Strategic Research Fund for the Marine Environment (SRFME)

Final report **December 2006**

concise **summary**

Edited by John K. Keesing, John N. Heine and Don Michel **CSIRO** Marine and Atmospheric Research

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Full copies of this report may also be downloaded from www.srfme.com.au

National Library of Australia
Cataloguing-in-Publication data:

Strategic Research Fund for the Marine Environment (SRFME) :

final report, concise summary.

ISBN 9781921232442 (pbk.).

1. CSIRO - Appropriations and expenditures. 2. Marine

sciences - Research - Western Australia - Finance. 3.

Marine resources - Research - Western Australia - Finance.

I. Keesing, John K. II. Heine, John N. III. Michel, Don.

IV. Strategic Research Fund for the Marine Environment.

354.5709941

Published by Strategic Research Fund for the Marine Environment, CSIRO, Australia

Preface

The Strategic Research Fund for the Marine Environment (SRFME) was established as a joint venture by the Western Australian State Government and the CSIRO in 2001 with the aims of building capability and capacity in marine science in Western Australia through the reestablishment of CSIRO's marine research capability and the training of postgraduate students, facilitating strong collaboration among the Western Australian marine science community, and conducting strategic research that is of benefit to Western Australia.

This concise summary of the SRFME Final Report summarises the contents of the two main volumes which run to over 500 pages. Volume 1 outlines the establishment of SRFME, the development of its research framework and research portfolio as well as its structure and governance in chapter 1 and details the SRFME Collaborative Linkages Program which was comprised of a set of PhD Scholarship Projects (chapter 2), SRFME Collaborative Projects (chapter 3) and SRFME State Linkage Projects (chapter 4). Volume 1 also introduces the SRFME Core Projects (chapter 5) and concludes with a list of publications arising from SRFME (chapter 6). Volume 2 of the SRFME Final Report comprises an overview summary (chapter 1), followed by detailed chapters on the scientific research conducted in the areas of physical oceanography (chapter 2), coastal and continental shelf pelagic community structure (chapter 3), coastal and continental shelf biogeochemistry and modelling (chapter 4), coastal benthic ecosystem structure and dynamics (chapters 5 and 6) and concludes with a description of the data archiving systems and the interactive data and model output visualisation software developed in SRFME (chapter 7).

A list of acknowledgements to the many people who have contributed to the success of SRFME is included elsewhere in this final report, but I would like to make special mention of a few in particular, whose support to me in my role as SRFME Research Director has been invaluable. I would like to thank Dr Nan Bray (CSIRO) and Dr Sue Meek (WA Government) who had the vision to develop and establish SRFME, and subsequent senior people in the WA State Government; Dr Bruce Hobbs, and CSIRO; Dr Greg Ayers, John Gunn, Dr Tony Haymet, Tim Moltmann, Dr John Parslow, Dr Ian Poiner and Craig Roy who all provided tremendous support. I would also like to thank other members of the SRFME Joint Venture Management Committee and Technical Advisory Committee, especially Dr Ray Masini, Peter Millington, Phillip Murray, Linda Penny and Dr Chris Simpson for their support and advice, CSIRO project Leaders; Dr Russ Babcock, Dr Peter Craig, and Dr Tony Koslow for their excellent science leadership, Lucy Kay for her tireless work for SRFME and John Heine for producing the final report.

Dr John Keesing

Research Director
Strategic Research Fund for the Marine Environment

31 December 2006

Foreword

Premier of Western Australia

FOREWORD BY THE PREMIER OF WESTERN AUSTRALIA
HON ALAN CARPENTER MLA

The $20 million Strategic Research Fund for the Marine Environment (SRFME) was established as a joint venture between the State Government of Western Australia and the CSIRO. Through this partnership, each invested $10 million to build capability and capacity in marine science in Western Australia, facilitate strong collaboration among the Western Australian marine science community, and conduct strategic research that is of benefit to Western Australia.

