

Figure 41: Canopy characteristics measured in fixed quadrats during the shading and recovery phases of the experiment A) stem density, B) maximum canopy height, C) average canopy height, D) canopy cover (n=4 ±SE). * = $p<0.05$.

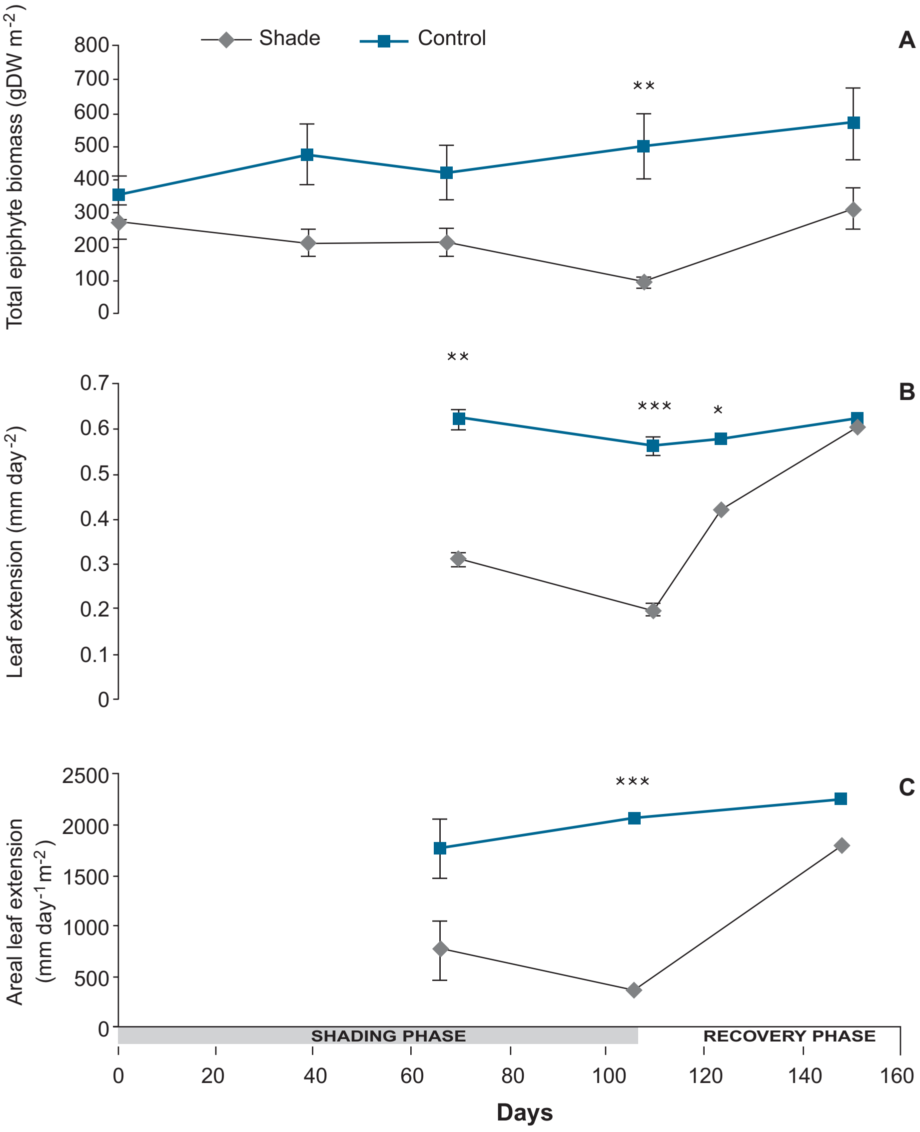

Figure 42: Epiphyte biomass and leaf extension during shading and recovery phases of the experiment A) epiphyte biomass, B) leaf extension, C) areal leaf extension (n=4 ±SE). * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).

PAR Attenuation through the canopy

After 106 days of shading there were significant differences in the amount of PAR attenuated by the canopy in the shaded and control plots (Light Attenuation Coefficient (LAC) = 2.38 and 0.59 m^{-1}, respectively), representing an almost two orders of magnitude difference in PAR penetration.

Sugars and starches

The most noticeable affects of shading on carbohydrate pools were in rhizome tissue: in the controls, concentrations did not change significantly over time, averaging 152 ± 16 $\mu g\ g^{-1}$ (Fig 43) while in shaded plants concentrations declined to about 26 ± 2 $\mu g\ g^{-1}$ during the shading before increasing to 70 ± 17 $\mu g\ g^{-1}$ over the recovery period.

Total soluble sugar concentration in the leaves was significantly affected by treatment and, after 38 days, was significantly lower in the shaded plants compared with control. Following this, the concentration of sugars in the shaded leaves remained steady, at about 100 μg/g, while in the controls it fell so that by the end of the shading period there were no significant differences between the two.

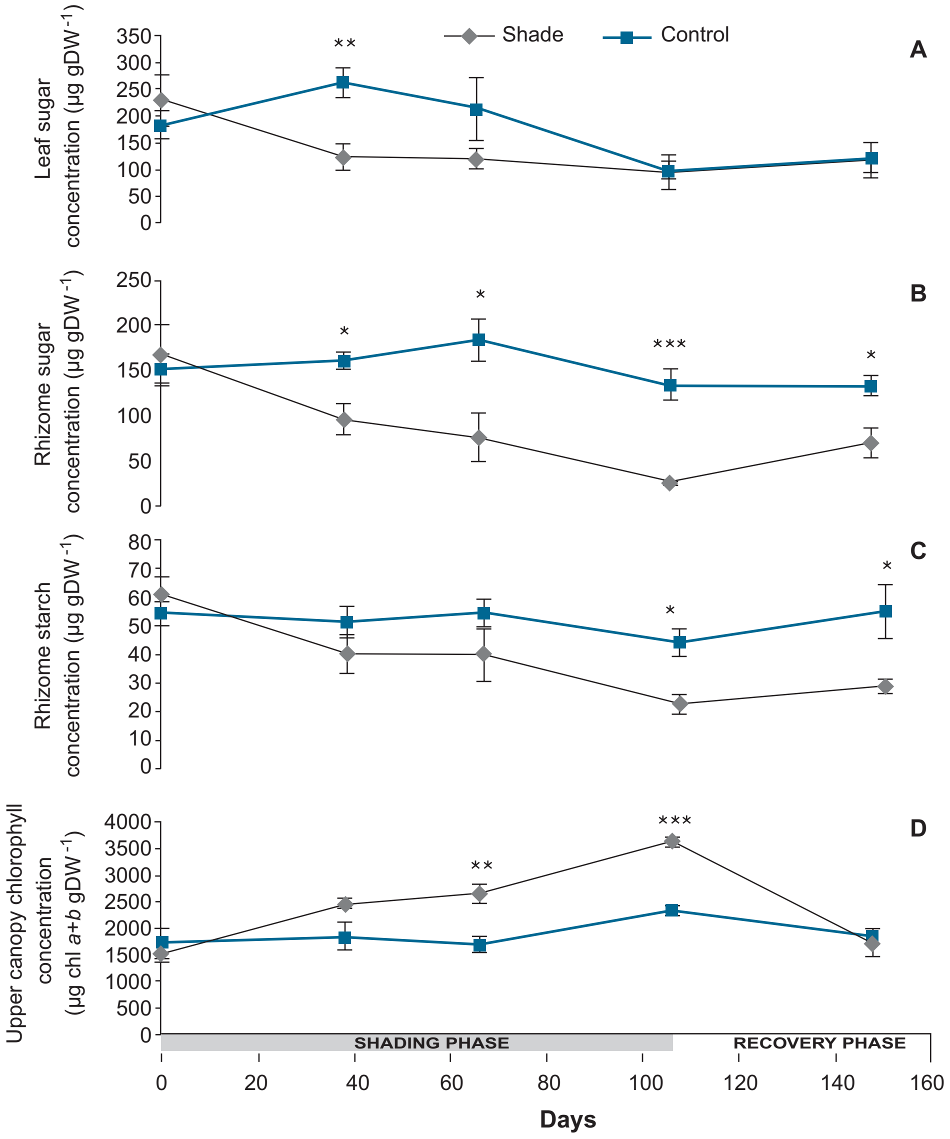

Figure 43: Carbohydrate and pigment characteristics of *Amphibolis griffithii* during shading and recovery periods A) leaf sugar, B) rhizome sugar C) rhizome starch, D) chlorophyll in the upper canopy (n=4 ±SE). Significant differences indicated by * ($p<0.05$), ** ($p<0.01$) and *** ($p<0.001$).

Chlorophyll

Shading had a significant effect on the chlorophyll concentration of leaves but only in the upper canopy. At the start of the shading period shaded and control plants had similar concentrations of chlorophyll in upper canopy leaves (about 1600 ug chl g^{-1}) but after 106 days this had increased to 3618 ± 96 ug chl g^{-1} in shaded plants, 55% greater than control plants (2332 ± 108 ug chl g^{-1}).

Overall findings

The study has clearly shown that severe reductions in the availability of PAR have significant effects on *Amphibolis griffithii* and its epiphytic algal assemblages over timescales of 1-3 months. It has also shown that most of the variables measured demonstrate significant recovery towards control characteristics within a similar period.

Seagrasses typically store excess photosynthates in the rhizome in order to overcome periods of unfavourable environmental conditions. It would appear that *A. griffithii* responded in this manner by drawing down the below ground sugar and starch stores. While the plants remained functional, they were clearly demonstrating a carbon deficit, suggesting that the minimum light requirements of *A. griffithii* are in excess of 10% of surface irradiance. Simultaneously, it appears that while carbon reserves were being remobilised from the rhizome there was a simultaneous reduction in the above-ground carbon demand through shedding of leaves, which have a much higher respiratory load than below-ground material. The dramatic reduction in above ground tissue would dramatically reduce the total plant respiratory load. The reduction in above ground biomass also had the effect of thinning the seagrass canopy and reducing self-shading. This may assist in recovery of the remaining leaves once PAR conditions improve.

The sugar and starch concentrations in *Amphibolis griffithii* tissues showed marked responses to PAR reduction. In shaded plots, leaf sugars initially declined rapidly then stabilised. Rhizome sugar concentrations also showed a decline following shading, though this decline continued through the period of unfavourable light conditions. Starch concentrations in the rhizome also declined but much later than rhizome sugars. The lag in the rate of rhizome starch decline relative to rhizome sugars is indicative of a physiological reallocation of resources and probably reflects a reallocation of rhizome sugars and, later, starches to the leaves.

Ecologically, one of the most significant findings was the decline in epiphyte biomass, to less than 20% of that in the unshaded areas. Seagrass epiphytes are a preferred food source for a range of vertebrate and invertebrate grazers. While it is difficult to scale small-scale experimental results to whole ecosystem consequences, if the decline in epiphytic biomass noted in this study were replicated over the large spatial scales then the trophic implications would be significant, as would the flow on affects for biodiversity functions of seagrass meadows.

Recovery

The majority of variables that responded to PAR reductions showed substantial recovery within 42 days. The extent and rate of the recoveries in these variables indicates *Amphibolis griffithii* is largely able to withstand a single episode of high intensity PAR reduction over the timescale of this study (3 months).

In concluding that *Amphibolis griffithii* is able to withstand short-term, intense reductions in the availability of PAR, it is important to note that:

1. the timing of the study coincided with the period of peak carbohydrate stores in *A. griffithii.* Imposed reductions in PAR at other times of year may generate more sever impacts or reduced capacity to recover;

2. rhizome starch concentrations showed less recovery after shading, suggesting that *A. griffithii* may be less able to withstand repetitive shading events; and

3. the shoots were not isolated from those in the surrounding meadow, offering the possibility for translocation of reserves from the meadow into the shaded shoots.

Summary and Conclusions

The response of the meadow-forming seagrass *Amphibolis griffithii* to about a 90% reduction in PAR was examined over a 3 month period and then over a subsequent 1 month recovery period. *A. griffithii* displays both shoot- and meadow-scale responses to reductions in PAR. At the shoot scale, total leaf biomass, the density of leaf clusters and the numbers of leaves per clusters all declined in shaded plots and after 3 months were about 30%, 50% and 60% of the controls, respectively. Leaf extension after 3 months of shading was one third that of the control plots. Epiphyte biomass in shaded plots was 18% of the controls after 3 months shading. Shading reduced the stores of carbohydrates in the rhizomes of shaded plants: sugar concentrations declined rapidly and continuously and after 3 months were less than 20% of those in controls; starch concentrations also declined but the decline lagged that of sugars. These within-shoot responses had the cumulative effect of producing responses at the scale of whole meadows, notably a thinner canopy with lower PAR attenuation. All variables showed a significant shift towards the values in control plots 42 days after removal of shading, indicating a significant capacity for recovery, though in many cases these remained significantly lower than the controls as did carbohydrate reserves in the rhizome.

It is concluded, that *A. griffithii* and its epiphytes respond rapidly to severe, short-term reductions in PAR availability but that the shoot- and meadow-scale responses allow the plant to respond rapidly to improved light conditions. The ecological implications of the findings are significant and suggest that there is a potential for flow-on effects to higher trophic levels. The results have informed the design of the main experiment, which will test the effect of different intensities, duration and timing of light reductions.

Date or intended date of completion: November 2007

Key personnel

Dr Kathryn McMahon has been appointed as a Postdoctoral Research Fellow on the project. She commences on 9 May 2005.

Students

Mr Michael Mulligan – M.Sc.
Mr Peter Quintana – M.Sc.

Conferences

- 6th International Seagrass Biology Workshop, Townsville, QLD: November 2004
- SRFME Mini Symposium – Benthic Ecology of the mid-west coast; April 2005.

Publications

Mackey, P, Collier, C and Lavery P.S. (in prep). The effects of reduced light availability in *Amphibolis griffithii* ecosystems.

3.3.7 Biodiversity of Marine Fauna on the Central West Coast

Principal Investigator

Dr Fred E Wells
Western Australian Museum
Locked Bag 49 Welshpool DC WA 6986
Phone: 9427 2809 Fax: 9427 2882 Email: fred.wells@museum.wa.gov.au

Note: This project has just commenced, and has no results to report as of this date.

Project Description

Background

The Technical Advisory Group of SRFME made a submission to the Joint Venture Management Committee for a three-year program to investigate ecological interactions in midwest coastal reef communities. The study will be built around the Jurien Bay Marine Park, using multiple-use management zones within the park as large scale manipulations of predator abundance. The study is a multidisciplinary one involving staff of CSIRO Marine Research, Western Australian universities and the Western Australian Museum. There are a number of objectives for the study including:

1. What are the trophic linkages of exploited species to other ecosystem components.
2. What are the pathways of transport of organic matter and nutrients between habitats and across the shelf.
3. How do exploited species in particular utilize the range of available coastal shallow water habitats (e.g. foraging in seagrass, sheltering on reefs).
4. What are the potential trophic (indirect) effects of variations in predator density.
5. What is the relative magnitude of spatial and temporal variability within and between key habitats and species (e.g. can we detect direct or indirect effects of fishing against the background of natural variability in recruitment or other variation at the habitat, seasonal and interannual levels).
6. How will populations of predatory species respond to variations in top-down (marine park protection) and bottom-up (primary productivity) processes. This component of the study will provide baseline data with which to assess the effects of fishing.

In order to maximize the information gained in the Midwest region, studies of ecological interactions can usefully be divided into the following sub-sections. These do not map directly onto the goals above, rather they provide a more practical framework through which to plan the research program. Not all of the goals will be achieved fully in this three year program (e.g. point 6) but all are necessary as the foundation of a long term project to assess ecological interactions in the context of ongoing human use and management of these coastal ecosystems. The three functional groupings of the project are:

1. Habitat characterization and benthic community biodiversity studies.
2. Studies of major predator groups (rock lobster, finfish) planned by the Department of Fisheries.
3. Trophodynamic studies.

The WA Museum component is largely part of project 1: Habitat characterization and benthic community biodiversity studies. These will include studies of major predators and trophic linkages and provide the basis for detecting longer term changes in benthic communities. They will go beyond Core and Linkage SRFME studies currently being conducted in the region to provide detail vital to the effectiveness of both studies of major predators and trophodynamic studies. Quantitative sampling will be stratified at the habitat level as well as among different management zones and will provide a quantitative basis for evaluating the relative importance of energy flow among various ecosystem components. Any indirect effects of fishing on benthic communities (seagrass and reefs) will manifest themselves at this level.

The Museum will also assist in component 3: Trophodynamic studies by providing identifications, etc of material collected.

These studies will need to include both rocky reef and seagrass habitats and require measurements of diversity, biomass and productivity of benthic primary producers, as well as invertebrates (including epifauna and epiflora). An understanding of seasonal variability is required in order to make accurate estimates of productivity as well as to allow any top down trends to be discerned from among seasonal and inter-annual variability. Our knowledge of variability in marine ecosystems often suffers from a lack of long term comparative data sets. Studies in the Midwest region provide an opportunity to understand ecological variability on decadal timescales by including historical comparisons of seagrass habitats surveyed in the 1980s (Seven Mile Beach, Cliff Head).

In parallel with the quantitative sampling described above, more extensive sampling targeted at documenting overall biodiversity will be conducted by WAM taxonomic experts. The broader scale Museum studies will provide a comparison of the biodiversity of selected groups as measured by experts in the groups compared with quantitative surveys undertaken in the same habitats.

Need

The shallow water marine biota of Western Australia can be divided into three distinct biogeographical regions. The north coast of the continent, from North West Cape to the Northern Territory border and extending to the southern part of the Great Barrier Reef in Queensland is tropical. Northern Australia is part of the vast Indo-West Pacific biogeographical zone which extends halfway around the world from the east coast of Africa through the tropical parts of the Indian and Pacific Oceans to Hawaii. The south coast of the continent is the southern Australian warm temperate region. This region extends from Cape Leeuwin, Western Australia eastwards across the southern part of the continent and up the east coast. Some species reach as far north as southern Queensland. The west coast of Western Australia, between North West Cape and Cape Leeuwin, is a region of biogeographical overlap where the tropical and temperate biotas mix in varying proportions. A study of gastropod molluscs found that 39% of species in the Perth region are tropical while the figure for the Abrolhos is about 70% (Wells 1980).

Superimposed on the tropical-temperate distributions is a small proportion of the biota which is endemic to Western Australia. These species may occur anywhere in the State, but are concentrated on the west coast. Endemics constitute a relatively small proportion of the biota, ranging from 5% in fish to 25% in shallow water echinoderms; overall about 10% of the shallow water fauna is endemic to the State (Wilson & Allen 1987; Morgan & Wells 1991; Hutchins 1994). While this is a small proportion, these species may be economically and/or ecologically important (Wells 1985). The western rock lobster *Panulirus cygnus* is the best example of an endemic species as it constitutes the largest single species fishery in Australia and is economically important throughout west coast.

The midwest region is thus in the overlap zone and has a mixture of tropical, temperate and endemic biotas. Inshore along the continental coastline the temperate biota dominates, while tropical species are abundant offshore at the Abrolhos and the west end of Rottnest Island. While these general patterns are well known, there are no quantitative data available on the relative proportions of tropical, temperate and endemic species for most taxonomic groups along the continental coastline between Perth and Geraldton.

Objectives

The objective will be to determine quantitatively the proportion of tropical, temperate, and WA endemic species of molluscs, corals, echinoderms, fishes, sponges, and decapod crustaceans at four localities in the west coast overlap zone: Cervantes, Jurien Bay, Green Head and Dongara. The quantitative structure of sampling will also enable the distribution of these taxa to be linked to smaller scale habitat associations within the Midwest coast region.

The taxonomic groups were chosen on the basis that they are ecologically important and Museum staff have the taxonomic expertise to identify the material. Groups such as polychaetes are also ecologically important, but there is no expertise in the State to identify the material. Fishes are included to provide comparability of the results with previous Museum surveys using the same techniques. They will be surveyed visually and by using limited rotenone sampling. Other investigators will be using visual censuses (but aimed at establishing community structure, sizes of fish, etc), beach seines, etc. The presence of a Museum expert will assist these groups in identifying uncommon species. The two components will thus be complementary.

Ascidians are also ecologically important, but will not be surveyed by the Museum. Dr Geordie Clapin of CSIRO and Justin McDonald of UWA have expressed interest in examining the ascidians. Dr Jane Fromont of WAM will make the Museum reference collections and literature resources available for their use.

Output and extension

Studies carried out by the museum will be added to the existing knowledge of the flora and fauna of the Jurien Bay region currently held by CALM. The work will also feed directly into the other studies of the project through published outputs as well as through direct interactions of Museum staff and members of other collaborative studies.

Planned outcomes

A published report providing quantitative information on the proportion of tropical, temperate, and WA endemic species of molluscs, corals, echinoderms, fishes, sponges, and decapod crustaceans at four localities in the west coast overlap zone: Cervantes, Jurien Bay, Green Head and Dongara. Sponges will be sorted into species units but species identifications will only be provided where histological processing to confirm identifications is not required.

Methods

Surveys will be taken at two localities in 2005 and two additional localities in 2006. Each locality will be broken into a variety of habitats such as exposed and protected rocky shores, seagrass, sand, and other habitats. The survey areas will encompass a range of such habitats across the coastal shelf, as well as the various zones within the Jurien Bay Marine Park. As far as possible these will match the habitats used by other groups for quantitative study. The plan is to conduct the fieldwork in April 2005, in conjunction with other groups working in the area at the same time (SRFME). The quantitative sampling will be conducted by taking advantage of the existing SRFME sampling program, which uses a quadrat-based sampling protocol. At each site 5 haphazard 0.25 m^2 quadrats will be destructively sampled to obtain quantitative samples of algae, sponges, ascidians, crustaceans, molluscs and echinoderms. Data describing the physical habitat characteristics will also be collected from each site, including rugosity measures and water quality measures. Surveys for coral cover will be conducted by line-intercept as part of the rugosity measurements which utilise a chain-based distance measure.

At each site extensive surveys designed to encounter as many species as possible will be undertaken using scuba by an experienced specialist in a taxonomic group. Dives will be standardized to one hour to make data comparable. The biodiversity of each taxonomic group recorded in each habitat will then be compared with the quantitative results obtained by other groups using quadrats. Working together, WAM experts will be able to assist the other groups in identifying their material, and help ensure quality control of their identifications.

Milestones

Autumn 2005: Completion of first field survey in April 2005, of two areas (probably Jurien Bay and Cervantes). Field identifications will be made where possible. Material brought to the Museum will be identified, voucher material databased and entered into the permanent collections.

September 2005: Report on results of first survey will be completed, including biodiversity information on molluscs, corals, echinoderms, fishes, sponges, and decapod crustaceans.

Autumn 2006: Completion of second survey in April 2006, of two areas (probably Green Head and Dongara). Field identifications will be made where possible. Material brought to the Museum will be identified, voucher material databased and entered into the permanent collections.

September 2006: Report on results of second survey will be completed, including biodiversity information on molluscs, corals, echinoderms, fishes, sponges, and decapod crustaceans. Individual papers will be written by the participants, or there may be a supplement of the *Records of the Western Australian Museum* describing the results.

Other related projects

This project is a core component of the SRFME project and complements biodiversity studies already undertaken by the Museum on a broader scale. These surveys include many areas to the north such as the Abrolhos, Shark Bay, and offshore reefs, which will allow the inshore west coast to be placed into a broader context.

Staff

Field:
Dr Fred Wells
Dr Jane Fromont
Melissa Hewitt
Glen Moore (part time technical officer for the project)

Laboratory:
Dr Fred Wells
Dr Jane Fromont
Melissa Hewitt
Glen Moore (part time technical officer for the project)
Corey Whisson
Dr Barry Hutchins
Diana Jones
Loisette Marsh

Literature Cited

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3.3.8 Ecological Interactions in Coastal Marine Ecosystems: The Fish Communities and Main Fish Populations of the Jurien Bay Marine Park

Principal Investigator

Professor Ian Potter
Director of the Centre for Fish and Fisheries Research
School of Biological Sciences and Biotechnology
Murdoch University, South St., Murdoch, WA 6150.
Phone: (08) 9360 2524 Fax: (08) 9360 6303 Email address: i.potter@murdoch.edu.au

Post-doctoral Fellow

David Fairclough
Post-doctoral fellow
Centre for Fish and Fisheries Research
School of Biological Sciences and Biotechnology
Murdoch University, South St., Murdoch, WA 6150.
Phone: (08) 9360 2229 Fax: (08) 9360 6303 Email address: d.fairclough@murdoch.edu.au

Note: This project has just commenced, and has no results to report as of this date.

Project Background

The Jurien Bay Marine Park, which encompasses the coastal waters between Green Head and Wedge Island and is managed by the Department of Conservation and Land Management (CALM), was gazetted in August 2003. The marine park includes areas that are (1) open to all types of fishing, (2) open to rock-lobster fishing only and (3) closed to all types of fishing. Although this marine park has already been established, there will be an interim period before the protected zones are enforced by CALM. During this study, sites will be sampled in the above three zones in the marine park to obtain baseline data on the community structures of the fish faunas and the relative abundances, size and age compositions, reproductive biology and diets of the main fish species.

The proposed study represents part of the first stage of a longer-term program that is aimed at understanding ecological interactions in coastal waters in the Jurien Bay Marine Park and at providing data that can be used to reveal any direct or indirect effects of fishing in the short and long term. The data collected on the above community and population parameters during our part of the study will be dovetailed with data obtained from studies of benthic macroinvertebrates, macroalgae, seagrass, algal drift and isotope analyses that are also being conducted at Jurien.

Objectives

The fish faunas and selected fish species will be sampled at sites in zones in the Jurien Bay Marine Park that are (1) open to all types of fishing, (2) open to rock-lobster fishing only and (3) closed to all types of fishing in order to determine the impact of fishing on fish communities and selected fish species. The sampling of different habitats in each zone, e.g. reefs, seagrass and unvegetated sand, and in different depths will facilitate an understanding of the ways in which ichthyofaunal composition is influenced by habitat type and/or water depth. The biological data that will be collected for key species, i.e. those that are important either ecologically (e.g. labrids, sparids, pomacentrids) and/or for the recreational and commercial fisheries of the region (e.g. dhufish, pink snapper, breaksea cod), will include size and age compositions, reproductive biology and diets. Data on the reproductive biology of important species will be used to determine their spawning periods and the types of habitat where spawning occurs. The dietary data will be used to elucidate the ways in which the prey of key species changes with increasing body size and the extent to which the dietary composition is influenced by habitat type and time of year. These data will be collated with those obtained from other studies (see earlier) to elucidate the interactions that occur within and between fish communities, trophic interactions within communities and the influence of fishing on the fish community and selected fish populations. Individuals of selected species will be tracked for several months and over several kilometres by using acoustic and different tagging techniques to assess the extent to which the species move between habitats and areas and how different levels of protection can benefit such species.

Sampling will also focus on obtaining sound data on the fish faunas of nearshore waters to establish which of those species, that are found in offshore areas and particularly around reefs, use nearshore shallows as a nursery area. These data are crucial for understanding the ways in which the movements of key species within the broad area of the Jurien Bay Marine Park are related to size and/or reproductive status.

Communication and dissemination of the results

The results of this study will be written up as part of a final report for the overall study and as papers for international journals to facilitate peer group reviews of the science. Popular articles will be produced for local magazines such as ProWest and Landscope. The target audiences will be as follows.

1. Environmental and fisheries managers, e.g. Department of Conservation and Land Management and Department of Fisheries Western Australia

2. Scientists

3. Recreational and commercial fishers

4. Western Australian community

Methods

The study will focus on sampling (1) sanctuary zones, (2) scientific reference zones and (3) unprotected zones at three main locations, i.e. Fisherman Islands, Jurien Bay/Hill River and Cervantes/Grey. Within each zone, sampling will be conducted in nearshore shallow, lagoonal/mid-depth and offshore deeper waters using techniques that are appropriate for sampling the different habitat types, i.e. reefs, seagrass and sand. A preliminary sampling trip in spring 2004 will be conducted to establish representative sampling sites. This will take into account advice from staff at the CSIRO who have been working in the area. Sampling trips will subsequently be conducted seasonally for two years using the following regime.

Reef habitats

Reef habitats at each site will be surveyed using underwater visual census (UVC). Nine 25 x 10 m strip-transect surveys will be conducted at each site on each sampling occasion and the number of individuals of each species and the sizes of selected commercial, recreational and abundant species will be estimated. The dominant algal species in 5 m blocks in each transect will be recorded. In addition, the sex of ecologically important species, e.g. baldchin groper, western king wrasse and dhufish, will be recorded whenever possible. Baited underwater video (BUV; Willis and Babcock, 2000) will be used, in conjunction with visual census, to provide data on the relative abundance of predatory species that, due to their high mobility, are usually underestimated in visual census. At each sampling site, at least three 30 min BUV deployments will be made at a time that will not impact on the UVC.

Nearshore sand and seagrass habitats

Nearshore bare sand and seagrass habitats will be sampled to determine which species use these habitats as nursery areas prior to migrating to reef areas. Nearshore unvegetated sites will be sampled using a 60.5 m long seine net. Four replicate samples will be obtained using each net in each of the three zones of the three main locations. Four replicate trawls will be conducted during the day in each season using a small tri-net in unvegetated and seagrass habitats in lagoonal habitats in the three zones at each location. The trawl net will be towed at a speed of *ca* 3 – 4 km h^{-1} and for a distance of *ca* 150 m. The distance trawled during each replicate will be measured using a Garmin GPS Map 185 global positioning system, which, together with the width of the mouth of the net, will enable the area of substrate trawled to be determined. This, in turn, will enable the density of fish species to be estimated.

A range of methods, e.g. gill nets, traps and rod and line fishing, will be trialled and the most appropriate of these will be used to determine which predatory species are found in the lagoonal reef, seagrass and sand habitats at night. These habitats will be sampled in each season.

The numbers of all species and of the main species will be converted to either a density or a catch rate depending on the sampling method used. Analysis of these data and of the number of species in the various habitat types in the three zones in the three locations in each season will be analysed using ANOVA (Underwood, 1999) and non-metric multidimensional scaling ordination as described in PRIMER v6 (Clarke, 1993; Clarke and Gorley, 2001; 2004). In the case of the multivariate analyses, ANOSIM will be used to determine whether the compositions of *a priori* groups are significantly different and, where significant differences exist, SIMPER will be used to determine which species characterize each of those groups.

Fish movement

Tagging, using acoustic tags and receivers and colour-coded tags, will be used to trace the movements of individual fish of selected species, as described in the original project outline. Up to 20 fish of different species, particularly species which are likely to demonstrate territoriality and or home range behaviour, will be tagged using acoustic tags (VEMCO VR2) that are surgically inserted into the fish. This will allow larger scale movements of animals to be tracked with an accuracy of approximately ±100 m using an array of at least 24 receivers that will cover an area of approximately 19 km^2 (see Ecological interactions proposal). Tagging and tracking of fish will be conducted in one of the main sanctuary zones.

Biological studies

(1) Size and age compositions and reproductive biology. Samples of representatives of the main recreational, commercial species and other more abundant species will be collected from sites representing the three zones to determine whether there is evidence that the size and age compositions of those species are influenced by the extent of fishing. Fish will be aged using the number of annuli in otoliths, a technique that has been successfully used for many species in our laboratory, e.g. Australian herring and dhufish, see Fairclough *et al*. (2000a), Hesp *et al*. (2002). The von Bertalanffy growth curve will be fitted to the lengths at age of the individuals of each species.

The pattern of gonadal development and determination of the spawning period of these species and, where applicable the type of hermaphroditism, will be ascertained using traditional methods, e.g. trends exhibited by gonadal and oocyte stages and gonadosomatic indices, an approach that we have also employed successfully on many previous occasions, see e.g. Fairclough *et al.* (2000b, 2004); Hesp and Potter (2003); Hesp *et al.* (2004).

(2) Dietary composition. Samples covering the full size range of selected species will be collected seasonally from different habitats in the three main zones of the marine park. Fish will be caught using line fishing, spearing, fish trapping and netting. Each of these species will be collected from the different habitat types that they occupy to elucidate any ontogenetic or habitat-related variations in diet. Stomachs will be removed and stored in 70% ethanol. The diets will be analysed using traditional methodology that will enable the size-related changes in the diet of those species to be elucidated, e.g. Platell and Potter (2001). Comparisons between the dietary composition of the fish faunas in different habitats will be made using non-metric multi-dimensional scaling ordination and associated tests, e.g. Clarke and Gorley (2004), Platell and Potter (2001).

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Outcomes

The study will yield data that will help elucidate the interdependencies of fish and benthic habitats, and the extent to which closure to fishing influences the ichthyofaunal composition and biology of key species in the Jurien Bay Marine Park. Those data will be of the type and quality that can be used by fisheries and environmental managers to develop more sophisticated plans for managing fish stocks in the Jurien Bay Marine Park.

Project Milestones

30/9/2005: Sampling sites will have been identified during an initial exploratory trip. The first three seasonal sampling trips will have been conducted. Data on species composition, abundance and size structure in different zones will have been collected and subjected to preliminary analyses. The otolith, reproductive and dietary material collected during the first two trips will have been processed in the laboratory and preliminary studies will have been conducted on ageing, reproductive and dietary aspects. Acoustic tagging and tracking will have commenced and the data from the first two trips will have been stored on computer and subjected to preliminary analysis.

30/9/2006: Sampling will have been conducted seasonally between spring 2005 and winter 2006 and the data on species composition and the abundance, age and size structure, reproductive biology and diets of selected species in the first of those seasons and all of those in the first year will have been analysed. Acoustic tagging and tracking will have been completed and analysis of the data collected will be underway.

30/9/2007: The eighth and final of the main sampling trips will have been completed. All of the data on the fish communities and the abundance, age and size structures, reproductive biology and diets of the main species will have been completed and analysed. A final report will have been written in which conclusions will be drawn as to the extent of any influences of closure to fishing on the fish community and main fish populations in the Jurien Bay Marine Park.

4. COLLABORATIVE LINKAGES PROGRAM: STATE LINKAGES PROJECTS

4.1 SRFME State Linkages Projects

The objective of this program is to engage state government agencies in the delivery of strategic research outcomes, in conjunction with CSIRO, Universities and other research providers. A total of $166,065 has been committed to the funding of 7 state linkages projects, to institutions such as the WA Museum, Department of Environment, Department of Conservation and Land Management, Department of Fisheries, and Murdoch University. Leaders from these projects have given presentations at SRFME symposia in June 2003 and 2004.

4.2 SRFME State Linkages Projects, PI's, and Affiliations

Project Title	**Institution**	**Principal**
Funding for the 12th International Marine Biological Workshop in Esperance, WA held in Feb. 2003	Western Australian Museum	Dr Fred Wells
Establishing Reference and Monitoring Sites to Assess a Key Indicator of Ecosystem Health (seagrass health) on the Central West Coast of Western Australia	Department of Environment	Dr Ray Masini
Baseline Biodiversity Monitoring in the Proposed Jurien Bay Marine Park – survey 3	Department of Conservation and Land Management	Dr Chris Simpson
Funds to Facilitate Student Research Projects at the Abrolhos Islands	Department of Fisheries WA	Mr Kim Nardi
WA Marine Algae: Taxonomic Studies and Identification Guide	Department of Conservation and Land Management Murdoch University	Dr Chris Simpson Dr John Huisman
The Flora and Fauna of Esperance, WA	Western Australian Museum	Dr Fred Wells
Supplemental Grant for Seagrass Responses to Light Availability	Edith Cowan University Through Department of Environment	Dr Paul Lavery Dr Ray Masini

4.3 SRFME State Linkages Projects Reports

4.3.1 Twelfth International Marine Biological Workshop: The Marine Flora and Fauna of Esperance, Western Australia

Dr Fred E Wells[1], Prof Diana I Walker[2], and Dr Gary Kendrick[2]
[1]Western Australian Museum. [2]University of Western Australia

Background

Western Australia is a huge State, occupying the western third of the continent. Until relatively recently, this vast coastline had been largely unexplored by scientists. The presence of some groups of organisms in the marine environment of Western Australia is still totally unknown. In 1986 Dr Fred Wells of the Western Australian Museum proposed that a series of marine biological workshops be held in Western Australia to allow scientists from interstate and overseas the opportunity to work with Western Australian scientists to generate scientific information about the marine environment of Western Australia. The proposal was accepted by the Museum and the WA Branch of the Australian Marine Sciences Association. From the outset the workshop has been a cooperative venture which has also included organisers from CSIRO (Dr Hugh Kirkman), and Murdoch University (Assoc Prof Roger Lethbridge). While the workshop organisers have changed from time to time, Prof Di Walker of The University of Western Australia has been actively involved since the Albany workshop. The Western Australian workshops have attracted about 200 scientists from leading institutions throughout the world: about one-half have been from overseas; one-fourth from the eastern states; and one-fourth from Western Australia.

The workshops are modelled on workshops held at the University of Hong Kong since 1977, and are numbered as part of an international series. Other workshops, devoted specifically to molluscs, have been held in Hong Kong, California, Portuguese Azores, and the Florida Keys.

Format

Established researchers are invited to participate in the workshop. The Australian Marine Sciences Association has provided funds to allow one or two graduate students to participate. Each participant is responsible for obtaining his/her own fare for travel to/from Perth, to the workshop locality and the cost of the workshop. Workshops are held in as inexpensive a manner as possible.

The local organisers provide basic accommodation, laboratory space, access to dive gear and boats. We know the local habitats and can arrange collecting and export permits, etc for the material collected. The workshops allow participants the opportunity to work on their own research projects with a minimum of hassle and organisational responsibilities. The presence of a number of other scientists at the workshop provides opportunities for joint research and a number of Western Australian scientists have taken advantage of the opportunities provided.

It takes two years to plan and organise a workshop, and for the participants to obtain funding for their participation. The field portion the workshop is for 17 days. Each participant is expected to undertake one or more research projects in his/her area of expertise and publish the results in a workshop proceedings. Proceedings are published three years after completion of the field portion of the workshop. All papers are refereed.

To date seven workshops have been held (including Esperance), and a total of 10 volumes have been published. A substantial portion of the workshop output has been devoted to documenting the marine flora and fauna of Western Australia (and the Northern Territory). There has also been considerable work on the ecology, physiology, functional morphology, and other aspects of the biology of various organisms. Recent workshops have benefited considerably from the preparation of papers by Alan Pearce of CSIRO and others which have drawn together published and unpublished information on the physical oceanography of the Houtman Abrolhos and the Dampier Archipelago.

Much of the work has been of immediate practical advantage to managers of the marine environment, including the Environmental Protection Authority, Department of Conservation and Land Management and the Department of Fisheries Western Australia.

Esperance Workshop

SRFME generously supported part of the costs of the Esperance workshop, which was undertaken in February 2003. There were 28 participants in the field program. In addition to participants from WA, there were scientists from South Australia and Victoria. Overseas participants were from China, Germany, Singapore, Thailand, United Kingdom, and the United States.

The goal of the marine biological workshops is to substantially increase the rate of exploration of the marine biology of Western Australia by attracting interstate and international colleagues to the State to work in a particular geographic area for a short period of intensive fieldwork. As the participants pay their own fares, etc, no attempt is made to specify what research they should undertake. However, as with previous workshops, the research can be divided into several components:

Documentation. There is considerable need in the State for basic documentation of the biota which inhabits our waters. Many groups have never been examined by specialists. In conjunction with examination of specimens at the WA Museum, the workshops offer a unique opportunity for systematic research. New species were found at Esperance of marine mites, oligochaetes, molluscs, mysids, tanaids, and pycnogonids. Range extensions, often on the scale of hundreds of kilometres, were made in many taxa.

Animal biology. A number of studies were made of the biology of animals, including reproductive biology of coralliophilid snails, feeding of the snail Lepsiella on limpets, ecology of trochid snails, infauna of Bandy Creek, bivalve ecology and morphology, and epiphytic grazers on seagrasses.

Plant biology. There is a rich diversity of marine algae and seagrasses in the Recherche Archipelago. Considerable work was undertaken in documenting this biota and exploring the roles the plants play in the ecosystems, both algae and seagrasses. Studies included the distribution of rhodoliths, growth rates of seagrasses, nutrient status of inshore and offshore plants, and experimental work with the plants.

Plant-animal interactions. Two studies integrated relationships between plants and animals. One was on the diverse fauna inhabiting the algal rhodoliths. The other was on an intriguing sponge-algal association found during the workshop.

Benthic mapping project. A group led by Dr Gary Kendrick of the University of Western Australia is currently undertaking a major program of benthic habitat mapping in the Recherche Archipelago, funded by the Fisheries Research and Development Corporation and the Strategic Research Fund for the Marine Environment. Many of the WA scientists at the workshop are also involved in the habitat mapping project, allowing considerable synergies between the two programs which will benefit both.

Publicity. One important aspect in furthering marine science in Western Australia is to make the findings available to the public. This was done in the following ways: newspaper articles in *The Age* (Melbourne), *West Australian, Esperance Express*, and *Kalgoorlie Miner*; radio interviews on ABC regional radio, ABC Perth and ABC Melbourne; and a television interview on GWN News. In addition, Sarah Coote and Corey Whisson visited local primary schools to talk to students about the workshop and what was happening.

Publications and/or outcomes to date.

Wells, F.E., Walker, D.I. and Kendrick, G. 2005. *Proceedings of the twelfth international marine biological workshop: The marine flora and fauna of Esperance, Western Australia*. Western Australian Museum, Perth. In press. (2 volumes, approx. 600 pages)

4.3.2 Establishing Reference and Monitoring Sites to Assess a Key Indicator of Ecosystem Health (Seagrass Health) on the Central West Coast of Western Australia

Principle Investigator

Adjunct Prof. Ray Masini, Marine Ecosystems Branch, Policy and Coordination Division, Department of Environment

Co-Investigators

Dr Cam Sim, Marine Ecosystems Branch, Policy and Coordination Division, Department of Environment

Assoc. Prof. Paul Lavery, School of Natural Sciences, Edith Cowan University

Dr Chris Simpson, Marine Conservation Branch, Department of Conservation and Land Management

Introduction

The Department of Environment has a responsibility to protect the Western Australian (WA) marine environment from threats posed by waste discharges and habitat loss.

An environmental quality management framework (EQMF) which is consistent with the *National Water Quality Management Strategy* (ANZECC/ARMCANZ 2000) documentation is a key policy tool being implemented to protect environmental quality in WA. The EQMF is underpinned by Environmental Values (EVs) and associated Environmental Quality Objectives (EQOs) which are established through community consultation as recommended by ANZECC/ARMCANZ (2000).

Each EV and its associated EQOs have sets of environmental quality requirements. These are the Environmental Quality Criteria (EQC) that are used to evaluate whether EQOs are being achieved.

A reference site approach has been adopted for developing some of the EQC. This approach requires targeted collection of ecological data at unimpacted reference sites. To maximise utility over time it is preferable that these sites are located where they will be offered long term protection such as in sanctuary zones in marine conservation reserves.

This project has been specifically designed to provide sufficient baseline data to derive EQC for seagrass health, which is a fundamental indicator of ecosystem health in coastal environments of southwest WA. Specifically, we aim to broaden geographic coverage of seagrass health monitoring in WA by establishing reference sites in the mid-west region of WA. The Jurien area has been selected as the focal point for this work because it is within the Jurien Bay Marine Park and is an area that is predicted to be a centre for urban expansion in the future. We also aim to monitor the Jurien sites in a manner that ensures the data complement those collected in Perth. The project design should allow us to evaluate the potential for transferability of indicators and EQC between regions.

Aims/objectives

1. Quantify the natural spatial and inter-annual variability in proposed seagrass health indicators on the central west coast of WA for a period of three years;

Major findings/outcomes

This objective has been achieved. Two permanent reference sites for monitoring seagrass health have been established in the Jurien Bay Marine Park. The sites were established in April 2003 and are located within *Posidonia sinuosa* meadows in the Fisherman Islands Sanctuary Zone and the Boullanger Island Special Purpose (Puerulus) Zone. At each site, 24 permanent relocatable quadrats have been established at each of three discrete depths (2.5 m, 3.5 m and 5.5 m) using methods described by Lavery and Westera (2003). The coordinates for each site are shown in Table 5.

A range of seagrass health indicators (ie. seagrass shoot density, shoot height, percent cover) were monitored at the reference sites in 2003, 2004 and 2005. The data provide valuable new information about the natural spatial and temporal variability of *P. sinuosa* meadows in the mid-west of WA.

Table 5. Locations of reference sites established in the Jurien Bay Marine Park.

Location	Depth	UTM Coordinates		Location	Depth	UTM Coordinates	
		East	North			East	North
Fisherman Is.	2.5m	307146	6664594	Boullanger Is.	2.5 m	307929	6644723
	3.5 m	306940	6665428		3.5 m	307955	6644916
	5.5 m	306417	6664328		5.5 m	307971	6645019

Figure 44 shows natural variation in the shoot density of *P. sinuosa* meadows at three depths at Fisherman Islands and Boullanger Islands measured in 2003 and 2004. The data show minimal interannual variation at all sites except Fisherman Is. 2.5 m. As well as displaying the greatest interannual variation, average seagrass shoot density at Fisherman Is. 2.5 m is higher than at the other sites in Jurien for both years. Early exploratory analysis of the 2005 data indicate a similar and persistent pattern at this site.

Data reports containing summary figures and raw data have been submitted to the SRFME Research Director each year of the program.

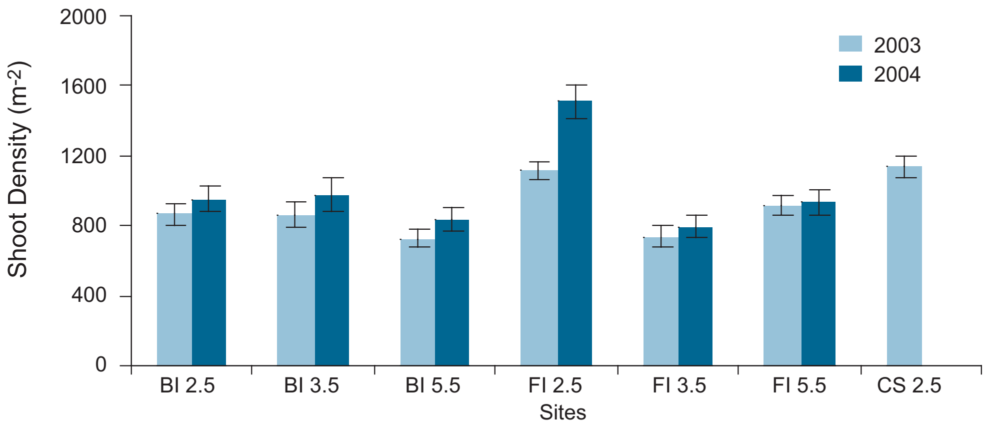

Figure 44: Mean shoot density of *Posidonia sinuosa* at three depths at two sites in the Jurien Bay Marine Park in 2003 and 2004. Data from a 2.5 m site in Perth's coastal waters is included for comparison. BI=Boullanger Island. FI=Fisherman Islands. CS=Cockburn Sound reference. Error bars are standard errors.

1. Enable comparisons to be made between natural variability in seagrass health indicators at sites in the vicinity of the proposed JBMP and in Perth's southern metropolitan coastal waters;

Major findings/outcomes

This objective has been largely achieved. The three-year data set for seagrass health in the Jurien Bay Marine Park will enable comparisons to be made between natural variability in Jurien and Perth.

2. Provide an information base to make an assessment of the transferability of proposed seagrass health indicators and proposed criteria to the central west coast of WA and other areas of WA's coastal marine waters;

Major findings/outcomes

This objective has been achieved. The data set that has been collected in the Jurien Bay Marine Park will enable an assessment to be made of the potential for cross-regional transferability of seagrass health indicators and criteria.

3. Enable Government agencies to broaden the geographic coverage of the environmental quality management framework currently being implemented in Perth's coastal waters;

Major findings/outcomes

This objective has been largely achieved. The seagrass health data collected during this project will form the basis of environmental quality criteria that underpin the environmental quality management framework that is being implemented throughout the State on a priority basis.

4. Enhance strong collaboration between university researchers, key Government natural resource management agencies and SRFME researchers.

Major findings/outcomes

This project strengthens previously established collaborative research arrangements involving the Department of Environment and Edith Cowan University. It has also provided established sites and baseline data that have benefited other collaborative research projects in the area (eg. Funded under an ECU/Industry Partnership program). The project has also exposed Department of Conservation and Land Management regional staff to contemporary seagrass monitoring methods which will be essential for monitoring the Park in the future.

The project also initiated tangible collaborations with SRFME staff who utilised the Department's research vessel in Jurien.

Problems that transpired during dredging for the Geraldton Port Enhancement Project highlighted the importance of baseline seagrass health data. Recognising the need for robust seagrass health data for environmental management, collaborators working on this project contributed to the development of a large strategic seagrass research project in Jurien which has been jointly funded by the SRFME Collaborative Projects fund and the Geraldton Port Authority. The project involves strong collaboration between ECU and CSIRO researchers and aims to address questions about the effects of light availability on seagrass health.

Discussion

Two permanent reference sites have been established within the Jurien Bay Marine Park and data have been collected over three years to develop environmental quality criteria that underpin the environmental quality management framework being implemented in WA. Importantly, by enabling collection of data in advance of significant urban and industrial expansion in the mid-west region, this project allows the State to act strategically to counter and manage threats to environmental quality before or as they emerge, rather than needing to seek solutions to problems after they arise.

Data collected during this project enhances our understanding of natural variability of key seagrass health indicators and broadens the geographic coverage of reference data which will be used to derive criteria by 100's of kilometers. However, due to the relatively short period of time since collecting the year three data we have not yet undertaken the detailed analyses necessary to evaluate variability of seagrass health indicators between Jurien and Perth and assess the potential for transferability of indicators and criteria. We plan to undertake more detailed analyses of data to address these issues in coming months.

Some minor variations to the project have occurred during its implementation. One such variation involved changing the monitoring times from April when the sites were established to January. The decision to monitor the Jurien sites in January was taken so that seagrass health data were collected in Perth and Jurien were at similar times of the year and the effects of seasonal variation could be eliminated from the cross-regional comparisons of the data. A minor variation to the project proposal is that reference sites have not been established at 7 m depth. Despite carrying out site selection surveys over broad areas of the Jurien Bay Marine Park, suitable *P. sinuosa* meadows were not found at 7 m depth.

Data loggers were deployed to measure photosynthetically active radiation (PAR) and temperature at the sites during 2003 and 2004. Unfortunately, the loggers either failed or the data from these deployments is considered to be too unreliable for use. The Department is currently investigating the purchase of higher quality PAR and temperature loggers. When purchased these could be deployed at the reference sites to gather physical data that may assist in the interpretation of seagrass health data. Accordingly, the Department is committed to explore opportunities to undertake an additional field program in January 2006 to monitor seagrass health and, if possible, gather PAR and temperature data from the sites.

Summary and Conclusions

The objectives set for the project have been largely achieved, though further work is necessary to make cross-regional comparisons of natural variability and to evaluate potential for transferability of seagrass health criteria.

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Conferences attended, or presentations given

R. Masini. Presentation of progress at the Strategic Research Fund for the Marine Environment Symposium, 18 February 2004, CSIRO Floreat.

Publications and/or outcomes to date

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4.3.3 Baseline Biodiversity Monitoring in the Proposed Jurien Bay Marine Park, Survey 3

Dr Graham Edgar
University of Tasmania
Tasmanian Aquaculture & Fisheries Institute
GPO Box 49, Hobart, TAS, 7001
Email: g.edgar@utas.edu.au Ph: (03) 6227 7277 Fax: (03) 6227 8035

Dr Neville Barrett
University of Tasmania
Tasmanian Aquaculture & Fisheries Institute
GPO Box 49, Hobart, TAS, 7001
Email: n.barrett@utas.edu.au Ph: (03) 6227 7210 Fax: (03) 6227 8035

Kevin Bancroft
Marine Conservation Branch
Department of Conservation and Land Management
47 Henry Street, Fremantle WA 6160
Email: kevinb@calm.wa.gov.au Ph: (08) 93370102 Fax: (08) 94305408

Dr. Russ Babcock
CSIRO Marine Research, PO Box 5, Wembley WA 6913
Email: russ.babcock@csiro.au Phone: (08) 9333 6535 Phone: (08) 9333 6555

Introduction

Concurrent with the implementation of a network of Marine Protected Areas (MPAs) in Western Australia comes the need for effective monitoring programs to assess the ability of MPAs to achieve management aims. Only by studying changes that occur in MPAs following protection can we assess the true value of MPAs as baseline reference areas for quantifying ecosystem effects of fishing in the coastal zone, and the success of current conservation and fisheries management strategies. Potential benefits of MPAs include those related to protection of spawner biomass and conservation of critical habitats.

In order to properly determine whether changes observed within MPAs are the result of protection rather than natural variation in space and time, scientifically-credible baseline surveys within and adjacent to proposed MPAs are needed prior to protection from fishing, with subsequent survey of locations at biologically meaningful time intervals. Ideally, baseline surveys should be conducted over several years to assess the scale of inter-annual variability before the MPA is declared.

In the present project, we undertook quantitative surveys of fishes, macroinvertebrates and algae on reefs in the Jurien Bay Marine Park (JBMP) in October/November 2003. These surveys represent a baseline data set, given that JBMP was declared on 31 August 2003 but fishing restrictions had not been gazetted nor sanctuary or scientific reference zones marked in the field in 2003.

The JBMP area surveyed is centred around the towns of Jurien and Cervantes and extends for approximately 80 km of coastline to a distance of 5 km offshore. The MPA is characterised by an extensive offshore development of limestone pavement, structured reef, seagrass beds, sand banks and islands that provide a protective barrier from the prevailing swells and seas. Wave height generally declines substantially eastward of a series of reefs running north-south at a distance of 5-7 km offshore. The inner three kilometres of coastal waters essentially form a protected lagoon with water depths <5 m and isolated structured reefs outcrop from sand and seagrass. The most highly protected management zones within the MPA comprise 7 sanctuary zones (4% of the area) and 3 scientific reference areas where commercial lobster fishing and shore-based line fishing are allowed but other extractive activities prohibited (17% of the area).

Underwater visual censuses of fish, large mobile invertebrates and macroalgae were undertaken at 7 to 9 sites within each of the major management zone types (general use, sanctuary and scientific reference area). Surveys utilised similar techniques to those currently used for MPA monitoring in Tasmania, New South Wales and Victoria as part of a continental-scale study of the effectiveness of marine protected areas (MPAs). The survey methodology covers several assemblage types, having been designed to maximise quantitative information collected on a variety of species in the limited diving time available. This methodology should not only detect changes in heavily exploited species, but also any cascading ecosystem effects of fishing as well as patterns of long-term change in the region.

Aims/objectives

The objective of the project is to provide baseline data on the biodiversity of marine habitats within various management zones in the proposed Jurien Bay Marine Park. This information will be consistent with and supplement biodiversity information collected in two previous surveys undertaken by the University of Tasmania's survey team.

Discussion

Baseline surveys conducted in the Jurien Bay Marine Park have provided a broad-scale description of inter-site and inter-annual variation in communities of reef fishes, large mobile invertebrates and cover-forming plants and animals. The selection of 7-9 sites within each management zone should be sufficient to detect biologically meaningful change for the species examined – a doubling in population numbers for common species or an increase of ≈ 3 species in number of species richness per transect. From the results of the Tasmanian MPA study (Edgar and Barrett, 1999), and a workshop examining MPA monitoring techniques (Barrett and Buxton, 2002), it appears that six sites would be the accepted minimum number of "replicates" per treatment for an effective monitoring program.

Nevertheless, the sampling design could be improved by increasing the number of sites investigated in sanctuary zones. We recommend that two additional sites in sanctuary zones be monitored in future surveys to provide a fully balanced design with nine sites in each zone. The relatively low number of sites currently sampled in sanctuary zones reflects a slight change in zone boundaries from those proposed when the initial survey was undertaken. Additional sites would best be located in the large sanctuary zone block immediately south of Jurien Bay township, providing that reefs of sufficient depth and extent can be found amongst the predominance of shallow sand and seagrass in this block. Given the importance of following trends in rock lobster abundance, we also recommend that the total area surveyed for rock lobsters in future years is doubled by counting animals present on both sides rather than one side of the transect line.

Ideally, surveys should be repeated each year following enforcement of the MPA zoning scheme, at least for the first few years until population responses start to stabilise. In addition to its MPA value, a long-term data set possesses a variety of other uses, including as a tool for tracking regional changes in biodiversity associated with climate change or invasive species. Because a wide range of species have been surveyed, the experimental design should have sufficient power to detect ecosystem shifts as well as changes in the abundance of target fishery species.

Comparison of the overall relationship between sites based on assemblage data indicates that, while there is some degree of variation between sites within each zone category, the management zones broadly overlap and therefore future comparisons between zones are valid using current sites and experimental design. Our surveys were confined to moderately-sheltered inshore reefs of the region because sanctuary zones are all located in this ecosystem type. We note that, because sanctuary zones do not encompass any offshore reef habitat, the full range of ecosystem types within the JBMP remains to be adequately protected. We therefore recommend that a sanctuary zone be extended to include the outer reef, and that the monitoring program is extended to at least three outer reef sites in different zones.

Summary and Conclusions

Quantitative data are now available on densities of fishes, macroinvertebrates and plants on lagoonal reefs in the Jurien Bay Marine Park. Relative to variation between sites, the flora and fauna at different sites generally exhibited a low level of change between years for sites with data collected previously. With the exception of somewhat anomalous sites in the north near Fishermans Island, the biotic composition of sites was interspersed with respect to the three major MPA management zones – sanctuary, scientific reference and general use, with no zone possessing a predominance of one particular biotic assemblage type. Thus, data collected encompassed the range of variability within zones, allowing rigorous comparative analysis of change through time. Because a wide range of species have been examined, ecosystem shifts as well as changes in the abundance of target species should be detectable following the protection of areas from fishing.

The selection of between 7 and 9 sites within each management zone appears to provide sufficient replication to detect biologically meaningful change for the species examined. Nevertheless, to restore a fully balanced design following slight changes to the management zone locations originally proposed, we suggest that an additional two sites in sanctuary zones are monitored in future. Additional sites should be located in the large sanctuary zone immediately south of Jurien Bay if reefs of sufficient size to encompass 200 m long transect lines can be found in that area, which is presently unmonitored. We also recommend that (i) at least one sanctuary zone should be extended to the outer reef region to protect the full range of biodiversity within JBMP, (ii) monitoring should be undertaken at sites on the outer reef, and (iii) the number of 50 m x 1 m transect blocks monitored per site be increased from 4 to 8 for rock lobsters.

Analysis of the baseline data set indicated no significant differences between zones in number of fishes, macro-invertebrate or plant taxa per 50 m transect. Once fishing restrictions pertaining to different management zones are adequately enforced, surveys should be repeated on an annual basis until differences between zones stabilise. Such a monitoring scheme would provide time-series information on trends in the abundance of species of interest in different management zones, information on indirect impacts of both rock lobster fishing and general recreational and commercial fishing on ecosystems, and regional changes associated with such factors as climate change.

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4.3.4 Assessing the Benefits of Closed Fishing Areas for Spawning Aggregations and Egg Production for Coral Trout

G. Hyndes – Edith Cowan University, PI
K. Nardi – Department of Fisheries, Co-PI
J. StJohn – Department of Fisheries, PI

Introduction

Coral trout is a valuable finfish species that inhabits coral reef systems in Australia. Like most other finfish species, coral trout is managed mainly through catch and size limits, however, closed fishing areas also provide a measure of protection from exploitation. Worldwide, closed fishing areas have been shown to provide larger and more fish within their boundaries (Roberts *et al*. 2001, Nardi *et al*. 2004) review by (Halpern 2003). However, there is limited empirical data to show that they provide benefits to fish stocks. This project aims to examine whether closed fishing areas provide a benefit to coral trout at the Abrolhos Islands, Western Australia.

Current research on the coral trout *P. leopardus* has focused on the populations in the Great Barrier Reef (Ferreira and Russ 1992, Russ *et al*. 1996, Light and Jones 1997, Samoilys 1997, Zeller 1997, Adams *et al*. 2000). At the Houtman Abrolhos Islands, Western Australia, Nardi *et al*. (2004) demonstrated an increased size and abundance inside no-take zones (Reef Observation Areas) compared to adjacent fished areas. These results have formed the basis for this current study, that is, to examine the potential flow on effects to the fishery as a part of the biomass build up inside the reserve. An application for an Australian Postgraduate Industry Award (APAI) was submitted in December 2003 to provide a PhD scholarship for the study.

Aims/objectives

- To determine the age and growth of fished populations of *P. leopardus* at the Abrolhos Islands
- To compare the age structure of *P. leopardus* populations inside and outside Reef Observation Areas (ROAs)
- To describe several spawning aggregations of *P. leopardus* populations inside and outside ROAs
- To assess the reproductive output of spawning aggregations of *P. leopardus* inside and outside ROAs.

Discussion

The project was approved by ARC in mid 2004. A suitable PhD candidate was sought through advertising between September and October 2004. The scholarship advertisement and selection criteria (Appendix 1) were distributed through various universities and government agencies which resulted in 7 respondents. A candidate was selected (Jason How) and commenced on the 1st of February 2005.

The initial phase of the project has required the preparation of a proposal, including details of experimental design, timeline and budget accompanied with relevant literature review and synthesis. This is currently being undertaken by the student.

As the project requires a biological assessment of Coral Trout in order to address the objectives, the student, in conjunction with the supervisory panel (G. Hyndes and J. StJohn), has established links with members of the fishing community to procure the necessary samples. However, to date there appears to be a small commercial catch from which to sample. This has been exacerbated by the tendency to sell Coral Trout whole, thereby limiting the ability of the project to gain samples. Foreseeing this as a potential problem later in the project, the collection of another species has begun. The Red-throated or Sweetlip Emperor *Lethrinus miniatus* is another species which is found on the mid-west coast of Western Australian and to date has not had the biology studied. This species also appears to benefit from fishery protection areas (D. Watson, unpublished data) making it a suitable species to replace Coral Trout should this latter species continue to produce low sample numbers.

Summary and Conclusions

At this preliminary stage, there are no conclusions that can be drawn as there is little data available. The PhD project is at the proposal stage, which will define its structure over the following 3 years. Currently the viability of *Plectropomus leopardus* as the focal study species is being assessed.

References

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Appendix 1

Advertisement and selection criteria for PhD position.

Edith Cowan University – School of Natural Sciences

Expressions of Interest
PhD student (APAI scholarship)

An exciting new ARC Linkage project will commence in late 2004 examining coral trout *Plectropomus leopardus* at the Houtman Abrolhos Islands, mid-west region of Western Australia. This project will assess the impacts of closed fishing areas on the reproductive output of coral trout, a commercially valuable tropical coral reef species, important both in tropical Australia and in other coral reef systems. The Abrolhos Islands are ideally suited to such a study as four spatial areas closed to fishing for finfish were established 10 years ago. Underwater visual censuses have shown that in the last decade both the density and size of coral trout have significantly increased within these closed areas. Thus, this project provides a unique opportunity to test empirically one of the most important questions surrounding the scientific debate on closed areas – do populations within the boundaries benefit the populations outside?

We encourage exemplary students to apply for this three year APAI that provides an annual stipend of $23,556. Adequate in-kind support and research monies to cover costs of field-work, travel and consumables are available. The project would suit a student who is interested in biological research with outcomes for fisheries management as well as work in close collaboration with the Department of Fisheries, WA and industry. The successful student would be required to start by the end of 2004.

Applicants must have been (or about to be) awarded a first or upper second-class honours degree and have a BSc in marine biology and ecology or fishery sciences. A proven track record in peer-reviewed publications is highly desirable. Other qualifications required include – open water diving qualifications or higher, a boat handling certificate (TL3) or equivalent or higher and a current C Class or equivalent drivers licence. The student must be able to work in remote areas under limited or no supervision and have extensive field-work experience, particularly in relation to diving, boating and fish sampling activities. Work or research experience in one or more of these areas, fisheries biology, ichthyology, reproductive biology and marine ecology. A proven ability to liaise and work in collaboration with members of the fishing industry would be an advantage

For further information please contact Dr Glenn Hyndes, Edith Cowan University via email (g.hyndes@ecu.edu.au) and Dr Jill St John, Department of Fisheries WA via email (jstjohn@fish.wa.gov.au). Expressions of interest addressing the above criteria close on the 29th October 2004.

4.3.5 Providing Marine Algal Taxonomic Expertise to Coastal Ecosystem and Biodiversity in Western Australia, a Core CSIRO Work Priority Area, and Preparation of an Interactive Key to the Seagrass Epiphytes

John Huisman, Murdoch University
Dr Russ Babcock, Project Manager, CSIRO Marine Research
Dr Julia Phillips, Marine Ecologist, CSIRO Marine Research
Dr Chris Simpson, Project Manager, Department of Conservation and Land Management
Neville Marchant, WA Herbarium, Department of Conservation and Land Management

Introduction

Benthic plants (algae and seagrasses) are a dominant component of most inshore marine ecosystems in Western Australia, and several CSIRO projects presently underway incorporate macroalgal surveys to establish baseline community structure. One of SRFME's core research projects, *Coastal Ecosystems and Biodiversity in Western Australia* has as a primary objective the 'provision of representative baseline assessments'. It is imperative that these surveys be based on reliable and consistent taxonomic information if they are to provide meaningful habitat and community characterizations. This project uses the taxonomic expertise of John Huisman to ensure consistent and accurate identifications of the macroalgae. In addition to the benefits to CSIRO core research, this project will contribute to 'Florabase', a CALM endeavour to document information regarding Western Australia's plant life. This information is web-based and, in part, made available to the public.

Aims/Objectives

This project has several objectives. The first is to provide taxonomic expertise to SRFME core research projects, the results of which will enhance our knowledge of Western Australia's marine flora and will be used to provide information to establish and update CALM's 'Florabase', the web-based repository of information pertaining to Western Australia's plants. The second objective is to construct an interactive key to the algal epiphytes occurring on seagrasses. This key will use the program LUCID and will be an extremely valuable resource for monitoring the health of Western Australia's seagrasses, as epiphyte composition and load is regarded as a key indicator of ecosystem health.

Results

This project is still in its infancy, work having begun in mid January 2005 and then only at 20% time (one day per week). Nevertheless, we have made significant progress and the backlog of unidentified/tentatively identified specimens has been cleared, most being named to species level. These names have been incorporated into the 'Coastal Ecosystem' project. Many of the specimens represent range extensions for the species and are therefore of value in establishing accurate distributions. Once these specimens have been curated they will be lodged with the WA Herbarium and their details entered into Florabase.

As a result of this work, the extremely rare red alga *Gelidiella ramellosa* (Kützing) Feldmann & Hamel has been recognized in the Perth specimens. This species was originally described from collections made over 150 years ago from Western Australia (Kützing 1843) and has not been found in the region since that time (Womersley 1994). Materials have been sent to Dr Wilson Freshwater (University of North Carolina) for DNA sequence analyses and a collaborative paper is being prepared. Dr Freshwater is the acknowledged expert in the Gelidiales, the red algal order to which *Gelidiella* belongs.

With regard to the 'Seagrass Epiphyte Interactive Key', John Huisman attended the CALM workshop on using LUCID for developing interactive keys and purchased the updated version of the software, which is now usable on the web. A list of known epiphytes has been compiled (over 200 species) and building of the key has commenced. In addition, images of seagrass epiphytes are being compiled; most of these are being newly acquired but several will be sourced from John Huisman's existing collection.

Summary

Despite having only recently begun, this project has made significant advances, having already added new distributional data and rediscovered an extremely rare species. In addition, substantial progress has been made toward building the interactive key to the seagrass epiphytes.

References

Kützing, F. T. 1843. *Phycologia generalis.* Leipzig.

Womersley, H. B. S. 1994. *The Marine Benthic Flora of Southern Australia. Part IIIA*. Australian Biological Resources Survey, Canberra.

No conferences or presentations as yet.

No publications as yet. A manuscript is being prepared reporting the finding of *Gelidiella ramellosa*.

4.3.6 Assistance for the Publication of *The Marine Flora and Fauna of Esperance, Western Australia*

Principal Investigator

Dr Fred E Wells
Western Australian Museum (currently on secondment to the WA Dept of Fisheries)
Western Australian Museum Francis Street, Perth WA 6000
Email: fwells@fish.wa.gov.au Phone: (08) 9482 7342

Collaborating Personnel and Agencies

Prof Diana I Walker
Department of Plant Science (Botany)
University of Western Australia, 35 Stirling Highway, Nedlands WA 6009
Email: diwalker@cyllene.uwa.edu.au Phone: (08) 9380 2089

Dr Gary Kendrick
Department of Plant Science (Botany)
University of Western Australia, 35 Stirling Highway, Nedlands WA 6009
Email: garyk@cyllene.uwa.edu.au Phone: (08) 9380 3398

Background to the proposal

Since 1988, the Western Australian Museum, University of Western Australia, WA Branch of the Australian Marine Sciences Association and other agencies have combined to conduct a series of marine biological workshops in Western Australia. The State covers a huge area with a coastline of over 12,000 km and three marine biogeographic regions. The WA coast has impressive sections which have been established as marine parks, and marine ecosystems support productive fisheries which underpin the economies of many coastal towns. The short European history, large distances, inaccessible coastline, few marine biologists, and other factors combined to make the marine ecosystems of Western Australia poorly known, and the rate of discovery was low. In recognition of this, the marine biological workshop series was established to encourage interstate and overseas scientists to come to Western Australia to work in a single area for about 17 days on one or more research projects of their choosing, with the goal of publishing the results three years later in a joint workshop proceedings.

The workshops have been held as part of a numbered international series which started at the University of Hong Kong. Similar workshops, which concentrated on molluscs, have been held at the University of Hong Kong, in the Portuguese Azores, California and the Florida keys. A similar marine biological workshop was be held by AMSA SE Queensland in Moreton Bay in February 2005, and further mollusc workshops are planned for Thailand (2005) and Singapore (2006).

The Australian program has been phenomenally successful. Seven workshops have been held: Albany (1988), Rottnest Island (1991; 1996), Darwin (1993 organised by AMSA NT); Houtman Abrolhos Islands (1994); Dampier (2000) and Esperance (2003). To date the results of six of the workshops have been published. A list is attached. These publications total 10 volumes and over 3,500 pages. They provide a wealth of information on the marine biology of the western half of Australia. Over 300 new species, 20 new genera and 2 new families have been described. In addition there are hundreds of range extensions, with many taxa being recorded for the first time in Australia. There is considerable information which has been used by marine managers in maintaining coral reefs, mangroves, seagrass meadows, estuaries and other habitats. For example, about a third of the papers cited in *Management of the Houtman Abrolhos System* were published in the proceedings of the Abrolhos workshop. The workshops have deliberately been held in different geographic locations to cover the three marine areas of the State: tropical north coast, temperate south coast and west coast overlap zone.

The most recent workshop was held at Esperance on the south coast in February 2003. Twenty-eight people from Western Australia, South Australia, Victoria and six overseas countries (China, France, Singapore, Thailand, United Kingdom, and United States) participated in the workshop. The field component was generously supported by SRFME.

The present proposal is for SRFME assistance to publish the proceedings of the 2003 Esperance workshop. The assistance will provide top up funds for the publication, limited use of colour, and hard binding. While the information and printing are otherwise identical to soft bound volumes, the use of colour and hard binding considerably increases the durability and appearance of the volumes.

Objectives of the project

The goal of the workshop program is to document the flora and fauna of the area being examined. In the ease of taxonomic papers, participants are encouraged to also utilise zoological specimens held in the collections of the Western Australian Museum or botanical material held by universities. All holotypes are deposited in the WA Museum or WA Herbarium.

Other papers examine subjects such as distributional patterns, ecology of particular species, groups, or habitats, physiology, and functional morphology.

These papers develop a considerable amount of information rapidly, and cost effectively, that would not otherwise become available. In general participants pay their own way to Australia and their costs at the workshop; their home institutions pay their salary both during the workshop and the write-up phase. In addition to the workshops themselves, a number of professional partnerships have been developed which have resulted in further work, both in Western Australia and elsewhere.

Proposed work program

The field component of the workshop was held in Esperance in February 2003. Since that time manuscripts have been submitted for consideration for publication. They have been peer reviewed in a standard format, and if accepted, have been or will be revised. A number of papers are nearly ready for typesetting. Three have already been page proofed, totalling 120 printed pages. In all, there will be 24-¬26 papers which together will appear in two volumes of about 500-600 pages.

Linkages with SRFME research priorities and core projects

This project is closely linked with SRFME Core Project 2, Coastal Ecosystems and Biodiversity. SRFME generously supported part of the costs for the field component with a grant of $ 15,000, and two SRFME staff participated. The proceedings of the Esperance workshop will provide considerable information on the marine biodiversity and coastal ecosystems of the Recherche Archipelago region.

Relevance to State government polices and programmes

The WA government has an active program of developing marine parks in the State. The 1994 report on a representative system of marine reserves for the Western Australia listed the Recherche Archipelago as an area worth further consideration. This work is being undertaken by CALM. In conjunction with a number of State government departments, the National Oceans Office is targeting the southwest as the first part of Western Australia to be examined for bioregional marine planning. Documentation of marine biodiversity is an integral part of the WA Museum's program in documenting the marine fauna of Western Australia. The WA Herbarium in CALM has a similar responsibility for flora and works in conjunction with the universities. The WA Department of Fisheries is actively considering options for aquaculture for the Recherche Archipelago. All of these agencies will benefit from publication of the results of the Esperance workshop.

In addition, there is a major study in progress of the Esperance Archipelago, centred at UWA. The workshop was done in close collaboration with the UWA study.

Proceedings of Previous Australian Workshops

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Wells, F.E., Walker, D.L, Kirkman, H., and Lethbridge, R. (Eds). 1990/91. *Proceedings of the third international marine biological workshop: The marine flora and fauna of Albany, Western Australia*. Western Australian Museum, Perth. 2 volumes, 722 pages

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Wells, F.E., Walker, D.I., and Jones, D.S. 2003. *Proceedings of the eleventh international marine biological workshop: The marine flora and fauna of Dampier, Western Australia*. Western Australian Museum, Perth. 587 pages.

Esperance Workshop Participants

Dr Roger Bamber	Natural History Museum	London, England
Dr Ilse Bartsch	Forschungsinstitut Senckenberg	Hamburg, Germany
Dr Rudiger Bieler	Field Museum of Natural History	Chicago, Illinois, USA
Dr Anne Brearley	The University of Western Australia	Nedlands, Western Australia
Dr Marion Cambridge	The University of Western Australia	Nedlands, Western Australia
Ms Sarah Coote	The University of Western Australia	Nedlands, Western Australia
Ms Nisse Goldberg	The University of Western Australia	Nedlands, Western Australia
Ms Emily Glover	Natural History Museum	London, England
Prof Carole Hickman	University of California	Berkeley, California, USA
Dr John Keesing	CSIRO Marine Research	Floreat, Western Australia
Dr Gary Kendrick	The University of Western Australia	Nedlands, Western Australia
Prof Alan Kohn Mrs Marian Kohn	University of Washington	Seattle, Washington, USA
Mr Alan Longbottom Mrs Joy Longbottom	Honorary Associate	Western Australian Museum, Perth, Western Australia
Dr Justin McDonald	The University of Western Australia	Nedlands, Western Australia
Mr Tim Moore	Flinders University	Adelaide, South Australia
Dr Julia Phillips	CSIRO Marine Research	Floreat, Western Australia
Mr Kitithorn Sanpanich	Institute of Marine Sciences	Burapha University, Bang Saen, Thailand
Dr S.A. Shepherd Mrs Anna Shepherd	South Australian Research and Development Institute	Adelaide, South Australia
Dr Tan Koh Siang	National University of Singapore	Singapore
Prof John Taylor	Natural History Museum	London, England
Prof Di Walker	The University of Western Australia	Nedlands, Western Australia
Dr Hongzhu Wang	Chinese Academy of Sciences	Hubei, Wuhan, China
Dr Jan Watson	MuseumVictoria	Melbourne, Victoria
Dr Fred Wells	Western Australian Museum	Perth, Western Australia
Mr Corey Whisson	Western Australian Museum	Perth, Western Australia

Marine Flora and Fauna of Esperance, Western Australia (List not complete)

Introduction

Introduction to the marine biology of the Recherche Archipelago, Western Australia. Gary Kendrick, Euan Harvey, Justin McDonald, Fred Wells and Di Walker.

Fauna

The Tanaidaceans (Arthropoda: Crustacea: Peracarida: Tanaidacea) of Esperance, Western Australia. Roger N. Bamber.

The Pycnogonids of Esperance, Western Australia. Roger N. Bamber.

Western Australian *Werthella* (Copidognathinae: Halacaridae: Acari), description of a new and notes on related species. Ilse Bartsch.

The Australian Agauopsis fauna (Halacaridae: Acari), with description of new and known species of Western Australia. Ilse Bartsch.

The rhombognathine fauna of Australia (Rhombognathinae: Halacaridae: Acari) with notes on the fauna of Esperance, Western Australia. Ilse Bartsch.

Anatomy and morphology of *Stephapoma nucleogranosum* Verco, 1904 (Caenogastropoda: Siliquariidae) from Esperance Bay, Western Australia. Rudiger Bieler and Luiz Ricardo L. Sunone.

Venerupis. Bieler

Checklist of marine fishes of the Recherche Archipelago and adjacent mainland waters. J. Barry Hutchins.

Anthropogenic enhancement of marine invertebrate diversity and abundance: Intertidal infaunal invertebrates along an exposure gradient at Esperance, Western Australia. Alan J. Kohn and Amanda Blahm.

Diets of the predatory gastropods *Cominella* and *Conus* at Esperance, Western Australia. Alan J. Kohn, Kaitlin M. Curran and Brenda J. Mathis.

Rhodoliths: The inside story. Brenda J. Mathis, Alan J. Kohn, and Nisse A. Goldberg.

Solitary Ascidiacea from shallow waters of the Archipelago of the Recherche, Western Australia. Justin I. McDonald.

Echinoderms of the Archipelago of the Recherche, Western Australia. Justin I. McDonald.

Ontogenetic changes in diet, feeding behaviour and activity of the western blue groper, *Achoerodus gouldii*. S.A. Shepherd.

Notes on the southern endemic southern Australian corallivorous gastropod *Coralliophila mira* (Neogastropoda: Coralliophilidae). Tan Koh-Siang.

Another bloody bivalve: anatomy and relationships of *Eucrassatella donacina* from south Western Australia (Mollusca: Bivalvia: Crassatellidae). John D. Taylor, Emily A. Glover and Suzanne T. Williams.

Hydroids of the Archipelago of the Recherche and Esperance, Western Australia: Annotated List, Redescription of Species, and Description of new Species. Jeanette E. Watson.

The marine molluscs of Esperance Bay and the Recherche Archipelago, Western Australia. Fred E. Wells, Alan F. Longbottom and Joy Longbottom.

Feeding of *Lepsiella flindersi* (Adams and Angas, 1863) on the limpet *Patelloida alticostata* (Angas, 1865), near Esperance, Western Australia. Fred E. Wells and John K. Keesing.

Flora

A catalogue of the marine plants found in the western islands of the Recherche Archipelago, Western Australia, with notes on their distribution in relation to island location, depth, and exposure to wave energy. N.A. Goldberg and G.A. Kendrick.

First record of tetrasporangia in *Herposiphoniella plurisegmenta* Womersley. Nisse A. Goldberg and John M. Huisman.

Variability of leaf morphology and growth in *Posidonia kirkmanii* growing in a spatially structured multispecies mosaic. Tim N. Moore, Marion L. Cambridge and Peter G. Fairweather.

Use of C:N ratios to assess the nutrient status of macroalgae growing at different depths in the Esperance region, Western Australia. Julia C. Phillips.

CHAPTER 5

5. SRFME CORE PROJECT ONE

5.1 Biophysical Oceanography off Western Australia: Dynamics across the Continental Shelf and Slope

5.2 Investigators

CSIRO Marine Research, Floreat, WA: Tony Koslow (Project Leader), Alan Pearce, Nick Mortimer, Joanna Strzelecki, Peter Fearns, Christine Hanson

CSIRO Marine Research, Hobart, TAS: Lesley Clementson, Rudy Kloser, Tim Ryan

University of Western Australia: Harriet Paterson, Stéphane Pesant, Anya Waite

Murdoch University: Barbara Muhling, Lynnath Beckley

Curtin University: Leon Majewski

Department of Environment: Ashrafi Begum

5.3 Executive summary

The aim of the SRFME Biophysical Oceanography project is to characterize the continental shelf/slope pelagic ecosystem off southwestern WA: its productivity and dynamics, and the physical, chemical and biological factors driving variability along dominant spatial and temporal scales. To achieve this, we undertook monthly sampling from 2002 – 2004 along an onshore-offshore transect off Two Rocks from nearshore to the outer continental shelf (100 m water depth), which we extended quarterly to offshore waters (1000 m depth). Cruise sampling was combined with satellite observations of sea-surface temperature (SST), ocean colour and altimetry, and subsurface measurements of currents and temperature from moorings. The program involved six core research components:

1) The physical structure and nutrient dynamics within the water column
2) Phytoplankton community composition, biomass and productivity
3) Microzooplankton communities and their grazing dynamics (reported in Section 2.3.13)
4) Mesozooplankton communities and their grazing dynamics
5) Ichthyoplankton community composition and ecology (reported in Section 2.3.5)
6) Spatial structure of zooplankton and micronekton communities

Standard sampling protocols included: meteorological (wind, air temperature) observations from coastal stations; vertical CTD (conductivity-temperature-depth) casts with concurrent measurement of *in situ* fluorescence, dissolved oxygen and subsurface irradiance; discrete water column samples for analysis of salinity, dissolved nutrients (nitrate+nitrite, ammonium, phosphate and silicate), chlorophyll *a*, HPLC pigments, particulate organic carbon, phytoplankton and microzooplankton species composition and abundance, primary production, and microzooplankton grazing; sediment trap deployments for measurement of vertical carbon fluxes; bongo net samples for mesozooplankton biomass, species composition, grazing rates and secondary production; low-frequency acoustic transects, and high-frequency acoustic vertical profiles in combination with targeted water column zooplankton sampling.

Summer conditions on the shelf and offshore were characterized by a shallow upper mixed layer, with a strong thermocline and well stratified water column. Surface waters were nitrate-depleted and generally contained low phytoplankton biomass levels (< 0.2 mg m^{-3}), overlying a deep chlorophyll maximum (DCM) located between the 0.1% and 1.0% light levels. The DCM was frequently associated with a deep nitracline (≥ 100 m water depth). In contrast, in late autumn and winter, the upper mixed layer deepened and stratification generally weakened, leading to shoaling of the nitracline and DCM layer and increased phytoplankton biomass. Satellite observations indicate that the late autumn/early winter bloom is a coherent feature from approximately the Abrolhos Islands to Cape Leeuwin and coincides with intensification of the Leeuwin Current, leading us to hypothesize that enhanced meander and eddy activity may stimulate upwelling or convective mixing.

Phytoplankton biomass and production integrated over the water column was higher offshore, although maximum volumetric chlorophyll concentrations were generally observed inshore. Annual phytoplankton production over the study period was 46 g $C.m^{-2}.yr^{-1}$ inshore and about 115 g $C.m^{-2}.yr^{-1}$ on the shelf and offshore – relatively oligotrophic for a coastal environment. Not unexpectedly, more biomass and production was in the small size phytoplankton size fraction (< 5 um). Distinct phytoplankton assemblages were observed on the inner shelf and further offshore, and between summer and winter. The outer shelf and offshore stations were characterised by high prochlorophyte and unicellular cyanobacteria populations, while small flagellates and periodic diatom blooms dominated inshore waters. Small haptophytes were ubiquitous.

Zooplankton biomass was also generally greatest in late autumn and winter. The assemblages differed significantly in nearshore and shelf/offshore waters and between winter and other seasons, following patterns among species groups observed elsewhere in coastal waters. Experiments have been carried out to assess zooplankton secondary production based on copepod egg production, and the results are being compared with a new enzyme assay and simple models based primarily on body size and temperature.

A three-frequency (70, 120 and 200 kHz) acoustic system was used to sample along the onshore-offshore transect during quarterly cruises. Mixing frequencies appears promising as a means to separate major groups, and to assess relationships between topography and water mass features and the broad-scale distribution of large zooplankton and nekton. A 6-frequency, high frequency (256 kHz – 3 megaHz) acoustic system (TAPS) was used in conjunction with an in situ pump sampler to assess the vertical distribution of zooplankton. Initial results are promising, showing good agreement between acoustic and pump sample profiles of zooplankton abundance.

The project also integrates two postgraduate projects, reported elsewhere, characterizing microzooplankton and ichthyoplankton assemblages in the region; the role of microzooplankton grazing is also being assessed. The Biophysical Project is working closely with biogeochemical modelers to develop a regional biophysical model that nests the region's hydrodynamics and its nutrient-phytoplankton-zooplankton dynamics.

Over the next year, analyses will be completed and results written up for publication in refereed scientific journals. Plans are being made for a follow-up project to develop regional oceanographic monitoring of the biological environment, based on developing algorithms relating satellite ocean colour, SST and altimetry to primary productivity and possibly nutrients. A proposal has been submitted for ship-time on the RV *Southern Surveyor* for a synoptic cruise in late autumn/early winter to test hypotheses linking Leeuwin Current and phytoplankton bloom dynamics; the cruise would also examine regional coherence in oceanographic processes during this dynamic time of year. Plans are also being made to develop a project off Ningaloo Reef to examine nutrient-plankton dynamics and the exchange between the reef and pelagic environments.

5.4 Introduction

5.4.1 Background

The dominant oceanographic influence on the pelagic ecosystem off the west coast of WA is the Leeuwin Current, the world's only poleward-flowing eastern boundary current (Cresswell and Golding 1980) (Fig. 45). The Leeuwin Current (LC) flows predominantly along the shelf break, bringing warm, nutrient-poor water in its surface layer southward and, as a downwelling current, is generally held to be responsible for the region's low pelagic productivity, relative to other eastern boundary current regions (e.g. the California, Peru and Benguela Current regions) (Pearce 1991). The Leeuwin Current is highly seasonal, peaking in the autumn and winter and reduced in summer when it flows against the prevailing southerly 'sea breeze,' which drives north-flowing counter-currents inshore of the LC over the shelf – the Ningaloo Current in the north and Capes Current in the south. Leeuwin Current flow is also closely linked with the ENSO cycle, being weaker during El Niño years when the Indonesian Throughflow is reduced: the Throughflow sets up the meridional pressure gradient that drives the LC (Feng *et al*. 2003, 2004).

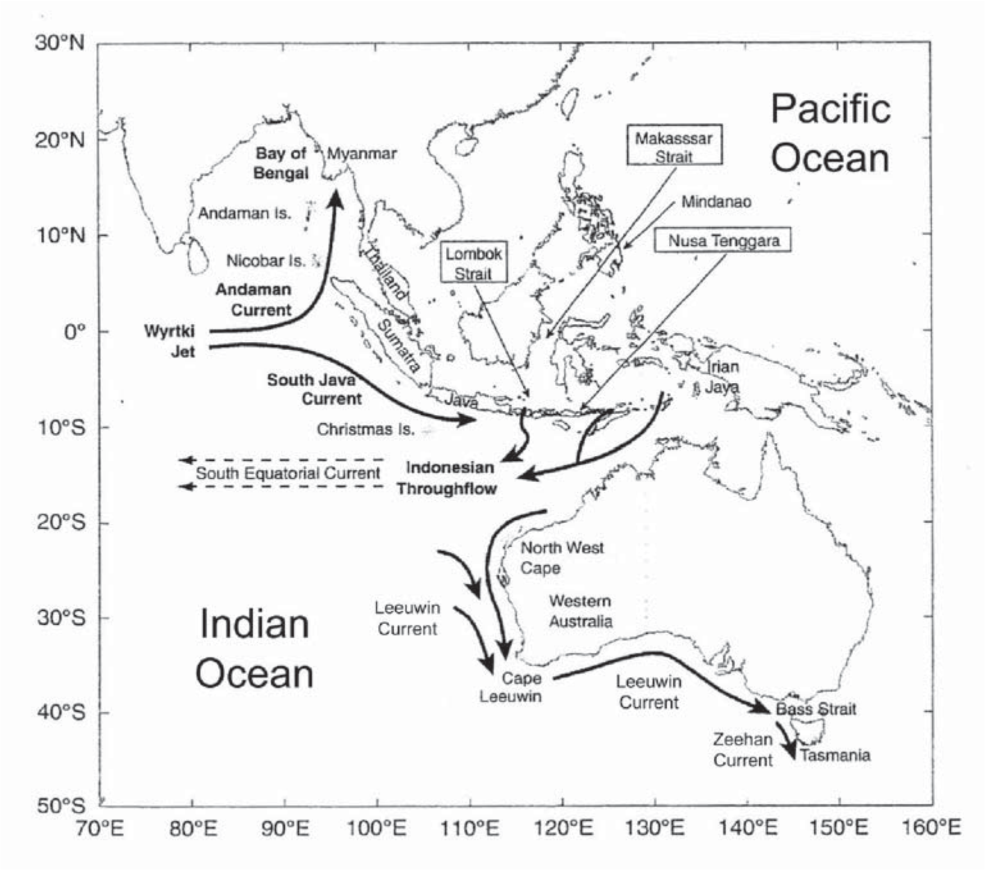


Figure 45: Schematic of the major surface currents in the eastern Indian Ocean, illustrating the connection between the Pacific and Indian Oceans through the Indonesian archipelago (adapted from Godfrey 2001).

Recruitment to the western rock lobster (*Panulirus cygnus*) fishery, Australia's most valuable single-species fishery, is closely correlated to the Leeuwin Current and ENSO cycle (Caputi *et al.* 2001), along with recruitment to other fisheries (e.g. whitebait, pilchard) (Caputi *et al.* 1996). A model of larval transport indicates that differential transport is probably not responsible for the correlation with western rock lobster recruitment, suggesting that it is based on changes in biological productivity (Griffin *et al.* 2001). Interestingly, rock lobster recruitment is higher during La Niña years, when flow of nutrient-poor LC water is enhanced. However until recently the biophysical dynamics of this system were virtually unstudied: the seasonal cycles of the plankton in coastal, shelf and Leeuwin Current waters were not described, and the potential links between climate variability and biological productivity were not known. As recently as 1998, the plankton cycle off WA was believed (mistakenly) to follow the typical temperate shelf pattern characterised by a strong spring bloom and low productivity in summer and winter (Longhurst 1998).

Management of marine resources and habitats requires that we distinguish the effects of natural climate variability and climate change from anthropogenic effects. The aim of the project is to examine how climate forcing influences nutrient, phytoplankton, zooplankton and micronekton dynamics across the shelf with application to fisheries, management of marine protected areas and coastal processes.

5.4.2 Objectives

The objectives of the Biophysical Project are to:

- Describe biophysical ocean structure, its seasonal cycle and interannual variability based on remote sensing data and monitoring temperature, salinity, nutrients, phytoplankton (chlorophyll and other pigments) and zooplankton along an onshore-offshore transect north of Perth (Two Rocks).
- Measure primary productivity and parameters related to zooplankton grazing and productivity at selected stations.
- Apply acoustic methods to monitor zooplankton and higher trophic levels and assess fine-scale distributions based on Tracor Acoustic Profiling System (TAPS) (6 frequencies, 300 kHz - 3 megaHz) and underway 38 and 120kHz frequencies
- Input data and collaborate in development of biophysical NPZ models for the coastal zone and shelf.

5.4.3 Field program

An extensive field research program was undertaken over a 3-year period (2002 – 2004) off the southwestern coast of Western Australia. The study was conducted along an 85 km oceanographic transect off Two Rocks, WA (Fig. 46).

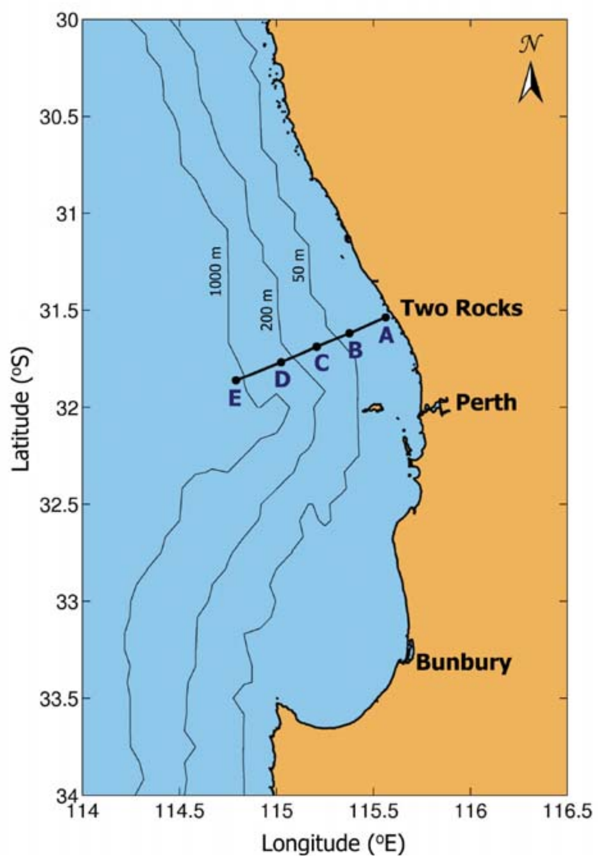


Figure 46: Location of the Biophysical Oceanography 'Two Rocks Transect', north of Perth, Western Australia.

Five core stations (A to E; Table 6) were sampled on a monthly to quarterly basis, and encompassed inshore (Stn A: 15 m depth), inner shelf (Stn B: 40 m), outer shelf (Stn C: 100 m), shelf-break (D: 300 m) and offshore (Stn E: 1000 m) regions (Fig. 47). In addition to the full sampling programs at these five stations, between-station CTD (conductivity-temperature-depth) profiles were undertaken during the quarterly cruises of 2003 and 2004 (at stations AB, BC, CE and DE; Table 6). Complete details of the sampling program and methodologies used are included in Section 5.5. Over the duration of the study, 27 research cruises were successfully completed (Table 7), resulting in a comprehensive temporal dataset of integrated biological, chemical and physical oceanography within the southwestern Australian region.

Table 6.
Location, nominal water depth and distance offshore of the Two Rocks Transect stations.

Station	Latitude (°S)	Longitude (°E)	Depth (m)	Distance (km)
A	31.5195	115.5980	15	4
AB	31.5363	115.5594	36	14
B	31.5772	115.4632	40	27
BC	31.6183	115.3652	50	32
C	31.6484	115.2956	100	40
CD	31.6799	115.2210	150	50
D	31.7215	115.1230	300	61
DE	31.7650	115.0198	700	73
E	31.8118	114.9092	1000	85

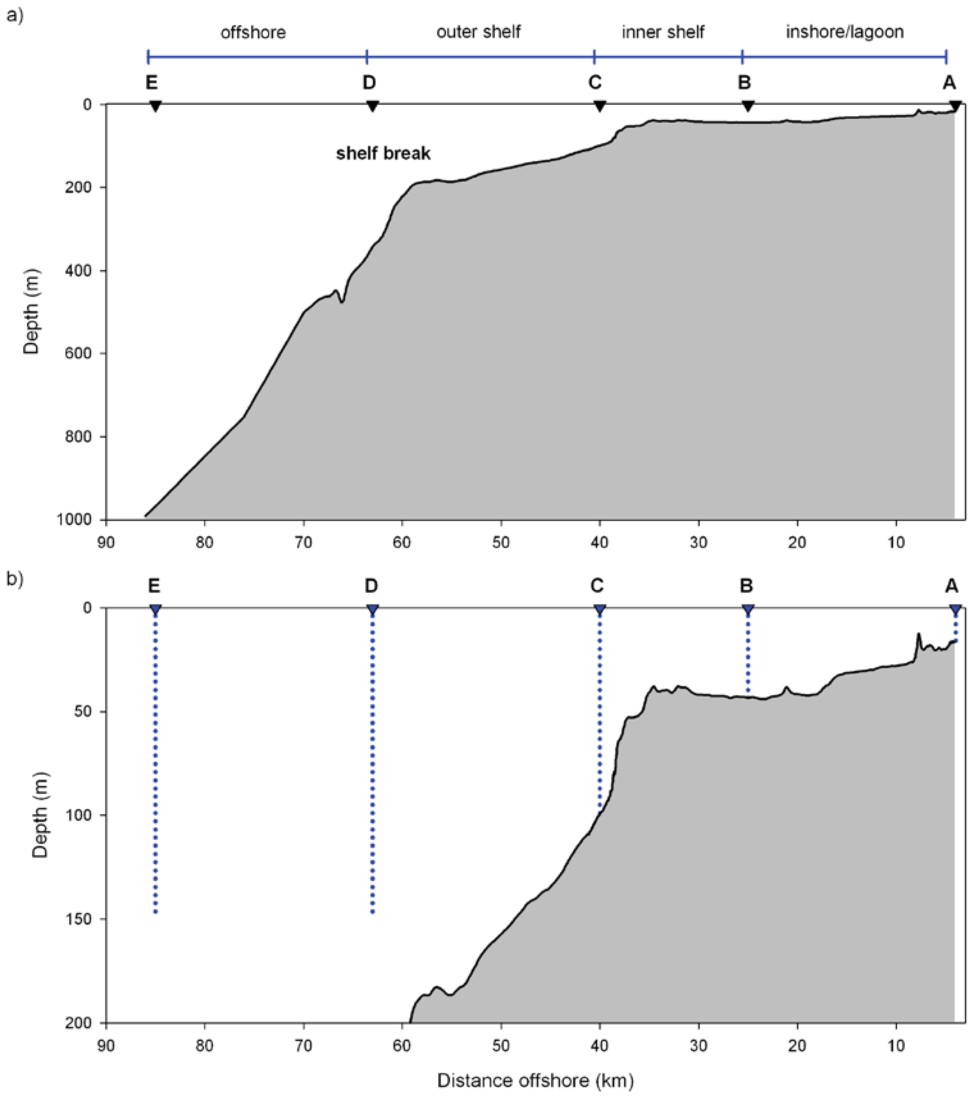


Figure 47: Cross-shelf profile of the Two Rocks Transect stations (A to E), illustrating a) large scale bathymetry (to 1000 m water depth) overlaid with region labels, and b) detailed bathymetry (to 200 m water depth) with an indication of maximum sampling depths.

Table 7. Summary of the Biophysical Oceanography surveys undertaken during the 3-year field program off Two Rocks, WA.

Voyage	Month	Year	Season	Vessel	Stations
MI200201	Feb	2002	Summer	Maritime Image	A, B, C, E
MC200202	Mar	2002	Fall	Mesocat	A, B
MC200203	May	2002	Fall	Mesocat	A, B, C
NA200204	Aug	2002	Winter	Naturaliste	A, B, C, D, E
MC200205	Nov	2002	Spring	Mesocat	A, B, C
MI200206	Dec	2002	Summer	Maritime Image	A, B, C, D, E
MC200301	Jan	2003	Summer	Mesocat	A
NA200302	Feb	2003	Summer	Naturaliste	A, B, C, D, E
MC200303a	Mar	2003	Fall	Mesocat	C
MC200303	Apr	2003	Fall	Mesocat	A, B, C
NA200304	Apr	2003	Fall	Naturaliste	A, B, C, D, E
MC200305	Jun	2003	Winter	Mesocat	A, B, C
MC200306	Aug	2003	Winter	Mesocat	A
SS200307	Aug	2003	Winter	Southern Surveyor	A, B, C, D, E
MC200308	Sep	2003	Winter	Mesocat	A, B, C
SS200309	Oct	2003	Spring	Southern Surveyor	A, B, C, D, E
NA200311	Dec	2003	Summer	Naturaliste	A, B, C, D, E
SS200401	Jan	2004	Summer	Southern Surveyor	A, B, C, D, E
MC200402	Apr	2004	Fall	Mesocat	A, B, C
MI200403	Apr	2004	Fall	Maritime Image	A, E
MC200404	Jun	2004	Winter	Mesocat	A, B, C
MI200405	Jul	2004	Winter	Maritime Image	A, B, C, D, E
MC200406	Aug	2004	Winter	Mesocat	A, B, C
NA200407	Sep	2004	Spring	Naturaliste	A, B, C, D, E
MC200408	Oct	2004	Spring	Mesocat	A, B, C
MC200409	Nov	2004	Spring	Mesocat	A, B, C
NA200410	Dec	2004	Summer	Naturaliste	A, B, C, D, E

5.5 Major findings

Six primary aims/tasks were established to meet the objective of determining spatial (onshore-offshore) and temporal (seasonal and interannual) patterns of variability in the biological oceanography of southwestern Australia. These included measurement of:

1) Physical structure and nutrient dynamics within the water column
2) Phytoplankton community composition, biomass and productivity
3) Microzooplankton communities and their grazing dynamics
4) Mesozooplankton communities and their grazing dynamics
5) Ichthyoplankton community composition and ecology
6) Spatial structure of zooplankton and micronekton communities

Aims 3 and 5 (microzooplankton and ichthyoplankton dynamics) formed the basis for two PhD projects, undertaken by Harriet Paterson (UWA) and Barbara Muhling (Murdoch), respectively. The findings from these student components are reported elsewhere within the SRFME Interim Report (see Section 2.3).

5.5.1 Oceanography and meteorology

5.5.1.1 Introduction

Ocean currents and the physical/chemical water properties play a major role in the abundance and distribution of phytoplankton and zooplankton on the continental shelf. The water movements as well as the temperature and salinity along the Two Rocks Transect vary both spatially and temporally over a range of scales. Over short scales of hours and kilometres, diurnal variations, cross-shelf mixing processes and changes in the vertical structure of the water column contribute to the patchiness of the plankton regime. Few-day (generally weather-related) events include reversals in the current systems and variations in the exchange of heat and moisture between the ocean surface and the atmosphere. Perhaps the best-defined (and probably the most important) cycle for most parameters is the seasonal change in the currents and water properties across the continental shelf. Finally, El Niño/ Southern Oscillation (ENSO) events are important on scales of months to years.

The oceanographic measurements made during the 3-year SRFME period along the Two Rocks Transect were effectively from the quasi-monthly boat surveys (largely using the CTD profiler), and thus only address the seasonal pattern. However, the 3-year period can be placed in a longer-term perspective using time-series data from other sources such as coastal sea level, satellite-derived sea-surface temperature (SST) and wind, thus addressing the question of how representative was the SRFME period of overall environmental conditions along the southwestern coast. Finer-scale resolution can be obtained from daily satellite observations of ocean colour and SST, and from several moorings placed along the transect at the beginning and end of the study period that monitored currents and temperature.

Within these limitations, this section uses the CTD surveys in conjunction with satellite imagery to describe the ocean currents and water properties along the Transect, and hence deduce the main seasonal patterns with particular attention to the cross-shelf variability. The mooring data is being analyzed for the final report.

5.5.1.2 Large-scale perspective

Monthly values of the Southern Oscillation Index (SOI), Fremantle sealevel (FMSL) and the Reynolds satellite-based SST (Reynolds & Smith 1994) anomalies were plotted for the decade 1994 to 2005 (Fig. 48) to assess whether the SRFME Biophysical study period (2002 to 2004) was typical of the longer-term situation. The SOI is an index of the strength of El Niño/Southern Oscillation (ENSO) events, reflecting the ‘see-sawing’ of atmospheric pressure between the Pacific and Indian Oceans, and the consequent effects on the wind field and ocean circulation in the equatorial Pacific Ocean. Fremantle sealevel is an indicator of the strength of the Leeuwin Current (Pearce and Phillips 1988, Feng *et al*. 2004), with higher sealevels indicating a stronger southward flow. The Reynolds SST has been extracted for the 1 degree block 31° to 32°S, 115°E to the coast to represent the larger-scale temperature regime.