The outcomes described in these two volumes of the SRFME Final Report, even at over 500 pages, seek only to summarise the vast amount of work undertaken in SRFME by CSIRO and its collaborators in Western Australian universities, State agencies and Museum. From this report, it is apparent that the goals for SRFME have been impressively exceeded.

Encouraged by the track record of success in SRFME, the State Government has recently announced investment of a further $21 million to establish the Western Australian Marine Science Institution (WAMSI). In doing so, they have demonstrated the Government's commitment to ensuring the capability and capacity for marine science in Western Australia is maintained and grown. Through WAMSI, the strategic research needs of the State will continue to be addressed and the strong partnerships, such as those established with the CSIRO through SRFME, will endure.

Through WAMSI, the Western Australian State Government looks forward to further outstanding marine science outcomes, from CSIRO and its collaborators, which contribute to the wise management of Western Australia's marine environment and the sustainable development of its natural resources.

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30 JAN 2007

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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 final report completed in December 2006 is aimed at presenting SRFME's achievements to date to its members, stakeholders and collaborators. Some of the work presented here is still in progress and will be completed over the coming year. 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 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 2006. 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, operational oceanography and multiple use management.

Capability and capacity have also been further developed in Western Australia through SRFME's Postgraduate Scholarship program and the SRFME Collaborative Projects program. SRFME funded 12 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 participated in the SRFME Core Projects and were co-supervised by staff from CSIRO and state research or 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 has met 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 final report. Volume 1, 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 contain the SRFME Collaborative Projects and State Linkage Projects reports respectively and Chapter 5 provides an overview of the large SRFME Core Projects: Biophysical Oceanography, Coastal Ecosystems and Biodiversity and Integrated Modelling. Chapter 6 provides a list of all the publications arising from SRFME to date. Volume 2 covers the SRFME Core Projects beginning with a summary and synopsis of the research in Chapter 1, Chapter 2 on Oceanography, including the Indian Ocean and role of the Leeuwin Current, as well as Inshore Dynamics and Hydrodynamic Modelling, Sediment Dynamics, and Wave Propagation and Dissipation, Chapter 3 on Coastal and Shelf Pelagic Community Structure, including temporal and spatial variability in primary and secondary productivity, Chapter 4 on Biogeochemistry and Modelling, including a review of regional nutrient dynamics, Chapter 5 on Benthic Ecosystem Structure, including spatial and temporal variability in animal and plant diversity, Chapter 6 on Benthic Ecosystem Dynamics, and Chapter 7 on Data Access and Visualisation tools. Much of this work is now completed and has been published in PhD theses, technical reports and the primary literature, and the data, models and tools developed during SRFME are available to researchers and natural resource managers.

Summary of Major Achievements and Findings from SRFME

The following dot points highlight some of the achievements of SRFME and key scientific outcomes arising from the research programs:

- CSIRO and the Western Australian government invested $10 million each into the SRFME initiative and coinvestment by SRFME's collaborators added approximately $2.3 million more into SRFME research projects.
- SRFME funded a total of over $2.8 million to 32 projects under its SRFME Collaborative Research Program to Western Australian research organisations in addition to the 3 SRFME Core Projects conducted by CSIRO.
- SRFME has increased Western Australia's marine research capability by increasing CSIRO's permanent WA based marine science staff complement from 4 to 25.
- SRFME has facilitated the training of 12 PhD students, many of whom have already graduated and found employment in WA universities and state government agencies or won overseas postdoctoral fellowships.
- SRFME established collaborative partnerships involving 10 different research organisations across the state and commonwealth governments and the university sector.
- Projects funded wholly or in part by SRFME have so far generated 140 publications (see publications list on page 27).
- SRFME held six well attended marine science symposia presenting the results of its research regularly to a wide audience.
- SRFME has produced an on-line interactive data and model output interrogation tool which has been distributed to Western Australia's state government natural resource management agencies.
- SRFME organised and hosted the First International Whale Shark Conference in Perth in May 2005. Delegates from 23 countries attended and the conference proceedings has been accepted for publication as a special issue of the journal *Fisheries Research*.
- SRFME helped fund the Twelfth International Marine Biological Workshop held in Esperance in February 2003. The outcomes of this workshop have produced a two volume proceedings containing 29 scientific papers on the marine flora and fauna of Esperance region.
- A set of 23 scientific papers about the Leeuwin current and its eddies have been submitted for publication in a special issue of the international journal *Deep Sea Research II*. This special issue has been edited by SRFME scientists.
- SRFME was awarded the CSIRO Go for Growth Award 2004 "For the successful promotion and implementation of a new direction in strategic environmental marine science in Western Australia."
- Tony Koslow was awarded an international prize; the Don McAllister Medal for Marine Conservation for contributions to the conservation of deepwater coral environments.
- SRFME has produced a high resolution climatology for temperature, salinity, nitrate, phosphate, silicate and oxygen off the Western Australian coast. From this climatology, the Leeuwin Current, the South Australian Current, and the Zeehan Current off western Tasmania are found to be joined into the longest eastern boundary current (5,500 km) in the world during the austral winter, which has an important effect on poleward transport of tropical biota along the west to south coast of Australia.

- SRFME has quantified the annual and ENSO-related interannual variations of the Leeuwin current. The average flow rate of the Leeuwin Current is about 3.4 x 10^6 m^3s^{-1}. The strength of the current varies by about a factor of 2 over the year, being weakest in summer, when it is opposed by southerly winds, and strongest in winter. It is also about 40% stronger during a La Nina year than during an El Nino year.
- SRFME has quantified the nature of the linear relationship between the Fremantle sea level and the strength of the Leeuwin Current, with 7.5 cm of sea level corresponding to 1 million m^3s^{-1} of flow. These results justify the wide use of the Fremantle sea level as an index for the Leeuwin Current.
- A SRFME project has found that 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.
- SRFME has calculated that the water temperature at coastal stations off WA rose by around 0.017 ºC per year over the last 50 years, consistent with the global temperature rise attributed to climate change. At the same time, salinity off the WA coast has also increased. There is also a clear suggestion of a lengthening warm season.
- BLUElink ReAnalysis (BRAN), is a global physical model, and has been 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.
- The "Boxing Day tsunami" was captured by the tide gauge at SRFME 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. Sea-level oscillations with a period of about 1 hour persisted for another two days.
- SRFME has shown that, inshore, in water depths around 20 m, currents follow the wind direction, principally north in the summer and south in the winter, with the water speed close to 3% of the wind speed. At 100 m depth, surface waters tend to follow the wind direction, while waters below 50 m flow south under the influence of the Leeuwin Current. Water temperatures are warmer inshore during the summer but, during the winter the Leeuwin Current keeps the offshore water warmer. In 100 m, the surface water is about 2 ºC warmer than the bottom, but the water is well-mixed during the winter.
- SRFME wave and sediment modelling, calibrated against measurement, suggest that the wave climate in southern coastal waters is sufficient to keep inshore sand mobile for most (> 60%) of the time, with an increase in winter.
- SRFME found that wave amplitude diminishes rapidly across reef platforms typical of south-western Australia, with measurements at Marmion showing 1/3 reduction within 1500 m.
- SRFME has shown how eddies form south of the Abrolhos Islands (29ºS) from meanders of the Leeuwin Current. The eddies are more intense when the Leeuwin Current is flowing strongest, in the winter and in La Nina years. Warm-core eddies drift from the shelf offshore and may persist for months. The eddy drift carries a volume of water roughly equivalent to flushing the southern shelf twice per year. The eddy-induced cross-shelf transport of productive water from the shelf to the open ocean may influence the western rock lobster recruitment process. The relationship between enhanced Leeuwin flow and eddy activity on shelf productivity may explain the positive correlation between Leeuwin flow and recruitment to the western rock lobster.
- The late-autumn and early-winter bloom appears to be at least partially explained by enhanced vertical mixing, and the transport, by eddies, of nutrient-rich water from the shelf. Both of these mechanisms have been demonstrated by simplified, 1-dimensional biogeochemical modelling and fully 3-d modelling. From satellite data, the offshore flux of phytoplankton biomass by warm-core eddies is estimated as equivalent to about 4 $\times 10^5$ tonnes of carbon per year.