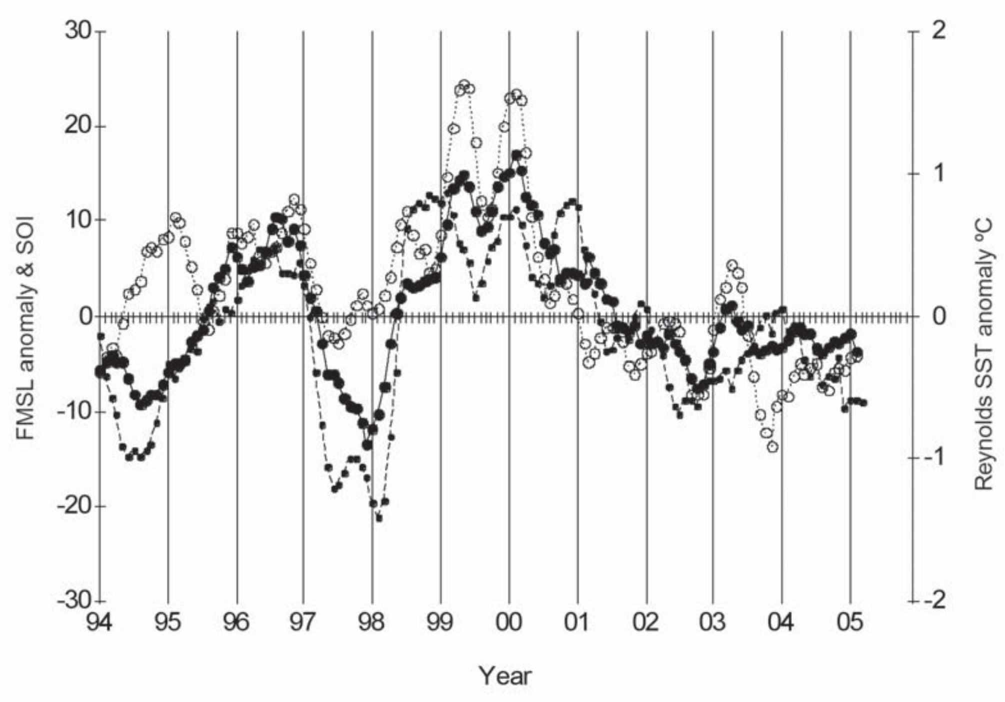


Figure 48: Monthly values of the Southern Oscillation Index (SOI -- small dots), Fremantle sealevel anomaly (FMSL -- filled circles) and the Reynolds satellite-based SST anomaly (SST -- open circles) between 1994 and 2004. The anomalies were derived by subtracting the long-term annual cycle from the individual monthly vales, and all 3 datasets have been smoothed by a simple 5-month moving average to reduce smaller-scale variability.

As found by Pearce and Phillips (1988) and Caputi *et al*. (2001), there was a close relationship between the SOI and sealevel throughout this period, indicating that the Leeuwin Current was flowing strongly during the La Niña periods (relatively high sealevel) and more weakly in ENSO years. The water temperature generally followed the same pattern, with higher temperatures in La Niña years when the strong Leeuwin Current was transporting more warm water southward. However, the temperature anomaly actually rose during the ENSO event of 1994 and was near average during the 1997 event, and the temperature was also relatively low in late 2003; these cannot be explained at present.

Following the two strong ENSO events in 1994 and 1997 and the La Niña of 1999-2000 (when the SST reached record levels), the SRFME Biophysical study period was characterised by neutral or weak ENSO conditions with a weak ENSO in 2002. The strength of the Leeuwin Current was therefore about (or slightly below) average, and water temperatures were within a degree of the longer-term average.

5.5.1.3 Meteorology

The wind plays a crucial role on coastal waters on a variety of temporal and spatial scales, being responsible for forcing coastal current systems, coastal upwelling, and vertical mixing of the water column. Wind data for the period 2000 to 2004 have been acquired from the Bureau of Meteorology stations at Rottnest Island (assumed representative of the offshore waters) and on the coast at Ocean Reef, as well as from the National Tidal Centre facility in Hillarys Marina. The original wind measurements at the two AWS sites are at 1-minute intervals but these have been converted to hourly values for the present analysis, and monthly averages have also been derived to more clearly show the seasonal wind fields. Air temperatures are available from the Rottnest and Hillarys sites, and sea temperature (within the Marina) from Hillarys.

Seasonal wind variations

The overall mean wind speed over the 5-year period at Rottnest Island was 7.5 m·s^{-1}, marginally weaker at 6.2 m·s^{-1} at Ocean Reef and appreciably lower (3.2 m·s^{-1}) at the semi-sheltered Hillarys site. The latter site is probably not representative of the coastal waters and will not be used in this analysis except to confirm the consistency of the seasonal pattern across the shelf.

As a result of the annual meridional migration of the subtropical high-pressure belt, a pronounced seasonal cycle is evident in the monthly mean wind vectors at all three sites (Fig. 49). Through much of the year, the meridional wind stress is predominantly northward, albeit with a weak southward component in winter. During the summer months when the high-pressure belt is furthest south, the zonal wind stress is westward (offshore) but as the belt moves northwards in winter, this switches to a strong eastward, or onshore, component.

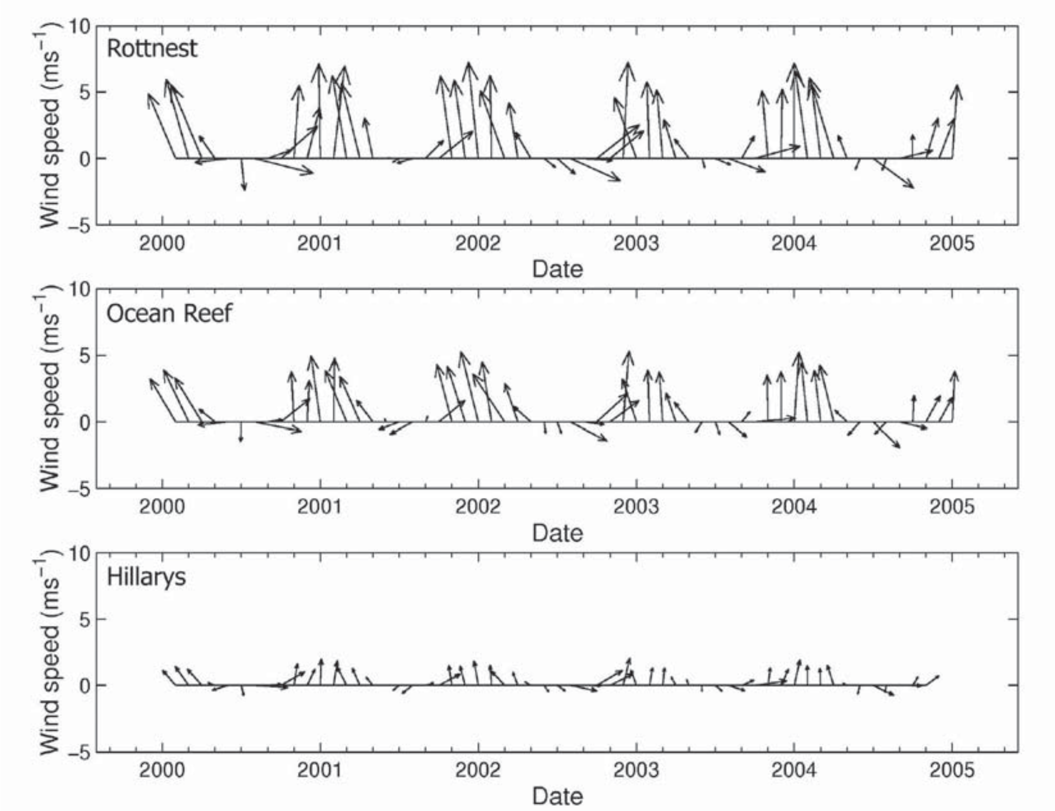


Figure 49: Monthly mean wind vectors from Rottnest Island (representing open-shelf conditions), Ocean Reef (coastal) and Hillarys Marina (sheltered).

Although the monthly vector-averaged winds display this clear seasonal pattern, the seasonal variation in the scalar wind speed is much smaller (Fig. 50a). The summer months still experience the strongest winds of about 9 m·s^{-1} (Rottnest Island) and 7 m·s^{-1} (Ocean Reef), largely a result of the strong afternoon seabreezes, but the mean wind speed in winter is still well over 5 m·s^{-1}. The effectiveness of the wind in mixing the near-surface waters (as the cube of the wind speed; data not shown) is highest in summer, but strong mixing events can also be experienced in the other seasons as well. Because of the speed cubed, the relatively small differences in wind speed between offshore (Rottnest Island) and the coast (Ocean Reef) translate into a large cross-shelf change in wind mixing effectiveness. The Rottnest Island values are therefore probably more appropriate for Transect stations C, D and E, whereas stations A and B would be better represented by the Ocean Reef winds. This cross-shelf variation may also be important for wind forcing of the coastal ocean circulation models.

The ratio of the mean vector and mean scalar wind speeds is termed the wind "stability" (Neumann 1968), an index of the relative persistence of the wind in a particular direction. Because of the persistence of the summer wind regime, the stability is very high during the summer months (around 80%), whereas the stability is below 20% during the stormy winter period when the wind direction changes frequently as the storms pass through (Fig. 50b).

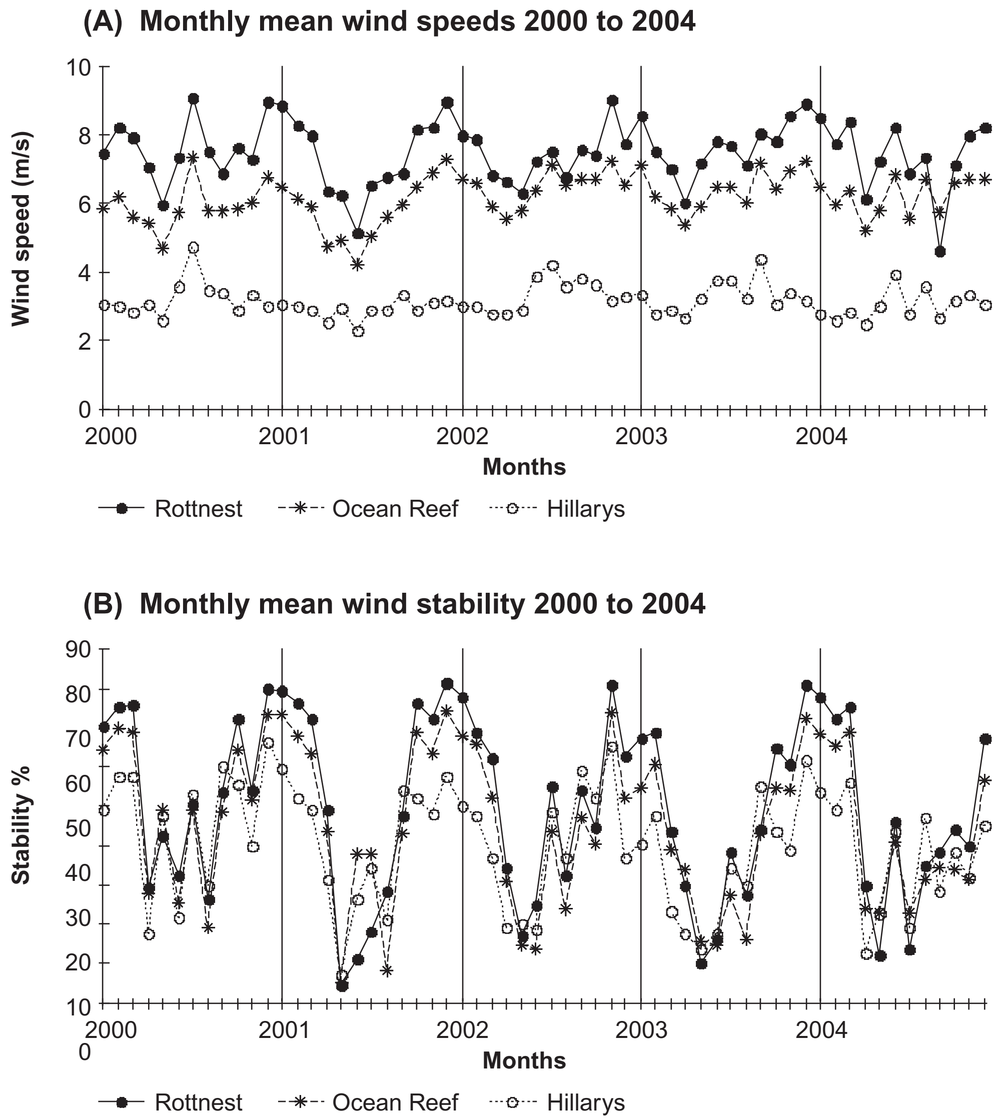


Figure 50: a) Monthly mean wind speeds, and b) monthly mean wind stability (defined in the text), from Rottnest Island (filled circles), Ocean Reef (asterisks) and Hillarys Marina (open circles).

Seasonal temperature variations

Monthly mean air temperatures at Rottnest Island and at Hillarys follow a very similar seasonal cycle (not shown here), with peak temperatures of about 22° to 23°C in February and lowest temperatures of 14° to 15°C in August. Hillarys temperatures are about 0.5°C higher than the Rottnest Island temperatures in summer, and marginally lower in winter.

Interannual variations

Superimposed on the regularity of the seasonal cycle are some differences in wind regime from year to year (Fig. 49), most evident during the weaker winter months. While the alongshore wind components at Rottnest Island and Ocean Reef (not shown) were reasonably consistent during the summer months of each year, the southward tendency in winter was stronger in 2000 and 2004 than in the other years and appreciably weaker during 2001 and 2003.

5.5.1.4 The Leeuwin Current and shelf currents

Satellite images and the Leeuwin Current

Thermal infrared data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) and ocean colour information from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite have been used to provide a larger-scale perspective (both spatially and temporally) to the Two Rocks monthly transects. Colour thermal images of the southwestern continental shelf and offshore waters show the position and structure of the Leeuwin Current and Capes Current, while the chlorophyll concentrations derived from SeaWiFS often reveal subtle tracer patterns related to the current features. Both these sensors are limited by cloud, so no useful images can be obtained during cloudy periods. It must be borne in mind that while strong sea-surface temperature (SST) gradients tend to reveal the dominant flow features during the autumn, winter and early spring months, there are periods and regions when the SST gradients may be weak (especially near the coast) and cannot be unambiguously interpreted in terms of current streams.

The SST images indicate that the Leeuwin Current tends to flow along the outer continental shelf and upper slope, but may intrude onto the shelf or meander well offshore. There is a high degree of variability in the structure and position of the current from month to month, and the Two Rocks monthly voyages which extended only to station C in 100 m water depth were sometimes completely inshore of the Leeuwin Current.

Seasonally, Leeuwin Current flow is minimal during summer. It intensifies during late autumn (Godfrey and Ridgway 1985), such that current meanders and eddies form in late April through June. Leeuwin Current flow remains strong through winter, and eddies often mature and spin off in winter and spring (Fig. 51). The eddy kinetic energy of the Leeuwin Current is substantially higher than that of any other eastern boundary current (Feng *et al.* in press).

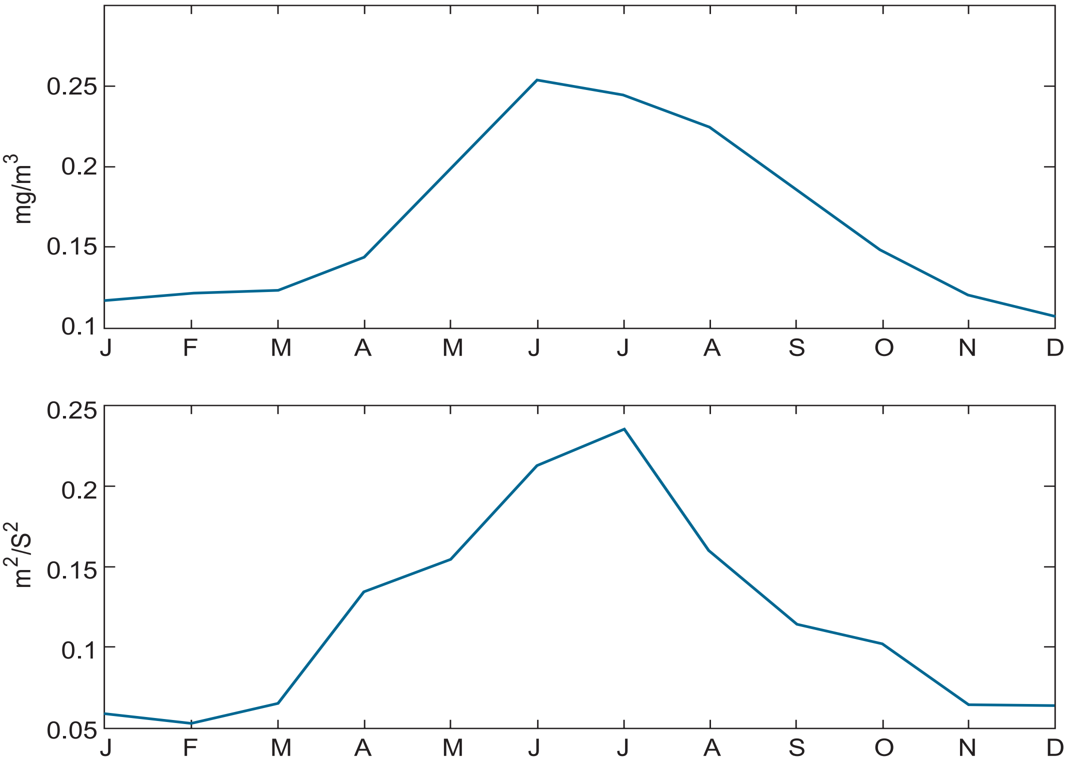


Figure 51: The climatological average for chlorophyll (upper) and eddy kinetic energy (lower) along the coast of WA. The chlorophyll was estimated from the data in Figure 47 and the eddy kinetic energy from satellite altimeter data (Feng *et al*. in press).

In May 2002, during an El Niño year (monthly voyage MC200203), the Leeuwin Current front was lying at station D along the shelf-break and the warm water was apparently confined to the shelf (Fig. 52a). The SST gradually rose from a narrow cool (21.5°C) boundary layer at the coast into the current (peak about 22.5°C) and then dropped sharply by 2°C in the offshore waters. The digital transect (not shown) also indicates a bimodal structure with SST variations within the Leeuwin Current itself.

By contrast, in late April 2003 (during quarterly voyage NA200304), there was a large meander extending Leeuwin Current water from mid-shelf (station C) to well offshore, with a small cool (clockwise) eddy at the shelf-break west of Rottnest Island (Fig. 52b). Because of this large area of warm water, interpretation of the currents from SST images alone is difficult.

A summer image in February 2002 (during quarterly voyage MI200201) showed a weak current pushing southwards along the shelf-break (Fig. 52c); there was a coastal boundary layer of warm (locally-heated) water, then the cooler northward flow of the Capes Current and the narrow weak Leeuwin Current.

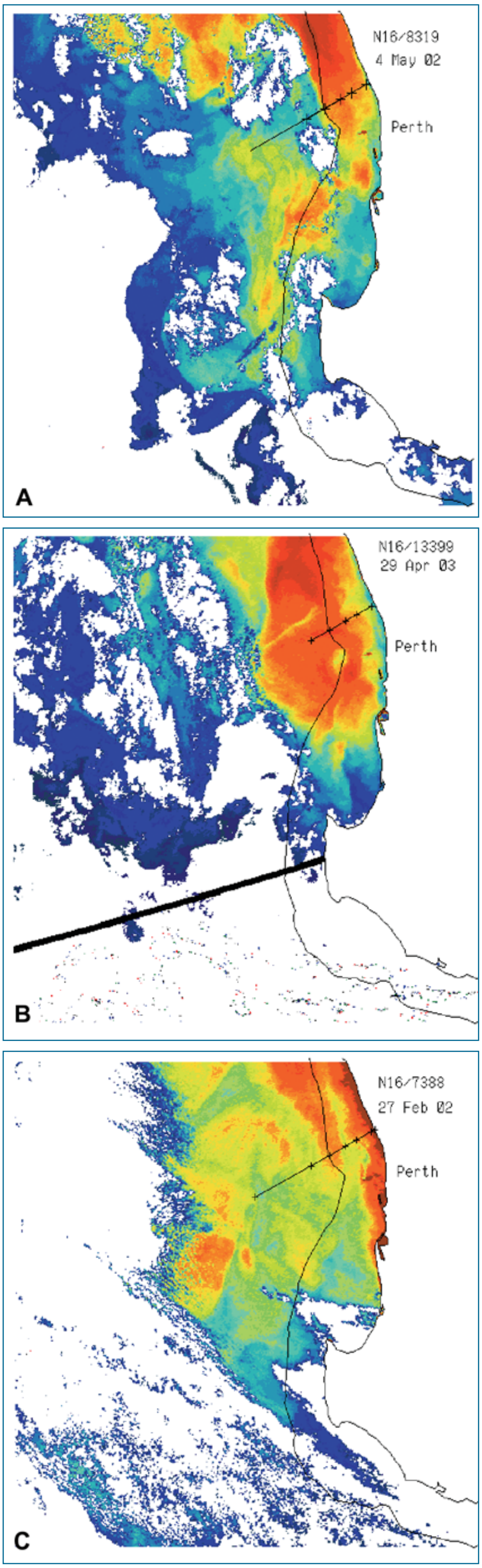


Figure 52: NOAA/AVHRR SST image showing the Leeuwin Current in a) May 2002, b) April 2003, and c) February 2002. Warmest water (the Leeuwin Current) is shown in red/orange, cooling through yellow/green to the coolest water in blue. Mottled white patchy areas are clouds. The black line represents the 200 m isobath (the approximate edge of the continental shelf) and the Two Rocks Transect stations A to E are indicated. NOAA data courtesy of WASTAC

A unique feature of the phytoplankton cycle off WA, seen in the satellite data, is a marked bloom in late autumn/early winter, which coincides with the seasonal intensification of Leeuwin Current flow. This feature extends from the Abrolhos Islands to Perth (26º – 32ºS latitude) (Fig. 53). We suggest two potential mechanisms to explain this relationship:

i) the meanders and eddies that form during this autumn/early winter period (Fig. 48) (Morrow and Birol 1998) may drive upwelling as they flow in toward the continental slope, and

ii) the cooling of the Leeuwin Current as it flows south may lead to vertical mixing of nutrients into the upper mixed layer.

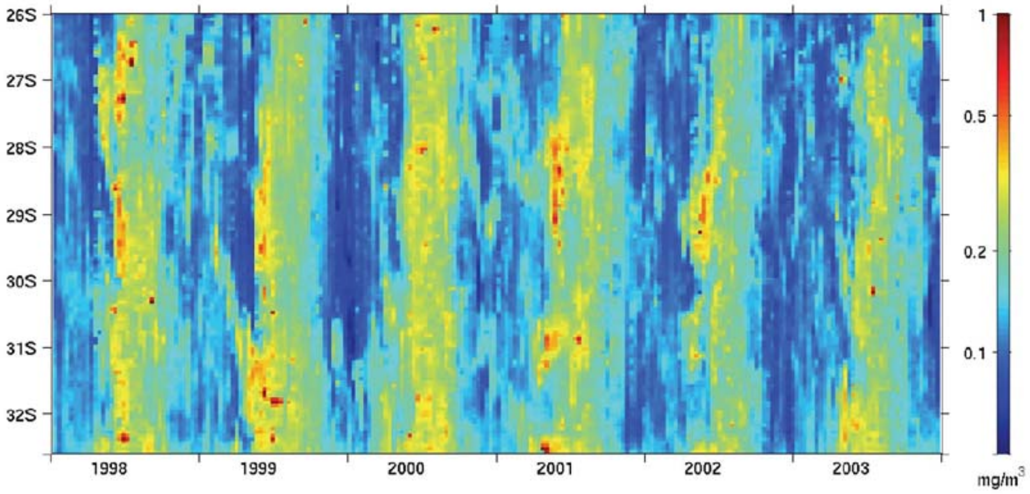


Figure 53: The distribution of chlorophyll estimated from SeaWiFS ocean colour data along the shelf break off the west coast of WA from 26º - 32ºS from 1998 – 2003. A late autumn/early winter bloom extends along the coast, with relatively high chlorophyll levels maintained through much of the winter (Feng *et al*. in press.).

After examination of the satellite images for the SRFME period, supplemented by historical observations, it appears that the Leeuwin Current influences continental shelf waters off southwestern Australia in four ways:

a) strong southwards advection of warm tropical water along the outer shelf and upper slope;

b) meanders and eddies driving upwelling or vertical mixing of nutrients in late autumn and early winter ;

c) mesoscale meandering onto the shelf which entrains higher-productivity coastal waters and exports them into offshore eddies;

d) smaller-scale cross-shelf mixing processes, including tongues of Leeuwin Current water penetrating across the shelf towards the coast.

5.5.1.5 Oceanographic transects: water properties

The monthly Two Rocks surveys covered the three shelf stations (A, B and C), while the longer quarterly surveys included stations D and E and also permitted day and night sampling at selected stations. Conductivity-temperature-depth (CTD) casts were made at each station using a Seabird Model SBE 19+ instrument. A fluorometer, underwater quantum sensor (for measurement of Photosynthetically Active Radiation; PAR) and oxygen sensor were attached to the CTD, and the package was deployed on a rosette sampler equipped with 5 to 10 L Niskin bottles. Water samples collected at standard oceanographic depths (and also targeting the depth of the fluorescence maximum) were subsequently analysed for salinity, chlorophyll *a* and dissolved nutrients (nitrate+nitrite, silicate, phosphate and ammonia). The CTD sampling frequency was 4 Hz, giving 4 samples per m depth interval at a lowering rate of 1 m s^{-1}. The casts were made down to near the seabed or to a maximum of 150 m in deeper water (with some occasional deeper casts, especially during the Southern Surveyor voyages), and repeat casts at some station positions. Extra CTD-only stations (AB, BC, CD and DE) were occupied between the standard stations during the 2003 and 2004 quarterly cruises to improve the cross-shelf spatial resolution (Table 6). A total of 181 casts were made over the 3-year period.

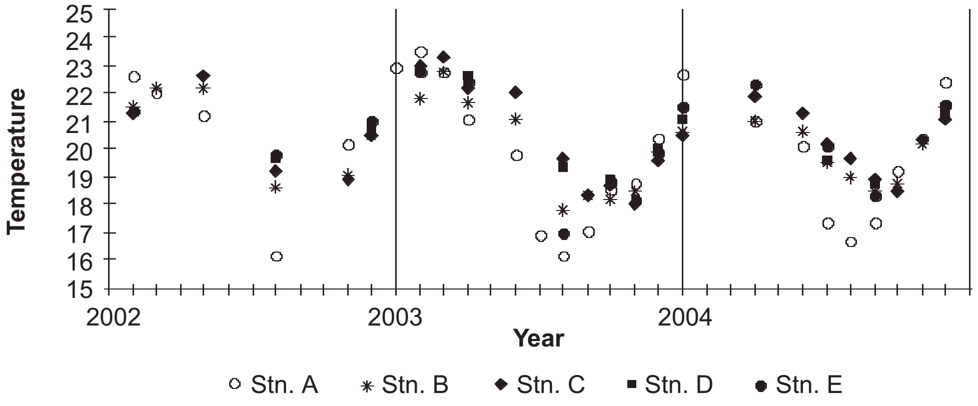
Standard Seabird software was used to process the raw datastream and provide 1-m depth-averaged profiles which were used for all subsequent data analysis. Profile plots of all parameters were generated, followed by vertical sections to standardised length and depth scales.

Seasonal cross-shelf structure and water masses

The near-surface temperatures and salinities for all the stations are plotted in Figure 54. As would be expected, there is a strong seasonality in the cross-shelf temperature/salinity structure, reflecting both the advection of warm low salinity water in the Leeuwin Current and the gain/loss of heat from/to the atmosphere. The greatest variability occurred in the shallow coastal waters where air-sea and moisture fluxes are the dominant factor. At the inshore station A, temperatures varied from 16 – 17 °C in August to 23°C in mid-summer (a 7°C annual range), whereas in the Leeuwin Current (usually encountered at station D) the seasonal change was between 19° and 23°C (a 4°C range). The cross-shelf temperature structure in summer results from coastal heating (a narrow band of warm nearshore water in the coastal boundary layer: Zaker *et al*. in press, Pearce *et al*. submitted), slightly cooler water in the northgoing Capes Current, and then warming again into the (weak) Leeuwin Current. With the rapid loss of heat to the atmosphere in autumn/winter from the shallow nearshore waters, coincident with the inflow of warmer water in the strengthening Leeuwin Current along the outer shelf, there can be a marked temperature rise of up to 5°C between the shore and the shelf-break. The coolest water <17°C was encountered only at station A between July and August.

Inshore salinities rose from 35.4 in winter (precipitation and coastal run-off) to 36.4 in summer (evaporation in the shallow water), an annual range of 1 psu, while the corresponding range in the Leeuwin Current was between 35.4 and 35.8 (only 0.4 psu). The elevated salinities >36 psu between January and April did not extend as far as the mid-shelf station B (25 km offshore).

(A) Time series 5m temperature 2002 to 2004



(B) Time series 5m salinity 2002 to 2004

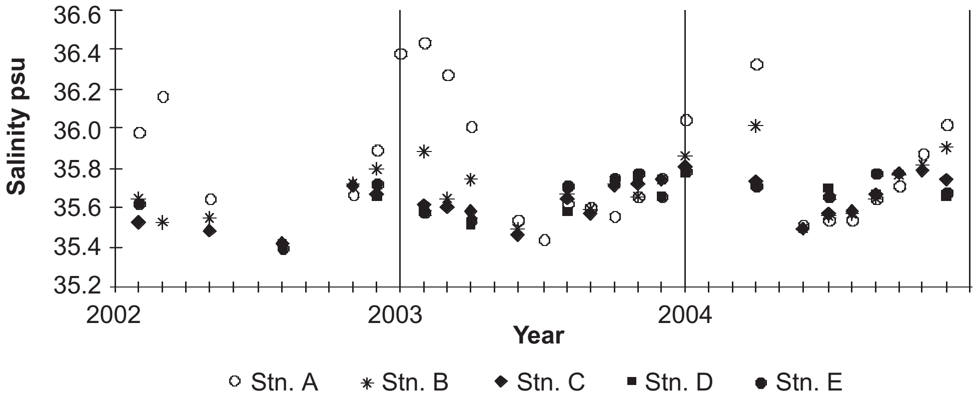


Figure 54: Near-surface (5 m depth) a) temperature, and b) salinity at the Two Rocks Transect stations A to E from the 1-m depth-averaged CTD profiles.

Vertical structure and stratification

Mixing of nutrients upwards into the photic zone is partly governed by the vertical stratification of the water column, which in turn depends on the temperature and salinity structure. In many studies, temperature alone is used to define the water column stability, but in WA coastal waters salinity changes may on occasion be sufficiently important that they should also be taken into account. We are accordingly analysing the vertical structure using the derived sigma-t profiles.

The CTD 1-m depth-averaged profiles were smoothed by a simple 5-point moving average to reduce small-scale variability, and the surface and bottom mixed-layer depths (MLD) have been defined as the top-most and bottom portions of the water column with a sigma-t gradient of < 0.002 m^{-1}. The pycnocline has been defined as a layer where the gradient exceeds 0.01 m^{-1}. The derived MLDs were visually compared with the plotted profiles to confirm the analysis. However (as also found by Holm-Hansen *et al*. 2004), MLDs could not always be unambiguously defined if the density increased steadily with depth, and there were occasions where multiple pycnoclines and MLDs occurred down the water column. In many cases on the shelf, the water was effectively isopycnal right down to the bottom and so the surface MLD was equal to the water depth.

A simple indication of the strength of the vertical structure at each station was quantified by a ‘Gross Stratification Index’ (GSI), defined as the difference between the near-surface (5 m) and bottom densities divided by the depth interval and multiplied by 100 (effectively a modified mean density gradient).

There were appreciable differences in stratification between summer and winter, with important implications for nutrient profiles and resultant primary production. As an example of the summer situation, Figure 55 shows the vertical structure in December 2002. The surface mixed layer was shallow, with a strong thermocline and well stratified water column (so that the temperature at 150 m offshore was as low as 16°C). Salinity changes were by comparison insignificant. Chlorophyll *a* levels (derived from the fluorescence profiles using a regression relationship against extracted chlorophyll a measurements) were extremely low in surface waters (< 0.2 mg m^{-3}), with a weak deep chlorophyll maximum (DCM) of about 0.5 mg m^{-3} at 100 m depth. The bulk of the DCM was located between the 0.1% and 1.0% light levels (Fig. 51), and shoaled towards the shelfbreak, with maximum chlorophyll levels found near the seabed at stations A and B. Nitrate was generally depleted (<0.2 µM) throughout the upper water column, with a distinct nitracline at 100 m water depth (coincident with the DCM).

By contrast, in autumn the offshore mixed layer extended down to 100 m and the (weaker) thermocline was found below this depth (Fig. 56). The chlorophyll maximum was located at ~ 50 m depth (well above the 1.0% light level), and chlorophyll levels on the shelf reached > 1 mg m^{-3}. There was also an extensive pulse of high nitrate water (> 1 µM) intruding from offshore into the lower part of the water column towards the shelf, possibly an upwelling-like event associated with the eddy structure visible in the satellite image of Figure 52b. Similarly high nitrate levels were also noted on the shelf at Station A.

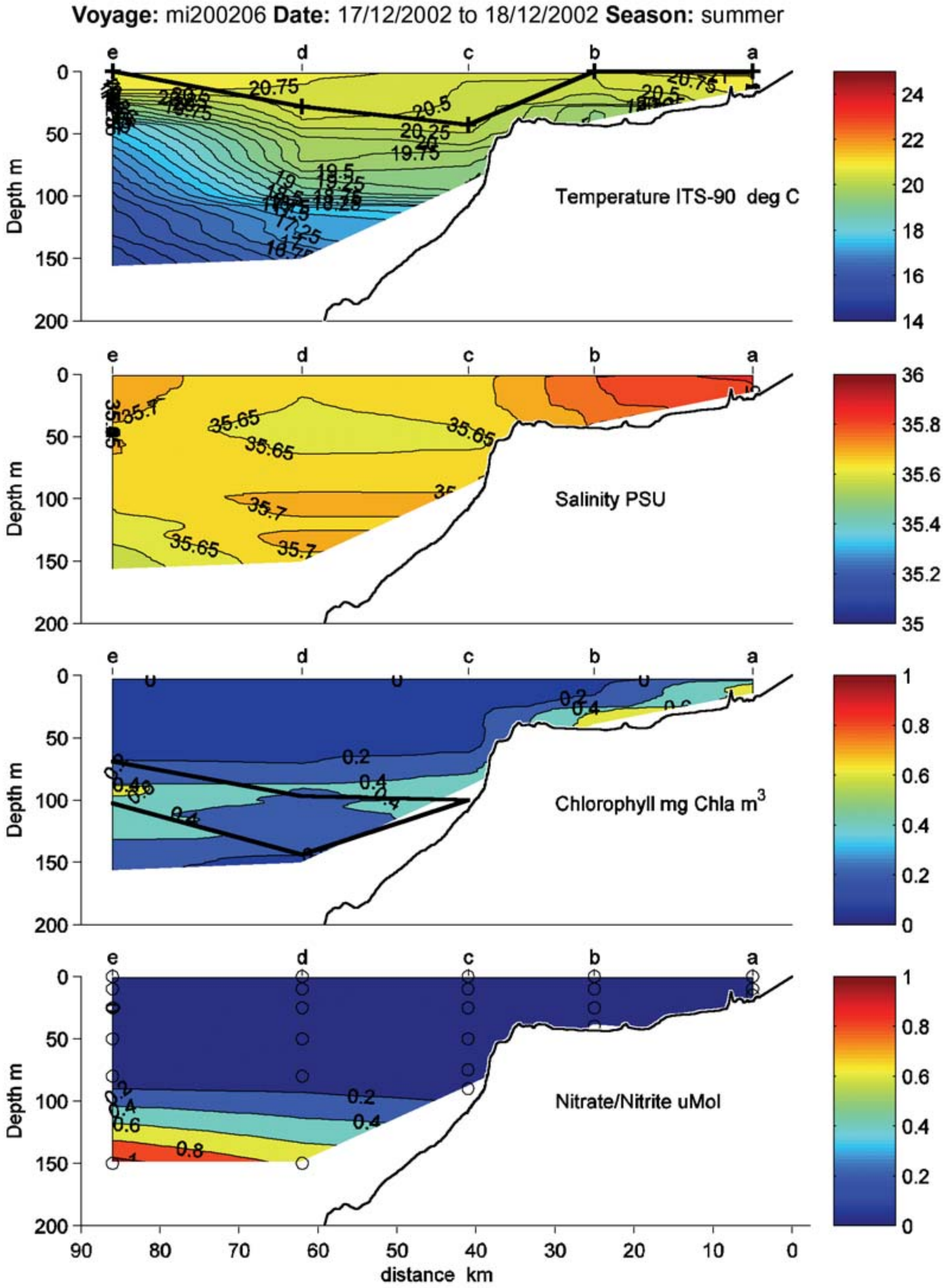


Figure 55: Vertical cross-shelf sections of temperature (upper panel), salinity (second panel), chlorophyll concentration (third panel) and nitrate/nitrite (bottom panel) from the CTD stations in December 2002. The solid line in the upper panel represents the upper mixed-layer depth (defined in the text), and the two lines in the chlorophyll panel show the depths of the 1% and 0.1% light levels from the PAR sensor.

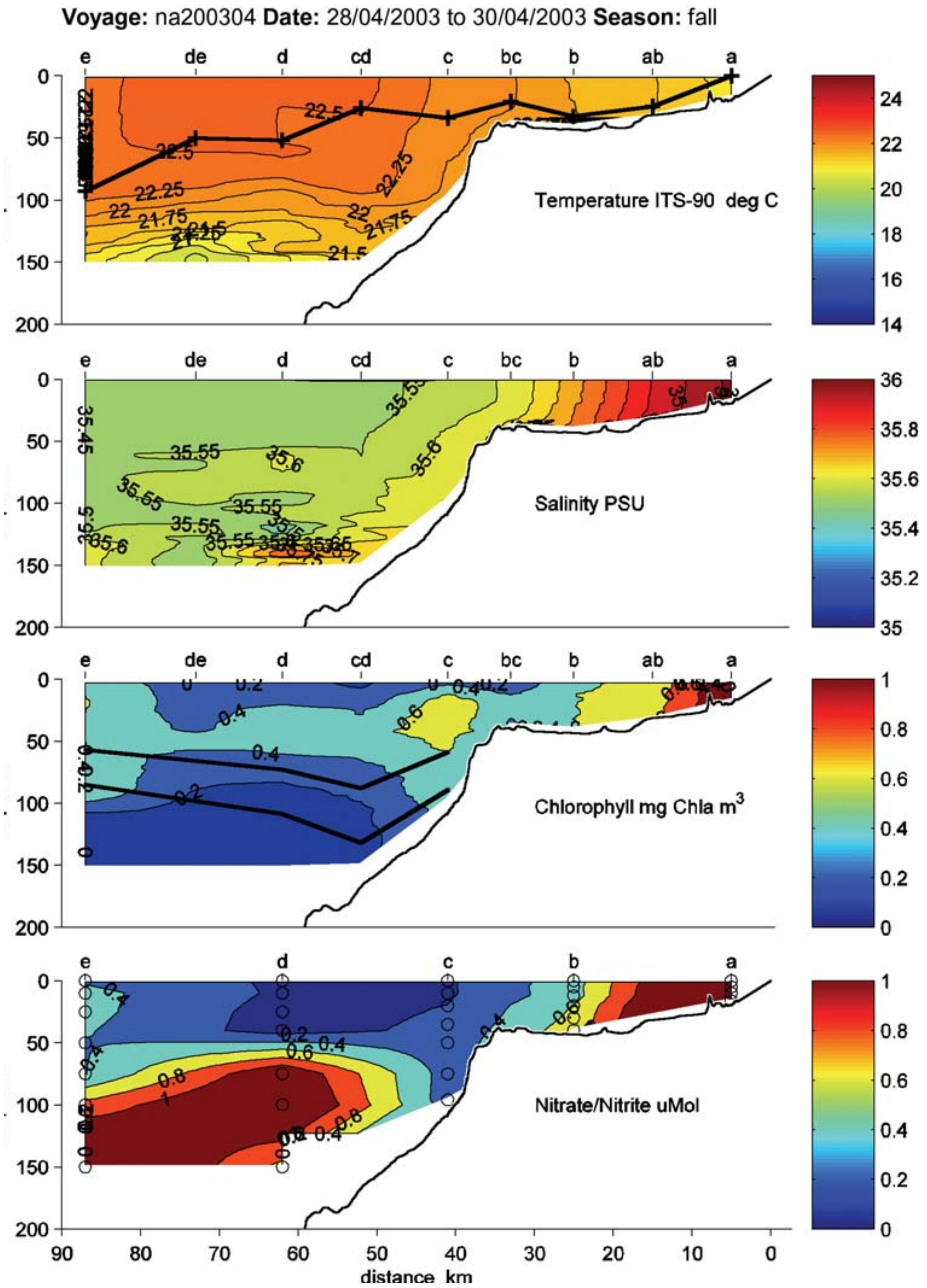


Figure 56: Vertical cross-shelf sections of temperature (upper panel), salinity (second panel), chlorophyll concentration (third panel) and nitrate/nitrite (bottom panel) from the CTD stations in April 2003. The solid line in the upper panel represents the upper mixed-layer depth (defined in the text), and the two lines in the chlorophyll panel show the depths of the 1% and 0.1% light levels from the PAR sensor.

Despite small-scale local variability, the seasonal relationships illustrated above tended to follow a similar pattern over the 3-year sampling period. For example, at station E (Fig. 57), the vertical stratification (as indicated by the GSI, gross stratification index) was generally highest in the summer months and weakest (with the deepest mixed layers) in autumn and winter. In winter, the DCM shoaled to 50-80 m from a summer depth of 100 m, with a concurrent increase in chlorophyll a concentrations from summer to winter. Volumetric particulate primary production at Station E was generally maximal at < 50 m water depth in fall and winter (Fig. 57). However, in spring 2004, production peaked at ~ 75 m water depth, coincident with a strong nitracline located at 75 – 100 m depth. In general, nitrate was relatively low (< 0.2 μM) within surface waters, with the nitracline located near 100 m water depth. An unusual surface pulse of nitrate was measured in May 2003, coincident with a breakdown of the summer stratification.

Seasonal variations in temperature were evident across the shelf, with a suggestion of a small lag in timing from inshore to offshore (Fig. 58). The shallow shelf stations were generally well-mixed vertically throughout the year, with some evidence of sporadic upwelling at station C (e.g. in the spring of 2003).

Satellite SST and chlorophyll a time-series

In addition to the colour images and SST transects described above, digital temperatures and chlorophyll (chl) *a* concentrations have been extracted from the daily overpasses to show shorter-term variations in the temperature and chl *a* levels and thus complement the monthly boat surveys. For both SST and chl *a*, the mean and standard deviation of 3*3 pixel arrays centred on the Two Rocks stations (A to E) have been extracted from the daily satellite data for the SRFME period 2002 to 2004 (SST) and the longer period 1998 to 2004 (chlorophyll *a*). The SeaWiFS data have embedded cloud quality flags; cloud detection for the temperature data has been based on threshold SST limits and the spatial variability over the 3*3 arrays as defined by the standard deviations. The accuracy of the satellite SSTs and further details of the data processing are documented in the Remote Sensing section of this report.

The satellite temperatures have been derived from the brightness temperatures in the AVHRR Bands 4 and 5 using the Non-Linear SST algorithm for the NOAA-16 and NOAA-17 satellites. The seasonal cycle stands out clearly in both the daily and monthly mean (Fig. 59) plots. Summer temperatures near the coast peaked at about 23°C in February while the offshore (Leeuwin Current) water was warmest at about 22°C in between February and May. The cross-shelf gradient reversed in winter, when coastal temperatures were down to 17°C in August/September while the Leeuwin Current maintained the offshore winter temperature at about 19°C in September/October. These values agree well with the spot CTD near-surface temperatures discussed above.

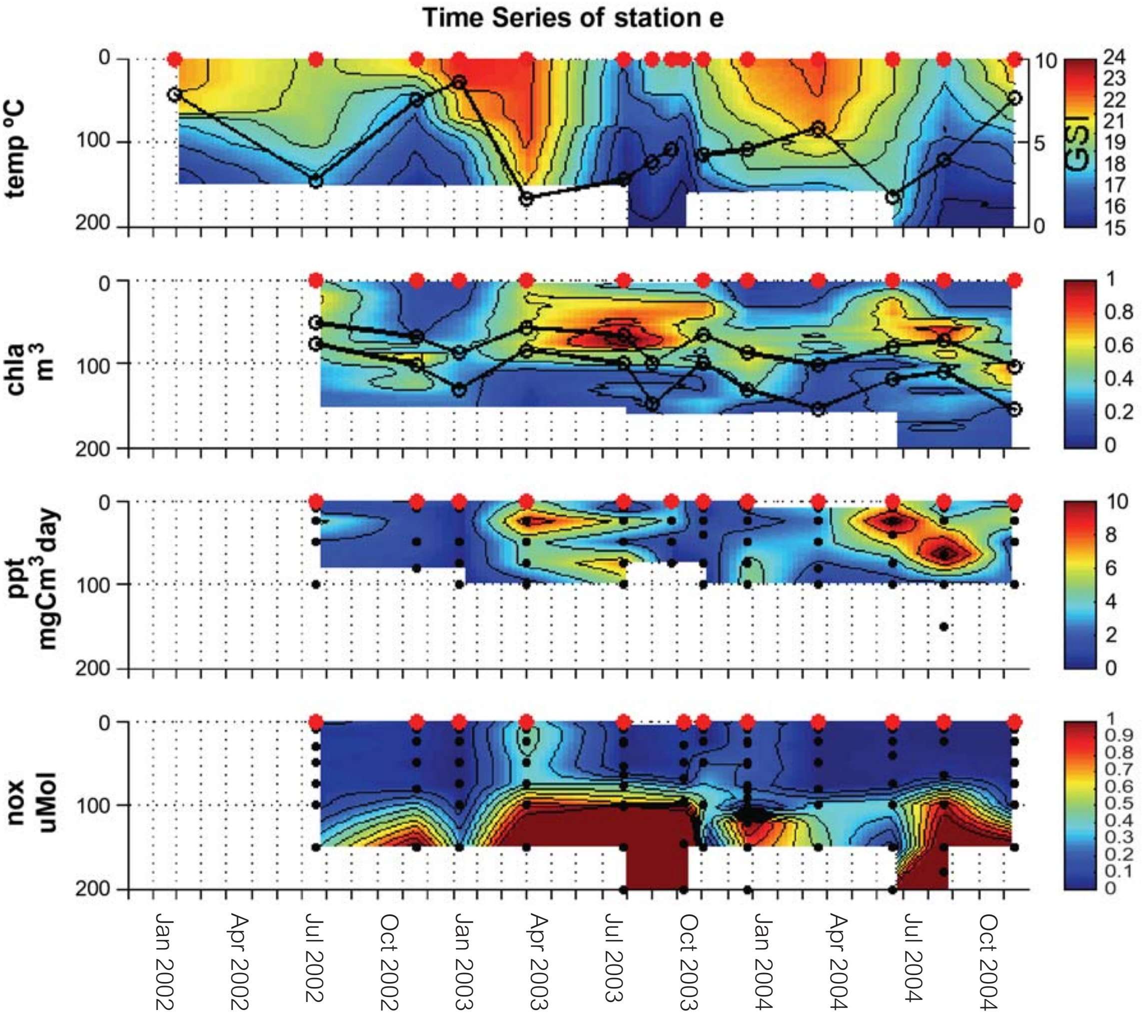


Figure 57: Time-series of temperature (upper panel), chlorophyll concentration (second panel), primary productivity (third panel) and nitrate/nitrite (bottom panel) at station E derived from the quarterly CTD casts and bottle samples over the 3-year sampling period. The solid line in the temperature series is the Gross Stratification Index (defined in the text), and the two lines in the chlorophyll panel show the depths of the 1% and 0.1% light levels from the PAR sensor. The solid dots in the lower 2 panels show the bottle sampling depths.

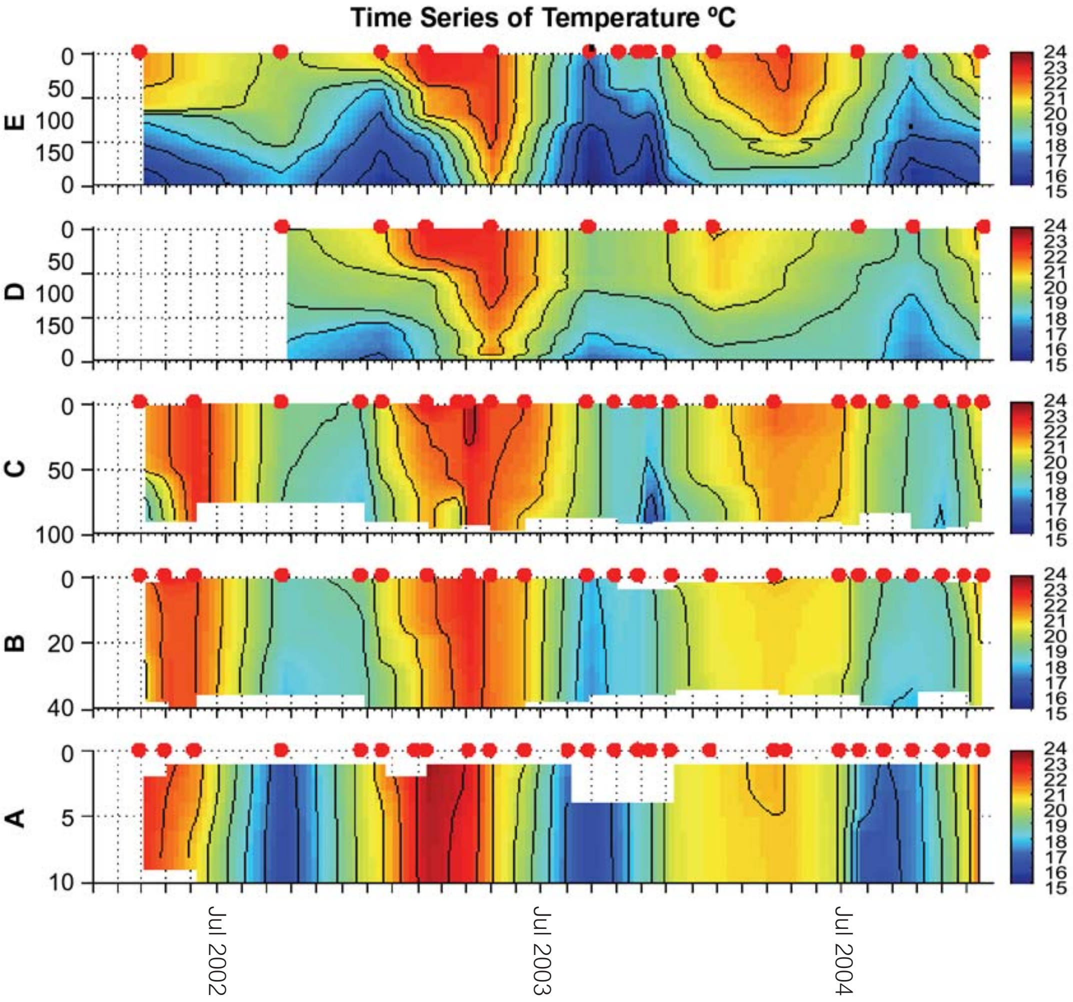


Figure 58: Time-series of temperature at the CTD stations E to A over the 3-year sampling period. Note the variable depth scale.

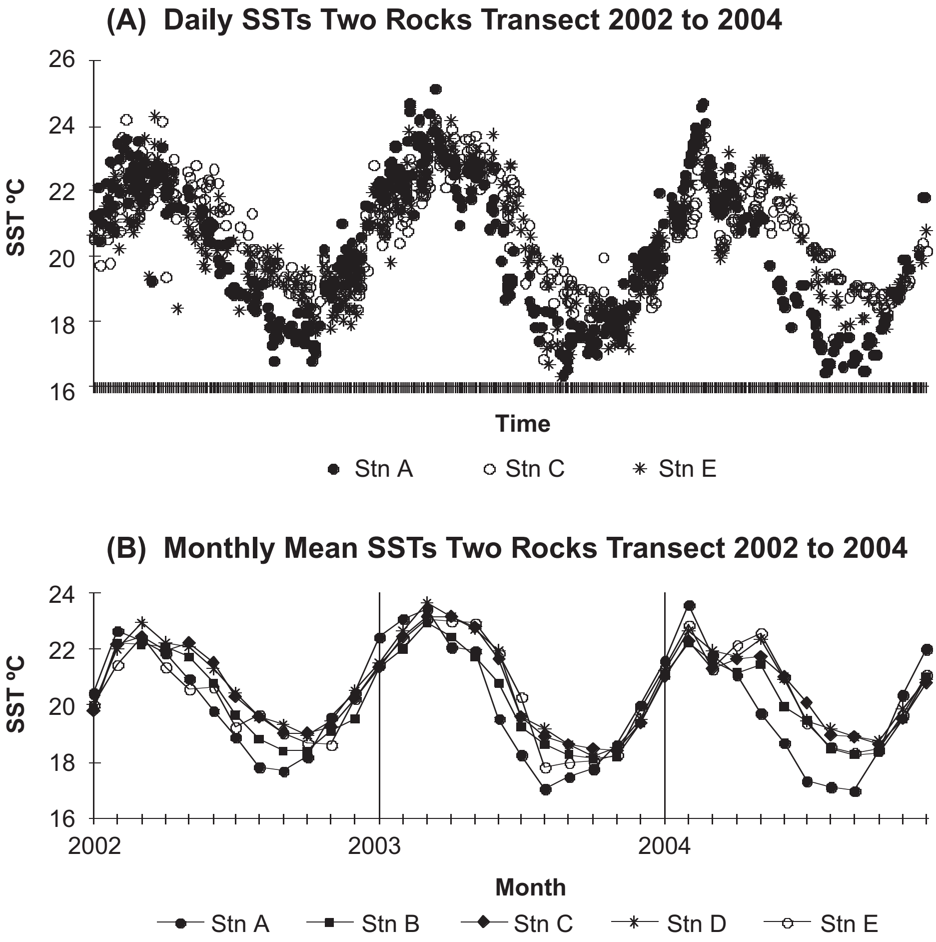
Chlorophyll *a* concentrations have been derived from the SeaWiFS data using the standard SEADAS algorithm for so-called 'Case 1' waters in which the water colour is dominated by phytoplankton (generally representative of open-ocean conditions). Because of penetration of the water column by the visible wavelengths, the derived chlorophylls are representative of the near-surface layer down to some 20 or 30 m depth. This raises the issue of 'shallow-water' effects, where some of the reflectance received by the satellite in shallow coastal waters is from the seabed, while other signal is from suspended sediment in the water ('Case 2' waters). The chl *a* concentrations derived for water less than about 30 m deep (such as Stn A) are therefore likely to be artificially enhanced. For the same reason, only the chlorophyll in the upper 20 to 40 m of the water column is sampled by the satellite and so any deeper chlorophyll maximum layers will not be included.

Time-series concentrations at the Two Rocks stations have been extracted from the SeaWiFS dataset for the period 1998 to 2004 in a similar way to the SSTs. Validation of the satellite chlorophyll levels against *in situ* water samples taken during the boat surveys is described in the Remote Sensing Section of this report.

The chlorophyll *a* levels were generally low, typical of southwestern Australian coastal waters (Department of Environmental Protection 1996, Pearce *et al*. 2000, Pearce *et al*. submitted, Fearns *et al*. submitted). There was a high degree of variability in the individual daily chl *a* levels (Fig. 60), to some extent reflecting natural phytoplankton patchiness in both time and space but also the inherent accuracy limits of the chlorophyll algorithm. As explained earlier, the apparently elevated chlorophyll levels at station A, which is in about 20 m water depth, may be artificially high due to seabed reflectance and the presence of Case 2 waters. It should be borne in mind that these interim daily values have not yet been fully 'quality-controlled' and so some of the spikes may not be real and may therefore bias some of the discussion below.

Monthly mean chl *a* concentrations were averaged from the daily values in each month. There was a clear seasonal pattern across the shelf with peaks during the winter months, and a steadily decreasing concentration with greater distance offshore (Fig. 61). The overall mean concentration at the mid-shelf station B was over 0.6 mg m^{-3} chl *a* in June, falling to 0.2 mg m^{-3} during the summer months. Offshore in the Leeuwin Current (stations D and E), corresponding values were 0.3 to 0.4 mg m^{-3} (winter peak) and about 0.1 mg m^{-3}.

Despite the high degree of daily (and monthly) variability, there was evidence of interannual variability as well although the changes were not always consistent across the shelf. Ignoring station A for the reasons given above, the winter concentration at station B (mid-shelf) rose substantially during the winters of 2002 to 2004 although the lower summer values were more consistent over the whole period. There was little change at station C apart from a slightly lower chl *a* level in winter 2003. Station D encountered elevated concentrations in the winters of 2002 and 2004, while at the outermost station E the peaks were in 1999 and 2004. Because of this inconsistency across the shelf (and the present uncertainties in the data), it is difficult to relate these interannual variations to the annual ENSO and sealevel events discussed below. Once the quality control has been finalised, any real relationships may be clearer.



(A) Daily SSTs Two Rocks Transect 2002 to 2004

(B) Monthly Mean SSTs Two Rocks Transect 2002 to 2004

Figure 59: a) Daily AVHRR SSTs (cloud-permitting) for the Two Rocks stations A, C and E between 2002 and 2004, and b) the mean annual sea-surface temperature cycle at the Two Rocks stations derived from the AVHRR.

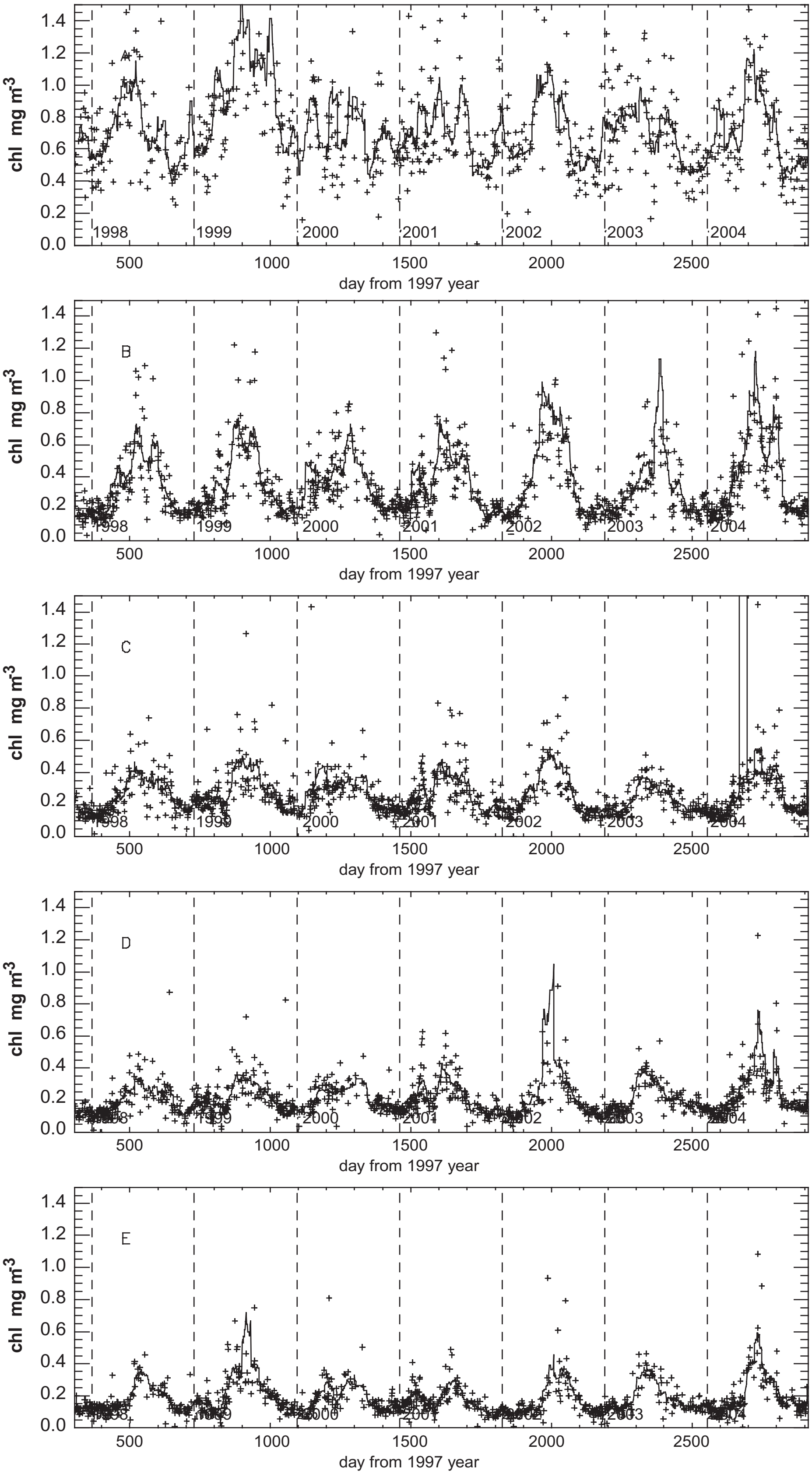


Figure 60: Daily SeaWiFS chlorophyll concentrations at the Two Rocks stations A (top panel) to E (bottom panel) between 1998 and 2004 (cloud permitting). The solid line is a 31-day moving average. There are some as yet unedited “spikes” in the data which require quality control.

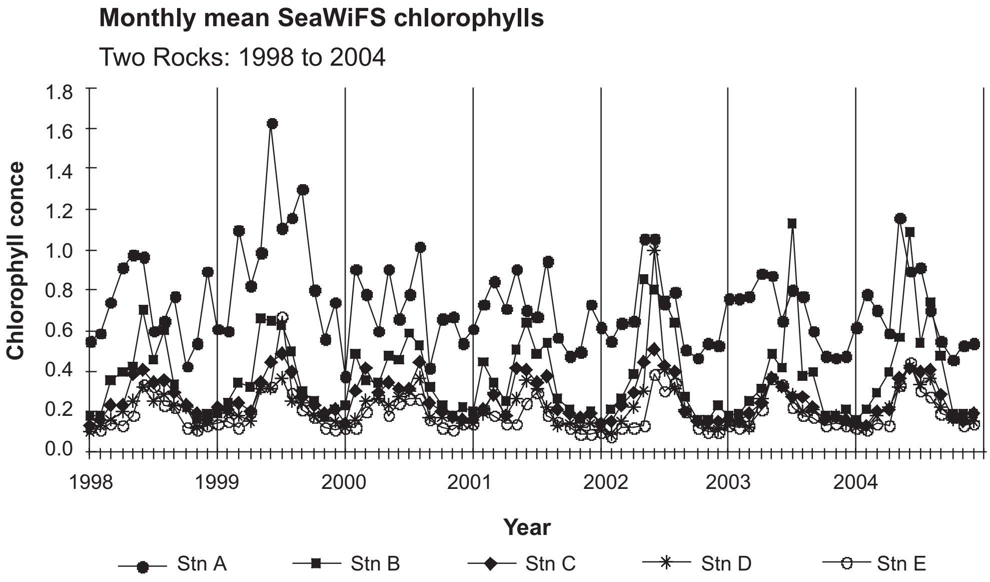


Figure 61: Monthly mean near-surface chlorophyll concentrations at the Two Rocks stations derived from daily SeaWiFS data between 1998 and 2004.

5.5.2 Phytoplankton dynamics

One objective of the SRFME Biophysical Oceanography Program was to determine spatial and temporal patterns of variability in phytoplankton biomass, production and community composition. To that end, S. Pesant *et al.* (C. Hanson, F. Verspech and A. Waite) participated in all SRFME Biophysical cruises in order to determine these parameters, using standard methods (e.g. JGOFS protocols). These included size-fractionated measurements of phytoplankton biomass (as both chlorophyll *a* and particulate organic carbon), primary production (using the ^{14}C-uptake method), and sediment flux measured using drifting sediment traps. Phytoplankton community composition was quantified with two methods: traditional cell counts (using light microscopy) on samples preserved in acidic-Lugol's solution; and detailed pigment analyses (using High Performance Liquid Chromatography; HPLC) on phytoplankton collected on glass-fibre filters. Chemotaxonomy software (CHEMTAX) was used to identify the proportion of nine taxonomic groups based on the ratios of pigment markers.

For the phytoplankton study, a total of 102 stations were sampled in the course of 27 cruises. At each station, up to 7 depths were sampled to describe the vertical distributions of these parameters, for a total collection of 508 water samples. Results obtained by our group contributed to several presentations by Pesant, Koslow and Hanson, and will lead to several publications in peer-reviewed international journals.

Below, we discuss important methodological aspects that must be considered before using the biomass and production data reported in the SRFME Biophysical database. We also present key results and discuss their implications.

5.5.2.1 Biomass and primary production – methodological considerations

Conversion of fluorescence to chlorophyll *a*

The conversion of fluorescence to chlorophyll *a* has been determined with care using data from all cruises (Figure 62). The predicted values of chlorophyll a concentration (in mg m^{-3}) = 0.0361 +1.1636*fluorescence (in volts). The upper and lower prediction limits were computed separately due to the asymmetry of the spread around the predictive regression. The latter should be used for display purposes only, whereas the prediction limits should be used in computations or modelling exercises to consider a range of values.

The upper predicted limit for chlorophyll *a* concentration (in mg m^{-3}) is given by:

$$-0.0361+1.1636*\boldsymbol{fluorescence}+2.6650*\sqrt{0.0069*(1+1/66+((\boldsymbol{fluorescence}-0.3838)^{2}/2.3037))}$$

The lower predicted limit for chlorophyll *a* concentration (in mg m^{-3}) is given by:

$$-0.0361+1.1636*\boldsymbol{fluorescence}-2.6330*\sqrt{0.0025*(1+1/89+((\boldsymbol{fluorescence}-0.3749)^{2}/3.7920))}$$

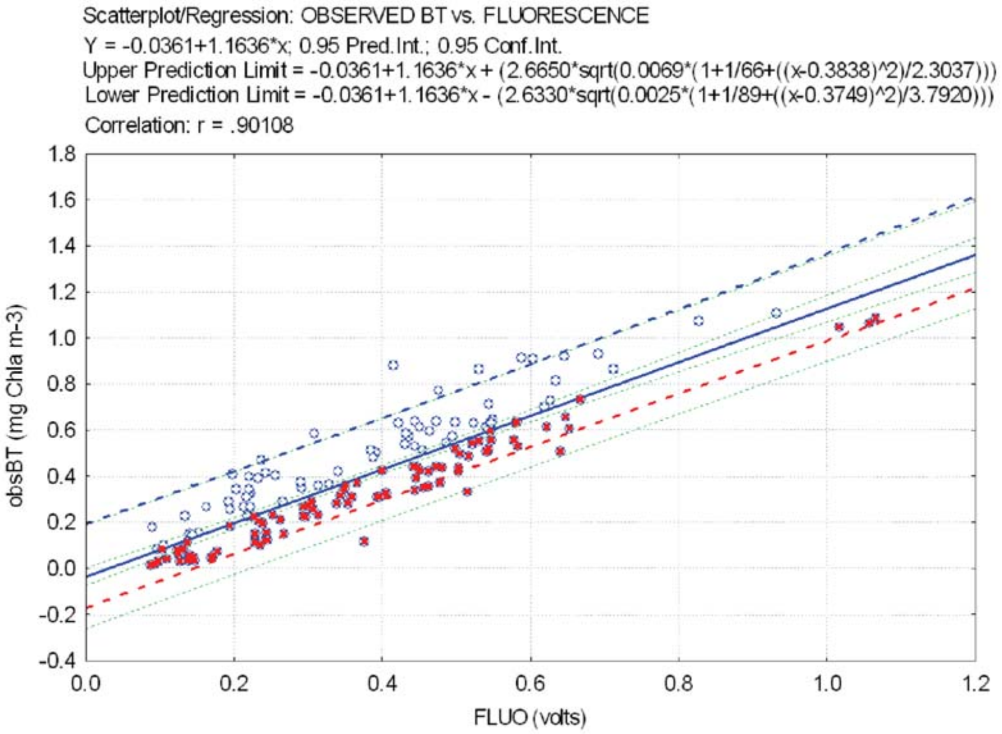


Figure 62: Regression (y = -0.036 + 1.164x) used to convert fluorescence measured on the rosette sampler (FLUO in volts) to chlorophyll *a* (obsBT in mg Chla m^{-3}). Upper (blue) and lower (red) prediction limits were computed separately due to the asymmetry of the spread.

Uncertainties in primary production data – simulated *in situ* irradiance and temperature

A first source of uncertainty in primary production data has to do with the method used to incubate the samples. Instead of conducting *in situ* incubations where samples are returned to their depth of origin in sealed bottles on moored lines for the duration of incubation, we incubated samples on deck using shades to simulate *in situ* irradiance conditions and using running water, pumped from 2-5m below surface, to regulate temperature inside the incubator (Fig. 63). The former method is often used in shallow seas while the latter is the preferred method in high seas where moored lines are not convenient. Furthermore, the sampling schedule of SRFME cruises did not allow a return to the sampling site to recover moored lines after 24h incubations.

The transmittance spectrum of each coloured shades used on the incubator are shown on Figure 64. Over the range of wavelengths that are absorbed by chlorophyll *a*, these compare well to the spectra of light transmittance described by Jerlov (1976) for type I oceanic waters. Therefore, light conditions in the incubator are of little concern. On the other hand, temperature was sometimes a concern when the flow of water circulating in the incubator varied. Temperature was monitored regularly and the flow adjusted accordingly. At a few occasions the flow completely stopped for several hours, in which case results were discarded.

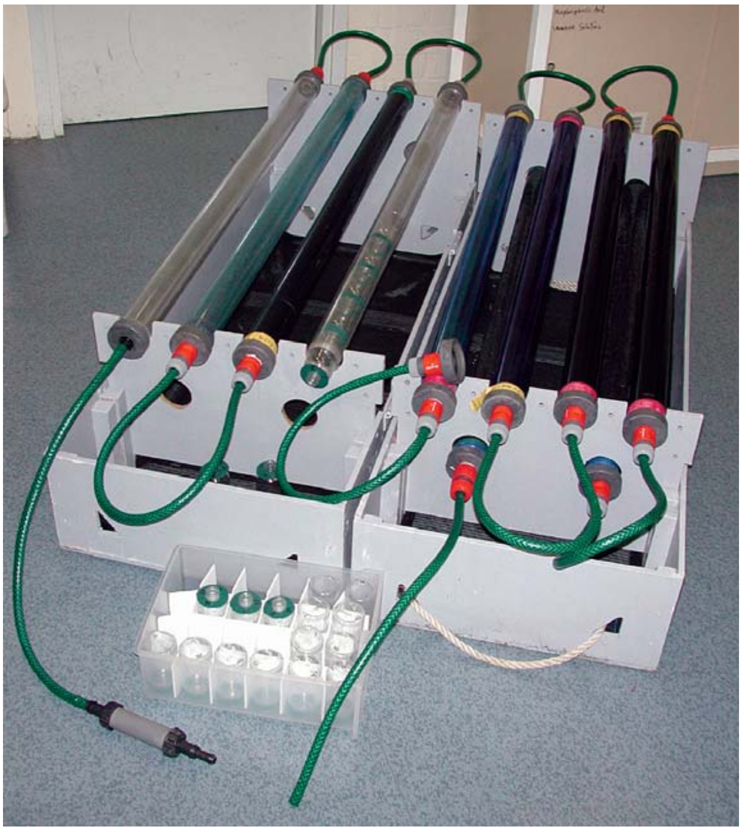


Figure 63: Picture of the simulated *in situ* irradiance deck-incubator.

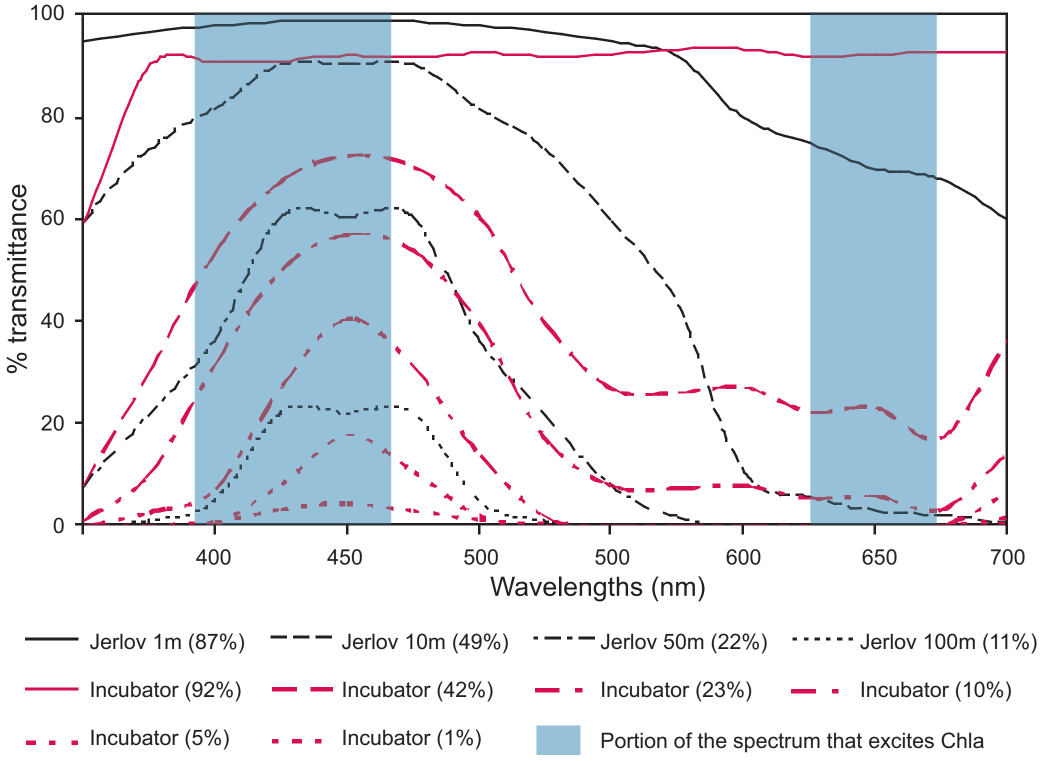


Figure 64: Comparison of the transmittance spectra for the coloured shades used on the incubator and those predicted by Jerlov (1976) for oceanic type I waters.

Uncertainties in primary production data – reporting the particulate fraction

It is standard practice to measure primary production by collecting particulate matter on filters at the end of incubations and to measure the amount of labelled carbon (^{14}C or ^{13}C), nitrogen (N) or oxygen (^{18}O). We used C as a label for our experiments because of the lower costs involved and mainly because of the lesser volumes of sample required. In addition to the standard measure of “total particulate” primary production, we size-fractionated primary production by separating ‘large’ from ‘small’ phytoplankton, using a size threshold of 5 µm. This size cut-off is meant to separate groups of phytoplankton that are functionally distinct, notably diatoms, silicoflagellates and haptophytes from small flagellates and cyanobacteria. These three particulate fractions of primary production are reported in the SRFME Biophysical database.

More recently, scientists have measured the fraction of primary production that ends up in the form of dissolved organic matter, hence called “dissolved” primary production. That fraction originates from phytoplankton exudation, autolysis, viral lysis and from sloppy feeding by micro- and meso-zooplankton. The latter group of zooplankton is of little concern here as they are rarely present in incubation bottles. Dissolved production is documented to sometimes exceed particulate primary production. In addition to particulate primary production, we have measured dissolved primary production at every station. The latter measure generally exceeded particulate production by a factor of up to 4.2 (Fig. 65) although in 70% of all experiments, that factor was less than 2. Thus, values of particulate primary production reported in the SRFME Biophysical database are generally underestimating primary production. These are however comparable to most primary production data reported in the literature since dissolved production is not yet a standard measure. Dissolved primary production values can be obtained from S. Pesant.

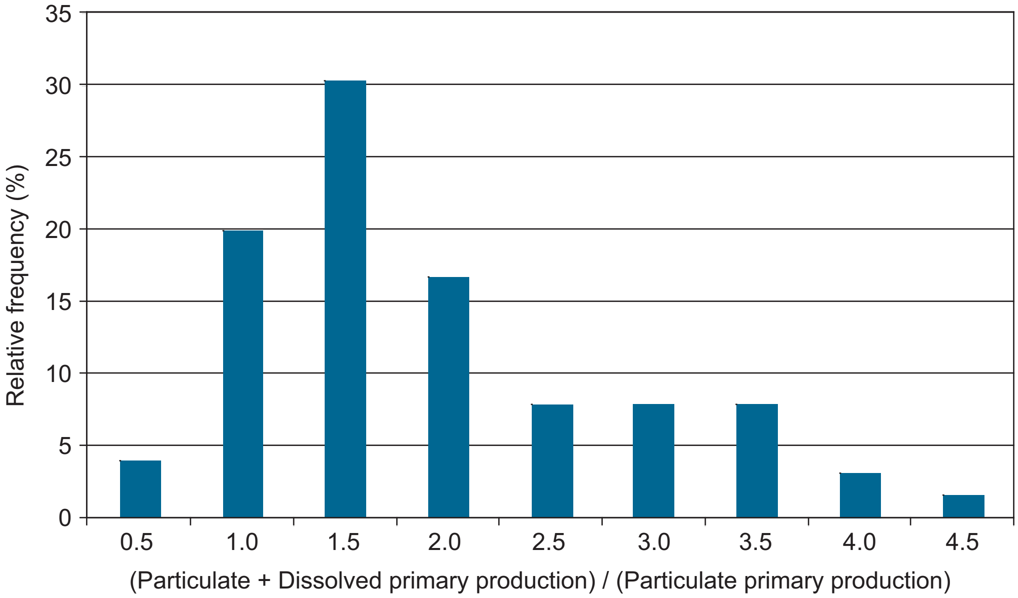


Figure 65: Frequency distribution of the ratio of particulate+dissolved primary production over particulate primary production for all primary production experiments done as part of the SRFME biophysical programme. This ratio indicates the extent to which primary production reported in the SRFME database could be underestimating the total amount of carbon fixed by phytoplankton.

Uncertainties in primary production data – converting to hourly values

Some modelling exercises require hourly or 12h day time rate of primary production. It is common practice to obtain these estimates from 24h (dawn-to-dawn) incubations, but that conversion is not straight-forward since part of the carbon taken-up during day time is respired during night time, hence the term 'net' as opposed to 'gross' primary production. The daily cycle of carbon uptake is exemplified in Figure 66 and shows extremely low to negative uptake (i.e. net respiration) during night time at stations A, C and E. These results indicate that 12h day time rates are higher than 24h rates by a factor 2.0 to 4.3. To obtain hourly rates, we recommend first converting 24h rates to 12h rates using these factors, and then applying a factor 1/10 to 1/12 depending on the photoperiod.

Uncertainties in primary production data – grazing during incubations

The last source of uncertainty addressed here concerns the presence of grazers in the incubation bottles, notably heterotrophic protozoa (ciliates, nano- and dino-flagellates). Their presence may affect primary production measurements. A large portion of ingested primary production remains in the particulate matter and hence is included in our measure of primary production. On the other hand, a relatively smaller fraction is respired by grazers and hence lost from our measure of primary production. Therefore, primary production reported in the SRFME database is net of phytoplankton and protozoa respiration.

Finally, grazing may shift primary production from one size fraction to another. Large size protozoa that feed on small size phytoplankton would, for example, shift part of primary production from the 'small' to the 'large' size fractions. Likewise, sloppy feeding or exudation by protozoa would increase the proportion of 'dissolved' primary production. These uncertainties are difficult to assess but we performed a series of dilution experiments (Fig. 67) that demonstrate the possible impact of these processes at stations A, C and E.

At all stations, 'large size' primary production is enhanced by 10-25% when grazing is reduced or conversely, 'large size' primary production is repressed by grazers naturally occurring in the sample. The same can be said of 'small size' primary production at station A. These result suggest that, in spite of their 'large' size, diatoms and haptophytes along the Two Rocks transect may be food items to protozoa. Losses to protozoa respiration and to the "dissolved" fraction may also explain in part these results.

In contrast, at stations C & E, 'small size' primary production is repressed by ca. 50% when grazing is reduced or conversely, "small size" primary production is enhanced by grazers naturally occurring in the sample. One explanation for this surprising result is a very tight coupling between nutrient uptake by 'small size' phytoplankton and nutrient recycling by grazers. Grazers would then be essential to support primary production by small size phytoplankton at the shelf break and offshore.

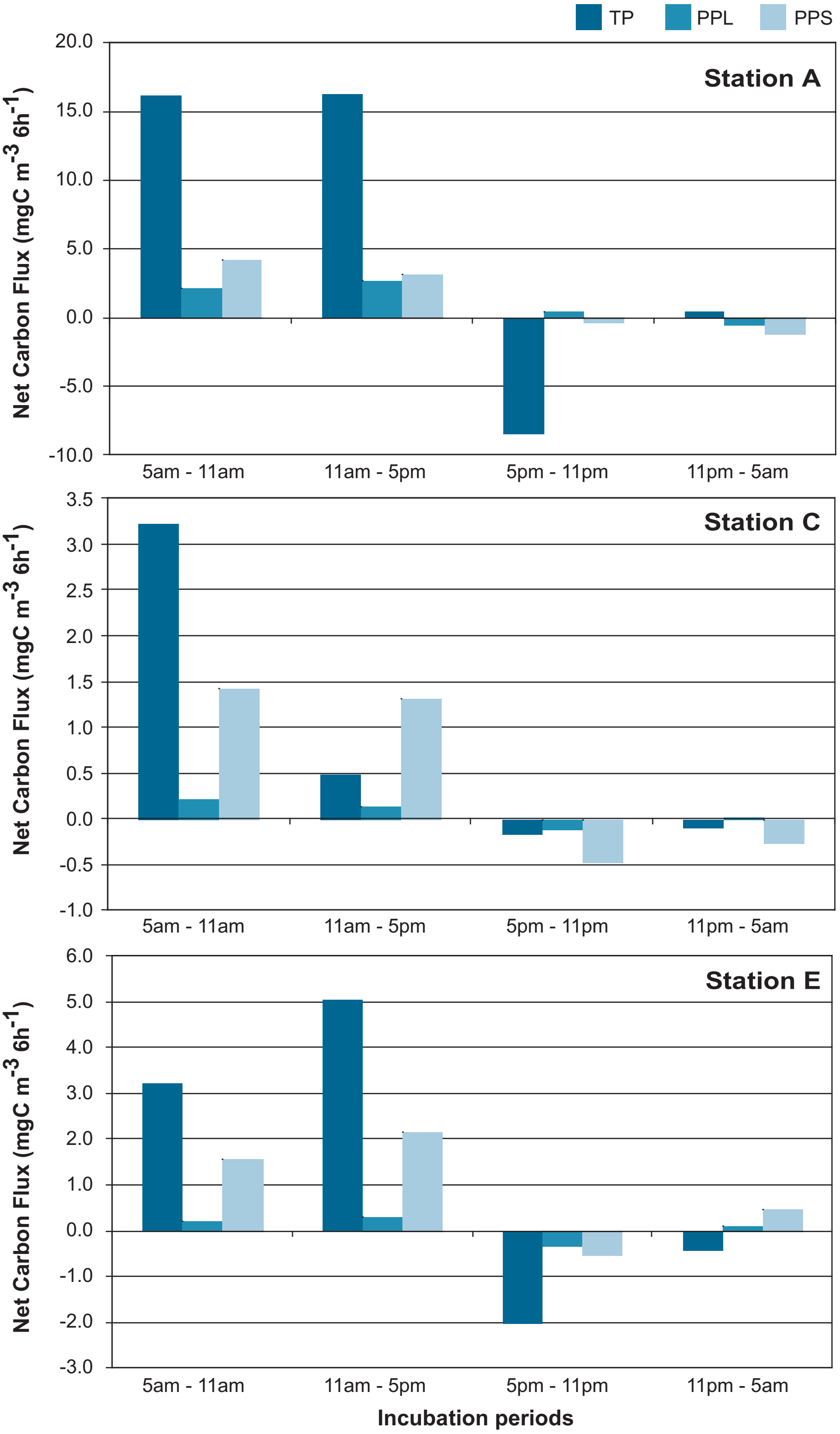


Figure 66: Net carbon flux measured during time series incubations performed in the field during the September 2004 SRFME cruise, using near surface samples from Stations A, C and E. Positive fluxes correspond to a net uptake of CO_2, whereas negative fluxes correspond to a net release of CO_2 by the nano- and micro-planktonic community (i.e. bacteria, protozoa and algae). TP is Total (dissolved+particulate) carbon flux; PPL and PPS are particulate carbon fluxes in the “large” and “small” size fractions.

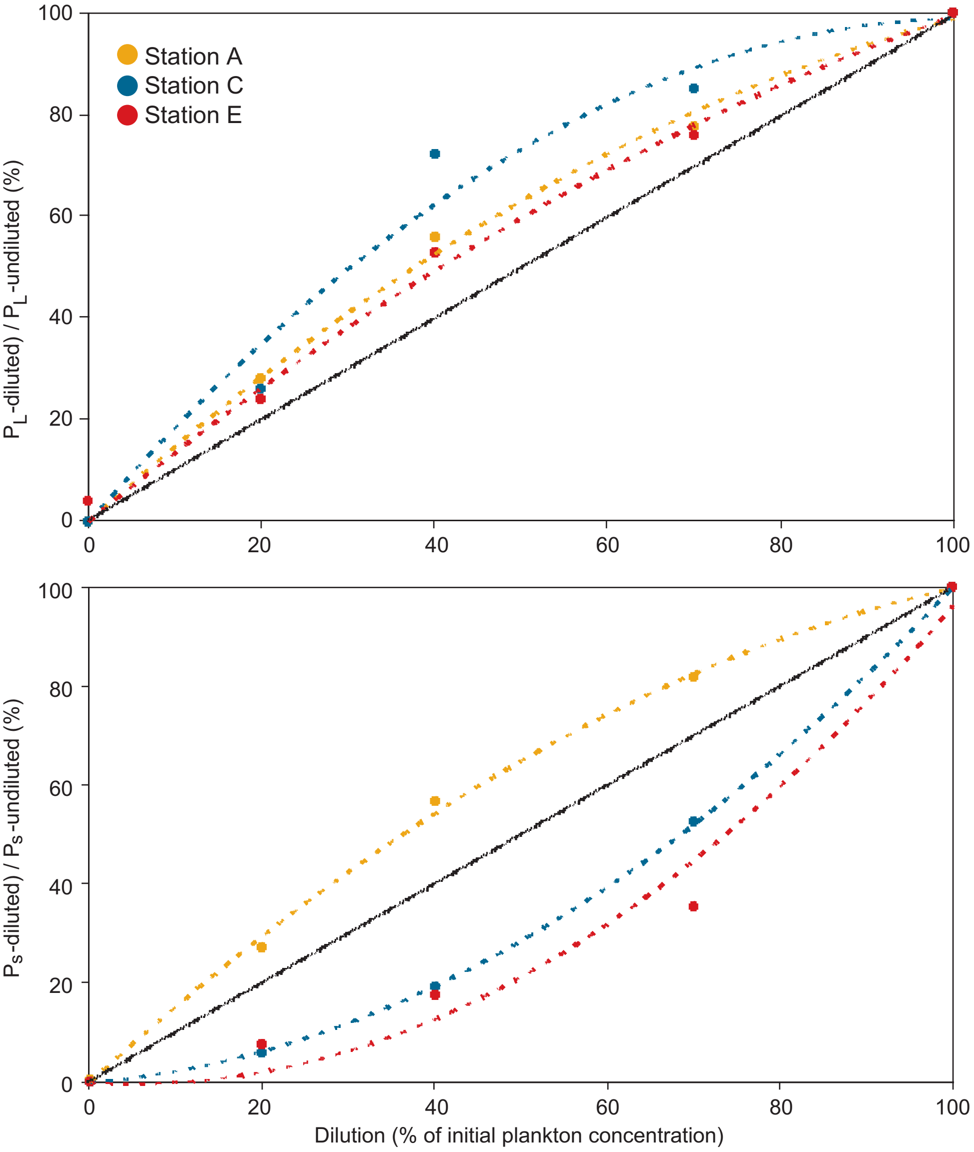


Figure 67: Dilution experiments performed in the field during the September 2004 SRFME cruise using surface samples at stations A, C and E. Samples were treated as regular primary production samples. Primary production is expressed as % of primary production in the undiluted sample. Top: 'Large size' primary production; Bottom: 'Small size' primary production.

5.5.2.2 Results and discussion

Phytoplankton biomass and production

In an attempt to summarise the data reported in the SRFME database, mean values of depth-integrated phytoplankton biomass (BT in mg Chl*a* m^{-2}) and production (PP_T in mg C m^{-2} day^{-1}) were computed for each month of the year (Table 8). Annual estimates of depth-integrated phytoplankton production (g C m^{-2} $year^{-1}$) were also computed for 2002, 2003, 2004 and for the three years combined (Table 9). To provide reference values for the inspection of temporal patterns in primary production, we also present annual mean values of daily phytoplankton production, computed simply as « annual value / 365 days » (Table 9).

Annual phytoplankton production is 2-3 times higher on the shelf and offshore compared to the lagoon (Table 9). This of course does not include primary production associated with the benthos in the lagoon, which can considerably exceed phytoplankton production and is an important source of nutrient and organic matter for the pelagic community. Linkages between the SRFME Biophysical and Benthic (Coastal) Programs are essential to address the marine ecosystem in the lagoon. Annual phytoplankton production also shows that 2002 was less productive (Table 9), perhaps in response to El Niño conditions as discussed by Koslow *et al*. at the SRFME symposium.

A closer look at the annual cycle of phytoplankton biomass reveals that monthly mean values are considerably higher on the shelf and offshore during the autumn and winter months, but are comparable to those found in the lagoon during the summer months (Table 8; Fig. 68). In contrast, phytoplankton biomass remains relatively unchanged in the lagoon throughout the year and ‘large size’ phytoplankton are not persistent in the lagoon, but occur rather episodically (Fig. 69). However, in general, the small size fraction (< 5 µm) increased in dominance of both biomass (as mg chl *a* m^{-2}) and primary production (as mg C m^{-2} d^{-1}) from inshore to offshore regions (Fig. 70).

Temporal patterns in phytoplankton particulate production are more obscure. Annual mean daily production values from Table 9 provide a visual reference for the inspection of these patterns in Figure 71. The data suggest that primary production in the lagoon is higher during spring and autumn months (although a summer peak was observed in 2004; Fig. 72) whereas on the shelf and offshore, primary production is higher from autumn through early spring. Remote sensing should provide better temporal and spatial resolution to address these questions, given that its products are validated with *in situ* measurements such as those presented here. The greatest challenge in this respect is to link surface chlorophyll *a* to integrated primary production, thus resolving the vertical distributions of phytoplankton processes. Depth integrated chlorophyll *a* biomass can be predicted quite nicely by surface values at station E, but we lose confidence in the relationship as we move inshore (Fig. 73). Generally, relationships between surface chlorophyll *a* and depth integrated primary production were not significant (not shown). Further efforts to resolve the vertical distributions of phytoplankton processes will be made using 24h P vs. I curves that were conducted since August 2002.

Phytoplankton community structure

The microscopy and chemotaxonomy results each illustrated important, but somewhat different, features of phytoplankton community composition. Only results to August 2003 will be discussed in this interim report, as the remainder of the HPLC samples are currently being processed. High proportions of dinoflagellates, especially in offshore waters during summer, were identified in the cell counts (Fig. 74). The HPLC pigment results revealed that this group was almost exclusively heterotrophic (i.e. lacking in photosynthetic pigments), and therefore most closely affiliated with the microzooplankton community. As further illustrated in Figure 74, there was generally a poor correlation between the HPLC and cell count data. For example, the haptophytes were found to be a significant proportion of the phytoplankton community based on pigments, but were not evident in the cell counts. Additionally, the diatoms generally accounted for a larger proportion of the total community in the cell count data compared with the pigment-based results.

Such discrepancies between chemotaxonomic and microscopic data are not uncommon (Schluter *et al*. 2000), as the former provides an estimate of biomass (as chl *a*) while the latter can only estimate numerical abundance (in the absence of biovolume information), which is generally a poor indicator of biomass especially for small flagellates (Garibotti *et al*. 2003). The HPLC data also allows for the quantification of the full picoplanktonic (0.2 – 2 µm) and nanoplanktonic (2 – 20 µm) size fractions (Jeffrey *et al*. 1999), as compared to the lower size limit of 5 µm for light microscopy. Given the predominance of 'small size' (< 5 µm) phytoplankton in the SRFME region, chemotaxonomy is proving an important tool for evaluating community composition. However, cell count data will continue to provide valuable species-specific information, which is specifically required for developing accurate regional pigment ratios as used in the CHEMTAX program for evaluating HPLC data (Mackey *et al*. 1996).

Preliminary CHEMTAX analysis of the SRFME pigment results were undertaken using ratios representative of 'equatorial species' as given in Mackey *et al*. (1996). Region-specific pigment ratios for southwestern Australia are currently being developed by L. Clementson at the CSIRO Marine Research laboratories in Hobart, and will available shortly. The preliminary CHEMTAX results were examined with hierarchical cluster analysis, using the Bray-Curtis similarity coefficient, to identify groups of stations with similar phytoplankton assemblages. Six main clusters each containing samples with > 75% similarity were identified (Fig. 71). There was a distinct separation of samples based primarily on season and location offshore. In both summer and winter sampling periods, the shelf and offshore stations (C to E) were statistically separate from the inshore and inner shelf stations (A and B), primarily due to high prochlorophyte and unicellular cyanobacteria populations in offshore waters (Fig. 75). A mixed assemblage of small flagellates (including cryptophytes, prasinophytes and chlorophytes) was most prevalent on the shelf, with periodic diatom blooms dominating the cell counts within inshore waters (Fig. 74). Haptophytes were ubiquitous across the transect and throughout the seasons (Fig. 75). These results confirm the importance of 'small size' phytoplankton (especially picoplankton and flagellates) in the overall phytoplankton community composition of the SRFME region.

Table 8. Monthly mean values of phytoplankton biomass (B_T in mg Chl*a* m^{-2}) and particulate primary production (PP_T in mg C m^{-2} day^{-1}) and standard deviations in parentheses for 2002-2004.

	Station A		Station B	Station C		Station D	Station E	
Month	B_T	PP_T	B_T	B_T	PP_T	B_T	B_T	PP_T
Jan (1)	5.3 (----)	243.7 (----)	2.7 (----)	13.9 (----)	434.4 (----)	20.9 (----)	32.0 (----)	316.5 (----)
Feb (2)	11.6 (7.1)	70.1 (43.0)	7.9 (1.5)	25.7 (2.9)	88.3 (74.0)	28.5 (----)	21.7 (----)	35.3 (----)
Mar (3)	12.3 (4.47)	96.1 (99.6)	32.2 (8.8)	30.4 (6.2)	152.2 (43.5)	n/a	n/a	n/a
Apr (4)	9.1 (7.1)	165.6 (98.9)	23.7 (4.3)	51.4 (0.8)	358.2 (341.9)	29.1 (----)	48.4 (25.1)	385.1 (204.8)
May (5)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Jun (6)	6.0 (2.4)	87.3 (6.1)	27.0 (10.6)	45.7 (0.8)	552.0 (319.3)	n/a	n/a	n/a
Jul (7)	3.2 (0.11)	43.0 (12.5)	40.7 (----)	29.3 (----)	232.3 (----)	24.2 (----)	54.3 (----)	500.2 (----)
Aug (8)	10.3 (10.4)	111.1 (80.6)	32.1 (19.6)	62.2 (17.3)	300.8 (90.5)	61.0 (5.5)	69.6 (7.9)	318.4 (137.4)
Sep (9)	5.7 (----)	148.9 (----)	16.4 (----)	27.0 (----)	369.4 (----)	41.3 (----)	33.2 (4.0)	656.4 (----)
Oct (10)	24.7 (3.8)	233.1 (177.2)	39.0 (----)	24.7 (12.3)	86.6 (51.0)	39.0 (----)	32.2 (----)	93.6 (----)
Nov (11)	6.8 (4.4)	137.0 (67.7)	10.3 (0.8)	35.3 (2.6)	584.7 (135.1)	n/a	35.5 (----)	n/a
Dec (12)	6.0 (4.4)	108.0 (58.4)	11.4 (4.2)	14.8 (4.3)	264.0 (404.8)	35.8 (21.5)	24.5 (15.0)	127.7 (69.4)

Table 9. Estimates of annual phytoplankton particulate production (g C m^{-2} year $^{-1}$) computed by temporal integration of monthly mean values listed in Table 8; Annual mean values of daily phytoplankton particulate production (PP$_T$ in g C m^{-2} d^{-1}) computed as « annual value / 365 days » are in parentheses.

	2002	**2003**	**2004**	**All years combined**
Station A	29.5 (0.081)	63.5 (0.174)	59.3 (0.162)	46.3 (0.127)
Station C	97.7 (0.268)	83.6 (0.230)	158.8 (0.435)	114.5 (0.314)
Station E	---	125.8 (0.345)	140.1 (0.384)	136.2 (0.373)

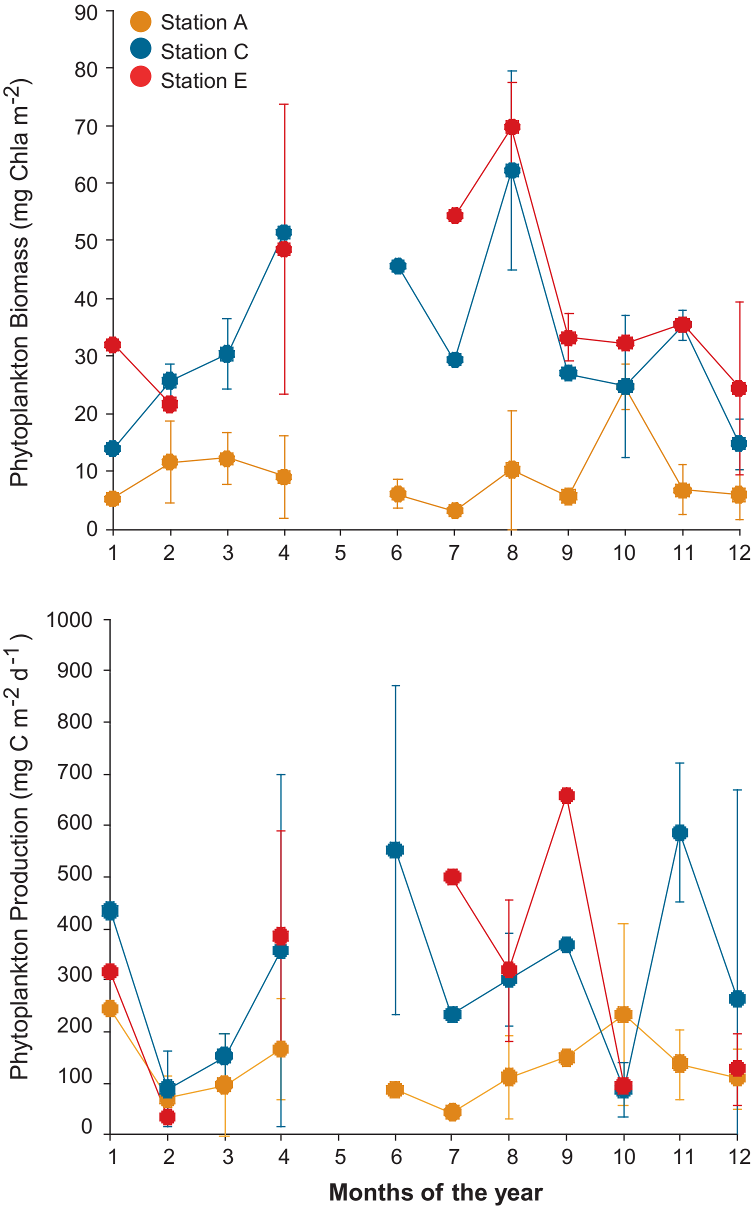
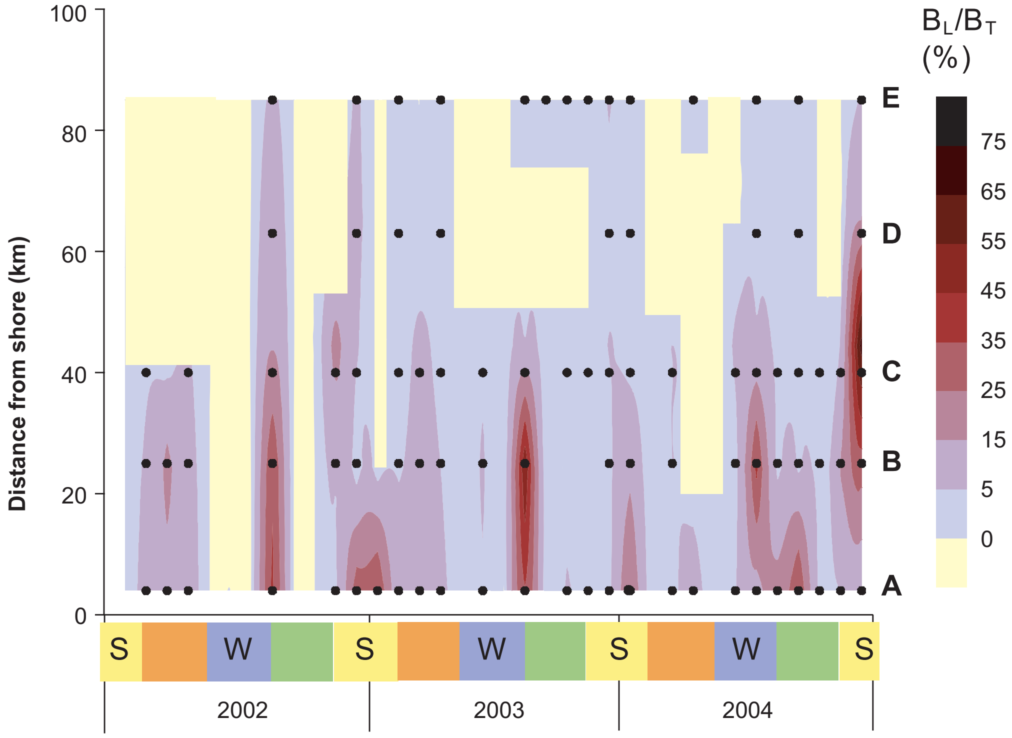


Figure 68: Time series of monthly mean phytoplankton biomass (top; BT in mg Chl*a* m^{-2}) and particulate production (bottom; PP$_T$ in mg C m^{-2} day $^{-1}$) for stations A, C and E. Monthly mean values were computed from all data collected during the SRFME biophysical programme 2002-2004, and are reported in Table 8. Standard deviations are shown as vertical error bars.



Source: S. Pesant unpubl.

Figure 69: Spatial and temporal distributions of phytoplankton for all samples collected near the surface during the SRFME programme 2002-2004. B_L/B_T (%) is the proportion of phytoplankton biomass in the large size (5 μm) fraction. S is summer and W is winter.