- The first detailed temporal study of biophysical oceanographic dynamics across the Perth continental shelf has revealed a marked contrast between summer and winter plankton dynamics. Low productivity and a deep chlorophyll maximum layer were observed in summer when the upper water column was strongly stratified. Increased Leeuwin flow and eddy activity in late autumn/early winter were associated with enhanced nutrient input to the upper mixed layer, a peak in primary production, increased phytoplankton concentrations and a shoaling of the chlorophyll maximum layer. Distinct onshore/offshore assemblages were found for all major pelagic groups: phytoplankton, microzooplankton, mesoplankton and ichthyoplankton.
- 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, were discovered. The results from this work will be published in a special issue of *Deep Sea Research*.
- A new method was developed to assess, simultaneously, the grazing of micro- and mesozooplankton on phytoplankton assemblages.
- A rare protist (radiolarian *Coelodiceras spinosum*) was caught in a sediment trap placed within an upwelling eddy in 2003, and has only been identified in six locations globally, three of which are in the Southern Hemisphere. A total of 12 specimens have been identified and its description has not been updated since the original publication by V. Haecker in 1909.
- SRFME has provided one of the most detailed spatial and temporal studies of IOPs (inherent optical property) and AOPs (apparent optical property), for any marine area in Australia. This dataset will provide an excellent base for refining the standard algorithms of the current ocean colour sensors for use in southern Western Australia, thus providing an important tool for scientists and managers of this marine environment.
- 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. Significant differences in the abundances and biomass of target and by-catch fish species (eg. Dhufish and Breaksea Cod) were also found between the sanctuary and adjacent areas open to fishing. Fish predation on grazing invertebrates such as urchins and snails was higher where fishing has reduced fish numbers. However, these differences do not presently appear strong enough to lead to the creation of "barren grounds" such as those that occur on other coasts in Australia and elsewhere worldwide.
- In a SRFME project on the biodiversity of marine fauna on the central west coast, four species of the isopod family Sphaeromatidae collected in this study have not before been recorded in Western Australia. Extended species ranges have been determined for nine species of echinoderms found in the area: seven northwards from the Fremantle/Rottnest area and two southwards from Dongara and Shark Bay.
- In a "voyage of discovery" on the outer continental shelf and continental slope, WA Museum staff have discovered several new records and range extensions of mollusc species, as well as possible undescribed (new) species. These await investigation and confirmation. Such examples include the first record of a *Conus* species in Australia and a range extension and rare live specimen of *Austroharpa wilsoni* Rehder, 1973.
- Signficant progress has been made towards the 'Seagrass Epiphyte Interactive Key', by John Huisman. This is a list of known seagrass epiphytes (over 200 species) which will take the form of a interactive identification key on CD.
- SRFME scientists John Huisman, Julia Phillips and C Parker produced a 72 page booklet which is an illustrated guide entitled *Marine Plants of the Perth Region*.
- An introduced isopod species *Sphaeroma serratum* was found in high densities in the Jurien Bay marina.

- A new species of macroalgae, named *Sargassum kendrickii* was described by N. Goldberg and J. Huisman, and named after SRFME researcher and Sargassum expert from UWA, Dr Gary Kendrick.
- The extremely rare red alga *Gelidiella ramellosa* (Kützing) Feldmann & Hamel was found in SRFME specimens collected off Perth. This species was originally described from collections made over 150 years ago from Western Australia, and has not been found in the region since that time.
- In a pilot study, a seagrass species, *Amphibolis griffithii* and its epiphytes responded rapidly to severe, short-term reductions in light availability but the shoot- and meadow-scale responses allow the plant to respond rapidly to improved light conditions after a short period of time. This work will allow us to better predict and manage the responses of seagrass meadows to the effects of dredging.
- The structure of reef algal communities in eastern Geographe Bay, as well as their seasonal cycles, was found to differ strongly from that of other parts of the west coast, mainly as a consequence of seasonal sediment and detritus re-suspension.
- Modelling of wave climate at Jurien Bay indicated that almost 75% of the variation in species diversity of algae could be explained by the strength of the wave exposure. This has implications for the creation of representative systems of marine protected areas, as well as for understanding the impacts of climate change and climate variation in the region.
- SRFME has described several characteristic algal community types and shown that some habitat types are much more important and widespread than previously thought. Many reefs are a patchwork of different algal communities, rather than being dominated by kelp forests. These findings may have important implications for our understanding of how reef ecosystems function.
- SRFME has characterised reef algal and invertebrate communities at sites from Jurien Bay to Cape Naturaliste. The character of these communities is largely similar along this gradient, justifying their inclusion in a single bioregion, but important differences were described at smaller scales.
- The role and importance of reef algae in marine food webs was shown to be disproportionately higher than that of seagrass. Importantly, because algae can be dislodged and drift many kilometres from their reef of origin, reefs can provide very important food subsidies for distant seagrass and sand habitats.

About SRFME

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.

Background to SRFME

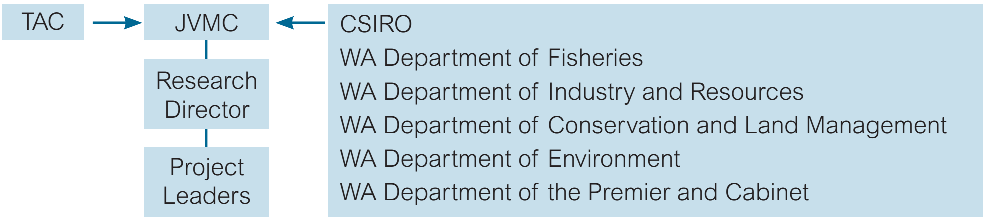
In July 1998 CSIRO approached the Western Australian Government and began a dialogue aimed towards strengthening CSIRO's presence in Western Australia. The State government formed the Marine Research Taskforce, which conducted a two-day workshop in October 1998 to identify the State's marine science 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 CSIRO to develop a solution to this funding situation.

In January 2000, the Western Australian Government agreed to jointly establish and manage the Strategic Research Fund for the Marine Environment (SRFME) with CSIRO. 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.

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.



SRFME Joint Venture Management Committee

The Joint Venture Management Committee (JVMC) comprises senior executives from each of the Department 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) (2003-2004)	Chief Scientist and Executive Director, Office of Science & Innovation, Department of Premier & Cabinet
MR PHILLIP MURRAY (Chairman) (2004-2006)	Manager, Science Policy, Office of Science, Technology and Innovation, Department of Industry and Resources
DR CHRIS SIMPSON (2001-2006)	Manager, Department of Marine Conservation, Conservation & Land Management
DR PAUL VOGEL (2001-2002)	Department of Environment and Water Catchment Protection.
DR RAY MASINI (2003-2006)	Manager of Marine Management & Protection, Department of Environment
MR PETER MILLINGTON (2001-2006)	Director of Fisheries Management Services, Department of Fisheries WA
MR RICHARD CRADDOCK (2001-2004)	General Manager, Safety & Environment, Petroleum Division, Department of Industry and Resources
MR GRAHAM COBBY (2005-2006)	General Manager, Business Development and Planning, Department of Industry and Resources
DR NAN BRAY (2001-2002)	Chief of Marine Research, CSIRO
DR TONY HAYMET (2003-2005)	Chief of Marine and Atmospheric Research, CSIRO
MR JOHN GUNN (2005-2006)	Deputy Chief, Research, Marine and Atmospheric Research, CSIRO