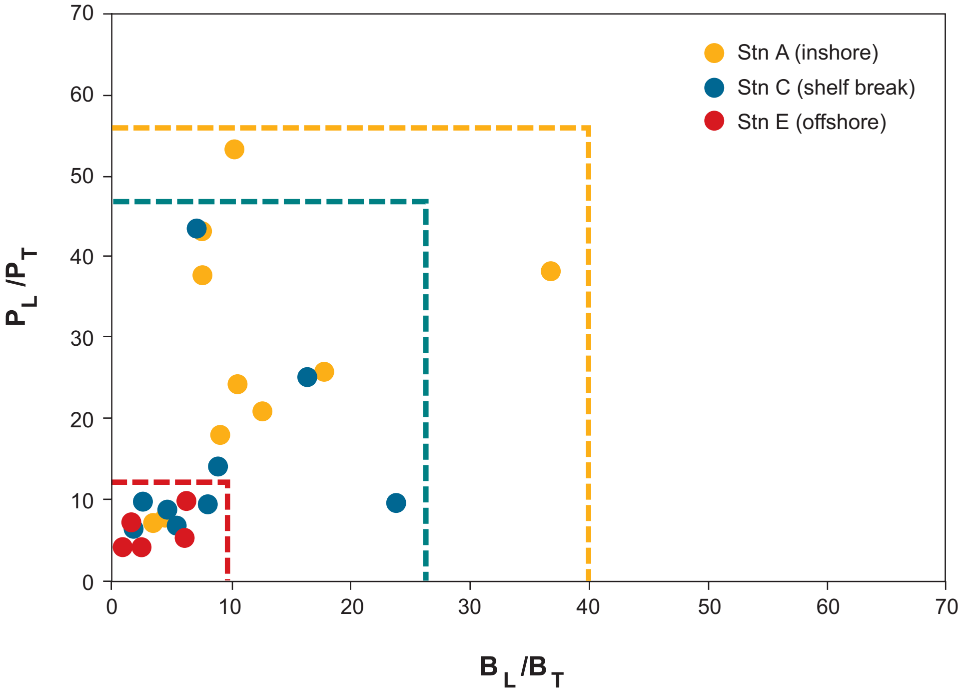


Figure 70: The relative proportion of 'large size' phytoplankton biomass (B_L) and particulate production (P_L) as a function of distance offshore.

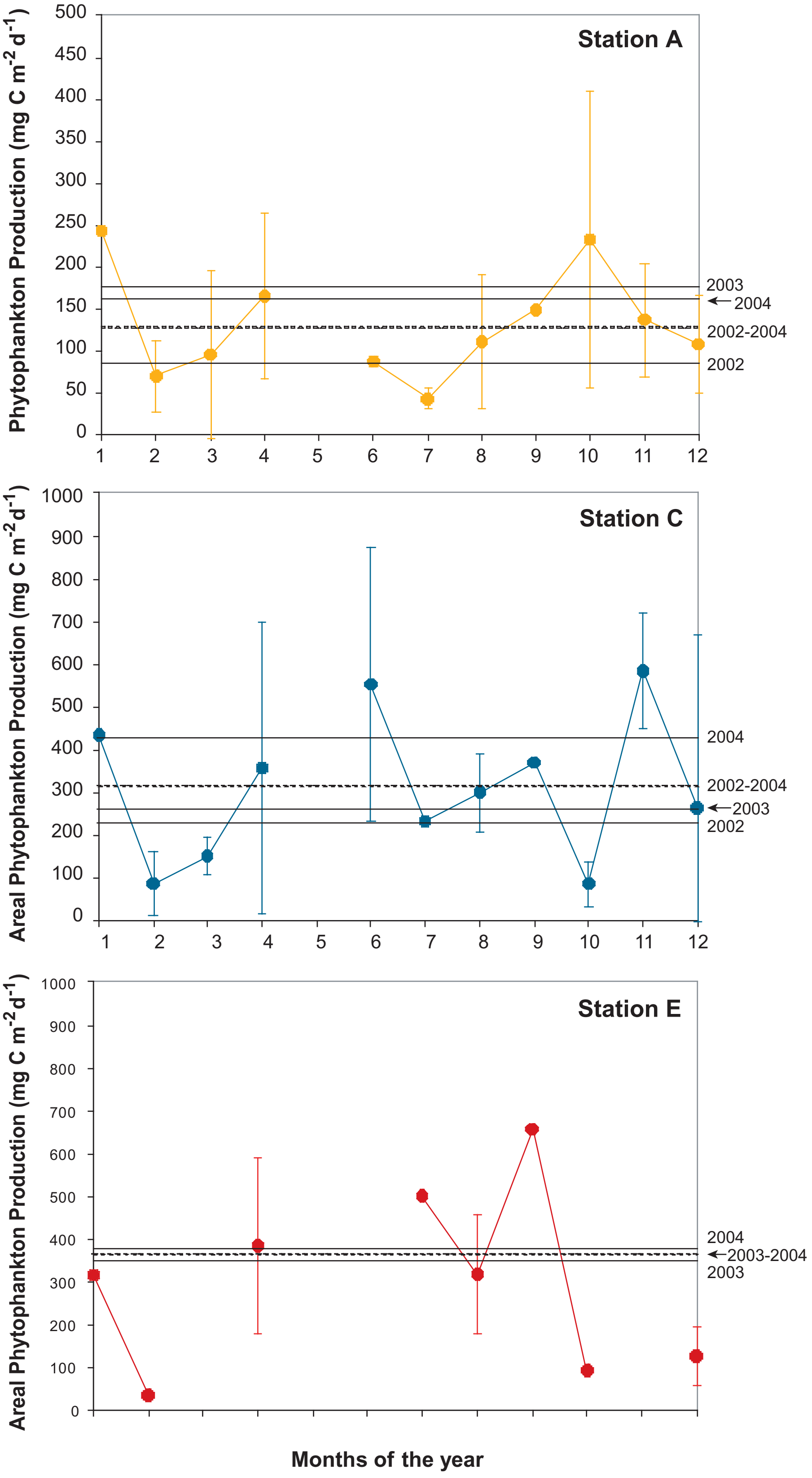
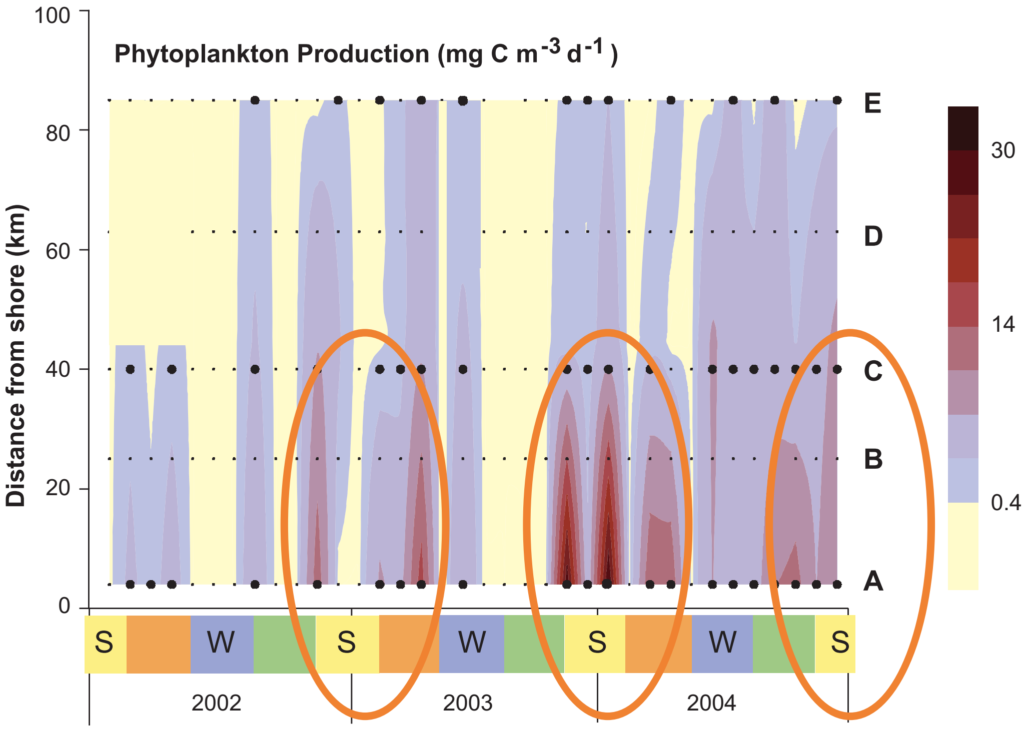


Figure 71: Time series of monthly mean phytoplankton particulate production (PPT in mg C m^{-2} day^{-1}) for stations A, C and E. Monthly mean values were computed as in Figure 64. Standard deviations are shown as vertical error bars. Horizontal lines show annual mean values of daily phytoplankton production as reported in Table 9.



Source: S. Pesant unpubl.

Figure 72: Spatial and temporal distributions of phytoplankton particulate production (PPT in mg C m^{-2} day^{-1}) for all samples collected near the surface during the SRFME program 2002-2004. S is summer and W is winter. Orange ellipses show periods of the year when episodes of high production tends to occur more frequently inshore.

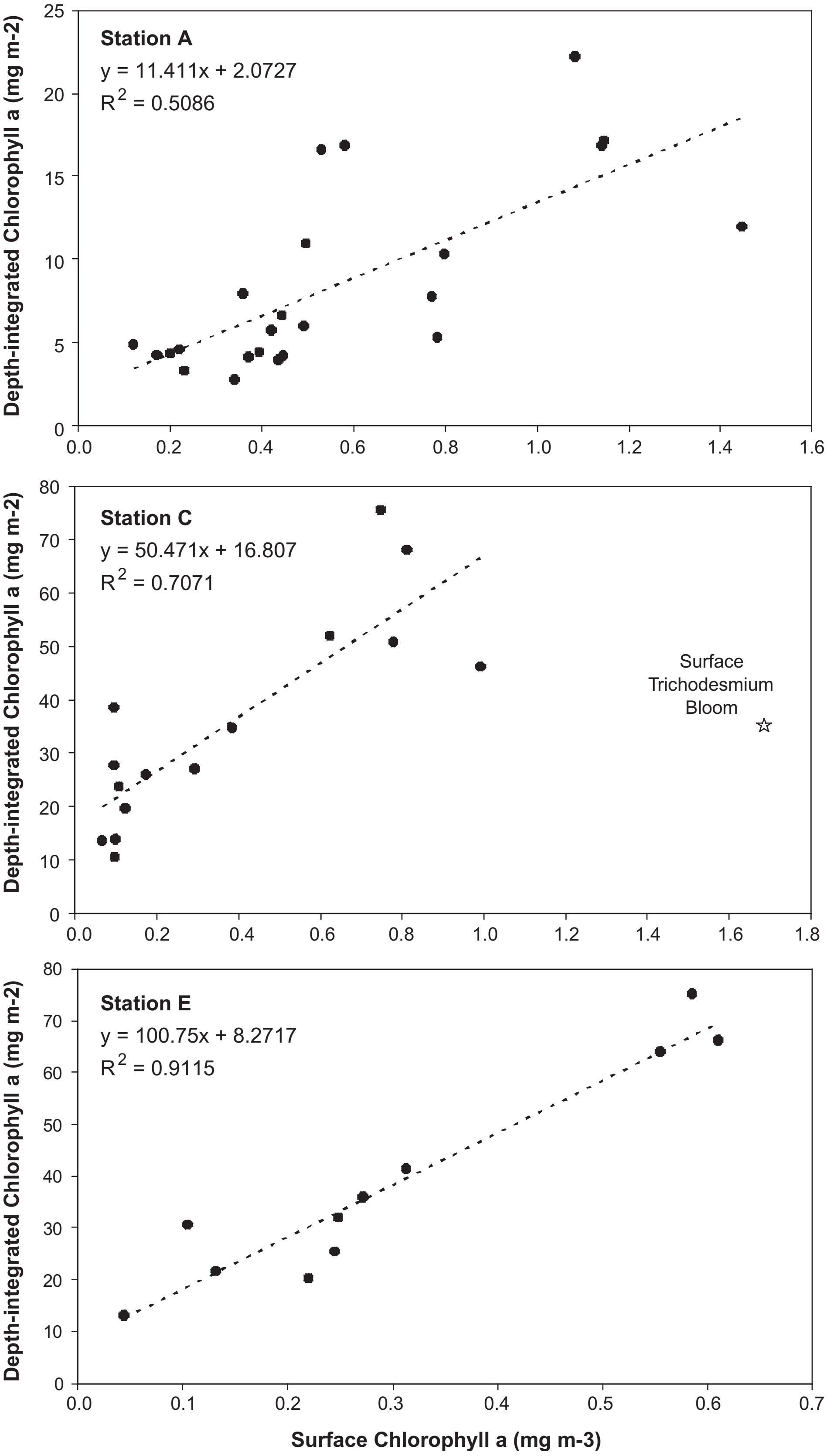
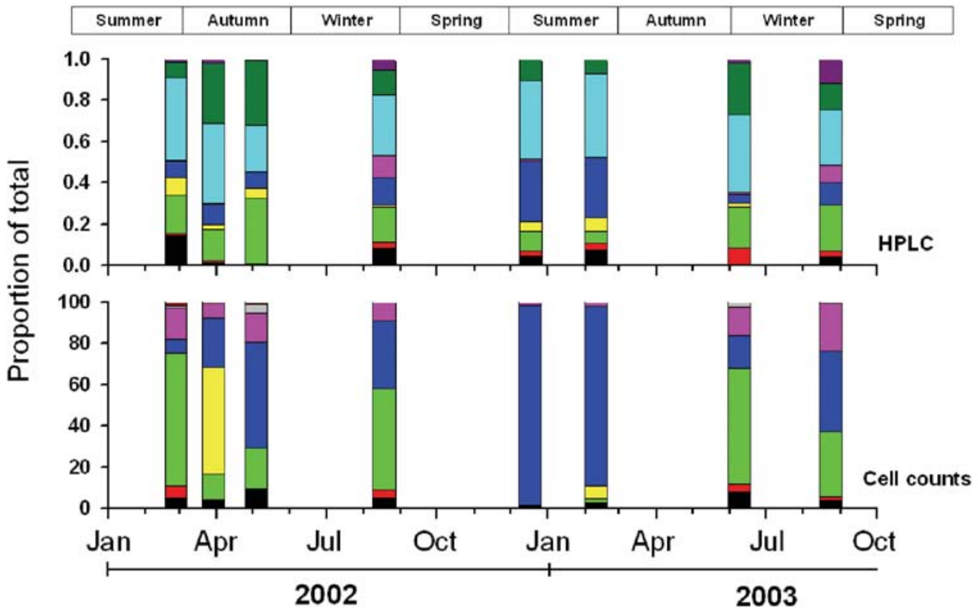


Figure 73: Predictive regressions of depth-integrated chlorophyll *a* biomass (mg Chl*a* m^{-2}) vs. surface chlorophyll *a* biomass (mg Chl*a* m^{-3}) for Station A, C and E. The two parameters were determined from extracted phytoplankton pigments.

a) Station A (inshore waters)



b) Station E (offshore waters)

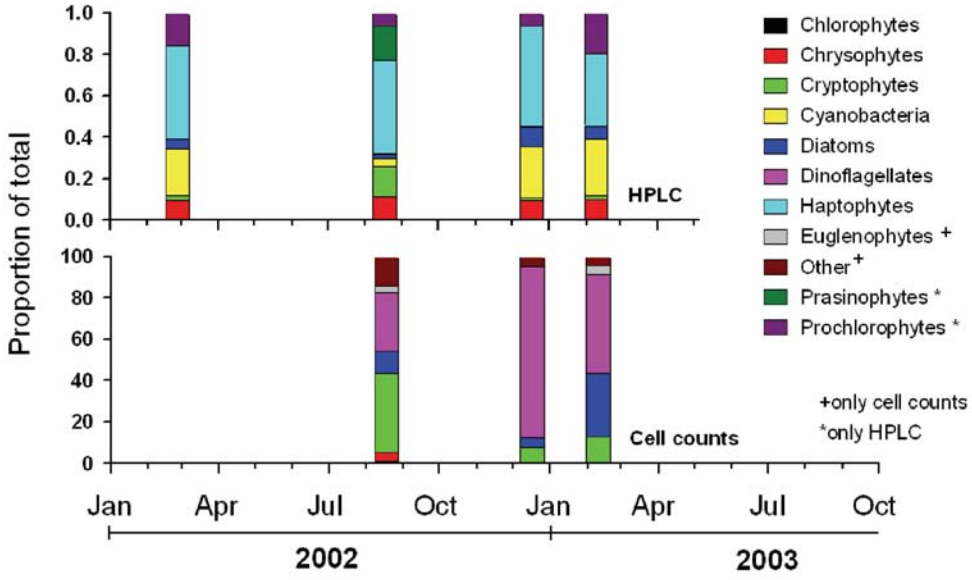


Figure 74: Comparison of phytoplankton community composition (from surface samples) as determined by two methods: detailed pigment analyses using High Performance Liquid Chromatography (HPLC), and cell counts using light microscopy (where dominant genera were identified and counted within eight major taxonomic groups). Results are displayed from quarterly sampling within a) inshore, and b) offshore waters.

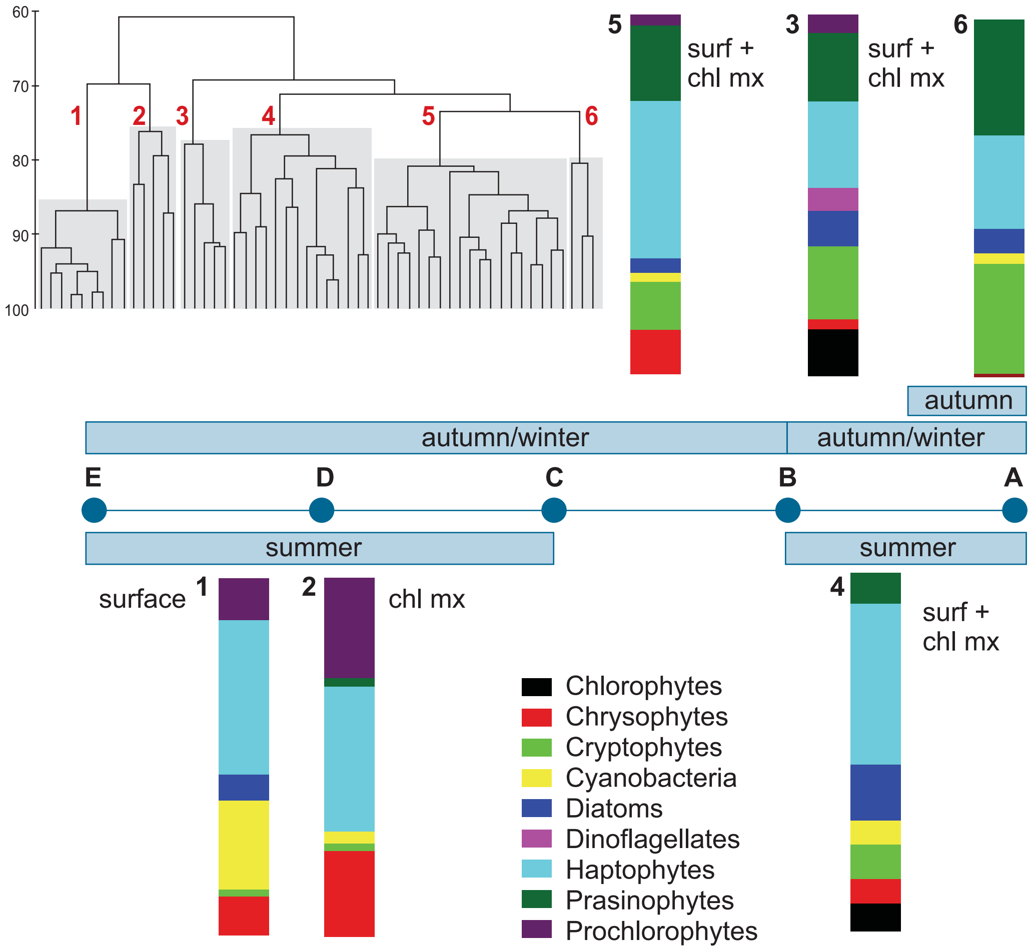


Figure 75: Phytoplankton community composition as evaluated using HPLC pigment analysis and the CHEMTAX program. Cluster analysis identified six main groupings of sample with > 75% similarity. These groups are displayed according to sampling position along the Two Rocks transect (onshore to offshore from Stations A to E) and season collected.

5.5.3 Mesozooplankton dynamics

5.5.3.1 Mesozooplankton communities: abundance and biomass

Introduction

The aim of this component of the zooplankton study is to characterize mesozooplankton communities, their dynamics across the continental shelf and to assess their variability along temporal and spatial scales. It has application to fisheries, managements of protected areas and coastal processes.

Methods

Mesozooplankton were collected at each station along the Two Rocks transect with replicate double-oblique bongo net (60 cm diameter) tows, with 355 µm and 100 µm mesh nets to sample both macro- and mesozooplankton. Biomass was estimated based on measurement of dry weight. The 100 µm tow was split on board, filtered through 80 µm mesh and dried at 60º C to constant weight. The Primer statistical package was used for multivariate analysis. Non-metric Multidimensional Scaling based on Bray Curtis similarity was performed on double square root transformed data. Seasonal and onshore/offshore differences in copepod assemblages were tested with ANOSIM (non parametric simulation/permutation test), and SIMPER was used to determine the species contributing most to seasonal and spatial dissimilarities.

Results

Total abundance of zooplankton ranged from 500 to 12 000 individuals m^{-3} (Fig. 76a). Most of the zooplankton consisted of copepods with abundances ranging from 300 to 10 000 individuals m^{-3} (Fig. 77b). Peaks in copepod abundance occurred in late summer and fall following diatom blooms. There was less difference in abundance between shelf and offshore stations in winter than in summer. Copepods offshore were more abundant in winter than in summer, similar to the abundance of phytoplankton.

Depth integrated abundance peaked in autumn nearshore and on shelf, and offshore abundance was greater in winter than in summer (Fig. 76a).

Zooplankton biomass was estimated as dry weight. In general, volumetric biomass of zooplankton nearshore was higher than at offshore stations (Fig. 77). Biomass was higher offshore in winter than in summer, similar to the abundance of zooplankton. Depth integrated biomass was higher in winter at all stations (Fig 77 a).

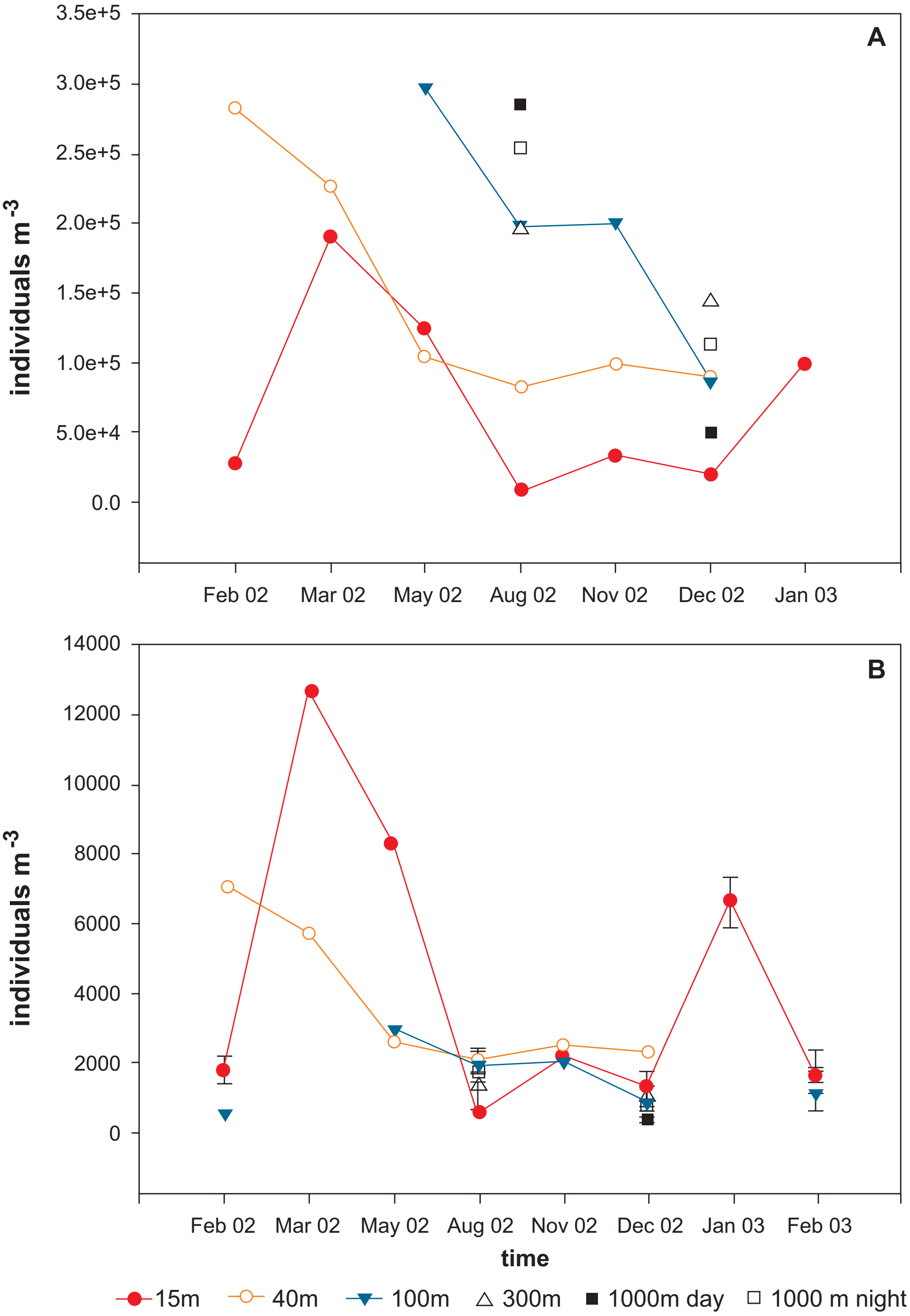


Figure 76: a) Depth integrated abundance, and b) total abundance of mesozooplankton at five stations.

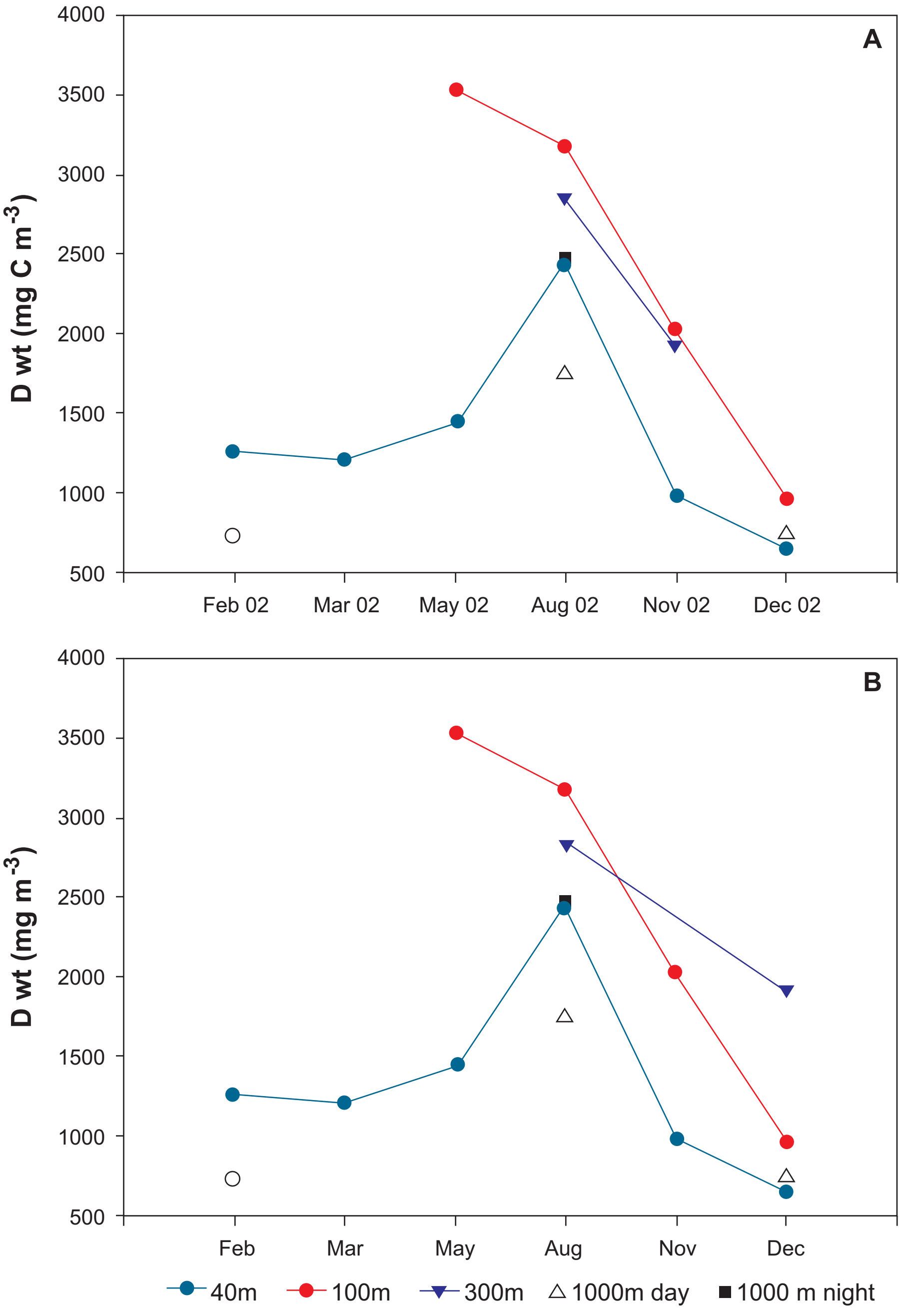


Figure 77: a) Depth integrated biomass, and b) biomass of zooplankton.

The most nearshore station was excluded from the analysis. This station is located in about 10 m of water and it is impossible to exclude suspended sediment from the samples. The elimination of inorganic sediment can be achieved by measuring ash-free dry weight. However, we will use a newly described method of estimating zooplankton through image analysis (Alcaraz *et al*. 2003). It can provide more reliable estimations with the additional benefit of assessing the distribution of biomass into classes of zooplankton, i.e. copepods, cladocerans, tunicates, chaetognaths and invertebrate larvae.

Copepod assemblages showed significant differences between summer and winter sampling, between autumn and winter, autumn and spring and winter and spring; on the other hand, they did not vary much among summer, spring and autumn (Fig. 78).

Species that contributed most to the seasonal differences were *Acartia, Oithona rigida*, *Microsetella, Paracalanus* (summer species) and *Canthocalanus, Coryceus, Euterpina* (winter species).

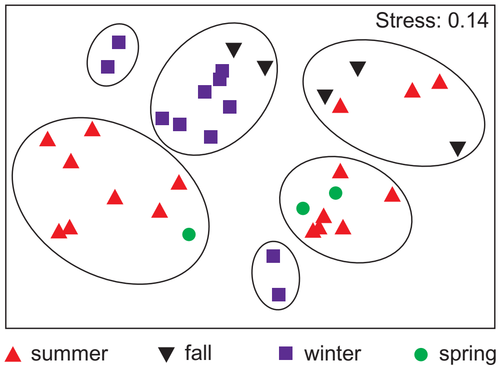


Figure 78: Copepod assemblages: seasonal pattern.

Spatially there were three major assemblages: nearshore, shelf and offshore (Fig. 79). Station A had a consistent nearshore community; station B (40 m water depth) consisted mostly of neritic species but some shelf species occurred at certain times; station C (100 m water depth) had shelf species at all sampling times and stations D (200 m water depth) and E (1000 m water depth) included offshore species most of the time. Some of the species that consistently contributed most to differences between nearshore and offshore assemblages were: *Oithona rigida, Acartia, Macrosetella, Microsetella, Temora turbinata*, (nearshore species) and *Pleuromammma, Euchaeta, Candacia, Eucalanus* (offshore species). These genera are cosmopolitan and are commonly observed to have such neritic or offshore distributions elsewhere (Boxshall and Halsey 2004).

A similar analysis was carried out on the total zooplankton assemblage, which produced comparable results (Fig. 80). The cladocerans, *Evadne* sp and *Penila avirostris*, which occurred in large numbers in summer, contributed most to the seasonal pattern (Figs. 81, 82). *Penilia avirostris*, brachyuryan larvae and polychaete larvae were present mostly nearshore and contributed along with the copepods to the spatial patterns.

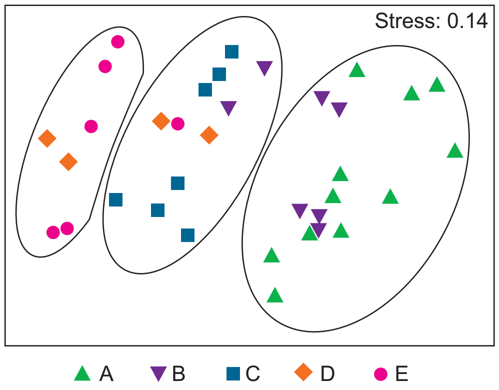


Figure 79: Copepod assemblages: spatial pattern.

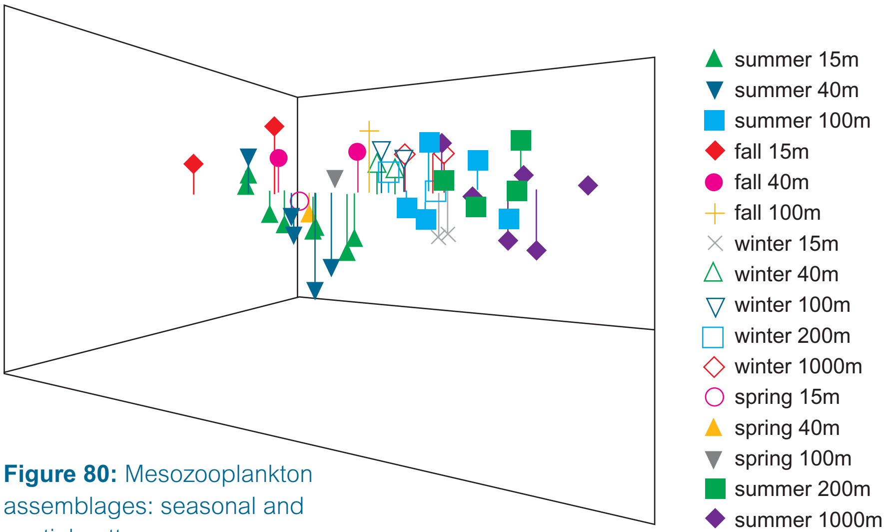


Figure 80: Mesozooplankton assemblages: seasonal and spatial patterns.

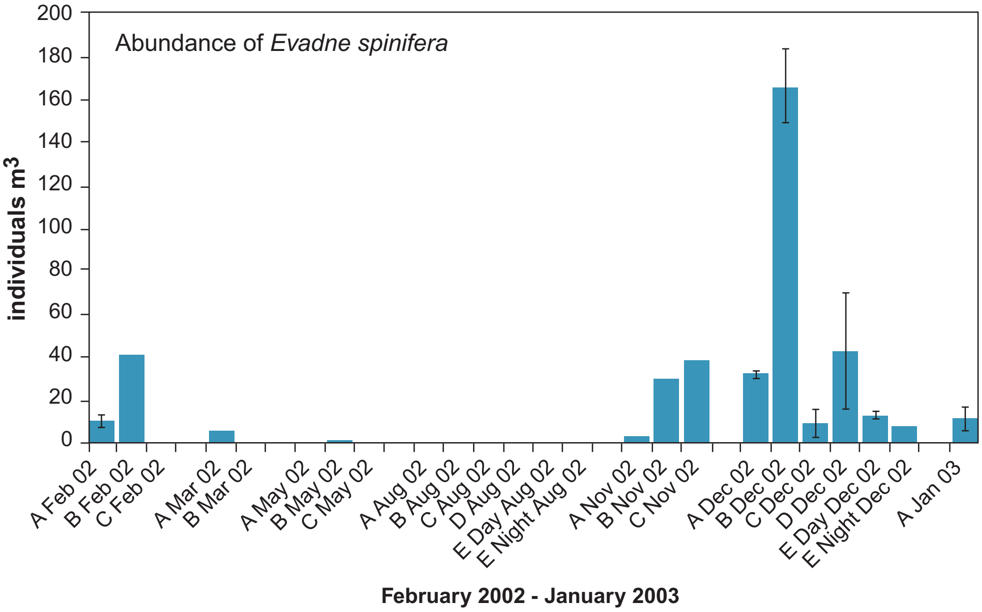


Figure 81: Abundance of cladoceran *Evadne spinifera*.

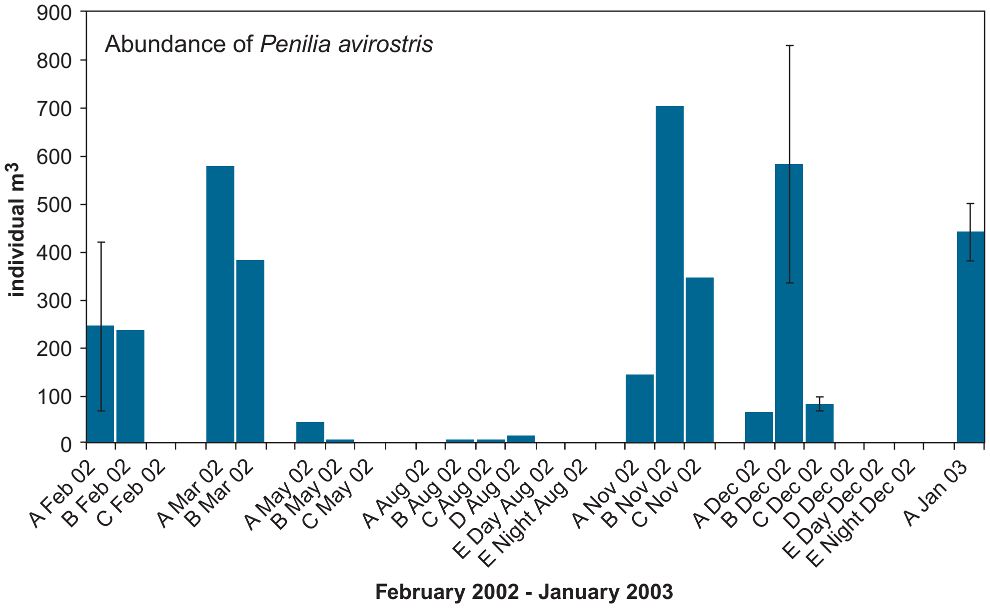


Figure 82: Abundance of cladoceran *Penilia avirostris*.

Discussion

Preliminary analysis of mesozooplankton community structure across the Two Rocks transect indicates clear differences among all groups for nearshore, shelf and offshore assemblages. Stations A and B are significantly different in summer and winter. These stations are also different to Stations C, D and E. In groups for which data are available, there is also evidence of substantial interannual, as well as seasonal, variability.

5.5.3.2 Mesozooplankton: estimation of secondary production

Introduction

The estimation of secondary production allows us to:

- make predictions about the health and productivity of the ecosystem as a whole
- make predictions about ecosystem responses to climatic and environmental perturbations
- contribute to the understanding of the interconnectedness of biological processes at different trophic levels and the role of physical ocean processes that allow development of management strategies which focus on the whole ecosystem

In particular, mesozooplankton production is often viewed as a key link between physical processes and their influence on primary production at the base of the food chain and the feeding and growth of larval and juvenile fish that regulates fishery recruitment. Fundamental to this hypothesis is that food availability is limiting in trophic interactions at both the phytoplankton-zooplankton and zooplankton-fish levels.

There are routine methods in estimating primary production, but there is no commonly accepted and routine method for measuring secondary production. The 'direct method', based on weight increase, is difficult to follow in nature. The 'egg production method' is the most commonly employed, but it is tedious and time consuming. New approaches related to studies of specific enzyme activity are being developed but they need testing against more routine methods like egg production. There are global models of growth based on physiological parameters that are temperature dependent and weight specific (Runge and Roff 2000). These models assume that food is unlimited, consequently they may be only giving an approximation of growth and reproduction, and direct measurements might be needed for more precise estimates.

Methods

Secondary production experiments were conducted during two RV *Southern Surveyor* cruises in August 2003 (SS200307) and January 2004 (SS200401). Two field methods and two models were used to estimate secondary production. The egg production method is based on the fact that copepod somatic growth ceases in adult females, and the growth rate is therefore assumed to be equivalent to egg production. This method has good spatiotemporal resolution, because fecundity is both time and site specific. It reflects the integration by the adult female of environmental variables prevailing during accumulation of gonadal material. This method assumes that all stage specific instantaneous growth rates are equal. This was tested and found to be true in *Centropages, Acartia tonsa, Calanus pacificus, C. finmarchicus*. For many other species, rates decline with copepodite stage, and also food limitation may exist for the adult but not the juvenile. Rates of production can be estimated from the specific egg production rate, which equals the growth rate of females. Also, the method assumes that egg production immediately after capture reflects the spawning behaviour in the sea at the same period.

Copepods used for the egg production method were collected by slow vertical Bongo tows using 355 and 100µm solid codends. Individual females were placed in 70 ml plastic containers with particle free seawater. Females were incubated for 24 hrs under a 12h dark:12 h light cycle and ambient temperature.

The second field method employed was a new amino acid method. Aminoacyl t-RNA synthetases (AARS) are a group of enzymes that catalyse amino acid (αα) activation and the transfer of activated amino acid to their tRNAs (Fig. 83). It is a first step in protein synthesis, and AARS activity is therefore directly related to protein synthesis. The relationship between protein synthesis and growth was observed in cephalopods and fishes. Chang *et al*. (1984) developed a continuous assay for AARS activity. They measured activity based on the release of pyrophosphate (PPi) during aminoacylation (incorporation of PPi into ATP) of tRNA assessed as oxidation of NADH by PPi. This method is inexpensive, using a commercial Sigma kit and a spectrophotometer. Sample of copepods are homogenised with buffer and centrifuged. PPi reagent is added, kept for a few minutes and the decrease in absorption is read at 340 nm for 10 minutes. Oxydation of NADH produces reduction in absorption (Yebra and Hernandez-Leon 2004).

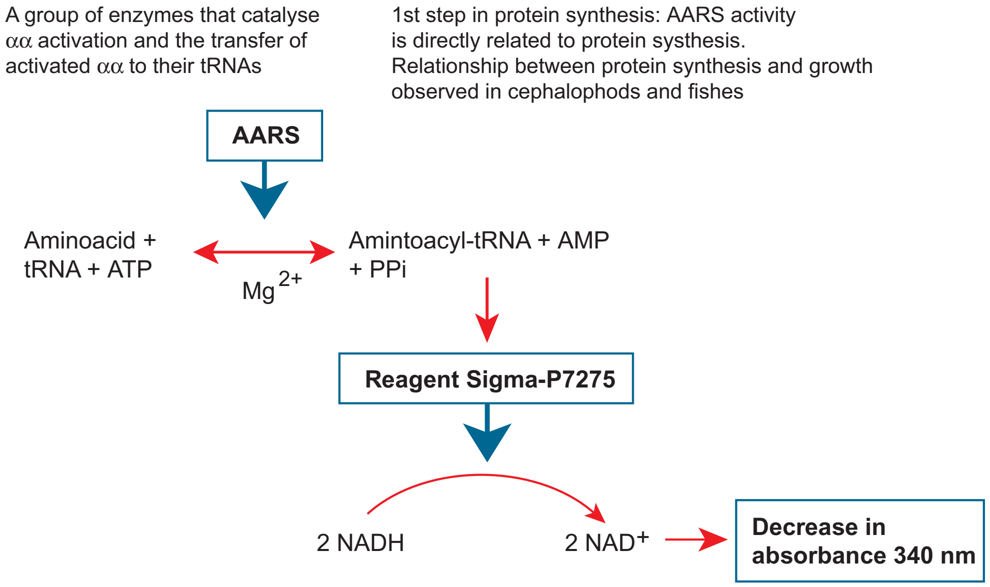


Figure 83: Aminoacyl-tRNA synthetases continuous spectrophotometric assay (Chang *et al*. 1984).

We applied the Hirst and Lampitt (1998) model to our data. In this model, copepods are characterized according to spawning type (broadcast or egg carrying) and life stage. In adults, growth equals reproduction and in juveniles growth is reflected by weight gain. We also used the physiological model of Ikeda and Motoda (1978). In this model, growth is a function of body weight and temperature. Respiration rate is a function of body weight, and oxygen consumption is converted to carbon using a respiratory quotient of 0.8. Ingestion rate was not measured directly, but rather the gross growth efficiency was assumed to be 0.3 with an assimilation efficiency of 0.7.

Results

Estimation of secondary production using the egg production method was found to be lower than estimation using AARS method and the two models (Fig. 84). At some times, there was a good agreement among several methods i.e. Station A and Stations C, D, E in winter and Station A stations in summer. The two models show good agreement at Station D and Station A in summer. The Hirst Lampitt model and the AARS method showed good agreement in offshore stations in winter.

Copepod production estimated using the egg production method ranged from 0.4 to 10 mg C m^{-2} d^{-1}. This is comparable to production measured in the North West Cape region of Western Australia (McKinnon and Duggan 2003) (Table 10).

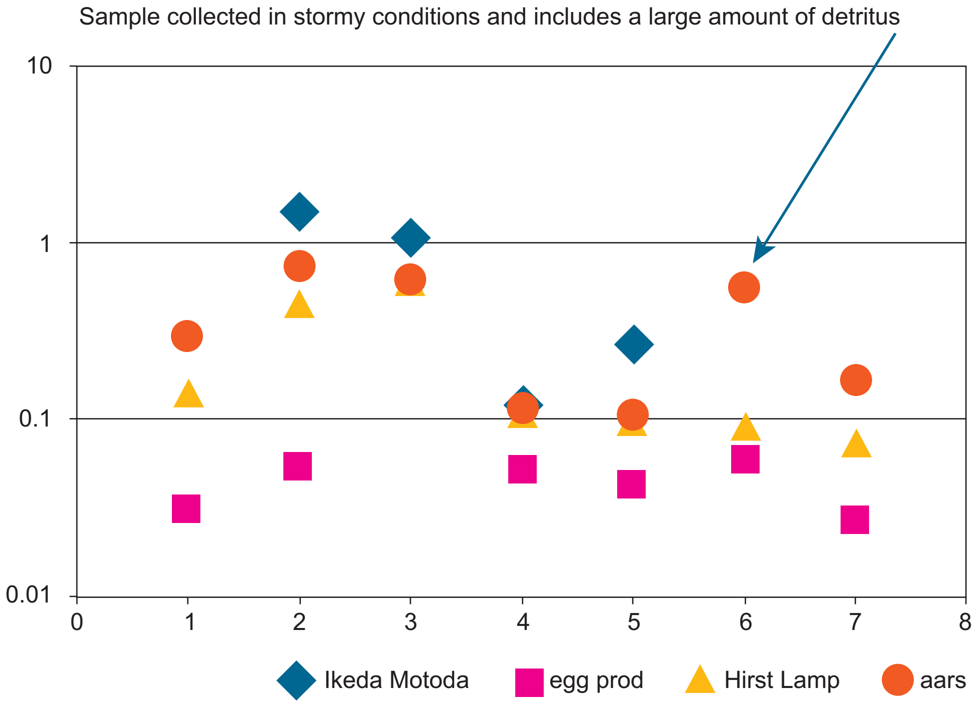


Figure 84: Estimation of secondary production using the two field methods and models.

Table 10. Secondary production in different regions.

Location	Production mg C m^{-2} d^{-1}	Environment
North West Cape	7.5	Subtropical shelf
North West Cape	11.5	Subtropical shelf
Kaneohe Bay	151	Tropical Bay
Western Port Bay	7.5	Temperate Bay
Western Agulhas Bank	40	Upwelling shelf
Western Agulhas Bank	400	Upwelling shelf

Phytoplankton is a potential food source for copepods, and therefore the relationship between secondary production estimated using enzyme and egg production methods and chlorophyll biomass (Fig. 85) and primary production (Fig. 86) was tested. There was no relationship between secondary production and either total or large phytoplankton biomass and between secondary production and either total or large phytoplankton production.

Only a small proportion of phytoplankton was utilized by copepods (Table 11).

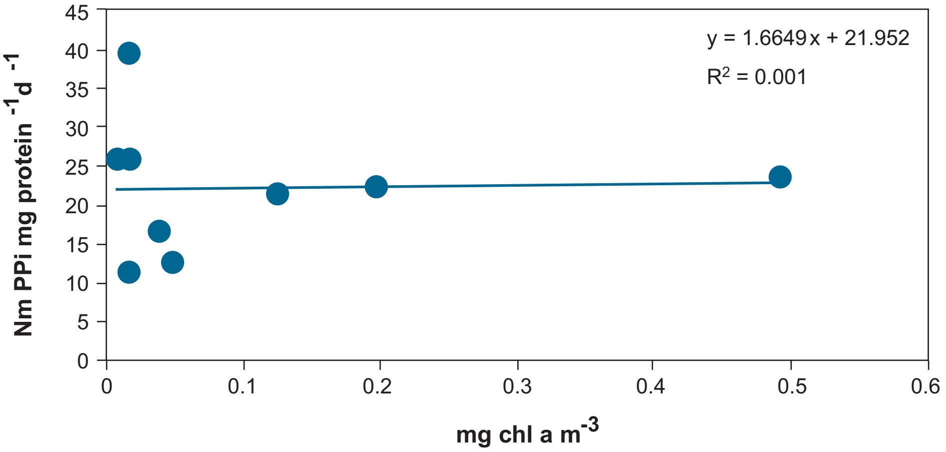


Figure 85: Relationship between secondary production (AARS method) and large phytoplankton biomass

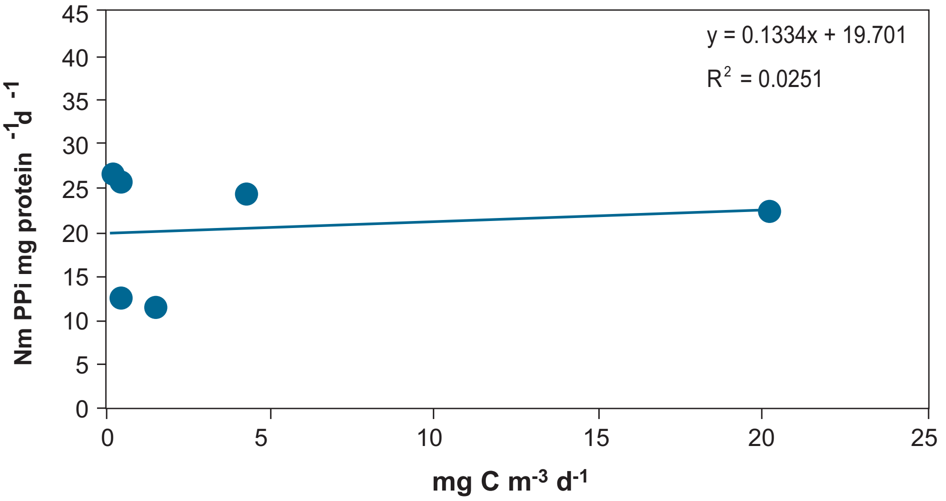


Figure 86: Relationship between secondary production (AARS method) and large phytoplankton production

Table 11. Copepod production as a proportion of primary production.

Method	% total primary production	% large fraction of primary production
Egg production	0.2 – 1.6	0.6 - 52
AARS enzyme	1 – 25	1.7 - 250
Ikeda and Motoda model	2.13 – 44.92	0.5 - 499
Hirst and Lampitt model	0.8 – 24	1.61 - 267

Discussion

Secondary production was low in comparison with productive marine environments, but comparable to estimates off Australia's North West Cape. Our AARS enzyme and egg production method results were more similar to the results predicted by the Hirst and Lampitt (1998) model than the Ikeda and Motoda (1978) model. There was no correlation between phytoplankton biomass and secondary production. This is not surprising considering that most phytoplankton in our region are small and not grazed by mesozooplankton (see Section 5.4.3.3 below). Between 0.2 and 44.92% of total primary production will sustain the estimated levels of secondary production (Table 11). However, secondary production was at times a very high proportion of primary production if only contribution by large phytoplankton was considered. Note secondary production predicted by models may represent and overestimate of the actual *in situ* rate if copepods were food limited. In addition most copepods are omnivores eating protozoa (Boxshall and Halsey, 2004) and detritus and phytoplankton is only a portion of food available for copepods. In future, we will estimate zooplankton grazing and production as part of the SRFME biogeochemical model, which will incorporate realistic estimates of prey availability along with temperature- and size-based estimates of physiological processes.

5.5.3.3 Mesozooplankton grazing

Introduction

Estimating grazing losses in aquatic systems is fundamental in current research on carbon cycling in pelagic and benthic food webs (e.g. Rivkin *et al*. 1996, Hammer *et al*. 2001). Food web models and recent studies predict that planktonic food webs are dominated by the classic food web (phytoplankton → copepods → fishes) when large phytoplankton are abundant, but when small phytoplankton dominate the microzooplankton becomes a major food source for mesozooplankton and the microbial food web takes over (picoplankton + bacteria + heterotrophic flagellates → ciliates → copepods; Rivkin *et al*. 1996, Sommer *et al*. 2002, Calbet and Saiz 2005). However, even in productive systems where large diatoms can be abundant, microzooplankton can be the principal herbivore and protozooplankton herbivory provides the major route for phytoplankton transfer to higher trophic levels (Nielsen *et al*. 1993, Nielsen and Hansen 1995). The classic or herbivorous food web develops in areas where there is a rich supply of nutrients, the water is well-mixed, and production is supported by new nitrogen. The microbial web predominates in stratified waters, where the permanent thermocline prevents nutrients from mixing upwards from deep waters, leading to low productivity that relies mainly on regenerated nitrogen (Legendre and Rassoulzadegan 1995). Food web interactions influence the biogeochemistry of the ocean (Legendre and Rassoulzadegan 1996). Export to deep waters is mainly through the sedimentation of ungrazed algae and production of faecal pellets. In most cases, only a small fraction of large cell phytoplankton is grazed, resulting in a large export of particulate organic carbon. With the microbial food web, carbon export is minimized through efficient recycling of nutrients and organic matter by bacteria and small protozoa (Calbet 2001). Therefore, food web structure determines ocean carbon cycling and the magnitude of the export of organic matter and benthic-pelagic coupling.

Knowledge of the planktonic food web structure can also be used to predict the productivity of higher trophic levels. Since only 10% of the energy available to an organism in a particular trophic level is available to the next trophic level, the additional trophic levels in the microbial food web will lower the energy available for fish as compared to the classic food web.

The aim of our study was to contribute to the understanding of trophic interactions in southwestern Australian waters, and to quantify the direct and indirect influences of mesozooplankton on lower trophic levels, with a view to providing data for biogeochemical modelling. Prior to the current project, there had been no studies of feeding by mesozooplankton on various components of the natural mixed assemblages of phytoplankton and microzooplankton from our region.

Small (<5 μm) phytoplankton dominate biomass and productivity along the Two Rocks transect. Large cells are more important mostly inshore at times (see Section 5.4.2 of this report). *Trichodesmium*, a diazotrophic, colonial cyanobacterium, forms periodic surface blooms nearshore, in shelf waters and offshore.

Mesozooplankton grazing estimates were measured in two ways: the gut pigment content method, and the clearance rate method derived from bottle incubations. The gut pigment method provides data directly from the field. However, this method can underestimate grazing rates due to pigment degradation within the gut, and the method measures feeding on chlorophyll-bearing prey only. Bottle incubations quantify omnivorous feeding, but suffer artifacts including animal stress, crowding of grazers, and turbulence (Calbet 2001).

Methods

The experimental work was conducted at sea during quarterly cruises from August 2002 to December 2004. The grazing experiments were conducted at Station A (15m water depth), Station C (100 m water depth) and Station E (1000 m water depth) along the Two Rocks transect. Water from the surface was collected by bucket and placed into 3 L polycarbonate bottles. This water was used as a food source. Since the natural seawater contained a negligible amount of mesozooplankton, screening for zooplankton was not necessary. Mesozooplankton were collected using 0.5 m^2 Bongo nets with 355 and 100 μm mesh and non-filtering cod ends. Nets were towed obliquely from 10 m to the surface at about 2 knots for 5 minutes. Once on deck, the contents of the codends were gently poured into a 20 L container. Free swimming and healthy looking organisms were transferred into polycarbonate bottles filled with water from the surface. The treatments consisted of three concentrations of mesozooplankton: low, medium (2 × low concentration) and high (4 × low concentration). Four replicates per treatment and four controls without mesozooplankton were prepared. An additional group of bottles was filled with surface seawater and filtered immediately to assess phytoplankton biomass at the start of the incubations.

The incubations began immediately and continued for 24 hours in a seawater-cooled incubator screened to reproduce irradiance just below the surface of the ocean. The food (microzooplankton and phytoplankton) was kept in suspension by rotating the bottles several times a day. After the end of incubations, mesozooplankton grazers were collected for identification and biomass determination, and a 200 ml subsample was collected from each replicate and preserved in 10% Lugol's for microzooplankton food items enumeration. The remaining water was filtered through a GF/F filter and stored in liquid nitrogen while at sea, and transferred to a -80° C freezer in the laboratory prior to analysis. Feeding rates on total phytoplankton were measured by monitoring changes in chlorophyll *a* concentrations. Chlorophyll *a* was extracted for 24 hours in 90% acetone and analysed on a Turner fluorometer using standard techniques (Strickland and Parsons 1972). In addition, one replicate of each treatment and control was analysed using HPLC to obtain additional information of phytoplankton selectivity.

Results and discussion

To date, grazing experiments from 2004 have been analysed for feeding on phytoplankton. Grazing experiments with microzooplankton and mesozooplankton showed marked contrasts in chlorophyll responses among treatments. Figure 87 illustrates the typical response of phytoplankton when most of the phytoplankton biomass and production consists of small size cells. In the microzooplankton – phytoplankton treatment (Control), chlorophyll decreased, suggesting that microzooplankton was feeding on phytoplankton. An addition of a low amount of mesozooplankton (low grazers) resulted in net growth of chlorophyll *a* suggesting either increased phytoplankton growth due to influx of regenerated nutrients or reduced grazing from microzooplankton due to predation by mesozooplankton, or both. When medium and high levels of mesozooplankton grazers where added, growth of phytoplankton was low suggesting that mesozooplankton was feeding on both microzooplankton and phytoplankton.

When close to 50% of phytoplankton biomass consisted of large diatoms the biomass of phytoplankton decreased with increased grazers' concentration (Fig. 88). This suggests that mesozooplankton were the principal grazers. An increase of phytoplankton biomass in the control (+phytoplankton, + microzooplankton) confirms that microzooplankton exerted relatively small grazing pressure on phytoplankton.

In December 2004, phytoplankton biomass and production was dominated by *Trichodesmium*, a colonial marine cyanobacterium. Phytoplankton biomass did not change in the Control treatment compared to biomass at the start of experiment, and increased in all three treatments that included mesozooplankton (Fig. 89). Reports on the trophodynamic fate of *Trichodesmium* concluded that it is not grazed by most herbivores. The one confirmed grazer of *Trichodesmium* is the pelagic harpacticoid copepod *Macrosetella gracilis* (O'Neil *et al*, 1996, Capone *et al*, 1997). *Macrosetella gracilis* is present in our samples, but in low abundance (see Section 5.4.3.1).

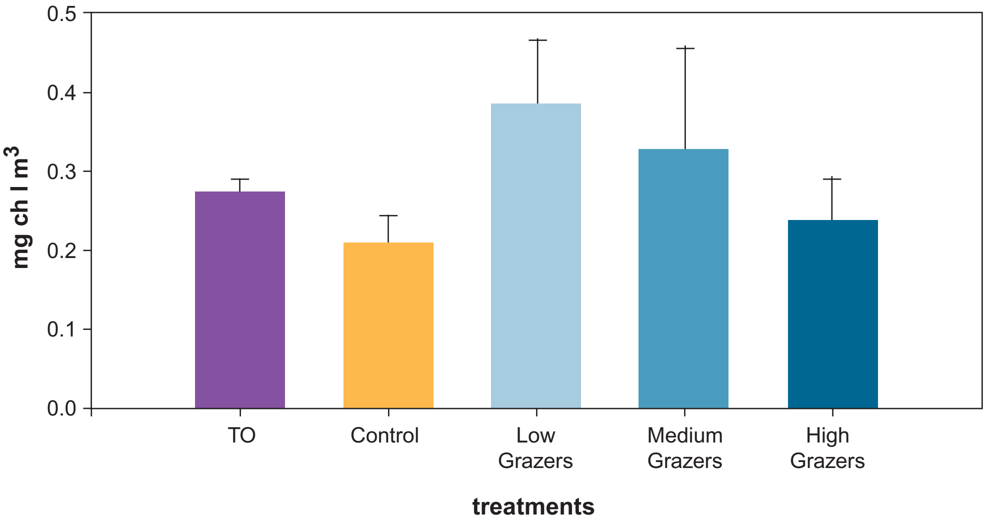


Figure 87: Phytoplankton grazed at Station C (100 m water depth) in September 2004 (error bars are standard deviation). T0 is a sample taken at the beginning of the experiment; Control includes phytoplankton and microzooplankton but no mesozooplankton.

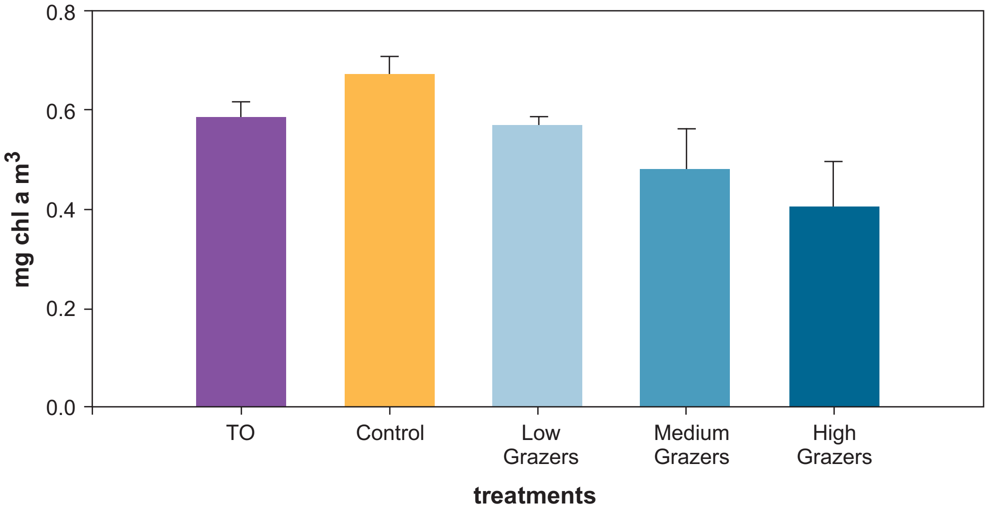


Figure 88: Phytoplankton grazed at Station A (15 m water depth) in September 2004 when 50% of phytoplankton are large diatoms. Error bars are standard deviation.

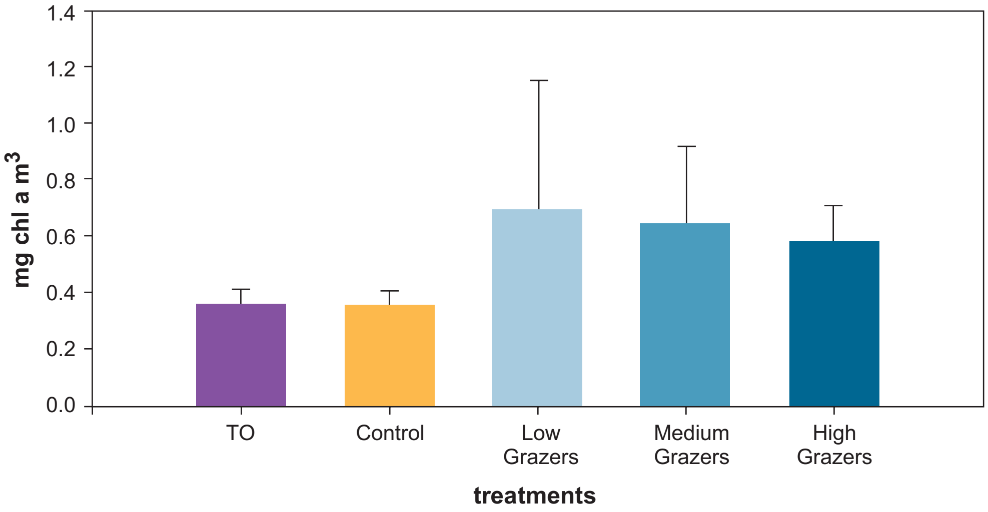


Figure 89: Phytoplankton grazed at Station C (100 m water depth) in December 2004 when *Trichodesmium* is 100% of large phytoplankton. Error bars are standard deviation.

5.5.4 Bioacoustics

5.5.4.1 Introduction

An acoustic methodology is being developed to characterise the spatial and temporal variability of continental shelf marine life along the Two Rocks transect. Acoustic remote sensing enables scientists to map a cross section of the ocean and view the interaction of marine life with seabed and oceanographic features. It also has the potential to provide quantitative metrics within and between seasons on the numbers and densities of major trophic groups from plankton to fish.

To identify marine life from plankton (weakly swimming but mostly drifting small organisms 0.1 – 200 mm) to large nekton (organisms that can propel themselves independent of the currents in the water mass, e.g. fish) requires the use of many acoustic frequencies. In this study 9 frequencies are being used ranging from 70 kHz to 3 MHz. The acoustic maps enable biological and physical samples to be better targeted and provide the necessary spatial and temporal context. Likewise, the physical and biological samples are critical for the interpretation of the acoustic signatures and training of the multi-frequency remote sensing algorithms. To sample the marine life from phytoplankton to nekton, sea water pumps and variable meshed nets are used. These point samples of marine life can be used to “truth” the acoustics and relate the samples to the across-shelf patches observed in the acoustics. It is often difficult to capture the organisms seen by the acoustics, due to avoidance of the nets and the ability to accurately target scattering layers. At 70 kHz, the acoustic frequency is also selective towards larger organisms (macrozooplankton to micronekton). Current biological sampling methods using small meshed nets will under-represent or totally miss these animals. One way to assist in the identification and numbers of these species is to use multi-frequency acoustic methods.

5.5.4.2 Low frequency bioacoustics

Aims/objective

To develop and apply acoustic methods to map and monitor zooplankton and micronekton at low frequencies: 70, 120 and 200 kHz.

Work completed

Nine voyages with acoustic transects (Table 12) have been completed using a specifically designed pole-mounted three frequency echo sounder (Table 13). The system has been calibrated at the CSIRO Marine Research (Hobart) transducer calibration facility, and in the field using a standard tungsten carbide reference sphere method (Foote *et al*. 1987). A fuller calibration and operational understanding of the Simrad ES60 has led to significant improvements in the accuracy and precision of acoustic measurements (Ryan and Kloser 2004). The manufacturers of the instrument have acknowledged the most significant problem identified by Ryan and Kloser (2004), and are implementing a fix in the next software release.

Table 12. Indication of the acoustic multi-frequency data (70, 120 and 200 kHz) collected during the quarterly Two Rocks transects from December 2002 to December 2004 on three vessels (MI = Maritime Image, NA = Naturaliste, SS = Southern Surveyor) over four seasons.

Voyage	Start Date	End Date	Season	70kHz	120kHz	200kHz
MI200206	17/12/2002	18/12/2002	Summer		•	
NA200302	9/2/2003	11/2/2003	Summer	•	•	•
NA200304	28/4/2003	30/4/2003	Autumn	•	•	•
SS200307	23/8/2003	27/8/2003	Winter	•	•	•
NA200311	1/12/2003	4/12/2003	Summer	•		•
SS200401	20/1/2004	28/1/2004	Summer	•	•	•
MI200403	18/4/2004	20/4/2004	Autumn	•	•	•
NA200407	20/9/2004	23/9/2004	Spring	•	•	•
NA200410	15/12/2004	18/12/2004	Summer	•	•	•

Table 13. Technical details of the SRFME low frequency Simrad ES60 acoustic system used throughout the sampling period. Note that the sound velocity was set at 1500 ms^{-1} for all instruments.

Equipment	Model
70 kHz single beam 11^0 transducer	ES70-11
120 kHz split beam 7^0 transducer	ES120-7C
200 kHz single beam 28^0 transducer	ES200-28

Results and discussion

The analysis of the acoustic data is an area of active research, with preliminary results describing the Two Rocks transect at one frequency. The Two Rocks across-shelf acoustic transect (70 kHz on the 29 April 2003; NA200304) highlights the dominant seabed and water column spatial features (Fig. 90). The acoustic map provides seabed attributes of depth and the water column biological structure. The acoustic reflectivity at 70 kHz highlights the aggregations of biological life within the water column over the 85 km long transect. High acoustic reflectance is associated with the cooler, more saline and high chlorophyll water mass located at Stations A to B (Fig. 90, inset). Internal wave mixing and high chlorophyll is observed on the outer shelf (Stations C to D). Vertical migration of the deep scattering layer, which moved from ~ 600 m depth to 100 m depth at sunset, is evident at station E. This cross sectional view of the water column provides a window into the subsurface structure of pelagic communities, their spatial/temporal extent and association with oceanographic conditions and seabed features. There was a significant correlation between patches of high acoustic reflectance and high chlorophyll levels (see Section 5.5.1.4, Figure 55).

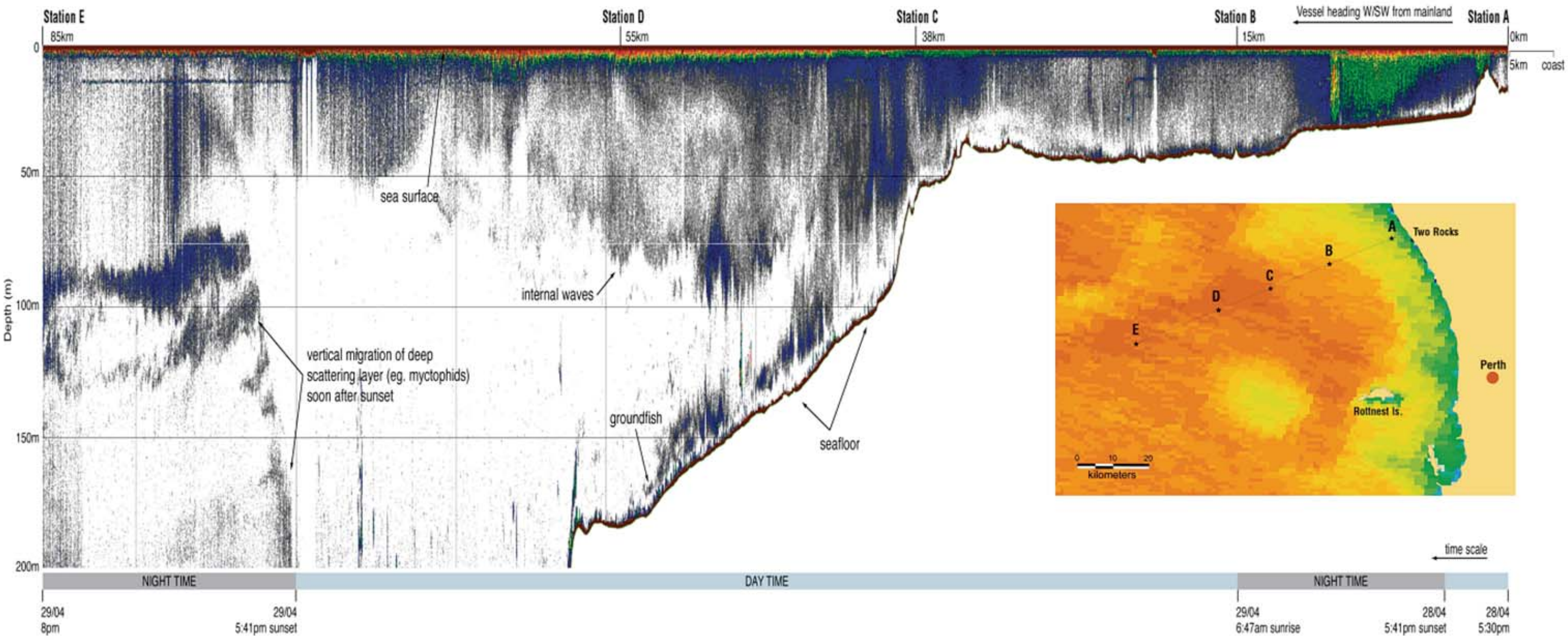


Figure 90: Acoustic echogram at one frequency (70 kHz) of the Two Rocks transect, with the vessel moving from Station A on the coast to Station E offshore. Low acoustic reflectance (volume reverberation) is shown in blue and high reflectance is shown in red. The insert of a satellite image of ocean temperature variation along the transect (high to low temperature from orange to blue) gives the sea surface context of the acoustic data.

Distinguishing broad categories and abundance of marine life is possible using multiple acoustic frequencies in combination with acoustic scattering models (Kloser *et a*l. 2002). Figure 91 shows an example of species differentiation using our three-frequency system of 70, 120 and 200 kHz. Both the 70 kHz (Fig. 91a) and 200 kHz (Fig. 91b) volume reverberation echograms show two thin layers centred at 30 m and 90 m depth. When the two frequencies are combined using an amplitude-mixing algorithm (Fig. 92c), it is clear that the layers have different acoustic properties. The 30 m layer is dominated by the 70 kHz signal (green), whereas the 90 m layer is dominated by the 200 kHz signal (red). The 90 m layer is characteristic of a non-gas bladdered animal (e.g. euphausiids), as such organisms have a very much higher reflectivity at 200 kHz compared to 70kHz. Conversely, the 30 m layer has lower reflectivity at 200 kHz compared to 70 kHz, which is a characteristic of gas-bladdered animals (e.g. larval fish). These layers must be accurately targeted with the biological sampling to determine their composition and construct appropriate acoustic scattering models.

All nine voyages with acoustics data are currently being processed, calibrated and quality-checked. These transects will provide both qualitative and quantitative information regarding within-season, between-season and inter-annual variability of the biomass, distribution and patterns of marine life from zooplankton to micronekton. Maps of acoustic reflectance will be used to provide spatial context to other biological and physical sampling carried out along the Two Rocks transect (Fig. 90). Using the collected biological data, acoustic models determined by the dominant scattering type for the appropriate species such as a gas-filled or fluid-filled shape (e.g. Stanton and Chu 2000), will be used to determine 'acoustic-scattering' groups, distribution and abundance along the Two Rocks transect.

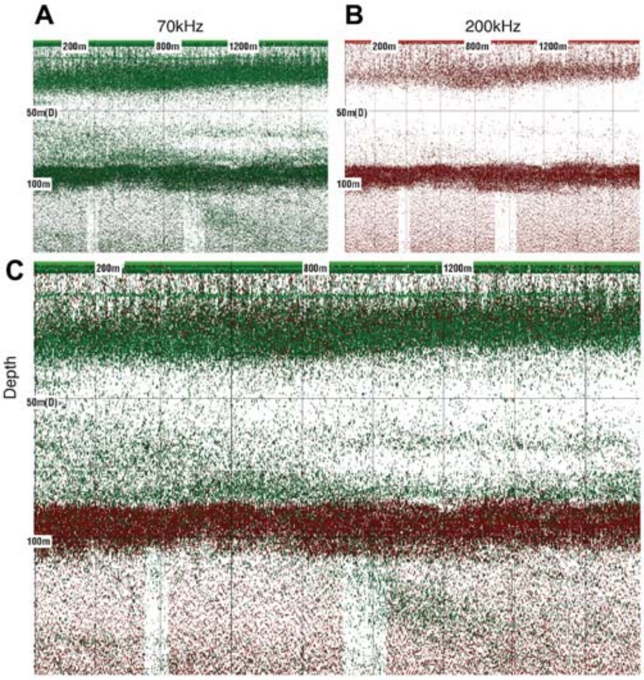


Figure 91: Acoustic species identification example using two frequencies at a) 70 kHz (green), b) 200 kHz (red), and c) amplitude mixing of the two frequencies to highlight species differences (Kloser *et al.* 2002).

5.5.4.3 High frequency bioacoustics

Aims/objective

To develop and apply acoustic methods to assess fine scale vertical distributions of mesoplankton at high frequencies: 265, 420, 700, 1100, 1800, 3000 kHz.

Work completed

To investigate mesoplankton (0.2 - 20 mm), higher frequencies must be employed than those normally used in fisheries acoustics. To determine both size and abundance of zooplankton and micronekton multiple frequencies are required (Holliday and Pieper 1995). This study has been conducted using a Tracor Acoustic Profiler System (TAPS; Table 14), in conjunction with a specially designed Discreet *In situ* Plankton Sampler (DIPS). The DIPS unit can collect six discrete plankton samples from the water column, while TAPS collects concurrent acoustic data (Fig. 92).

Table 14. Relevant specifications of the Tracor multi-frequency TAPS system when deployed in cast mode.

Serial Number	14
Operating frequencies	265, 420, 700, 1100, 1850, 3000 kHz
Transmit power	100 W (nominal)
Pulse length	336 uSec (fixed)
Ping rate	3/ second (each channel)
Beamwidths	8 degrees @ -3dB points (nominal)
Cast-mode sample volume	0.005 m^3
Maximum operating depth	192 m

The TAPS unit has six frequencies ranging from 265 kHz to 3 MHz. These frequencies have been chosen to span the transition between Rayleigh to geometric scattering for fluid-filled animals such as copepods. The acoustic profiler has primarily been deployed in 'cast mode', where a finite volume of water (5 L) at a fixed range (1.5 m) from TAPS is sampled as the instrument is lowered through the water column. The DIPS unit is operated from the surface, and combined with a real-time display of TAPS data, allows the operator to target features of interest in the water column.

Extensive trials and experiments have been undertaken during the SRFME Biophysical program to develop the application of this technology and associated biological sampling, as this is an area of acoustic science new to Australia.

The TAPS and DIPS units were used extensively during the 2004 field season, with 50 vertical profiles and 120 plankton samples collected. These plankton samples are currently being digitized using a microscope fitted with a CCD camera. The digital pictures are then processed using ImageJ (Abramoff *et al*. 2004) to determine the volume and equivalent spherical radius (ESR) of each animal (Fig. 93; Alcaraz *et al*. 2003). The ESR is the radius of a sphere that contains the same volume as the organism. Once dominant ESR size classes are known, backscatter models appropriate to organism shape and composition can be calculated to predict the frequency response (Fig. 90; Holliday 1992). Based on these backscatter models, the multi-frequency TAPS data can be inverted using non-linear least-squares to give estimates of biota size and abundance (Holliday and Pieper 1995).

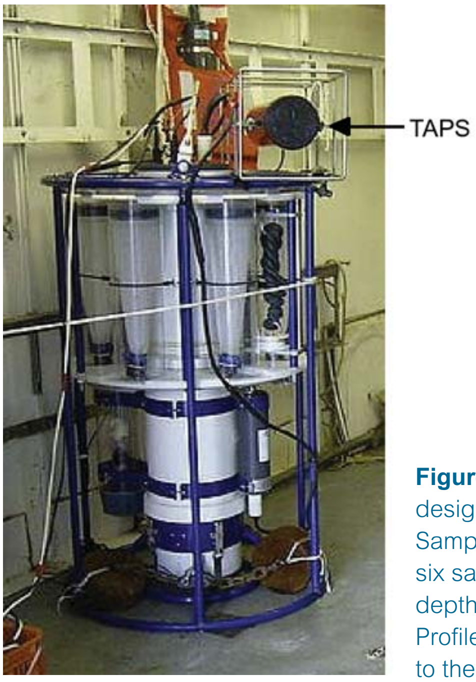
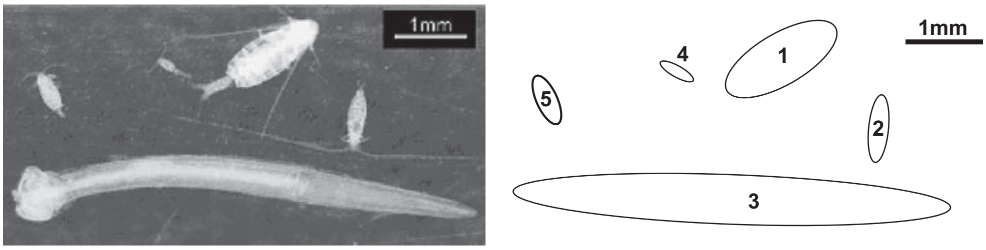


Figure 92: Picture of the specially designed Discreet *In situ* Plankton Sampler (DIPS), that can collect six samples at targeted water depths, with the Tracor Acoustic Profiler System (TAPS) attached to the upper right of the frame.



#	Taxa	Area (mm^2)	Major (mm)	Minor (mm)	Volume (mm^3)	ESR (mm)
1	copepod	0.821	1.605	0.652	0.357	0.440
2	copepod	0.168	0.865	0.248	0.028	0.188
3	chaetognath	2.755	5.542	0.633	1.163	0.652
4	copepod	0.041	0.451	0.114	0.003	0.090
5	copepod	0.134	0.654	0.260	0.023	0.177

Figure 93: Example of biota measured for acoustic truncated fluid sphere model development, showing the necessary simplifications of body shapes. The associated table quantifies the biota cross sectional area, major and minor axes, volume and equivalent spherical radius (ESR). The organisms were collected from 27 m water depth, with the frequency response as shown in Figure 94 (below).

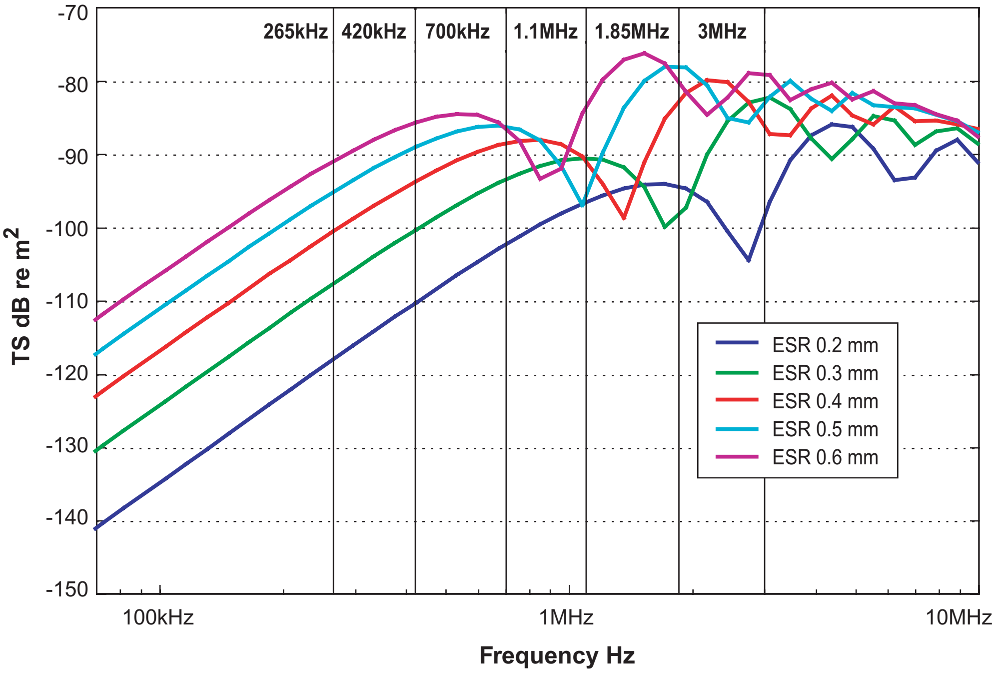


Figure 94: Model of predicted target strength (TS dB re 1 m^2) of a truncated fluid sphere with equivalent spherical radius (ESR) of 0.2 to 0.6 mm at frequencies of 70 kHz to 3 MHz (Holliday 1992).

Results and discussion

Initial results indicate there is considerable acoustic frequency variability both within and between station locations, and according to time of day and depth sampled; these variations are due to distinct biotic differences. As an example, two samples from Station E are compared (Fig. 91). Sample 47 was obtained from 27 m at ~ 23:00 h (and contained larger organisms with relatively high abundance), while sample 51 was obtained from 154 m at ~ 18:00 h (and contained smaller organisms with relatively low abundance). There is a distinct positive relationship between the acoustic volume reverberation (Sv; Fig. 95a) and mesozooplankton abundance and size (as estimated from the DIPS samples; Fig. 95b).

Predicted acoustic scattering strengths at a range of frequencies can be determined using the biota information derived from digitized DIPS samples combined with acoustic models (Holliday 1992, Stanton and Chu 2000). The predicted acoustic signal strength for each of the six TAPS frequencies can be calculated for DIPS sample assemblages using the scattering models. The observed *in situ* acoustic backscatter can then be compared with the backscatter predicted from the model. This method of investigation is often referred to as solving the forward problem (Holliday and Pieper 1995, Fielding *et al*. 2004).

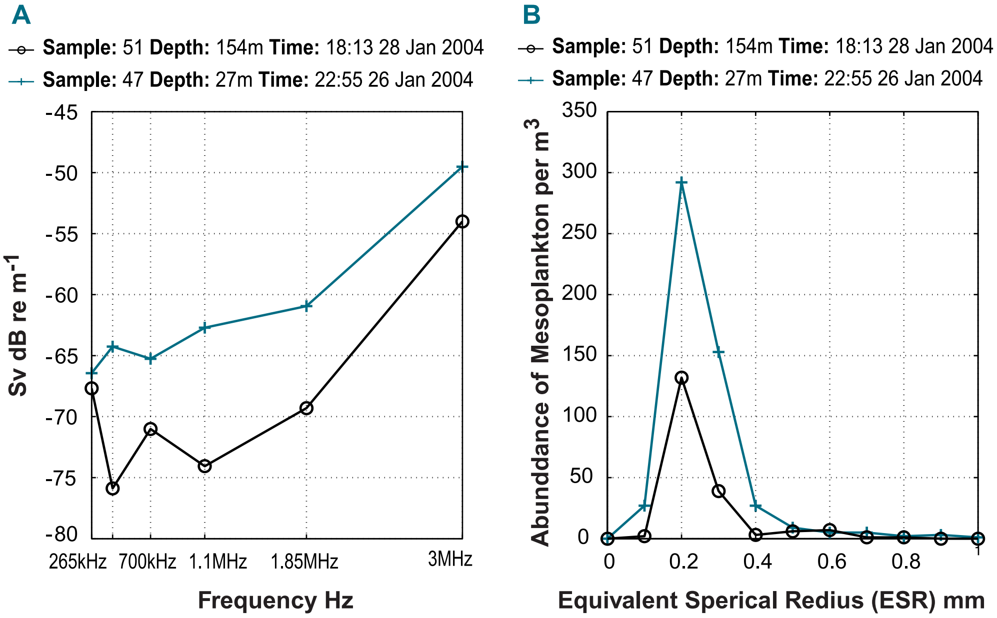


Figure 95: Results from samples obtained at 154 m water depth (black circle) and 27 m water depth (blue cross) showing, a) the volume reverberation (Sv dB re m^{-1}) response at the six frequencies, and b) the abundance and measured equivalent spherical radius (ESR) of the biota. The predicted truncated fluid-filled model response as a function of frequency is shown in Figure 94.

The remote acoustic sensing methodology can be limited due to noise when sensing low densities of biota with multiple frequencies. The signal returned from the biota needs to be above the noise limit for all frequencies for this method to work optimally. At typical density levels experienced along the Two Rocks transect, the plankton density within the 5 L acoustic sample ranges from 3 to 10 individual organisms per ping. These levels are extremely low when compared to over 200 organisms per ping obtained in more productive waters such as the Irish Sea (Holliday 1992). This highlights the difficulty of using acoustics to study plankton in the relatively oligotrophic conditions experienced off Western Australia. Work is now underway in the development of special signal processing techniques and acoustic models tailored specifically to these conditions.

Current investigations are looking at both physical models and statistical (pattern recognition and dimension reduction) methods of interpreting the high-frequency data where patterns in the frequencies are combined with oceanographic data on temperature, salinity and fluorescence, in addition to the pump samples.

5.4.4.4 Summary and conclusion

Significant progress has been made in developing the equipment, sampling and processing methods of applying both low and high frequency acoustics to observing and quantifying the biota in Western Australian waters. The next year will see the output of standardised data products that could be obtained from this type of sampling, and synthesis with other remote sensing and physical samples.

The challenge, beyond the technical application of these new technologies for ocean sensing, is our ability to optimise their usage in conjunction with numerical and empirical models for sustainable ecosystem objectives. Alternate sampling strategies using autonomous, moored, drifter, glider and vessels of opportunity platforms could be incorporated in this observation strategy. A framework linking an observation strategy with process understanding and numerical and empirical modelling remains the next (or constant) challenge.

5.6 Acknowledgements

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- The Masters and crews of the RV *Southern Surveyor*, RV *Naturaliste*, and RV *Maritime Image*;
- Fisheries Western Australia and TAFE for charter of the RV *Naturaliste* and *Maritime Image*;
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Pesant, Feng, Fearns, Pearce *et al*. – Oceanic and atmospheric forcing of pelagic marine systems off WA: Small- to medium-scale forcing and variability.

Ecosystem structure

Pearce, Feng *et al*. – Structure and dynamics of the pelagic ecosystem along an onshore-offshore transect off southwestern Western Australia, 2002 – 2004: physical and chemical oceanography.

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Paterson *et al*. – Structure and dynamics of the pelagic ecosystem along an onshore-offshore transect off southwestern Western Australia, 2002 – 2004: microzooplankton.

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Koslow, Pesant *et al*. – Structure and dynamics of the pelagic ecosystem along an onshore-offshore transect off southwestern Western Australia, 2002 – 2004: simple carbon budgets.

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CHAPTER 6

6. SRFME CORE PROJECT TWO

6.1 Coastal Ecosystems and Biodiversity

6.2 Investigators

CSIRO Marine Research, Floreat, WA: Russ Babcock (Project Leader), Geordie Clapin, Paul Dean, Peter Fearns, Tim Harriden, Matt Kleczkowski, Martin Lourey, Nicole Murphy, Alan Pearce, Julia Phillips, Alison Sampey, Mat Vanderklift, Mark Westera

CSIRO Marine Research, Hobart, TAS: Lesley Clementson, Andy Revill

Curtin University: Wojciech Klonowski

University of Western Australia: Marion Cambridge

Flinders University: Tim N. Moore

6.3 Executive summary

The aim of the SRFME Coastal project is to characterize the coastal benthic ecosystems of southwestern WA, with particular focus on benthic reef ecosystems, their productivity and dynamics, and the physical, chemical and biological factors driving variability along dominant spatial and temporal scales. To achieve this, we undertook 3-monthly seasonal sampling from 2003 – 2005 at a series of coastal sites situated between Cape Naturaliste in the south and Jurien Bay in the north. Benthic Sampling was integrated with satellite observations of SST, ocean colour and subsurface measurements of other water column properties, as well as sediment biogeochemical sampling. Within this region benthic sampling was nested at Regional (100s km) Local (10s km) and Site (1 km) scales and within each of the regions additional sites were sampled to incorporate site scale variability along cross-shore gradients.

The program involved nine core research components:

1) Correlate patterns with physical environmental variables (e.g. light, nutrients, wave energy, transport)

2) Describe biogeographic patterns in benthic community structure

3) Quantify seasonal and inter-annual variability at key sites

4) Determine the effects of nutrient availability in benthic reef communities

5) Describe patterns in community structure determined by ecological interactions

6) Determine principal sources of nitrate supply to the shelf

7) Determine the role of biogeochemical nutrient cycling in pelagic ecosystems

8) Characterise spatial and temporal variability in coastal ocean water column productivity using chlorophyll concentration as a proxy, and SST using remote sensing technology

9) Characterise spatial and temporal variability in coastal sediment transport and benthic habitat distribution using remote sensing technology

Standard protocols included sampling to obtain data on: benthic algal species diversity and biomass, benthic invertebrate diversity, abundance and biomass, substratum physical characteristics, depth, invertebrate recruitment, light attenuation, TSS, chlorophyll *a*, particulate organic carbon, nutrient concentrations, salinity, as well as CTD casts with concurrent measurement of *in situ* fluorescence, dissolved oxygen and subsurface irradiance; discrete water column samples for analysis of salinity, dissolved nutrients (nitrate+nitrite, ammonium, phosphate and silicate), chlorophyll *a*, HPLC pigments, particulate organic carbon, phytoplankton and microzooplankton species composition and abundance. Biogeochemical sampling protocols include sampling of sediment cores, and interstitial waters, sampling for microphytobenthos, *in situ* O_2 microprobe sediment measurements and *in situ* benthic respirometry chamber deployments.

The coastal ecology program's ocean colour group has developed the capability to routinely download, archive and process remote-sensed data from a number of applications. This capacity feeds into all aspects of the SRFME program, and has been extensively validated by a field sampling program including both case 1 and case 2 waters. The remote sensing and concurrent validation have produced time series of SST and chl *a* for the study area that indicate a clear seasonality in coastal chl *a* with summer minima and winter maxima in May-August. This seasonal trend in phytoplankton biomass is attributable to an overall increase in phytoplankton rather than to the abundance of any particular taxon. Winter chl *a* trends are paralleled by a seasonal trend in total suspended solids (likely to be mainly algal detritus) and CDOM. The parallel trends in phytoplankton biomass as well as in re-suspended matter and CDOM suggest that an important seasonal source of N in coastal waters is indeed likely to be from sources in or near the bottom or sediments. Analysis of broad scale spatial and temporal data sets suggests that further offshore an additional source of nutrients is likely to be deeper mixing related to a deepening of the mixed layer mixing nutrients into the euphotic zone. These trends in phytoplankton biomass are relative and WA coastal waters are very low in phytoplankton productivity compared with other coastal waters around the world.

Algal and invertebrate communities both display latitudinal trends in community structure between the northern most sites at Greenhead, and the southern most sites at Cape Naturaliste, though this pattern is most clear in the algae. To date over 400 species of algae and seagrasses and 530 taxa of invertebrates have been recorded. There was significant variation in algal community structure within the three study regions of Jurien, Perth and Geographe Bay, as well as among sites within locations. Preliminary analysis suggests that reef topography plays some role in this variation, though further analysis including a wider range of physical variables is still to be completed. The study of this variability holds significant prospects for informing our understanding of physical factors important to algal assemblage structure. Initial analysis of the trends for invertebrates suggests these may follow a similar pattern of variability at small scales.

Seasonal trends were apparent in benthic algal biomass, and these appear to stem from both seasonal changes in the physical environment and intrinsic life history attributes of some key brown algal species. *Sargassum* spp. undergo a seasonal growth, reproduction and senescence with maximum biomass in winter and spring, and sites dominated by this genus showed overall trends in keeping with this. Most sites however were dominated by either the kelp *Ecklonia radiata* or mixed red and brown algal assemblages, and these sites showed a minimum biomass in winter and spring, correlating with decreased light penetration through the water column and increased storm activity. Thus there appears to be an inverse seasonal relationship between overall benthic algal biomass and phytoplankton biomass, ultimately linked to the same seasonal weather factors of storm activity and wave shear on the inner shelf.

Studies of spatial subsidies between reefs and seagrass habitats have established that detached reef algae are exported to adjacent seagrass beds, and are consumed by seagrass-associated fauna. The large quantities of detached algae suggest that this might form a considerable trophic link between reefs and adjacent seagrass habitats. In some places the spatial extent of this trophic link extends more than 300m away from the reefs. The biomass of detached reef algae increased with increasing proximity to the shore, with large accumulations occurring at some inshore reefs. Transport of drift macrophytes (reef algae and seagrass) to inshore reefs is considerable, and forms an important trophic link between inshore reefs and habitats further offshore. The spatial extent of the inshore-offshore linkages appears to be at least several kilometres.

Similar trophic linkages are likely to exist between reef predators and prey species found in seagrasses. Studies to date have focused on establishing the existence of gradients in predator density and population structure that can be used to examine the influence of reef-associated predators on seagrass fauna. At the Kingston Reef Sanctuary area on Rottnest Island the population of rock lobster greater than minimum legal size has been shown to be more than ten times greater than in areas outside the sanctuary subjected to recreational fishing. Sampling to assess the relative abundance of prey items has been undertaken at sites across this gradient and holds the potential to increase our understanding of important trophic relationships in Western Australia's coastal benthic ecosystems.

Over the next year the coastal project will concentrate on completing the processing of samples and analysis of data as well as preparing results for publication in refereed scientific journals, though significant amounts of data collection remain in the area of sediment nutrient flux sampling. Plans are being made for follow-up projects to investigate the roles of physical disturbance and recruitment on benthic communities on the temperate west coast and to determine the relative importance of linkages between water column and benthic processes among different regions. Remote sensing of ocean colour may play an important role in this, as well as in more extensive application of remote sensing to mapping of shallow water coastal habitat types. Plans are also underway to experimentally assess the role of both physical (nutrients and sediment) and ecological (herbivory and predation) disturbances to existing ecological processes. The potential for similar research programs at Ningaloo is also under development and may offer the opportunity to better integrate our understanding of ecological processes between the tropics and temperate areas.

6.4 Introduction

The goal of the SRFME Coastal Ecosystems and Biodiversity Project is to characterise and understand the mechanisms underlying natural variability in diversity and dynamics of biogeochemical and ecological processes in the water column, sediment, and benthic community assemblages in selected southwestern Australian coastal marine ecosystems. This knowledge will better enable us to determine their likely response to human influences and ensure their future health and sustainability. Western Australia is unusual in possessing high-biomass, high-productivity benthic ecosystems despite the relatively low-nutrient waters of this coastal region that result from the low-rainfall environment as well as the influence of the Leeuwin current. The project focuses mainly on reef habitats since these have been less intensively studied than the seagrass habitats of southwestern Australia. The geographic scope of the work includes areas between Greenhead and Geographe Bay.

The project has been designed with three functional components, benthic ecology, biogeochemistry, and remote sensing in order to provide an integrated picture of how biogeochemical and oceanographic processes interact with benthic ecosystems, and conversely, how the benthic ecosystems may influence processes in the overlying water column. The approach used has been to conduct parallel ecological, biogeochemical and remote-sensing studies to examine patterns and processes at a range of different scales in space and time as a means of relating physical factors to ecological pattern and process. In addition, this design provides us with the ability to assess whether observed variation is likely to be greater than that expected on a seasonal or regional level. Quarterly seasonal sampling for ecological, sediment and water column parameters has been undertaken at each of three regions; Geographe Bay, Perth, and Jurien, and within these regions sampling has been conducted at a range of locations separated by tens of kilometers. Sampling sites are nested within these locations and are separated by less than 10 km.

6.5 Coastal Project

Benthic Ecology: spatial and temporal variation in patterns and processes

Overall Objective: To characterise and quantify key patterns in assemblage structure and ecological processes in representative benthic reef habitats from south West Australian coastal waters. This understanding will enable us to better predict the location and spatial extent of habitats and their response to disturbance.

Specific objectives:

- Correlate patterns with physical environmental variables (e.g. light, nutrients, wave energy, transport)
- Describe biogeographic patterns in benthic community structure
- Quantify seasonal and interannual variability at key sites
- Determine the effects of nutrient availability in benthic reef communities
- Describe patterns in community structure determined by ecological interactions

Patterns in Physical Environmental Parameters

In order to relate physical parameters to the biological communities we described the physical characteristics of the reefs surveyed as well as recorded light attenuation through the water column and sampled dissolved nutrients (ammonia, nitrate, nitrite, silica phosphate and organics) and particulates (TSS, chlorophyll *a* and organics) for surface waters only. Water samples have only been collected since autumn 2004. Depths, rock types and a subjective measure of reef relief were recorded at each quadrat sampled. Quantitative measures of reef relief were also measured at both quadrat (1m) and site (10m) scales.

Study sites

Thirty five sites have been studied so far in the project; 5 sites from Greenhead, 10 from Jurien Bay, 2 from Two Rocks, 9 from Marmion, 7 from Bunbury and 2 from Cape Naturaliste (Figure 96 & Table 15). Within each locality 2 core sites are sampled each season, the remaining sites are usually only sampled once in order to capture spatial variation related to cross-shelf position and depth within each locality.

The average depths of reefs sampled ranged from 2.2m at North Essex in Jurien Bay to 15.9m at BBY15M at Geographe Bay. Most of the reefs sampled are less than 7m but there is at least one deeper (>10m) site sampled in each region, Fisherman's Island 12m and Seaward Ledge 13m at Jurien Bay, Little Island West 1, 3 Mile Reef North & South and Horseshoe Reef West 1 at Marmion and BBY15M, BBY08, and BBY14M at Geographe Bay. The core sites are all inshore sites of less than 7m depth.

The majority of the reefs sampled were limestone reefs; the exceptions to this are granite reefs located at Cape Naturaliste (Eagle Bay and Quarries) and one site at Bunbury (BBY08). The relief of core sites range from flat limestone reefs at the Bunbury sites (South Bunbury and Dalyellup), through medium relief reefs at the Marmion sites (South Lumps, Whitford Rock) and Julia Rocks at Greenhead, to high relief reefs at the remaining Jurien sites (Fisherman Island Sanctuary Zone 3 (FISZ3), Wire Reef, Booka Valley Rocks) and the Two Rocks sites (Cook Lump, Map Reef) (Table 15). The Cape Naturaliste sites are medium to high relief granite boulders and cobbles interspersed with low relief sand-covered patches of reef.

Rugosity codes did not always reflect the subjective assessment of reef topography. Some of the discrepancies between these measures reflect the different scales of assessing the rugosity of a reef. The subjective measure of reef relief looks more at the elevation of the reef above the bottom, while the quantitative rugosity measures the topography of the tops of the reef where sampling takes place so a reef could be classed as a high relief reef using the subjective measure as it is elevated from the bottom but the rugosity code is only of moderate value and this reflects the topography of the reef not going all the way to the bottom (eg. Seaward Ledge 6m).