DR PAUL WELLINGS (2001)	Deputy Chief Executive, CSIRO
DR IAN POINER (2001-2004)	Deputy Chief, Research, Marine Research, CSIRO
MR TIM MOLTMANN (2004-2006)	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, Department of Premier & Cabinet
MS LUCY KAY (Secretary)	PA to the Research Director, SRFME

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, CSIRO
DR PETER THOMPSON (2001-2002)	SRFME Project Leader, CSIRO
DR PETER CRAIG	SRFME Project Leader, CSIRO
DR RUSS BABCOCK	SRFME Project Leader, CSIRO
DR TONY KOSLOW	SRFME Project Leader, CSIRO
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 (2001-2003)	Manager, Safety & Environment, Department of Industry and Resources
MS KIM ANDERSON (2003-2006)	Manager, Safety & Environment, Department of Industry and Resources

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.

The SRFME Framework

Research carried out through funding from SRFME has been focused within a framework of priorities developed by 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.

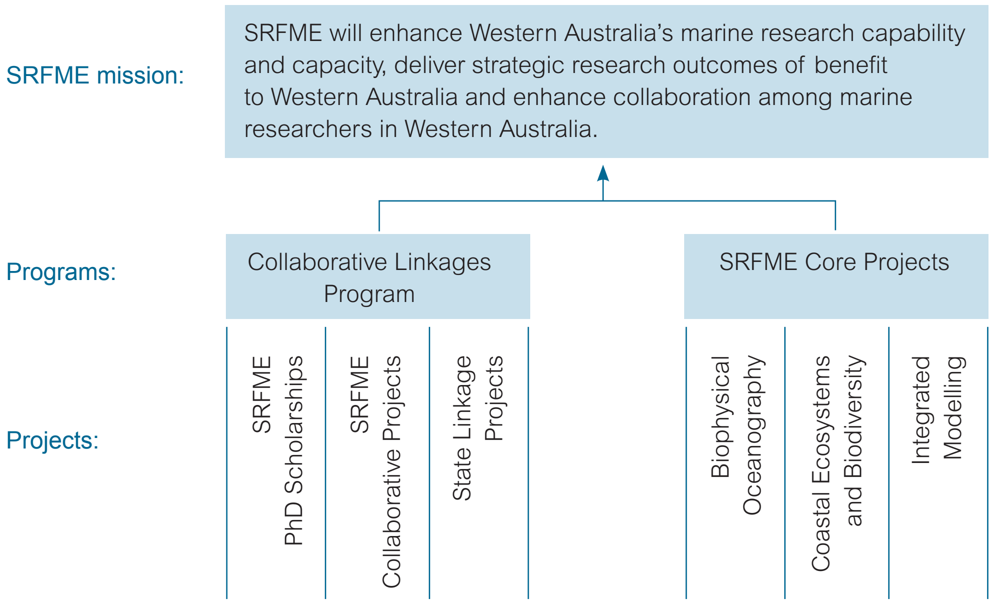
The framework of relative emphases consisted of the following:

- 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.

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.



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. SRFME Collaborative Linkages Program includes the SRFME PhD Scholarships, SRFME Collaborative Projects and SRFME State Linkage Projects.

SRFME PhD Scholarships

The objective of the SRFME PhD Scholarship scheme was to deliver strategic research outcomes and capacity building through postgraduate training as well as strengthening and broadening the outcomes from SRFME Core projects. The PhD scholarship projects also served to facilitate greater collaboration between universities and scientists in CSIRO and State Government agencies.

The PhD scholarship scheme involved SRFME and Western Australian universities co-investing in PhD stipends, operating funds and supervision costs to a total value of about $1.2 million. SRFME's investment into the scheme was about $650,000 with Western Australian universities contributing the balance.