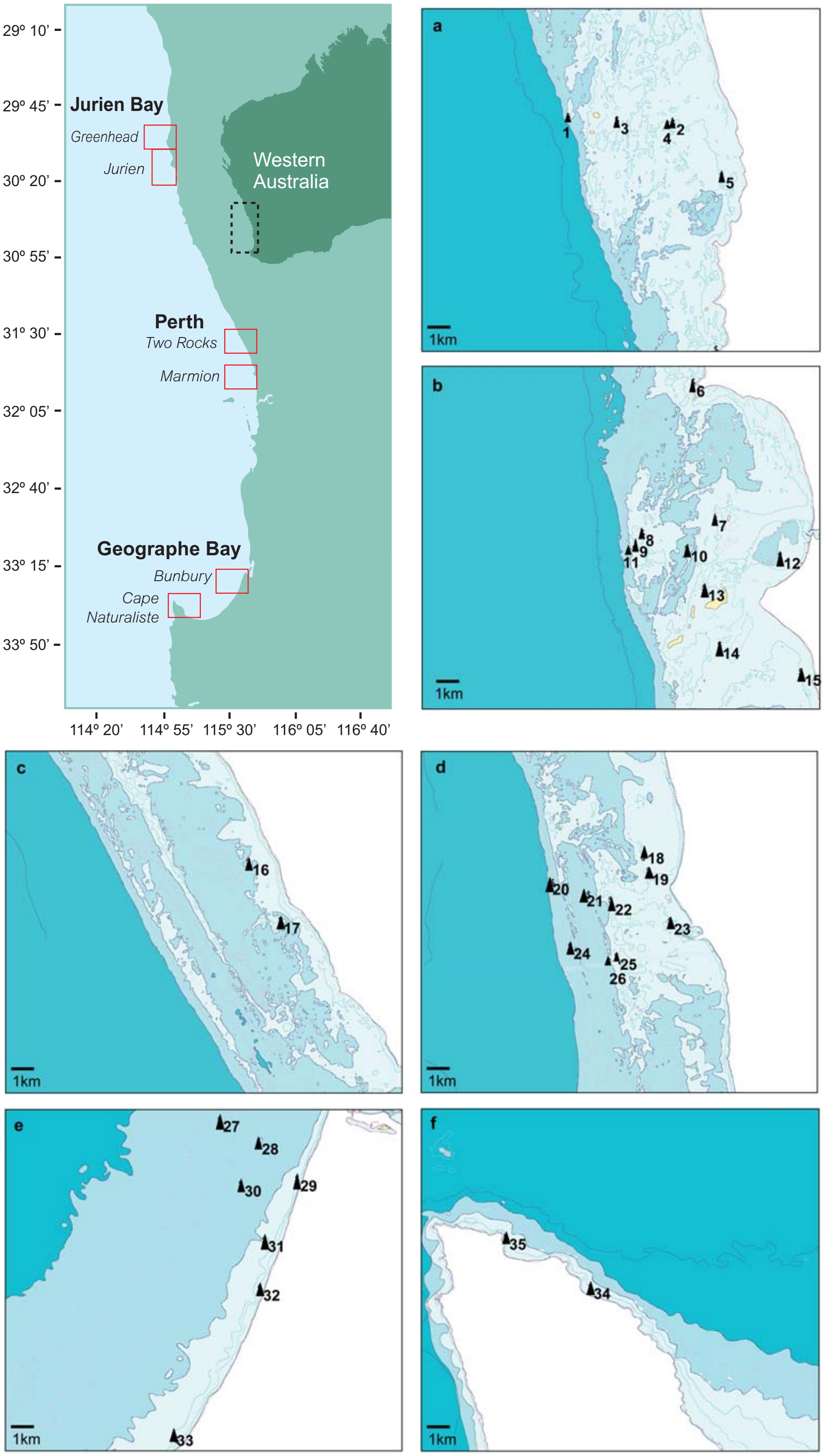


Figure 96: SRFME Coastal Ecosystems and Biodiversity Project study area showing the regions, locations and sites within each locality a) Greenhead, b) Jurien Bay, c) Two Rocks, d) Marmion, e) Bunbury and f) Cape Naturaliste. Site numbers are from Table 15. Colour shading on locality maps, white, mainland; yellow, islands; light, 0-10m; mid, 10-20m; dark, 20-50m. Contour lines represent intermediate isobaths.

Table 15. Sampling depths, reef relief and rugosity codes for all sampling sites. Core sites are indicated in bold. Reef relief, L – flat reef (0 – 10 cm), M – medium relief reef (10 – 100 cm), H – high relief reef (> 100cm), B – boulders, C – cobbles, * – granite reefs.

					Rugosity Code			
		Depth (metres)			Site		Quadrat	
No.		Mean	Range	Relief	Mean	St Dev	Mean	St Dev
	Jurien							
	Greenhead							
1	Fisherman's Island 12m	12.8	(12.5 - 13.2)	M	1.0	(0.1)	1.1	(0.1)
2	FISZ 1	4.8	(4.2 - 5.5)	M	1.2	(0.1)	-	-
3	FISZ 2	3.8	(3.4 - 4.2)	-	1.3	(0.2)	-	-
4	**FISZ 3**	**4.1**	**(2.5 - 5.8)**	**H**	**1.4**	**(0.2)**	**1.5**	**(0.2)**
5	**Julia Rocks**	**2.8**	**(1 - 4.4)**	**LMH**	**1.3**	**(0.1)**	**1.3**	**(0.2)**
	Jurien Bay							
6	North Head	4.6	(4.3 - 4.9)	MH	1.3	(0.05)	1.4	(0.2)
7	Favourite Island	6.2	(6.1 - 6.4)	L	-		-	-
8	Seaward Ledge East 06	6.5	(5.8 - 6.8)	LHC	1.2	(0.1)	1.4	(0.3)
9	Seaward Ledge 6m	7.0	(6.1 - 8.4)	H	1.3	(0.1)	1.2	(0.1)
10	North Marker	9.7	(9 - 10.2)	L	1.3	(0.1)	-	-
11	Seaward Ledge 13m	13.6	(13.3 - 14)	M	1.1	(0.1)	1.1	(0.1)
12	**Wire Reef**	**5.1**	**(4 - 6.3)**	**H**	**1.6**	**(0.1)**	**1.6**	**(0.3)**
13	North Osprey	2.8	(2.5 - 3.1)	LM	1.4	(0.1)	-	-
14	North Essex	2.2	(1.9 - 2.5)	H	1.5	(0.1)	-	-
15	**Booka Valley Rocks**	**4.1**	**(2.8 - 5.2)**	**H**	**1.7**	**(0.2)**	**1.8**	**(0.2)**
	Perth							
	Two Rocks							
16	**Cook Lump**	**5.8**	**(3.5 - 8)**	**H**	**1.3**	**(0.05)**	**1.4**	**(0.3)**
17	**Map Reef**	**5.8**	**(3.7 - 7.1)**	**H**	**1.9**	**(0.3)**	**1.8**	**(0.4)**
	Marmion							
18	**South Lumps**	**5.5**	**(4.4 - 7.2)**	**LM**	**1.2**	**(0.1)**	**1.4**	**(0.2)**
19	**Whitford Rock**	**4.4**	**(2.9 - 5.6)**	**LM**	**1.5**	**(0.2)**	**1.6**	**(0.3)**
20	3 Mile Reef North	15.5	(14.8 - 16.2)	LM	-	-	1.1	(0.2)
21	Little Island West 1	14.0	(13.4 - 15)	M	-	-	-	-
22	Little Island	4.6	(4 - 5.3)	M	-	-	-	-
23	Cow Rock	4.2	(3 - 5.1)	H	-	-	1.5	(0.2)
24	3 Mile Reef South	13.6	(13 - 14.2)	M	-	-	1.1	(0.2)
25	Outer Horseshoe Reef	6.5	(6.2 - 6.8)	L	-	-	-	-
26	Horseshoe Reef West 1	13.8	(13.4 - 14.2)	L	-	-	-	-
	Geographe Bay							
	Bunbury							
27	BBY15M	15.9	(15.1 - 16.2)	L	1.0	(0.05)	1.1	(0.0)
28	BBY08	10.8	(10.4 - 11)	L*	1.2	(0.1)	-	-
29	**South Bunbury**	**7.0**	**(6.5 - 7.4)**	**LM**	**1.4**	**(0.2)**	**1.3**	**(0.2)**
30	BBY14M	13.7	(13.2 - 14.2)	L	1.2	(0.1)	1.1	(0.1)
31	BBY10B	9.4	(9.2 - 9.5)	L	1.1	(0.1)	-	-
32	**Dalyellup 1**	**6.4**	**(5.6 - 7.2)**	**LM**	**1.1**	**(0.4)**	**1.2**	**(0.1)**
33	Capel 5	2.5	(2.2 - 2.6)	MH	1.4	(0.1)	1.7	(0.1)
	Cape Naturaliste							
34	**Eagle Bay**	**5.7**	**(4.9 - 6.6)**	**LMHBC***	**1.4**	**(0.2)**	**1.6**	**(0.3)**
35	**Quarries**	**4.9**	**(3.8 - 5.5)**	**LMHBC***	**1.2**	**(0.1)**	**1.5**	**(0.6)**

Nutrients

Available nitrogen was measured in the form of ammonium (NH_4) and total oxidised nitrogen (NO_x) the combination of nitrate (NO_3) and nitrite (NO_2) (Figure 97). In the majority of samples NO_x makes up a larger portion of available nitrogen than NH_4. Mean levels of available nitrogen were highest during autumn 2004 particularly at Two Rocks, Jurien Bay and Marmion localities. Mean levels at Marmion were also elevated above that of the other sites during winter 2004, summer 2005 and autumn 2005. Mean phosphate (PO_4) levels at the majority of sites ranged from 0.3 to less than 0.01 μM^{-L}, and were highest at Marmion (0.28 μM^{-L}) and lowest at Bunbury (0.04 μM^{-L}) (Figure 98). There was little seasonal change in phosphate levels.

Chlorophyll *a*

Mean Chlorophyll *a* levels were highest in Bunbury (1.53 μM^{-L}) and lowest at Jurien Bay (0.5 μM^{-L}) (Figure 98). Mean Chlorophyll *a* levels did not vary much between autumn and winter and data is as yet unavailable for spring and summer. This is consistent with the trends in nutrient availability.

Suspended solids

Total suspended solids (TSS) levels ranged from 0.9μg^{-L} at Jurien Bay to 1.83μg^{-L} at Bunbury with levels at Bunbury and Marmion generally higher than other localities (Figure 98). Seasonally, TSS was highest in winter (1.99 μg^{-L}) and lowest in summer (0.96 μg^{-L}) (Figure 99). Mean Silica levels ranged from 0.93 to 1.65μg-L at Marmion and Greenhead respectively (Figure 99). Silica levels were generally lowest in summer (0.53 μg^{-L}) and highest in winter (1.99μg^{-L}) (Figure 99) .

Light attenuation

Light attenuation coefficient showed a clear seasonal trend across most locations with attenuation increasing from autumn to winter and the highest attenuation recorded during spring then dropping off during summer (Figure 100). Bunbury generally had the highest attenuation coefficient, which also corresponds to the high levels of Chlorophyll *a* and TSS particularly during winter and spring.

These trends were also quite apparent to the divers conducting sampling at each locality as changes in underwater visibility. Visibility was very low at Bunbury sites during spring 2004 with a distinct reduction to almost zero visibility within 1 to 2 m above the bottom. Because water samples were collected near the surface however, this stratification of highly turbid water near the bottom is not fully reflected in the TSS samples.

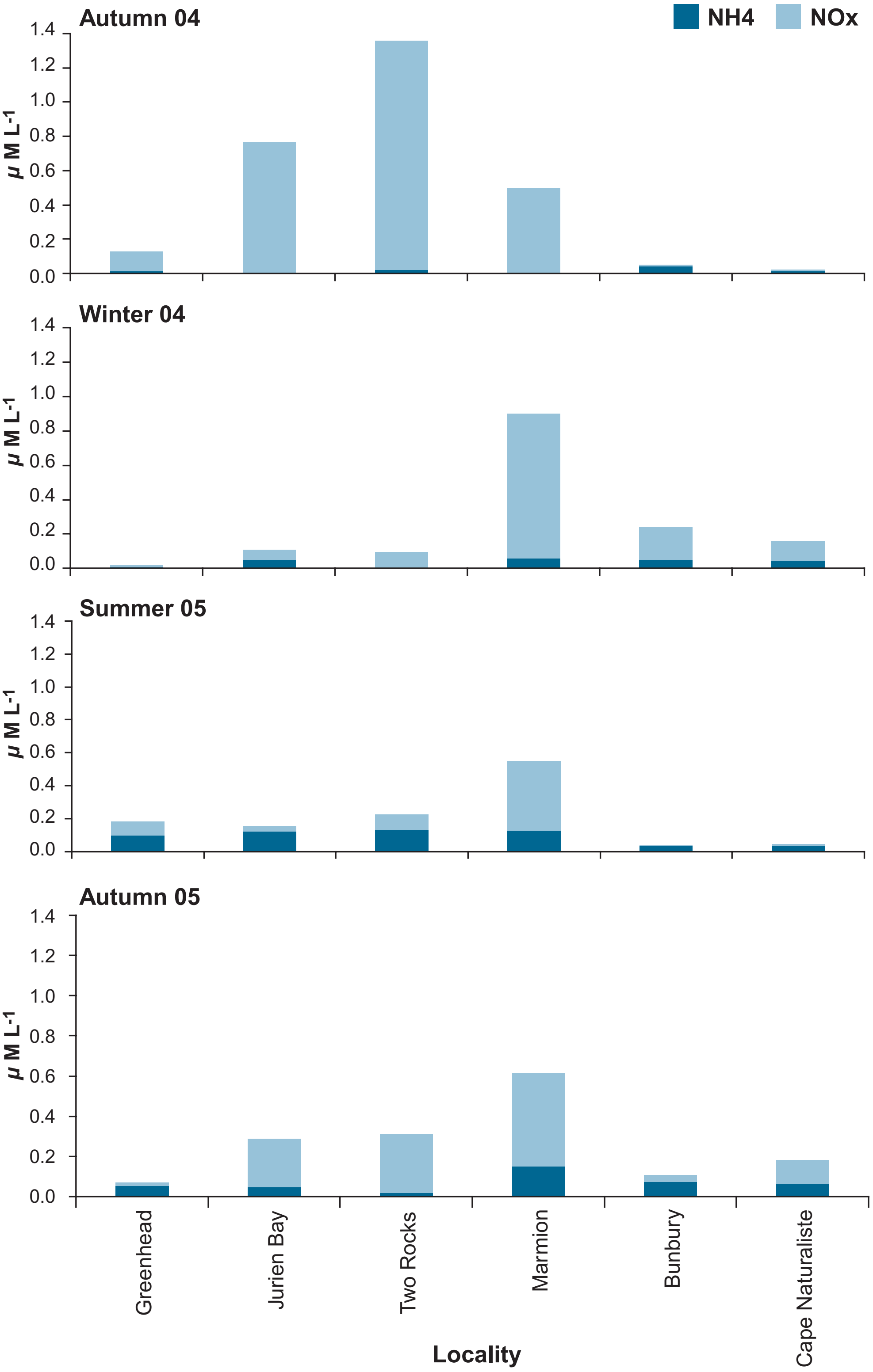


Figure 97: Mean Nitrate (NO_x) and Ammonium (NH_4) recorded from sites within each locality. Spring data is unavailable.

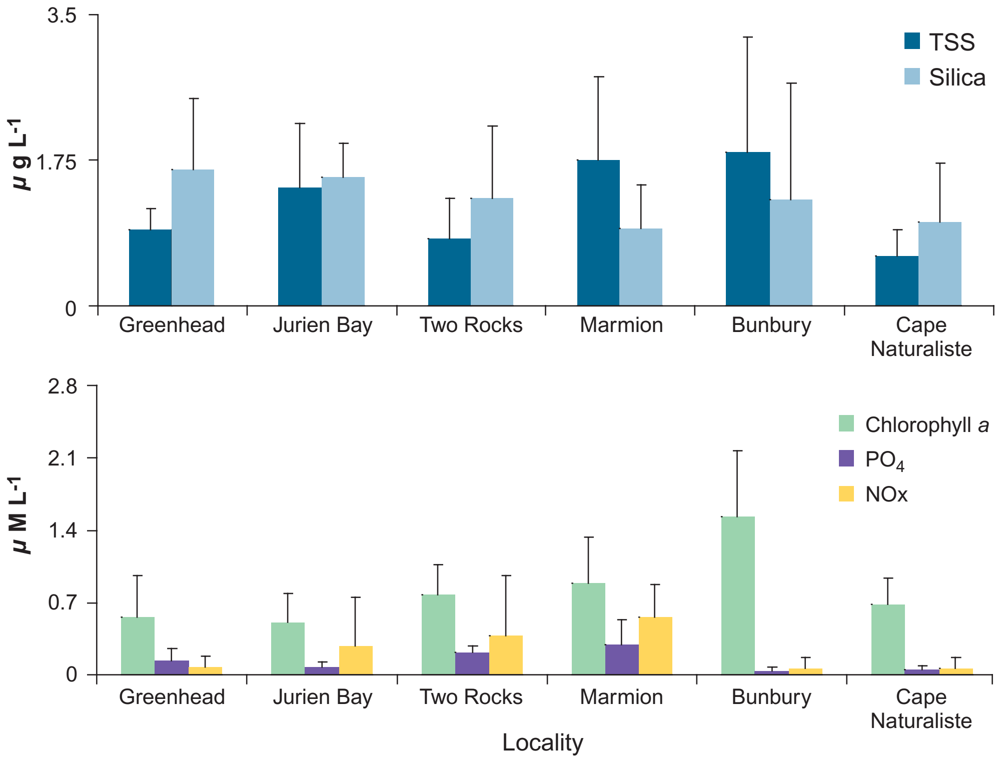


Figure 98: Locality average (+ sd) of Total Suspended Solids (TSS), Silica, Chlorophyll *a*, PO_4, and NO_x for all sites and seasons.

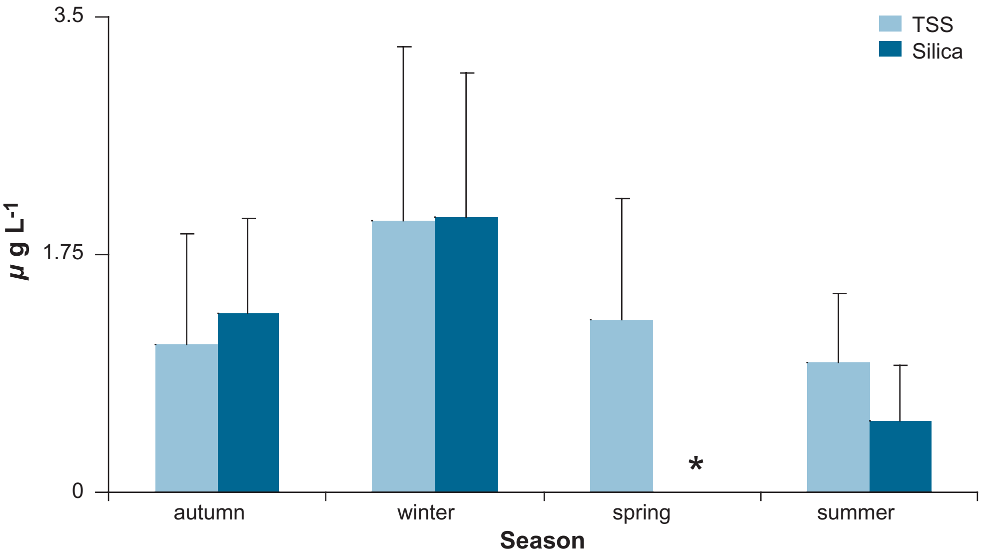


Figure 99: Seasonal average (+ sd) across all sites of Total Suspended Solids (TSS), Silica and Chlorophyll *a*. * data unavailable.

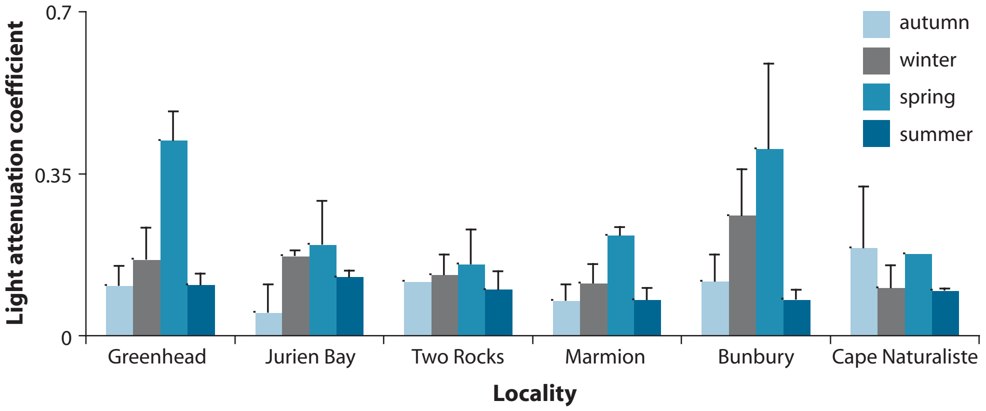


Figure 100: Seasonal average (+ sd) light attenuation recorded from all sites within each locality.

Spatial and temporal patterns in algal communities

Introduction

Rocky reefs are an important habitat type in nearshore coastal waters, supporting a diverse assemblage of benthic marine macroalgae (Huisman & Walker 1990, Phillips *et al* 1997). Benthic algal assemblages are a key component of coastal productivity, provide habitat and food for marine invertebrates and fish, contribute to biogeochemical cycles, and can exert influence over nearby habitats such as seagrass meadows (Van Elven *et al* 2004). Despite their recognised importance, comparatively little is known of the ecology of the algal habitats along the lower west coast of Western Australia. As a consequence, research into the benthic algal assemblages is a major focus of the SRFME coastal ecosystems project since an understanding the mechanisms that structure algal assemblages is vital to our understanding of ecosystem processes and functioning.

Aims/objectives

The overall aim of the benthic algal research is to characterise and understand the mechanisms underlying natural variability in diversity in algal assemblages in coastal marine reef ecosystems. To address this overall aim, quarterly sampling of reef algal assemblages has been conducted at different spatial and temporal scales to address more specific aims:

Aim 1: To create an inventory of algae species recorded within the SRFME region.

Aim 2: To characterise the spatial variation in algal assemblages in nearshore reef habitats.

Aim 3: To characterise the temporal variation in algal assemblages in nearshore reef habitats.

Aim 4: To examine environmental correlates of algal assemblage structure.

A. Major findings of each aim

Inventory of benthic macroalgae

To date, over 400 species of benthic marine plants (ie. macroalgae and seagrasses combined) have been identified from the SRFME study area. This includes numerous range extensions of species' distributions, and the 'rediscovery' of a red alga, *Gelidiella ramellosa*, not recorded from Western Australia for over 150 years. Voucher specimens of algae from each region are being collated and will ultimately form part of the marine plant collection of the WA Herbarium. The distribution of marine plant species among the three SRFME regions is represented diagrammatically in Fig. 101.

Species richness was comparable between regions; Perth, Geographe Bay and Jurien have had a total of 229, 243 and 280 species recorded, respectively. Jurien had the highest number of species unique to that region (71), while 140 species have been recorded in all three regions. Although the Jurien and Geographe Bay regions are geographically disjunct, it is interesting to note that 31 species occur in both regions, indicating a broad geographic distribution of these species along the lower west coast of Western Australia.

In all three regions, species richness was dominated by red algae (Division Rhodophyta), accounting for 56-70% of all species recorded (Figs 102-104). Among the regions, brown algae (Phaeophyta) accounted for 17-34% of species richness but were the dominant component in terms of biomass in the Jurien and Perth regions. This is explained by the large size of the fucalean (eg. *Sargassum, Cystophora, Platythalia*) and laminarian (eg. *Ecklonia*) brown algae that were common on reefs in these regions. Within Geographe Bay, the Naturaliste sites were dominated by brown algal genera including *Sargassum*, *Cystophora*, *Platythalia* and *Cystophora*, while the latter three genera were absent from Bunbury reefs.

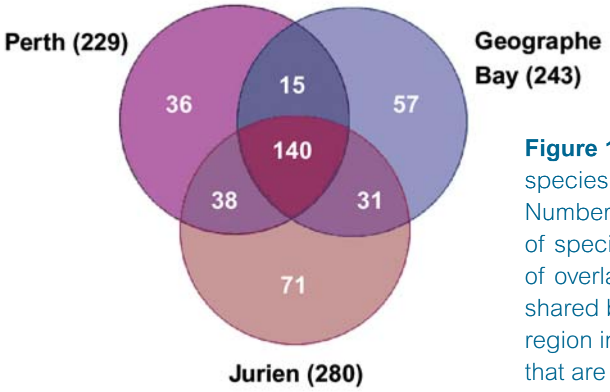


Figure 101: Distribution of marine plant species among the SRFME regions. Numbers in parentheses are total number of species found within a region. Areas of overlap indicate the number of species shared between regions; the central region indicates the number of species that are common to all three regions.

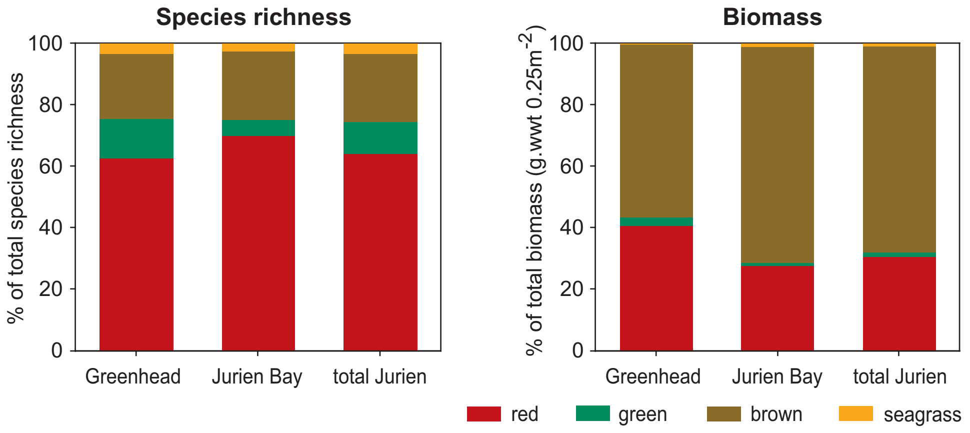


Figure 102: Contribution of each algal division and seagrasses to total species richness and total biomass in the Jurien region.

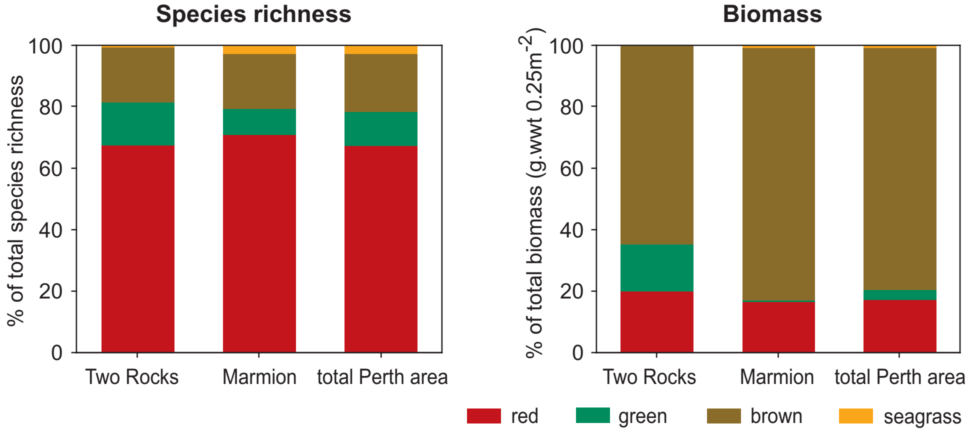


Figure 103: Contribution of each algal division and seagrasses to total species richness and total biomass in the Perth region.

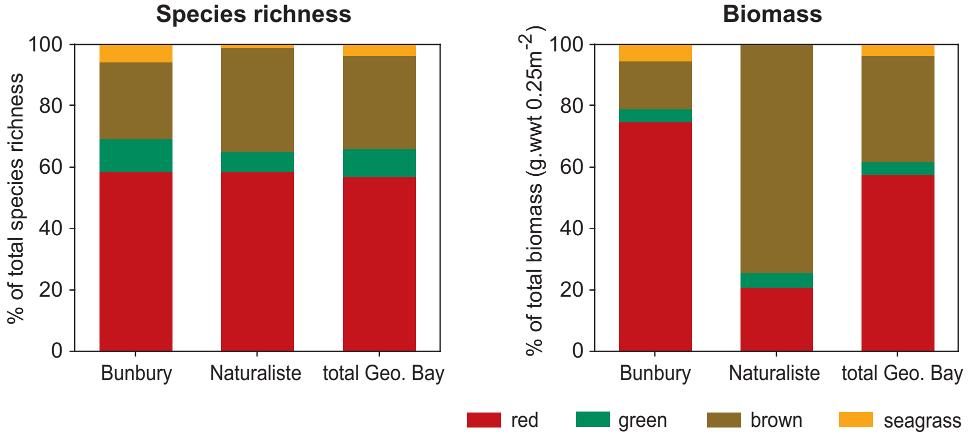


Figure 104: Contribution of each algal division and seagrasses to total species richness and total biomass in the Geographe Bay region.

Spatial variation in algal assemblage structure

At the largest spatial scale (ie. region), some pattern in algal assemblage structure was evident. Although an analysis of similarities (ANOSIM, conducted in the computer package PRIMER) indicated a substantial degree of overlap in assemblage structure among the three regions (Global *R* = 0.37, *P* = 0.001), post-hoc pairwise comparisons showed Perth and Geographe Bay to have significantly different algal communities (*R* = 0.649, *P* = 0.001). The dissimilarity in assemblages was driven by abundance of the kelp, *E. radiata*; 7.5% of samples in Geographe Bay contained *E. radiata*, compared to 70% in Perth (determined from a percentages of similarities analysis, SIMPER, conducted in the computer package PRIMER).

Ecklonia radiata was also responsible for defining similarity between regions. As mentioned, the average abundance of *E. radiata* on Perth reefs was 70%, which accounted for 64.9% of the similarity between reefs in this region (SIMPER). The abundance of *E. radiata* in the Jurien region was also high (39% of samples and 31.6% contribution to similarity; SIMPER), resulting in no significant difference in algal assemblage structure between the two regions (*R* = 0.174, *P* = 0.001; ANOSIM).

When comparing within regions, reefs in the Perth region (Fig. 105a) had an average similarity of 42% in species composition between reefs (SIMPER). The similarity of species composition on reefs in the Jurien and Geographe Bay regions was considerably lower, at 25% and 21% respectively. The relatively high degree of similarity in species composition among reefs in the Perth region was again driven by the abundance of the kelp, *Ecklonia radiata*, on Perth reefs (SIMPER).

Comparison of algal assemblages within each locality indicates statistically significant differences between the six localities (*R* = 0.546, *p* = 0.001; ANOSIM; Fig. 105b, Table 16). Furthermore, differences in algal assemblages were usually large between localities within a region; localities within Jurien and Geographe Bay had reasonably dissimilar algal assemblages (Table 16). Algal species composition was most similar between reefs within the Jurien Bay and Marmion localities (*R* = 0.111, *p* = 0.003; ANOSIM), both of which have a number of reefs dominated by *Ecklonia radiata* forests.

The clustering of Jurien Bay, Two Rocks and Marmion localities in Fig. 105b can be explained by a common suite of species that typify algal assemblages in these areas. The brown algae *Ecklonia radiata* and *Sargassum* spp., along with several red algae including *Pterocladia lucida, Rhodymenia sonderi, Amphiroa anceps* and *Curdiea obesa*, were abundant at all localities and all species were among those with the highest contribution to the similarity in assemblage structure between reefs (SIMPER). The clustering of Greenhead and Cape Naturaliste results from *Sargassum* spp. (SIMPER) being the dominant canopy-forming brown algae on reefs in these two areas, in contrast to *E. radiata* which dominates the canopy structure at Jurien Bay, Two Rocks and Marmion.

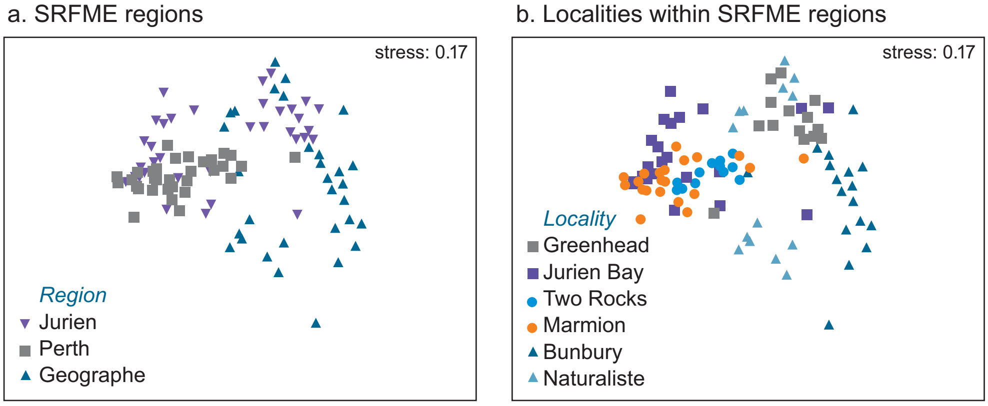


Figure 105: Multidimensional scaling of macroalgal assemblages found on reefs in the SRFME study area. Data points grouping together have similar species composition.

Table 16. Results from a 1-way analysis of similarities (ANOSIM) among localities and post-hoc pairwise comparisons between localities.

	R statistic	*P*
Global test	0.546	0.001
Pairwise comparisons		
Bunbury vs. Cape Naturaliste	0.601	0.001
Bunbury vs. Jurien Bay	0.82	0.001
Bunbury vs. Greenhead	0.461	0.001
Bunbury vs. Marmion	0.86	0.001
Bunbury vs. Two Rocks	0.696	0.001
Cape Naturaliste vs. Jurien Bay	0.61	0.001
Cape Naturaliste vs. Greenhead	0.498	0.001
Cape Naturaliste vs. Marmion	0.771	0.001
Cape Naturaliste vs. Two Rocks	0.601	0.001
Jurien Bay vs. Greenhead	0.624	0.001
Jurien Bay vs. Marmion	0.111	0.003
Jurien Bay vs. Two Rocks	0.225	0.007
Greenhead vs. Marmion	0.828	0.001
Greenhead vs. Two Rocks	0.651	0.001
Marmion vs. Two Rocks	0.407	0.001

* calculated from rank similarities between groups: $R = 1$ indicates strong separation between groups; $R \approx 0$ indicates null hypothesis is true, that there is no difference between groups.

Jurien region

The species composition of algal assemblages on reefs in Greenhead and Jurien Bay showed some degree of overlap (Fig. 106) but differed in the presence of many foliose and turfing species of a more sub-tropical distribution being found on reefs at Greenhead. Differences in assemblage structure also resulted from shifts in the abundance of canopy-forming brown algal species: on reefs in Greenhead, *Sargassum* spp. occurred in 17.1% of samples compared to *Ecklonia radiata* in only 1.3% of samples; in Jurien Bay *E. radiata* was the dominant canopy species in 24.9% of samples while *Sargassum* spp. were recorded in only 10.8% (from SIMPER analysis).

The clustering of sites in the Jurien region shown in Fig. 106b can be broadly divided in two according to their algal assemblages. Those sites grouping to the right of the diagram are characterised by *Ecklonia radiata* being the species having the highest contribution to similarity between samples from those sites. The sites ranged from those with a continuous canopy of *E. radiata* (>80% contribution to similarity between sites; SIMPER) to those with a mixed *E. radiata*-fucoid canopy (*E. radiata* contribution between 23-44%; SIMPER). With the exception of the Fish 12 site, all sites dominated by *E. radiata* were found in the Jurien Bay locality.

Sites grouped to the left side of Fig. 106b were predominantly characterised by an abundance of *Sargassum* spp., which accounted for 15-82% of similarity in algal assemblages (SIMPER). Low turfing and foliose algae were also an important component of algal assemblages on these reefs.

Favourite Island was unique among the Jurien reefs, being the only site where the dominant species was a seagrass (*Amphibolis griffithii*). The dispersion of Favourite Island samples in Fig. 106b results from a number of foliose red algae that were common to many reefs in the Jurien region, and were growing interspersed among the seagrass at Favourite Island. Pairwise comparisons of algal assemblages at all reefs in the Jurien region indicated that Favourite Island has a distinct species composition compared to all other reefs (*R* between 0.63 – 1, *P* ≤ 0.08; ANOSIM). The most similar reefs in terms of species composition were East Seaward 6m and Seaward 13m (*R* = 0.131, *P* = 0.17; ANOSIM).

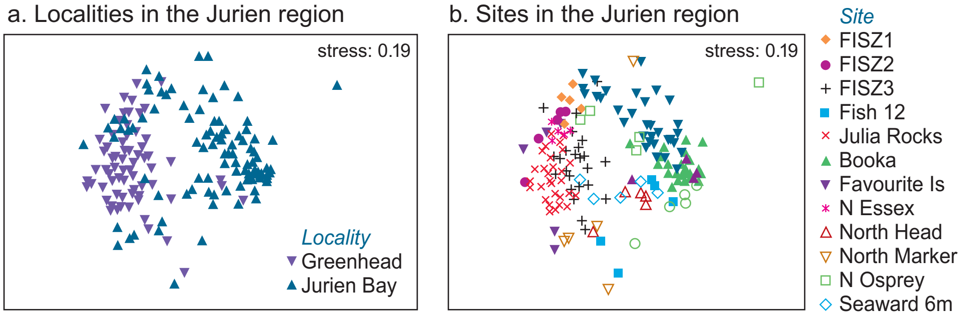


Figure 106: Multidimensional scaling of macroalgal assemblages found on reefs in the Jurien region. Data points grouping together have similar species composition.

Perth region

Geographic location of reefs in the Perth region did not affect species composition, with sites at Two Rocks and Marmion having similar, and overlapping, overall algal assemblage structure (*R* = 0.172, *P* = 0.001; ANOSIM) (Fig. 107a). Reefs sampled on the 3 Mile Reef chain in Marmion were *a priori* divided both geographically (North vs. South) and on the presence of an overlying canopy of brown algae (+ C vs. – C). Those sites without a canopy of brown algae (namely, 3 Mile N – C and 3 Mile S – C) clustered together (*R* = 0.328, *P* = 0.08; Fig. 107b) according to their assemblage structure, which can be classified as a turfing/low foliose algal assemblage (from SIMPER analysis). Analysis of the species characterising the assemblage structure at remaining sites revealed that the three other main habitat types are present in the Perth region; *Ecklonia radiata* forest (found at Horseshoe West, Little Island, Little Island West, South Lumps, Whitford Rock, Cook Lump and Map Reef), *Sargassum*-dominated assemblage (Outer Horseshoe) and a mixed brown algal canopy assemblage (3 Mile N + C and 3 Mile S + C) (SIMPER).

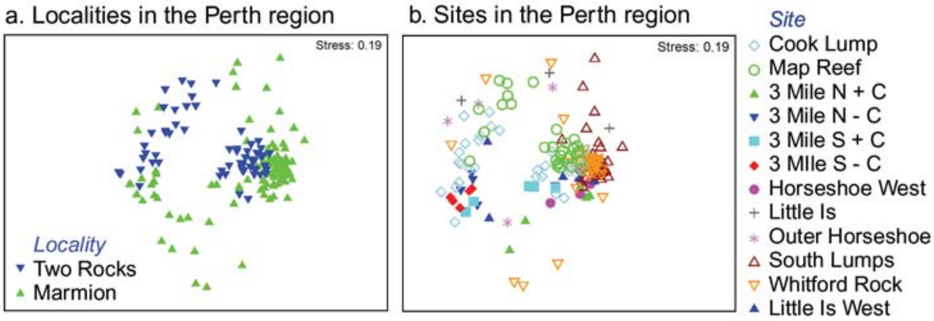
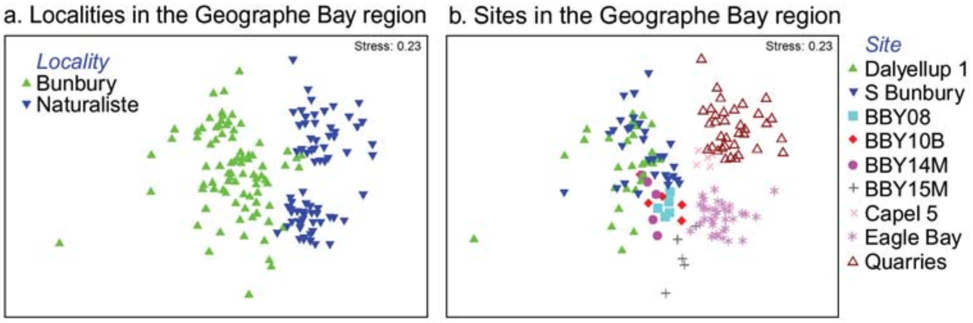


Figure 107: Multidimensional scaling of macroalgal assemblages found on reefs in the Perth region. Data points grouping together have similar species composition.

Geographe Bay region

Algal assemblages in the Geographe Bay region could be separated by their geographic location, with assemblages from Bunbury reefs differing from those found on Cape Naturaliste reefs ($R = 0.401$, $P = 0.01$; Fig. 108a). Assemblage structure on reefs at Quarries was characterised by the abundance of brown algae belonging to the Cystoseiraceae (eg. *Platythalia, Cystophora*), which was unique among reefs in Geographe Bay (from SIMPER analysis). As a result, analysis of the similarity between species composition on all reefs showed that Quarries was well separated from all other reefs ($R \leq 0.688$, $P = 0.001$ in all comparisons; ANOSIM) although there was some overlap in species composition with Capel 5 ($R = 0.492$, $P = 0.001$). The clustering of Capel 5 samples close to those from Quarries (Fig. 108b) is explained by the abundance of the coralline red algae *Amphiroa anceps* and *Metamastophora flabellata*, which were among the top three algae contributing to similarity among samples at both sites (SIMPER).

Remaining reefs in Geographe Bay had an algal assemblage structure that could be broadly split into two habitat types. Eagle Bay was the only reef in the region to be dominated by *Sargassum* spp., while the other reefs were characterised by a low algal assemblage dominated by a mix of coralline and foliose red algae (1-way SIMPER). This latter habitat type was restricted to reefs in the Bunbury locality.


a. Localities in the Geographe Bay region

b. Sites in the Geographe Bay region

Figure 108: Multidimensional scaling of macroalgal assemblages found on reefs in the Geographe Bay region. Data points grouping together have similar species composition.

Temporal variation in algal assemblage structure

Temporal variation in algal assemblage structure has been examined at the four sites within each region. These sites have been sampled between two and four times in each season.

Jurien region

Strong seasonal patterns in algal assemblage structure were evident only at the FISZ3 reef (Fig. 109). At this site, which can be classified as a *Sargassum*-dominated assemblage, the abundance of species varied significantly between seasons ($R = 0.706$, $P = 0.001$; ANOSIM). This seasonal variation can be explained by the life cycle of the dominant genus, *Sargassum*, a brown alga which produces long primary branches bearing reproductive structures during mid-winter and spring (Womersley 1987). Following the release of spores, plants die back to a basal rosette of fronds in summer and autumn (Womersley 1987). This seasonal development cycle results in dramatic variations in the abundance of *Sargassum* at different times of the year, and is reflected in Table 17.

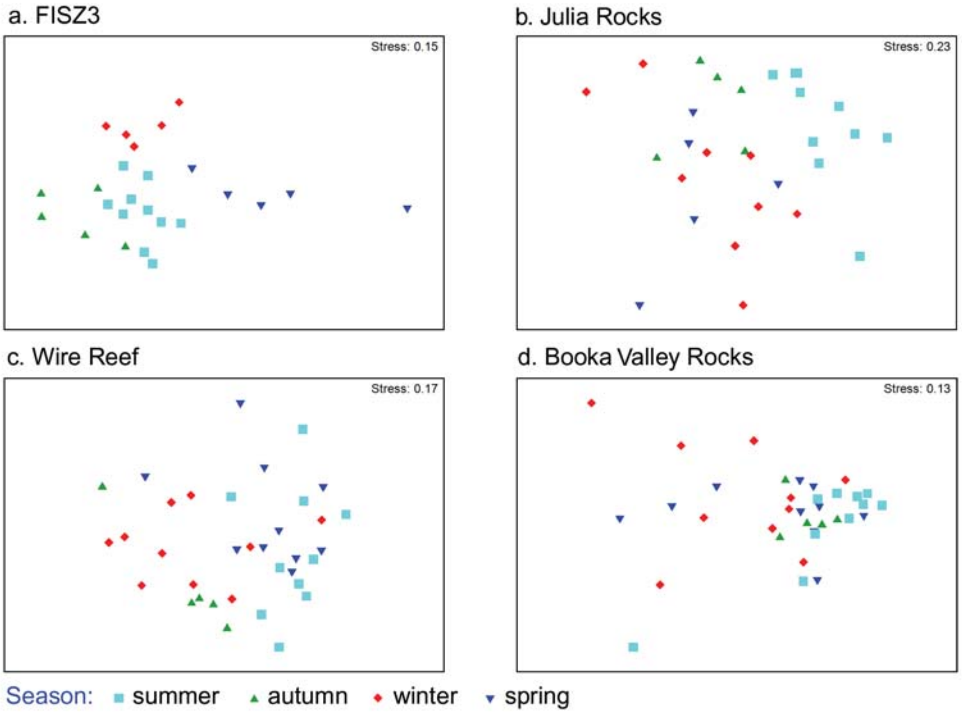


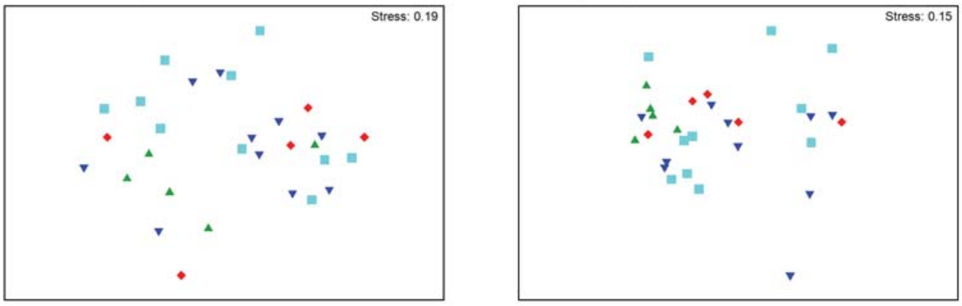
Figure 109: Multidimensional scaling of seasonal variation in macroalgal assemblages found on reefs in the Jurien region. Data points grouping together have similar species composition.

Table 17. Seasonal abundance and contribution of the five algal species with the highest contribution towards similarity in assemblage structure in each season at Fisherman's Island Sanctuary Zone 3 (FISZ3). Results are from a 1-way analysis of percentages of similarity (SIMPER) of species contributions, conducted in PRIMER.

	Mean Abundance (% of samples)	Contribution (%) to similarity between samples
Summer		
turfing spp.	7.90	16.53
Hypnea spp.	6.75	11.84
Padina spp.	4.93	8.22
Sargassum spp.	5.62	8.05
Laurencia clavata	3.01	4.50
Autumn		
turfing spp.	4.78	12.87
Sarcomenia delesserioides	5.95	12.33
Sargassum lacerifolium	7.00	11.37
Curdiea obesa	7.11	10.49
Lobophora variegata	2.46	7.44
Winter		
Sargassum spp.	22.62	35.64
Sargassum sp. *JJR1*	14.52	16.93
Hypnea spp.	8.51	9.46
Lobophora variegata	4.30	8.15
Metamastophora flabellata	5.49	6.35
Spring		
Sargassum linearifolium	18.16	44.47
Sargassum spinuligerum	13.94	26.48
Sargassum spp.	4.46	10.48
Lobophora variegata	3.05	5.34
Hypnea spp.	5.18	5.07

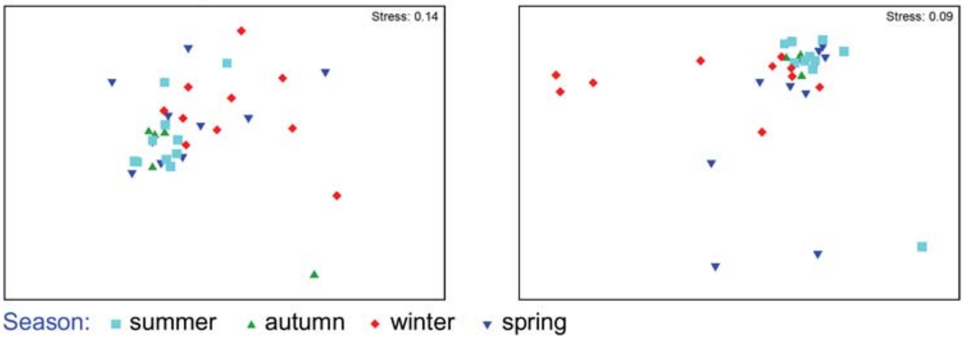
Perth region

The four core sites in the Perth region are reefs colonised by an *Ecklonia radiata* forest and its associated understorey. Unlike *Sargassum, Ecklonia* does not have a seasonal developmental cycle and as such its abundance remains relatively constant across seasons. The annual persistence of the *E. radiata* forest at Cook Lump, Map Reef, South Lumps and Whitford Rock is reflected by the absence of seasonal patterns in assemblage structure on these reefs (Fig. 110). On all reefs, *E. radiata* was the single highest contributing species to similarity of assemblage structure within each season (% contribution ranged between 24-44%; SIMPER).



a. Cook Lump

b. Map Reef



c. South Lumps

d. Whitford Rock

Figure 110: Multidimensional scaling of seasonal variation in macroalgal assemblages found on reefs in the Perth region. Data points grouping together have similar species composition.

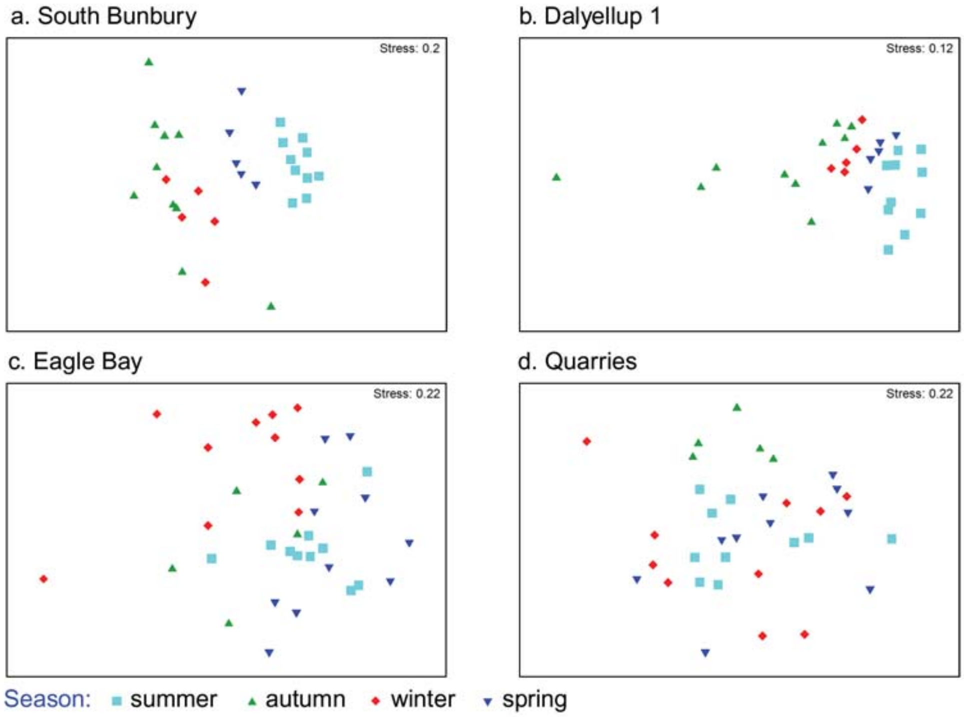


Figure 111: Multidimensional scaling of seasonal variation in macroalgal assemblages found on reefs in the Geographe Bay region. Data points grouping together have similar species composition.

Geographe Bay region

Among the four core sites in the Geographe Bay region, only those on Bunbury reefs (South Bunbury and Dalyellup 1) showed seasonal variation in algal assemblage structure (Fig. 111). On these reefs, the coralline red alga *Amphiroa anceps* is abundant throughout the year, but variations in the abundance of co-occurring foliose algal species are driving the seasonal differences shown in Fig. 111a-b. Fluctuations in the seasonal abundance of foliose algal species is likely related to seasonal sand inundation of these low relief reefs, along with a persistent nepheloid layer that has been observed in the Bunbury region in winter and spring. The associated reduction in light penetration to the seafloor (Fig.100), and its effects on algal abundance, are discussed later in this section.

Canopy-forming brown algal abundance

The presence of a canopy of brown algal species on many reefs in the SRFME project area, which may vary in seasonal abundance, led to an examination of the abundance of this subset of the algae. For those reefs where *Ecklonia radiata* is the dominant canopy-forming brown alga, namely those in Jurien Bay, Two Rocks and Marmion, seasonal variation in abundance is likely to be due to removal of biomass during disturbance events such as storms rather than as a result of any biological factor (Fig. 112). On reefs in Greenhead, where *Sargassum* is the dominant canopy-forming brown alga, its seasonal developmental cycle is clearly reflected in variation in seasonal abundance (Fig. 112).

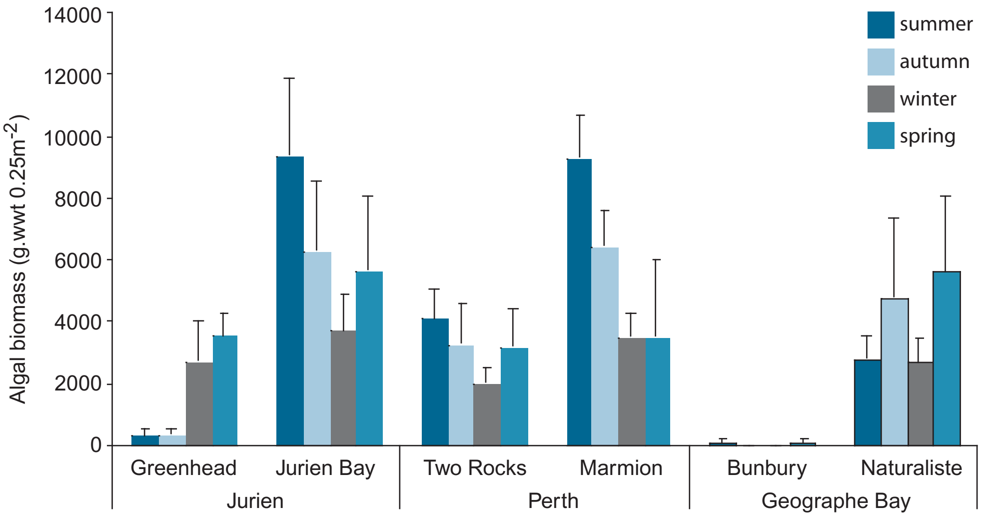


Figure 112: Seasonal variation in the mean biomass (+ SE) of canopy-forming brown algae species.

Environmental correlates of algal assemblage structure

A number of environmental factors have been measured in order to determine any effect on algal assemblage structure. The effects of depth, reef relief and light attenuation will be reported on here, but measurements of nutrient levels, total suspended solids, reef rugosity and wave energy (see Section 7.8) are continuing at core sites in the SRFME project area and will allow more detailed examination at smaller spatial scales.

Depth

The depth of the overlying water affects light penetration and wave/swell energy at the reef surface, and consequently can affect algal assemblage structure. In all regions within the SRFME project area, where reefs were in depths between 2-15 m, there was no clear separation of overall algal assemblages by depth category ($R \leq 0.297$, $P \leq 0.003$ in all regions; ANOSIM) (Fig. 113).

Within Geographe Bay, algal assemblages on shallow (< 5 m) and deep (> 10 m) reefs were significantly different ($R = 0.781$, $P = 0.001$; ANOSIM) (Fig. 113c). This difference, however, is likely to have been affected by the inclusion of the Quarries samples in the < 5 m category, since the uniqueness of the assemblage structure on this geographically separate reef has been discussed elsewhere in this section. For this reason, the effect of depth on assemblage structure was analysed separately for reefs in the Bunbury locality only. The resulting 2-dimensional plot suggested a gradient in assemblage change with depth (Fig. 113d). Although there was no overall effect of depth on the species composition ($R = 0.27$, $P = 0.001$; ANOSIM), post-hoc pairwise comparisons did support the theory that assemblage structure varied significantly on shallow (< 5 m) and deep (> 10 m) reefs ($R = 0.725$, $P = 0.001$; ANOSIM). However, the inclusion of more shallow reefs in future analyses would be required to validate this conclusion.

Reef relief

Reef relief categories of low, medium or high relief were assigned on the basis of site rugosity codes (Table 15); reefs with a rugosity of 1.0–1.19 were classified as low relief, 1.2–1.49 were medium relief, and > 1.5 were high relief.

Although there was some overlap in assemblage structure, reefs in the Jurien region show separation according to reef relief ($R = 0.446$, $P = 0.001$; ANOSIM) (Fig 114a). High relief reefs that have been studied in Jurien support *Ecklonia radiata* forests, while medium and low reliefs reefs are characterised by mixed brown algal assemblages and low foliose assemblages, respectively. Reef relief affects the orbital velocity of water movement on the reef surface, which may in turn influence the settlement and survival of different algae species.

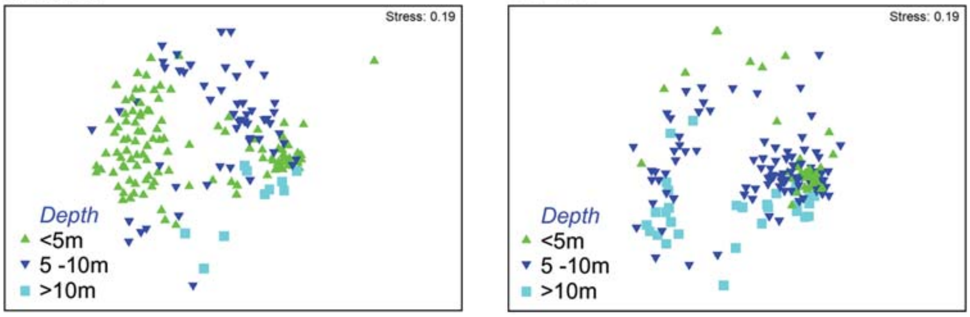
Reefs studied in the Perth region are dominated by high and medium relief reefs, and although inclusion of additional low relief reefs would strengthen any interpretation, the results to date indicate that relief is having no effect on the structure of algal assemblages ($R = 0.019$, $P = 0.2$; ANOSIM). Reefs in the Geographe Bay region fell into the low or medium relief categories only, but data in Fig. 114c are separating on the basis of geographic location (ie. Cape Naturaliste vs. Bunbury sites) rather than any effect of relief.

Light attenuation

As illustrated in a previous section, the attenuation of light by the water column showed a seasonal trend at most localities. The most pronounced seasonal patterns in light attenuation were observed at Greenhead and Bunbury, but this was only strongly correlated to the algal assemblage at the latter locality. In Bunbury, the persistence of a distinct nepheloid layer close to the seafloor in winter and spring of 2004 was strongly negatively correlated to algal biomass on reefs at South Bunbury and Dalyellup 1 (-0.71 and -0.82, respectively) (Fig. 115).

a. Jurien

b. Perth



c. Geographe Bay

d. Reefs in the Bunbury locality

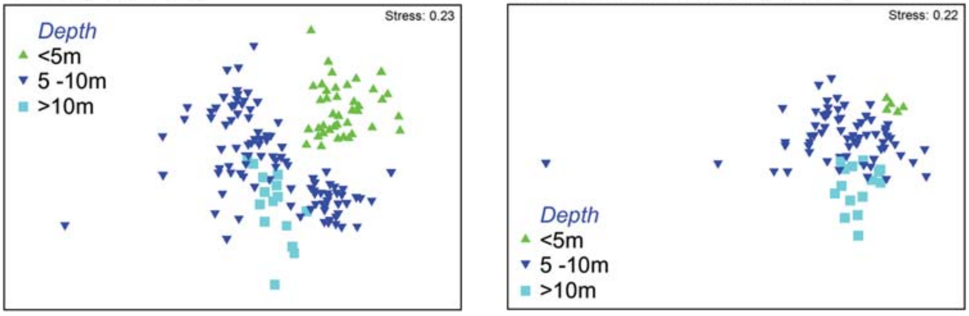


Figure 113: Multidimensional scaling of variation in the structure of macroalgal assemblages found on reefs at different water depths in the SRFME study area. Data points grouping together have similar species composition.

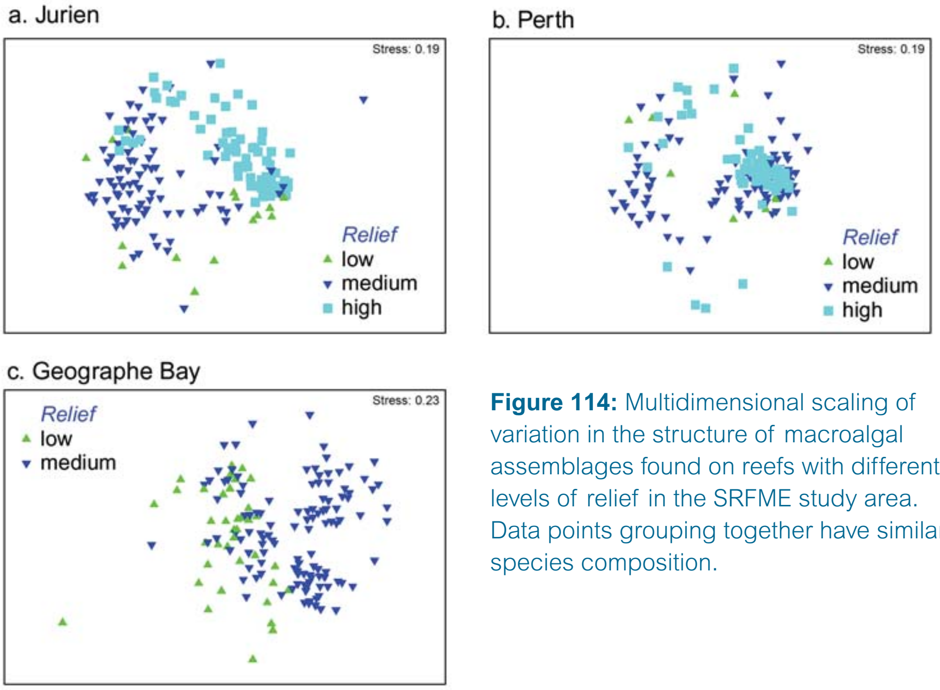


Figure 114: Multidimensional scaling of variation in the structure of macroalgal assemblages found on reefs with different levels of relief in the SRFME study area. Data points grouping together have similar species composition.

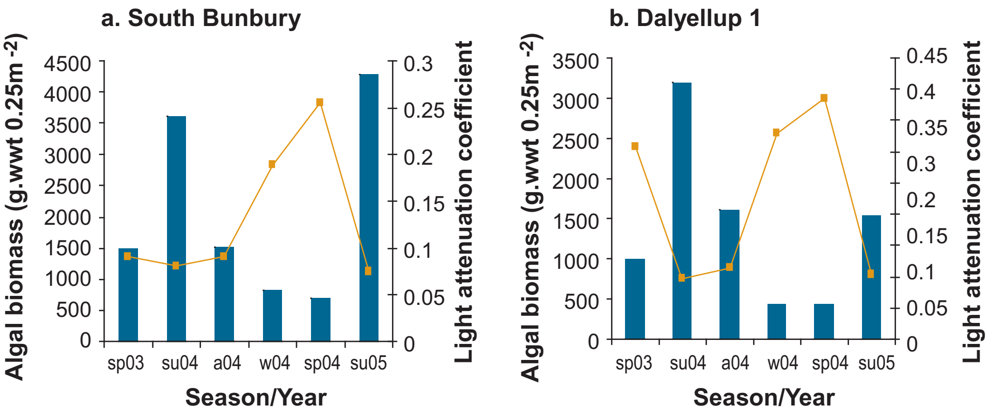


Figure 115: Seasonal algal biomass and light attenuation coefficients at two sites within the Bunbury locality (Geographe Bay).

Discussion

At the regional scale there were clear biogeographic trends from the north to the south of the SRFME study area. These results extend the trend of transition in algal assemblages from the State's lower west through to southern coastline as described by Wernberg *et al*. (2003). However, this broad trend overlies significant small-scale variation at the locality scale and even at the scale of sites within localities, where the spatial distribution of algal community types was relatively patchy. The underlying factors responsible for this smaller-scale variability are not yet well understood, but the single most important factor revealed by analyses so far appears to be reef relief. Relief may interact with other factors such as nutrient availability and water motion, and a full analysis to be completed when all data for these parameters becomes available is likely to increase our understanding of small-scale variability.

The importance of seasonal factors also varied at the locality and site scales, and it appears that an understanding of the underlying reasons is more straightforward. Reefs dominated by *Sargassum* spp. displayed seasonality in algal assemblage structure that was directly related to the life history of this genus. Low profile reefs at Bunbury are exposed to high levels of turbidity and/or sand scour during winter and spring, with a concomitant change in algal biomass. Even sites dominated by the perennial kelp *Ecklonia radiata* showed seasonal trends in biomass with summer maxima and winter minima. This may be related to higher growth and lower erosion rates of *E. radiata* in summer (Kirkman 1989).

Species richness in all regions was high (> 220 spp.) and comparable to a survey of the Marmion Marine Park (202 species; Simpson & Ottaway 1987) and to the Esperance region on WA's south coast (220 species; Goldberg & Kendrick 2004). Given the species richness within each region, it is interesting to note that the presence (or absence) of a single species, *Ecklonia radiata*, accounted for so much of the variation in algal assemblages, even at the greatest spatial scale. It is also worth noting that a continuous, closed canopy of *E. radiata* exerts a strong influence over the composition of understorey species (Phillips *et al*. 1997), with the result that as few as one to five other algal species may be recorded in these habitats. Further investigation is required into any associations between invertebrate and fish assemblages associated with *E. radiata* habitats versus other algal habitat types.

Acknowledgements
Dr John Huisman, Carolyn Jenour.

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Conferences attended, or presentations given

Phillips JC. Algae of the Jurien Region. Strategic Research Fund for the Marine Environment Symposium, CSIRO, Floreat, 18 February 2004.

Phillips JC. Benthic Algal Assemblages. Strategic Research Fund for the Marine Environment Workshop, CSIRO, Floreat, 9 February 2005.

Publications and/or outcomes to date

Phillips JC (2005) Use of C:N ratios to assess the nutrient status of macroalgae growing at different depths in the Esperance region, Western Australia. In: FE Wells, DI Walker and GA Kendrick (eds). *The Marine Flora and Fauna of Esperance, Western Australia*. Western Australian Museum, Perth.

Cambridge ML, Phillips JC, Moore TN (2005) Nitrogen and phosphorus concentrations in leaf tissue of the seagrasses Posidonia kirkmanii and P. australis from Esperance, Western Australia. In: FE Wells, DI Walker and GA Kendrick (eds). *The Marine Flora and Fauna of Esperance, Western Australia*. Western Australian Museum, Perth.

6.6 Spatial patterns in invertebrate communities

Invertebrates constitute a major proportion of all marine biodiversity, playing an integral part in marine ecosystems through trophic dynamics. The contribution of marine invertebrates to biodiversity in Western Australia, was investigated in the form of species richness and taxonomic representation as part of the SRFME initiative.

Sampling of Invertebrates

Sites from the SRFME regions of Jurien, Perth and Geographe Bay were sampled twice seasonally from winter 2003, to summer 2005 (see Table 15). Sampling for invertebrates involved the recording of species, their number and size (length and/or width in mm) of those animals from the 1m^2 quadrat. Invertebrates were also collected from the 0.25m^2 sub-quadrat as part of the algae collection process, with these animals later weighed and identified.

Sampling of the 1m^2 quadrats included solitary or mobile invertebrates >10mm in size, with the 0.25m^2 quadrat sampling providing data on invertebrates <10mm in size. As the sampling target of the 0.25m^2 quadrat is the collection of algae, the sub-sampling of invertebrates is incidental. Invertebrates collected from the 0.25m^2 quadrat were therefore largely epifaunal, or associated with algal holdfasts.

Where possible, samples were identified to species level. Specimens that were not identified in the field were collected for follow-up verification. An invertebrate reference collection for the SRFME region has also been established.

Data analysis

Abundance data from 0.25m^2 and 1m^2 quadrats recorded from the SRFME regions of Jurien, Perth and Geographe Bay were extracted from the Benthic Ecology ACCESS database. Only species with confirmed identity (pending verification) were used in analyses.

Data were analysed using the software package PRIMER 6
(Plymouth Routines In Multivariate Ecological Research).

Overall Square Root transformation was applied to abundance (count) data.
A Bray-Curtis similarity resemblance matrix was then generated and data analysed through ordination by non-metric multidimensional scaling, with a restart value of 50. The factors of Region, Locality, Site, Depth and Rugosity (relief) were used in analyses with results displayed in the form of Scatter Plots. Analysis of Similarities (ANOSIM) was applied to these factors to test significance, and Similarity Percentages (SIMPER) used to address species contributions between and within factors.

Overview of invertebrate assemblages from the SRFME region

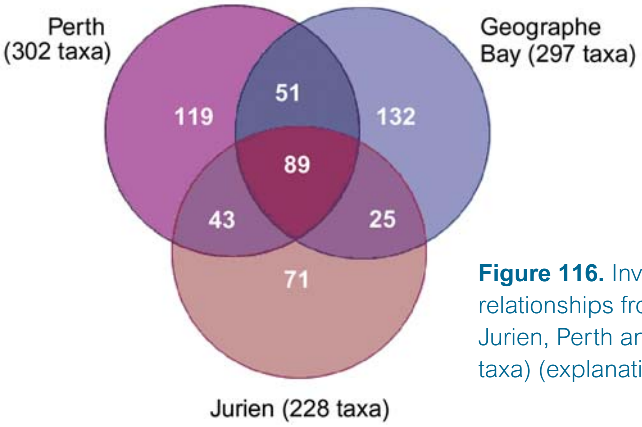


Figure 116. Invertebrate species relationships from the SRFME regions of Jurien, Perth and Geographe Bay (530 taxa) (explanation as for the algae).

A total of 530 taxa were recorded from the SRFME regions. Of the 530 taxa, 228 were recorded from Jurien, 302 from Perth and 297 from Geographe Bay (Figure 116). Within regions, 71 taxa were only recorded for Jurien, 119 from Perth and 132 from Geographe Bay (Figure 116). Between regions, 43 taxa were shared between Jurien and Perth, 25 taxa between Jurien and Geographe Bay and 51 taxa between Perth and Geographe Bay, with 89 taxa recorded from all three regions (Figure 116).

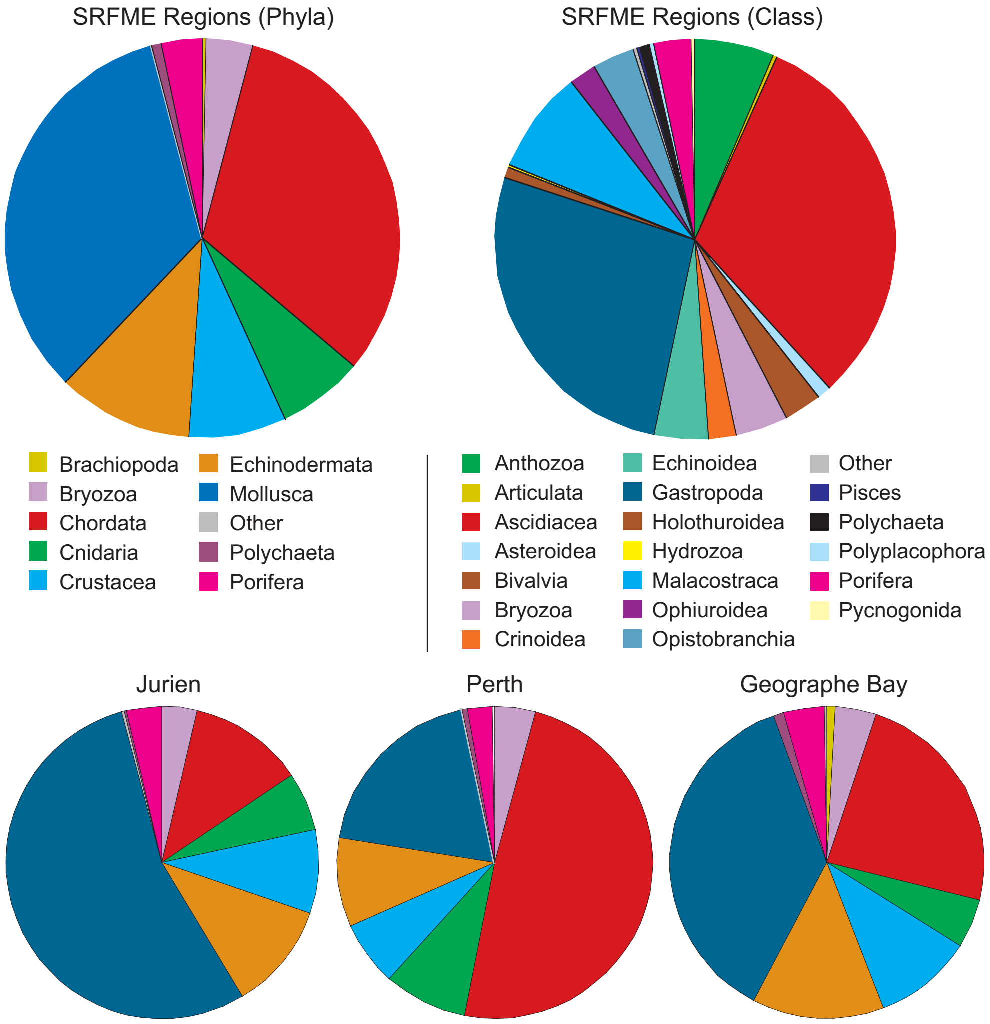


Figure 117: Composition of invertebrate assemblages from the SRFME region and within the SRFME regions of Jurien, Perth and Geographe Bay.

The phyla Chordata and Mollusca were found to be the two dominant invertebrate taxa of invertebrate assemblages of the SRFME regions. The Echinodermata, Crustracea and Cnidaria were also roughly equal in their contribution, followed by the Bryozoa and Porifera. The majority of the Chordata was comprised of the class Ascidiacea, with Gastropoda comprising the majority of the Mollusca (Figure 117).

Within the SRFME regions, variation in the contribution of the Chordata (Ascidiacea) and Mollusca (Gastropoda) represented the main differences between the regions of Jurien, Perth and Geographe Bay. The Echinodermata, Crustacea, Cnidaria, Bryozoa and Porifera all contributed equally in each region (Figure 117).

Comparison between SRFME regions

Data were examined separately at the 0.25m^2 and 1m^2 levels to address broad scale relationships between the SRFME regions of Jurien, Perth and Geographe Bay and their localities and sites.

SRFME regions-0.25m^2 quadrat

At the 0.25m^2 quadrat level, a very weak north-south gradient was found to separate Jurien, Perth and Geographe Bay (R=0.147 p=0.001) and their localities (R=0.138, p=0.001) (Figure 118). This indicates that biogeographical and/or physical parameters both within and between these regions and localities, are affecting the distribution of invertebrates in these areas. The latitudinal pattern among localities follows a pattern similar to that seen at the regional level.

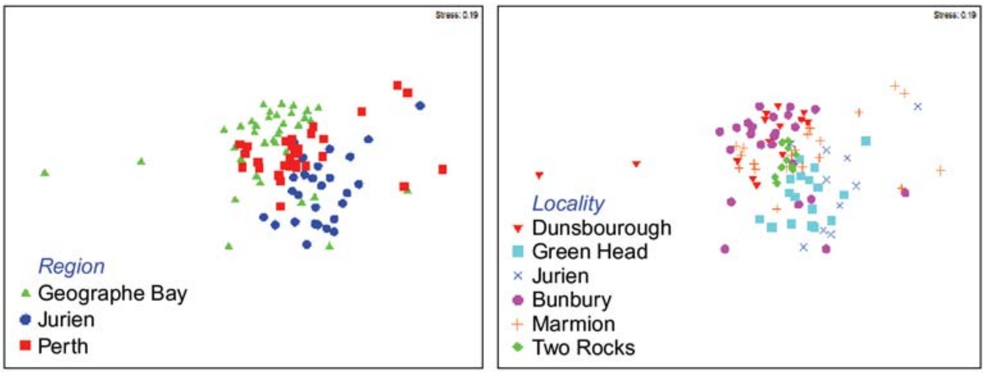


Figure 118: MDS plots for the factors of region and locality between SRFME regions (0.25m^2 quadrat).

Sponges (pooled biomass) were found to dominate species assemblages at the 0.25m^2 quadrat level in all three regions. Additionally, Bryozoa also dominated assemblages in Perth and Geographe Bay, with Gastropods dominating in Jurien.

Between localities, numbers of *Pyrene bidentata* (Gastropoda, Mollusca) were found to drive dissimilarity (SIMPER), except for Dunsborough and Marmion, and Dunsborough and Bunbury, where *Ophicantha* sp. 1 (Ophiuroid, Echinodermata) drove assemblage differences.

SRFME regions-1m^2 quadrat

At the 1m^2 quadrat level, a stronger separation was found between Jurien, Perth and Geographe Bay (R=0.33, p=0.001) and their localities (R=0.408, p=0.001) (Figure 119). Again, the MDS ordination suggests a continuous, though overlapping, transition between localities along a north-south gradient.

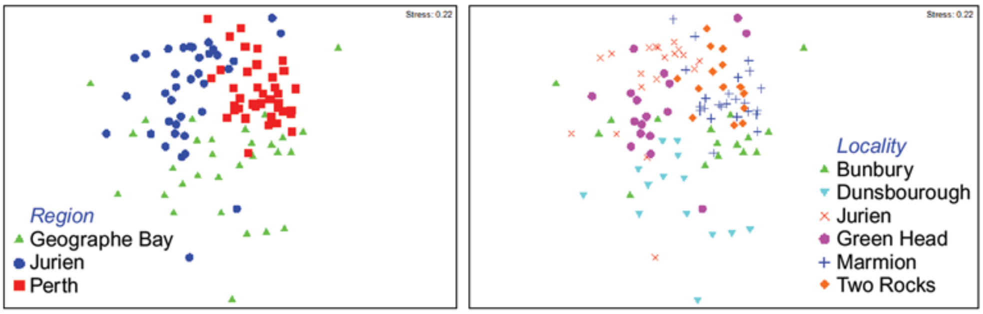


Figure 119: MDS plots for the factors of region and locality between SRFME regions (1m^2 quadrat).

Ascidians were found to dominate species assemblages in all three regions, with Echinoderms also dominating assemblages in Jurien and Perth.

Between localities, numbers of *Cnemidocarpa pedata* (Ascidiacea, Chordata) were found to drive dissimilarity. The exceptions to this were Dunsborough with Green Head, where *Cenolia trichoptera* (Crinoid, Echinodermata) drove assemblage differences; Dunsborough with Jurien, where *Heliocidaris erythrogramma* (Echinoidea, Echinodermata) drove assemblage differences; Dunsborough with Marmion, where *Herdmania momus* (Ascidiacea, Chordata) drove assemblage differences, and Jurien with Green Head where *Serpulorbis sp.* (Gastropod, Mollusca) drove assemblage differences.

Comparison within SRFME regions

Invertebrate abundance – 1m^2 quadrat

The was little or no sign of significant separation between localities within any of the three SRFME regions, either for the 0.25m^2 quadrat data or the 1m^2 quadrat data. For the 1m^2 quadrat data, based on larger (>10mm) solitary invertebrates, there was a slightly stronger suggestion of pattern at the among-site level. While this pattern was statistically significant, its meaningfulness is unclear as R values ranged between 0.36 and 0.22 (Jurien, R=0.356; Perth, R=0.344; Geographe Bay, R=0.219 (Figure 120).

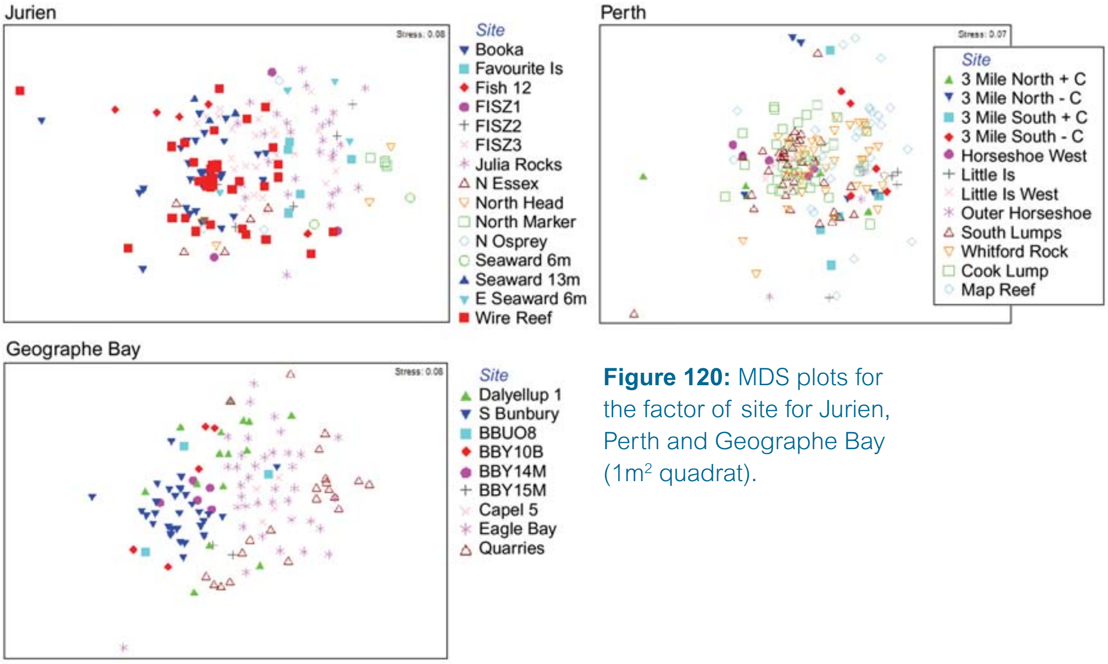


Figure 120: MDS plots for the factor of site for Jurien, Perth and Geographe Bay (1m^2 quadrat).

Echinoderms, Ascidia, Sponges (mixed biomass), Bryozoans (mixed biomass), Gastropods and Cnidaria were found to dominate the species assemblages at the sites of Jurien and Green Head. Comparison between sites from Jurien and Green Head (55 in total) found dissimilarity to be driven by *Heliocidaris erythrogramma* (Echinoidea, Echinodermata) (15), *Herdmania momus* (Ascidia, Chordata) (15), *Isaurus cliftoni* (Anthozoa, Cnidaria) (8), *Porifera* sp. *4* (Porifera) (8), *Brachidontes erosa* (Bivalvia, Mollusca), *Pyrene* sp. (3), *Pyrene bidentata* (Gastropoda, Mollusca) (1) and *Tryphyllozoan monoliferum* (1).

Ascidia (mixed biomass) and Gastropods were found to dominate species assemblages at the sites of Marmion and Two Rocks. Comparison between sites from Two Rocks and Marmion (20 in total) found dissimilarity to be driven by *Cnemidocarpa pedata* (Ascidiacea, Chordata) (13), *Herdmania momus* (Ascidiacea, Chordata) (5), *Turbo torquatus* (Gastropoda, Mollusca) (1) and *Plesiastrea versipora* (Anthozoa, Cnidaria) (1).

Ascidia, Echinoderms, Crinoids, Cnidaria and Holothuroids were found to dominate the species assemblages at the sites of Bunbury and Dunsborough. Comparison between sites from Bunbury and Dunsborough (15 in total) found dissimilarity to be driven by *Cnemidocarpa pedata* (Ascidiacea, Chordata) (5), *Cenolia trichoptera* (Crinoidea, Echinodermata), *Stichopus mollis* (Holothuroidea, Echinodermata) (2), *Plesiastrea versipora* (Anthozoa, Cnidaria) (1), *Polycarpa viridis* (Ascidiacea, Chordata) (1) and the “sand-encrusted meat pie” *Ascidian* sp. (Ascidiacea, Chordata).

There were no significant trends among sites at different depths or with different rugosity values.

Discussion

The SRFME region was found to be dominated equally by the phyla Chordata and Mollusca, with the class Ascidiacea comprising the majority of the Chordata and the class Gastropoda comprising the majority of the Mollusca (Figure 116).

Between the SRFME regions of Jurien, Perth and Dunsborough, the relative abundance of Gastropods and Ascidians had the strongest influence on differences in species assemblages (Figure 116).

The strongest trends among the data currently available are for the 1m^2 quadrat level, relating to the larger solitary and mobile invertebrates. A pattern in invertebrate assemblages at the level of location is suggested, following a north-south latitudinal trend. This trend is also suggested, but more weakly, at the regional level.

Within regions, individual sites tended to separate out more strongly than localities. This did not clearly relate to any of the physical environmental factors tested so far. Further analysis of site-level patterns will focus on incorporating additional physical information, and including data on algal community type in order to better understand variability.

6.7 Spatial patterns in Jurien Bay fish communities

Introduction

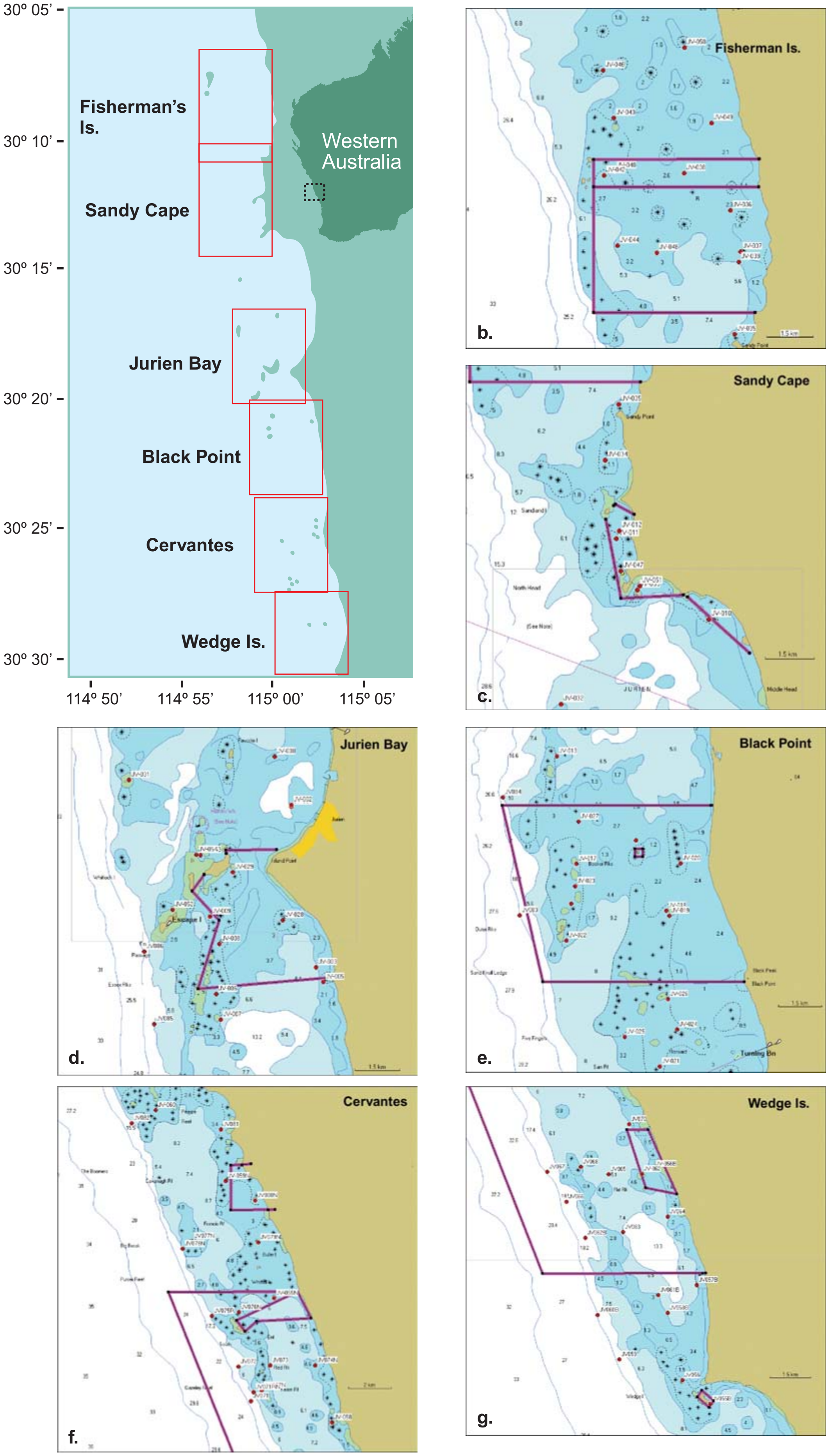
The objective of this study was to investigate patterns in the distribution of reef-associated piscivorous fish on coastal reefs of WA. In particular we were interested to understand how communities varied on the scale of kilometers across the coast, from inshore, shallow, sheltered reefs to more exposed reefs further offshore surrounded by deeper waters. Jurien Bay was chosen as the location for this study since it is broadly representative of the west coast habitats north of Geographe Bay, and also because it presents the opportunity to gather information on fish distribution and abundance before new no-take marine park zones in the area came into full effect. This work is therefore part of a longer term project to examine the effects of fishing and ecological interactions on coastal reefs.

Methods

A total of 84, 30 minute baited underwater video (BUV) drops were made in the Jurien region. Cameras were Sony TRV-19 digital minicams, fitted with wide-angle lenses to maximize field of view. The video stands held the camera vertical and were similar to stands used in previously published work (Willis *et al.* 2004). Vertical deployments were chosen for the reason that fish are present only within a known volume of water, and are usually near the bait when counted, making estimates of size more accurate. Previous trials with vertical systems at Rottnest Island indicated that differences between reef areas may be most evident as differences in size. Single-camera systems were chosen rather than stereo systems as the single cameras are more compact and can be more rapidly deployed than stereo systems. Further efficiency was gained through the use of a programmable circuit board that automatically activated and shut off the camera at the appropriate times after deployment so that the camera was ready to use again immediately after retrieval.

Drops were placed on reefs or at the reef edge if required in order to avoid snagging the gear. Deployments were distributed between two types of sampling strata: reef position (inner, middle and outer reefs) and management zone (general use, scientific reference, and sanctuary zones). Efforts were made to ensure that where possible samples around each zone straddled the zone and that they included multiple samples at successively greater distances from the zone boundaries (Fig. 121a-g). The bait consisted of 3 WA pilchards and was replaced on each drop, and data were analysed as MaxN, or the maximum number of fish of each species visible under the camera at one time. This statistic is used to avoid counting individuals multiple times. Fish size was measured at the time of MaxN using digital image analysis software (SigmaScan).

Figure 121: BUV study areas in the Jurien Bay region.



Results

At this time results are preliminary and require further analysis, including a second season of sampling. Inshore-Offshore trends are apparent (Fig 122) although these require cautious interpretation as the stress value is relatively high (0.18).

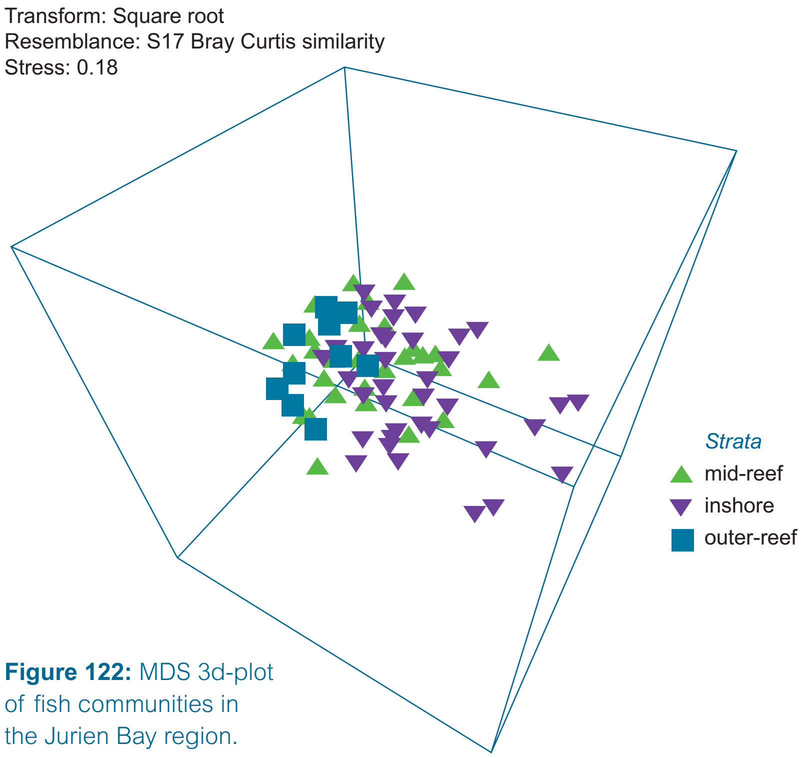


Figure 122: MDS 3d-plot of fish communities in the Jurien Bay region.

The fish assemblages differed little with respect to cross-shelf position (ANOSIM Global R = 0.079, p<0.001). Despite a significant p value, the low R value indicates that cross-shelf position appeared to explain little of the variability in the assemblages. Pairwise comparisons showed a similar pattern (Middle *vs* Inshore Global R= 0.078, p=0.004; Outer *vs* Inshore Global R=0.16, p=0.049) and once again the low values for R indicate there was little absolute difference in the assemblages. There was no differentiation in fish assemblage among management zones. Low R values aside, species contributing most strongly to the dissimilarity between Inshore and other reefs were the Western King Wrasse (*Coris auricularis*), Banded Toadfish (*Torquigener pleurogramma*), Skipjack Trevally (*Pseudocaranx dentex*), Western Butterfish (*Pentapodus vitta*), Maori Wrasse (*Ophthalmolepis lineolatus*), Lined Dottyback (*Labracinus lineatus*), Brown-spotted Wrasse (*Notolabrus parilus*), Footballer Sweep (*Neatypus obliquus*), Breaksea Cod (*Epinephelides armatus*) and Red-banded Wrasse (*Pseudolabrus biserialis*). Western King Wrasse were the most abundant species recorded (n=1251), and were almost an order of magnitude more numerous than the next most abundant species the brown wrasse (n=245). Most of these species showed clear though highly variable trends across the shelf. These trends in abundance were in different directions for different groups of species. Western King Wrasse, Red-banded wrasse, Maori Wrasse and Breaksea Cod were all most abundant offshore (Fig. 123a).

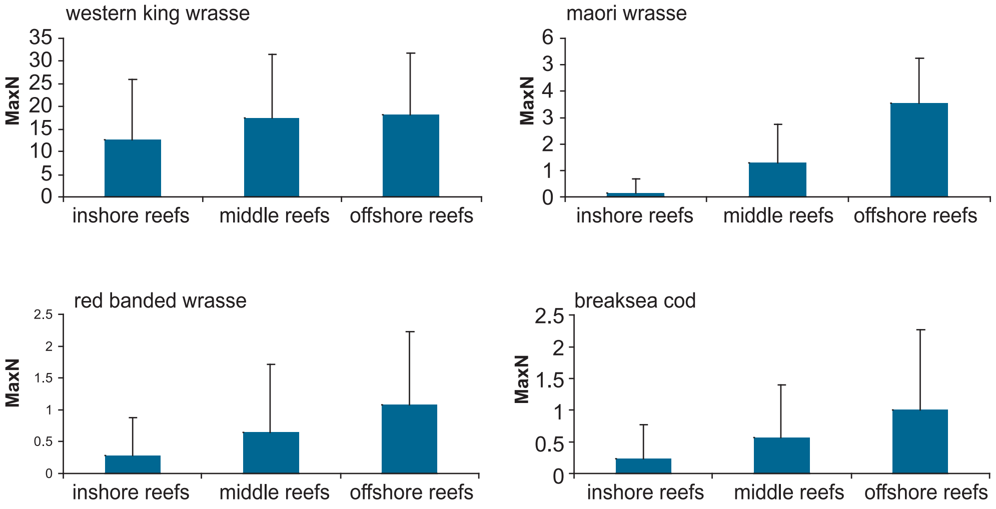


Figure 123a: Relative abundance of "offshore" species among reef strata.

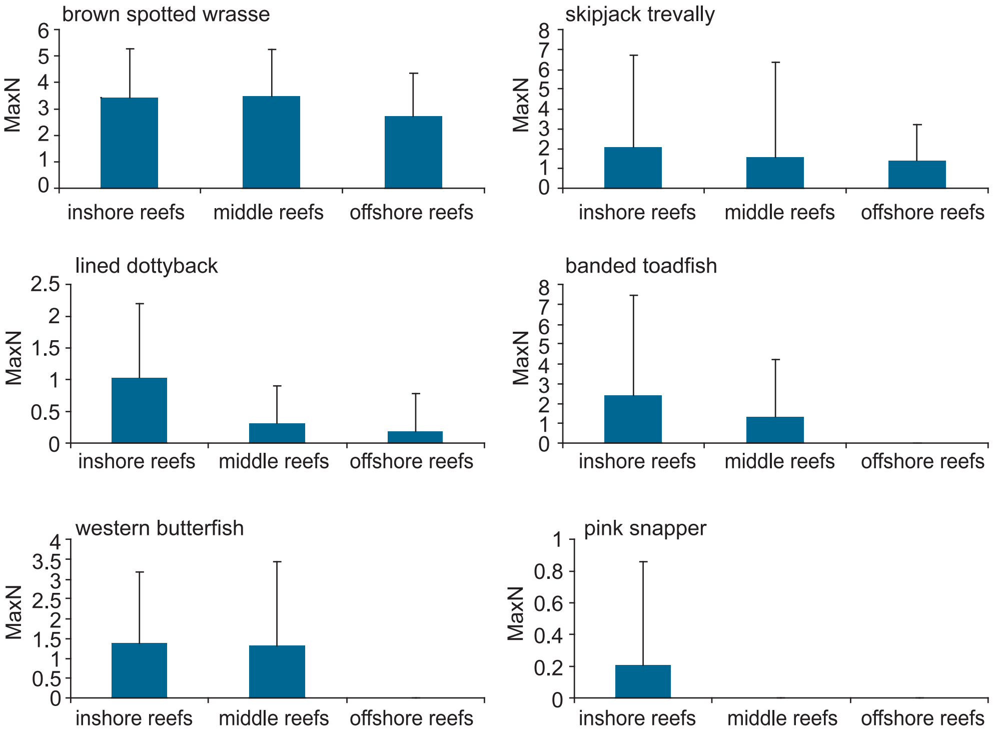


Figure 123b: Relative abundance of "offshore" species among reef strata.

The opposite trend was shown by the Brown-spotted Wrasse, Skipjack Trevally, Lined Dottyback, Banded Toadfish and Western Butterfish (Fig. 123b). Although it was relatively rare (n=8), and not a significant contributor to dissimilarity, the Pink Snapper (*Pagrus auratus*) are a significant commercial and recreational species that were only found on inshore reefs.

Among these dominant species there was a significant trend in size among reef strata for only one, the Skipjack Trevally which were 60-70 mm larger at midshelf and offshore sites than at inshore sites (ANOVA, $F_{(149,2)}$, $p<0.0001$). Thus size and abundance of this species showed opposite trends.

Discussion

The differentiation of fish communities across the coast at Jurien into inshore reef and mid-outer reef assemblages might be expected, given the difference in the variation in nature of the physical environments. It is therefore somewhat surprising that the cross-shore trend, if it exists, is weak at best. However a similar situation appears to exist for algal assemblages at Jurien, where variability at the site level appears to be more pronounced than at a cross-shore level. (Fig. 106b). Elsewhere in Australasia inshore-offshore trends have been found in other similar temperate fish assemblages (Brook 2002). It is possible that with an additional year of data, and when additional environmental variables are incorporated, clearer patterns will emerge.

The dominance of wrasses in all reefs across the coast was a prominent feature of the data set, indicating that it is important to understand this group if we are to appreciate the role of fishes in the ecosystem. Furthermore, the wrasses are important components in differentiating assemblages across the coast.

There were fewer, larger Skipjack Trevally on offshore reefs, and more numerous smaller fish on inshore reefs. This may reflect a developmental or ontogenetic difference in habitat preference by this species. Other species may show similar differences in habitat use, though further analysis is required to confirm this. Inshore reefs appear to be important for sublegal size Pink Snapper (mean size 350 mm) as these were the only reefs where these fish were found.

The data provide a strong basis for detecting any change in fished species that may flow directly from changes in management and zoning, and there are no significant differences in the fish assemblages in different management zones at the present time. The BUV method has proved particularly good at measuring the abundance of wrasses and trevally which form an increasingly important part of the recreational catch in coastal nearshore waters such as those in the Jurien Bay Marine Park. The method also detected other species of interest to anglers but which no longer form a large part of catches for most anglers, these species include Pink Snapper, Western Australian Dhufish, (*Glaucosoma hebraicum*), King George Whiting (*Sillaginodes punctata*) and Breaksea Cod.

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6.8 Depth-related variation in nutrient availability on temperate reefs: Use of C:N ratios to assess the nutrient status of macroalgae growing at different depths in the Esperance region, Western Australia

Introduction

Nitrogen is considered the nutrient limiting primary production in temperate coastal waters and its availability plays a dominant role in regulating macroalgal growth and production (Duarte 1992). Nitrogen availability may be monitored by measuring the N concentration in seawater, or by monitoring the N content of algal tissue. The latter approach is considered to more accurately indicate the actual availability of N for algal growth and production as well as integrating the nutrient regime over some time period prior to sampling (Fujita 1985, Wheeler & Björnsater 1992). Internal soluble tissue pools of N represent the immediate past nutrient history of an alga, while other measures such as the ratio of carbon to nitrogen (C:N) reflect the availability and subsequent incorporation of N into various compounds over a longer time period.

Coastal surface waters around Australia are generally nutrient-poor (Rochford 1980, Hatcher 1991). Upwelling can deliver nutrients to surface waters and make them available for algal production, but the presence of the southward flowing Leeuwin Current results in an absence of persistent upwelling off the Western Australian coastline (Gersbach *et al* 1999). Few data exist for nutrient levels in seawater in the Esperance region but available information suggests low nitrate concentrations (typically <1 µM) (NODC 2001). Despite the low nutrient levels, the standing crop of macroalgae in areas around the Recherche Archipelago (including Esperance) is 1.4 to 8 kg wet weight per m^2 (Goldberg & Kendrick 2004).

This paper examines the nutrient status of macroalgae growing at different depths in the Esperance region, Western Australia. Nutrient status was assessed using C:N ratios. Evidence for N-limitation among the algae was also examined.

Materials and Methods

Eight algal species from two divisions, growing at different depths, were collected from various locations around the Esperance (33º 56'S, 121º 51'E) region of Western Australia (Fig. 124) over a 7-day period in February 2003. Algal material was collected opportunistically using SCUBA in shallow water depths or by dredge samples from deep sites; as a result the absence of species from a site or depth is not indicative of its distribution, but is an artefact of sampling effort. Similarly, it was not possible to replicate sites within the depth categories chosen (see below). The red algae examined were *Dasya extensa* Sonder *ex* Kützing, *Gloiosaccion brownii* Harvey, *Hypnea ramentacea* (C.Agardh) J.Agardh, and *Osmundaria prolifera* Lamouroux. The brown algae examined were *Asperococcus bullosus* Lamouroux, *Dictyopteris muelleri* (Sonder) Reinbold, *Lobophora variegata* (Lamouroux) Womersley *ex* Oliveira and *Lobospira bicuspidata* Areschoug. Table 18 gives the taxonomic affinity of each species and details of collection sites and depths.

Figure 124: Map of collection sites in the Esperance region. 1 = Esperance Bay (west), 2 = Wylie Head, 3 = Wylie Bay, 4 = Lion Island, 5 = Esperance Bay (east), 6 = Table Island, Duke of Orleans Bay. ▲ = position of CSIRO coastal data station deployed from 1979-1981 to collect hydrological data including nitrate levels.

Seawater N levels were not sampled directly. Archival data were obtained from the CSIRO Coastal Data Station (Fig. 124) deployed off Esperance from 1979-1981. The station monitored nitrate levels approximately monthly, from surface waters to 50 m depth in 10 m increments.

Clean algal material (n = 3-6) was dried at 80°C for 48 h and total C and total N in finely ground replicate samples were determined by dry combustion using LECO CHN-1000 analyser (LECO Corp., St. Joseph, MI, USA). The % tissue C and % tissue N were standardised to algal dry weight (g) and C:N ratios were determined on an atomic basis.

Table 18. Taxonomic affinities, collection sites and depths for the eight species of macroalgae investigated in this study.

Species	**Order**	Table Island 33°54S 122°35E 5 m	Wylie Bay 33°49S 121°59E 5 m	Lion Island 33°52S 122°01E 10 m	Wylie Head 33°50S 121°59E 22 m	Esperance Bay E 33°57S 122°01E 33 m	Esperance Bay W 33°53S 121°56E 38 m
Rhodophyta							
Dasya extensa	Ceramiales		✔	✔	✔		
Gloiosaccion brownii	Rhodymeniales			✔			✔
Hypnea ramentacea	Gigartinales	✔		✔		✔	✔
Osmundaria prolifera	Ceramiales		✔		✔		
Phaeophyta							
Asperococcus bullosus	Dictyosiphonales	✔		✔		✔	
Dictyopteris muelleri	Dictyotales	✔		✔	✔		✔
Lobophora variegata	Dictyotales	✔				✔	✔
Lobospira bicuspidata	Dictyotales	✔		✔	✔		

For each species, samples were pooled into categories based on the depth of the collection site: 0-9 m, 10-19 m, 20-29 m, and 30-39 m. One-way analyses of variance (ANOVA) or *t*-tests were used to examine for differences in C and N content at different depths separately for each species, at $P < 0.05$. Where ANOVAs indicated significant differences between depths, post-hoc multiple comparisons were performed using Tukey tests. All analyses were performed using SigmaStat (v3.1, SPSS Inc, USA).

Results

Seawater nitrate levels in waters to 30 m depth during 1979-1981 were at or below 0.4 μM at all times, apart from one occasion (February 1980) when 1 μM was recorded at 10 m depth (Fig. 125). Less data were available for > 30 m depth at this station, but the data show that higher nitrate concentrations occurred in late February 1981 at 40 and 50 m depths (Fig. 125).

Among the red algae, tissue C content was lowest in *Gloiosaccion brownii* from the 0-9 m depth category with values between 16.1–22.0% of dry weight (Fig. 126a). *Hypnea ramentacea* from 30-39 m depth had significantly lower % C than at shallower depths (Tukey's test, $P < 0.001$) while % C of *Dasya extensa* and *Osmundaria prolifera* did not vary with depth. With the exception of *Lobospira bicuspidata*, the % C of brown algae was significantly lower at 30-39 m depths (Tukey's test, $P < 0.05$ or t-test, $P < 0.001$).

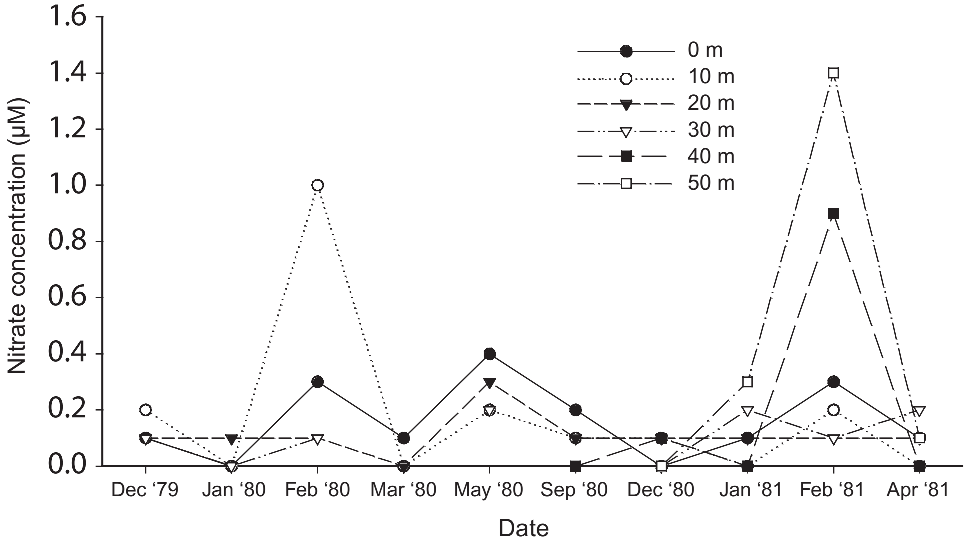

Figure 125: Nitrate levels in seawater monitored by the CSIRO Esperance Coastal Data Station, 1979-1981. Data represent single values only for each sampling event.

Tissue N content in the red algae varied with depth between 0.96–3.47% of dry weight (Fig. 126b) but the variation within species was not significant. Variation among the brown algae was less, with values ranging between 1.00–2.07%. *Dictyopteris muelleri* showed no difference in %N at depths < 20 m but values increased with increasing depth (Tukey's test, $P < 0.05$). For *Lobophora variegata*, plants growing at 30-39 m had greater N content than plants at 0-9 m.

C:N ratios among the red algae ranged between 10.1–23.8. The red algal species showed little variation in C:N ratios with depth; although there was some evidence of a trend towards lower C:N values with increasing depth, any intraspecific variation was insignificant (Fig. 126c, 1-way ANOVA or t-test, $P < 0.1$ in all cases). All brown algae except *Lobospira bicuspidata* showed significant decreases in C:N with increasing depth. C:N ratios of brown algae were generally higher compared to those of red algae, with values ranging between 18.9–36.2.

Discussion

The C:N ratio of macroalgae has been used to infer their nutrient status, with values above a proposed critical limit of 10 (D'Elia & DeBoer 1978, Harrison & Druehl 1982) indicating N-limitation and values below suggesting N-storage. All species investigated in this study had C:N ratios above 10 at all depths, suggesting N-limitation, although values for *Osmundaria prolifera* were only slightly higher than this proposed critical limit. However, the usefulness of C:N ratios in assessing nutrient status of algae is reliant on C levels remaining relatively stable, such that much of the variability in the C:N ratio is dominated by variation in N concentrations in the algal tissue (Duarte 1990, 1992). This was not the case in this study, with half the species (mostly browns) showing declining levels of C with increasing depth. Given that C was not constant for these species, it can be assumed that variation in the C:N ratio with depth were due to changes in C metabolism rather than changes in nutrient status. Also, reduced light intensity often results in the accumulation of nitrogenous compounds due to reduced growth demands (Lapointe *et al*. 1984) which again would lower C:N ratios. For those species in which C levels remained constant with depth, namely *Dasya extensa*, *Gloiosaccion brownii, O. prolifera* and *Lobospira bicuspidata*, C:N ratios also remained unchanged. That the red algae generally showed less influence of depth (and light) on C:N ratios could suggest better adaptation to low light conditions than brown algae.

The ability of macroalgae to store N as a variety of compounds suggests that total N may be a better indicator of both N status and N availability (Phillips & Hurd 2003). A tissue N content of approximately 2% of dry weight has been proposed as a critical N concentration for macroalgae, below which growth would be N-limited (Hanisak 1979, O'Brien & Wheeler 1987). In this study, only *Osmundaria prolifera* consistently had tissue N levels above 2% while *Hypnea ramentacea* and *Lobospira bicuspidata* had values >2% at some, but not all, depths. Any such variations in tissue N are difficult to interpret, however, since the N requirement for growth and photosynthesis are affected by light, the levels of which decrease with depth.

When comparing between species, variation due to differences in morphology, phylogeny and ecology must be considered. For instance, brown algae tend to have higher C:N ratios than red algae (Niell 1976, Atkinson & Smith 1983, Lapointe 1989). Large, structurally complex algae will be more buffered from changes in the external environment (Hatcher 1991) while the high surface area to volume ratio of sheet-like forms (eg. *Lobophora variegata*) can confer an advantage in N acquisition across cell membranes (Phillips 2001). Also, the thin sponge layer covering all branches (Huisman 2000) of *Osmundaria prolifera* plants used in this study could not be removed prior to analysis and would have resulted in slightly elevated values for N content. For reasons such as these, if nutrient status of algae is to be used as a surrogate for past N availability, the use of a single, widely distributed species is recommended.

It is important to note that some variation in the nutrient status of the algae examined may be attributable to site- and/or species-specific conditions. All brown algae in the 0-9 m depth category were collected from Table Island in the Duke of Orleans Bay. This bay has a small caravan park but lacks any permanent townsites, hence nutrient levels are unlikely to be significantly enhanced by human activities. Remaining sites were located in the greater Esperance Bay which may receive nutrient inputs as a result of domestic and industrial activities associated with the Esperance townsite. Although the N content of the algae investigated do not suggest differences due to site, ideally any future study would control for any variation in site-specific nutrient regimes.

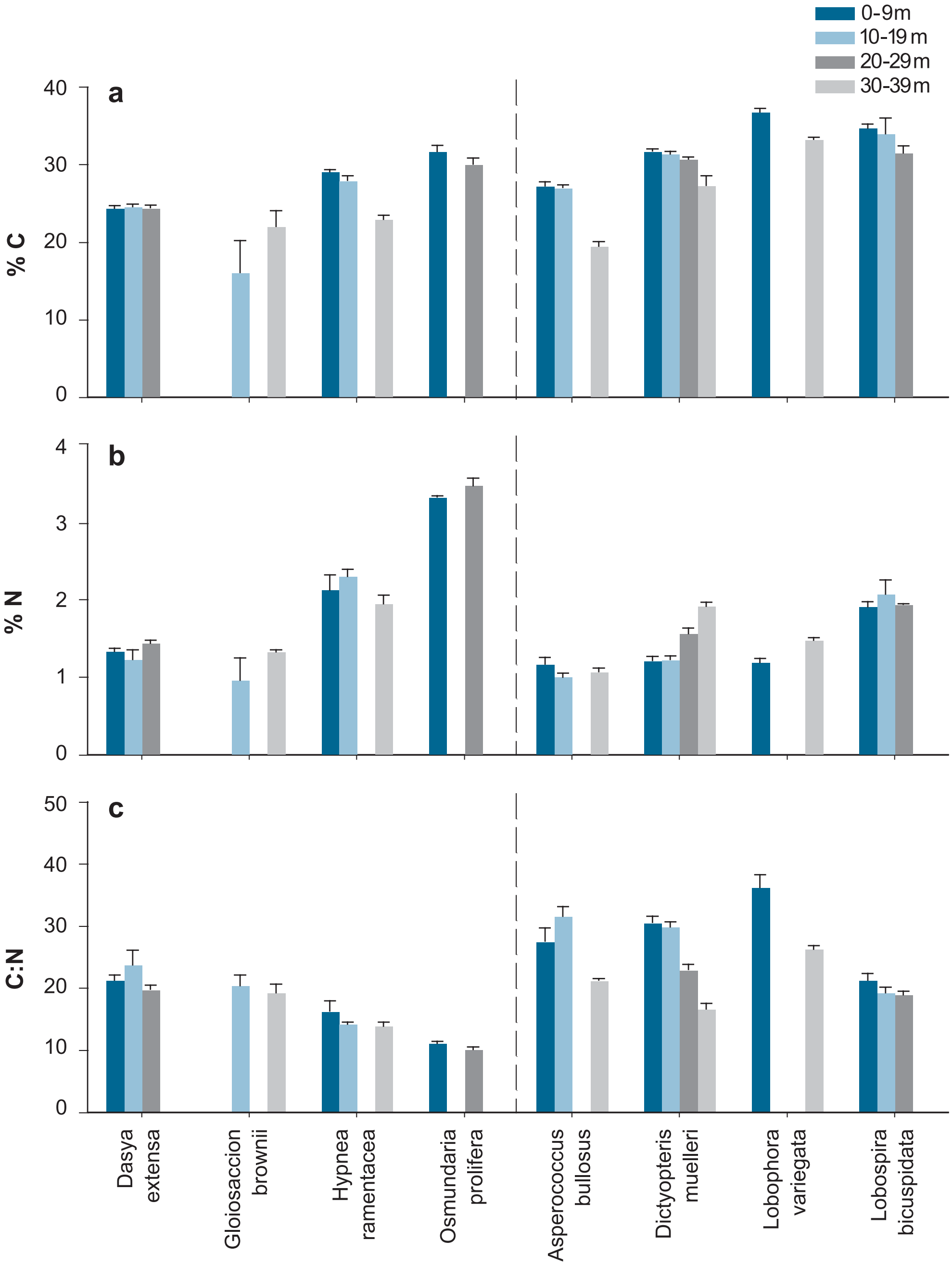

Figure 126: Tissue C and N content of eight species of macroalgae collected from different depths within the Esperance region, Western Australia. a) Tissue C content (% dry weight); b) tissue N content (% dry weight); c) tissue C:N ratio (atomic basis). Data are means ± SE, n = 3 except for *Hypnea ramentacea* and *Lobophora variegata* from 30-39 m, where n = 6. Vertical dashed line separates red algae (on left of figure) and brown algae (on right).

In summary, there was little evidence to suggest that the nutrient status of algae growing at different depths in the Esperance region varied due to differences in nutrient supply, and all species were considered N-limited. While C:N ratios remain a useful tool for assessing the nutrient status of algae, and can act as a surrogate for determining nutrient availability when a single species is used, the integral coupling between photosynthesis, C metabolism and N metabolism (Turpin 1991) require that confounding factors such as light and depth are accounted for.

Acknowledgments

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6.9 Differential nutrient utilization by meadow forming seagrass species: Nitrogen and phosphorus concentrations in leaf tissue of the seagrasses *Posidonia kirkmanii* and *P. australis* from Esperance, Western Australia

Introduction

The concentration and ratios of nitrogen and phosphorus in plant tissues are an indication of plant nutrient status. They have been most frequently reported for leaves in seagrasses (Duarte 1990, Hemminga and Duarte 2000). This paper aimed to measure nitrogen and phosphorus concentrations in the leaves of two seagrass species, *Posidonia kirkmanii* Kuo and Cambridge and *P. australis* Hook. f., at Wylie Bay near Esperance, in the Archipelago of the Recherche, Western Australia, 33º 50'S, 121º 00'E. This report is linked to a study on leaf growth and morphology of these species (Moore *et al*., 2005). Three species of seagrass, *Posidonia kirkmanii* Kuo & Cambridge, *P. australis* Hook. f. and *Amphibolis griffithii* (J.M. Black) den Hartog, co-occurred in a mosaic of small patches at 2-4 m water depth in the shelter of a granite headland. Each species existed within defined patches several meters in diameter, with a narrow perimeter of bare sand 10-20 cm wide separating the species.

Seagrasses near Esperance grow in clear, very low-nutrient waters along a coastline consisting mainly of white siliceous sand and granite headlands: the hinterland also has extremely low-nutrient soils, no large rivers and hence very few sources of nutrients from the land. Despite these apparent limitations to plant growth, seagrasses flourish in the cool waters and several species of *Posidonia* are noted for their size, particularly *Posidonia kirkmanii*. This species has robust leaves up to 150 cm in length and more than 1 cm wide (Kuo and Cambridge 1984), and may form an exceptionally dense leaf canopy when growing in mature stands. Leaf elongation rates are, however, very slow (Moore *et al*., 2005), indicating very slow turnover rates of the leaf canopy. This study provided an opportunity to compare the nutrient status of *P. kirkmanii*, for which there is no information beyond morphometrics and distribution records in the original species description (Kuo and Cambridge 1984), with data from a better known congeneric species, *P. australis* Hook. *f.*

This paper aimed to compare nitrogen and phosphorus concentrations in newly grown and older leaf tissue of *P. kirkmanii* and *P. australis* collected from the centres and edges of patches.

Methods

Field sampling

A 0.25 m^2 quadrat (50 x 50 cm) was placed haphazardly in the centre and the edge of four monospecific patches of *P. kirkmanii* (Pk) and four patches of *P. australis* (Pa) to give a total of 16 samples. The sampling design is shown in Fig. 2 of Moore *et al.* (2005). There was generally no zone of patch overlap where shoots of different species might intermingle, so each species could be sampled separately at the boundary of adjoining patches. All leaf blades within each quadrat were punched with a small pin at the level of the sediment surface in order to measure leaf extension rates. Quadrats were marked with a steel pole driven into the sediment, and labelled with flagging tape to identify each quadrat.

After a period of 8 days (10th-18th February, 2003), divers returned to the study site (Fig. 127), and retrieved all the above-ground plant material within the quadrats. All seagrass leaves were cut at the sediment surface with a razor blade, and then labelled, bagged and frozen for future analysis.

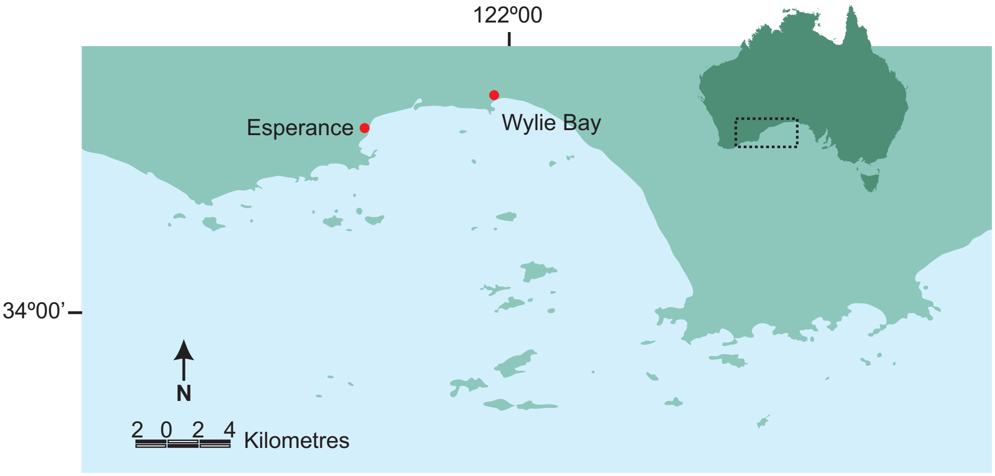

Figure 127: Map of the Esperance region in Western Australia, with the study area at Wylie Bay.

Nutrient analyses

In the laboratory, leaves were scraped free of epiphytes and examined for punch marks. Only intact leaves with distal ends not torn or frayed were used for measuring leaf growth (11-17 per quadrat); thus the number of leaves actually punched in the field was greater than the number used for analysis. New leaf growth below the punch mark and unmarked new leaves, which had emerged since marking, were separated from the old material above the punch marks, measured, then dried to constant weight (*ca*. 2 days) in an oven at 80ºC. A 5 cm section was taken from the newly grown portion near the base of each leaf and from the older part ca 20 cm above the base for nutrient (N, P) analysis. Samples were ground to a fine powder in a ball-mill.

The ground samples were initially prepared using a foliage digest for macroelements with a wet ash procedure using sulphuric acid and hydrogen peroxide (Linder 1944, Wolf 1982). Each set of samples included two digestion tubes containing a known standard. Concentrations of nitrogen and phosphorus were determined by automated colourimetric methods (Technicon Instruments, 1977).

The determination of nitrogen was based on a colourimetric method in which an emerald green colour is formed by the reaction of ammonia, sodium salicylate, sodium nitroprusside and sodium hypochloride in a buffered alkaline medium at a pH of 12.8-13.0. The ammonium-salicylate complex was read at 660 nm. The determination of phosphorus was based on the colourimetric method in which a blue colour is formed by the reaction of ortho-phosphate molybdate ion and antimony ion followed by the reduction with ascorbic acid at an acidic pH. The phosphomolybdenum complex was read at 660 nm. At the start of each period of analysis a standard curve of known concentrations (typically 5 ppm to 30 ppm for nitrogen and 0.5 ppm to 5 ppm for phosphorus) was produced to create a regression equation. This equation was then used to calculate the concentrations of nitrogen and phosphorus. Regular internal standards were run to ensure there was no drift occurring within the apparatus. If drift occurred, further regression equations were developed to adjust for this drift. The digested reference standards were run to determine the accuracy of the results. Results were adjusted for this recovery. All results fell within acceptable limits.

Data were statistically analysed using MacAnova v4.13 for 3 factors (species, leaf part, stand position) with leaf part and stand position as nested factors in Species. The analyses were run separately for each of N and P concentrations and N:P ratios. The ANOVA model was species + leaf part (species) +stand position (species).

Derived parameters

Leaf parameters and derived values for standing stocks, leaf growth and nutrient incorporation of *P. kirkmanii* (Table 21), were obtained as follows: leaves were counted for each 0.25 m^2 quadrat from the centre of a *P. kirkmanii* patch (n=4), and their lengths and widths measured. Leaf areas were calculated. Leaf density (number of leaves per m^2) was estimated by multiplying the number of leaves from the quadrats by four. Shoot density was estimated by dividing number of leaves per m^2 by the average number of leaves per shoot (2.57), estimated from a single clump of 18 shoots excavated from the same area as the quadrat sampling. Leaf area index (LAI: leaf area per unit ground area, $m^2\ m^{-2}$), was estimated by multiplying the total area of the leaves in each quadrat by four. The leaf biomass (standing crop) was estimated from leaf area per m^2 multiplied by the mean leaf mass per unit area (LMA) for older leaf tissue, reported in Moore *et al*. (2005). Leaf growth rate per unit area of meadow was derived from the mean growth rate per leaf over the sampling interval of 8 days in summer (Moore *et al*., 2005) multiplied by the leaf density. Values were expressed on a leaf area basis and shown as daily and annual rates. Values for nitrogen and phosphorus incorporated annually into new growth were derived from the concentrations of N and P in mature leaf tissue from the centres of patches (0.87 mg N m^{-2} leaf, mg P m^{-2} leaf), multiplied by leaf growth rate.

Results

There were significant differences in nitrogen (N) and phosphorus (P) concentrations between species and N and P concentrations were higher in older leaf tissue of *P. australis* than in those of *P. kirkmanii* (Table 19, 0.15 vs. 0.07 mg g^{-1} N, 0.013 vs. 0.009 mg g^{-1} P, $P < 0.0001$). There were also significant differences for new leaf tissue: *P. australis* had higher N but lower P concentrations than those in *P. kirkmanii* (0.12 vs. 0.07 mg g^{-1} N, 0.014 vs. 0.02 mg g^{-1} P, $P < 0.0001$).

Table 19. Results of analysis of variance testing for differences in N, P and N:P ratio. Factors examined were species, leaf part (nested in species) and stand position (nested in species). Bold type indicates sources of variation where differences are significant at $P < 0.05$.

Source	d.f.	MS	*F*	*P*
a) N				
Species	1	2.856	490.867	**< 0.0001**
Species (leaf part)	2	0.262	45.044	**< 0.0001**
Species (stand position)	2	0.008	1.315	0.286
Residual	26	0.006		
b) P				
Species	1	0.0005	1.125	0.299
Species (leaf part)	2	0.022	44.483	**< 0.0001**
Species (stand position)	2	0.0001	0.233	0.794
Residual	26	0.0005		
c) N:P				
Species	1	620.17	69.803	**< 0.0001**
Species (leaf part)	2	404.04	45.477	**< 0.0001**
Species (stand position)	2	5.103	0.574	0.57
Residual	26	8.885		

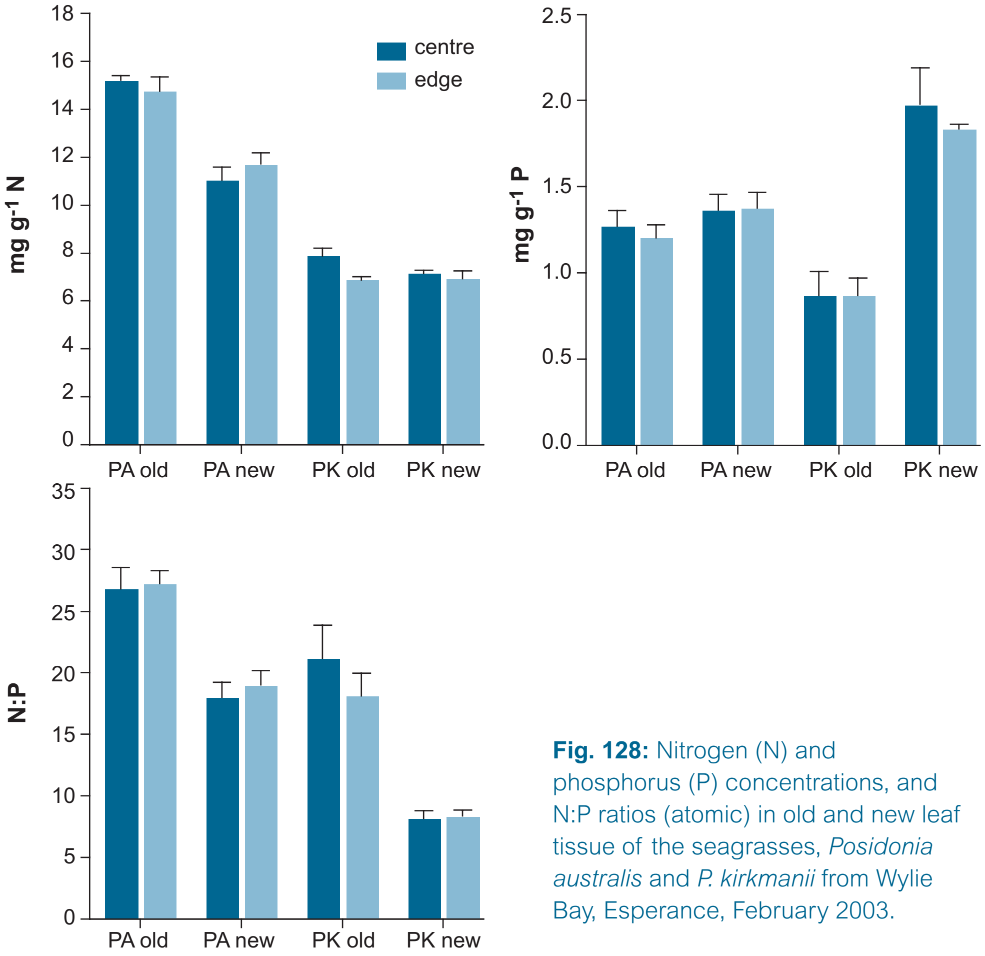

Fig. 128: Nitrogen (N) and phosphorus (P) concentrations, and N:P ratios (atomic) in old and new leaf tissue of the seagrasses, *Posidonia australis* and *P. kirkmanii* from Wylie Bay, Esperance, February 2003.

The two species showed a difference in nutrient allocation to old and new leaf tissue: *P. australis* had higher N concentrations in the older tissue ($P < 0.0002$) but similar P concentrations, whereas *P. kirkmanii* had similar N concentrations but significantly higher P concentrations ($P < 0.0003$). This also showed clearly in the atomic N:P ratios, which were very low (8:1) in the new tissue of *P. kirkmanii* compared with those of *P. australis* (18:1) Neither species showed a difference in N and P concentration between the same leaf tissue type from centres or edges of patches (Fig. 128).

In contrast to differences in nutrient concentrations for the older leaf tissues between species, there were no significant differences in the N:P ratio (atomic ratio 17 to 22:1) or between leaves from the centre or edges of patches. Newly grown tissue near the leaf bases, particularly for P. *kirkmanii*, had lower N:P ratios (4:1 by wt, or atomic ratio 7:1).

Discussion

Nitrogen and phosphorus concentrations were low, or very low for *P. kirkmanii*, compared with values for other seagrass (Cambridge and Hocking 1997, Duarte 1990, Forqurean *et al*. 1992, Hocking, Cambridge and McComb 1981, Klumpp and van der Valk 1984) or terrestrial plants (Marschner 1995). Position at the centre or edge of a patch did not influence N and P concentrations, in contrast to a marked effect on leaf length, width and growth rates reported in Moore *et al*. (2005). Following extensive compilation of data for 27 seagrass species over a broad range of geographic locations, Duarte (1990) showed that most N and P values for seagrasses were clustered at the low end of the observed range of values, suggesting that nutrients are not usually accumulated at levels much above those required for normal functioning, but that there is a rather close coupling of internal nutrient pools to leaf growth.

Nutrient concentrations in plant leaves, particularly those of nitrogen, are also an indication of physiological functioning through traits such as photosynthetic capacity (Field *et al*. 1983) and leaf life span (Chabot and Hicks 1982, Reich 1998), and relative growth rate (Lambers and Poorter 1992, Garnier and Vancaeyzeele 1994) and leaf life span. Many of these universal relationships linking N concentrations (expressed per unit of leaf mass) to leaf traits, are, however, inappropriate to apply to seagrasses, because of their contrasting leaf anatomy (Cambridge and Lambers 1998). In seagrass leaves, the photosynthetic apparatus, which contains a large proportion of the plant's nitrogen compounds is found primarily in the epidermal cells, instead of in the internal mesophyll cells. Differences in leaf thicknesses thus have a large effect on N concentration when this is expressed per unit leaf mass, and account for the apparently severely limiting nutrient concentrations (< 0.18 mg g^{-1} N) reported for the Australian species of *Posidonia* (Duarte 1990). When N concentrations are expressed per unit leaf area (Table 20) which is more appropriate considering the anatomy of seagrasses and also takes into account the functional surface area of the photosynthetic tissue, a rather different picture emerges. *Posidonia australis* and *P. kirkmanii* had amongst the highest concentration of N, similar to that of *Syringodium* from Rottnest. Most of the dry matter in the leaf consists of internal tissues, mostly parenchyma cells are which effectively dilutes the N contained in the thin layer of epidermis when N is expressed on a mass basis. These species are thus likely to be extreme examples of the lack of relationship between N expressed per unit dry weight and traits such as photosynthetic capacity and relative growth rate.

Table 20. Mass per unit leaf area (LMA) and nitrogen concentration per unit leaf area: comparison of *Posidonia kirkmanii* and *P. australis* at Wylie Bay, Esperance with seagrass species from Rottnest Island (Cambridge and Lambers 1998). Mean values for LMA are reported in Moore *et al*. (2005) for *P. kirkmanii* (98 and 112 g m^{-2} for newly grown and older leaf tissue, respectively, at the centre of single species patches, and 88 and 98 g m^{-2} for newly grown (shown in brackets) and older leaf tissue, respectively, at patch edges), and for *P. australis* (66 g m^{-2} for older tissue only at patch centres and edges, new growth not measured). Total N analyses for Rottnest samples were made on microsamples (1-3 mg) of dried leaves ground to a fine powder from pooled samples, using an elemental analyser (Carlo Erba 1106 CHNOS, Milano, Italy

Species	Leaf mass per unit area g m^{-2}	N per unit leaf area g N m^{-2}
***Posidonia kirkmanii* (centre)**	**112(98)**	**0.87(0.71)**
***Posidonia kirkmanii* (edge)**	**98(88)**	**0.67(0.61)**
***P. australis* (centre)**	**66**	**1.00**
***P. australis* (edge)**	**66**	**0.98**
P. coriacea	139	0.95
P australis	46	0.58
P. sinuosa	61	0.79
Amphibolis antarctica	35	0.64
A. griffithii	35	0.75
Thalassodendron pachyrhizum	30	0.54
Heterozostera tasmanica	18	0.43
Halophila ovalis	23	0.59
Syringodium isoetifolium	80	1.00

The ratio of N:P for the older leaf tissue was in the normal range for higher plants, including aquatic macrophytes (8 to10:1 by weight, atomic ratio 17 to 22:1), indicating a balance of nutrition (Lambers *et al*. 1998). There was no difference between species or between leaves from the centre or edges of patches. Newly grown tissue near the leaf bases, particularly for *P. kirkmanii*, had lower N:P ratios (7:1). These leaf sections had not yet developed and were very pale and rather soft compared with the older leaf material. Their lower N:P ratios result from lack of development of the photosynthetic apparatus, and hence less nitrogen, compared to older leaves. Seagrasses have a higher proportion of structural carbon compared to most terrestrial plants or phytoplankton and algae: for example the Redfield ratio is C:N:P 106:16:1 (Redfield *et al*., 1963). The median values for C, N and P concentrations in seagrass leaves (33.5%, 1.9% and 0.24% of tissue dry weight) are equivalent to a median atomic C:N:P ratio of 435:20:1.

Posidonia kirkmanni is the most robust of several closely related species with tough, leathery leaves, deeply buried rhizomes and long anchoring roots, which have been grouped into the *P. ostenfeldii* species complex (Kuo and Cambridge 1984). The study site at Wylie Bay near Esperance provided a rare opportunity to study dense meadow-like stands of *P. kirkmanii* in shallow waters. As there is no information on the growth or ecology of this species, a series of parameters were derived for standing stocks, growth and nutrient pools and incorporation into new growth to provide a basis for comparison with better studied *Posidonia* meadows in Western Australia at Warnbro Sound near Perth at a similar depth, 2.5 m (Table 21). Data for *P. kirkmanii* were collected in summer, when standing stocks and growth rates were likely to be close to their maxima and it is likely that the daily averages and annual rates calculated here from a short growth interval (8 days) in summer are an over-estimate, as they could not include slower growth rates which usually occur in winter.

Table 21. Leaf parameters and derived values for standing stocks, leaf growth and nutrient incorporation into new growth (mean±sd), *Posidonia kirkmanii* at Wylie Bay, Esperance. *Growth parameters derived from a single short-term leaf marking experiment in summer only. Comparisons with *P. australis* and *P. sinuosa* from Warnbro Sound near Perth, using summer maxima for leaf lengths, LAI and standing stocks, annual averages[1] for growth and nutrient incorporation, summarized from Cambridge and Hocking (1997).

	P. kirkmanii	***P. australis***	***P. sinuosa***
Max. leaf length (mm)	1470	500	700
Range of leaf widths (mm)	5.1-12.6	9-12	5-8
Area per leaf (Mean ± sd,mm^2)	822±80	-	-
Leaf density (leaves m^{-2})	481±121	-	-
Shoot density (shoots m^{-2})	187±47	600	1100
LAI (m^2 leaf m^{-2} ground area)	3.89±0.68	4-6	4-6
Leaf biomass(g dw m^{-2})	463±77	320	350
N in standing leaf biomass (g N m^{-2})	3.44±0.61	2.2[1]	2.2-3.0[1]
P in standing leaf biomass (g P m^{-2})	0.38±0.07	0.28[1]	0.25-3.0[1]
Growth (mm^2 d^{-1})*	80±25	-	-
Growth (m^2 leaf m^{-2} d^{-1})*	0.039±0.01	0.092	0.062
Growth per year (m^2 leaf m^{-2} y^{-1})*	14.05±3.52	14-16[1]	10-14[1]
N incorporation (g N m^{-2} y^{-1})*	12.36±3.10	12[1]	10-15[1]
P incorporation (g P m^{-2} y^{-1})*	1.36±0.34	1.5-1.8[1]	1-1.5[1]

Leaf lengths were 2-3 times longer than for *P. australis* and *P. sinuosa* but shoot densities were much lower, resulting in a lower leaf area index and lower standing biomass (Table 21). Nitrogen and phosphorus pools in the leaf canopy were higher in *P. kirkmanii* than the annual averages for *P. australis* and *P. sinuosa*. Growth rates were much lower for *P. kirkmanii* even when using summer growth rates, which resulted in low estimates of annual incorporation of N and P into new leaf tissue compared to *P. australis* and *P. sinuosa*. These derived values from a brief study of *P. kirkmanii* suggest that this robust species grows very slowly in the clear, oligotrophic waters on the south coast, and so has low incorporation rates of nutrients into new growth. Turnover rates of biomass are also likely to low with long life spans for individual leaves, so that despite slow growth rates, the characteristically dense canopy of long leaves is able to develop.

Conclusions

Nitrogen and phosphorus concentrations expressed per unit dry weight were low, or very low in the case of *P. kirkmanii*, compared with values for other seagrasses. The ratio of N:P for the older leaf tips was in the normal range for higher plant tissues, including aquatic macrophytes, indicating a balance of nutrition. There were significant differences in nitrogen and phosphorus concentrations between species: N and P concentrations were higher in older leaf tissue of *P. australis* than in those of *P. kirkmanii.* New leaf tissue of *P. australis* had significantly higher N but lower P concentrations than new leaf tissue of *P. kirkmanii*. There was no difference in leaf nutrient concentrations from the centre or edges of patches for either species. Growth rates appear to be much lower for *P. kirkmanii* even when using summer growth rates, compared to *P. australis* and *P. sinuosa*.

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6.10 Ecological interactions

Increased density, biomass and egg production in an unfished population of Western Rock Lobster (*Panulirus cygnus*) at Rottnest Island, Western Australia.

Introduction

The Western Rock Lobster (*Panulirus cygnus*) provides the basis for the single largest fishery in Western Australia, and is the largest rock lobster fishery in the world with an annual commercial catch of approximately 10-11,000 tonnes (Hall *et al*. 2000). This level of catch has followed a roughly constant or slightly increasing trend since the 1970's, as has fishing effort (Chubb and Barker 2003). The fishery is generally considered to be well managed and sustainable, and it was the first fishery to receive accreditation by the Marine Stewardship Council in 2000. It is currently estimated that the total biomass levels of Western Rock Lobster are 80% to 90% of unfished levels (IRC Environment 2003), and that egg production in 1999-2000 was around 22% of original unfished egg production (Hall & Chubb 2001). Thus there may be significant changes in *P. cygnus* population structure, though not necessarily in total biomass, as a result of fishing.

Studies of rock lobster populations in other parts of the world have shown, using no-take marine protected areas (MPAs), that there can be significant changes to population structure but also to total biomass inside these areas relative to fished areas (Kelly *et al*. 2000, Edgar and Barrett 1999, Lafferty and Kushner 2000, Goni *et al*. 2001, Acosta 2002, Rowe 2002). However such changes are not observed universally, possibly because some MPAs lack suitable habitat (Mayfield *et al*. 2000) or where populations are highly mobile relative to the size of unfished areas (McGarvey 2003). Small areas of the Western Australian coastal waters are protected by a range of spatial fishing closures that offer varying levels of protection from fishing. While some level of population recovery might be expected in areas closed to fishing due to a reduction in fishing mortality, there are also reasons why this may not necessarily occur. *Panulirus cygnus* is a migratory species, moving into deeper water at the age of around 4 years (Chubb *et al*. 1999), and most of the spatial closures within its range are located in relatively shallow waters, often within coastal reef systems. Since *P. cygnus* reaches legal size at around this age, it may be that there is little if any detectable effect of fishing on shallow water populations. We examined the population of rock lobsters in a no-take marine sanctuary at Rottnest Island to assess the extent to which it differed from populations in adjacent coastal areas. The identification of strong spatial gradients in lobster abundance would provide a valuable tool for investigating the ecological roles of rock lobster in the WA coastal ecosystem.

Methods

Study area

Rottnest Island and its coastal waters out to 800 m from shore are managed by the Rottnest Island Authority. Waters surrounding the island are managed by the RIA under state fisheries legislation that excludes commercial fishing of all kinds as well as recreational spearfishing. All other legal forms of recreational fishing, including potting and diving for rock lobsters, are permitted. The close proximity of Rottnest Island to the city of Perth results in high levels of recreational fishing pressure around the Island (L. Beckley Pers. Comm.). Consequently the entire study area was within a multiple-use Marine Protected Area that included the no-take Kingston Reefs Marine Sanctuary, in which all forms of fishing and collection of marine life are prohibited, as well as sections of coast open to recreational fishing. The marine sanctuary at Kingston Reefs was established in 1986 and has been well policed by island rangers and members of the public as it is an area with high levels of boating traffic. Maximum depth within the reserve is approximately 10 m but the majority of the area lies at depths of around 5 m. The sanctuary zone is triangular in shape, covering 145 ha and contains both reef and sand habitats typical of those found around the eastern end of Rottnest Island.

Sampling design

The design of the study was such that it compared lobster populations on reefs with varying management status (STATUS) as well as at varying distances from the centre of the sanctuary (DISTANCE). Spatial variability was examined at two levels, AREA and SITE. The marine sanctuary was divided into four areas of approximately equal size, as were the adjacent coastal areas (Fig. 129), giving four fished and four unfished areas (AREA). At two sites (SITE) nested within each of these areas replicate transects were conducted to determine the density, size and sex of resident lobster populations.

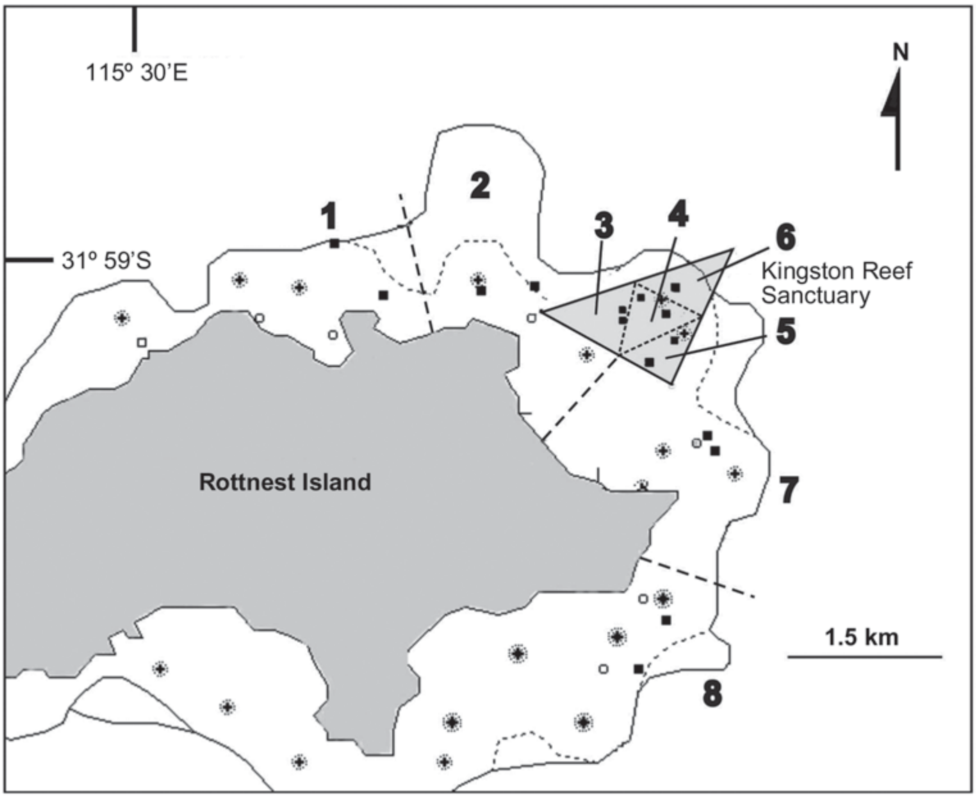

Figure 129: Map of the study area at Rottnest Island.

Transects were 50 x 5 m belt transects that were run parallel to depth contours at depths between 4 and 8 m depending on the site, and were deployed over areas that had the potential to hold lobsters (medium to high relief reef with caves, ledges or overhangs). Lobsters were recorded and their size and sex estimated visually to the nearest 5 mm (MacDiarmid 1991). All transects were conducted in November to December 2003 by three divers trained to estimate lobster size prior to commencing surveys. Calibration of diver visual estimates involved visually estimating the carapace length (CL) of a lobster, then capturing it and measuring the carapace length with vernier calipers (Fig. 130). Additional calibration checks were made opportunistically throughout the survey period. Calibration data obtained in this way can be used to correct size estimates for any bias. Where possible the sex of each lobster was also determined. Where size or sex could not be positively determined, these were recorded as unknown.

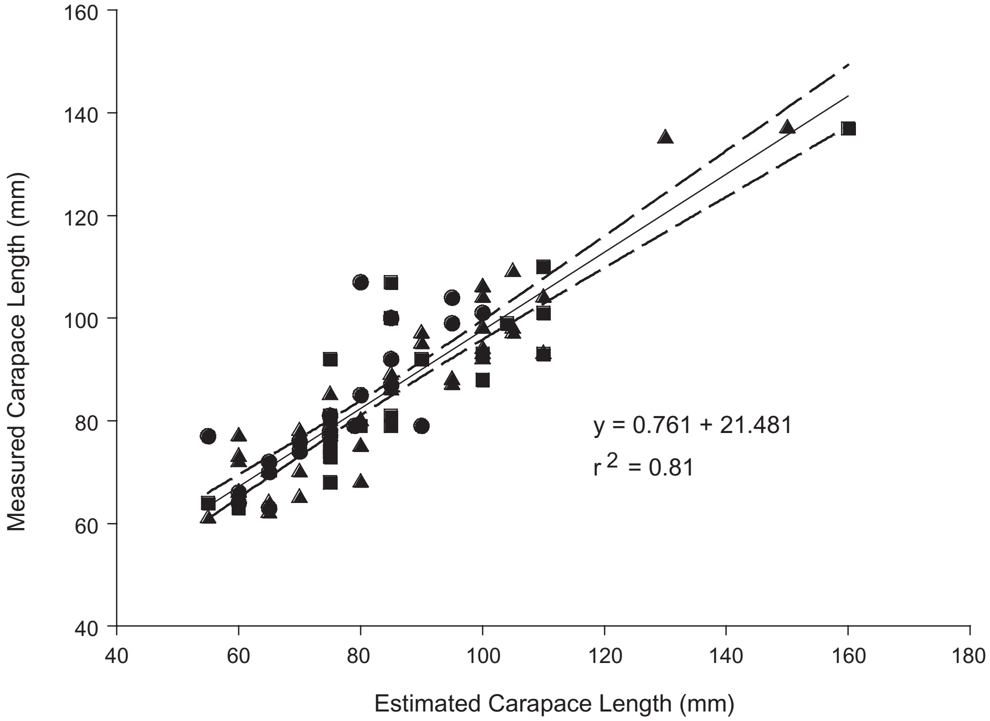

Figure 130: Lobster measurements used to calibrate the visual estimates of lobster size in the study. Different symbols indicate data from the three observers.

Data analysis

Crayfish are social animals, often aggregating for mating or to utilize available shelter. Because of this the count data are overdispersed and non-normally distributed. Accordingly the data for lobster density were analysed using the Poisson distribution, and a mixed-effects log-linear model used to fit the data using the GLIMMIX macro (Littell *et al*. 1996, Millar and Willis 1999) using SAS v.8. The model treated STATUS, DISTANCE and STATUS × DISTANCE as fixed effects, where STATUS indicated sanctuary or non-sanctuary status and DISTANCE indicated the rank distance from the centre of the sanctuary, with areas 4 & 5 falling within distance category 1, areas 3 & 6 distance 2, areas 2 & 7 distance 3 and areas 1 & 8 distance 4. The nested factors AREA(DISTANCE) and SITE(AREA) were random and treated as co-variates in the analysis.

Data for all lobsters were analysed, and subsets of the data were analysed separately for legal sized animals (> 77 mm CL), and for those less than legal size. Lobster sizes in fished and unfished areas were tested using ANOVA.

In order to assess the effects of fishing on lobster biomass, lobster carapace lengths were converted to biomass using the equations:

$$W = 0.0016068\ CL^{2.8682} \quad \text{males}$$
$$W = 0.0025053\ CL^{2.778} \quad \text{females}$$

Where W = weight in g, and CL = carapace length in mm (Hall and Chubb 2001). Similarly carapace length estimates could be used to estimate egg production using the relationship:

$$E = 2(1.92)\ CL^{2.69}$$

where E = the number of late stage eggs borne by a female lobster larger than the size at maturity (95 mm CL in the southern zone, Hall and Chubb 2001). Rather than make any assumptions about the sex of lobsters where their sex could not be positively determined, lobsters of unknown sex were excluded from the comparison. Data for biomass and fecundity were summed for each transect and analysed as for the density data.

Results

There was a close relationship between estimated size and actual measures of carapace length ($r^2 = 0.81$, $F_{1,94} = 396$, $p < 0.001$) however the slope of the regression was significantly different from 1:1 ($t_{96(2)} = -6.24$, $p<0.001$) and had a y-intercept of 21.481 ($t_{96(2)} = 19.9$, $p<0.001$), indicating that the size of small animals was often underestimated, while the size of larger animals was often overestimated. Part of this bias may be due to pronounced allometric changes in the relative leg length of large male *P. cygnus*. Estimates were corrected using the appropriate relationship (Fig. 130) to remove systematic bias in size estimates.

During the study 1160 lobsters were counted. Population structures varied markedly between sanctuary and non-sanctuary areas (Fig. 131) with a greater proportion of lobsters above minimum legal size inside the sanctuary zone. Another feature of the sanctuary zone population was the presence of large males (over 115 mm CL) that were absent from the fished areas. Modal size (CL) was 8.5 mm larger in the sanctuary zone ($F = 82.07$, $p < 0.001$, Fig. 132). While there was a slightly higher abundance of male lobsters overall the ratio of females to males (0.89:1) was not significantly different from 1:1. Due to the cryptic behaviour of the lobsters it was not possible to positively determine the sex of 600 (48%). While this is a high proportion it is unlikely to have biased the results of the overall comparison since very similar proportions of lobsters of unknown sex were recorded in both fished (44%) and unfished areas (49%).

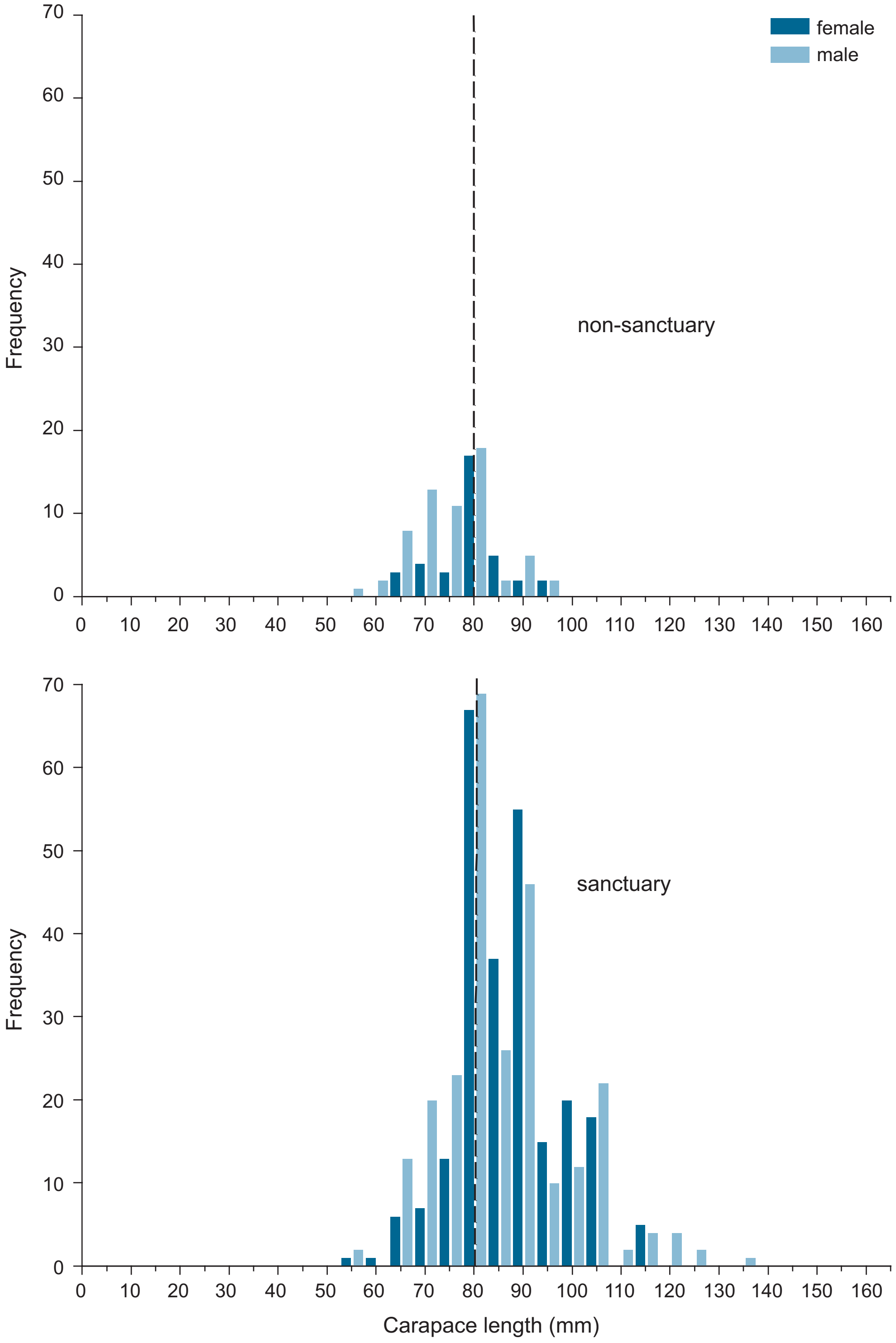

Figure 131: Population structure of *Panulirus cygnus* in the Kingston Reefs Marine Sanctuary and in adjacent fished areas.

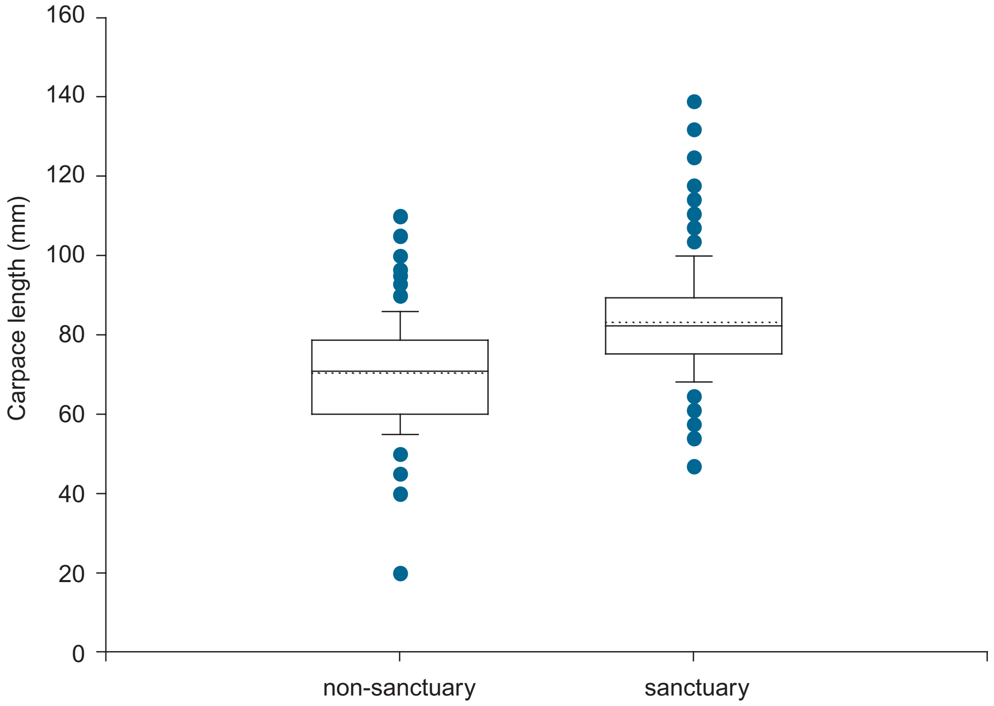

Figure 132: Size of lobsters in the Kingston Reefs Marine Sanctuary and in adjacent fished areas. Box plots are medians and 25th and 75th percentiles (solid line), mean (dashed line) 5th and 95th percentiles and outliers (filled circles)

The overall density of rock lobsters was higher within the marine sanctuary than outside it ($t_{63(2)}$ = -4.2, P<0.001) with an estimated density of 26.5 lobsters per transect inside compared with only 4.1 lobsters outside, a ratio of 6.5 (Table 22). Lobster density did not co-vary significantly with the factors SITE and AREA (Table 23). The density of both legal ($t_{63(2)}$ = -3.95, P<0.001) and sub-legal ($t_{63(2)}$ = -2.95, P<0.001) sized lobsters was higher inside the sanctuary (Table 23), though this difference was much more pronounced for legal sized animals, which were estimated to be 13.1 times more abundant inside the sanctuary (Table 22). Lobsters below the legal size limit were only 3.2 times more abundant in the sanctuary. For lobsters of all sizes densities varied significantly with distance (Table 23) and were highest at the centre of the sanctuary, declining to the lowest values at the most distant areas (Fig. 133).

Table 22. Density, biomass and egg production of spiny lobsters in the Kingston Reef Marine Sanctuary and adjacent fished areas.

	Sanctuary mean	**Non-sanctuary mean**	**Sanctuary: Non-sanctuary ratio**	**Ratio for lower 95% CI**	**Ratio for upper 95% CI**
Total density (250 m^{-2})	26.5	4.1	6.5	15.0	3.9
Legal density (250 m^{-2})	18.2	1.4	13.2	58.4	5.9
sublegal density (250 m^{-2})	8.5	2.7	3.2	6.7	1.8
biomass (kg.ha^{-1})	527.9	55.1	9.6	7.9	29.9
fecundity (eggs ha^{-1})	5.8×10^5	6.5×10^4	8.8	6.2	19.3

Table 23. Variation in spiny lobster abundance in and around the Kingston Reef Marine Sanctuary. Results of a Generalised Linear Mixed Model of lobster density (number per transect).

Counts	All lobsters		Legal lobsters		Sublegal lobsters	
Term	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**
Extra-Poisson variation	2.97		2.58		1.89	
Variance components						
AREAS(DIST)	0.08	0.14	0.09	0.17	0.02	0.13
SITE(AREAS)	0.05	0.08	0.08	0.10	0.07	0.12
DISTANCE effects						
1	3.5137	0.6841	3.1427	0.7479	2.3385	0.6217
2	2.968	0.295	2.5796	0.3225	1.896	0.2757
3	1.8671	1.4655	0.8737	2.141	1.3784	1.374
4	0.5507	0.8706	-1.0001	1.2135	0.3704	0.847

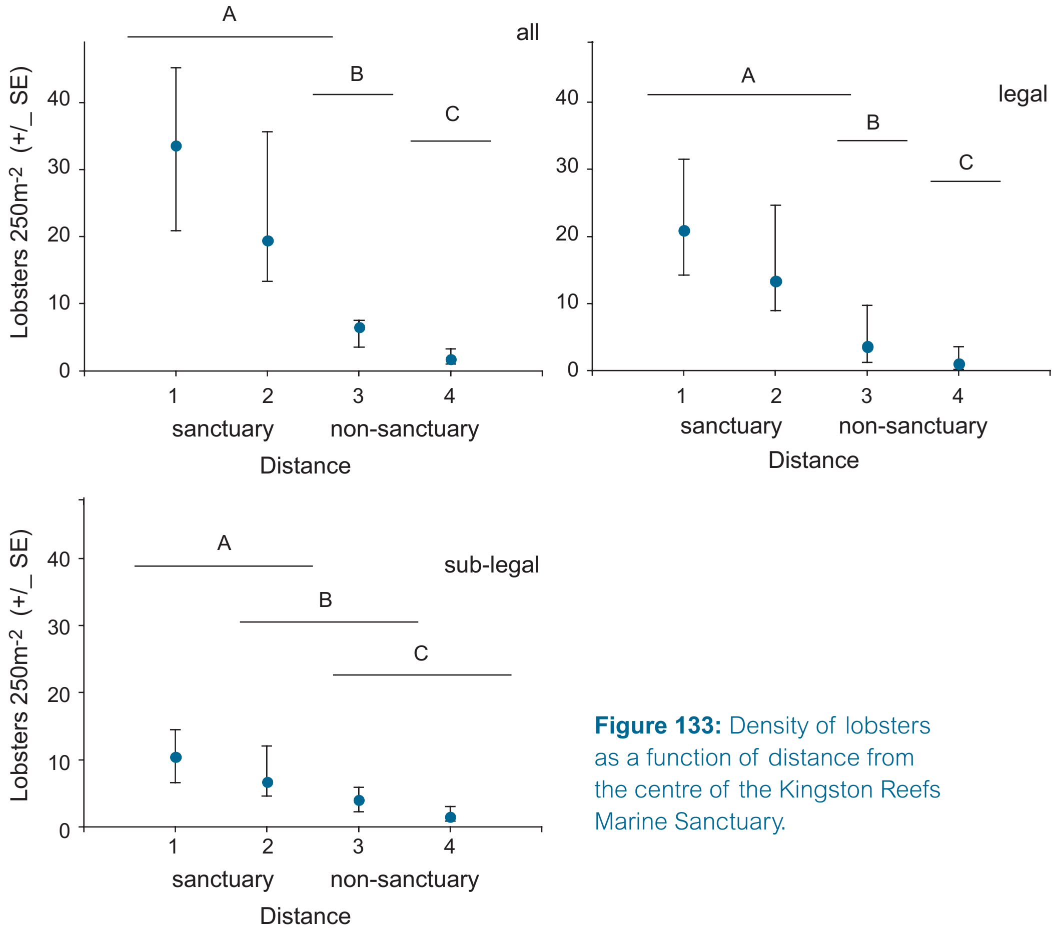

Figure 133: Density of lobsters as a function of distance from the centre of the Kingston Reefs Marine Sanctuary.

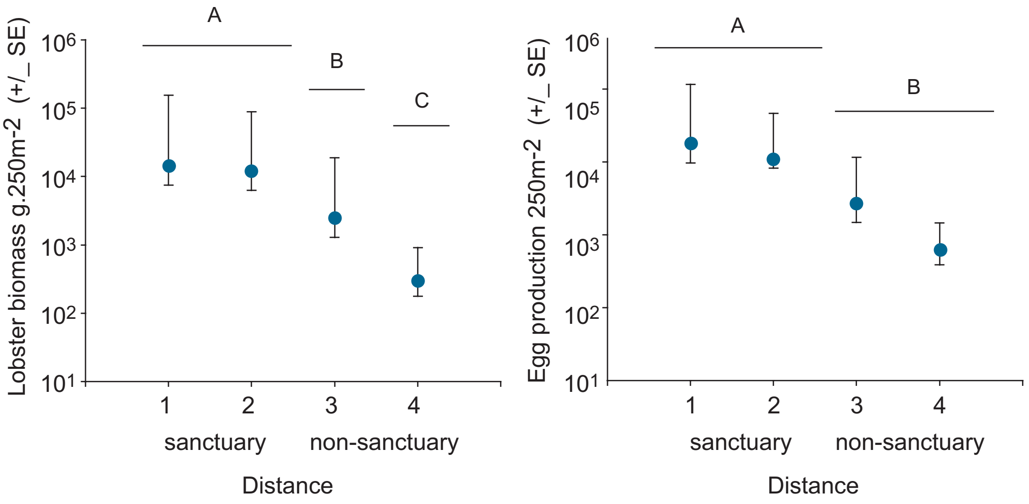

Figure 134: Biomass and egg production of lobsters as a function of distance from the centre of the Kingston Reefs Marine Sanctuary.

As a consequence of higher densities and larger sizes of lobsters in the sanctuary significant differences were found there, both in terms of biomass ($t_{24(2)}$ = 3.7, P<0.001) and fecundity ($t_{63(2)}$ = -4.1, P<0.001) of lobsters (Table 22, Table 24). For example a lobster of 75 mm CL is estimated to weigh approximately 387 g, while a lobster of 100 mm CL would weigh more than twice this amount (876 g). The estimated biomass of lobsters in the sanctuary was 527.9 kg ha^{-1} of reef habitat, 9.6 times higher than the estimated 55.1 kg ha^{-1} in fished areas outside. Fecundity followed a similar trend, with egg production estimated to be 8.8 times higher inside the sanctuary (5.8 x 10^5. ha^{-1}) than outside it (6.5 x 10^4. ha-1). Both lobster biomass and egg production were uniform among areas within the sanctuary (Fig. 134). While biomass declined progressively with distance from the reserve boundary, egg production did not vary with distance (Fig. 134).

Table 24. Variation in spiny lobster biomass and egg production in and around the Kingston Reef Marine Sanctuary. Results of a Generalised Linear Mixed Model comparison of lobster biomass (total weight per transect) and egg production (total egg production per transect).

	Biomass – All lobsters		**Egg Production - All lobsters**	
Term	**Estimate**	**SE**	**Estimate**	**SE**
Extra-Poisson variation	5.6941		6.4285	
Variance components				
AREAS(DIST)	0.0408		0.1266	
SITE(AREAS)	0		0.0625	
DISTANCE effects				
1	9.5818	0.842214	6.9269	0.576501
2	9.3842	0.658245	6.4285	0.281262
3	7.8075	0.676865	7.8919	0.302842
4	5.6941	0.016169	6.4285	-0.30802

Discussion

There were significant trends in density, biomass and egg production of *P. cygnus* with all three parameters being significantly lower outside the boundaries of the Kingston Reef sanctuary zone, and decreasing with distance from the centre of the sanctuary. These results are similar to the majority of other published studies of no-take marine protected areas which have shown increases in one or more of these parameters (e.g. Kelly *et al*. 2000, Goni *et al*. 2001). We believe that reduced fishing mortality within the sanctuary is the most likely explanation for these trends at Rottnest Island. Because the study could not be replicated at several sanctuary zones and the lack of data from prior to the sanctuary's creation, this interpretation must be applied cautiously (c.f. Willis *et al*. 2003). However the design of the study included multiple areas within the fished and unfished zones, and the consistent patterns of lobster abundance in all the areas within the two zones suggests that the overall pattern is likely to be a result of zoning status rather than random spatial variation. If the pattern is caused by fishing as we suggest, it implies that recreational fishing has very strong effects on this population, since there is no commercial fishing within the study area, or within 800 m of the Rottnest shore.

Size-dependent variation in lobster abundance was evident between sanctuary and fished areas, a fact which was evident in their contrasting population structures. There were more large lobsters in the sanctuary zone, and the mean size of lobsters there was larger. Furthermore, individuals of sizes ≥ 100 mm CL were only found inside the sanctuary. The largest individuals (≥ 115 mm CL) found in the sanctuary were all males. While the majority of lobsters in any given cohort are expected to move from shallow coastal areas to deeper waters (≥ 30 m, Chubb *et al*. 1999) as they reach maturity the substantial numbers of large mature lobsters in unfished shallow waters surrounding Rottnest suggest that these individuals can and do accumulate in shallow habitats given the opportunity. If, as we argue, gradients in lobster abundance, biomass and egg production are a result of fishing, then the potential impact of fishing on shallow water lobster populations may be much greater than has been assumed (IRC environment 2003).

Differences in density between zones were significant for lobsters below the minimum legal size as well as for those above legal size. The density of lobsters greater than legal size was 13.2 times higher inside the sanctuary, while for those lobsters less than legal size it was only 3.2 times greater. While a difference in density of legal-sized lobsters is expected under conditions of no-take zoning, and the strongest effect was found for these lobsters, there should be no difference in density of lobsters below legal size if fishing was the only factor driving variation in abundance. We propose two non-exclusive hypotheses as potential explanations for the pattern of abundance in sub-legal sized lobsters. The first is that differences in habitat result in more lobsters being found in the sanctuary areas, and the second is that the presence of large lobsters may attract other smaller lobsters to these areas. We believe the first hypothesis is unlikely to be a full explanation for variation in juvenile abundance in this case. In all areas surveys were restricted to reef areas that contained potential lobster shelter (caves, ledges and crevices) as well as feeding habitat, and that there did not appear to be any systematic difference between sanctuary and non-sanctuary zones in this regard. With respect to the second hypothesis, there is evidence from other lobster species that juveniles are gregarious and that larger animals are the focus for aggregations of smaller individuals (Butler *et al*. 1999). Therefore the presence of large animals in the Kinston Sanctuary could lead to an accumulation of smaller animals through an active process of aggregation (c.f. Childress and Hernkind 1997, Nevitt *et al*. 2000). Further studies involving multiple reserves are required in order to test these two hypotheses. The findings of such research would have significant implications for spatial management for fisheries and conservation.

Trends in lobster abundance and biomass as a function of distance from the centre of the sanctuary indicate that the influence of the sanctuary zone may extend beyond its boundaries. The form of this relationship is similar to what might be predicted (Kramer and Chapman 1999) but differs in detail from patterns described for other exploited species. Using a similar sampling design applied to the fish *Pagrus auratus*, a pattern of reduced relative abundance just inside the boundaries of the Leigh Marine Reserve has been shown (Willis *et al*. 2000), while in the case of *Panulirus cygnus* at Rottnest Island there appears to be an increase in abundance just outside the reserve boundary. The difference in these patterns could be due to differences in the relative movement rates of the two species, the pattern and intensity of fishing behaviour, or to both. In either case the attribution of such patterns to “spillover” or the net export of biomass (Russ 2002) requires measurements of both immigration and emigration across the boundaries of reserves or sanctuary, neither of which are available for the Kingston Reef Sanctuary.

Based on the current models of the state of the *P. cygnus* fishery, it is estimated that egg production of the stock is around 22% of unfished levels (Hall and Chubb 2001) and that the biomass of the stock is at least 80% of its unfished levels (IRC Environment. 2003). The difference between fished and unfished levels of biomass and egg production in the Kingston Reef Sanctuary suggests that, at least around Rottnest Island, lobster populations are around 10% of unfished biomass and 11% of unfished egg production. The conclusions that can be drawn from this study are restricted in scope and generality for obvious reasons, because only one sanctuary has been studied and we have no data prior to the sanctuary’s creation. Nevertheless the data suggest that there is a *prima facie* case for further studies of this kind, involving no-take areas throughout the range of the stock. The minor risks posed by establishing a system of no-take areas for research are likely to balance favourably against the more substantial risks attached to maintaining the status quo for a fishery that may be at significantly lower levels than previously estimated. A range of other benefits for stock assessment, risk assessment and the understanding of lobster ecology are also likely to accrue (Chubb 1994).

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6.11 Spatial subsidies: trophic linkages among habitats at local and cross-shelf scales

Introduction

The focus of the research is on understanding spatial and trophic linkages in reef-seagrass ecosystems, in particular, how important spatial subsidies (i.e. movement of food resources from one habitat to another) are for the productivity of reef ecosystems.

To address questions of the spatial extent of ecological processes, studies must encompass relevant spatial scales. To date, much of what we know about marine ecosystems has been gleaned from experimental manipulations at the scale of a few meters or less. Understanding spatial subsidies between habitats needs to be addressed at scales of hundreds of meters, and possibly kilometers. The research is conducted with sampling at these relevant spatial scales, so that the extent and magnitude of linkages can be quantified.

The overall aim of research on spatial subsidies is to understand and quantify the importance of trophic linkages between habitats, particularly reef and seagrass habitats. The approach to addressing this aim has been to conduct surveys and experiments designed to test specific hypotheses. Specifically, it is predicted that at scales of hundreds of meters, the amount of drift macroalgae in seagrass beds will vary with increasing distance from reef, and that this drift algae forms an important potential food source for seagrass fauna. At larger scales, it is predicted that with increasing proximity to the shore there will be a gradient of increasing drift macroalgae biomass on reefs due to net shoreward transport of drift algae, and that this drift algae will constitute an important food source for reef-dwelling invertebrates.

Methods

The biomass of drifting reef algae was measured at six reefs in Marmion Lagoon and six reefs in Jurien Bay. In both locations, three of the reefs were surrounded by meadows of *Amphibolis* spp, and three reefs were surrounded by meadows of *Posidonia sinuosa*. The potential for consumption of detached reef algae was measured by experiments in which consumption of tethered pieces of kelp *E. radiata* was measured over five days. Patterns in the biomass of drift with proximity to shore were measured on five reefs near Fremantle, on eight occasions. The reefs were located at varying distances from shore. The potential for consumption of drifting kelp was assessed by measuring the consumption of tethered pieces of kelp over three days at Mewstone. Pieces of kelp were either fixed so they could not drift, or attached to pieces of fishing line to mimic drift, in plots with and without the sea urchin *H. erythrogramma*.

Results

Biomass of drifting reef-algae in seagrass beds

The biomass of detached reef algae varied from reef to reef and with distance from reef, but not between Marmion Lagoon and Jurien Bay (overall mean 0.33 kg fw m^{-2} ± 0.05 SE) or between *Posidonia* and *Amphibolis* meadows. The amount of detached reef algae present in adjacent seagrass habitats at the various distances away from the reefs generally varied between 1-15% (overall mean 3.6% ± 0.7 SE, maximum 23%) of the biomass of attached algae in an equivalent area on the nearest source reefs. The patterns of distribution of detached reef algae with distance were not consistent at all reefs (Fig.135, Fig. 136). However, with few exceptions the biomass of detached reef algae at 0 m (immediately adjacent to reefs) was higher than all other distances – at most reefs the highest biomass of detached reef algae occurred at 0. These results show that there is often accumulation of detached reef algae at the base of the reefs. There was generally little difference in the biomass of detached reef algae on the reef and the 10 m and 50 m distances. The biomass of detached reef algae at distances of >300 m showed inconsistent patterns, being higher than the biomass of detached reef algae at other distances at some reefs and being lower at others. Importantly, however, this demonstrates that at some places there were substantial accumulations of detached reef algae in seagrass beds up to hundreds of metres from the nearest reef.

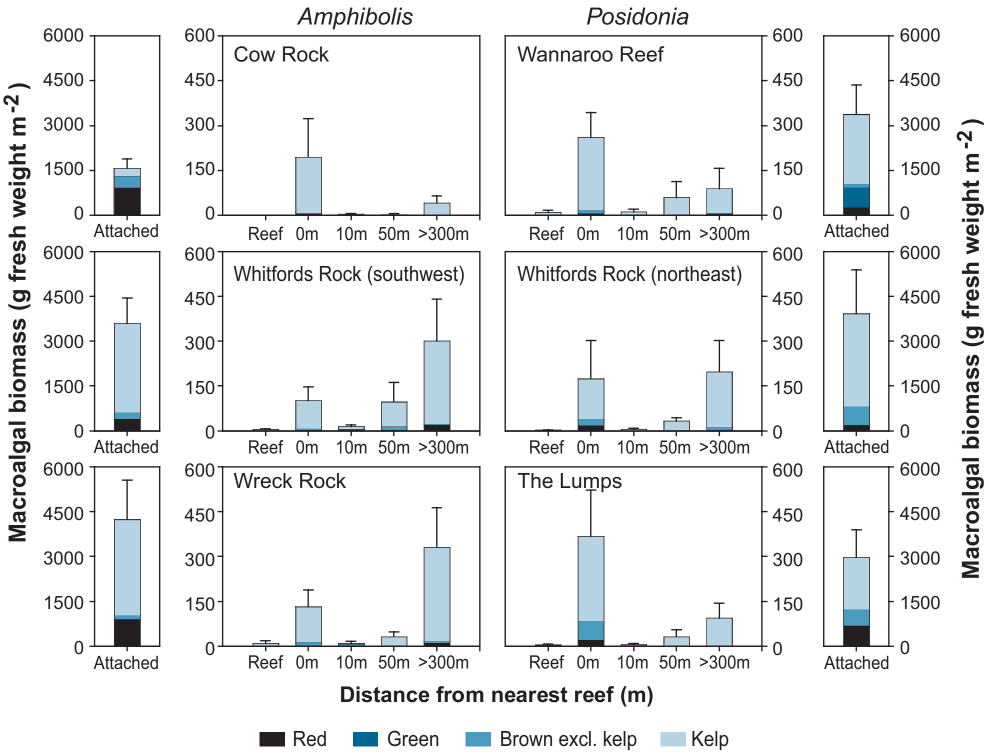

Figure 135: Biomass of attached and drift reef algae at six different reefs in Marmion Lagoon. Three of the reefs were adjacent to *Amphibolis* beds, and three were adjacent to *Posidonia* beds. At each reef, drift was surveyed on the reef, and in the seagrass at four distances from the reef.

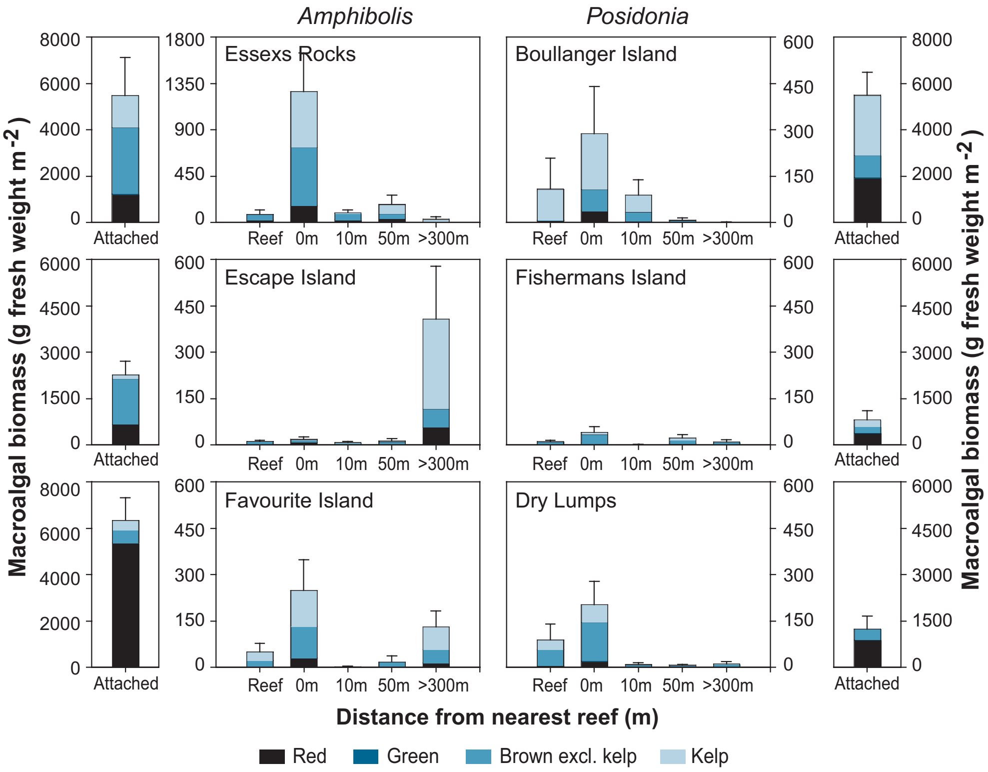

Figure 136: Biomass of attached and drift reef algae at six different reefs in Jurien Bay. Three of the reefs were adjacent to *Amphibolis* beds, and three were adjacent to *Posidonia* beds. At each reef, drift was surveyed on the reef, and in the seagrass at four distances from the reef.

The proportion of biomass of the kelp *Ecklonia radiata* was greater in the drift than in the attached assemblage in both Marmion Lagoon (88% ± 2 SE in the drift vs. 47% ± 7 SE in the attached assemblage) and Jurien Bay (44% ± 9 SE vs. 16% ± 6 SE).

Consumption of drift kelp in seagrass beds

Overall, the consumption of tethered kelp was significantly higher in Jurien Bay (mean 17.2% ± 4.6 SE) than in Marmion Lagoon (mean 6.2% ± 3.5 SE). There were no differences in consumption of kelp between *Amphibolis* and *Posidonia* beds. Consumption did vary with distance from reef, but not in a consistent way – consumption was typically highest at 0 m, but in some cases was highest at >300 m. At most distances at most reefs, there was just less than 10% consumption of tethered kelp over the five days deployment. However, at some distances on half of the reefs there was between 25 – 75% consumption. There was a significant positive relationship between mean consumption and the mean density of herbivorous fish at 0 m ($r^2 = 0.92$, $p < 0.001$), but not at >300 m ($r^2 = 0.16$, $p > 0.3$; Fig. 137).

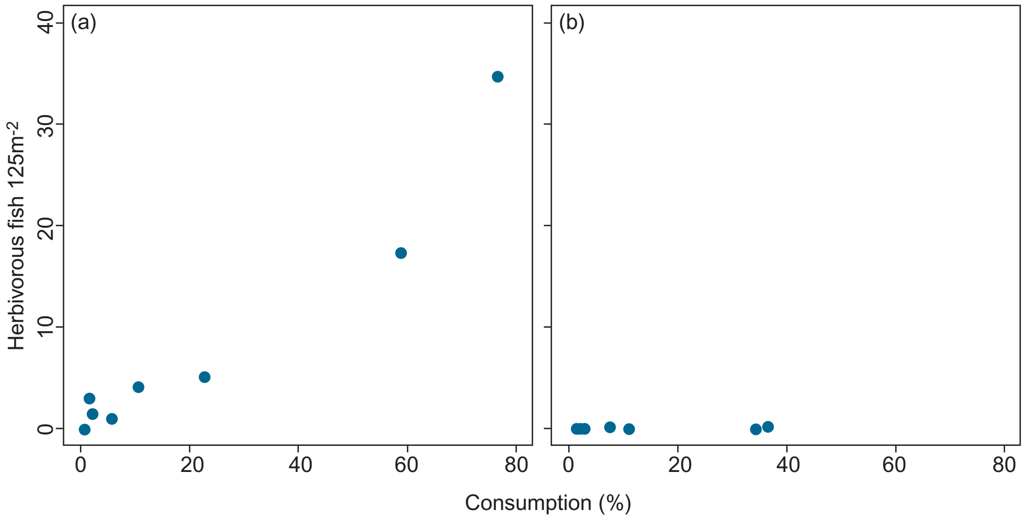

Figure 137: Relationship between the consumption (% consumed) of pieces of kelp tethered in the seagrass for five days and the density of herbivorous fish (a) immediately adjacent to the reefs, and (b) at distances of >300 m from the reefs.

Biomass of drift on reefs with proximity to shore

The biomass of drift macrophytes was dominated by four taxa, which together comprised 88% of the loose-laying biomass pooled over all reefs and dates; these were the seagrasses *Amphibolis* spp (35%) and *Posidonia coriacea* (35%), and the laminarian algae *Ecklonia radiata* (11%) and *Scytothalia doryocarpa* (7%). Biomasses of three taxa varied among reefs and dates of sampling. The biomass of drift *Amphibolis* was highest at Mewstone on each date (Fig. 138). The biomasses of *P. coriacea, E. radiata* and *S. doryocarpa* were variable in space and time, with no single reef yielding a consistently higher biomass of drift on all dates (Fig. 138).

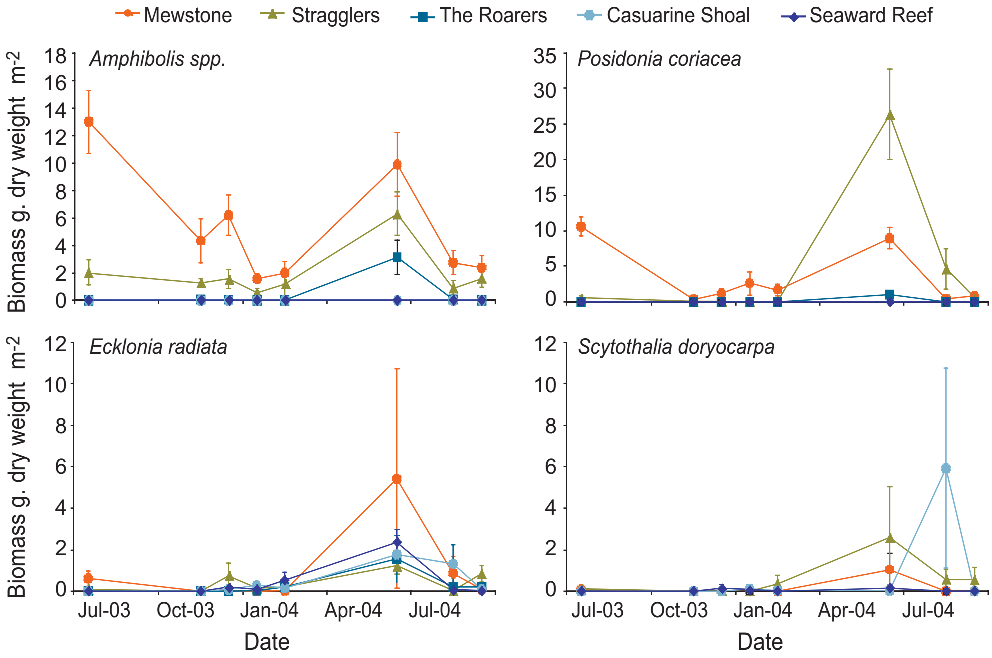

Figure 138: Biomass of drifting pieces of the four most abundant macrophytes laying loose on the reef surface, for each of the five reefs surveyed (± SE, n = 10).

The average monthly biomass of drift that was retained by the purple sea urchin *Heliocidaris erythrogramma* was positively correlated with the average monthly biomass of loose-laying drift for all four taxa (*S. doryocarpa*: $r^2 = 0.99$, $P < 0.01$; *E. radiata*: $r^2 = 0.46$, $P = 0.06$; *P. coriacea:* $r^2 = 0.50$, $P < 0.05$; *Amphibolis* spp: r2 = 0.36, P = 0.12). This suggests that *H. erythrogramma* relies heavily on drift.

Consumption of drift kelp on the reef

Rates of consumption of tethered kelp laterals varied between treatments on the two occasions that tethering was done (Fig. 139). For both occasions, drifting kelp pieces in plots with *H. erythrogramma* were consumed significantly more than any other treatment.

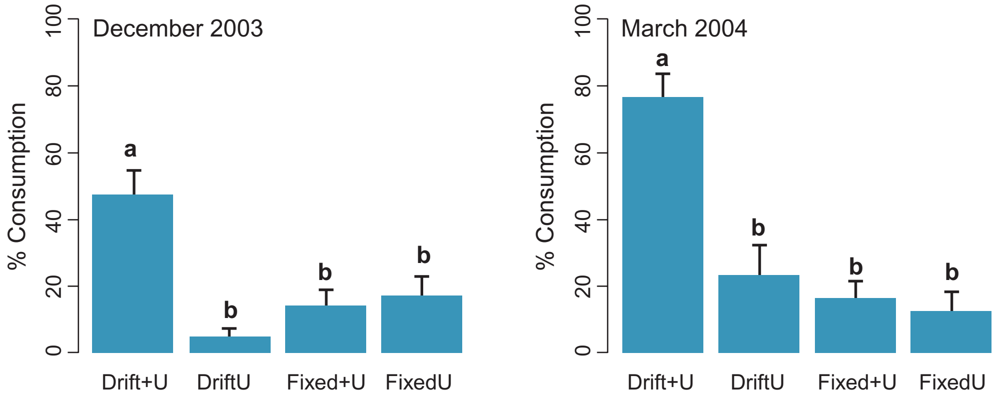

Figure 139: Consumption (% consumed over three days) of tethered pieces of drifting and fixed kelp in plots with and without *H. erythrogramma*. Groups sharing the same superscript letter (a, b) are not significantly different (determined by SNK tests).

Discussion

Accumulations of detached reef algae were found in seagrass beds adjacent to all reefs in Marmion Lagoon and Jurien Bay. In some places the biomass of detached reef algae was up to 15% of the biomass of attached algae in an equivalent area on the nearest reef (overall mean 3.6% ± 0.7 SE). The kelp *Ecklonia radiata* dominated the attached and the detached algae, and up to 77% of the biomass of *E. radiata* tethered in seagrass beds was consumed over a five-day period (overall mean 11.7% ± 0.5 SE). The study documented that detached reef algae are exported to adjacent seagrass beds, and are consumed by seagrass-associated fauna. The large quantities of detached algae suggest that this might form a considerable trophic link between reefs and adjacent seagrass habitats. In some places the spatial extent of this trophic link extends more than 300m away from the reefs.

The biomass of detached reef algae increased with increasing proximity to the shore, with large accumulations occurring at Mewstone. The drift was dominated by seagrasses and kelps, which do not grow in large quantities on the reef at Mewstone. High densities of the purple sea urchin *Heliocidaris erythrogramma* occur at Mewstone, and the study showed that these urchins trap and consume drift kelp. Transport of drift macrophytes (reef algae and seagrass) to inshore reefs is considerable, and forms an important trophic link between inshore reefs and habitats further offshore. The spatial extent of the inshore-offshore linkages appears to be at least several kilometres.

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Conferences attended, or presentations given

Vanderklift M. Drift seaweed as a food subsidy for seagrass and reef fauna. Applied Aquatic Ecology course seminar. University of Western Australia, 21 April 2005.

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6.12 Biogeochemistry: Pelagic nutrient supply and cycling

The overall aim of this project is to identify the main sources of nutrients to the western Australian coastal shelf and investigate nutrient cycling through the coastal food web to better understand productivity in this ecosystem.

Objectives

- Sources of nitrate supply to the shelf
- Biogeochemical nutrient cycling in pelagic ecosystems

Introduction

The coastal waters off southwestern Australia are unique compared to the west coasts of other southern hemisphere continents. The Leeuwin Current (Cresswell and Golding, 1980) transports nutrient poor water from the tropics southwards along the coast suppressing the large-scale upwelling observed on the west coast of Africa and South America (Pearce, 1991). As a result, dissolved nutrient levels and pelagic primary productivity are generally low (Johannes *et al.*, 1994) compared to the western margins of these other continents (Pearce, 1991). The shelf environment off southwestern Australia is also subject to a range of terrestrial anthropogenic nutrient stressors derived from agricultural, industrial and urban land use. Increased nutrient loadings have the capacity to considerably influence shelf primary production and drive eutrophication in some systems.

Unfortunately, background information on the seasonal and spatial nutrient dynamics of the Leeuwin Current and South Western Australian shelf waters are not common due to infrequent dedicated sampling. Data sets that include large spatial coverage and long time series are rare due to logistical constraints and interpretation of some of the available field data are complicated by small scale spatial and short term temporal variations between sampling cruises. Here we combine large numbers of observations from historical data sets collected in the region to generate a broad scale seasonal signal. This study uses a large scale database, the CSIRO Atlas of Regional Seas (CARS), to construct monthly climatologies of nutrient concentration, and other oceanographic parameters (salinity, temperature, and mixed layer depth) for the Western Australian Shelf and Leeuwin Current waters and describes the natural spatial (regional) and temporal (seasonal) nutrient distribution for shelf and oceanic waters off WA.

Climatology description

A. Physical properties

The dominant physical feature on the Western Australian Shelf is the Leeuwin Current (Cresswell and Golding, 1980) which is immediately obvious in the surface (10 m) sections as a southwards protruding tongue of warm, low salinity (Fig. 140) tropical water. The penetration of this low salinity water (35.5-35.6) from the north of our domain (Shark Bay), south along the shelf is greatest during the winter, May to August period (Fig. 140) when transport by the Leeuwin current is at its highest (Feng *et al.*, 2003). A gradual increase in the surface salinity of the Leeuwin Current as it travels towards the southern, Capes region suggests that there is exchange between the Leeuwin Current and surrounding water as it travels south (Fig. 140). The mixing that generates this gradual increase in salinity in the Leeuwin Current may be lateral to the west) or vertical (with waters at its base).

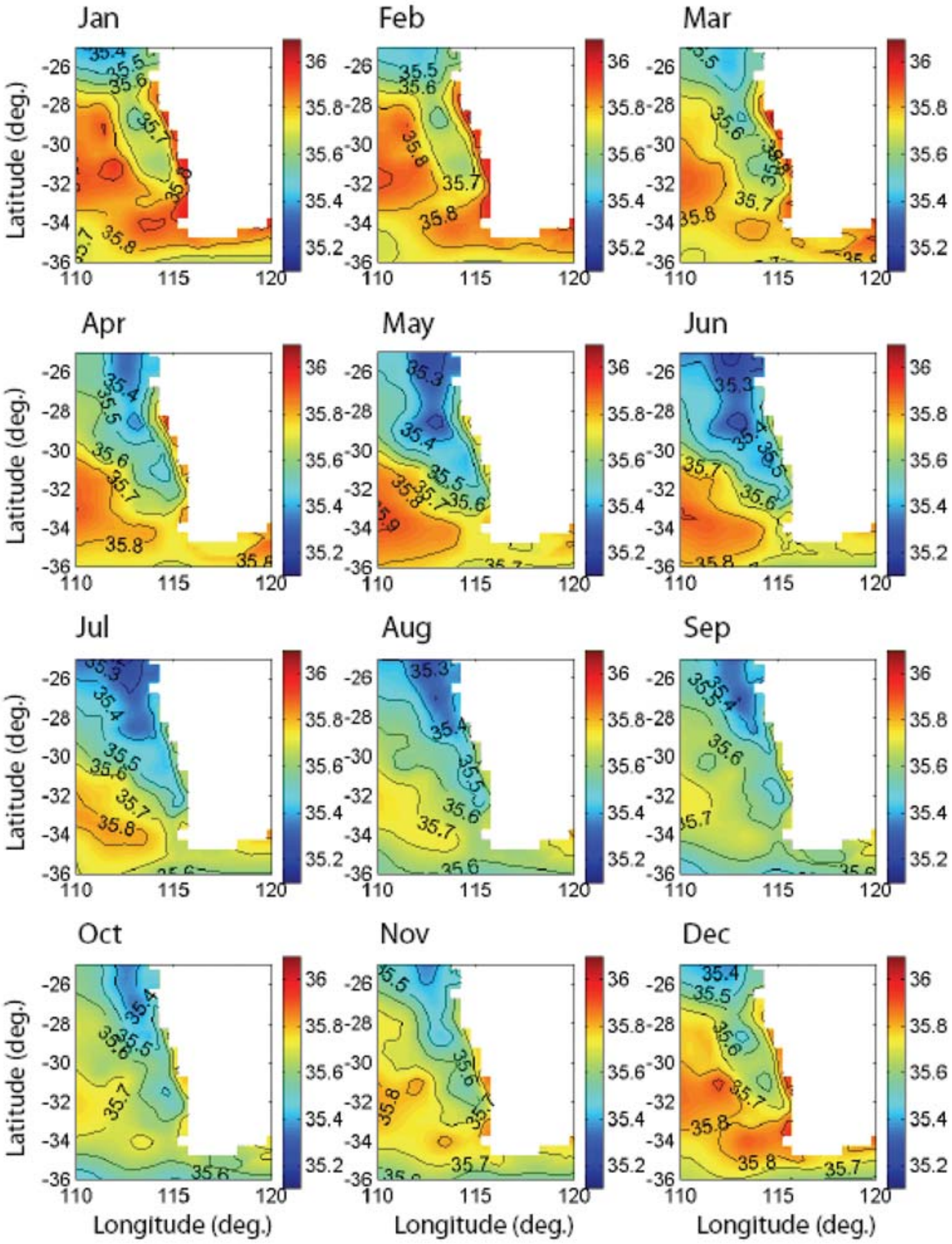

Figure 140: Monthly average distribution of salinity at 10 m derived from the CARS climatology.

B. Mixed layer depth

The mixed layer depth climatology suggests a seasonal deepening in winter (Fig. 141). In summer (December – February) the mixed layer is shallow (~30 m) and relatively uniform spatially, but in the winter (June – September) there are sections on the shelf and offshore that are considerably deeper (75 to 100 m) (Fig. 141). There was considerable spatial variation during winter, for example there appear to be large (~25 m) spatial variations in the mixed layer depth within the Leeuwin Current, i.e. compare 25 ºS (40 m) with 27 ºS (70 m) in June (Fig. 141). While it is possible that such spatial variations do occur within the Leeuwin Current, two factors may contribute to this variability. Firstly, the mixed layer itself may be ill defined. Secondly, where there are large inter-annual variations or in situations where the data are spatially patchy and temporally variable some uncertainty can result from interpolation errors. For these reasons, we are cautious with our interpretation of some of the spatial variations in the mixed layer data presented here. We do note though, that we are most interested in the well sampled Leeuwin Current and shelf areas where interpolation errors are likely to be low.

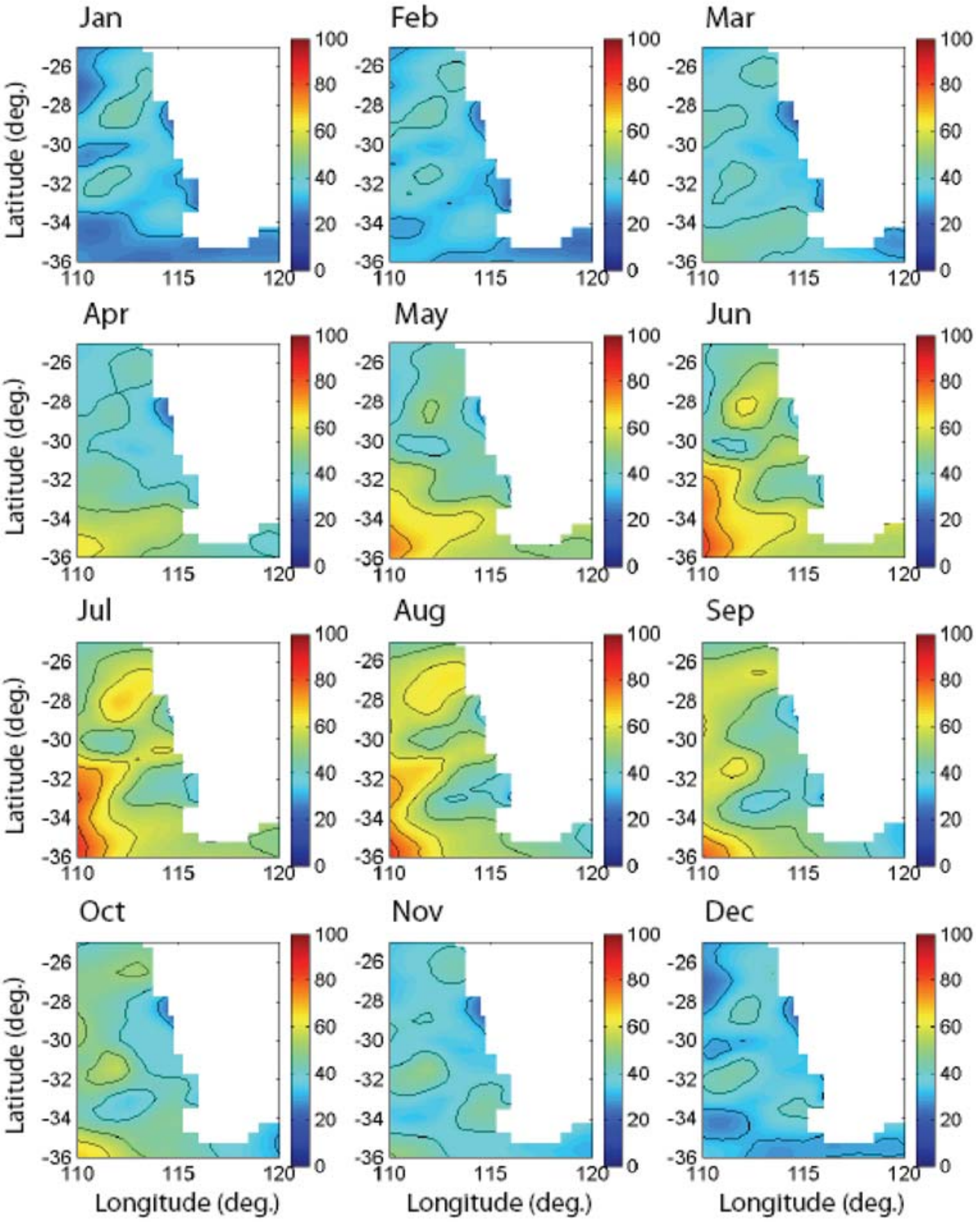

Figure 141: Monthly average mixed layer depth estimates from the CARS mixed layer depth atlas. Here the mixed layer depth is defined as the minimum depth at which abs (T - T(10m)) > 0.04ºC or abs(S -S(10m)) > 0.03 (see Condie and Dunn, submitted).

C. Nutrient distribution

All the surface waters under study here (i.e., the shelf, Leeuwin Current and offshore) are low in dissolved nitrate (<0.5 µM) throughout the year (Fig. 142). The seasonal progression of nitrate concentration is small, around 0.2 - 0.3 µM (Fig. 142) with the average ranging between 0.2 µM in February and 0.5 µM in June (Fig. 142). However, the variance in the nutrient observations about the mean is not negligible compared to the spatial and seasonal variations. Although the nutrient climatologies average a very large number of observations to derive the seasonal signal, giving a better chance at isolating that signal from this substantial background variability, we must nonetheless be cautious in the interpretation of the seasonal progression of these highly changeable parameters as it clearly fluctuates widely both spatially and temporally.

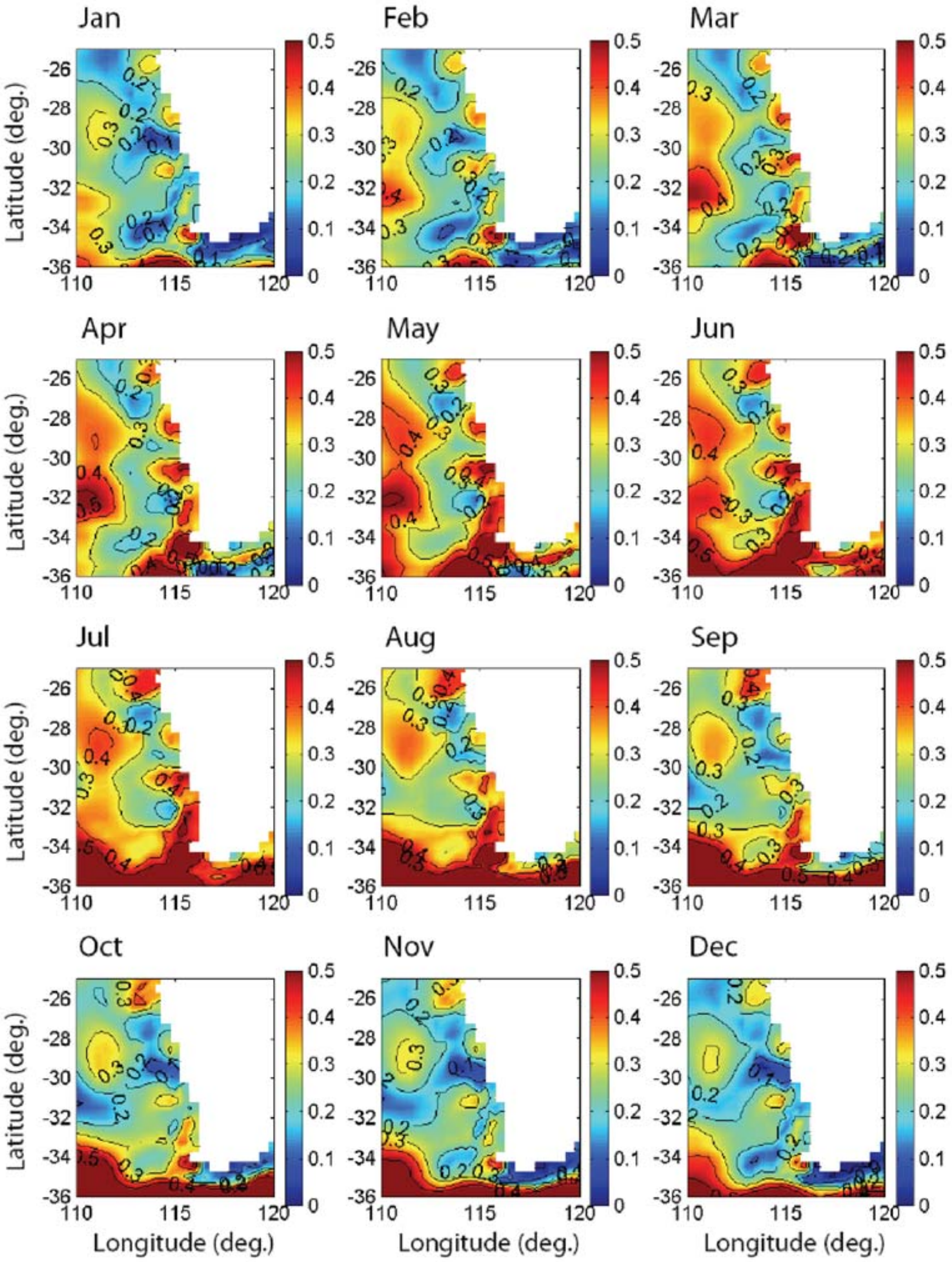

Figure 142: Monthly average distribution of nitrate (µM) at 10 m derived from the CARS climatology.

Phosphate concentration inshore on the shelf (up to 0.25 μM) is higher (typically double) than in the Leeuwin Current and the waters further offshore (Fig. 143). The northern Leeuwin Current waters are lowest in phosphate concentration (<0.1 μM) but gradually increase as it makes its way south (Fig. 143) possibly due to mixing with the deeper waters at its base or water off the shelf. On the shelf there are patches of elevated dissolved phosphate concentration during winter (Fig 143), presumably accumulating because it is not limiting and the shelf may be a source of phosphate to the Leeuwin Current as it travels southwards

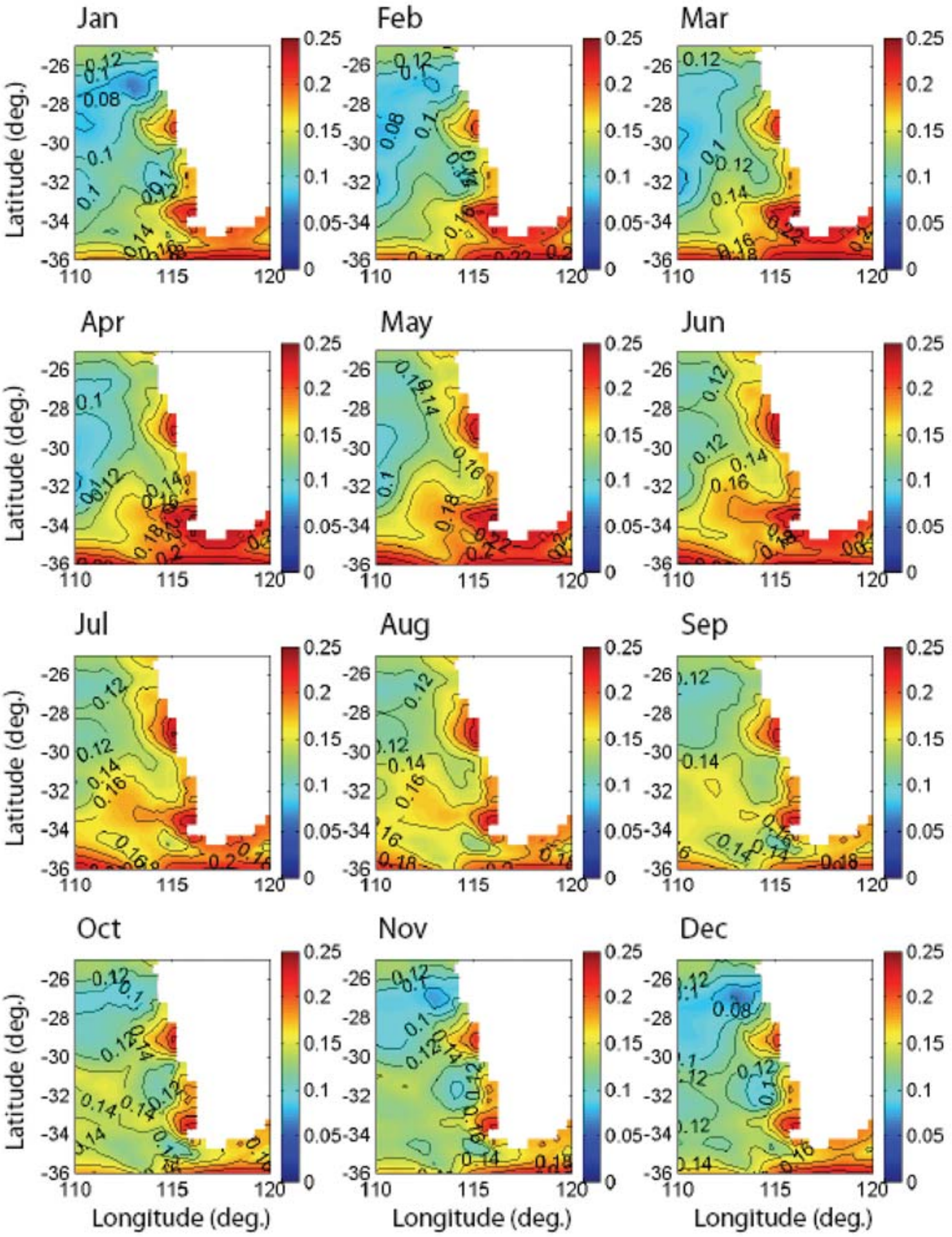

Figure 143: Monthly average distribution of phosphate (μM) at 10 m derived from the CARS climatology.

Surface waters of most of the southern Western Australian shelf and offshore of the Leeuwin Current are generally low (<2 μM) in silicate (Fig. 144), while the Leeuwin Current has slightly higher levels of silicate (~3-4 μM) than the shelf and surrounding waters (Fig. 144). The highest silicate concentrations (up to 4 μM) are in the very north of our domain, the source waters of the Leeuwin Current (Fig. 144).

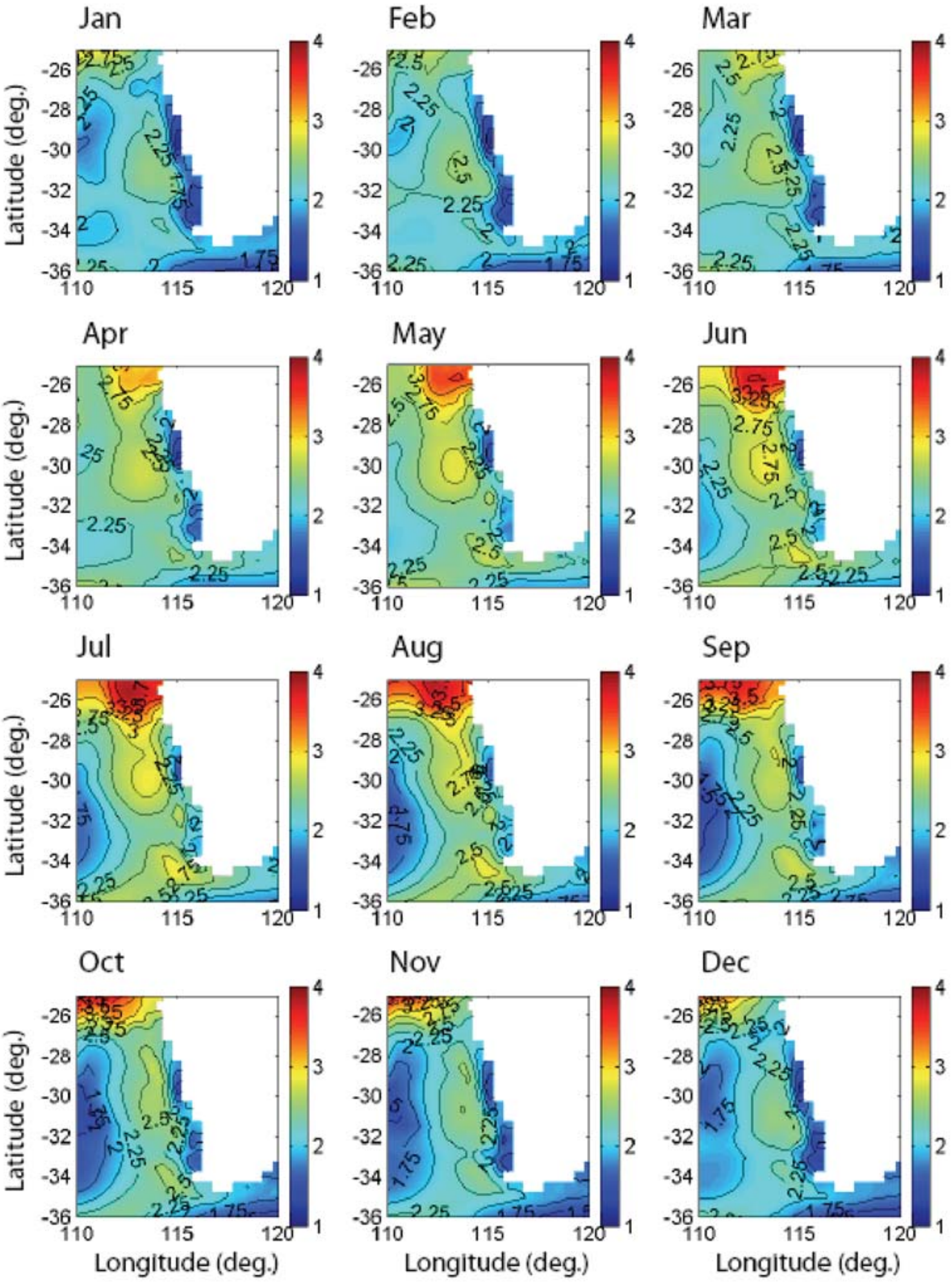

Figure 144: Monthly average distribution of silicate (μM) at 10 m derived from the CARS climatology.

D. Biomass

Chlorophyll *a* concentration was highest, up to around 1 mg m^{-3}, inshore immediately adjacent the coast (Fig. 145). Seasonally, chlorophyll *a* concentrations inshore, on the shelf and offshore were higher in the winter than in the summer (Fig. 145). The summer to winter chlorophyll *a* increase is around 0.25 mg m^{-3} (from 0 – 0.25 mg m^{-3}) in the Leeuwin Current and offshore (Fig. 145). In shore, the increase may be larger, possibly up to 0.75 mg m^{-3} (from 0.25 – 1 mg m^{-3}) between summer and winter (Fig. 145).

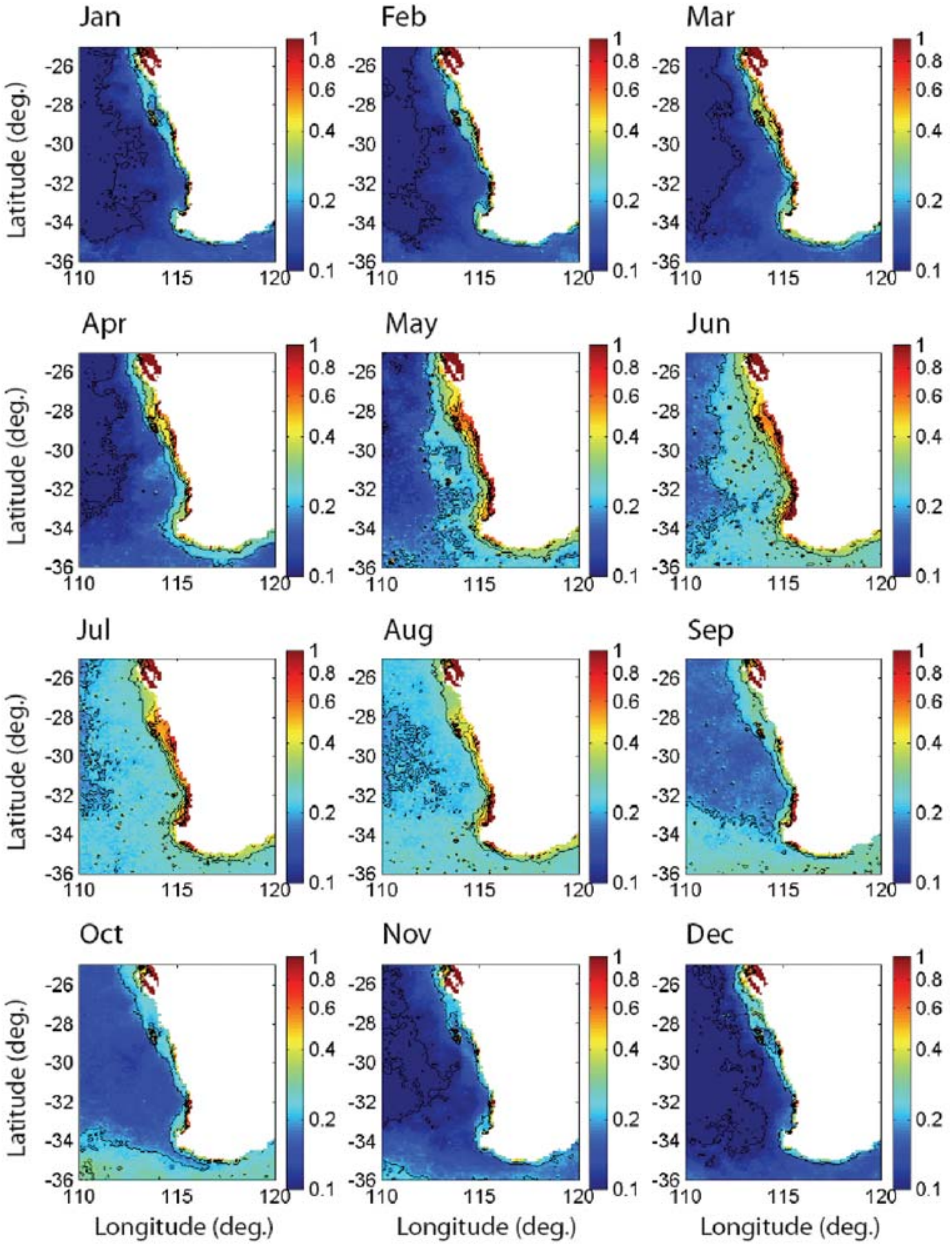

Figure 145: Monthly average distribution of chlorophyll *a* (mg m^{-3}) derived from six years of 9-km SeaWIFS data (September 1997 – August 2004).

Discussion

The surface waters of the southwestern Australian shelf, Leeuwin Current and offshore region are all low in nitrate throughout the year (Fig. 142). This low new nitrogen condition combined with a low N to P ratio (<4 compared to the ~16 required by phytoplankton (Redfield *et al*. 1963)) suggest that primary productivity in the coastal waters off the west coast of temperate WA is primarily nitrogen limited. As a result autotrophic and particularly phytoplankton communities are most likely to be susceptible to inputs of nitrogen from anthropogenic sources. Under nitrate limited conditions such as those found in this region, nitrate that is discharged or released during remineralisation of organic matter is probably rapidly consumed.

In contrast to the low nitrate concentrations throughout our domain, phosphate concentrations on the shelf are higher than in the Leeuwin Current and offshore (Fig. 143). This is not surprising as the major source of phosphorus on this downwelling shelf is probably terrestrial, delivered via rivers and drains or possibly in ground water. The cross-shelf phosphorus gradient is consistent with a terrestrial nutrient source (Fig. 143) and there is a small (but variable) seasonal increase (up to 0.1 µM) in phosphate on the shelf during winter, the period of highest rainfall and discharge.

Silicate is low year round on the shelf (Fig. 144) and may constrain diatom production in those waters. An increased dominance of diatoms at sites close to high silicate wastewater discharge in the Perth region tends to support the hypothesis that shelf diatom communities are co-limited (along with nitrate) by silicate (Thompson and Waite, 2003). In contrast, silicate is higher in the Leeuwin Current (3-4 µM) than surrounding shelf and open ocean (generally <2 µM) waters (Fig. 145) and the Leeuwin Current may be a source of silicate to these silicate poor regions. Whether the Leeuwin Current is a source of silicate to the silicate deficient shelf and open ocean surface waters will be dictated by the magnitude of lateral exchange between the Leeuwin Current and these waters. Although the gradual decrease in silicate concentration (Fig. 144) as the Leeuwin Current travels south may be attributed to uptake, a similar increase in salinity (Fig. 140) suggests that there is exchange between the Leeuwin Current and gyre/shelf waters.

Chlorophyll *a* concentration is highest, up to around 1 mg m^{-3}, inshore immediately adjacent the coast and decreases with distance offshore (Fig. 145) most likely sustained by terrestrial nutrient sources and/or resupply from the sediments. Seasonally, the SeaWIFS sections presented here suggest there is considerable biomass accumulation above summertime levels between May and August (Fig. 145). As this strong seasonal biomass accumulation occurs on the shelf, in the Leeuwin Current and offshore it is not completely explained by variations in terrestrial supply. A possible source is seasonal variations in Leeuwin Current nutrient supply. However, our climatology introduces variations in mixed layer depth as a possible driver for the summer – winter increase in biomass. The climatology suggests a seasonal deepening between summer (in December – February the mixed layer is ~30 m) and winter (in June – September there are areas on the shelf and offshore that are considerably deeper at 75 to 100 m) (Fig. 141). This deepening of the mixed layer would have promoted chlorophyll a accumulation by mixing deep water nutrients up into the euphotic zone.

Conclusions

The climatologies presented here are of sufficient resolution to identify important seasonal and spatial features of the oceanography and biogeochemistry of the region. The waters of the southwestern Australian shelf, Leeuwin Current and offshore are primarily nitrogen limited but diatom production in shelf waters may also be silicate limited. Compared to the shelf, the Leeuwin Current is high in silicate and exchange between the two water masses may supply silicate to the shelf. However, such exchange would also strip phosphate and possibly nitrate off the shelf.

A cross shelf (inshore to offshore) gradient in chlorophyll *a* biomass suggests that nutrients delivered from terrestrial sources play an important role in sustaining phytoplankton production on the shelf. A seasonal (summer – winter) increase in chlorophyll *a* biomass corresponds with a winter maximum in rainfall and discharge. However, the seasonal increase is ubiquitous across the shelf, increasing in areas well removed from terrestrial influence. As such a further source of nutrients must contribute to this seasonal accumulation. These climatologies suggest that a seasonal deepening of the mixed layer and associated mixing of deep water into the euphotic zone is a likely candidate in offshore and outer shelf waters.

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6.13 Remote Sensing of coastal ocean colour

6.13.1 Overview

Satellite and aircraft-based remote sensing has become an increasingly useful tool as SRFME has progressed, providing information to the three main SRFME core research projects on the surface, near-surface and shallow substrate conditions. These remote sensing data supplement the *in situ* surveys as well as provide input data and comparison data to modelling research. Satellite-derived sea-surface temperatures (SSTs), chlorophyll concentrations and light attenuation coefficients have provided spatial mapping around the survey sites as well as time-series data at the station positions.

CMR is a member of the Western Australian Satellite Technologies and Applications Consortium (WASTAC). Membership of this consortium affords CMR access to daily and archived remotely sensed data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR). Raw data from these sensors are received in real-time, pre-processed and archived at the Department of Land Information (DLI) in Floreat. Near-real-time data are accessed by CMR and processed to geophysical products on a daily basis.

Applications of the outputs from the remote sensing group are also used in the Biophysical, Coastal and Modelling Projects. The remote sensing group undertakes three broad components of work, remote sensing data processing, validation, and modelling and algorithm development. This section of the SRFME report describes each of these activities.

6.13.1.1 Remote sensing data processing

For each of the polar orbiting sensors, SeaWiFS, MODIS and AVHRR, there exist “standard” global algorithms for producing a suite of geophysical products.

The data from all these satellites are received on a daily basis in Perth by WASTAC, and facilities (both hardware and software) have been established for processing and analyzing the data.

SSTs have been derived from the AVHRR on the long-running series of NOAA satellites, while the ocean colour products have been derived from the SeaWiFS sensor which was launched in late 1997. Both thermal and ocean colour information are now also available from the morning and afternoon satellites holding the MODIS sensor but at this stage the products are still under development.

Advanced Very High Resolution Radiometer

The AVHRR samples in the visible, near-infrared, mid-infrared and thermal wavelengths, at a nadir pixel resolution of 1.1 km. Coverage is daily. Initially, the processed datasets were received from WASTAC via the Remote Sensing Services Group of DLI, but more recently the raw datasets have been routinely acquired and automatically processed in-house overnight; colour SST images of the SRFME region spanning the most recent five days of available data are displayed on the website http://www.per.marine.csiro.au/staff/Peter.Fearns/SST/fivedaysst.html.

Sea-surface temperatures have been derived from the thermal infrared brightness temperatures in AVHRR Bands 4 and 5, using the Non-Linear SST (NLSST) algorithm. The accuracy of this algorithm was tested against the near-surface CTD casts at the Two Rocks Transect stations (see section 6.13.3.5).

SeaWiFS

The SeaWiFS samples in six visible and two near-infrared channels, at a spatial resolution of approximately 1.1 km at nadir. Global coverage is near-daily. Raw data are downlinked from the satellite in Perth by WASTAC and archived in an encrypted format. License agreements with Orbimage Inc. provide a decryption key to enable decryption and processing of the raw data approximately one month after downlink. The raw data are processed to calibrated/navigated radiances by WASTAC. These radiance products are then processed in house by CMR to create standard geophysical products (see section 6.13.2). Validation of the SeaWiFS chlorophyll product is addressed in Section 6.13.3.

MODIS

The MODIS samples in 36 spectral bands ranging from the visible to the thermal infrared and from 250 m to 1 km resolution. Two satellites carry the MODIS instrument and provide a 10:30 am and a 1:30 pm view of our region every day. Raw data are downlinked by WASTAC and archived daily. The raw data files are accessed and processed in house to create standard geophysical products (see section 6.13.2). Validation of the MODIS chlorophyll product is addressed in Section 6.13.3.

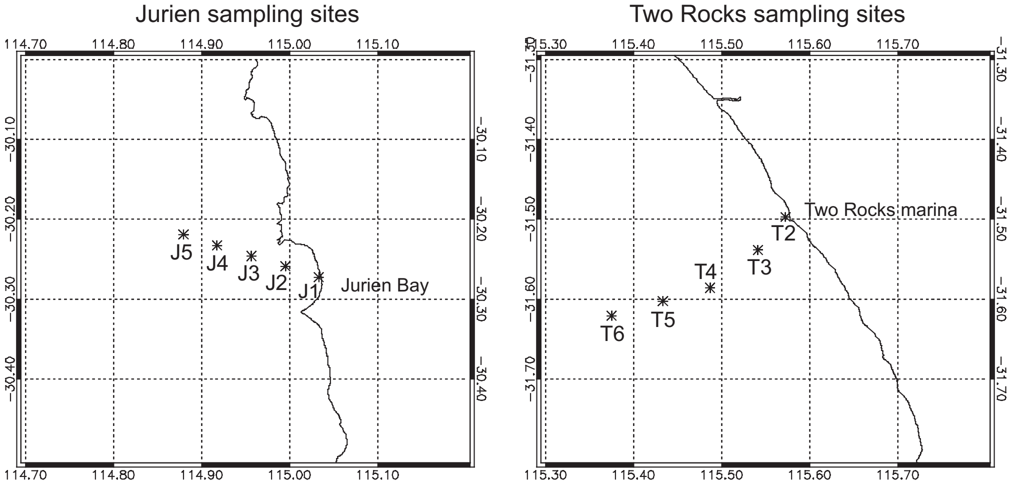
For all data sets, geophysical products are extracted at full resolution and binned spatially and temporally. The full resolution and binned data are made available to the other SRFME core research groups. The standard products are also used in the Remote Sensing Group validation work.

Time series of remotely sensed products are extracted routinely for specific locations. The station codes and locations for these sites are shown in Table 25. Stations A-E are located on the Biophysical Project transect (See Chapter 5). Stations T2-T6 are located on the Two Rocks transect, Stations J1-J5 are located on the Jurien Bay transect, and Stations B1-B6 are located on the Bunbury transect. Figure 146 shows maps of the Remote Sensing Group sampling transects. These sampling sites also provide data for the validation component of this work (Section 6.13.3). The data processing streams and standard algorithms are outlined in Section 6.13.2.

Table 25. Station codes and locations for routine data extraction.

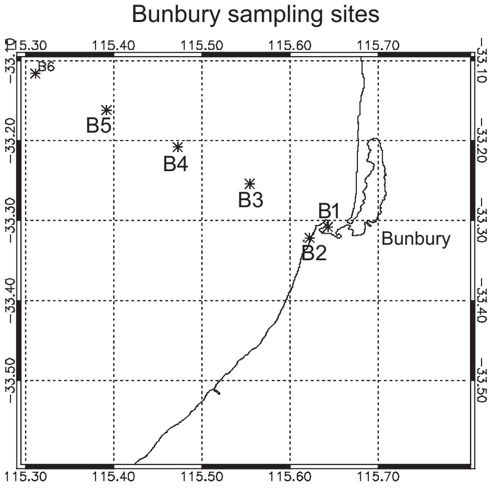
Water depths are also shown.

station	latitude	longitude	depth (m)
A	-31.537	115.555	15
B	-31.62	115.365	40
C	-31.682	115.221	100
D	-31.767	115.024	360
E	-31.865	114.795	1000
T2	-31.4974	115.557	7
T3	-31.5388	115.546	24
T4	-31.586	115.492	31
T5	-31.6028	115.438	42
T6	-31.6212	115.38	45
J1	-30.2727	115.038	6
J2	-30.2592	115	12
J3	-30.2463	114.962	20
J4	-30.2332	114.922	34
J5	-30.2195	114.885	42
B1	-33.3083	115.6481	6
B2	-33.3213	115.6295	8
B3	-33.2542	115.5604	22
B4	-33.2083	115.4792	29
B5	-33.1625	115.3979	34
B6	-33.1167	115.3167	38



Jurien sampling sites

Two Rocks sampling sites



Bunbury sampling sites

Figure 146: Locations of the Ocean Colour Group sampling transects. Station locations and depths are listed in Table 6.1

6.13.1.2 Validation

The validation work involves the field work and laboratory-based component of the Remote Sensing Group's research. The validation work essentially involves comparing remotely sensed products to *in-situ* measurements.

Field work is carried out at three main sites, Two Rocks, Jurien Bay and Bunbury.

Field work activities include:

- collection of water samples providing information on
  - chlorophyll concentration
  - pigments
  - spectral absorption
  - total suspended matter
  - nutrients

- deployment of instruments including
  - CTD
  - PRR600 profiling radiometer
  - ac-9
  - hydroscat
  - Zeiss dual channel hyperspectral radiometer

- collection of substrate samples for
  - classification
  - determination of spectral reflectance

Laboratory analysis includes:

- HPLC analysis
  - for determination of pigment composition and concentration

- Spectrophotometer analysis providing
  - particulate spectral absorption
  - CDOM spectral absorption
  - pigment spectral absorption

Samples of validation results and analysis of the comparison between in situ and remotely sensed products are shown in Section 6.13.3. Instrument descriptions and deployment protocols are outlined in Appendix 1. Water sample processing protocols and methods are outlined in Appendix 2.

6.13.1.3 Modelling and algorithm development

We show here two examples of the modelling work being undertaken as part of the Remote Sensing research. The first is modelling in support of the remote sensing product validation, and the second is the development of methods to map shallow water substrates using remote sensing data.

Jurien Data Validation

In simple terms, validation of remotely sensed data involves comparison of the remotely sensed product to the *in situ* product. Typically, the two values do not match exactly, so one has to decide how close the values have to be to declare a validated data point, or, in cases where two values do not agree, one has to account for the differences. Factors to consider include atmospheric correction, rough ocean surface effects, unexpected or unusual pigments or water column constituents, shallow water effects, or inappropriate choice of algorithm. An important aspect of the validation work is the modelling of optical processes. Inherent Optical Properties (IOPs) of constituents collected during field work are input to Hydrolight (Mobley, 1998) to estimate Apparent Optical Properties (AOPs). A better understanding of the relationships between IOPs and AOPs contributes to an improved validation exercise.

Examples of processing *in situ* optical measurements and modelling of these data are shown in Section 6.13.4.1.

Shallow water mapping

Development of new and/or improved remote sensing algorithms is supported by modelling of the physical processes affecting the remotely sensed signal. The current emphasis has been on development of algorithms for mapping shallow water substrates. The results of this shallow water mapping work are of value to the Coastal Project's benthic habitat mapping work and the Modelling Project's work involving modelling wave action in shallow coastal water (see Section 7.8).

We have developed methods for processing hyperspectral data to produce maps of shallow water benthic cover classification. Work is ongoing to explore the sensitivity of the mapping methods and development of methods to correct space-based hyperspectral data for the effect of atmospheric transmittance. An overview of the work is outlined in Section 6.13.4.2

6.13.2 Remote Sensing data processing

Satellite data are received and archived in Perth by WASTAC. These data are accessed by CMR automatically each day on a regular basis and processed through standard procedures to generate standard mapped geophysical products. Currently standard mapped products are within the limits 28º to 35º S and 112º to 116º E, and mapped to a Mercator projection at approximately 1 km resolution. These products are archived and made available to SRFME researchers. Sub-scenes may be extracted from the archived data to provide images of specific study sites, or geophysical data may be extracted for use in such tasks as time series analysis.

6.13.2.1 Digital Time-series

An example of one of the applications of the processed data is the production of time series at each of the SRFME sampling sites.

SST Time Series

Raw AVHRR data are accessed routinely from DLI and processed to Temperature products using the Common AVHRR Processing Software (CAPS) package (Turner *et al*. 1998). To provide temporal coverage between the monthly surveys, daily SSTs at the station positions A to E have been extracted from the AVHRR datasets (cloud permitting). To reduce small-scale variability, the mean and standard deviation of 3x3 pixel arrays centred on the station positions (Table 25) for all the AVHRR bands have been calculated for the SRFME period 2002 to 2004.

Removal of cloudy pixels is important for any quantitative application of the satellite temperatures. Cloud will generally be evident in the absolute SST being far too low, or in spatial variability of a group of pixels around the station position. The reflectance of cloudy areas will usually vary substantially. However, in the case of very uniform stratus-type cloud of similar reflectance, spatial differences in the temperatures may be unreasonably large. For this project, cloud screening has been accomplished using a sequence of tests based on the absolute NLSST, the near-infrared band B2 and the brightness temperature T4. A pixel was flagged as cloudy if:

a) NLSST < 14 °C or > 26 °C (absolute temperature threshold test);

b) Standard deviation of 3*3 arrays of B2 reflectance > 0.5 (spatial coherency test);

c) Standard deviation of 3*3 arrays of T4 > 0.5 °C (spatial coherency test);

d) Finally, a 31-day moving average was run and any SSTs falling outside 2 standard deviations of the mean have been deleted (temporal coherency test).

These limits were determined by visual inspection of the pixel values in cloudy and cloud-free areas. The simple tests were generally successful in removing the cloudy periods but on occasion also removed a few apparently valid pixels, so some refinement may be required. Overall, about half the data remained after the cloud-screening process.

The resulting daily SSTs were then averaged into monthly means, and a final annual cycle derived from the 3 years of data (Figure 147). See the Biophysical Project (Section 5.5.1.4) for further discussion of the results.

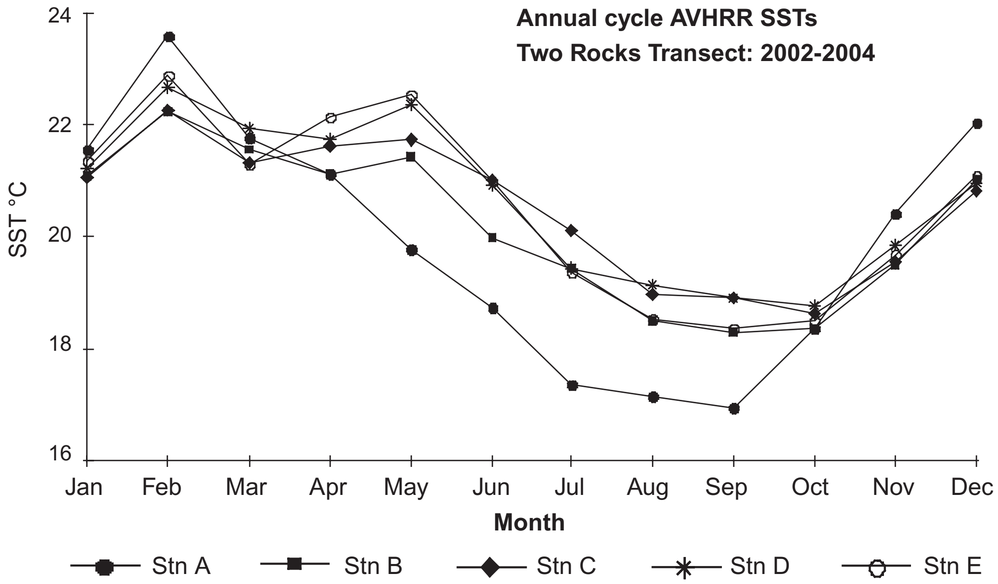


Figure 147: Monthly mean SST cycles at Stations A to E.

Chlorophyll Time Series

SeaWiFS data are processed using the SeaDAS processing software (Feldman, 2005). Each SeaWiFS pass (scene) is processed to produce chlorophyll concentration and diffuse attenuation at 490 nm (K_{490}) data, and remapped to a standard projection. SeaDAS associates "quality flags" to each pixel in an image. These flags are used to discard suspect data. For each of the SeaWiFS passes, data have been extracted from a 3x3 pixel array around each of the SRFME transect station locations. An example of the chlorophyll time series is shown in Ch. 5, Figure 61.

6.13.2.2 SST and chlorophyll images

High resolution imagery

SST images have been prepared for all the Biophysical Project monthly and quarterly surveys on the Two Rocks Transects using the mNOAA image display package. As the thermal IR cannot penetrate cloud, images are only available on cloud-free days; when the survey day(s) were cloudy, images from an adjacent day were processed.

The derived SST maps show thermal gradients associated with the Leeuwin Current and Capes Current and thus enable interpretation of the general current patterns, but weak gradients (often in summer) cannot always be unambiguously interpreted. In this way, changes in the structure and position of the Leeuwin Current and its associated meander/eddy field can be monitored. A typical winter SST image showing the Leeuwin Current is shown in Figure 148 (a). The red colours represent higher SST values. A typical summer SST image is shown in Figure 148 (b). The Leeuwin Current is not obvious in the summer image.

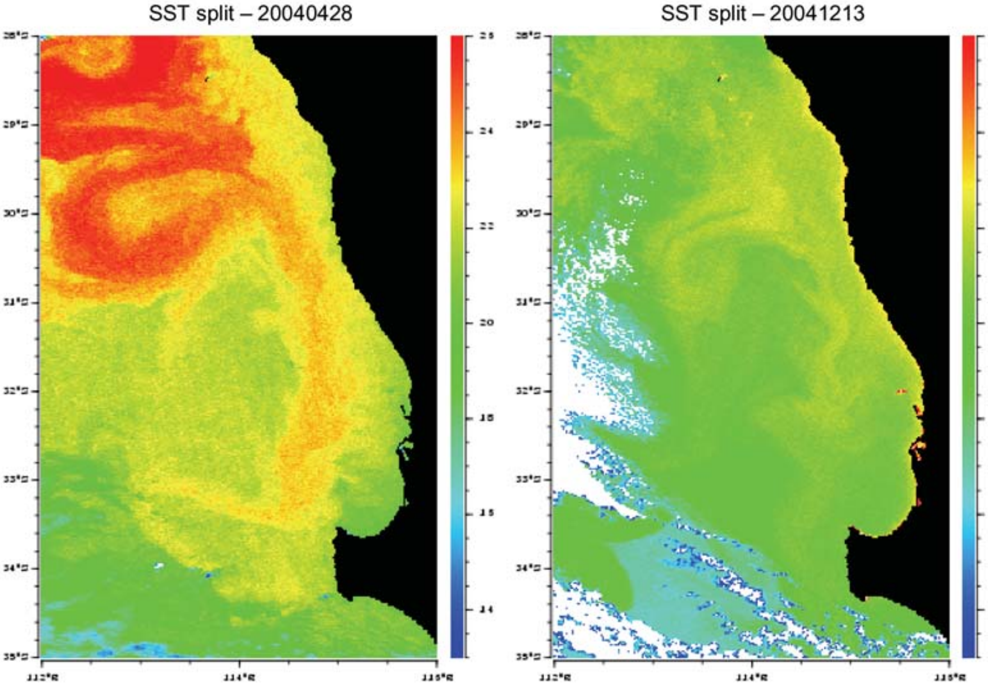


Figure 148: AVHRR-derived SST images for (left – a) 28th April 2004 and (right – b) 13th December 2004.

Chlorophyll maps from the SeaWiFS sensor are likewise restricted by cloud. The standard SeaWiFS data processing package, SeaDAS, detects cloud-affected pixels and flags these as suspect. Chlorophyll concentration maps often provide an invaluable complement to the thermal imagery as the chlorophyll can be used as a tracer to show subtle current patterns.

Two SeaWiFS chlorophyll images are shown in Figure 149. The left image is for the 28th April 2004, the right image is for the 12th December 2004. An image for the 13th December 2004 was not available. The black regions in each image are cloud. The northern portion of the 13th December image is missing due to the sensor changing its angle of tilt to avoid sun glint.

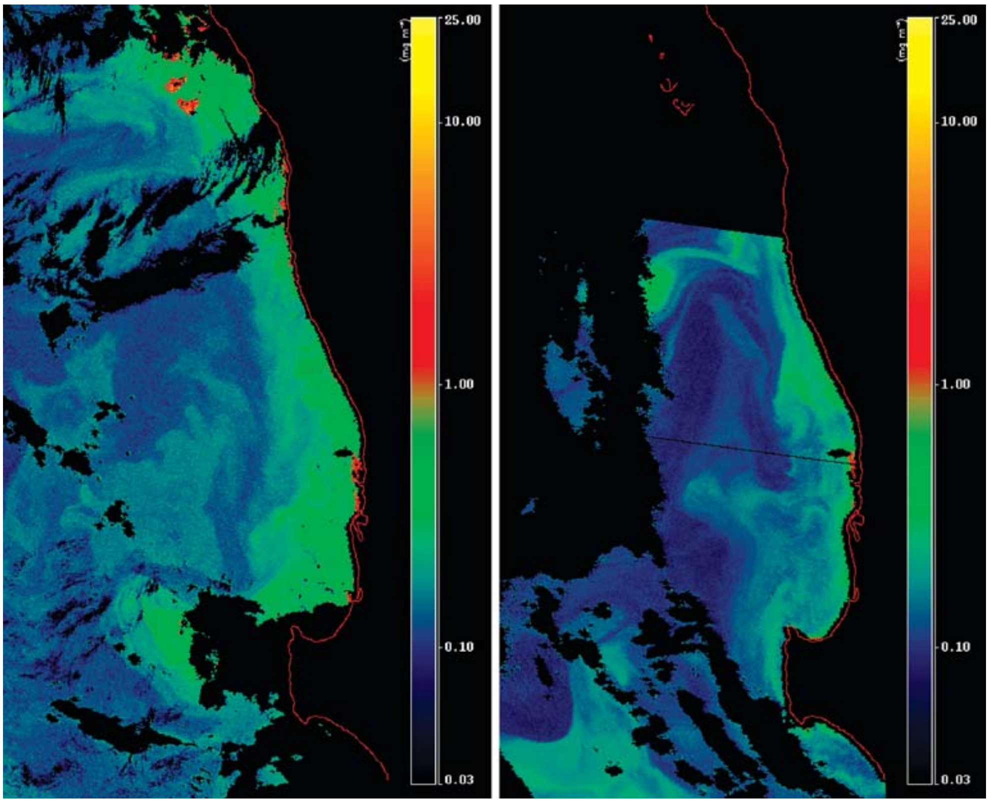


Figure 149: SeaWiFS-derived chlorophyll concentration images for (left – a) 28th April 2004 and (right – b) 12th December 2004.

Reduced resolution imagery

The presence of currents and eddies highlighted by chlorophyll images is also of use to support ocean circulation and sea surface height research. An example of the application of SeaWiFS data combined with Two Rocks Transect data is the exploration of onshore-offshore exchanges due to mesoscale eddies. Research within the Modelling Group aimed at studying the effects of mesoscale eddies is utilizing remotely sensed Sea Surface Height data coupled with SeaWiFS chlorophyll concentration maps. The Topex-Poseidon satellite orbits the Earth with a revisit period of 10 days. This altimeter aboard the satellite provides Sea Surface Height measurements along sub-satellite tracks in a "criss-cross" grid as shown in Figure 150.

The correlations between the altimeter sea level and chlorophyll anomalies along the altimeter track are shown in Figure 151 in blue. Correlations between onshore-offshore velocity and the chlorophyll anomalies are shown in red. The dashed lines in the figure are significance ranges. At the scale chosen for this study the correlation between chlorophyll concentration and onshore-offshore velocity appears to be less than significant at most latitudes. The correlation between altimeter-derived sea level and chlorophyll concentration appears to be significant. An example of a situation where this correlation may be observed is when an eddy associated with the Leeuwin Current moves off the shelf, carrying with it nutrients, thus supporting increased phytoplankton growth. The eddy is detected by the altimeter as a sea level anomaly, and the enhanced phytoplankton growth is detected by the ocean colour sensor as a chlorophyll concentration anomaly.

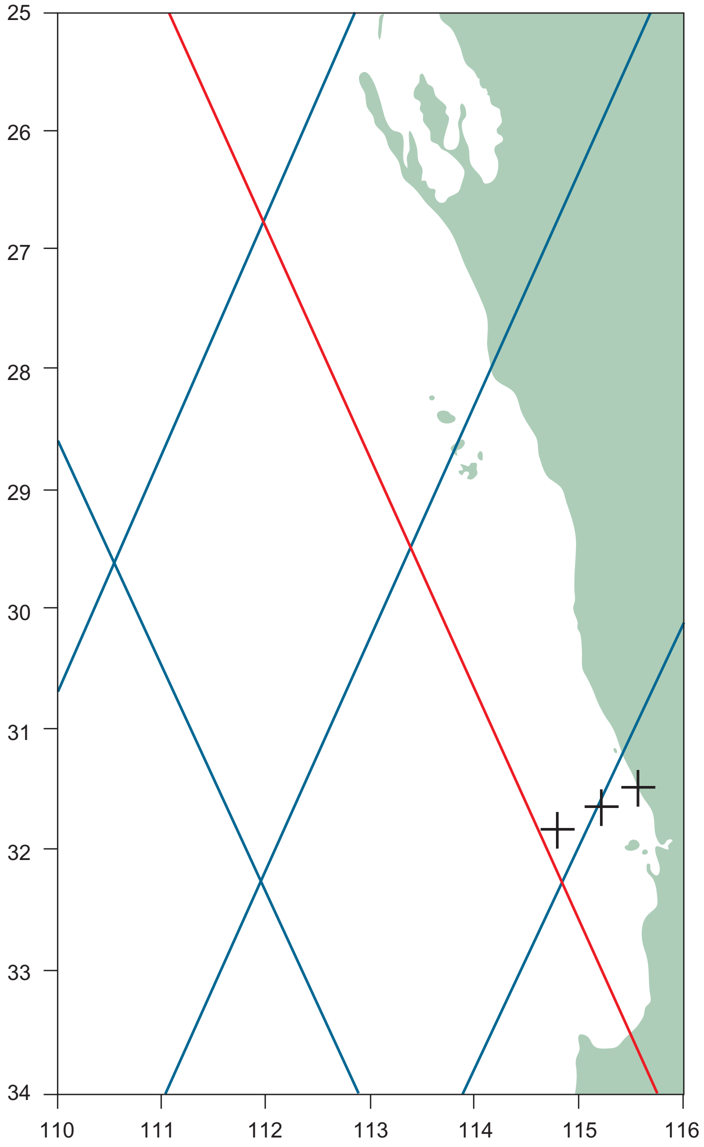


Figure 150: altimeter tracks relative to Two Rocks transect.

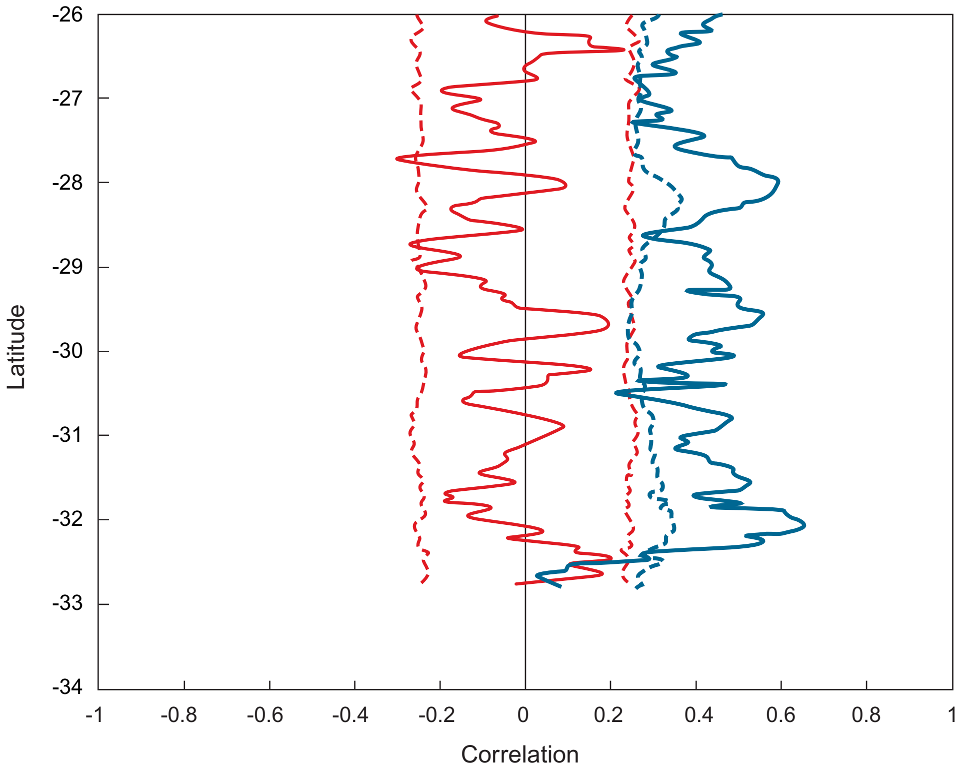


Figure 151: Correlation between the altimeter sea level and chlorophyll anomalies along the altimeter track (blue), as well as correlations between onshore-offshore velocity and the chlorophyll anomalies (red). The dashed lines are significance ranges.

The altimeter data are very accurate in terms of detecting sea surface height, but the spatial and temporal coverage is limited to the sub-satellite track and 10 day revisit schedule. The distribution of chlorophyll concentration as displayed in SeaWiFS data may also provide information on circulation patterns, eddies and currents. An example of a SeaWiFS chlorophyll concentration image showing circulation features is shown in Figure 152. The image shows chlorophyll concentration at 1 km resolution for the 8th May 2000. High chlorophyll concentrations are shown in red, lower concentrations are shown in green and blue. The black regions of the coast are clouds.

Work is underway within the Modelling Project to study the information provided by the altimeter data in the context of the circulation patterns displayed in ocean colour imagery. Considering the spatial scale of features detectable by the altimeter, and the persistence of such mesoscale features over time, it is possible to use spatially and temporally averaged chlorophyll images for this work. This averaging can decrease the effect of cloud and smooth out small scale changes. An example of chlorophyll data smoothed over 9 km and over 9 days is shown in Figure 153. Currently data are averaged over 2, 4 and 9 km resolutions and over periods of 5, 9 and 15 days.

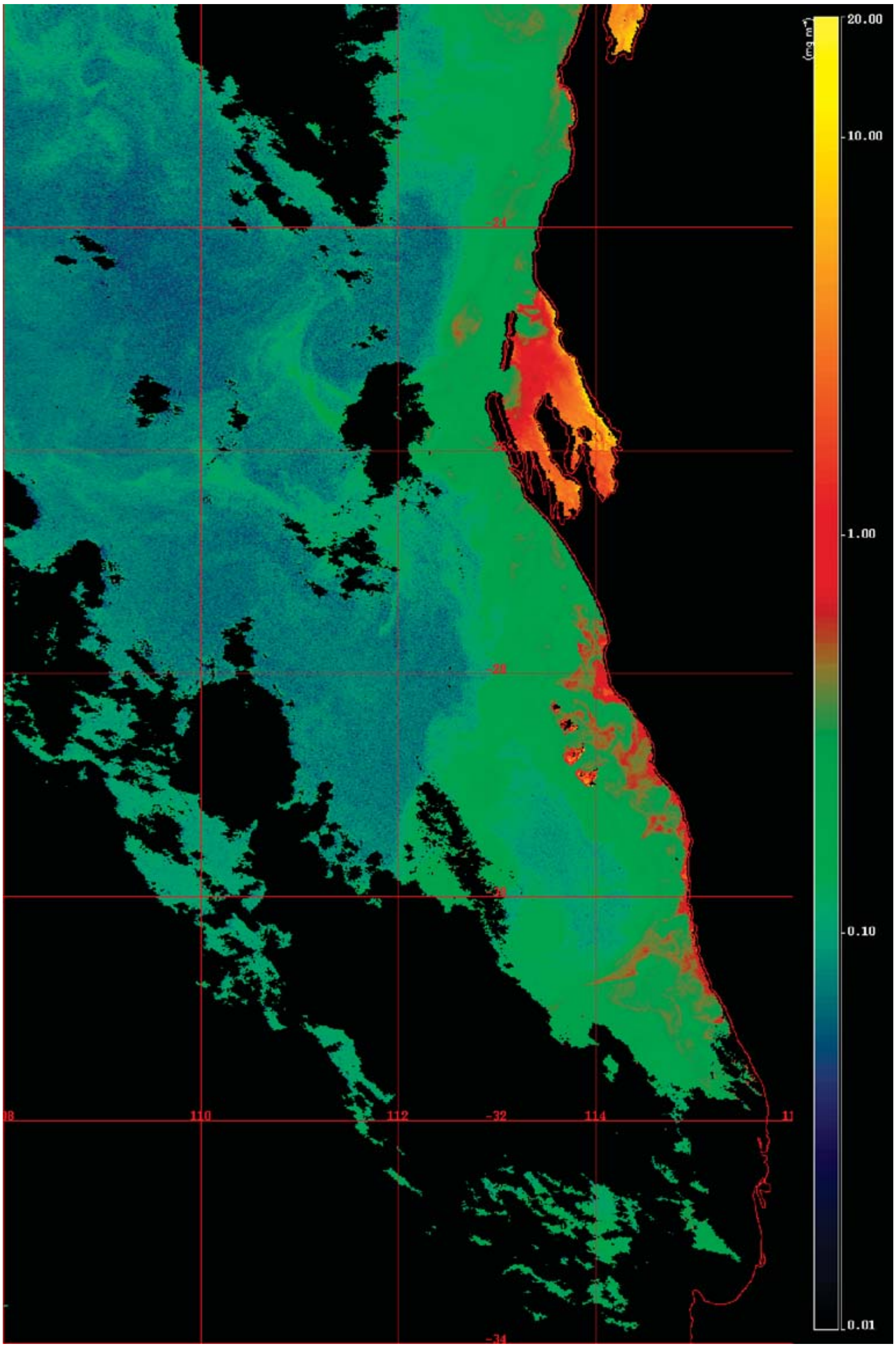


Figure 152: SeaWiFS chlorophyll image for the 8th May 2000. The spatial resolution is 1 km.

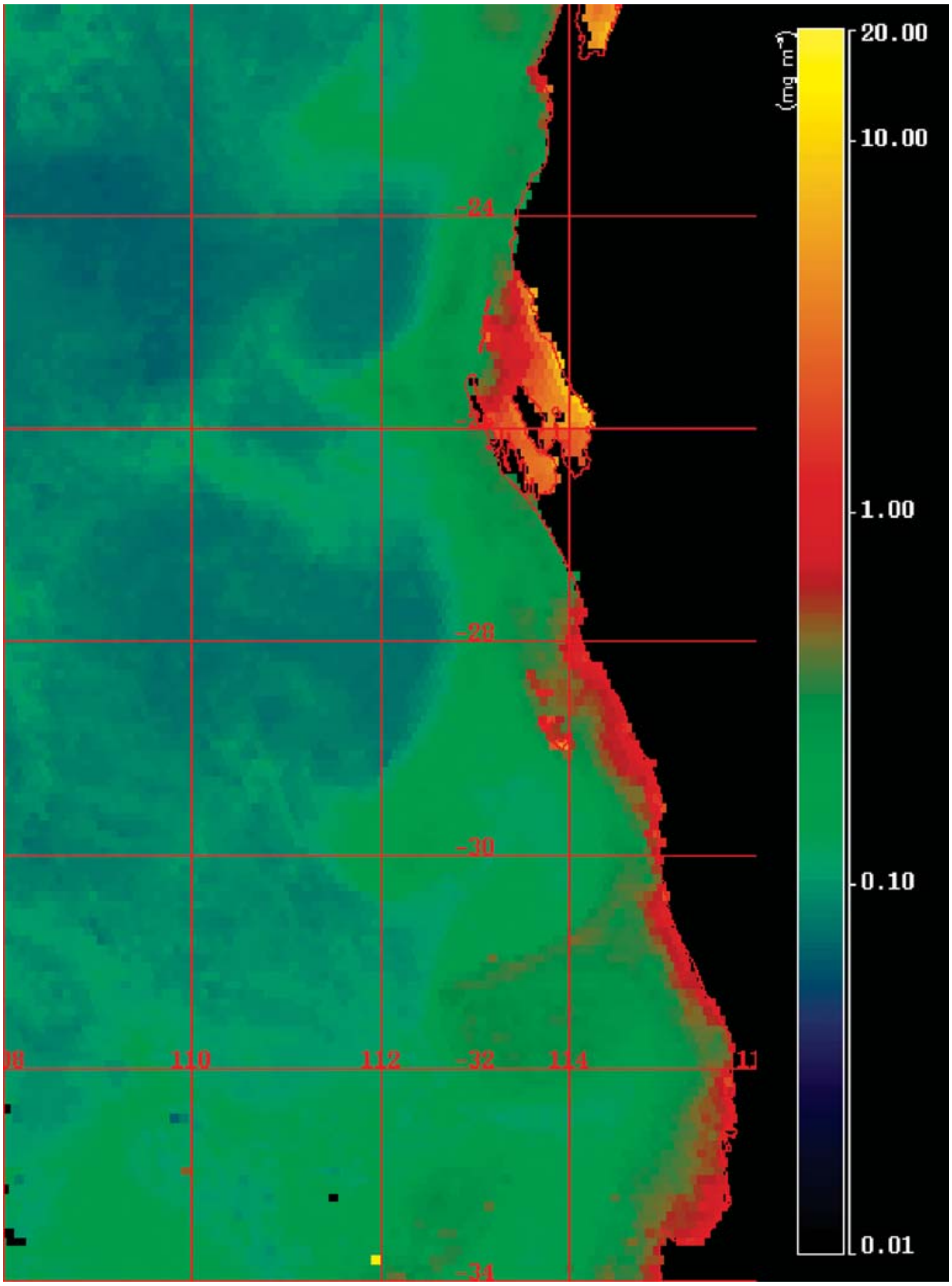


Figure 153: SeaWiFS chlorophyll image for a 9 day period centred on the 8th May 2000. The spatial resolution is 9 km.

6.13.3 Remote sensing validation

An increasing use of remote sensing products by managers of marine environments to further their understanding of ecosystem dynamics on increasing spatial and temporal scales, is totally dependent on a thorough understanding of the contribution and variation in the spectral absorption and scattering properties of the regional waters of interest.

In the past, most of the bio-optical data collected in both open-ocean and coastal areas have taken place in the northern hemisphere. As a result, the standard algorithms used to retrieve estimates of parameters such as light attenuation and chlorophyll and suspended matter concentrations from ocean colour sensors have been developed using primarily bio-optic data sets and atmospheric conditions from the northern hemisphere. These conditions are not always applicable to regions in the southern hemisphere where atmospheric conditions are clearer (Takashima *et al*. 2003), leading to inaccurate estimates of retrieved parameters and limited use of remote sensing as a tool for environmental managers.

Open-ocean (case 1) waters are considered to be well defined optically with total absorption generally dominated by the phytoplankton component which correlates well with the concentration of chl *a* (Morel and Maritorena, 2001). Coastal and estuarine (case 2) waters, by comparison, often have significant contributions to the total absorption from the detrital/non-algal and chromophoric dissolved organic matter (CDOM) components, causing retrieved estimates of chl a concentration to be over estimated (Babin *et al*., 2003).

The coastal and offshore waters off southern Western Australia are a unique oceanographic environment. The Leeuwin Current which flows south along the coast is the only poleward flowing eastern boundary current in the world, bringing warm, tropical, low nutrient water from the East Indian Ocean to the shelf and slope waters of Western Australia. In summer consistent strong southerly winds keep the Leeuwin Current offshore while in winter more variable winds allow it to flow at its strongest, often flooding onto the shelf. During summer, at the time of weakest flow in the Leeuwin Current, a second current – the Capes Current – flows north on the shelf, generally inshore of the 50 m isobar, bringing cooler water north as far as Shark Bay.

In January 2003 collection of an extensive set of inherent and apparent optical properties at three sites – Bunbury, Two Rocks and Jurien Bay (Fig. 146a-c) – along the Western Australian coast began. This data set is being developed to determine if and/or how the strong seasonal features observed in the climatology and oceanography off Western Australia affect the bio-optical characteristics of the shelf waters in this region. The data set will also be used to determine the validity of the standard algorithms used by the SeaWiFS, MODIS and MERIS ocean colour sensors for Western Australian waters and if found to fail, then the data set will provide a strong base for developing a regional algorithm.

6.13.3.1 Sample collection and methods

At each site, samples were collected at 5 km intervals along a transect that extended from inshore to approximately 25-30 km offshore where the water column depth was about 40–50 m. The outer-most station at each site was used as the main validation station for that site and was always occupied within 2 hours either side of midday local time. At each station, profiles of temperature, salinity and fluorescence were collected using a SeaBird 19plus conductivity – temperature – depth (CTD) sensor with a General Oceanics 12 bottle rosette equipped with 10 L Niskin bottles. The system also incorporated a flow through fluorometer (WETStar), an oxygen sensor (SeaBird) and a PAR sensor (Biospherical Instruments). Downward spectral irradiance and upward spectral radiance profiles were collected using a HydroRad-2 (HOBILabs) and PRR-600 radiometer (BSI); water leaving radiance was also measured using a Zeiss radiometer (Curtin University instrument) and profiles of total spectral absorption and attenuation coefficients were measured with an ac-9 (WETLabs). More detailed information on the deployment and operation protocols for all the instruments can be found in Appendix 1. In addition, water samples were collected from the surface and the Secchi depth of the water column for the determination of total suspended matter, the concentration and composition of phytoplankton pigments and the absorption coefficients of phytoplankton, detritus and CDOM. Aboard the vessel water samples were transferred from the Niskin bottles to 5 litre plastic carboys and stored in the cool and the dark until return to the land base (approx. 4 hours) for filtering. In general sample collection and analysis followed the protocols outlined in Ocean Optics Protocols for Satellite Ocean Colour Validation revision 5 (Mueller *et al.*, 2003). Methods used to analyse water samples for pigment composition and concentration and for the absorption coefficients of the dissolved and particulate fractions can be found in Appendix 2.

SeaWiFS images were provided by the SeaWiFS Project, NASA/Goddard Space Flight Centre and Orbimage using SeaDAS version 4.6 (July 2004). MODIS images were provided by the MODIS Project, NASA/Goddard Space Flight Centre, using algorithms developed by the MODIS Science Teams. For both sensors, retrieved chl *a* estimates were extracted from level 2 Local Area Coverage (LAC) data. Only retrieved chl *a* values that fell within 4 hours of the *in situ* sample being collected (overpass times could not be matched for all sensors) and within 2 km of the sample station were used. Mean values of retrieved chl *a* were the average of the nine closest pixels that complied with both the time and distance requirements. Apart from land masses, white areas in all images, indicate cloud in the region of the image.

6.13.3.2 Sample location

Jurien Bay, the northern most sampling location lies approximately 275 km to the north of Perth and is contained within the Jurien Bay Marine Park. A string of islands and reefs lie just off the coast sheltering the inshore waters of Jurien Bay. The first two stations on the sampling transect are inshore of the reefs while the remaining three sampling stations are in the more exposed waters outside of the reefs. Jurien Bay is a site for recreational fishing and the professional Western rock lobster industry. The Hill River, the smaller of two main rivers in the Moore – Hill River basin catchment area, discharges directly to the ocean just south of Jurien Bay. Flow in the Hill River is highly seasonal, only flowing during winter or after heavy rain within the catchment area. Much of the catchment area, inland of Jurien Bay, has been cleared for agricultural purposes.

Two Rocks lies 66 km north of Perth in a predominately light urban environment. There are no rivers or significant industrial or urban sources discharging to the ocean within several kilometers to the north or south of this sampling site.

Bunbury represents the southern most sampling site, lying 185 km to the south of Perth on the shoreline of Geographe Bay. Bunbury is an urban area (population in excess of 50,000) with a deepwater port and recreational marinas. The first station on the sampling transect lies within the port area, close to the outlet of the Leschenault Inlet which drains the Collie River basin catchment area. The remaining five stations are located offshore in Geographe Bay.

6.13.3.3 Results and Discussion

As of August 2004, a total of 24 trips had been made between the three sites to collect data for ocean colour validation. On occasion bad weather or boat failure prevented sampling at the offshore station and cloud during the satellite overpass times prevented the retrieval of in-water parameters, resulting in a total of 8 trips where validation could not be performed. Of the remaining 16 trips, estimates of chl *a* by MODIS coincided with 11 trips and by SeaWiFS with 8 trips. There were only 3 trips where the weather conditions were clear enough to allow retrievals by both sensors. On the 3 occasions where both MODIS and SeaWiFS estimates were obtained, the MODIS value was always slightly higher (Table 26).

Table 26. Mean values of retrieved chlorophyll *a* (mg m^{-3}) for 3 occasions when MODIS and SeaWiFS data were coincident.

Date	Site	MODIS – mean	MODIS - range	SeaWiFS – mean	SeaWiFS – range
18 Aug 2002	Two Rocks (T6)	0.54	0.50 – 0.58	0.44	0.41 – 0.46
10 Nov 2003	Two Rocks (T6)	0.31	0.29 – 0.34	0.24	0.23 – 0.24
21 Jan 2004	Bunbury (B6)	0.24	0.23 – 0.25	0.21	0.20 – 0.23

The relationship between *in situ* and retrieved chl *a* for the 16 trips is quite good (Fig. 154). There is, however, a small group of samples (within the red circle) which appear to diverge from the 1:1 relationship. All of these samples were collected during winter where winter was designated as the months between May and October and summer, the months between November and April.

One possible explanation for the poor correlation between the *in situ* and retrieved chl *a* values for these winter samples is that there is a seasonal effect in the bio-optical parameters of the water column.

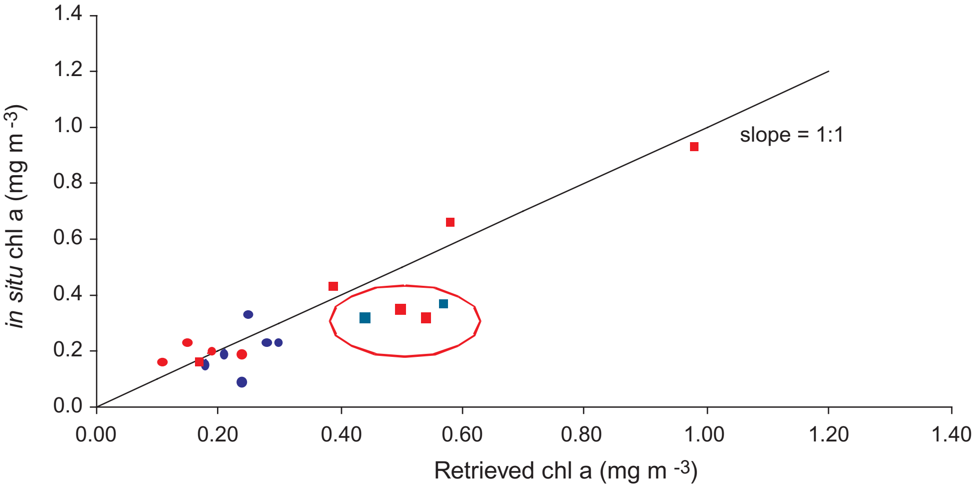


Figure 154: The relationship between *in situ* chl *a* (measured by HPLC) with the retrieved chl *a* estimates from the SeaWiFS and MODIS standard algorithms for winter (May – Oct) and summer (Nov – Apr). Solid circles represent summer months and solid squares represent winter months with blue – SeaWiFS and red – MODIS.

Profiles of salinity, temperature and fluorescence are recorded at each station along the transect at each site. Contour maps of each of the parameters can be plotted which help explain the water column conditions of the upper shelf region of a transect. An example of the relationship between salinity, temperature and fluorescence along the Jurien Bay transect during April 2004 is shown in Figure 155. Warmer water, probably from the Leeuwin Current, is in the surface waters at all stations except the most inshore (J1). The water column is stratified and the fluorescence signal is greatest at depth indicating that the phytoplankton biomass is probably also highest deeper in the water column. *In situ* samples collected at the surface and the Secchi depth would not provide this level of information. As more profiles are collected and analysed seasonal and interannual variation in each of the parameters can be determined for the upper region of the shelf waters.

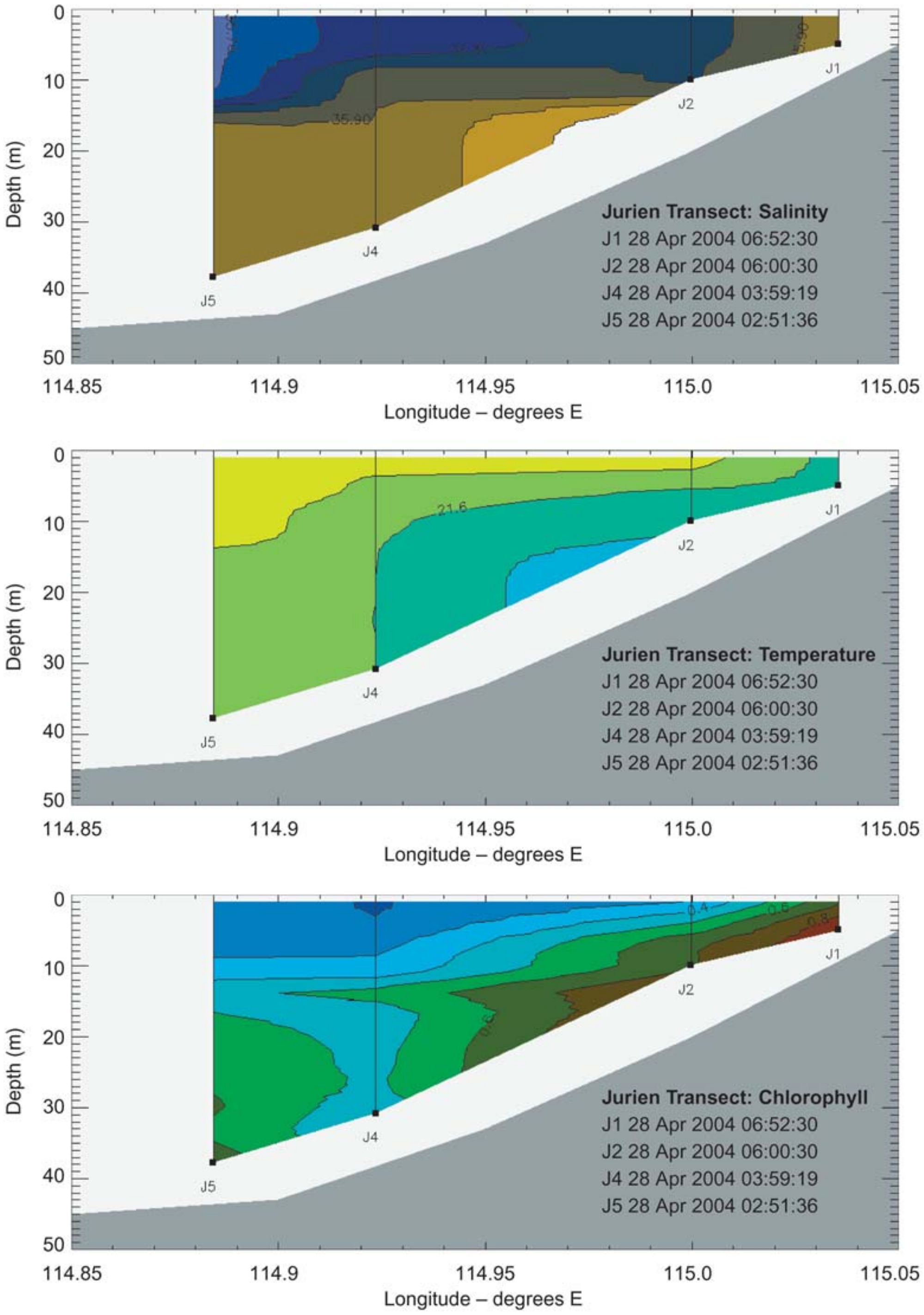


Figure 155: Cross sections of salinity, temperature and fluorescence for Jurien Bay on April 28 2004.

Secchi depth is shallower in winter than summer at the 3- (Jurien Bay) and 4- (Two Rocks and Bunbury) most offshore stations (Fig. 156a-c). This could be expected in a coastal area, due to storm events leading to increased land runoff and water column mixing during the winter months. At all sites the Secchi depth at the two most inshore stations does not show seasonal change and is probably explained by the shallow water column depth (< 8m).

On occasion the shallowing of the Secchi depth, in winter, corresponds with an increase in total suspended matter (TSM) in surface waters as seen at all sites during August - September 2003 (Fig. 157). TSM is the sum of all particulate matter in the water sample – live and senescent phytoplankton cells and inorganic and organic minerals. In most coastal areas, it may be expected that there would be a correlation between a shallower Secchi depth and storm events causing resuspension of bottom sediments and increased land runoff or an increase in phytoplankton biomass during an algal bloom; events that would all cause an increase in particulate material in the water column. However, often during summer, *Trichodesmium* cells and macroalgae debris are visually observed in the surface waters of the offshore stations with the presence of *Trichodesmium* being confirmed by microscopic identification. In early February 2003 significant numbers of *Trichodesmium* cells were observed by microscopic means in samples collected from the offshore station at the Two Rocks site (T6) and may explain the relatively high TSM value recorded for January 2003. Similar observations were made at the offshore station at the Bunbury site (B6) during March 2003 where high TSM values were also recorded.

TSM can be used as an indicator of water clarity, but provides no information as to what type of particulate material is affecting the clarity of the water. For remote sensing purposes there is a need to understand which component(s) are dominating the water column and potentially affecting the accurate retrieval of remotely sensed products such as chl *a*, TSM and chromophoric dissolved organic matter (CDOM) concentration.

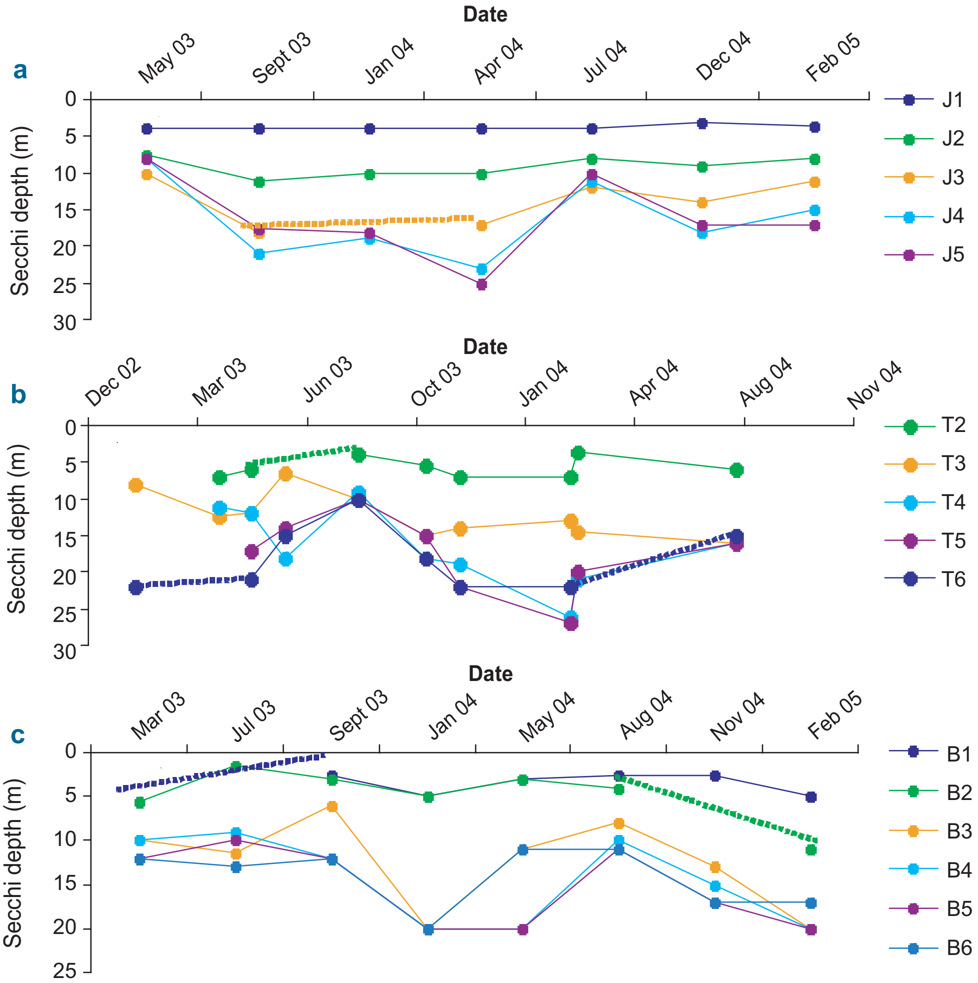


Figure 156: Secchi depth plotted against time for (a) Jurien Bay, (b) Two Rocks and (c) Bunbury. The dotted lines indicate that the station was not sampled during consecutive trips.

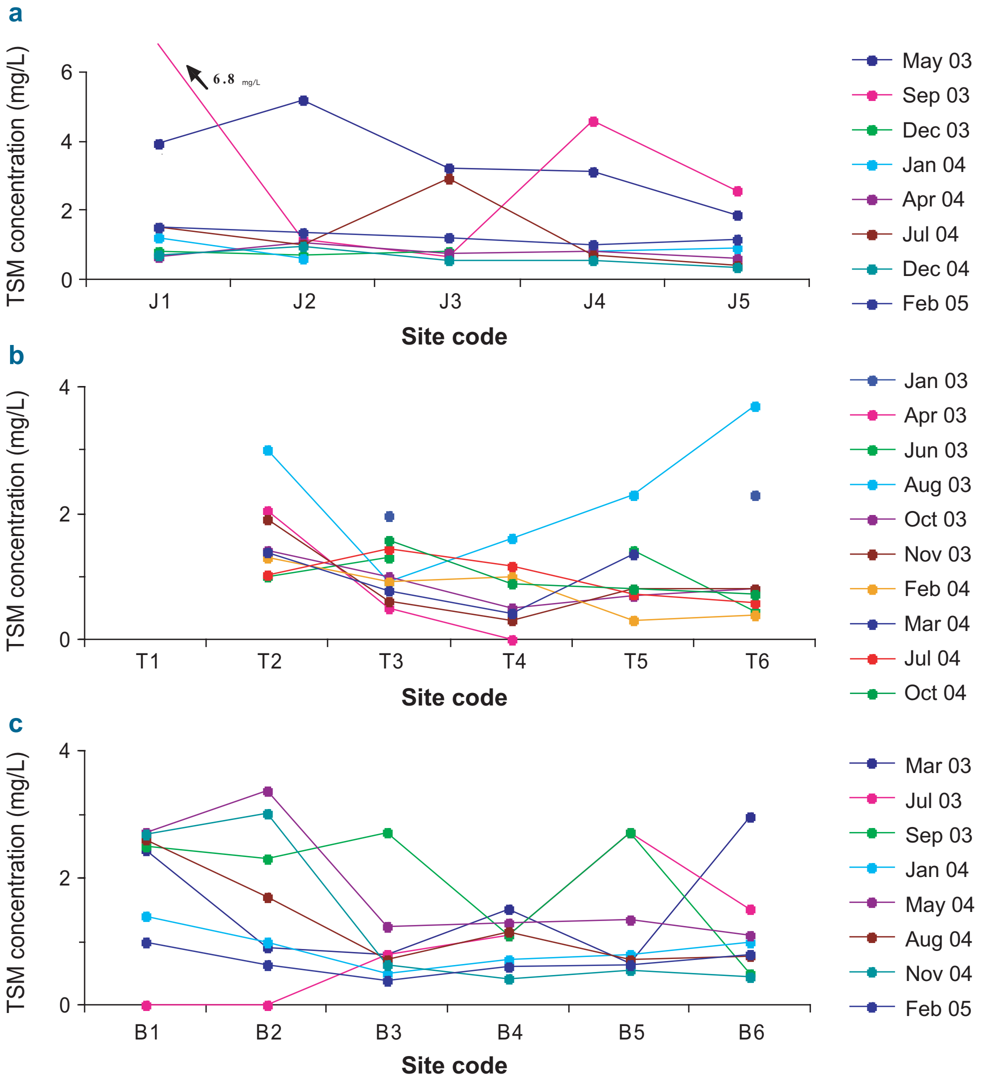


Figure 157: TSM plotted against time for (a) Jurien Bay, (b) Two Rocks and (c) Bunbury. Breaks in the lines indicate that a result was not available for consecutive trips.

Pigment analysis and diagnostic pigments have been used in this study to estimate the phytoplankton community composition and concentration at all stations and sites. Pigments which relate specifically to an algal class are termed marker or diagnostic pigments (Jeffrey & Vesk, 1997) and some of these diagnostic pigments are found exclusively in one algal class (e.g. prasinoxanthin which is only found in prasinophytes) while others are the principal pigments of one class but are also found in other classes (e.g. fucoxanthin in diatoms and some haptophytes; 19'-butanoyloxyfucoxanthin (19BF) in pelagophytes and some haptophytes). The presence or absence of these diagnostic pigments can provide a simple guide to the composition of a phytoplankton community including identifying classes of small flagellates that cannot be determined by light microscopy techniques. In this study the presence of fucoxanthin has been used to indicate diatoms; peridinin – dinoflagellates; 19'-hexanoyloxyfucoxanthin (19HF) – haptophytes; alloxanthin – cryptophytes; prasinoxanthin – prasinophytes; zeaxanthin – cyanophytes and chlorophyll *b* – green algae.

At this stage in the study, all the pigment samples are yet to be analysed and interpreted, so only data for the most offshore station which is also the validation station at the Two Rocks site will be presented. Stations T3 and T6 in this study correspond with stations A and B respectively in the Biophysical Project. Pigment samples were collected in both studies at these sites providing a larger time series of pigment results at these two stations compared to any of the other stations/sites.

In general, the time of highest biomass in the surface waters at station T6, on the Two Rocks transect (as for most of the stations on all transects), was during the winter months (May – October) (Fig. 158). This often correlates with the highest TSM values being recorded over the same months and may indicate that the majority of TSM in the winter months is algal material rather than sediment or non-algal material.

The composition of only the diagnostic pigments for station T6 on the Two Rocks transect (Fig. 159) reveals that the phytoplankton community is quite diverse, but extremely stable. The pigment composition indicates that diatoms, haptophytes, cyanophytes and green algae are present in the phytoplankton community all through the sampling period (Feb 2002 – July 2004), while cryptophytes and prasinophytes are present most of the time with a tendency to disappear during the summer months. Dinoflagellates are present infrequently and except for cyanophytes, the pigment data indicates that the ratio of the different algal groups changes little with the seasons. Cyanophytes show a significant increase during the summer months.

These preliminary results indicate that there is little seasonal succession within the phytoplankton community. The increase in cyanophytes could be due to either *Synechoccocus* spp. or *Trichodesmium* spp. cells or a combination of both species. Both of these species are commonly found in tropical and subtropical waters, such as the waters of the Leeuwin Current. However it is contrary to the dynamics of the Leeuwin Current which flows strongest in winter to have an increase in cyanophytes in summer. One possible explanation is that at station T6, which is on the shelf, the temperature of the surface waters in winter may be too cool to sustain a large population of cyanophytes.

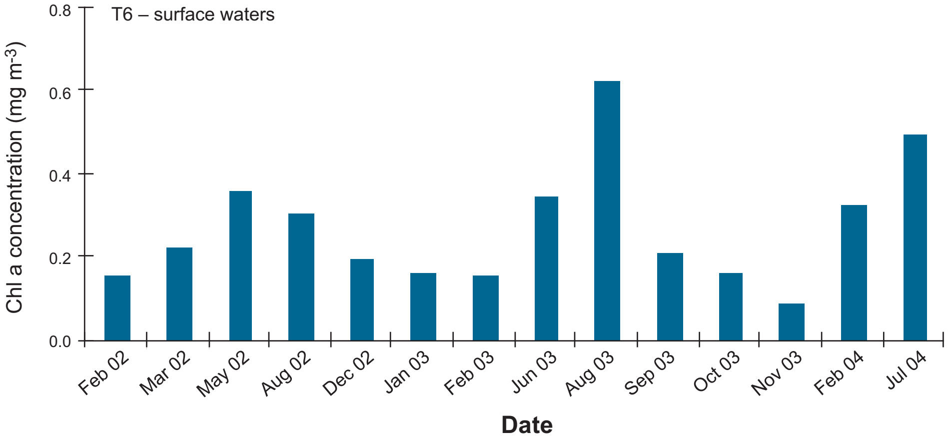


Figure 158: In situ chlorophyll a concentration as an estimate of biomass in the surface waters of station T6 on the Two Rocks transect plotted against time.

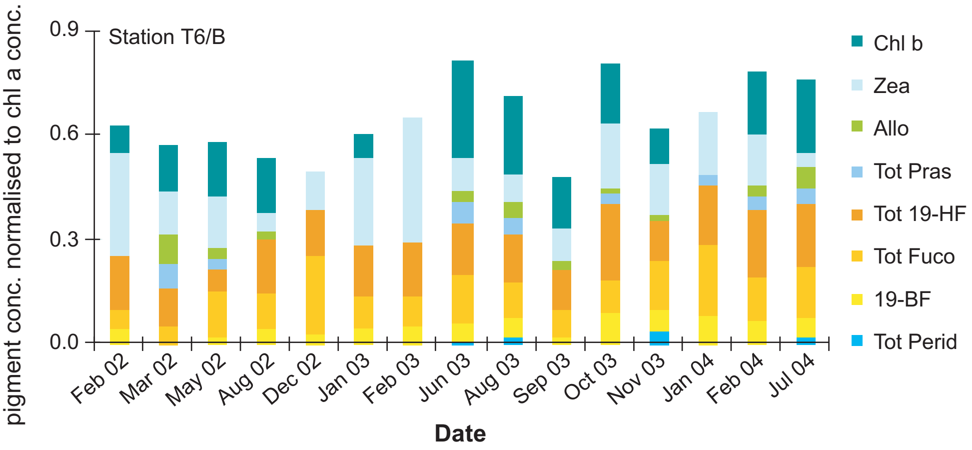


Figure 159: Pigment composition (diagnostic pigments only) plotted against time for the surface waters of station T6 on the Two Rocks transect.

There is also no evidence in the phytoplankton assemblage that the Capes Current which is said to flow north inside of the 50m contour in summer reached station T6 during this study. Further analysis of all the pigment data for all the sites together with temperature, salinity and fluorescence profiles and satellite imagery may provide a more complete explanation of why the phytoplankton community appears to be so stable throughout the year.

One of the suite of measurements made during this project is the absorption coefficients of the different components in the water column. Absorption coefficients for the CDOM, detrital and phytoplankton components are determined for each sample thus indicating the contribution of the different components to the total absorption of the water column at the different stations and sites. The typical shape of the spectra of each component is shown in Figure 160 with the spectra for phytoplankton showing absorption maxima at approximately 430 and 676 nm, while the spectra for the detrital and CDOM components approximate an exponential curve. The ocean colour sensors, SeaWiFS and MODIS have 8 channels or wavelength bands in the visible and near infra-red region of the spectrum where data are collected. The second channel is centered around 443 nm to detect maximum contribution from chl *a*. All results presented from this study will refer to values at 440 nm to coincide with data collected by the sensor.

At the Two Rocks and Bunbury sites there is a clear decrease in the value of $a_d(440)$ from inshore to offshore, while at Jurien Bay the $a_d(440)$ value is relatively constant along the entire transect (Fig. 161a-c). There is no discharge of rivers or urban/industrial sources near the Two Rocks site to explain the higher $a_d(440)$ values at the inshore stations while at Bunbury the innermost station (B1) is within the port area and close to the outlet of the Leschenault Inlet and station B2 is just outside the port area.

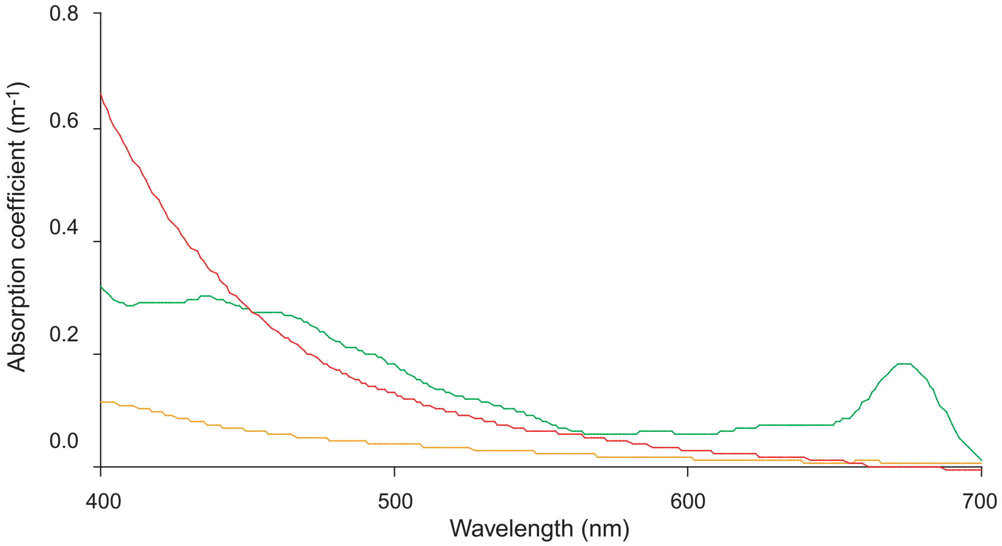


Figure 160: Typical spectra for the absorption coefficients for detritus (orange line), phytoplankton (green line) and CDOM (red line).

It is likely that stations B1 and B2 are influenced by the detrital matter from the inlet and the river basin that it drains. At Jurien Bay there appears not to be any difference in the $a_d(440)$ values between the innermost stations (J1 and J2) which are inside the reefs and the other stations which are outside the reefs. The highest $a_d(440)$ values are at the Jurien Bay site with average values of approximately 0.01 m^{-1} while average values at the Two Rocks and Bunbury sites are about 0.005 m^{-1}. Regardless of which site has the highest or lowest $a_d(440)$ values, these values would all be considered low for a coastal area and are remarkably constant throughout the year.

Similar to the $a_d(440)$ values, the values of $a_{CDOM}(440)$ also decrease from inshore to offshore, but for this component the effect is observed at all three sites (Fig. 161a-c). At Jurien Bay the $a_{CDOM}(440)$ values are much higher at the two inshore stations, inside the reefs, than at the stations outside the reefs, suggesting the inner two stations are probably affected by a terrestrial source. The Bunbury site also shows increases in $a_{CDOM}(440)$ values at those stations closest to the inlet. Excluding the inner-most stations, these $a_{CDOM}(440)$ values fall within the range suggested for case 1 waters (Kirk, 1983) and would be considered low in most coastal waters. Like the $a_d(440)$ values, there doesn't appear to be a seasonal pattern in the $a_{CDOM}(440)$ values at any of the sites.

Unlike the other components the $a_{ph}(440)$ values don't show an inshore to offshore decrease, showing instead quite similar values at all stations on a transect within any one trip at all sites (Fig. 161a-c). On occasion, higher values of $a_{ph}(440)$ are recorded at the inshore station on the Two Rocks and Bunbury site. At Jurien Bay, the phytoplankton community composition does not seem to be affected by the location of the reefs on the transect as $a_{ph}(440)$ values are similar at the stations inside and outside the reefs. As for the other components, the values of $a_{ph}(440)$ would be considered low for a coastal region.

a(440) values from the offshore station (T6) on the Two Rocks site have been compared with a(440) values from three coastal sites off Tasmania, two open-ocean sites in the Southern Ocean and two sites off Heron Island in oligotrophic Great Barrier Reef waters (Fig. 162).

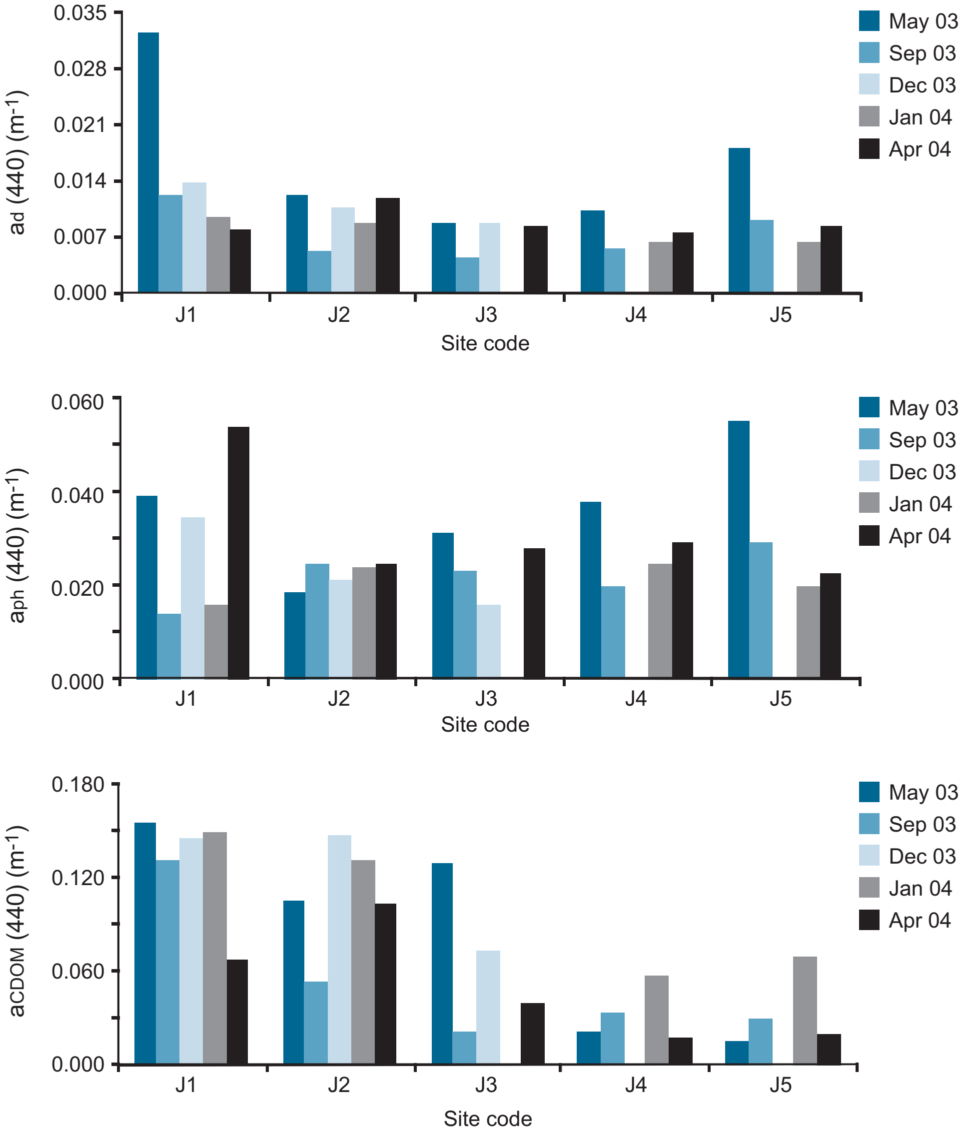


Figure 161a: The absorption coefficients for detritus, phytoplankton and CDOM measured at 440 nm for the stations at Jurien Bay.

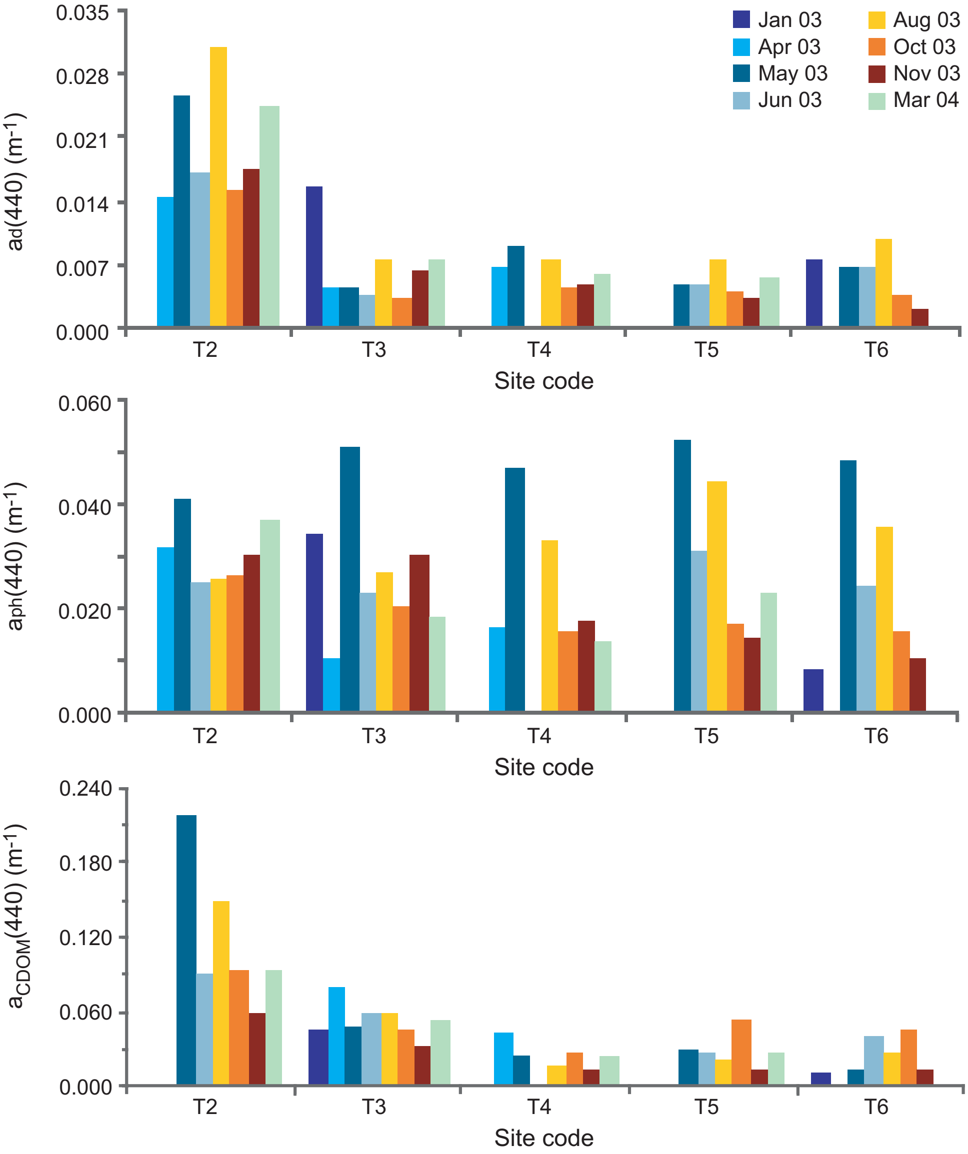


Figure 161b: The absorption coefficients for detritus, phytoplankton and CDOM measured at 440 nm for the stations at Two Rocks.

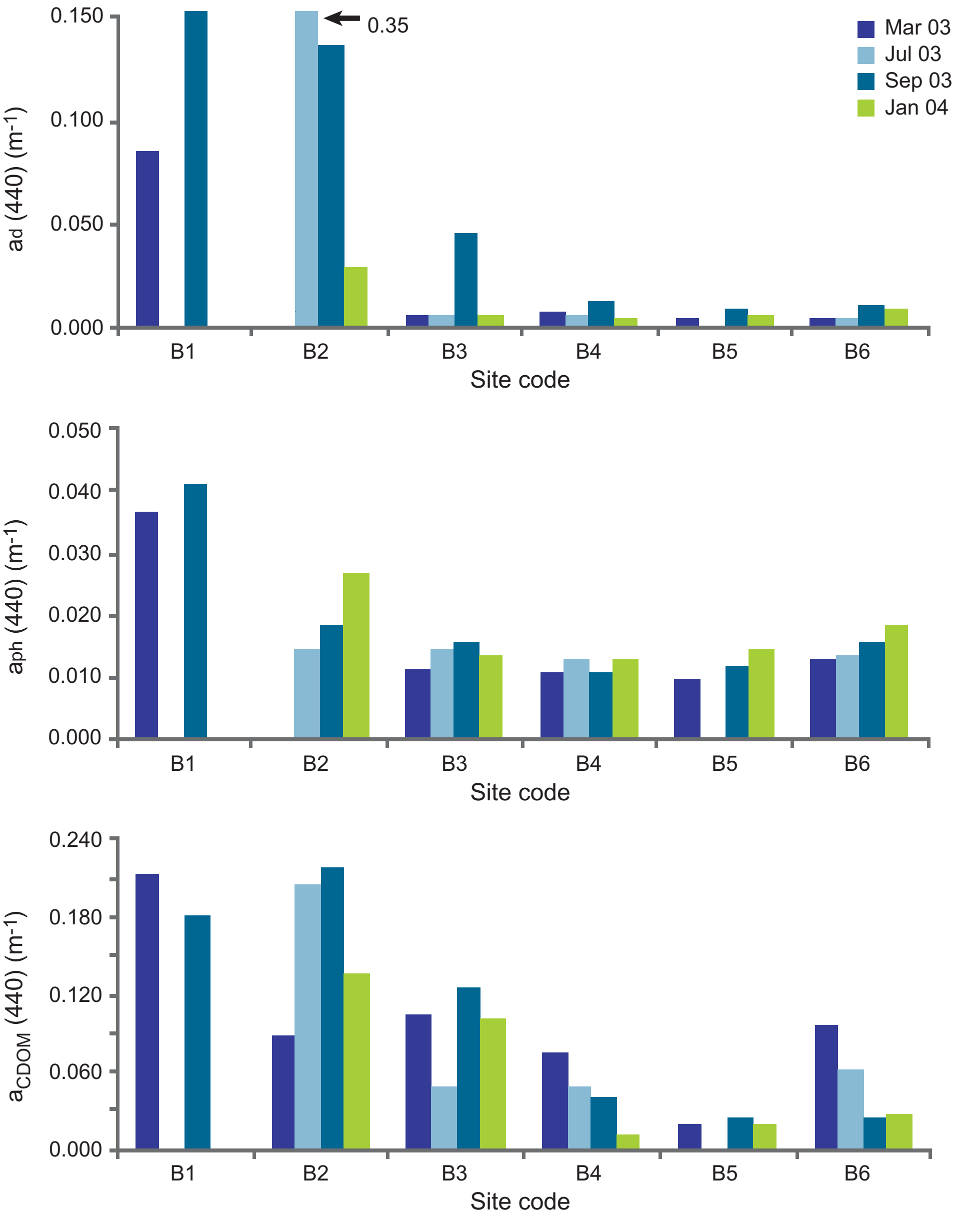


Figure 161c: The absorption coefficients for detritus, phytoplankton and CDOM measured at 440 nm for the stations at Bunbury.

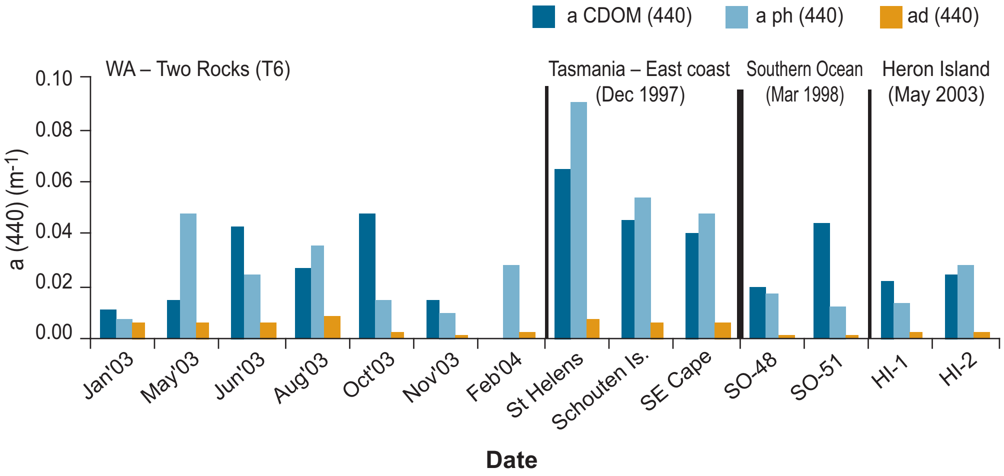


Figure 162: Comparison of a(440) values from a typical site in Western Australian coastal waters with other sites in Australian waters.

The Two Rocks a(440) values represent the range of values that were observed over the seasons within a year and are compared to a(440) values taken at just one point in time. However the values from the three Tasmanian sites were observed in summer when the a(440) values for all components are likely to be at their lowest and the a(440) values for CDOM and detritus at the Southern Ocean sites would show less variability over the seasons than a coastal site. The comparison between the four sites does confirm that the a(440) values observed in Western Australian coastal waters are low and comparable to values found in open-ocean or oligotrophic waters. This result suggests that the reasonably good relationship between *in situ* chl *a* and retrieved estimates of chl *a* using the standard algorithm of the SeaWiFS and MODIS sensors (Fig. 154) is due to the coastal waters of Western Australia being characterized optically as closer to case 1 waters than case 2 waters.

Although the absorption properties of the different components of the water column are low in Western Australian waters, the proportion of absorption due to each component can still affect the accuracy of the retrieved chl *a* estimate.

The percentage of absorption due to each component, including the water itself, has been calculated for the offshore station on each transect (Fig. 163). There are clearly times where the CDOM is the dominant component, contributing more to the total absorption than the phytoplankton. Under these circumstances, the satellite sensors would retrieve a chl *a* value which would be an over-estimate of the *in situ* chl *a*.

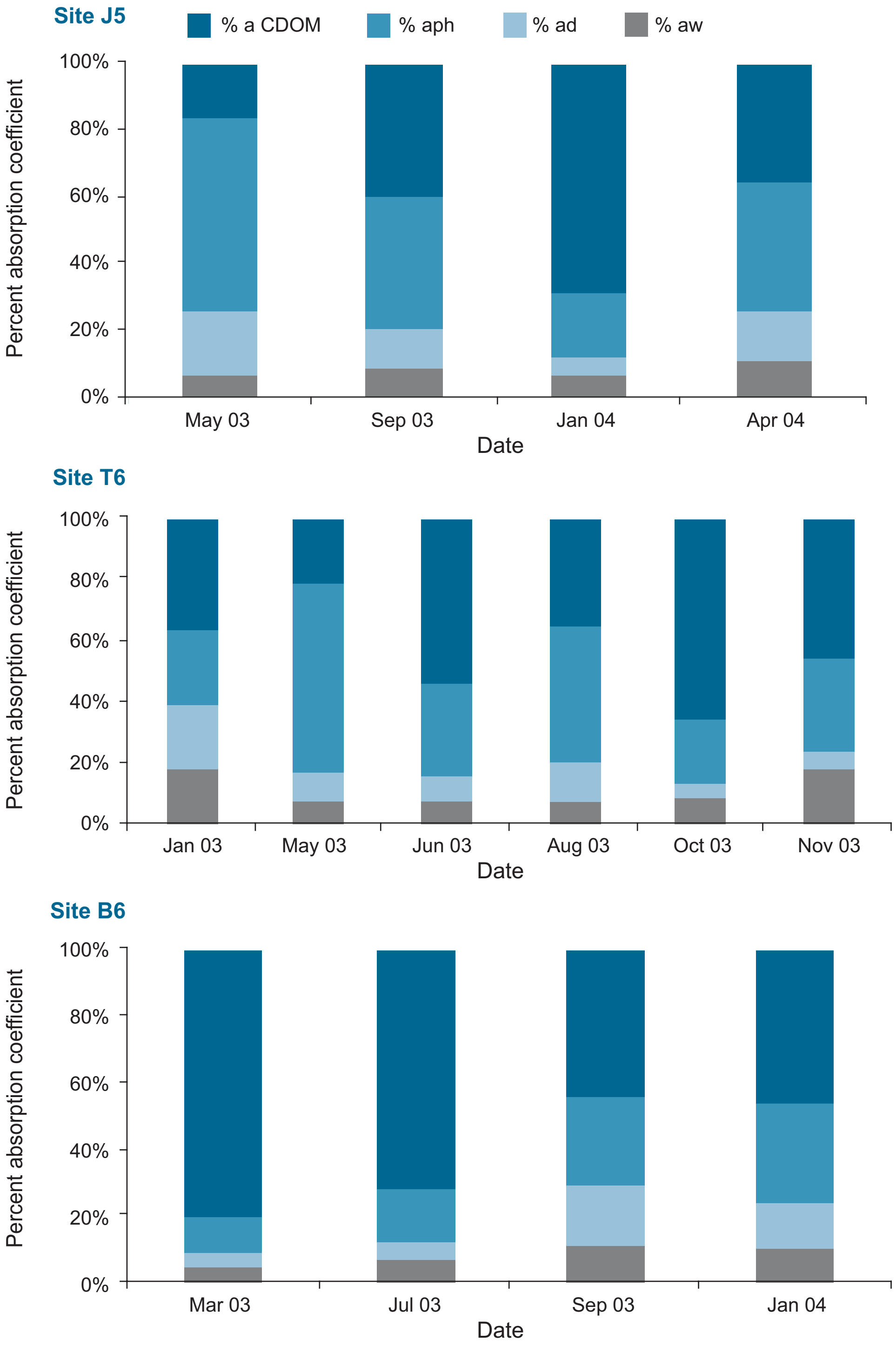


Figure 163: The percentage of the a(440) values for each component at the off shore station on the Jurien Bay, Two Rocks and Bunbury transects.

6.13.3.4 Summary

The coastal areas of southern Western Australia are unlike many other coastal areas in which the absorbance and scattering properties can be dominated by high sediment loadings or by high concentrations of CDOM. By comparison, the coastal waters of Western Australia have very low absorption properties. As the phytoplankton community appears to remain stable throughout the year, the difference between *in situ* chl *a* and retrieved chl *a*, at times, may be due to the higher contribution of CDOM than phytoplankton to the total absorption. This would cause the retrieved chl *a* estimate to be an over-estimate of the *in situ* chl *a* as has been observed on occasion.

From the limited data available, at the time of submission, it doesn't appear that the strong seasonal features seen in the climatology and oceanography of this region are reflected in the bio-optical characteristics of the coastal waters inshore of the 50 m contour. However the relationships observed, in these preliminary results, between the bio-optical parameters and the retrieved estimates of parameters will be tested further as the data set grows.

At the conclusion of the field work for this project (mid-2005), one of the most detailed spatial and temporal studies of IOPs (inherent optical property) and AOPs (apparent optical property), for any area in Australia will be available to researchers. This dataset will provide an excellent base for refining the standard algorithms of the current ocean colour sensors for use in southern Western Australian regions, thus providing an important tool for scientists and managers of this marine environment.

Acknowledgements

The authors would like to thank all staff and volunteers who have assisted with the field work, Kate Berry for lab analysis and WASTAC for the provision of routine satellite data processing. Some of the data used in this study were acquired as part of the NASA's Earth Science Enterprise. The algorithms were developed by the MODIS Science Teams. The data were processed by the MODIS Adaptive Processing System (MODAPS) and Goddard Distributed Active Archive Centre (DAAC) and archived and distributed by the Goddard DAAC. SeaWiFS data were provided courtesy of Orbimage.

6.13.3.5 SST validation

The accuracy of the satellite-derived SSTs has been assessed using the near-surface temperature profiles from the on-station CTD casts at each station. For this purpose, the temperatures nearest the water surface during each up-cast were extracted from the full-profile data (generally within 20 to 30 cm of the surface), and compared with the satellite NLSST on the same day. Where there were repeated CTD casts at a station, the cast nearest in time to the satellite overpass was selected.

There were 75 successful match-ups over the 3-year period (Figure 164). The bias (average of all the NLSST - CTD differences) was 0.09°C and the root-mean-square (RMS) difference was 0.48°C. As can be seen in the histogram (Figure 165), 49% of all comparisons fell within ± 0.25°C, 78% within ± 0.5°C, 85% within ± 0.75°C and 95% within ± 1.0°C. These results are very encouraging, indicating that almost 80% of the satellite observations were within 0.5°C of the *in situ* temperatures. However, about 5% of the differences were greater than 1°C.

Possible reasons for satellite-*in situ* differences include:

a) The spatial difference between the 1-km pixel areas sampled by the satellite compared with the spot CTD measurements;

b) The vertical profile difference between the satellite measurement (the so-called surface "skin" less than 1 mm thick) and the "bulk" measurement by the CTD (10 to 50 cm below the surface). Because of the generally strong winds in Perth coastal waters, however, the near-surface layer is usually well-mixed with minimal temperature differences in the uppermost few metres of the water column. The CTD casts show that temperature differences in the top 1 m of the water column were less than 0.1°C for 98% of the time, but 3 casts showed differences of 0.11°, 0.25° and 0.44°C. Skin minus bulk temperature differences are typically less than about 0.3°C.

c) Time differences between the satellite overpass and the CTD cast.

Some quantitative estimates of these factors for southwestern Australian waters have been made by Pearce *et al*. (submitted).

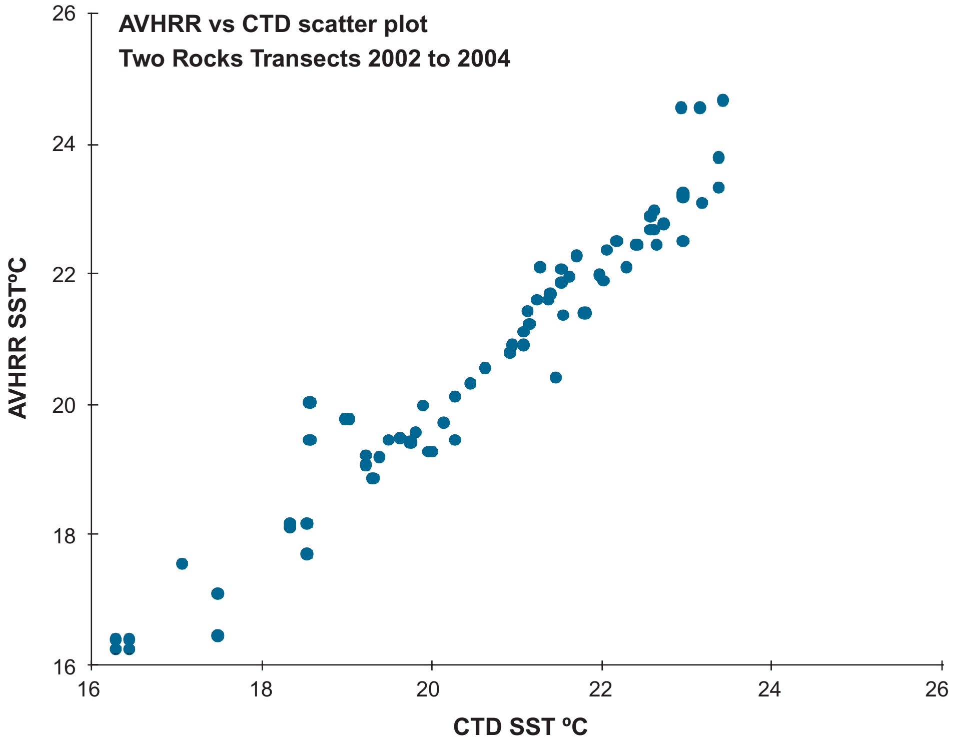


Figure 164: Scatter-plot of the satellite NLSSTs vs the *in situ* CTD temperatures from the Biophysical Two Rocks Transect CTD stations.

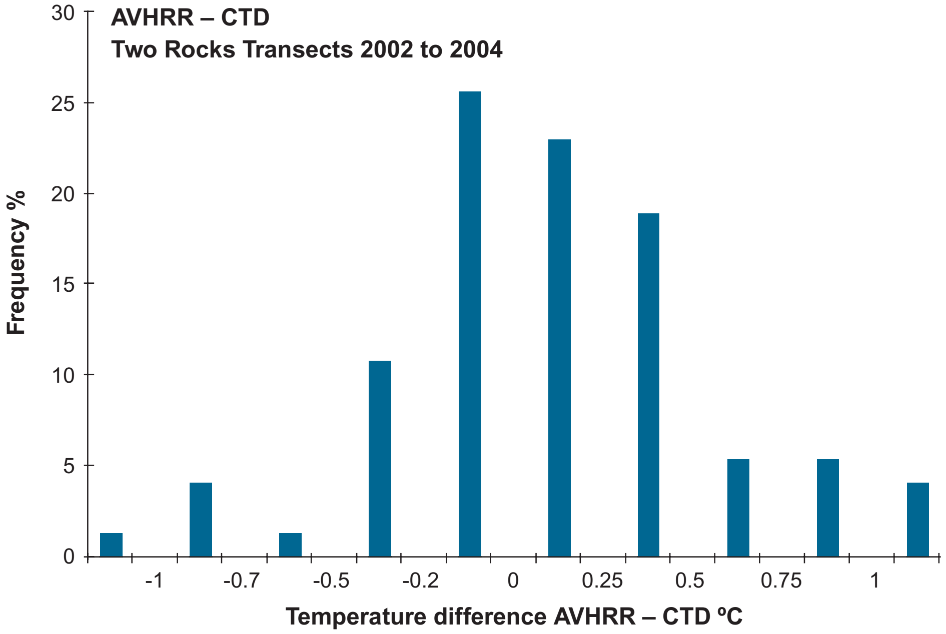


Figure 165: Histogram of the satellite NLSST – *in situ* CTD temperature differences from the Biophysical Two Rocks Transect CTD stations.

6.13.4 Modelling and algorithm development

The Ocean Colour Group currently focus on two aspects of optical modelling related to remote sensing. One is using *in situ* IOP data as input to the proprietary model Hydrolight to elucidate factors which may affect the goodness of validation data. The second thrust of the modelling work is the development of shallow water substrate mapping using hyperspectral remotely sensed data.

6.13.4.1 Modelling and validation

Absorption and attenuation data collected by the ac-9 are used as input to Hydrolight. The ac-9 data are corrected for temperature and salinity effects using contemporaneous CTD data , then smoothed and binned to produce vertical profiles of spectral absorption, *a*, and spectral attenuation, *c*, at nine visible wavelengths (see Appendix 1). The smoothed spectral absorption data for Jurien station J5 (mc200406, 28th April 2004) are shown in Figure 166, and smoothed attenuation data for the same station are shown in Figure 167. There is an increase in total absorption and attenuation at about 12-15 m depth. This increase in absorption occurs at the same depth as the increased chlorophyll fluorescence signal at station J5 shown in Figure 155. The discontinuity at 24 m depth is where the instrument sat at one depth for a period of time while water samples were collected. It is possible that the boat drifted during this time and absorption conditions changed slightly.

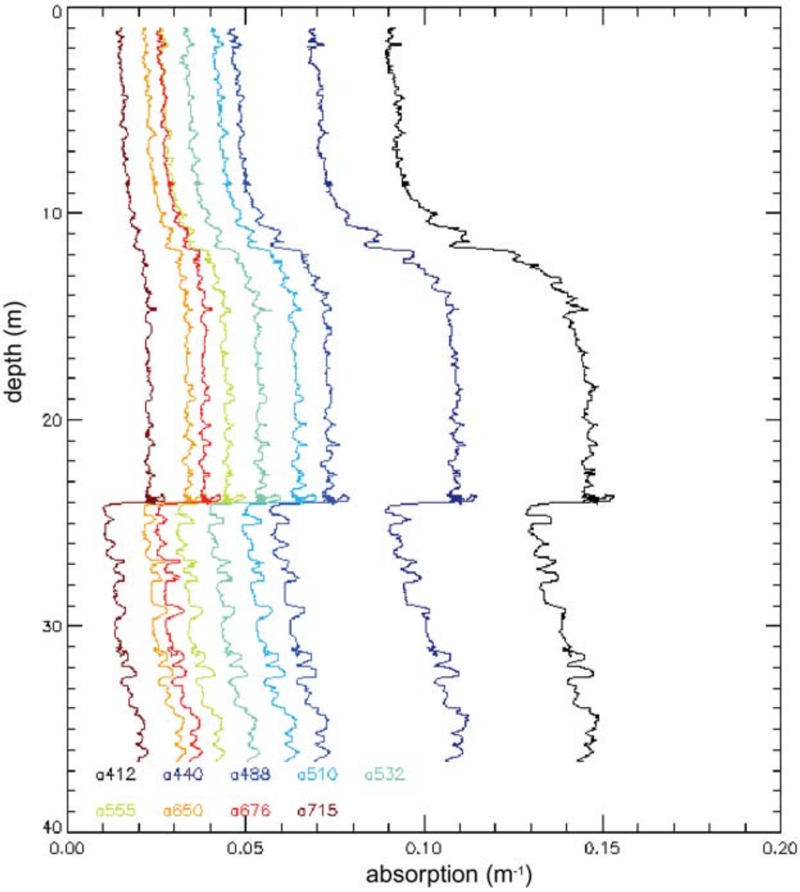


Figure 166: ac-9 derived spectral absorption profiles for Station J5 for 28th April 2004.

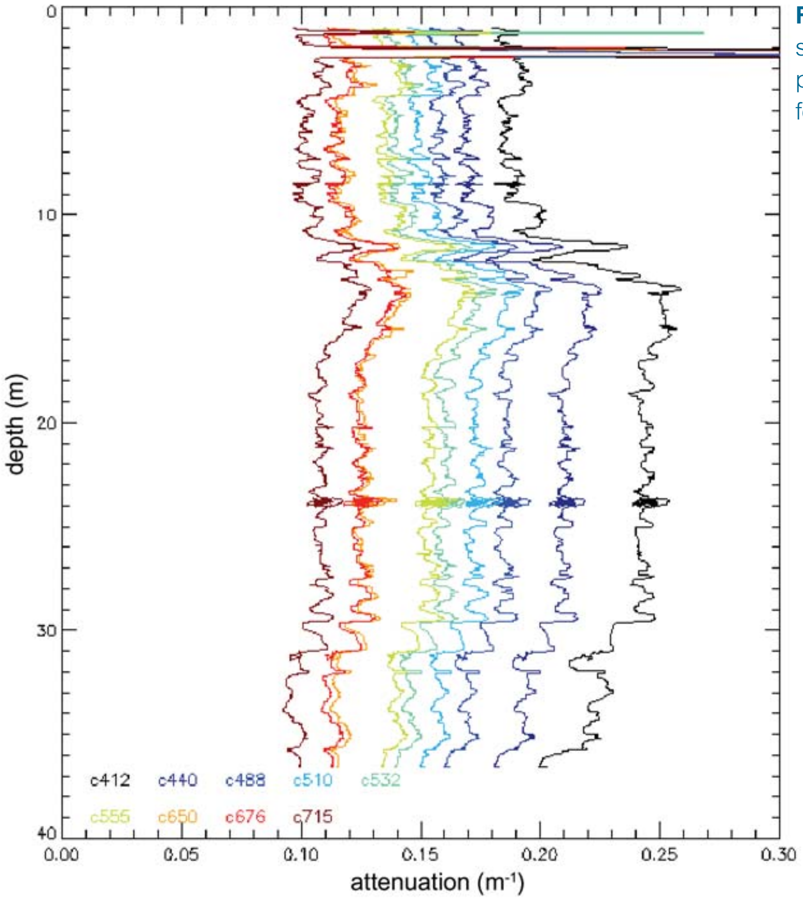


Figure 167: ac-9 derived spectral attenuation profiles for Station J5 for 28th April 2004.

For comparison with the ac-9 data we display temperature, salinity, fluorescence and Photosynthetically Active Radiation (PAR) profile data collected contemporaneously by the CTD/rosette. The four profiles are displayed in Figure 168. Each plot includes data from the instrument downcast and upcast. Data from the vertical profiles were incorporated in the cross section plots shown in Figure 155. The temperature, salinity and fluorescence profiles display a distinct change at a depth of approximately 15 m.

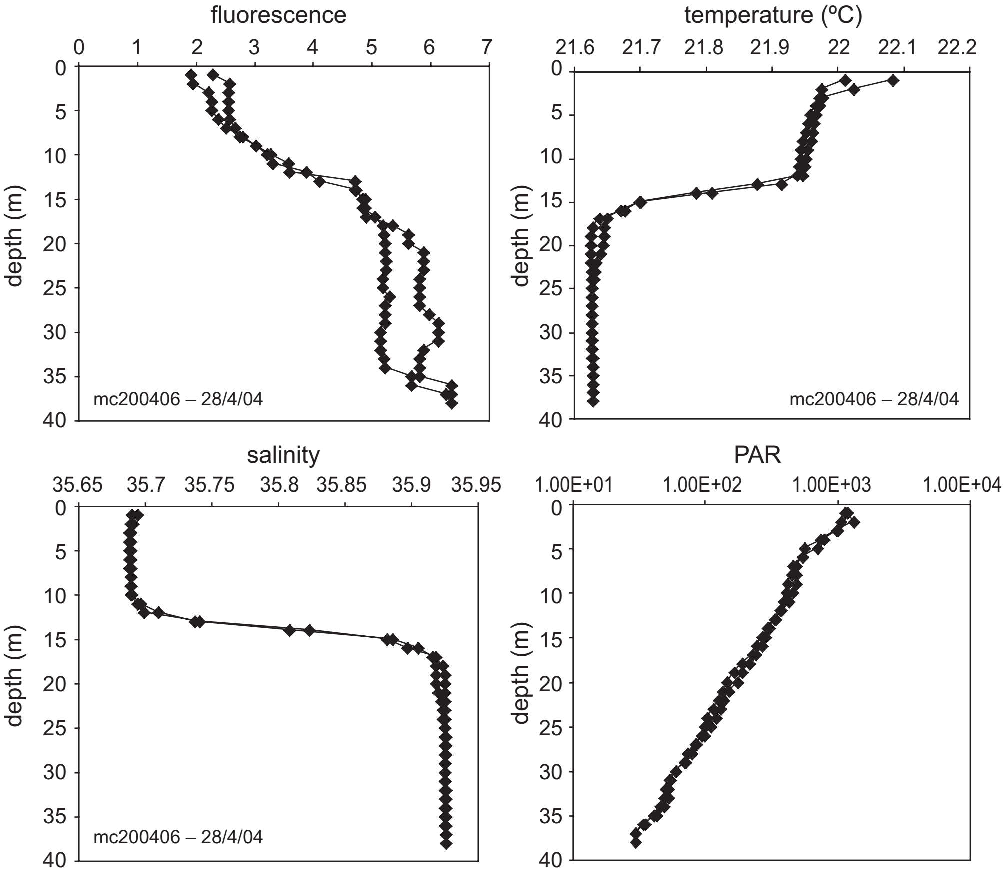


Figure 168: CTD-derived fluorescence, temperature, salinity and PAR profiles for Station J5 for 28th April 2004.

The ac-9 data were used as input to Hydrolight to control the vertical distribution of absorbers and scatterers in the water column. Hydrolight calculates the up- and downwelling spectral radiance/irradiance profiles, as well as the up- and downwelling spectral attenuation coefficients. The Hydrolight-calculated PAR profiles and attenuation coefficients are displayed in Figure 169. Figure 169a shows the spectral attenuation coefficient at the ocean surface (solid line) and at 40 m depth (dashed line). The feature of note here is that attenuation at the "red end" of the spectrum (towards 700 nm) is highest in the surface water relative to the deeper water, and attenuation is higher at the "blue end" (towards 400 nm) in the deeper water. Although the decrease in PAR with depth is relatively uniform (Figure 169b, also Figure 169d), the attenuation of PAR is higher near the surface than at depth. This high attenuation of PAR near the surface is due to the high absorption of red light by water (Pope and Fry 1997). As the red light is removed from the downwelling light stream, the remaining blue light is scattered, thus increasing the attenuation with depth. The decrease in attenuation of PAR at 24 m depth (Figure 169c) is due to the data collection artefact shown in Figure 166. The Hydrolight-calculated attenuation profile is also plotted in Figure 169d, along with the attenuation derived from the *in situ* PAR measurements. The dotted lines indicate the RAW data, and the dashed curve shows the raw data smoothed by a 15 point moving average. The level of agreement is encouraging.

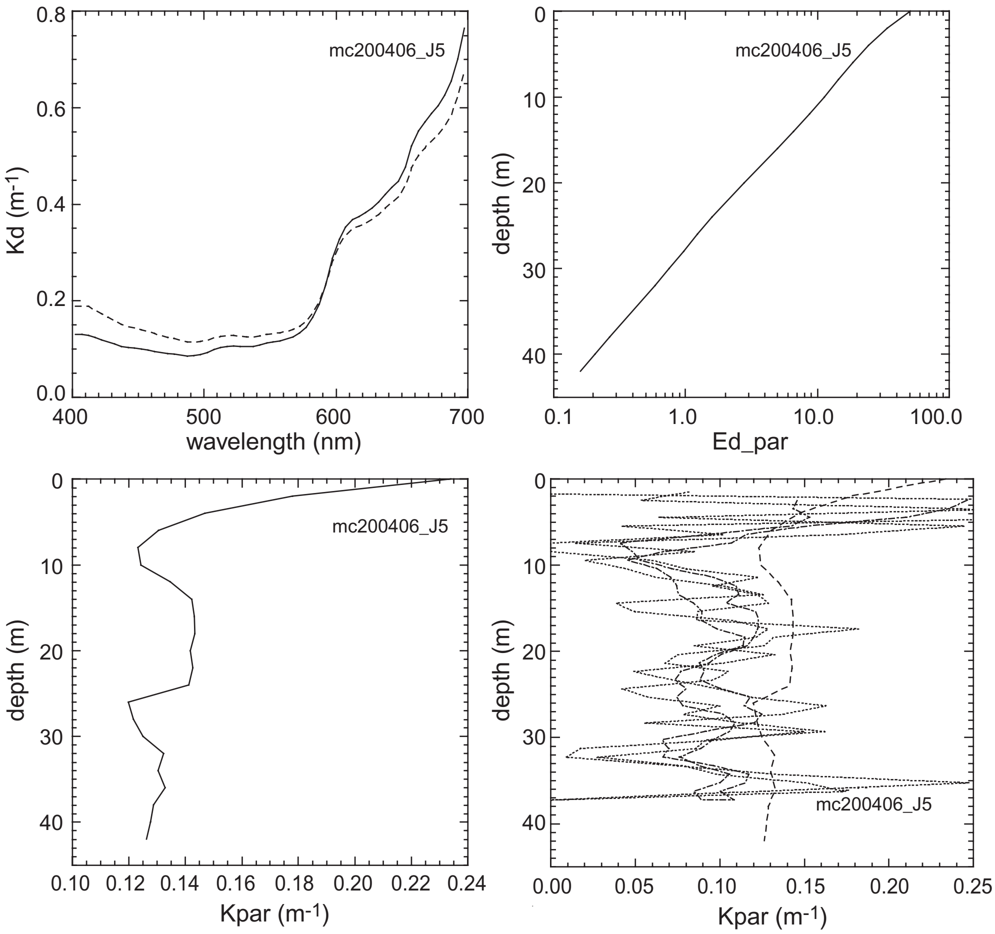


Figure 169: Hydrolight-calculated a) spectral diffuse attenuation coefficients at 0 m depth (solid line) and 40 m depth (dashed line), b) PAR profile, c) attenuation of PAR (K_{PAR}) profile using ac-9 data as an input, d) measured K_{PAR} (raw data – dotted line, smoothed data – dash/dot line) and Hydrolight-calculated data (dashed line) for Station J5 for 28th April 2004.

6.13.4.2 Hyperspectral Remote Sensing of Coastal Waters

One of the growing areas of interest in hyperspectral remote sensing is the application of hyperspectral data to mapping and monitoring of shallow coastal habitats. While one may apply “image processing” techniques to such data, a more rigorous approach is to analyse these data in the context of radiative transfer processes. In essence, an understanding of the optical processes within the water column, and optical interactions with the substrate, enable scientists to infer such parameters as water column constituent concentrations or benthic cover type from remotely sensed hyperspectral data.

For this work data collected by the HyMap sensor over Jurien Bay have been used to develop and test a model inversion process to retrieve substrate reflectance coefficients in shallow coastal waters. The end product is a map of substrate cover in terms of classification by colour and percentage cover.

Optical modelling

CMR, in collaboration with the Remote Sensing and Satellite Research Group at Curtin University, have implemented a simple shallow water reflectance model applicable to the optical domain present in many Australian coastal waters. The model is typically tuned to local conditions by including spectral characteristics of commonly occurring local substrates. The model is based on the work of Lee *et al* (1999). The remote sensing spectral reflectance, rrs, is given by,

$$r_{rs} \approx r_{rs}^{dp}\left(1-\exp\left\{-\left[\frac{1}{\cos(\theta_w)}+\frac{D_u^{C}}{\cos(\theta)}\right]\kappa H\right\}\right)+\frac{1}{\pi}\rho\exp\left\{-\left[\frac{1}{\cos(\theta_w)}+\frac{D_u^{B}}{\cos(\theta)}\right]\kappa H\right\}$$

where, r_{rs}^{dp} is the remote sensing reflectance of an infinitely deep water column, θ and θ_w relate to the illumination and viewing geometry, κ and D_u are light transmission functions, ρ is the substrate reflectance, and H is water depth. The light transmission functions may be expanded to include coefficients related to the optical properties of water column constituents, and these in turn related to concentration values for constituents such as chlorophyll and suspended sediment.

The model and inversion process (to retrieve substrate maps and water column constituent concentrations) have been tested and validated in a number of coastal environments. The applicability and sensitivity of the forward model may further be tested using a more advanced radiative transfer model, HYDROLIGHT (Mobley, 1998). This model employs sophisticated invariant imbedding techniques to solve the radiative transfer equation. Exploration of the optical extremes using advanced models such as HYDROLIGHT enables scientists to not only provide products such as habitat maps, but also provide estimates of confidence associated with such products.

Collection of library spectra

Classification of benthic substrates by remote sensing techniques depends upon a-priori knowledge of the spectral nature of the substrates present. Typically, spectra are selected from a spectral library. This spectral library is built up from numerous field campaigns to undertake *in-situ* measurements of substrate spectral properties. CMR have been involved in the collection of such spectra for a number of years, including campaigns measuring coral spectral properties on the Great Barrier Reef and spectral properties of numerous algae species in WA coastal waters. Reflectance spectra are measured with a dual channel Zeiss hyperspectral radiometer (see Appendix 1). The radiometer may be deployed by a diver to measure the reflectance spectrum *in situ*, or the diver may retrieve a sample of the benthic cover to measure the spectral reflectance in air. Reflectance spectra from a number of substrate “types” are shown in Figure 170. The spectra in each type may be normalised and averaged to create representative spectra for use in the inversion process.

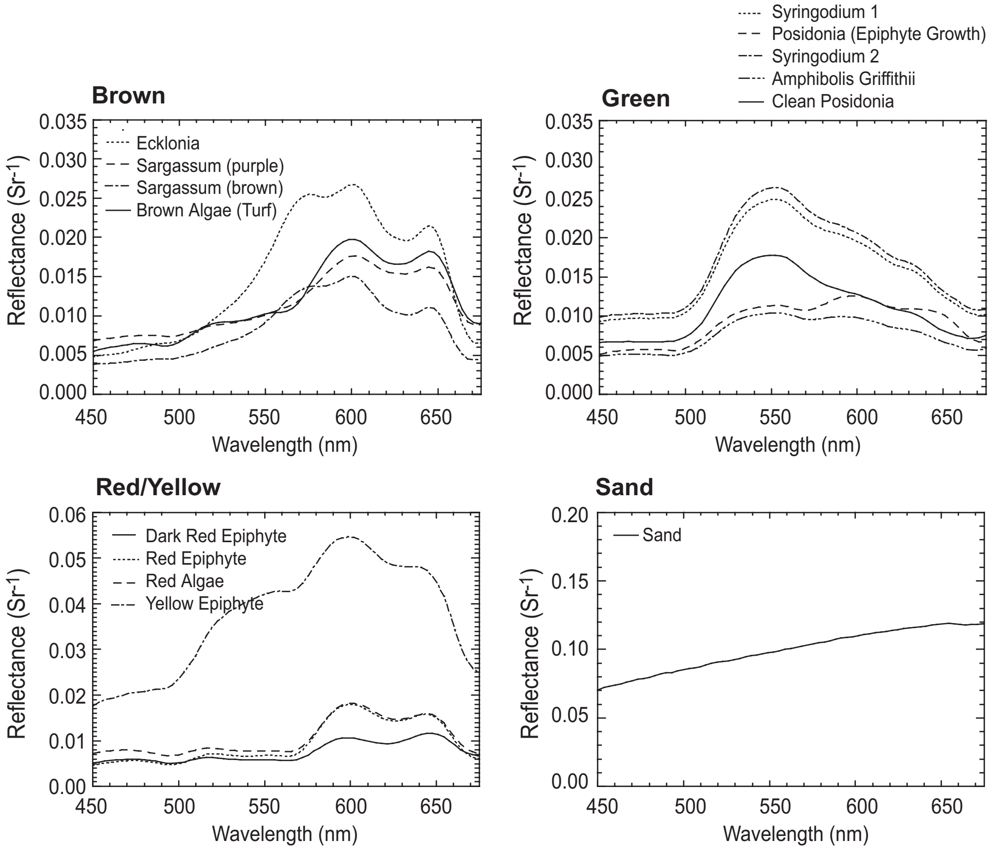


Figure 170: *In-situ* spectra of four different groups of substrate.

Water Sample analysis

Field campaigns also involve collection of water samples for subsequent laboratory analysis. This analysis enables determination the variability of optical constituents in the water column, which may in turn be related to validation of the optical model as well as included in estimates of confidence limits applied to retrieved substrate maps. The substrate mapping process involves inversion of the optical model to retrieve specific parameters. These parameters include water depth, substrate reflectance, chlorophyll and CDOM absorption and sediment scattering properties. The collection and analysis of water samples provides data to validate the model inversion process.

In-situ validation

A key to development and improvement of substrate maps derived from remotely sensed hyperspectral data is the ability to demonstrate rigorous validation. The CMR remote sensing team is linked closely to other research groups, including ecosystem modellers, benthic ecologists and biogeochemists. Each of these groups, as well as members of the remote sensing team, is able to provide expert data useful in validation of the remotely sensed substrate maps. Validation data have been provided from field programs involving diving, sampling and classification of substrates.

Figure 171 shows a Hymap "true colour" image of a 1.5 km by 1.5 km region in Jurien Bay. The inversion process returns three reflectance coefficients, one for each of three substrate groups. For this example the groups were, Green Vegetation, Brown Vegetation and Sand (averages of data in Figure 170). The three coefficients have been combined to create a three colour image of substrates classified by colour (see Figure 171). where blue represents sand, green represents green vegetation and red represents brown vegetation.

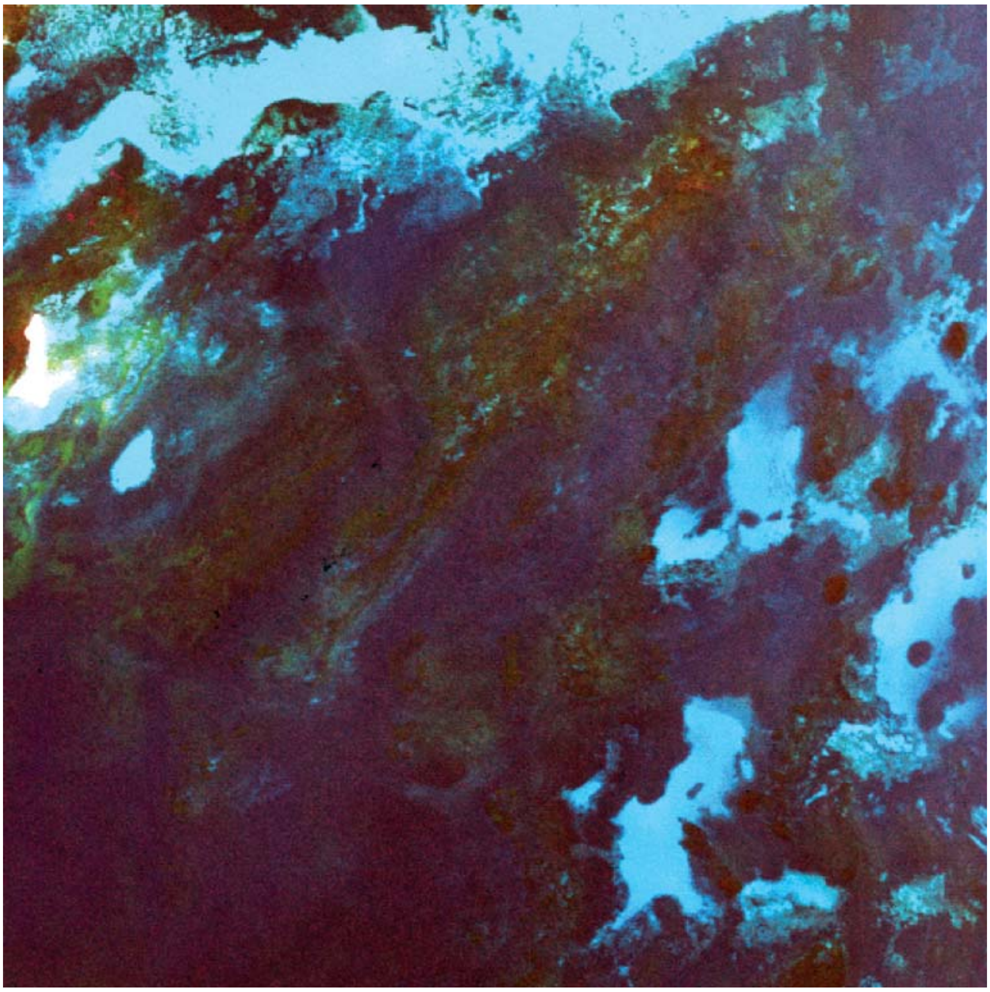


Figure 171: *In-situ* spectra of four different groups of substrate.

The locations of validation sites are shown in Figure 172. The numbered sites are listed in Table 27 with the bottom type classification as supplied by the Benthic Ecology Team. The ability of the inversion process to classify to this level of detail is encouraging. Work is continuing to develop methods of including estimates of levels of confidence to each classified pixel. The level of confidence is affected by factors including water depth, water turbidity, knowledge of substrate spectra and lighting conditions.

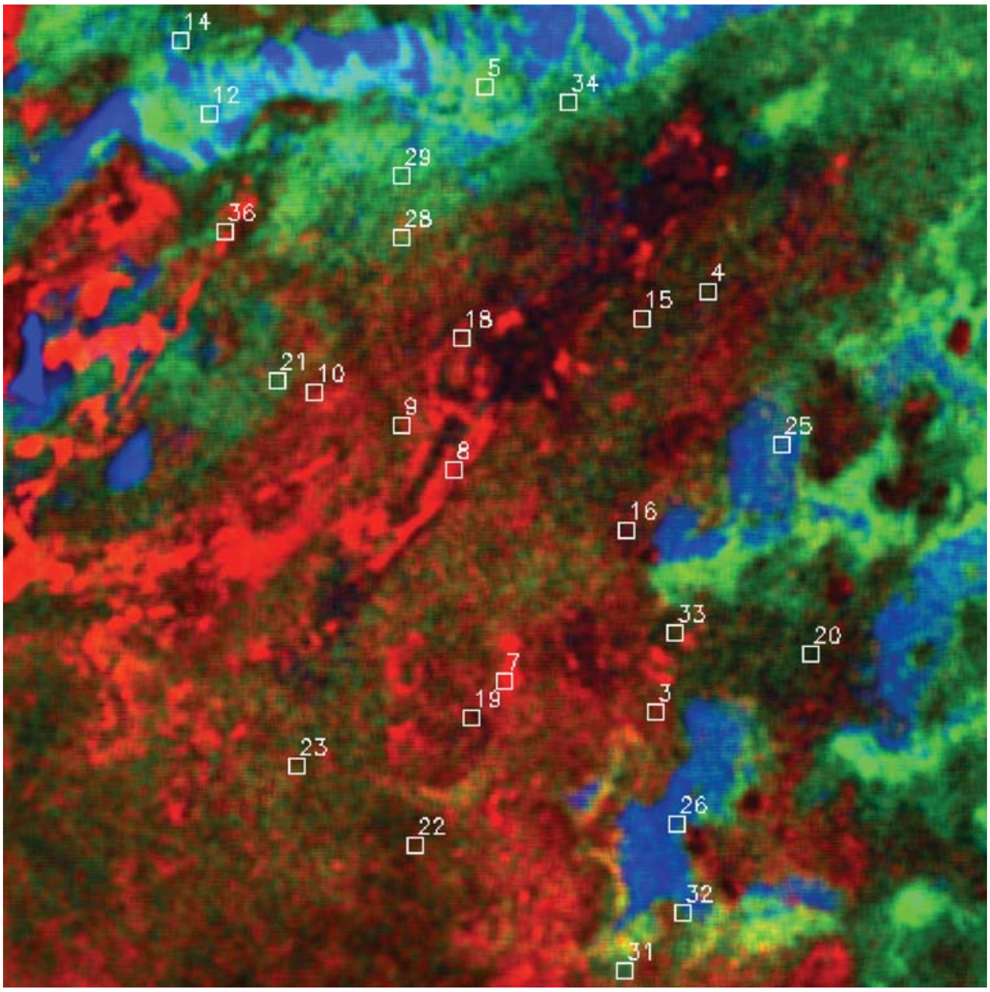


Figure 172: *In-situ* spectra of four different groups of substrate.

Table 27. Station numbers (see Figure 172), pixel colours and bottom types as reported by divers.

Station #		Bottom type
14	🟦	Sand
32	🟦	Mostly Sand/Patchy Halophila
26	🟦	Sand
25	🟦	Sand
12	🟩	Sand/Patchy Halophila
34	🟩	Sand/Patchy Halophila
29	🟩	Sand/Halophila
28	🟩	Sand/Halophila
5	🟩	Seagrass(dense)/Sand
31	🟩	Sand/Seagrass/Light Brown Epiphytes
21	🟩	Purple Sargassum/Seagrass/Brown+Yellow Epiphytes/Sand
33	🟩	Bare Reef/Purple Sargassum (Sparse)
20	🟩	Bare Reef/Purple Sargassum (Sparse)
4	🟩	Bare Reef/Purple Sargassum (Sparse)
10	🟥	Sargassum/Sand
8	🟥	Purple Sargassum/Brown Sargassum/Sand/Ecklonia(Dense)
3	🟥	Brown Sargassum/Brown Epiphytes
7	🟥	Ecklonia(Dense)
36	🟥	Ecklonia/Seagrass/Brown+Purple Sargassum
9	🟥	Purple Sargassum/Sand/Patchy Ecklonia/Epiphytes
19	🟥	Purple Sargassum/Brown Sargassum/Sand
23	🟥	Purple Sargassum/Sand/Brown + Yellow Epiphytes
22	🟥	Purple Sargassum/Sand/Brown Epiphytes
16	🟥	Brown Sargassum
15	🟥	Purple + Brown Sargassum/patchy Sand

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2. Seasonal effects in the inherent optical properties of Western Australian coastal waters: impacts on the validation of ocean colour sensors in this region. Ocean Optics XVII conference, Fremantle, Australia, October 2004.
3. Inherent optical properties of Western Australian coastal waters, EOC annual meeting, Hobart, March 2005.
4. Fearns, P., 2003 MODIS – Ocean Colour, 10th National Conference of AMOS: 10th-12th Feb. 2003, Perth, WA

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Appendix 1

INSTRUMENTS

ac-9

The ac-9 meter measures the water's absorption and attenuation coefficients at 9 wavelengths (412, 440, 488, 510, 532, 555, 650, 676, and 715 nm).

The instrument consists of the transmitter optics and filter wheel that use light, from a DC incandescent source, to create a narrow band spectral output. This light passes through the absorption and attenuation flow tubes and is then received by the detector. The voltage from the detector is amplified and converted to a digital value. The data from the ac-9 is corrected for temperature and salinity effects, scattering errors and instrument drift.

The ac-9 is attached to the rosette in a vertical orientation and a dedicated pump (Sea-Bird Electronics SBE-5) ensures the required flow rate (>1 litre/min) of sample water through the absorption and attenuation flow tubes. Before the sampling profile is undertaken the rosette is lowered to 10 metres for 5 minutes. This ensures that all air bubbles are removed from the system. The sampling profile is then undertaken at a rate as close as possible to 30cm/sec.

The ac-9 instrument is affected by temperature and salinity. Corrections for changes in these values must be applied to the raw ac-9 data. Co-incident temperature and salinity readings from the CTD are used. There is a different temperature and salinity correction coefficient at each wavelength

The corrected absorption coefficient is given by

$$a_{cor} = a_{orig} - \left[C_T\left(T_{orig} - T_{ref}\right) + C_S\left(S_{orig} - S_{ref}\right)\right]$$

where

a_{cor} is the corrected absorption coefficient
a_{orig} is the original (measured) absorption coefficient
C_T is the temperature correction coefficient
C_S is the salinity correction coefficient
T_{ref} is the reference temperature
T_{orig} is the original (measured) temperature
S_{ref} is the reference salinity
S_{orig} is the original (measured) salinity

A similar approach is used to correct the attenuation data for temperature and salinity effects. Following correction of the a and c data for temperature and salinity effects, the data are corrected for scattering effects. The proportion, *P*, of scattering not detected by the sensor is calculated,

$$P = \frac{a_{cor}}{c_{cor} - a_{cor}},$$

then the data are corrected for scattering

$$a = a_{cor} - P * \left(a_{cor} - c_{cor}\right)$$

Hydroscat-6

The Hydroscat-6 measures optical backscattering at six different wavelengths (442, 488, 550, 589, 676 and 850 nm). A light-emitting diode at each wavelength produces a beam of light in the water and a separate detector collects light that is scattered out of that beam by the water. The Hydroscat-6 can also measure fluorescence at two wavelengths (550, 676 nm).

The Hydroscat-6 is attached to the rosette in a vertical orientation and is deployed at the same time as the ac-9.

Radiometers

The Profiling Reflectance Radiometer PRR-600 (Biospherical Instruments) measures down-welling irradiance (E_d) and up-welling nadir radiance (L_u). The down-welling irradiance channels used are 412, 443, 490, 510, 555, 655 nm and PAR (Photosynthetically Active Radiation covering 400-700nm). The up-welling radiance channels are the same except a 683nm channel replaces the PAR. These channels have been chosen to be complement the SeaWiFS bands.

A hydroRad-2 (HOBILabs) is also used to measure down-welling irradiance and up-welling radiance (wavelength range 350nm – 850nm). These instruments are hand lowered over the side of the boat in a position that avoids the boat shadow.

A Zeiss radiometer is used to measure the water leaving radiance.

Appendix 2

METHODS

Pigment analysis

Four litres of sample water was filtered through a 47 mm glass fibre filter (Whatman GF/F), under subdued lighting, and then stored in liquid nitrogen until analysis. Pigment extracts were analysed using a HPLC (Waters) with photo-diode array detection. The separated pigments were detected at 436 nm and identified against standard spectra using Waters Millenium software. Concentrations of chlorophyll *a*, chlorophyll b, β,β,ε-carotene and β,β -carotene in sample chromatograms were determined from standards (Sigma) and all other pigment concentrations were determined from standards of purified pigments isolated from algal cultures. A more detailed description of the method can be found in Clementson *et al*. (2001).

Particulate and detrital absorption

Approximately 2 litres of sample water was filtered through a 25 mm glass fibre filter (Whatman GF/F), under subdued lighting, and then stored flat in liquid nitrogen until analysis. Optical density (OD) spectra for total particulate and detrital matter were obtained using a GBC 916 UV/VIS dual beam spectrophotometer equipped with integrating sphere. The OD spectrum of the phytoplankton pigment was obtained as the difference between the OD of the total particulate and detrital components. The optical density scans were converted to absorption spectra by first normalising the scans to zero at 820 nm and then correcting for the path length amplification using the coefficients of Mitchell (1990). The method is described in detail in Clementson *et al*. (2001).

CDOM absorption

Samples for CDOM analysis were stored in the cool and the dark until analysis and were filtered through a 0.2 µm polycarbonate filter (Millipore) immediately prior to analysis which was within 24-48 hours of collection. The CDOM absorbance was measured in a 10 cm path length quartz cell, from 200–900 nm, using the normal cell compartment of a GBC 916 or a GBC Cintra 40 UV/VIS spectrophotometer, with Milli-q water as a reference. Between sample scans, the reference cell was removed from the spectrophotometer to reduce temperature effects in the scans. The CDOM absorption coefficient (m^{-1}) was calculated using the equation

$$a_{CDOM} = 2.3(A(\lambda)/l)$$

where $A(\lambda)$ is the absorbance (normalised to zero at 680 nm) and l is the cell path length in meters.

An exponential function (equation 1) was fitted to all CDOM and detritus spectra

$$a(\lambda) = a_{(350)} .\exp(-S(\lambda -350)) + b \qquad (1)$$

over the wavelength range 350 to 750 nm. A non-linear least-squares technique was used to fit equation 1 to the untransformed data. The inclusion of an offset b allows for any baseline correction. In some samples, particularly samples containing cyanobacterial pigments, pigment extraction can be incomplete, leaving small residual peaks in detritus spectra at the principal chlorophyll absorption bands. To avoid distorting the fitted detritus spectra, data at these wavelengths were omitted when all spectra were fitted.

Total particulate spectra were smoothed using a running box-car filter with width 10 nm, and the fitted detritus spectra subtracted. Subtracting fitted detritus spectra minimised any artefacts due to incomplete extraction of pigments. The resulting phytoplankton spectra were base-corrected by subtracting absorption at 820 nm to obtain $a_{ph}(\lambda)$.

Total Suspended Material

Approximately 2 litres of sample water was filtered through a muffled pre-weighed 47 mm glass fibre filter (Whatman GF/F), under subdued lighting. To remove any salt, the filters were washed with approximately 50 ml of Milli-Q water and then stored flat in a numbered polycarbonate Petri-slide (Millipore) at 4°C. The filter was transferred to a glass Petri dish and dried for 2 hours in a 70°C oven. The filters were cooled and weighed and the process repeated until constant weight was attained.

Appendix 3

NOAA NLSST split algorithm

day
A*T11 + B*Tsfc*(T11-T12) + C*(T11-T12)*(sec0-1) + D

night
E*T11 + F*Tsfc*(T11-T12) + G*(T11-T12)*(sec0-1) + H

Tsfc is derived from the MCSST-split algorithm

day
W*T11 + X*(T11-T12) + Y*(T11-T12)*(sec0-1) + Z

night
P*T11 + Q*(T11-T12) + R*(T11-T12)*(sec0-1) + S

Coefficients from http://140.90.207.25:8080/EBB/ml/nicsst.html
http://noaasis.noaa.gov/NOAASIS/pubs/SST/noaa12sst.asc

NLSST then MCSST coefficients

day =
0.876992 0.083132 0.349877 236.667
0.963563 2.579211 0.242598 263.006

night =
0.888706 0.081646 0.576136 240.229
0.967077 2.384376 0.480788 263.94

Coefficients from http://noaasis.noaa.gov/NOAASIS/pubs/SST/noaa17sst.asc

NLSST then MCSST coefficients

day =
0.936047 0.0838670 0.920848 253.951
0.992818 2.49916 0.915103 271.206

night =
0.938875 0.0864265 0.979108 255.023
1.01015 2.58150 1.00054 276.590

CHAPTER 7

7. SRFME CORE PROJECT THREE

7.1 Integrated Modelling

7.2 Introduction

The overall objective of the SRFME Integrated Modelling Project is:
to provide quantitative descriptions of WA coastal and shelf ecosystems that will assist environmental managers to predict and monitor natural and human-induced change.

In SRFME, we have designed field programs that help us describe the functioning of the WA coastal ecosystems. As the data are interpreted, they enable us to define, first, descriptive models of the ecosystems, and then quantitative models. The quantitative models are mathematical, and take the form of computer codes. In the first instance, the models are compared with reality (data), to test their validity. As we build confidence in the results, they can then be used to help interpret the data, and further our understanding of the ecosystems. In particular, models can be used to fill in gaps in the inevitably sparse data that arise from field programs. The models help us integrate across scales, for example, from Indian Ocean scales down to coastal reefs, and across disciplines, from physics through to ecology.

7.3 Investigators

The first challenge for SRFME was to create a modelling team. Team assembly was most intense in 2003/4, and all positions are now filled, pending one arrival in June 2005. The Perth-based team members, and their primary disciplinary affiliation, are:

Physical oceanography
Ming Feng – large-scale ocean processes
Chris Fandry – shelf-scale dynamics
Graham Symonds – beach and reef dynamics

Biogeochemistry
Jim Greenwood – postdoctoral fellow

Habitat/ecosystems
Phillip England

Software development
Jason Waring
Irshad Nainar
Dirk Slawinski

There are also Hobart-based modellers with SRFME commitment:
Peter Craig (project leader), Karen Wild Allen (biogeochemistry), Nugzar Margvelashvili (sediment dynamics), Uwe Rosebrock (software development), and physical oceanographers Scott Condie and Ken Ridgway.

SRFME modelling has been able to build on, and contribute to, a significant modelling capability already in existence in CSIRO. In particular, we have an *Environmental Modelling Suite* (EMS), which consists of modules for hydrodynamics, sediment dynamics, and water and sediment biogeochemistry. The package was originally written for the Port Phillip Bay Study (Harris *et al*., 1996), and has been refined in many projects since then (e.g. Wild-Allen *et al*., 2005). SRFME benefits from, and shares responsibility for developing and maintaining the code.

Some SRFME modellers are also involved in a concurrent project called BLUElink, which is a partnership between CSIRO, the Bureau of Meteorology, and the Royal Australian Navy. Two products of this project are refinement of the *CSIRO Atlas of Regional Seas* (CARS), which provides oceanographic (physical and biological) climatological data around Australia, and the *BLUElink ReAnalysis* (BRAN), a global physical model, run from 1992 to 2004, with 10 km resolution off the WA coast. These data sets provide valuable insights into climate-scale influences on the shelf and coastal dynamics, in particular as boundary conditions for SRFME modelling.

Climate-change has been identified as one of the major threats of concern to coastal WA. The sensitivity of coastal dynamics to climatic influences is well documented, and probably best known through the relationship of rock lobster settlement to the El Niño cycle (e.g. Pearce and Phillips, 1988). Climate change may have many manifestations, for example through changes in storm frequency and intensity, the El Niño pattern, water temperature, water acidity, and nutrient supply from deep water or land runoff.

A more immediate threat to coastal waters is coastal development. The south-west of WA has one of the two fastest growing populations in Australia. Towns like Mandurah are growing at over 5% per annum, which means population-doubling in 15 years (Western Australian Planning Commission, 2000). Controversies over major coastal development are a fact of life in WA, but much development is incremental. The main impact on inshore waters of coastal population growth is increased nutrient levels (e.g. Australian State of the Environment Committee, 2001; GESAMP, 1990). WA has seen the impact of eutrophication and algal blooms in sheltered waters such as Cockburn Sound and the Peel Harvey estuary (e.g. DEP, 1996). Nutrients, and other contaminants, find their way into the marine environment through outfalls and drains, in land runoff and groundwater, and on airborne particles. Coastal development also brings physical disruption of ecosystems with activities such as port construction and dredging.

The most significant focus of SRFME is on coastal benthic habitat. The explicit assumption here is that the health of the benthos is indicative of the health of higher, and mobile, trophic levels that depend on it. Benthic habitat is also integrative, in the sense that it responds on longer, and more observable, time-scales than primary productivity in the water column.

However, the habitat models are the least established of the SRFME modelling suite. In general, marine models are less mature, and more empirical, as they become less physical and more biological. Hydrodynamic models require little tuning, sediment dynamics more, biogeochemical models (which describe water-column productivity) much more, and habitat models are still in early development stage.

We have consciously concentrated on process models in SRFME, that is, on models which describe the links between cause and effect. Process models contrast with correlative models, which rely on observed relationships (e.g. between the Southern Oscillation Index and lobster puerilis settlement), but do not explain the mechanisms for the link. Most models are in fact a combination of the two. In general, the more process-based a model, the more robust it is likely to be. That is, a model based on understanding is more likely to be valid when applied to circumstances beyond those that have been observed.

Ultimately, the models developed in SRFME are meant for use in circumstances beyond the observable. They are aimed to assist State managers with "what-if" scenarios. What if this town doubles in size, what if a port is built here, or what if climate change doubles the frequency of severe storms?

Realistically, SRFME will be of most benefit to decision-makers if the results are readily accessible. As part of the modelling project, we are developing tools that will enable managers to explore data from both models and the field, and to compare data sets. Some of these are already available. For example, the Argo website allows access to data from Argo profiling floats (measuring temperature and salinity) in deeper waters off WA. The most important tool is the *Data Interrogation and Visualisation Environment* (DIVE), which will be provided with SRFME data on disk. It is being released in prototype form with this report.

The modelling project is divided into 6 project areas:

- large-scale ocean processes
- hydrodynamics
- sediment dynamics
- biogeochemistry
- ecosystems
- management assessment

These areas are discussed individually in the following sections. However, it is important to remember that these are distinctions of convenience. SRFME's strength lies in its integration: across observation, data analysis and modelling, across disciplines, and across scales, from climate to surface waves.

7.4 Large-scale ocean processes (Ming Feng)

The objective in the *large-scale ocean processes* area is:
to characterise and understand large-scale and mesoscale variability in the Leeuwin Current that affect the physical and ecological environments off the WA coast.

Western Australia has a long coastline exposed to the Indian Ocean. The connection from the open ocean to the shoreline is primarily through the Leeuwin Current, the warm current that flows southward along the shelf break, exerting a controlling influence on marine life and Western Australia's weather. In investigating large-scale ocean processes, we have worked from the scale of the Indian Ocean itself, down through the Leeuwin Current to its eddies, establishing the dominant time scales, and interactions between length scales.

Over the time scales of multiple decades, necessary to investigate climate change, we are reliant on sporadic ship observations and coastal observations. The Fremantle tide gauge, operated since the late 1800s, provides one of the longest marine records in Australia. As shown in Fig. 173, Fremantle sea level rose by almost 0.2 m over the 20th century (Feng *et al.*, 2004), and its multi-decadal variability is largely determined by the Pacific Decadal Oscillation (Fig. 173e and f).

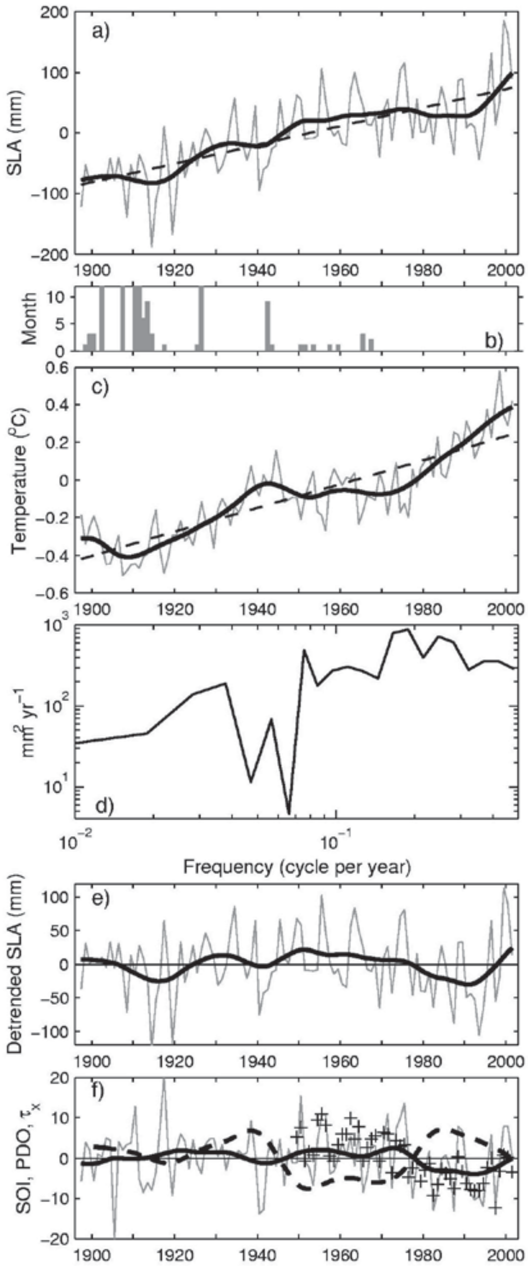


Figure173: (a) Annual mean Fremantle sea level anomaly, (b) numbers of months with missing sea level data, (c) global average surface temperature, (d) power spectrum of the Fremantle sea level anomaly, (e) annual mean detrended sea level anomaly, and (f) annual mean Southern Oscillation Index and average easterly wind stress anomaly at the equatorial Pacific (crosses, unit: 10^{-3} Nm^{-2}). The heavy lines in (a), (c), (e), and (f) are smoothed time series using a 19-year Hanning filter. The dashed lines in (a) and (c) show the linear trends, and the dashed line in (f) is the smoothed Pacific Decadal Oscillation index (from Feng *et al.*, 2004).

On shorter time scales, our ability to study large ocean dynamics has improved dramatically over the last 2 decades with the advent of satellite-mounted sensors. In the mid-1980s, sea-surface temperature (SST) maps became available. More importantly, in 1992, data from the first operational altimeter became available. The altimeter records sea-surface height (SSH), which can be considered as a measure of pressure, analogous to atmospheric pressure shown on synoptic weather charts. These data are analysed in conjunction with historic and contemporary data collected from ships to provide remarkable information on the ocean circulation.

Now, too, the world's oceans are dotted with autonomous Argo floats that profile the top 2000 m for salinity and temperature every 10 days. Several of these floats have been deployed off WA, with assistance from SRFME scientists, both in commissioning the buoys, and in developing the website for data display (see Section 7.10).

It has been known for many years that the Leeuwin Current and Western Australia's weather responds to the El Niño cycle, which is predominantly a Pacific Ocean phenomenon. In the early 1990s, an Indian Ocean oscillation, called "the Indian Ocean dipole", was identified, with a dominant period of around 2 years. The oscillation is clear in the sea surface heights of Fig 174, showing a low off the Indonesian coastline, and a high in the west, just south of the equator. In Feng and Meyers (2003), the temporal evolution of the Indian Ocean Dipole is described using satellite altimetry together with temperature profiles measured from ships of opportunity. Although the Indian Ocean dipole can be triggered by external forcing such as Pacific ENSO, the subsequent evolution is determined by the coupled air-sea interaction in the Indian Ocean. Possible influences of the Indian Ocean Dipole on climate in SW WA, as well as regional oceanography, in additional to ENSO influences, are being investigated.

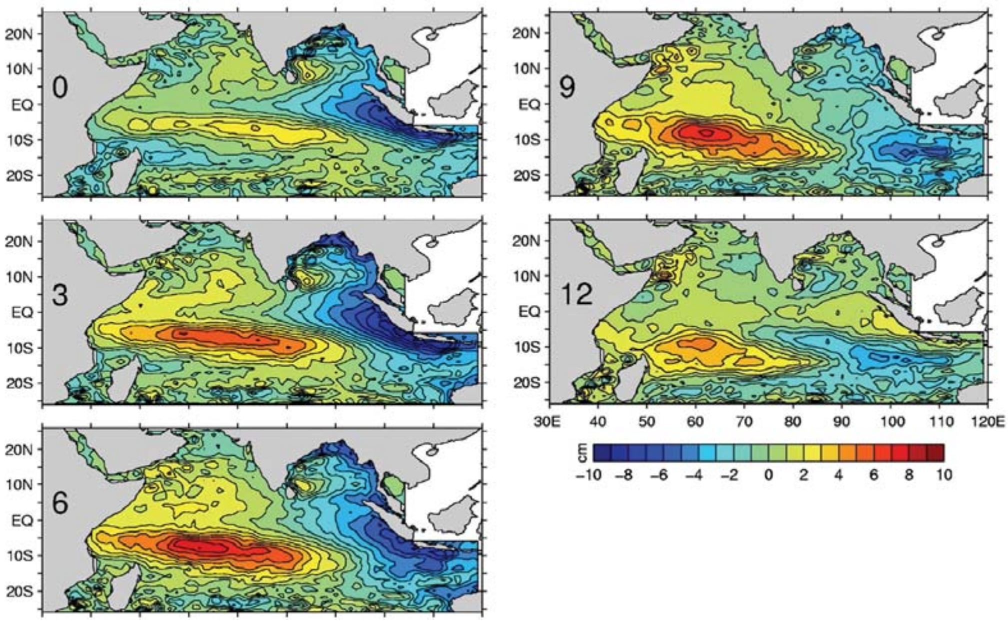


Figure 174: Extended empirical orthogonal function of satellite altimetry sea level anomalies in the Indian Ocean. The numbers in different panels denote the time lag in months (from Feng and Meyers, 2003).

Under SRFME, the high-resolution climatology in the CSIRO Atlas of Regional Seas (CARS) has been improved for the Western Australian region. Combining this with satellite altimeter and temperature data, Ridgway and Condie (2004) identified the continuity of the Leeuwin Current with the South Australian Current and the Zeehan Current off the western Tasmanian coast during austral winter (Fig 175). This system is described as “the longest coastal current in the world”.

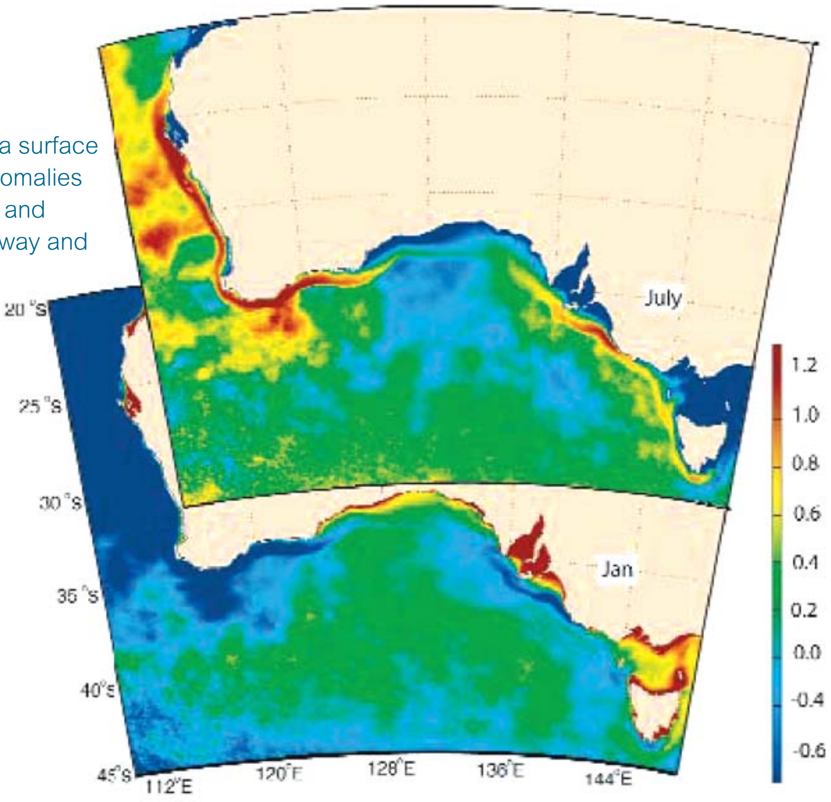


Figure 175: Sea surface temperature anomalies during January and July (from Ridgway and Condie, 2004).

The monthly climatology in CARS confirms that the Leeuwin Current is stronger during austral winter than summer, which is consistent with Fremantle sea-level variations. Generally speaking, Fremantle sea level is 3.4 cm lower than the climatological mean in an El Niño year, while it is 5.6 cm higher in a La Niña year (Fig. 176). A ship-of-opportunity upper-ocean temperature climatology has been extended to describe ENSO scenarios. Offshore sea level (dynamic height relative to 300 m) is closely related to the interannual variation of the Fremantle sea level, indicating that the Leeuwin Current pressure head drives the interannual sea-level variation at Fremantle. There is a linear relationship between the annual Fremantle sea level and the volume transport of the Leeuwin Current along 32°S, with 0.1 m in sea level corresponding to about 1.3x10^6 m^3s^{-1} in flow-rate (Feng *et al.*, 2003).

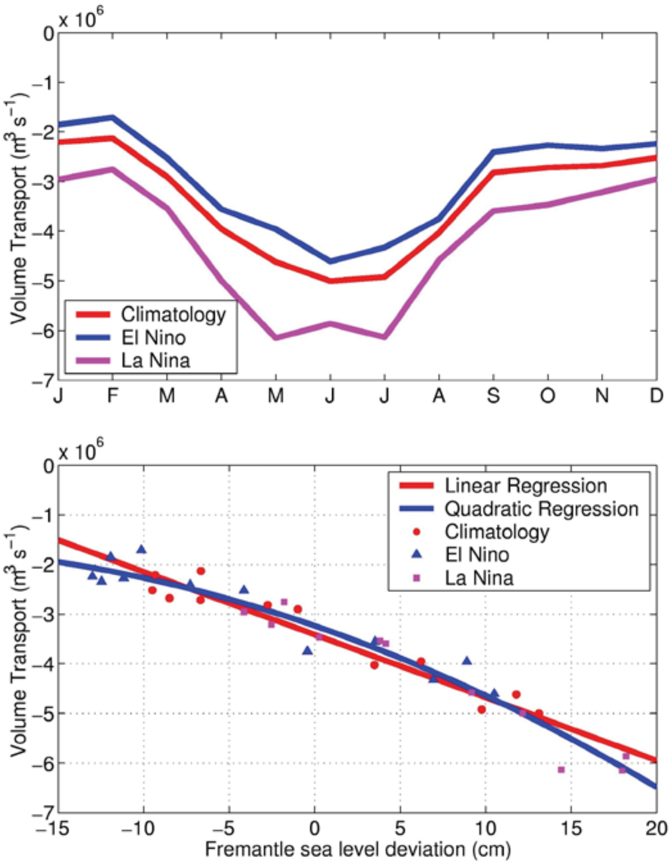


Figure 176: Monthly climatology, El Niño and La Niña scenarios of the Leeuwin Current volume transport and their quasi-linear relationship with Fremantle sea level (from Feng *et al.*, 2003).

Since the first sea-surface temperature images of the Leeuwin Current became available, we have consistently observed warm and cold eddies, of radii up to about 100 km, particularly on the offshore edge of the continental shelf, where the fast moving water meets the deeper, slower Indian Ocean. The altimeter allows us to estimate the energy in these eddies. As shown in Figure 177, the kinetic energy (indicated by the square of the eddy velocity) peaks in May-October at about 0.12 m^2s^{-2} (Feng *et al.*, 2005b). The eddies play an important role in carrying heat, and other quantities like nutrients, across the shelf. The offshore heat flux is estimated as $5x10^{12}$ W.

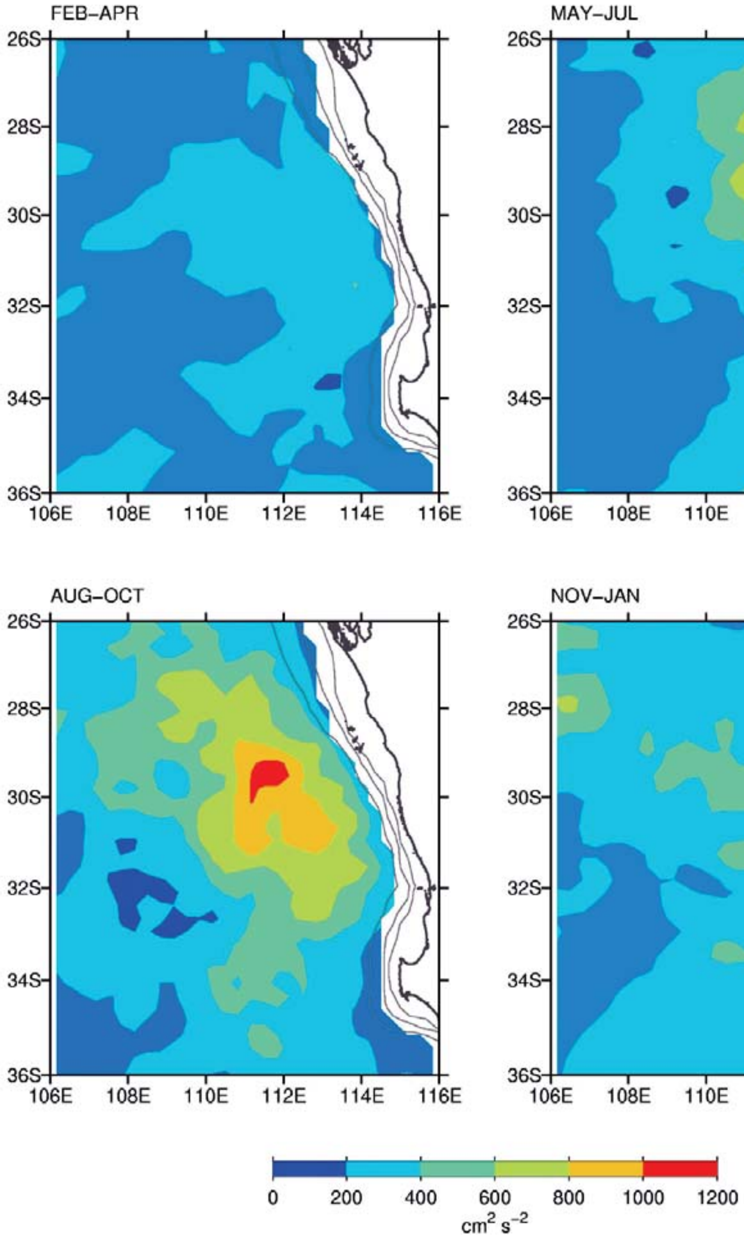


Figure 177: Seasonal evolution of the surface eddy kinetic energy off SW Western Australia inferred from satellite altimeter data (from Feng *et al*., 2005).

In 2003, the satellite data (altimetry, temperature, and ocean colour) were complemented by measurements taken from the RV *Southern Surveyor* in a cruise specifically designed to study the eddy dynamics (Feng *et al*., 2005c). Both a warm (anticyclonic) and a cold (cyclonic) eddy were sampled. The warm eddy was more energetic, and had relatively high biomass (Fig. 178). It contained a water volume equivalent to 19 days of Leeuwin Current flow.

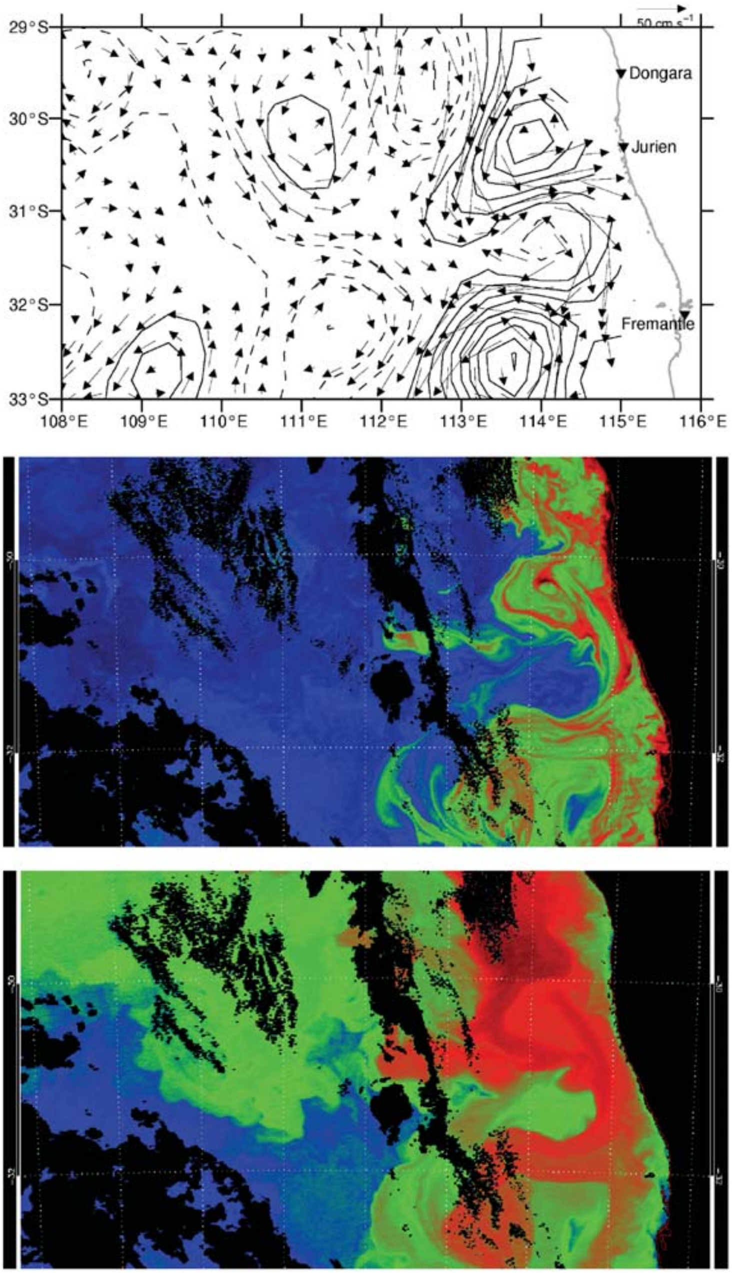


Figure 178: Snapshot of sea surface elevation (geostrophic current), temperature, and chlorophyll *a* concentration on 26 June 2003 (from Feng *et al*., 2005).

Concurrent with our increased capacity to measure the ocean, computer advances now allow large-scale, high-resolution modelling of the ocean circulation. The models blend in ("assimilate") data from satellites and floats to improve their accuracy. As noted in the previous section, CSIRO's *BLUElink* modelling has just (in May 2005) completed a run from 1992 to 2004 that provides a 3-dimensional picture of the Indian Ocean, with 10-km resolution along the WA coast. Within SRFME, we will be working (a) to validate the performance of the model, and then (b) to use it to provide more quantitative information, particularly on subsurface dynamics, which can only be inferred from satellite data. Analysis of the model results, combined with existing knowledge, will allow better description of the nature of the long and cross-shore transport in the Leeuwin Current and its eddies. It will also allow us to extract local dynamics, such as wind-driven upwelling, which tend to be concealed at the surface by the Leeuwin Current.

7.5 Hydrodynamics (Chris Fandry)

The large-scale ocean processes described in the previous section occur at scales from the Indian Ocean basin down to the Leeuwin Current, and on time-scales from seasons to centuries. Under *hydrodynamic modelling*, we are focused on scales from the Leeuwin Current inshore. The objective of the *hydrodynamic modelling* area is:
to describe the physical connectivity between offshore and inshore environments, and longshore environments, with particular view to nutrient supply and recruitment of coastal marine animals and plants.

The work has both a modelling and field component.

Obviously, the Leeuwin Current is expected to have a significant effect on the shelf and inshore waters of SWWA. We have noted in the previous section, for example, the relationship between the strength of the current and sea-level at Fremantle. The eddies will be a dominant, if not the dominant, mechanism for cross-shore transport of both physical and biological properties. However, as we move closer inshore, we expect tides and the local wind to be more effective in forcing currents.

In the past, modelling the shelf region of SWWA has been a significant challenge, because of the Leeuwin Current. The current is generated by the circulation of both the Indian and Pacific Ocean, and cannot be simply captured by a local model. The availability of global model data (from *BLUElink*, noted in the previous two sections) is a major advance. Now, a local model of the SW shelf region can be “nested” inside the global model, to capture the Leeuwin dynamics through the boundary conditions.

A three-dimensional, hydrodynamic model (called SHOC, for *Sparse Hydrodynamic Ocean Code*, see Herzfeld *et al*., 2005, Herzfeld and Waring, 2005) is part of the CSIRO *Environmental Modelling Suite* (see Section 7.3). It has been set up to investigate the currents, temperature and salinity (T and S) fields in the SRFME region off Western Australia. SHOC is a relatively conventional, primitive-equation model, that has undergone extensive development over the last decade, with application to a range of estuarine, coastal and shelf systems, including the Fitzroy River (Herzfeld *et al*., 2003), Port Phillip Bay (Walker, 1999), the Gulf of Carpentaria (Condie *et al*., 1999) and the North West Shelf, (Condie *et al*., 2003).

Over the past two years, the model has been extensively tested for its performance in realistically reproducing T and S, and current fields of the Leeuwin Current and its associated eddies in the SRFME region. The tests included different domain sizes, shapes and projections, horizontal and vertical resolutions, open-boundary conditions, forcings and horizontal and vertical mixing schemes. Several critical factors determined which version of the model was finally selected. Reproducing realistic annual cycles of T and S was one. Another was that the model simulated a Leeuwin current, at the right time of year and of the right magnitude. The horizontal resolution had to be sufficiently fine to resolve the Leeuwin Current and its eddies, but not so fine that model run-time was excessive (defined here to be more than a 3 days for a one year simulation).

During testing, the model was nested inside a preliminary version (described as “the spinup”) of the *BLUElink* output. The test year was chosen as 1999, which was the final year of the preliminary global runs. The selected model domain is the rectangular region shown in Fig. 179, which is identical to the horizontal *BLUElink* grid in this region. The grid resolution is 10km in the horizontal and in the vertical there are 30 layers with thicknesses gradually increasing from 3m near the surface to 260m at the maximum depth of 2000m. The model is initialised at 0000h on 1 Jan 1999 with sea-levels and T and S fields prescribed from the *BLUElink* output, and currents set to zero.

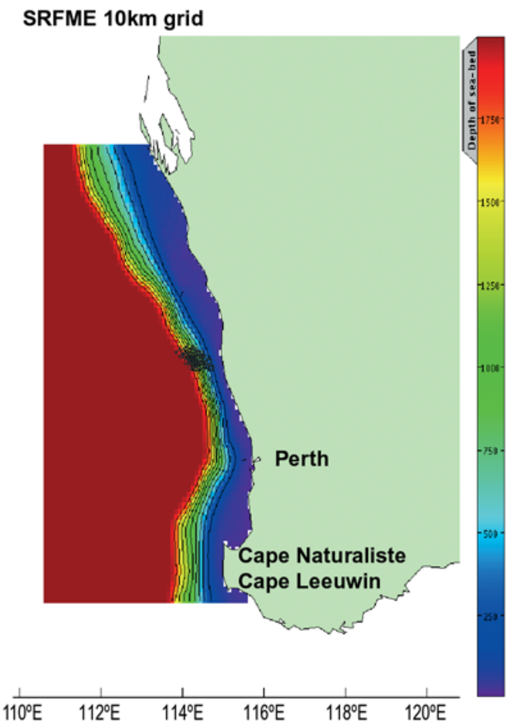


Figure 179: SRFME Model domain and bathymetry with maximum depth of 2000m.

Forcing at the ocean surface is by wind-stress and heatflux from the ECMWF (European Centre for Medium-Range Weather Forecasting) database of atmospheric fields. At the open boundaries, sea-level, T and S are prescribed from *BLUElink*, while the velocities are constrained to simplified, dynamically consistent, values. The three-dimensional T and S fields are also weakly relaxed to *BLUElink* fields, with a 180-day time-scale, throughout the model run. Further technical details of the model are described in Herzfeld *et al*. (2005).

Although the local model is being run at the same horizontal resolution as, and forced at the boundaries by, the global model, it is expected to give substantially improved results because it has:

- more sophisticated mixing ("turbulence closure") schemes
- higher-resolution bathymetry
- tides
- capacity for higher-resolution meteorological forcing.

Importantly, the local model can be rerun at will, to test different setup configurations and scenarios. The local model is also coupled to sediment and biogeochemical modules, within the *Environmental Modelling Suite*.

At this stage, the model has been run for the full 1999 year, with hourly outputs of T, S, sea-level and currents archived at all grid points. As an example of the output, Fig. 180 shows the surface currents and temperature distribution on 21 April 1999. Clearly evident are a strong, well-defined meandering Leeuwin Current with a maximum speed of 0.7m/s, and several cyclonic and anticyclonic eddies. The annual cycle of temperature at a nearshore site off Perth shows a maximum of just less than 24ºC in early March, and minimum of 17ºC in mid August. These values compare well with the climatological cycle near this site (Pearce and Pattiaratchi, 1999).

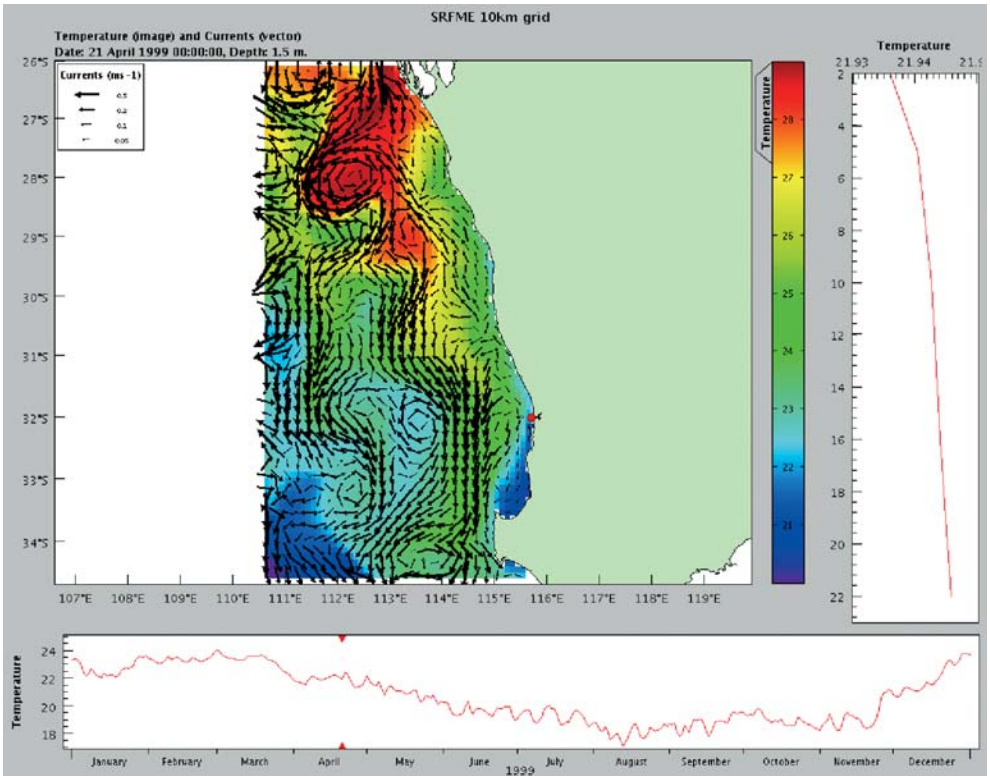


Figure 180: Surface currents and temperature fields on 21 April 1999. Also shown are the temperature profile and time series at the location marked with a red dot just offshore Perth.

The salinity structure on 7 July 1999 is shown in Fig. 181. It is characteristic of the observed salinity in winter (Cresswell, 1991), showing a southward tongue of low saline water from the surface to about 200m deep at 32ºS. A salinity maximum occurs at around 250m depth. The tongue of low saline water is the Leeuwin Current.

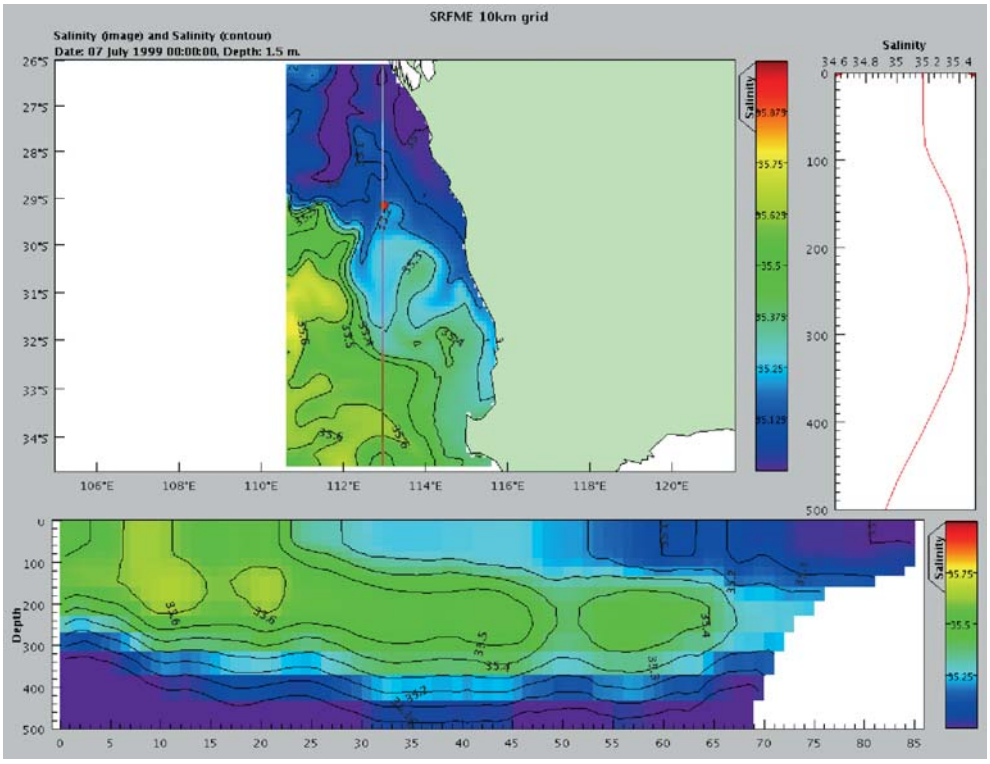


Figure 181: Salinity structure on 7 July 1999, including a section at 113º E, showing the tongue of low salinity Leeuwin Current water extending southwards to 32º S. A salinity profile is shown at the location marked by the red dot.

By 1 December 1999, the seasonal southerly winds in the SW of WA influence the circulation pattern. They have generated a well-defined, narrow Capes Current flowing northwards between the two capes, which broadens as it flows further northwards (Fig. 182). The presence of this wind-driven northward current during summer has been reported in several studies including Cresswell *et al*., (1989) and Pearce and Pattiaratchi (1999).

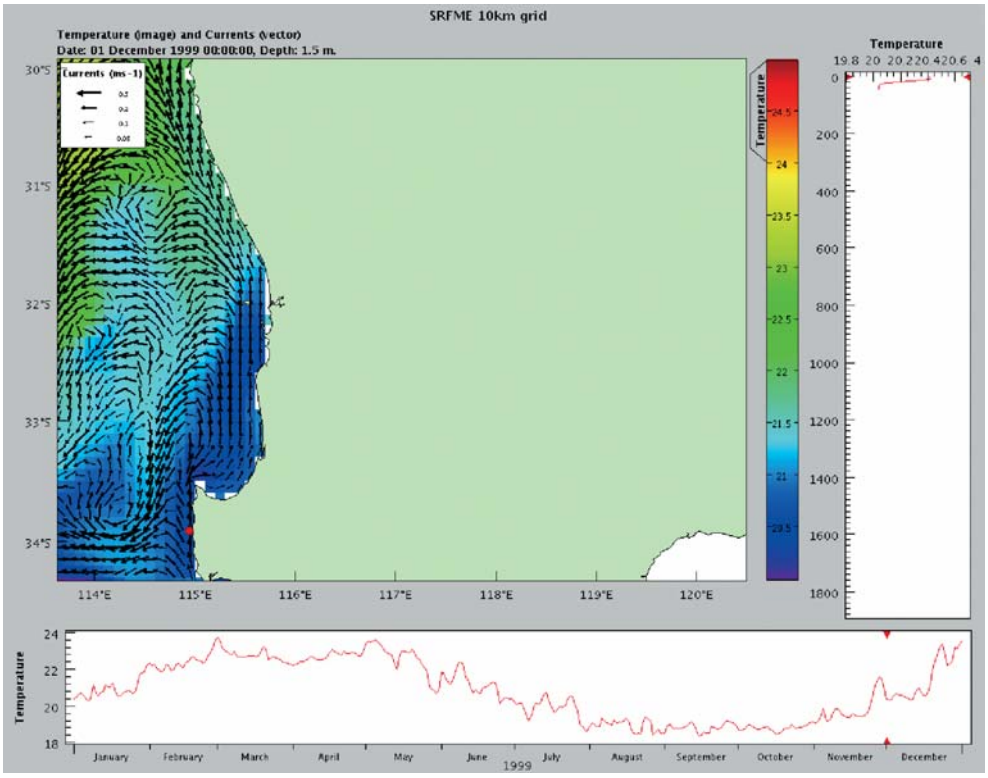


Figure 182: Surface circulation pattern and temperature field on 1 December 1991 showing the Capes current flowing northwards along the coast from Cape Leeuwin to Cape Naturaliste and further northwards beyond 30º S.

At the scale of the Leeuwin Current, the model can be tested against large-scale data, particularly those from satellites, as discussed in Section 7.4. However, these data do not have high enough accuracy and resolution in the shallower waters inshore of the mid-shelf.

To provide information on the inshore dynamics, three moorings have been deployed for July 2004 to July 2005 along the “Two Rocks Transect”, at sites, A, B and C, in water depths of 20, 40 and 100 m, respectively (Fig. 183). Moored instrumentation measures pressure, currents, CTD (conductivity, temperature and depth), oxygen, PAR (photosynthetically active radiation) and fluorescence. Ultimately, the data will be used to test the hydrodynamic model and to provide the basis for conceptual dynamical models. At the time of writing, data for the 6 months period July 2004 to January 2005 have been retrieved and partially analysed.

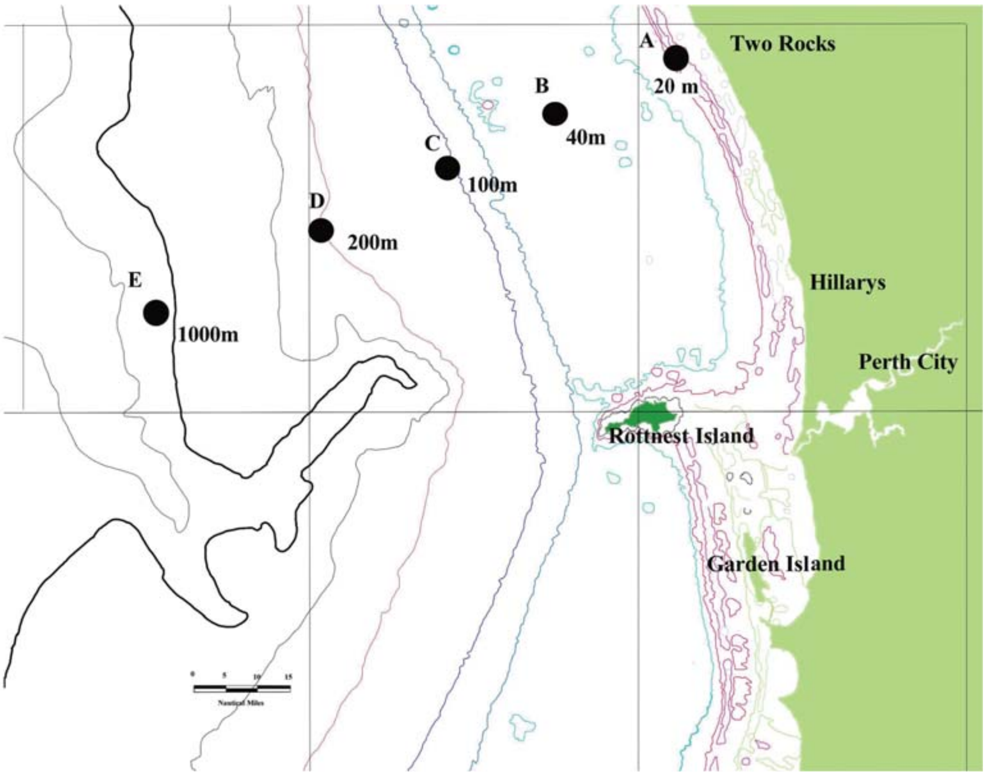


Figure 183: Location of instrument moorings at stations A, B and C.

As anticipated, currents appear to be predominantly wind-driven during the winter period at the inshore station A. Currents at 5 m and 10 m below the surface are almost equal and are well correlated with the wind (Fig. 184). Current peaks occur during storms, with the dominant event on 25 August 2004. The maximum current speed was 0.87 ms^{-1}, at 21:45 on 25 August (masked in Fig. 7.12 by the 12-hour averaging). The maximum current lagged the maximum wind speed of 13.5 ms^{-1} by some 18 hours.

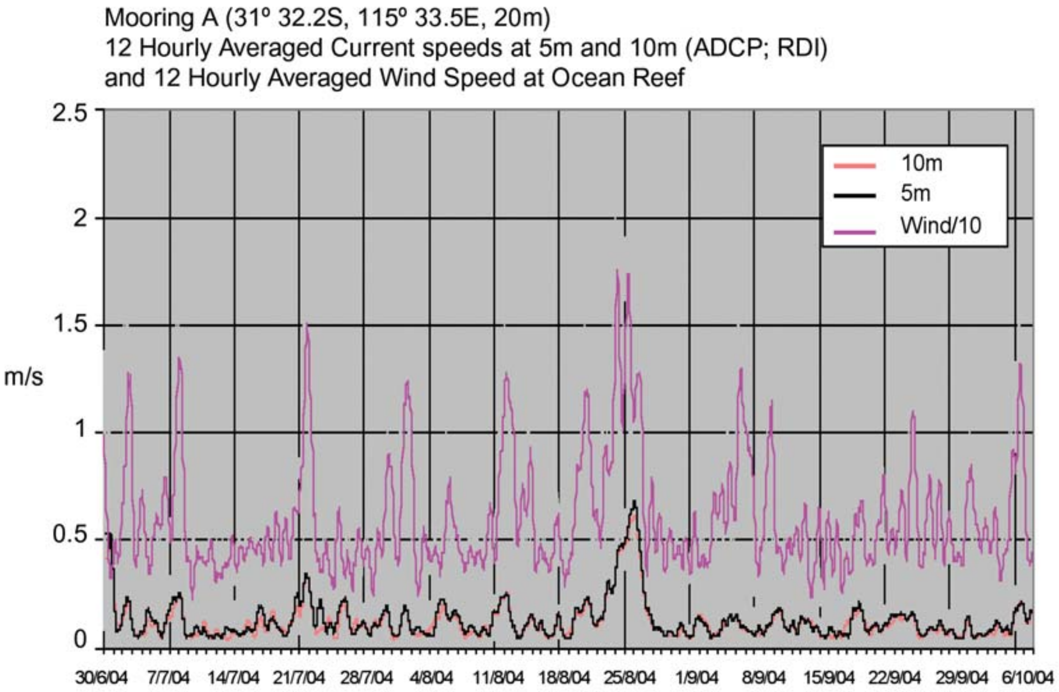


Figure 184: Comparison of 12-hourly averaged current speeds at 5m and 10m depth at Station A with 12 hourly averaged wind speed/10 measured at the nearby coastal site Ocean Reef.

The temperature data at Station A show that, during most of the winter, the water is well mixed below 10 m (Fig. 185). At site C, deeper temperatures are slightly cooler (usually by less than 0.5 ºC), but during storm periods the waters are well mixed from 10 m down to 100 m (Fig. 186).

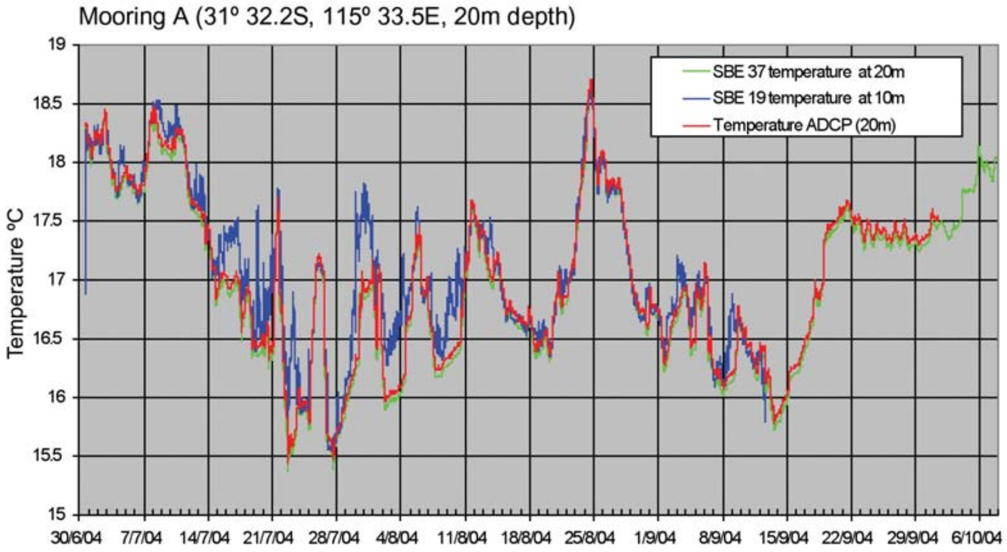


Figure 185: Temperatures at Station A measured by 3 different instruments, 2 at the bottom (20m) and one at 10m.

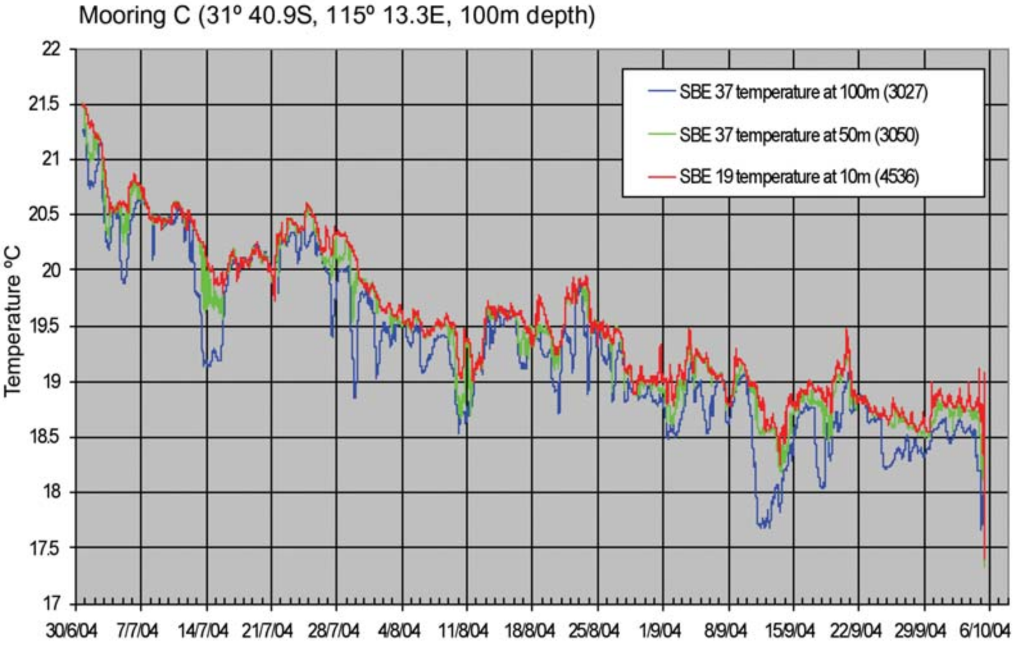


Figure 186: Temperatures at Station C at depths 10m, 50m and 100m.

Waters are also well mixed during the summer at station A, and there is a gradual warming of 4.5 ºC over the 3-month period from October to December (Fig. 187), similar to the climatological increase (Pearce and Pattiaratchi,1999). Also of note, temperatures offshore are higher than those inshore during winter because of the Leeuwin Current. Fig. 188 shows temperatures some 2 ºC warmer at Station B than at Station A, and a further 1 ºC warmer at Station C. However, local storms can cause strong horizontal and vertical mixing: this is especially evident during the event of 25 August, when temperature increased by over 2 ºC at Station A as inshore waters mixed with warmer offshore waters.

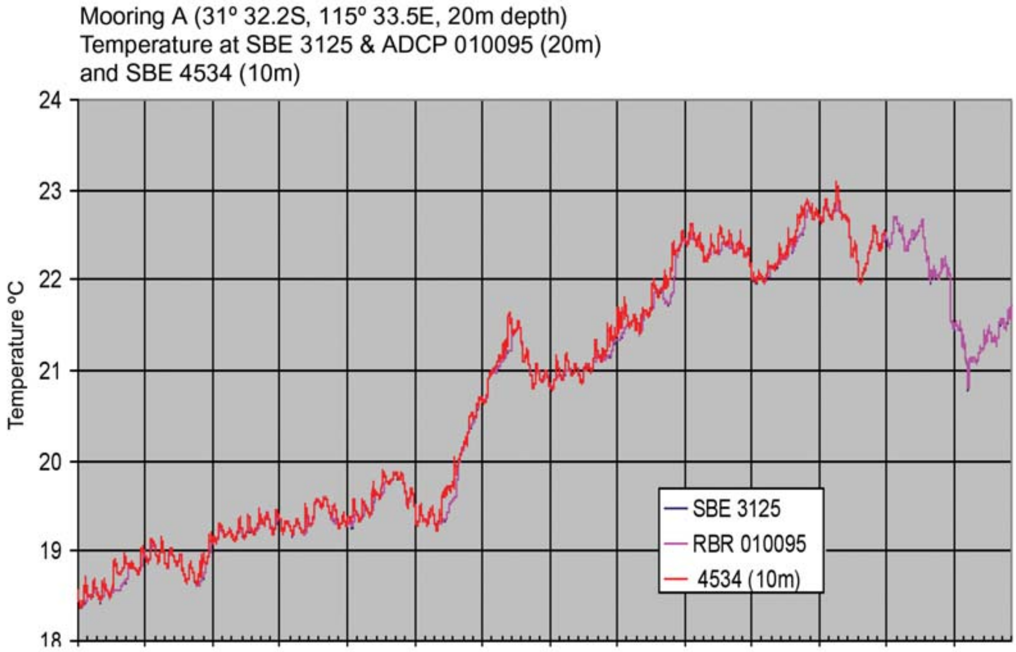


Figure 187: Temperatures at Station A measured by 3 instruments at the bottom (20m) and 10m during the summer period.

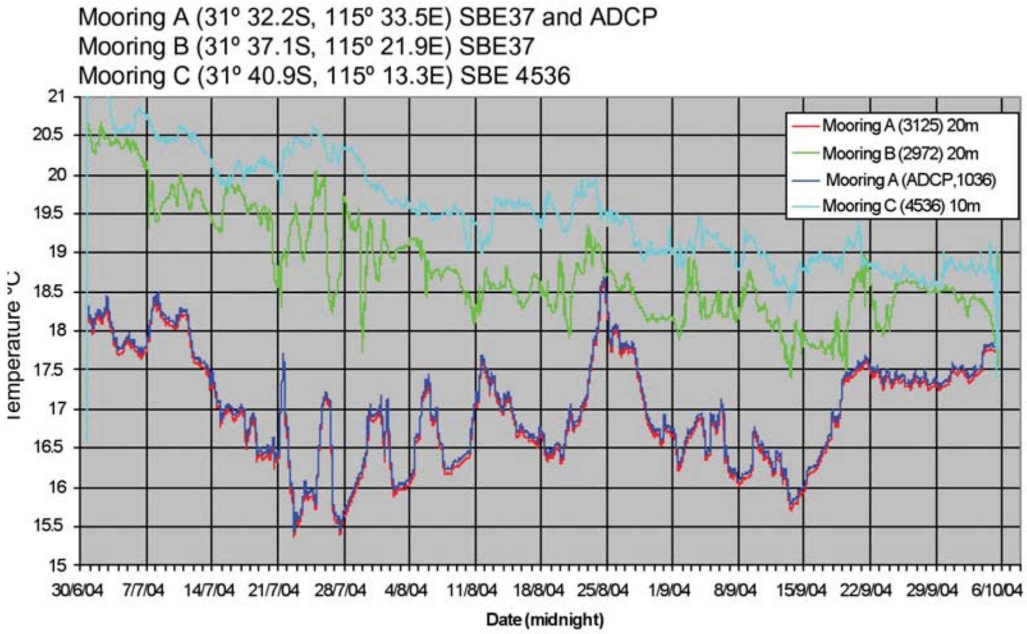


Figure 188: Temperatures at Stations A and B at 20m depth and at Station C at 10m depth.

As an item of curiosity, the "Boxing Day tsunami" was captured by the tide gauge at Station A. A sharp rise in pressure of 0.3 db, equivalent to a 0.3 m rise in sea-level, occurred at about 1500 on 26 December 2004 (Fig. 189). Sea-level oscillations with a period of about 1 hour persisted for another two days. This is typical of the observed effect of the tsunami at other places in the world.

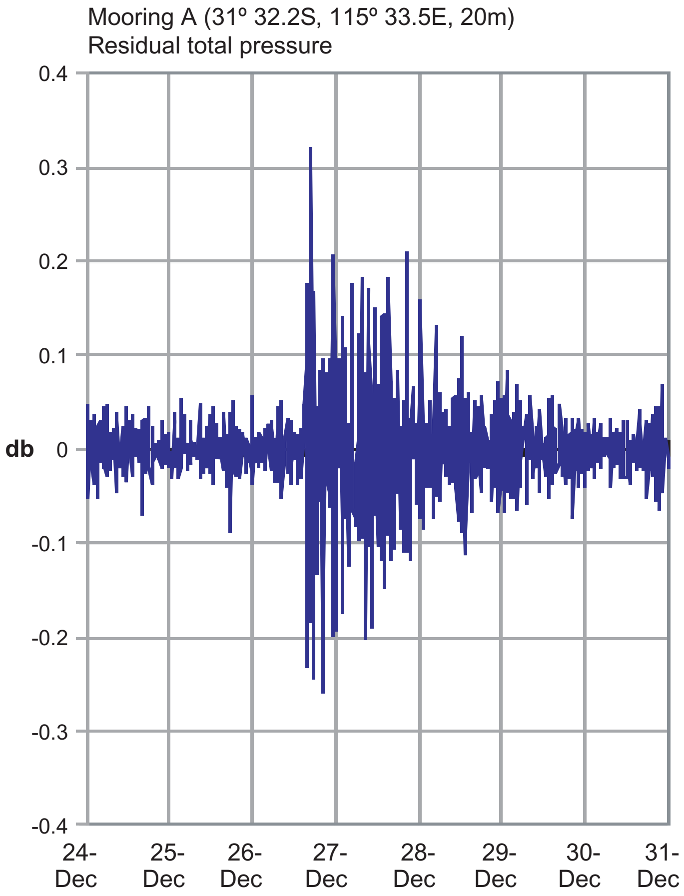


Figure 189: Residual pressure measured at Station A during the period of influence by the "Boxing Day" tsunami in 2004.

While the model SHOC has been applied in many coastal applications similar to SW WA, it has yet to be tested against the mooring data from Stations A, B and C. Further, while it is giving qualitatively acceptable results offshore for the Leeuwin Current and its eddies, tests are now underway to compare its performance against data from the 2003 *Southern Surveyor* voyages. These comparisons can now take advantage of the BLUElink global model archive.

When the hydrodynamic model is coupled to the biogeochemistry, the runtime increases by a factor of 8. For quick turnaround, the coupled model is already being run in 1-d form, to represent individual stations, and 2-d, representing a "slice" across the shelf. These applications are described in Section 7.7. We hope to derive a simplified, but still realistic, version of the model for the inshore region that is the focus of the benthic-ecology studies. A simplified numerical model would not only be faster, but would also justify simpler conceptual models of the inshore dynamics.

7.6 Sediment dynamics (Nugzar Margvelashvili)

Sediment dynamics are integral to the health of inshore communities. Sediments are suspended from the seabed by currents and waves, and may travel long distances before resettling. Suspended sediment may exclude light from, or even smother, benthic species. Many naturally occurring and introduced chemicals, including some nutrients, are hydrophobic, attach themselves to particles, and travel with them. Thus, the objective of the *sediment modelling* is:
by quantifying sediment mobility at the SRFME study sites, to assess (a) the role of sediments in biochemical transport, (b) the role of waves and sediments in biophysical processes, and (c) actual or potential change in sediment dynamics caused by human intervention, particularly dredging.

A sediment dynamics module is part of the *Environmental Modelling Suite*. It is documented (Margvelashvili, 2002) and, like SHOC (Section 7.5), has been developed and refined in applications around the Australian coastline including the Ord River (Parslow *et al*., 2003), the Fitzroy Estuary, Queensland, (Margvelashvili *et al*., 2003) and the North West Shelf (Margvelashvili *et al*., 2004). Some of these applications have been concurrent with, and of obvious mutual benefit to, SRFME.

The processes described by the sediment model are amongst the most complex and least understood in the EMS. These processes include: flocculation and settling of fine sediment, boundary-layer turbulence over a movable sea-bed, dynamics of seabed ripples, transport of mixtures of fine and coarse particles, and the role of biota. Further, sediments vary widely in their physical properties, so that studies done in one area or on one sediment type are not necessarily relevant to another area or type. Hence the model requires calibration against field data to determine empirical, site-specific parameters such as the critical shear-stress for sediment resuspension and deposition, the settling velocity of fine particles, bottom roughness, and the thickness of active sediment layer. The model also requires, as input data, the spatial distribution of sediments, by size particularly, on the seabed over the whole modelled region.

As part of SRFME, historic sediment data for the SWWA region have been collected, processed and analysed. The data include: fresh-water discharge and suspended sediment concentrations for major rivers discharging on the SW shelf (supplied by the WA Department of Environment); seabed characteristics on the shelf (for example, sand/mud/gravel/rock distribution maps) (Jenkins *et al*., 2003); suspended sediment concentrations on the shelf (Rosich *et al*., 1994); and other sediment-related data collated from open literature sources (e.g. Hodgkin and Hesp, 1998; Frances *et al*., 2001).

These accumulated data support the generally accepted view that river flows contribute little to the sediments on the SW shelf. The main sources of contemporary sediments for the coastal environment are likely to be associated with bioproduction in sea-grass meadows, reef erosion in the offshore regions, and erosion of cliffs and sandy shorelines (Hodgkin and Hesp, 1998).

Data from Jenkins *et al*. (2003) for sea-bed texture and suspended sediment characteristics were used to initialise the sediment model runs. Meanwhile, data from the SRFME moorings (see Section 7.5) have been processed and analysed in order to calibrate a 1-d sediment transport model.

The sediment model is fully coupled to the 3-d hydrodynamics and links seabed to water column by simulating bottom exchanges of particulate and dissolved materials. It simulates resuspension and deposition as well as bioirrigation and bioturbation, and provides the physical setting for simulating coupled pelagic and benthic biogeochemistry (Section 7.7). The coupled modelling system is diagrammatically represented in Fig. 190.

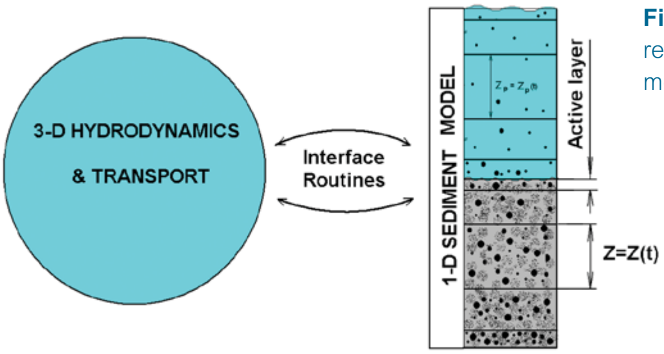


Figure 190: Diagrammatic representation of the sediment modelling module

Thus far, full 3-d simulations of the sediment transport on the shelf have been limited to preliminary model runs over the SW shelf and Jurien Bay. For Jurien Bay, the hydrodynamic modelling was accompanied by simulation of surface waves using the "third-generation" wave model SWAN (Ris *et al*., 1994; see also Section 7.8)

Figures 191a and b show light radiance and attenuation, respectively, for the whole SW region, as measured from the SeaWIFS satellite, averaged over the years 1988 to 2003. The two images show similar patterns that may be taken as representative of the suspended material in the water over the period. For comparison, Fig. 191c shows modelled suspended sediment after a 3-month simulation driven by mean wind and wave conditions. This is clearly a highly qualitative comparison, but the similarity between the patterns of sediment behaviour in the data and the model is very encouraging.

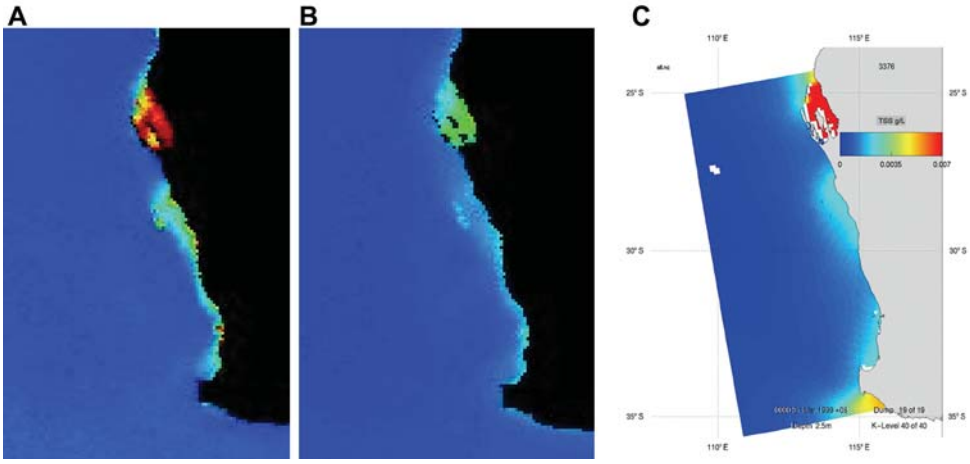


Figure 191: (a) Radiance and (b) diffuse attenuation at 555 nm (SeaWiFS satellite, spring 1998-2003), and (c) simulated concentration of suspended sediments after 3 months of the model run.

At a much smaller scale, Fig. 192 shows model results for Jurien Bay. The modelling domain is 50 km wide and 90 km long. It has 1 km horizontal resolution and 11 ("sigma") layers in the vertical. The model has idealised forcing in the form of constant westerly winds, and has no tides or stratification. Sediments are represented only by sand particles. Resuspension of sediment is driven by bottom friction associated with the combined action of waves and currents. The SWAN model for the waves incorporates wind-wave generation and propagation, as well as dissipation of the wave energy due to bottom friction, wave-breaking and white-capping. This run is for demonstration purposes only. As yet, there are no data with which to verify the model, and scenarios have yet to be established with the benthic ecology team.

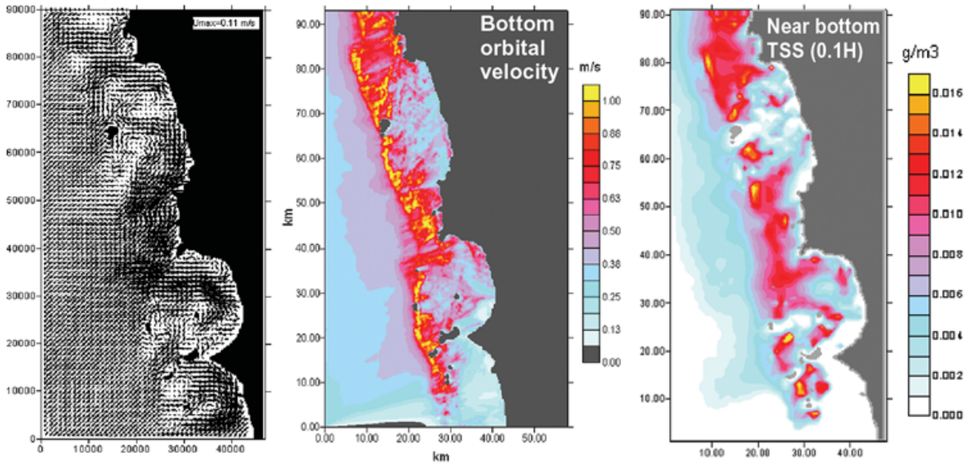


Figure 192: Near bottom currents, wave orbital velocities, and total suspended solids in Jurien Bay

By far the best data thus far for testing the model come from the Station A mooring (see Section 7.5 and Fig. 183). This mooring was equipped with a pressure gauge sampling in bursts at 2 Hz. The wave heights measured by the gauge can be converted to bottom velocities by linear wave theory. Figure 193 shows sample wave data from the first deployment.

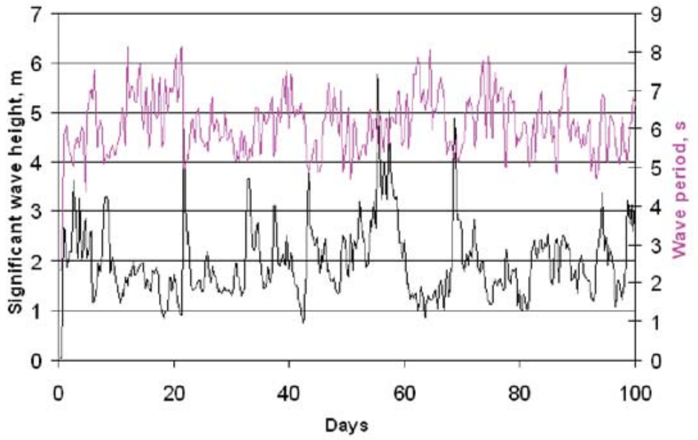


Figure 193: Significant wave-height and wave period (deployment site A; July-October 2004).

The mooring also had an acoustic Doppler current profiler (ADCP). An ADCP primarily measures profiles, over the water depth, of horizontal current velocities (e.g. Fig. 194). However, the concentration of suspended material can also be inferred from the strength of the backscatter signal (Thorne and Hanes, 2002; Holdaway *et al.*, 1999; see also Margvelashvili and Slawinski, 2004). Figure 195 shows the backscatter signal from 1.7 m above the seabed, and the 2 data lines on Fig. 196 show the inferred suspended sediment concentration. As can be seen from Fig. 196, the range of uncertainty in the concentration estimates covers a factor of about 3. The 25 August storm, referred to in Section 7.5, is obvious in the wave, velocity and concentration time-series of Figs 193 to 196.

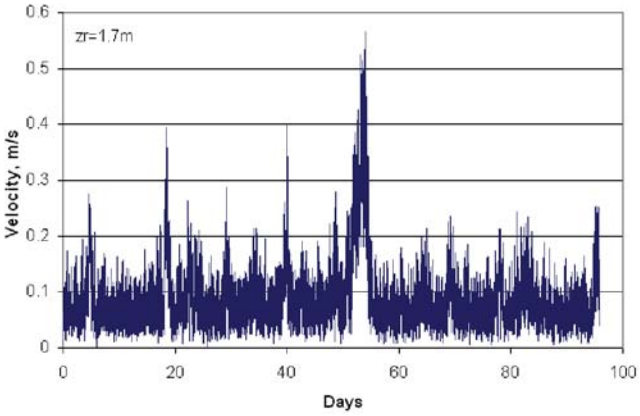


Figure 194: ADCP velocity measurements at deployment site A; July-October 2004; ~1.7 m above the bottom

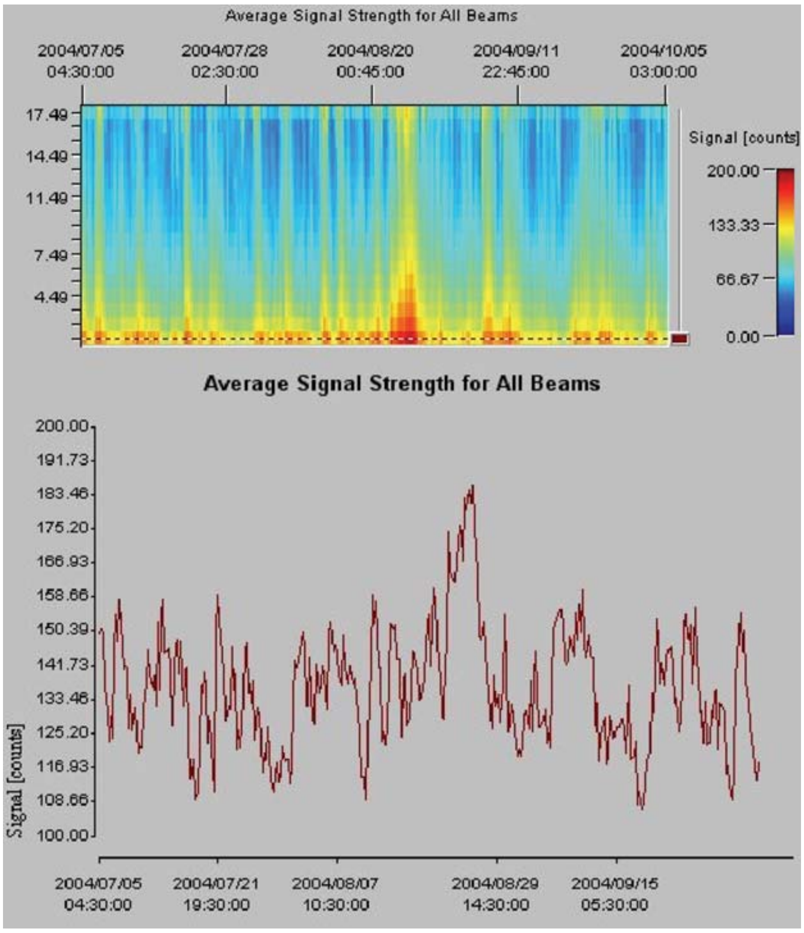


Figure 195: ADCP backscatter at deployment site A; July-October 2004.

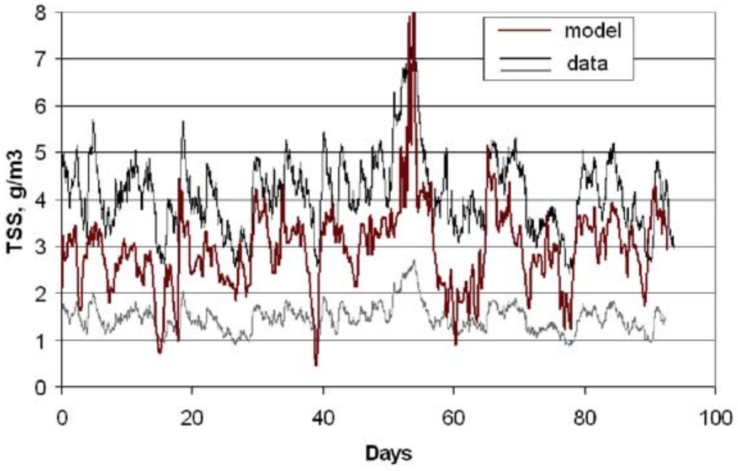


Figure 196: Modelled vs measured sediment concentration. (The data show the maximum and minimum concentration of sediments derived from ADCP backscatter).

The sediment dynamics model has been implemented in 1-d (vertical) form to simulate sediment resuspension and deposition at the Two Rocks Station A (20 m depth). The simulation period covered the first deployment and recovery, from July to October 2004. The model was driven with observed currents and surface-wave characteristics (Figs 193 and 194). Seabed sediments were represented by two classes of particles: sand and fines. Sand particles were assumed to have a single grain-size of 0.4 mm, which is the mean measured at the Ocean Reef site during the Perth Coastal Waters Study (Rosich *et al*., 1994). Settling velocity and the initial concentration of fine particles were estimated from bottle samples collected at Station A. The critical shear-stress required for initiation of the sediment motion was estimated to be approximately 0.3 Nm^{-2} (using Yalin's approach: van Rijn, 1993).

The modelled suspended sediment concentrations for Station A are shown in Fig. 196, compared with the estimates from backscatter data. The modelled data fall neatly into the range estimated from the backscatter.

The modelling suggests that, at the deployment site A, for the most of the modelled period, the bottom shear-stress exceeds the critical value of 0.3 Nm^{-2} (Fig. 197). As bed shear-stress increases from zero and reaches this critical value, a sediment particle resting on the seabed will be set in motion, moving along the bed by more or less regular jumps ("saltation"). If the shear-velocity increases further and becomes comparable with the particle fall-velocity, the sediment particles may go into suspension. In other words, the wave and current environment looks strong enough at site A to maintain a highly mobile near-bed region with appreciable movement of sand particles.

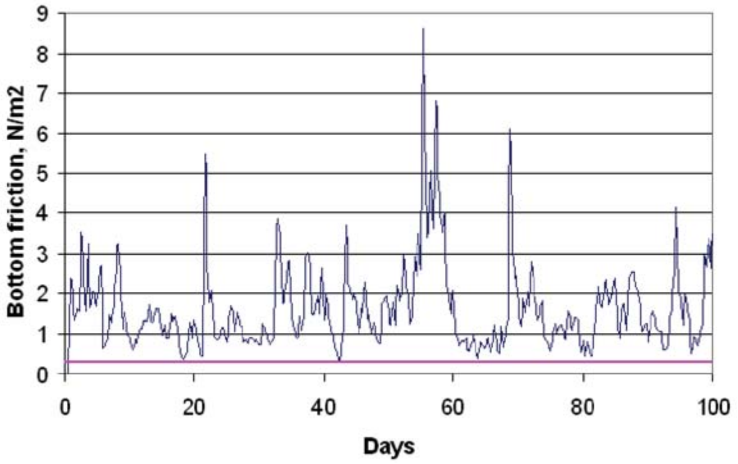


Figure 197: Calculated bottom friction at the deployment site A, in July-October 2004. (The red line shows critical shear required for initiation of motion of sand particles with 0.4mm diameter).

On the basis of the comparisons, we can have reasonable confidence in the model results. Clearly, the model can be further tested against later results from the moorings, as they become available, and against bottle samples from the transect cruises (see Chapter 5). It will now also become an integral component of the biogeochemical modelling.

7.7 Biogeochemical modelling
(Jim Greenwood and Karen Wild-Allen)

The objective of the *biogeochemical modelling* is:
by working closely with the SRFME field program, to develop a quantitative description of the (sediment and water-column) nutrient dynamics for waters off southwestern WA, with particular attention to the SRFME study sites, and with emphasis on (a) the role of nutrients in maintaining coastal habitat, and (b) the impact of changes in nutrient supply due to climate variability or human activity.

The biogeochemical model code is part of the *Environmental Modelling Suite*. The model simulates the cycling of carbon, nitrogen, phosphorous and oxygen through organic and inorganic dissolved and particulate phases within the pelagic water column, epibenthos and sediment layer (Fig. 198). EMS has a versatile structure to facilitate model development and the dynamic coupling of hydrodynamical, biogeochemical and sediment modules. Recent development and testing of the biogeochemical model has been through a laboratory style mesocosm test-case, described below, and in a realistic 3-d simulation of the seasonal evolution of the D'Entrecasteaux Channel in southeastern Tasmania, a project separate from SRFME, but involving some SRFME team members (Wild-Allen *et al.*, 2005).

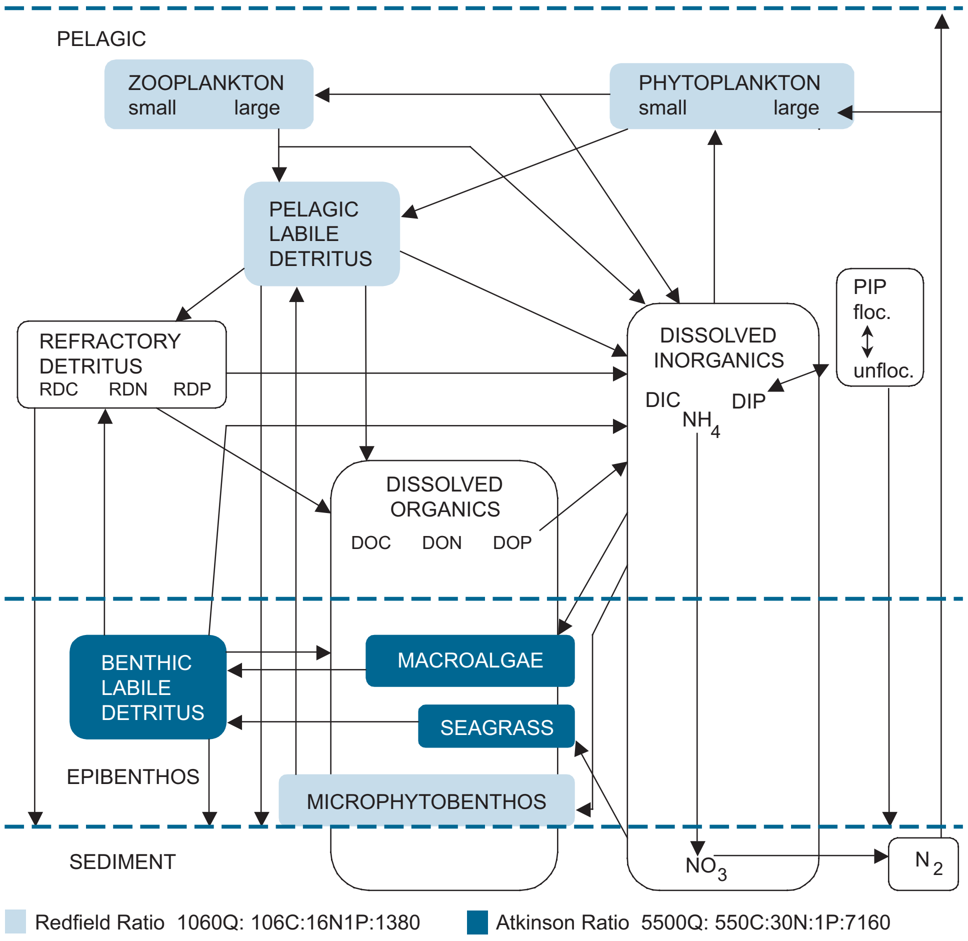


Figure 198: Biogeochemical model components and interactions.

The mesocosm test-case was designed to imitate a laboratory experiment where populations of phytoplankton are grown in a mesocosm under controlled conditions. It explored the biogeochemical processes encompassed in the model within a simple physical framework and provided a model system to investigate and clearly demonstrate biogeochemical model interactions and the influence of various parameter choices. Each test-case 'experiment' had a light phase with no phytoplankton loss terms and dark phase including zooplankton and mortality terms. The first part of the simulation demonstrated the dynamics of phytoplankton nutrient uptake and growth; the second part illustrated zooplankton growth, detrital dynamics and nutrient recycling. Example results from a light phase experiment with a single class of phytoplankton are shown in Fig. 199. The full set of results is described in Wild-Allen (2004).

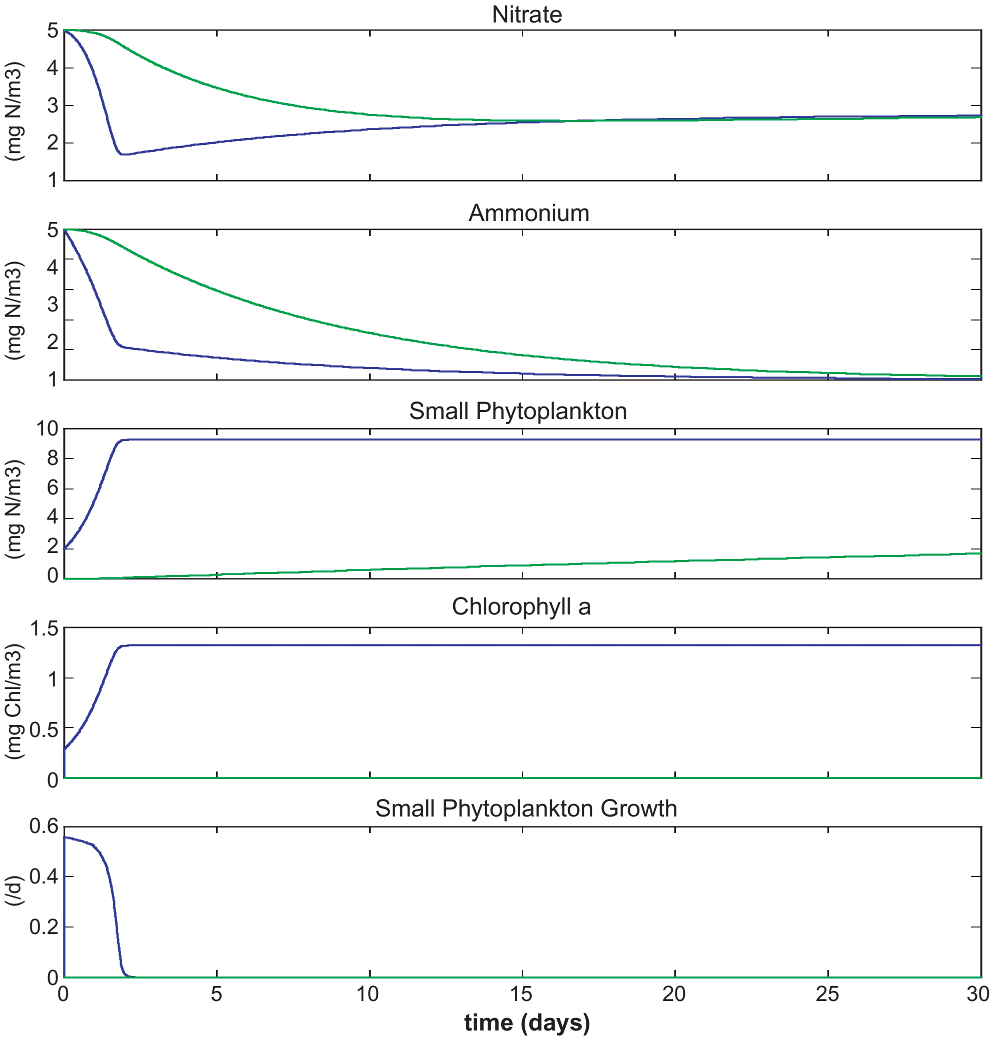


Figure 199: Modelled temporal evolution water column (blue) and sediment layer (olive) a) nitrate, b) ammonium, c) small phytoplankton nitrogen, d) chlorophyll a, and e) small phytoplankton growth rate.

The first field application of the coupled physical and biogeochemical model in SRFME has been to investigate primary production and consumption at Station E (see Fig. 183). The physical model is a 1-d version of SHOC (see Section 7.5), in particular incorporating the k-ε mixing scheme described by Burchard *et al*. (1998). In 1-d, cyclic conditions are applied at the north-south and east-west boundaries of the model, to avoid loss of mass and momentum. Further, temperature and salinity are restored, throughout the water column, towards the CARS climatology on a 30-day time scale. This restoration helps account for non-local advective heat and salt fluxes associated with the Leeuwin Current. The model domain extends to 1000m depth, divided into 50 vertical layers ranging from a thickness of 2.5m at the surface to 50m at the base. Wind stress, solar radiation and surface heat flux are prescribed 6-hourly from the National Centre for Environmental Prediction (NCEP) database.

The biogeochemical model is a simplified version of the full model shown in Fig. 198. It consists of 5 main compartments: 2 nutrients (ammonium and nitrate), phytoplankton, zooplankton and sinking detritus are coupled to the 1-D physical framework (Fig. 200). Temperature-dependent phytoplankton growth is limited by both light and nutrient availability, based on the mechanistic growth model of Baird and Emsley (1999). In this approach, autotrophic respiration is accounted for within the growth term and therefore does not appear as a separate flux in Fig. 200. Light availability is derived from total solar radiation and attenuated using a simple exponential decay, consisting of a background extinction coefficient and a phytoplankton-dependent term to represent self shading. A single zooplankton compartment is parameterised to represent dominance by microzooplankton, with relatively low growth efficiency and 50% of excretion directed toward the dissolved nutrient pool. Export of nitrogen to higher trophic levels is approximated by a quadratic mortality closure term which adds only to the sinking detrital pool. Detritus sinks at a constant rate of 10 md^{-1}, and decays with a constant first-order temperature-dependent rate. Ammonium oxidation is represented as an oxygen limited, temperature-dependent rate that is first-order with respect to ammonium. The pelagic model is coupled to a simple two-layer benthic compartment, so that sinking detritus arriving at the boundary is effectively remineralised and returned to the bottom water nutrient pools.

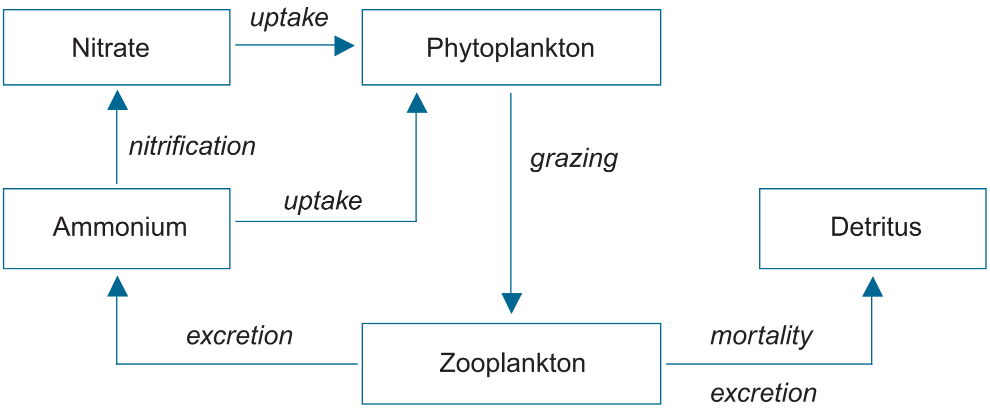


Figure 200: Schematic of the main compartments and fluxes of the biological model

The model is initialised at 1 January 2003 with observed temperature, salinity and nitrate fields, but with depth-constant values for all other state variables, and allowed to relax towards a repeating annual pattern (4 years).

The model captures some of the key biological features observed at station E during 2003. Most importantly, simulated production is characterised by a deep chlorophyll maximum during the austral summer that shoals to produce a surface chlorophyll maximum (Fig. 201), and a peak in integrated primary production (Fig. 202) during the winter. This behaviour is broadly consistent with observations, and redolent of more subtropical ocean regions. In the model simulation, the winter production appears to be driven by an intensification of vertical mixing and associated deepening of the mixed layer (Fig. 203) that effectively injects nutrients into the surface water (Fig. 204). The peak in winter production triggers increased export of sinking detritus with maximum fluxes of about 120 $mgCm^{-2}d^{-1}$ during December (Fig. 205). This compares with a measured flux of 85 $mgCm^{-2}d^{-1}$ at the same depth during January 2004.

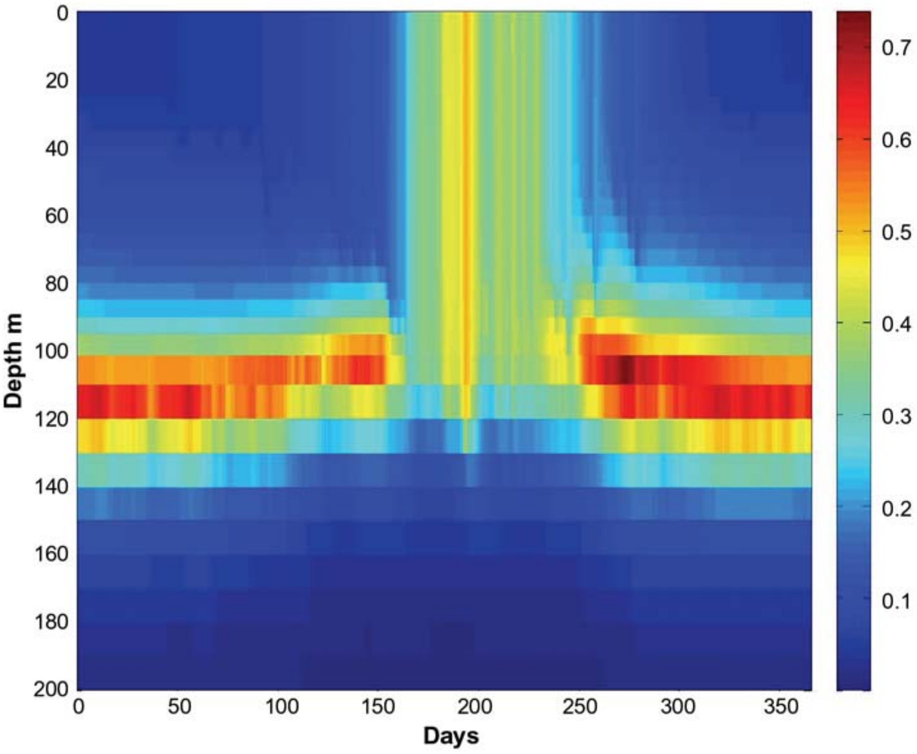


Figure 201: Modelled variation in vertical distribution of chlorophyll *a* (mg m^{-3}) in the upper 200m at station E during 2003

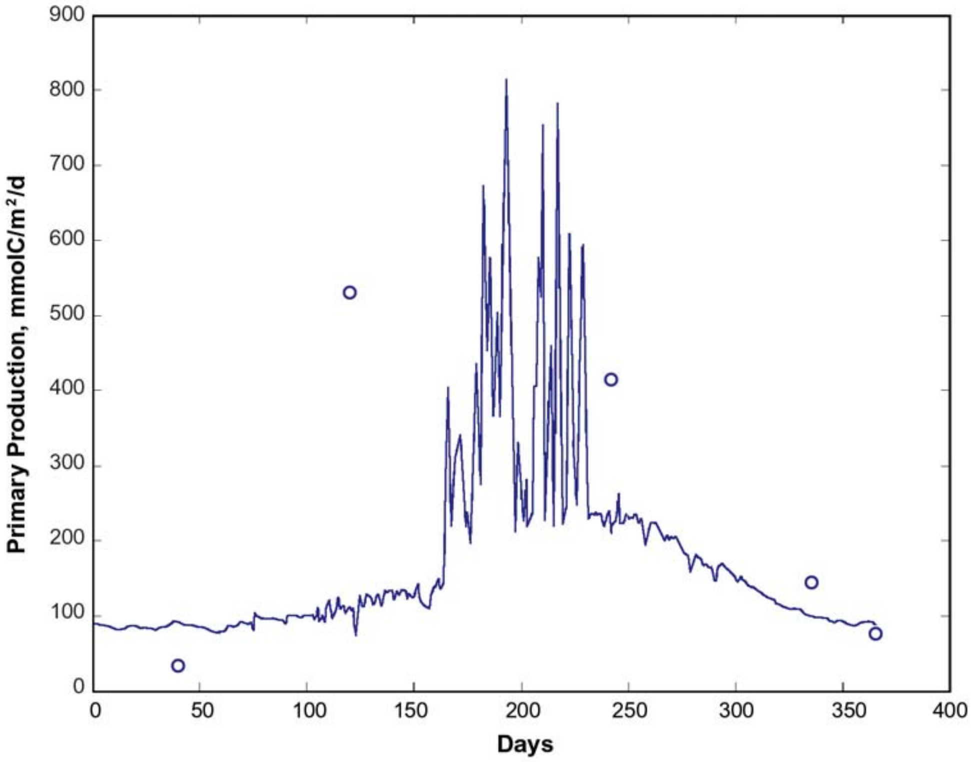


Figure 202: Modelled (solid line) and observed (open circles) seasonal variation in depth integrated primary production at station E during 2003.

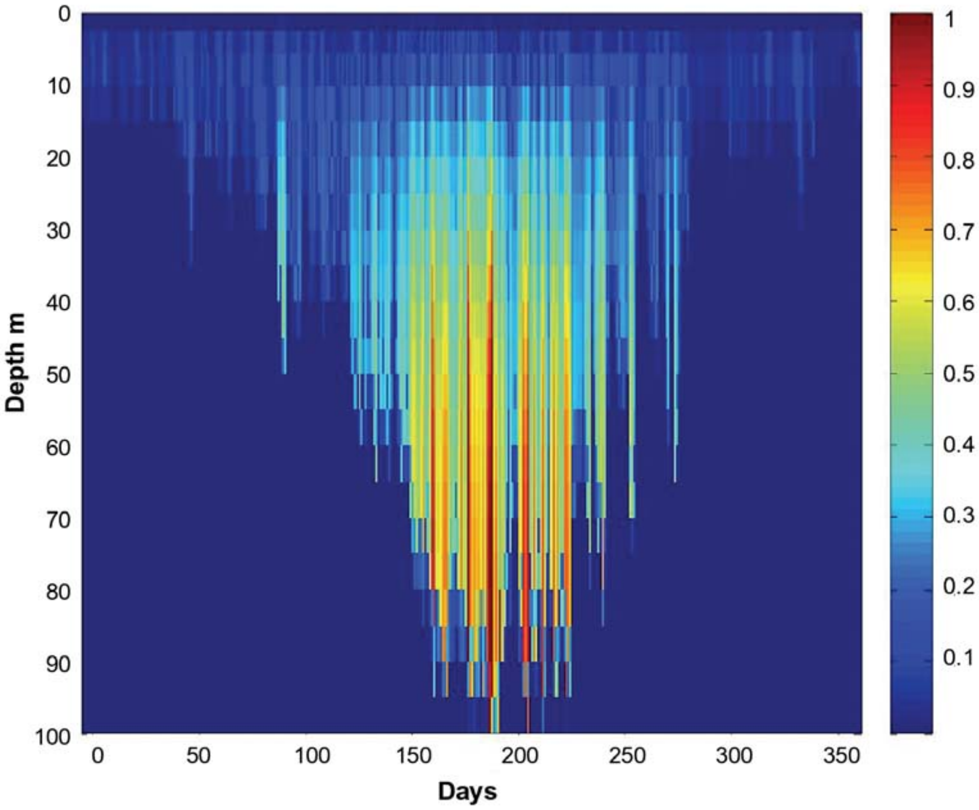


Figure 203: Simulated variation in vertical mixing coefficient, Kz (m2s-1) in the upper 100m at station E during 2003

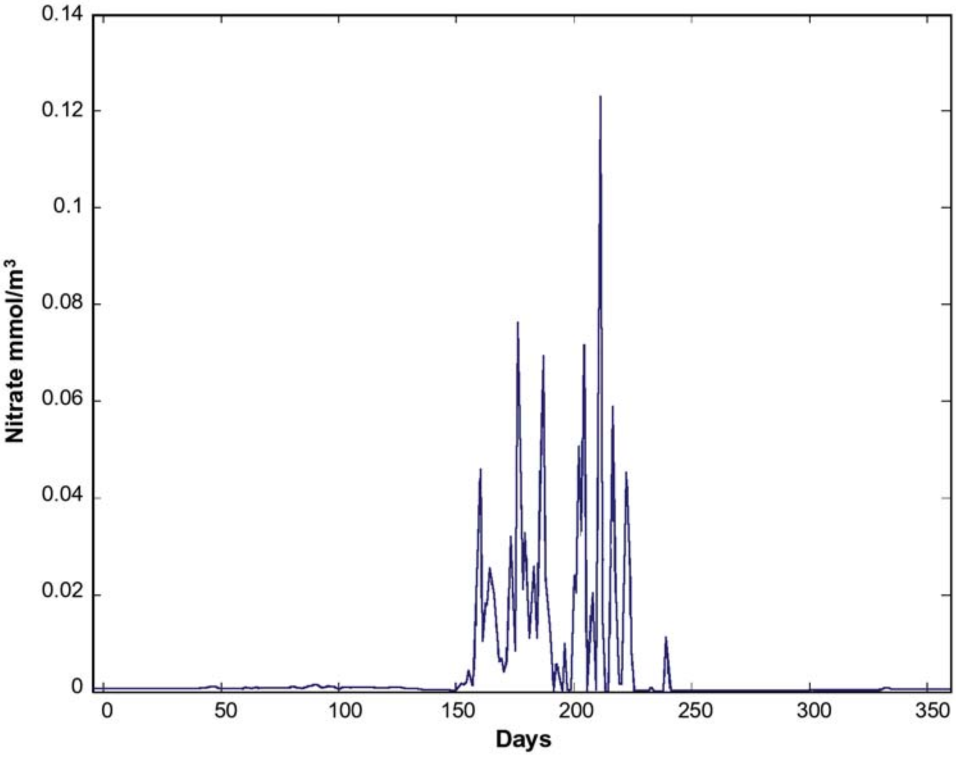


Figure 204: Simulated increase in winter-time surface nitrate (mmolNm^{-3}) in response to enhanced vertical mixing.

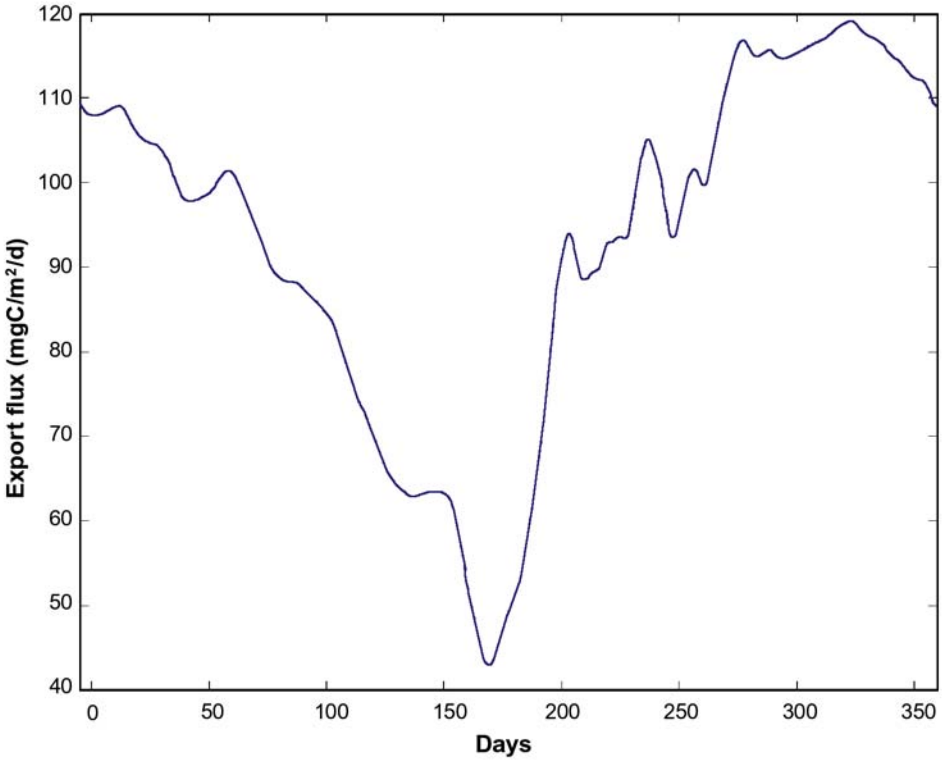


Figure 205: Variation in detrital export flux (mgCm^{-2}d^{-1}) at 180m depth at station E during 2003.

Despite the overall success of the model in reproducing these general features, a mismatch in the timing of the summer production maximum (Fig. 202) and underestimation of maximum chlorophyll concentrations by about 0.25 mg m^{-3} during the summer (see Section 5.4.1) suggest the influence of additional mechanisms not captured by the model.

On the positive side, the ability of the 1-d model to capture the broad-scale seasonal patterns in production at station E suggests a strong coupling between vertical mixing, nutrient supply and algal growth. In similar model runs, the winter intensification in vertical mixing appears to be independent of wind forcing, suggesting that surface heat flux is the dominant control that breaks down water column stratification and makes deep water nutrients available. Clearly the restoration of tem perature and salinity plays an important role in constraining this cycle that is otherwise driven by the prescribed air-sea heat flux. In fact, a weakening in temperature and salinity restoration out to 180 days was found to strengthen vertical mixing, resulting in a deeper winter mixed layer and higher overall production. In an associated issue, the apparent lag in the simulated winter production maximum suggests that the timing of this mixed-layer deepening is incorrect. This may simply reflect peculiarities between the density structure of the water column during 2003 and that represented by the climatology used for restoration. Interestingly however, attempts to eliminate the mismatch by restoring nitrate concentrations to observations of nitrate made during 2003 led to only minor improvement in the patterns of chlorophyll a and integrated primary production.

The model-simulated production shows considerable daily variation during the winter months with ‘spikes’ that often exceed the maximum values measured.   These bursts of photosynthesis appear to be closely associated with the sporadic injection of nutrients into the mixed layer resulting from variation in vertical mixing. Similar high temporal variability in production has been suspected at other oligotrophic locations (e.g. Williams *et al.*, 2004), suggesting that time-integrated estimates of production should be made cautiously.

Clearly, in an environment affected by the Leeuwin Current and its eddies, a 1-d model could not hope to capture all aspects of the biogeochemical dynamics. The modelling is presently being extended to both 2 and 3 dimensions in the SRFME domain. The 2-d model is a “slice” normal to the coastline along the Two Rocks transect (Fig. 183), presently configured as shown in Fig. 206. The 2-d model is primarily a tool for studying nutrient supply, and the role of cross-shore transport. It represents local processes such as mixing and upwelling by incorporating surface forcing, as in the 1-d model. Long-shore transport by the Leeuwin Current is included by relaxation of the cross-shore density field, again to the CARS climatology. The model can have high horizontal resolution inshore, tapering to coarse resolution offshore. It will enable the role of different nutrient sources, including shore-based, deep offshore, and atmospheric, to be examined. The model has the advantage that it will run very fast, relative to a full 3-d implementation, and can be used to test many scenarios.

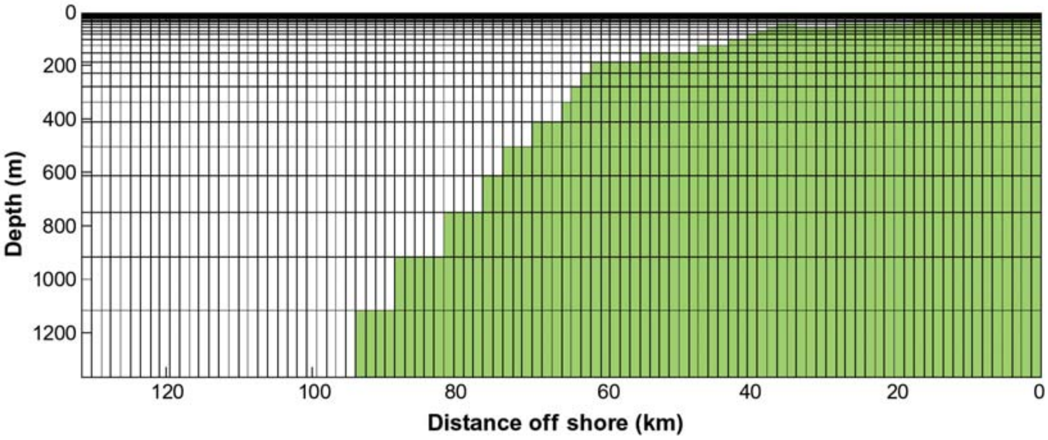


Figure 206: The 2-d biogeochemical model grid through the Two Rocks section.

The full 3-d model (with coupled hydrodynamics, sediments and biogeochemistry) is being implemented on the hydrodynamic model domain shown in Fig. 179, at the 10 km resolution described in Section 7.5. The biogeochemistry will be simplified from that shown in Fig. 198, which is more complicated than is necessary for this system, and is also computationally very demanding.

The simplified biogeochemical model has a similar design to that of Palmer and Totterdell (2001). This model is also being adopted within CSIRO for a global model that will be run with the *BLUElink* physics code. Although the global implementation is climatological, we are anticipating that results from the simulation will be used to define biogeochemical fluxes across the extensive open boundaries of the SRFME regional model.

The simplified model simulates the evolution of 8 state variables: phytoplankton, zooplankton, detritus, dissolved organics, oxygen, dissolved inorganic nitrogen, dissolved inorganic carbon and alkalinity (Fig. 207). The first four of these compartments have unique elemental ratios, whilst the latter four are specified in terms of oxygen, nitrogen, or carbon. Phytoplankton growth is controlled either by light, calculated by the tanh algorithm of Jassby and Platt (1976), or nutrient supply, using a Michaelis-Menton formulation. Zooplankton grazing is specified as a Holling type-3 rectangular hyperbola with prey refuge at low concentration. Grazing on phytoplankton and detritus is determined by specific clearance rates and zooplankton mortality is specified as a quadratic term. Detrital particles sink, and at the sediment interface particles can be buried by bioturbation or resuspended. Remineralisation occurs at a rate proportional to ambient oxygen concentration in both the water column and sediment layer. Dissolved inorganic material is included in the model as it may play an important role in coastal nutrient dynamics. It is modelled as a refractory pool with a slow turnover rate. Dissolved inorganic nitrogen includes nitrate, nitrite and ammonium in one compartment for computational efficiency. (In this formulation nitrification and denitrification dynamics cannot be simulated.) Oxygen and dissolved inorganic carbon include a term for air-sea flux, and alkalinity is calculated from the dissolved inorganic carbon concentration.

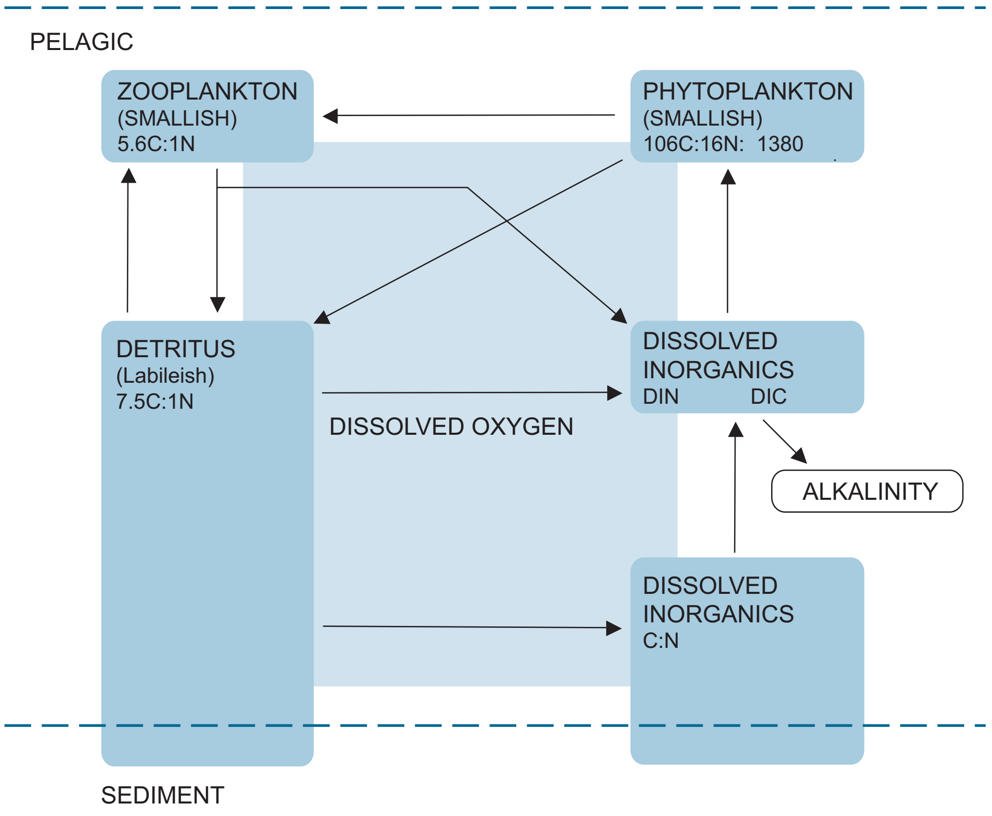


Figure 207: Simplified biogeochemical model for implementation at regional scale.

This simplified biogeochemical model is currently being developed within the flexible framework of the EMS. Initial testing is utilising the mesocosm and 1-d model implementations prior to a fully coupled 3D simulation.

7.8 Benthic habitat modelling (Phillip England)

The objective of the *ecosystem modelling* within SRFME is:
to develop (cause-and-effect) models of (the structure, health and function of) key coastal habitats, calibrated and validated from the coastal field program, that can (start to) be used in an adaptive management context to predict outcomes of changes to the system, and guide monitoring protocols.

Benthic habitat in waters shallower than 20m in southwest WA consists of bare sand, seagrass meadow or macroalgae-covered rocky reef in about equal proportions. Plant species richness and endemism in this zone is exceptionally high (Phillips, 2001) and there is substantial spatial variability in habitat types at all scales (Kendrick *et al*., 1999). Fine-scale variability is likely to reflect ecological responses to physical factors such as wave-induced physical disturbance (*ibid*.; Kendrick *et al*., 2004) and light availability rather than local adaptation or evolutionary divergence. Due to its likely importance, the influence of hydrodynamic forces on benthic habitat has been the focus of our habitat modelling effort, in the hope that the causes of the conspicuous fine scale variability can be understood.

We are taking two approaches to achieve this outcome. First, we are using wave modelling to predict the forces experienced by benthic organisms in and around the shallow reef systems that abound along the coast. These patterns are then being compared with observed habitat communities identified both by field sampling and by remote sensing (e.g. ocean colour). The second approach consists of constructing an ecological model that captures the successional dynamics in macroalgal habitats in relation to wave-driven disturbance regimes. The purpose of this model, which is based on the forest gap approach, is to understand the fine scale patterns (~1-10m) observed predominantly in macroalgal canopy species. This work is in its early stages and will not be described here.

When waves enter shallow water, they induce substantial hydrodynamic forces at the sea bed. These forces are likely to dominate the environment of benthic organisms in the euphotic zone and to be an important determinant of benthic marine habitats. Given that water depth affects wave properties, particularly the water velocity at the seabed, the complex topography found in reef zones makes the task of characterising the hydrodynamic forces of relevance to benthic organisms challenging.

We are using SWAN v4.0 (Ris *et al*. 1994), a spectral wave model which uses the shallow-water equation to estimate orbital water velocity at the bottom boundary layer (seabed) on a grided domain of bathymetry. Given wave conditions at the domain boundaries, SWAN models wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth, wind-generated waves, wave interactions, white-capping, bottom friction and depth-induced breaking, transmission through and reflection by obstacles, and diffraction.

The model predictions of orbital velocity at the seabed are being used to explore relationships between reef-zone topography, wave environments and observed benthic macroalgal habitat types. Initial investigations have focussed on reef-shelf in the vicinity of Jurien Bay north of Perth (30.2° S, 115.0° E). High-resolution bathymetry of inshore regions and observations of the wave climate were used to identify conditions for modelling. The complexity of the reef-shelf adjacent to the coastline is evident from the 3-d projection of the 30m grided bathymetry (Fig. 208). Depth varies from 0 to about 20 m on the coastal shelf, but drops off quickly at the western reef edge.

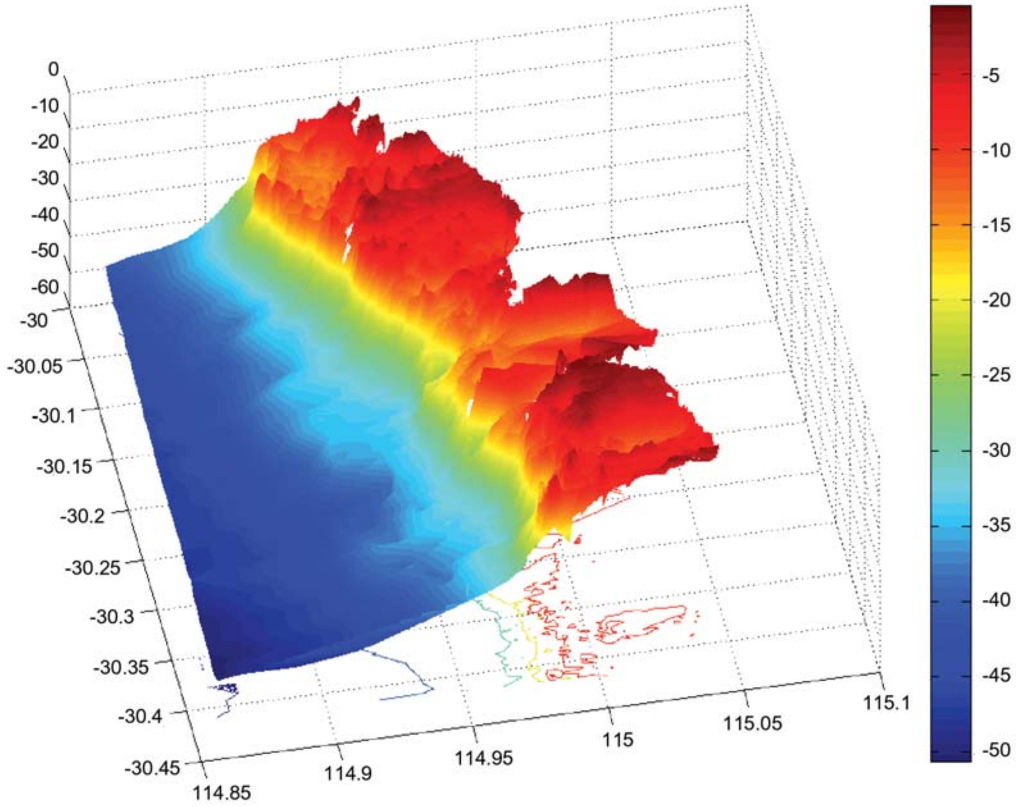


Figure 208: Bathymetry (metres below mean sea level) of the Jurien Bay region between the 50m isobath and the shore. Point depth-soundings recorded by the WA Department of Planning and Infrastructure out to the reef edges were interpolated onto a 30 m grid across the domain. Deeper bathymetry was obtained from Geosciences Australia's 1 km grid bathymetry database.

To identify the range of appropriate offshore wave conditions for the modelling, several data sources were used. Wave heights and directions are from 11 years of 12-hourly wind speeds and directions supplied by an NCEP data-assimilated model. Wave period was based on 2 years of DPI 12 hourly wave-buoy observations collected off Jurien Bay. The temporal resolution of the observational and model data is likely to have captured at least some of the storm conditions experienced in the region. Seasonal contrasts in the magnitude and direction of modelled ocean swell are evident (Fig. 209). For example, winter swell tends to be north westerly whereas in summer it is southerly and smaller. Significant wave heights in excess of four to five metres are predicted to occur in several seasons and wave buoy observations support this.

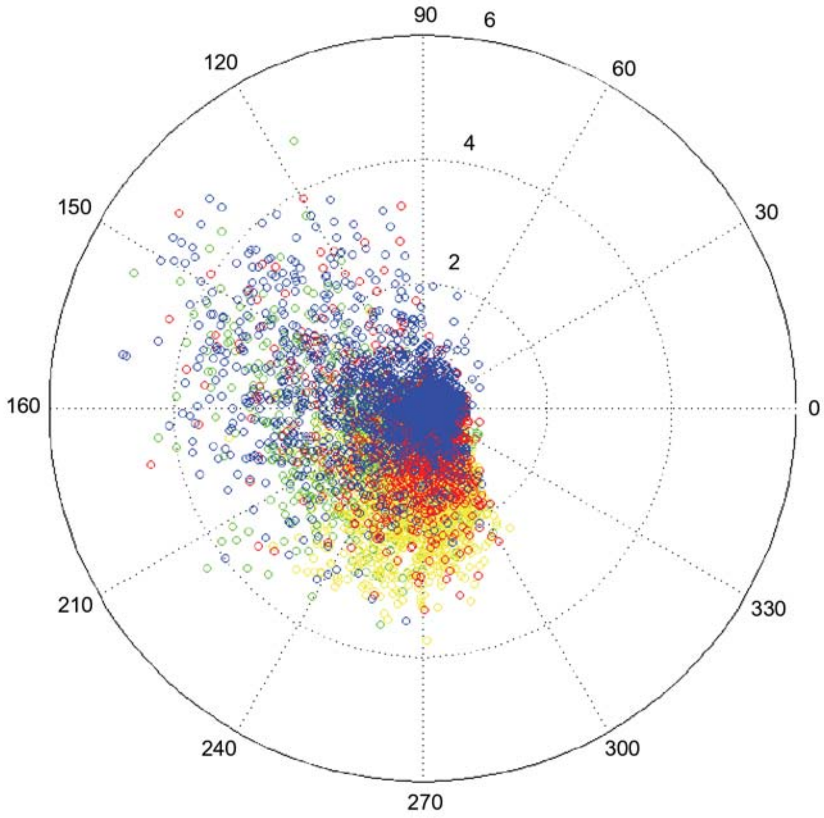


Figure 209: Modelled 12 hourly significant wave height (metres in radial axis) and wave direction (degrees relative to due westerly) based on US National Centre for Environmental Prediction wind data at Jurien Bay, coloured to show the season (blue, winter; green, spring; red, autumn; yellow, summer).

Approximately 800 scenarios were simulated to capture the relevant combinations of wave height, direction, and period, and wind speed and direction for Jurien Bay. The SWAN wave model estimates a diversity of parameters associated with propagation of waves through the modelled domain. At present, these results are being examined visually to reveal relationships between wave climate and topography.

The SWAN output (Fig. 210) shows that wave direction strongly affects the hydrodynamic forces experienced by different parts of the shallow-water reef environment. For example, the bottom orbital velocity seen at the western edge of the reef-shelf is sensitive to small shifts in prevailing wave direction. Large attenuation occurs close to the shore, especially in the lee of the island at 30.13°S.

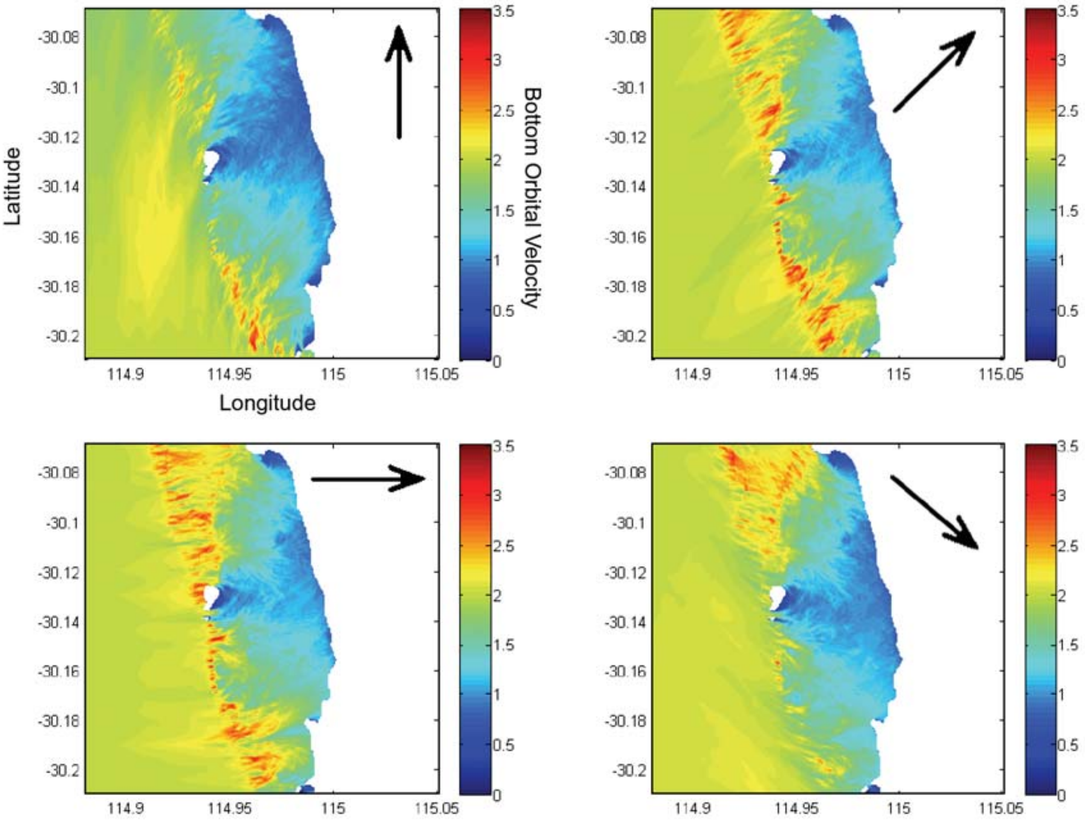


Figure 210: Representative SWAN model estimates of orbital velocity of water at the seabed with four different prevailing wave directions (arrows) and otherwise identical conditions at Jurien Bay. Significant wave height at the western boundary was 2m.

We are using several approaches to identify relationships between habitat type and hydrodynamic forces. In the first of these, maps of benthic habitat type inferred from ocean colour are compared to maps of modelled orbital velocity. Methods for classifying habitat types from reflectance spectra are described in Sec. 6.13.4.2. The approach is illustrated in Fig. 211: a grid of approximately one square kilometre was processed into three habitat types (bare sand, algae and seagrass), and each habitat map was then superimposed onto bottom orbital velocity estimates in the same area under a single set of conditions.

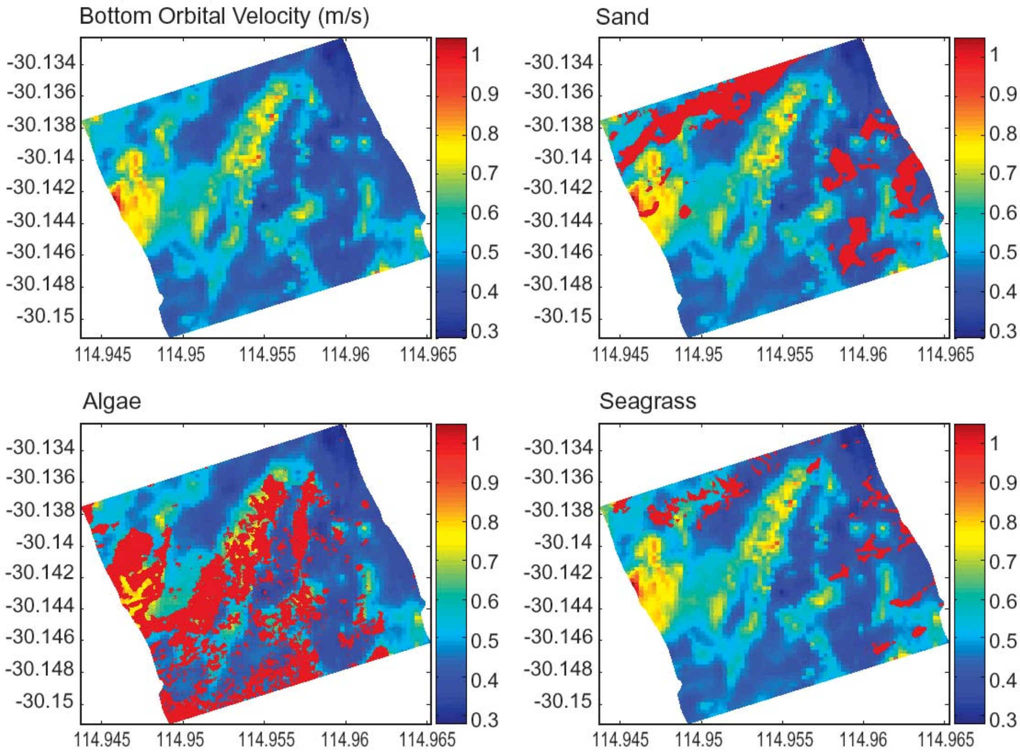


Figure 211: SWAN model estimates of orbital velocity at the seabed in the vicinity of Jurien Bay (identical in all four plots) overlayed with ocean colour-based classification of three bottom habitat types (bare sand, seagrass and macroalgae). Bottom types were inferred from reflectance measured using the airborne Hymap system (methods described elsewhere in this report).

Although the map of orbital velocity in Fig. 211 represents only a single parameter combination from the many that are possible, a correlation between algae and high orbital velocity can be seen, as can a correlation between bare sand and low orbital velocity, at least in the right corner of the domain. However, water depth also shows these correlations (data not shown), so it will be important to tease apart the contribution of each of these variables. To date our comparisons have been largely qualitative, but quantitative techniques are now being explored.

A second approach to relating the hydrodynamics and ecology utilises ecological data being collected as part of the Benthic Ecology group's field program (see Chapter 6). The group has made detailed measurements of macroalgal and invertebrate assemblage composition at numerous sites between Jurien Bay and Geographe Bay. We have selected a subset of these sites to capture the likely range of wave conditions experienced across the reef-shelf. At each site, the wave modelling then provides the hydrodynamic forces for correlating against various aspects of the ecology.

To illustrate this approach, Fig. 212 shows results of applying multidimensional scaling across 25 sites. Sites that group together on the basis of the similarity of species composition also group according to the magnitude of the most extreme orbital velocities they experience throughout the year. However, this analysis is preliminary and must be interpreted cautiously. For example, the observed clumping may also be a result of physical proximity, if nearby sites tend to have similar species composition and wave environments.

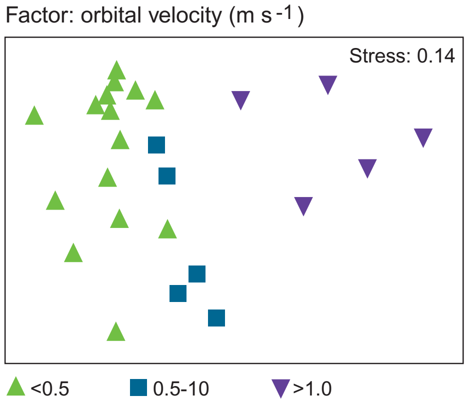


Figure 212: Multidimensional scaling of macroalgal assemblages found at five reefs (with five random samples per reef) in the Jurien Bay region labelled according to its typical orbital velocity under winter storm conditions (<0.5, 0.5-1.0 & >1.0 ms^{-1}). The clumping algorithm groups samples which have similar species composition together. Axes are dimensionless. Stress indicates the distortion required to collapse the higher dimensional ordination into the two shown here. The value indicated here is considered acceptable.

Thus far, we have combined tools from coastal engineering, remote sensing and benthic field ecology to improve our understanding of the critical processes shaping the coastal marine environment in SW WA. In the immediate future we will deploy velocimeters and pressure gauges on the reefs, to measure the wave-induced forces in the study areas. These will enable us to test the wave modelling, and possibly consider alternative modelling techniques. The ecological understanding will lead to better specification of the "gap model" which is presently under development to describe the dynamics of the habitat itself (e.g. England, 2004). Habitat is included empirically in the biogeochemical models (Section 7.7) for its role in nutrient cycling. The ongoing development of both the habitat and shallow-water biogeochemistry modelling will be mutually supportive, particularly as results from the field programs are analysed in detail.

7.9 Management Assessment (Peter Craig)

The objective of *management assessment* is:
to ensure that SRFME models provide a sound basis for coastal environmental management, by developing approaches that can be used to test the accuracy and robustness of the models, particularly in circumstances beyond those observed in the field program, and by incorporating monitoring and decision-making processes in the modelling.

Management assessment is the project module that houses the project management. Its delivery is mostly through the other project areas that have been described in preceding sections of this chapter. It is probably reasonable to claim that the most significant achievement in this project area has been the establishment of the SRFME modelling team in Western Australia through a recruitment program over the last 4 years, but particularly concentrated in the last two. The team now represents a significant modelling capability for the State.

This project area also accounts for the software development that will facilitate delivery of data and model results to State decision-makers. While SRFME publications will provide interpretation of the data, they can obviously display only a subset of those data, in limited format. We reason that State managers will have more confidence, and can exercise more flexibility, and their own interpretation, if they can easily explore the results themselves.

Two of the software tools provide access to specific data sets via websites. The first is the *Argo* website, that displays data from the drifting buoys in the Argo program (see Section 7.4). The second is *Aus-Connle*, which uses satellite altimeter data to estimate the drift of particles, such as larvae or pollutants, in the ocean. **WebOLIVE** is a general tool that gives access to gridded data such as model output. The most important tool, from the SRFME perspective, is *DIVE*, an interactive package that will allow spatial and temporal data to be viewed and compared. *DIVE* has an associated data structure, that will enable SRFME data to be supplied to, and explored by, management agencies on a digital medium, such as a DVD.

These packages are described more fully, with access details, in the following section.

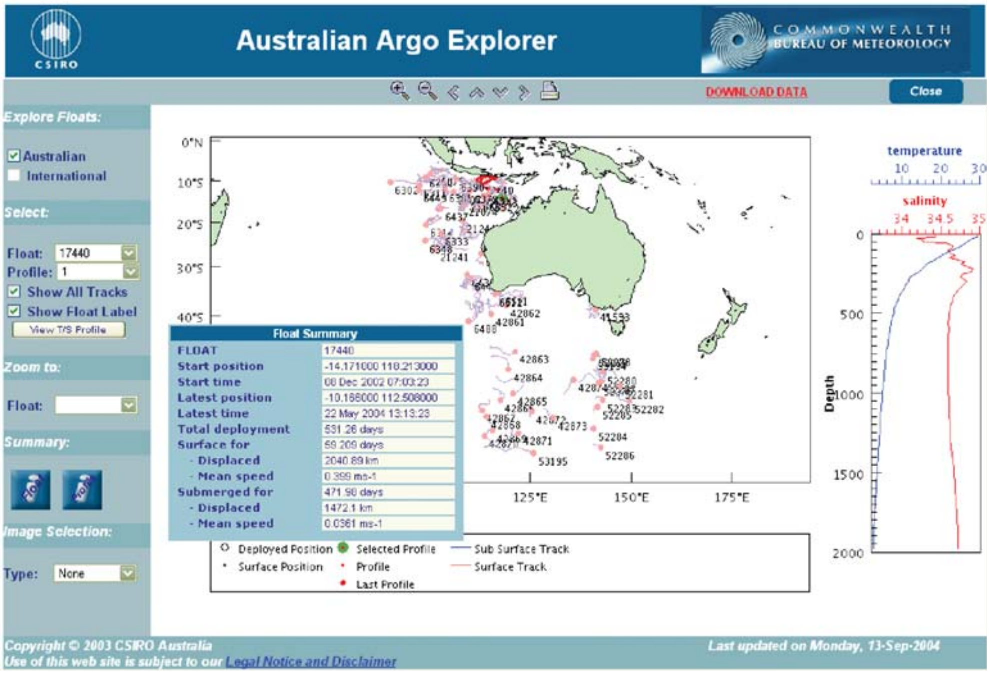
7.10 Visualisation and data delivery (Jason Waring, Irshad Nainar)

As discussed in previous sections, the SRFME Integrated Modelling Project has taken responsibility for development of software tools that will make both the SRFME data sets, and those from other projects, available to and explorable by WA marine managers, and the broader researcher community. The four products that have been developed are:

- *Argo website*
- *Aus-ConnIe* website
- *WebOLIVE*
- *Data Interrogation and Visualisation Environment*

Argo website

The Argo website provides an interactive data explorer to display tracks and vertical profiles from over 65 Argo vertical profiling floats which have been deployed in the Indian and Southern Oceans (see Fig. 213). It features near real-time comparison between Argo float data and statistically derived ("synthetic") temperature and salinity profiles.



Float: 17440
Profile: 1
☑ Show All Tracks
☑ Show Float Label
Float:
Type: None

Float Summary

FLOAT	17440
Start position	-14.171000 118.213000
Start time	08 Dec 2002 07:03:23
Latest position	-10.168000 112.508000
Latest time	22 May 2004 13:13:23
Total deployment	531.26 days
Surface for	59.209 days
- Displaced	2040.89 km
- Mean speed	0.399 ms-1
Submerged for	471.98 days
- Displaced	1472.1 km
- Mean speed	0.0361 ms-1

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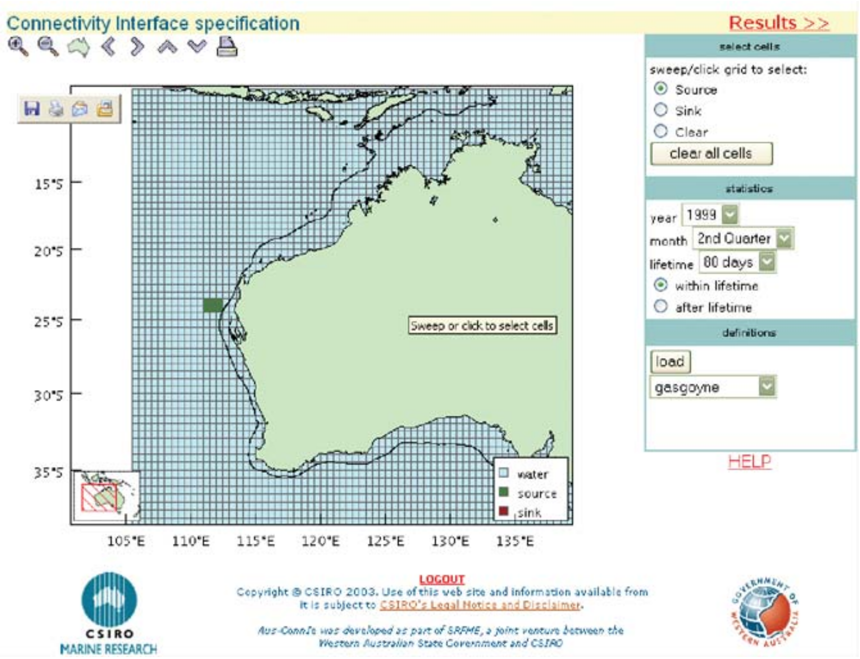
Last updated on Monday, 13-Sep-2004

Figure 213: The ARGO web explorer showing the drift tracks of over 65 floats.

The Argo website is located at http://www.per.marine.csiro.au/argo. It builds on a pre-existing website developed as part of the *Cooperative Ocean Observing Experiment* (COOE). The Argo website was developed under a collaborative agreement with the Bureau of Meteorology.

Aus-ConnIe website

The *Australian Connectivity Interface* (Aus-ConnIe) is a web-based tool developed to allow environmental scientists and managers to investigate the large-scale patterns of spatial connectivity around Australia (see Figs 214 and 215). It provides the user with an estimate of the probability that any two regions are connected by ocean circulation over a specified dispersion period (10, or 20 days for monthly averaging or 30, 40, 60 or 80 days for quarterly averaging). It is expected to find applications in areas such as larval dispersion and recruitment studies, and the development of scenarios and risk assessments for contaminant dispersion.



Connectivity Interface specification

Results >>

select cells

sweep/click grid to select:

● Source
○ Sink
○ Clear

clear all cells

statistics

year 1999

month 2nd Quarter

lifetime 80 days

● within lifetime
○ after lifetime

definitions

load

gasgoyne

HELP

LOGOUT

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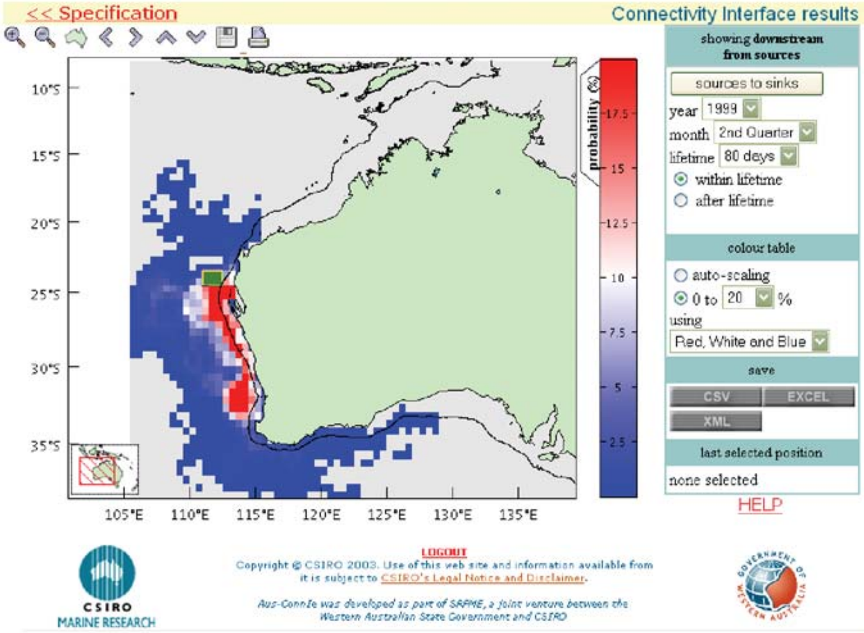
Aus-ConnIe was developed as part of SRFME, a joint venture between the Western Australian State Government and CSIRO

Figure 214: Aus-Connle specification page
– Selected source cells are shown in mid-green.



<< Specification

Connectivity Interface results

showing downstream from sources

sources to sinks

year 1999

month 2nd Quarter

lifetime 80 days

● within lifetime
○ after lifetime

colour table

○ auto-scaling
● 0 to 20 %

using

Red, White and Blue

save

CSV EXCEL XML

last selected position

none selected

HELP

LOGOUT

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Aus-ConnIe was developed as part of SRFME, a joint venture between the Western Australian State Government and CSIRO

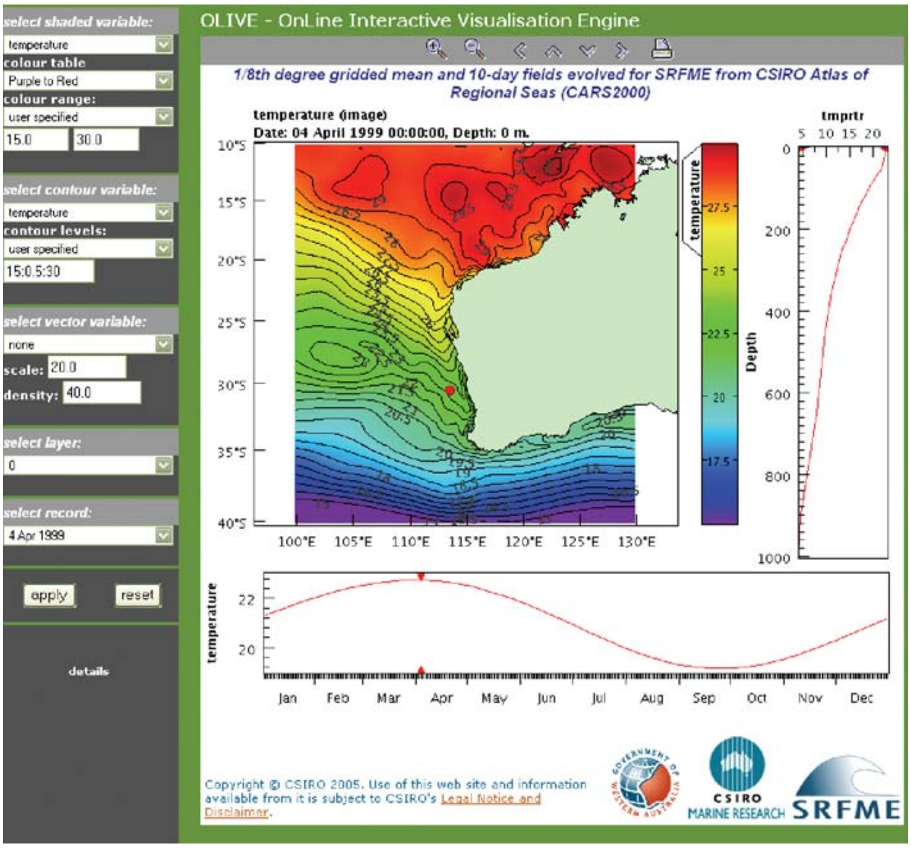
Figure 215: Aus-Connle results page. Note the Leeuwin current.

The *Aus-ConnIe* website is located at http://www.per.marine.csiro.au/aus-connie. Aus-ConnIe builds on the *JEMS-ConnIe* website developed as part of the *North West Shelf Joint Environmental Management Study* (NWSJEMS).

WebOLIVE

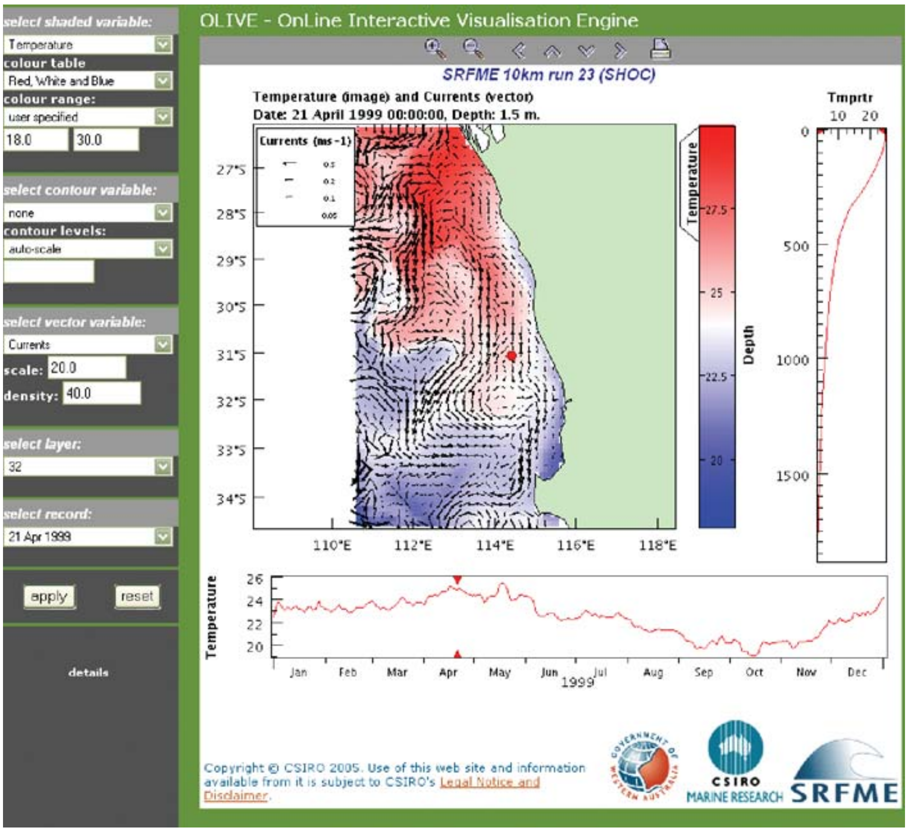
WebOLIVE is a web-based visualisation tool developed to allow users to explore gridded datasets (such as hydrodynamic model output and climatology atlases) using a standard web browser. Features include the ability to visualise selected variables for a given time and depth as coloured, contoured or vector maps, as well as interactively select a time-series and vertical profile for a specific location. Some controls are provided to permit refinement of the graphics (e.g. colour ranges and colour tables).

WebOLIVE has been integrated into the SRFME modelling website, allowing users to explore the CARS climatology and hydrodynamic model datasets (see Figs 216 and 217, respectively).



select shaded variable: temperature
colour table: Purple to Red
colour range: user specified 15.0 30.0
select contour variable: temperature
contour levels: user specified 15:0.5:30
select vector variable: none
scale: 20.0
density: 40.0
select layer: 0
select record: 4 Apr 1999

Figure 216: CARS (climatology) temperature fields displayed using WebOLIVE.



OLIVE - OnLine Interactive Visualisation Engine

SRFME 10km run 23 (SHOC)

Temperature (image) and Currents (vector)
Date: 21 April 1999 00:00:00, Depth: 1.5 m.

select shaded variable: Temperature
colour table: Red, White and Blue
colour range: user specified
18.0 30.0

select contour variable: none
contour levels: auto-scale

select vector variable: Currents
scale: 20.0
density: 40.0

select layer: 32

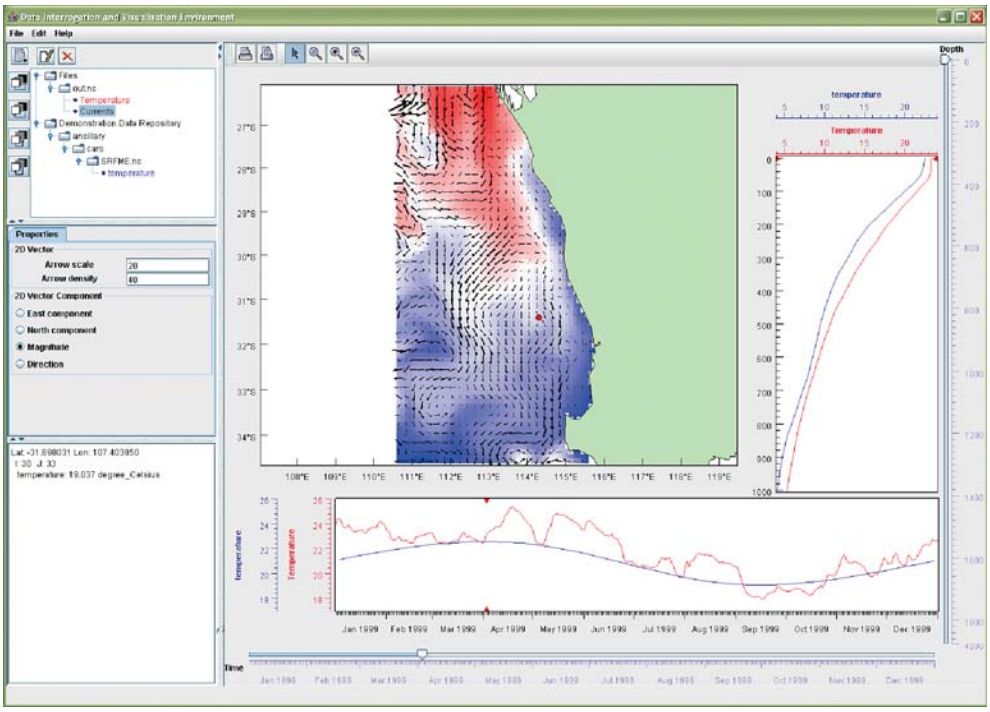
select record: 21 Apr 1999

Figure 217: Hydrodynamic model output displayed using WebOLIVE

Data Interrogation and Visualisation Environment

Many datasets have accumulated within SRFME through field programs, remote sensing and numerical model runs. Not only are these datasets large in volume but they are also diverse. They range from 4-dimensional model outputs to individual time-series and profiles.

The *Data Interrogation and Visualisation Environment* (DIVE) is a graphical tool to interactively explore and visualise volumetric time-varying gridded data (e.g. model outputs) and observational data (underway time-series, temperature/salinity profiles, and data collected from moored instruments). The tool provides users with the ability to view and compare datasets in space and time (e.g. Figs 218 and 219).

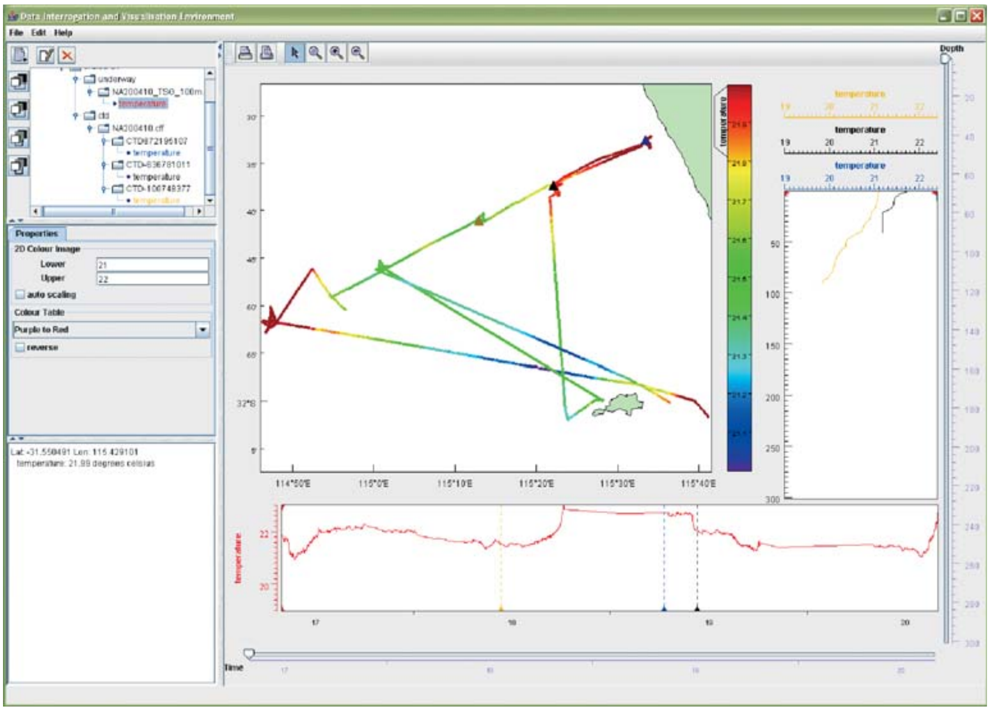


2D Vector
Arrow scale: 20
Arrow density: 40

2D Vector Component
○ East component
○ North component
● Magnitude
○ Direction

Lat: -31.698031 Lon: 107.403850
I: 30 J: 33
temperature: 19.037 degree_Celsius

Figure 218: Comparison of hydrodynamic model and CARS climatology using DIVE.



2D Colour Image
Lower: 21
Upper: 22
☐ auto scaling

Colour Table: Purple to Red
☐ reverse

Lat: -31.558491 Lon: 115.429101
temperature: 21.99 degrees celsius

Figure 219: Comparison of underway data and 3 CTD profiles using DIVE.

DIVE accesses observational and model data stored in the SRFME data repository. This is an hierarchical file-based data storage system to manage the processed and calibrated data collected or generated within SRFME.

The current version (1.0) of DIVE supports the display of data as maps (coloured maps, contours plots, vector arrows), time-series and vertical profiles. It supports the following streams of data:

- hydrodynamic model outputs.
- NetCDF files that conform to formats commonly used within the oceanographic community.
- climatological datasets.
- underway time-series data.
- temperature/salinity profile data (CTD casts).
- data measured by moored instruments.

A demonstration copy of DIVE is provided on the CD-based versions of this report. DIVE is a prototype tool that is being developed particularly for State managers and other external users of SRFME results. We welcome feedback on its usability and usefulness, as well as any suggestions on how it might be improved.

7.11 Conference attendance and presentations

Craig, P.D. SRFME Integrated Modelling. *Wealth from Oceans Flagship Workshop*, Hobart, 28-29 Jan 2004.

Craig, P.D. SRFME modelling: people and practice. *Annual SRFME Symposium*, Perth, 16 Feb 2004.

Craig, P.D. Physics, primary production and humans. *Wealth from Oceans Flagship Roadshow*, Hobart, 5 May 2004.

Craig, P.D. (Convenor) *Holloway Memorial Symposium, Australian Marine Sciences Association National Conference*. Hobart, 6-9 July 2004.

Craig, P.D. SRFME Integrated Modelling. *Wealth from Oceans Flagship 2003/4 Review*, Hobart, 14 July 2004

Craig, P.D. (Convenor) *SRFME Biogeochemistry Workshop*. Perth, 23-26 August 2004.

Craig, P.D. In an octopus's garden. Keynote address, *Australian Energy and Mining Conference 2004, CPA Australia*, Gold Coast, 25-27 Nov 2004.

Craig, P.D. (Convenor) *SRFME Internal Research Workshop*. Perth, 9 Feb 2005.

Craig, P.D. SRFME modelling: global to gap. *Annual SRFME Symposium*, Perth, 10 Feb 2005.

England, P.R. *Australian Marine Sciences Association National Conference*. Hobart, 6-9 July 2004.

England, P.R. (Convenor) *Groundwater impacts on the marine environment*. Floreat, 24 August 2004

Fandry, C.B.. SRFME Hydrodynamic Modelling: *Annual SRFME Symposium*, Perth, 16 Feb 2004.

Fandry, C.B. SRFME Hydrodynamics and Observations: *Annual SRFME Symposium*, Perth, 10 Feb 2005.

Feng, M., S. Wijffels, 2001: Preliminary results from a pilot Argo float program in the southeastern Indian Ocean. *Proceeding of 17th DBCP Science Workshop*, Perth, Western Australia, 22-26 October 2001.

Feng, M., G. Meyers, 2001: Interannual variability of the tropical Indian Ocean from extended EOF analysis. *BMRC Research Report No. 84*, Melbourne, Victoria, Australia, 14-16 November 2001, pp17-20.

Feng, M., S. Wijffels, 2002: Intraseasonal variability in the South Equatorial Current of the Southeastern Indian Ocean. *Australian Marine Sciences Association National Conference*, 10-12 July 2002.

Feng, M., G. Meyers, 2002: Interannual variability in the tropical Indian Ocean, a 2-year time scale of IOD. *2nd International Pacific Research Center Annual Symposium*, University of Hawaii, USA, 16-17 May 2002.

Feng, M., G. Meyers, A. Pearce, and S. Wijffels, 2003: On the relationship between the annual/interannual variations of Fremantle sea level and the Leeuwin Current. *10th AMOS 2003 General Conference*. Perth, Australia, 10-12 February 2003.

Feng, M., and G. Meyers, 2003: Interanaul variability in the tropical Indian Ocean. 7th *International Conference on Southern Hemisphere Meteorology and Oceanography*, Wellington, New Zealand, 24-28 March 2003.

Feng, M., Y. Li, and G. Meyers, 2003: Longterm variations of the Fremantle sea level, the footprint of climate variablity and climate change. *Symposium on Ocean Circulation and Climate Change*, Sayan, China, 28 November-2 December 2003.

Feng, M., 2003: Research Progress on the Indonesian Throughflow. *Conference on Future Physical Oceanography Research in China*, Qingdao, China, 22-23 December 2003.

Feng, M., Large-scale oceanography in the east Indian Ocean and annual/interannual variability of the Leeuwin Current. *SRFME Symposium*, 18 February 2004.

Feng, M., S.E. Wijffels, J.S. Godfrey, and G.A. Meyers. 2004. Do eddies play a role in the momentum balance of the Leeuwin Current? *AMSA2004*: Australian Marine Sciences Association. Hobart, Australia, 6-9 June 2004.

Feng, M. 2004: Tracking two oppositely-rotating eddies off the Western Australian coast, *AMSA2004*: Australian Marine Sciences Association. Hobart, Australia, 6-9 June 2004.

Feng, M., 2004: Tracking a dipole-eddy structure with satellite altimetry shipboard ADCP, and Argo float in the East Indian Ocean, American Geophysical Union Western Pacific Geophysics Meeting. 16-20 July 2004.

Feng, M., 2005: Physical environment in the SRFME region-the role of mesoscale eddies, SRFME Symposium. Perth, Australia, 10 February 2005.

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Greenwood, J.E., Biogeochemical modelling. *SRFME Symposium*, Perth, 18 February 2005.

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Nainar, I., Data Visualisation and Exploration (part 2), *SRFME Symposium*, Perth, 18 February 2004.

Nainar, I., Data storage and Visualisation, *SRFME Biogeochemistry workshop*, 23-26 August 2004.

Nainar, I., Data Interrogation and Visualisation Environment (DIVE), *SRFME Symposium*, Perth, 10 February 2005.

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7.12 Publications and/or outcomes to date

Condie, S.A., Waring, J., Mansbridge, J.V., Cahill, M.L. (2005). Marine connectivity patterns around the Australian continent, *Environmental Modelling and Software*, 20, 1149-1157.

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Feng, M., R. Lukas, P. Hacker, A. J. Plueddemann and R. A. Weller (2005a). “Upper ocean momentum balances in the western equatorial Pacific on the intraseasonal time scale”, *Deep-sea Research I*, 52/5 749-765.

Feng, M., S. Wijffels, S. Godfrey and G. Meyers (2005b). “Do eddies play a role in the momentum balance of the Leeuwin Current?”, *Journal of Physical Oceanography*, in press.

Liu, Y., M. Feng, J. Church, and D. Wang (2005). “Salinity Effect on Estimating Geostrophic Transport of the Indonesian Throughflow along the IX1 XBT section”, *Journal of Oceanography*, in press.

Feng, M., C. B. Fandry, L. Majewski and A. M. Waite (2005c) “Physical characterisation of an eddy pair in the Leeuwin Current system off the Western Australian coast”, Deep-Sea Research, completed manuscript.

Website of the Australian Argo Project
Argo website viewable at http://www.per.marine.csiro.au/argo

Website of Australian Connectivity
Aus-ConnIe website viewable at http://www.per.marine.csiro.au/aus-connie

Website of SRFME modelling project
Website viewable at http://www.per.marine.csiro.au/SRFME-modelling. The *WebOLIVE* data explorer permits the exploration of selected hydrodynamic model outputs (3d and 2d slice models), and the CSIRO Atlas of Regional Seas (CARS) climatology.

Demonstration CD of the Data Interrogation and Visualisation Environment (DIVE)
Supplied as part of the interim final report. Includes example datasets.

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CHAPTER 8

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Val Pearce, CSIRO

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Department of the **Premier and Cabinet**
Government of **Western Australia**
Office of **Science and Innovation**

Fish for the future

Department of **Fisheries**
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AND LAND MANAGEMENT
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