A total of fifteen scholarships were funded, starting in 2002 and 2003, and of these, twelve scholars remained enrolled during SRFME, including two at Curtin University, two at Edith Cowan University, two at Murdoch University, and six at the University of Western Australia. Many of the students carrying out the work towards a PhD degree were co-supervised by CSIRO scientists and staff from state research and management agencies.

Three SRFME scholar symposia have been held at the CSIRO Centre for Environment and Life Sciences at Floreat, Western Australia, in June 2003, 2004, and 2005. At these symposia, each student presented an up-to-date account of their research activities. To date, seven PhD scholars have completed their degrees. The remainder of the students plan to submit their theses in 2007. A description of each project and its results to date are given in Volume 1 of the SRFME Final Report.

SRFME PhD Projects, Students, and Affiliations

1. Morphological responses of seagrass meadows to light limitation and their application to environmental quality criteria. Catherine Collier, Edith Cowan University.
2. The role of detached macrophytes for fish production & biodiversity in coastal ecosystems. Karen Crawley, Edith Cowan University.
3. Use of surrogates for the rapid assessment of marine biodiversity. Nisse Goldberg, University of Western Australia.
4. Biogeochemical processes in seagrass sediments. Kieryn Kilminster, University of Western Australia.
5. The development and validation of algorithms for remotely sensing case II waters. Wojciech Klonowski, Curtin University.
6. 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.
7. Remotely sensing seasonal and interannual oceanic primary production for WA waters. Leon Majewski, Curtin University.
8. Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia. Barbara Muhling, Murdoch University.
9. The Biophysical Oceanography off Western Australia: Microzooplankton. Harriet Paterson, University of Western Australia.
10. Physical and chemical forcing of primary production in shallow coastal waters off southwestern WA. Florence Verspecht, University of Western Australia.
11. Comparisons of benthic macroinvertebrate communities in marine environments and nearby estuaries in south-western Australia. Michelle Wildsmith, Murdoch University.
12. The influence of microphytobenthos on nitrogen cycling in sediments. Hugh Forehead, University of Western Australia.
13. Uncertainty associated with alternative ecosystem representations. Sara Belmont, Murdoch University (withdrawn).
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).

SRFME Collaborative Research Projects

The other major component of the Collaborative Linkages Program is the SRFME Collaborative Research Projects scheme which invested about $2 million in projects which tackle interdisciplinary research topics in a collaborative way and add to the realisation 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 SRFME 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, Western Australian Universities and the private sector. The total value of the SRFME Collaborative Research Projects is about $4.3 million including coinvestment by SRFME, its collaborating research partners and the private sector. Two SRFME Collaborative Projects Symposia were held in June 2004 and March 2006. Some of these projects are still ongoing and will finish in 2007. A description of each project and its results to date are given in Volume 1 of the SRFME Final Report.

SRFME Collaborative Projects, Principal Investigators, 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 Glenn Hyndes – ECU	Dr Glenn Hyndes – ECU	Dr Mat Vanderklift – CSIRO Dr Russ Babcock – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster	Dr Glenn Hyndes – ECU	Dr Glenn Hyndes –ECU	Dr Russ Babcock – CSIRO Dr Mat Vanderklift – 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 Jane Fromont, Dr Fred Wells – WA Museum	Dr Jane Fromont, 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

State Linkage Projects

The final component of the SRFME Collaborative Program is the State Linkage Projects scheme. SRFME invested $155,000 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. Nine State Linkages Projects were funded to institutions such as the WA Museum, Department of Environment, Department of Conservation and Land Management and the Department of Fisheries. Leaders from these projects have given presentations at SRFME symposia in June 2003 and June 2004. Some of the projects remained ongoing at the end of 2006. A description of each project and its results to date are given in Volume 1 of the SRFME Final Report.

SRFME State Linkages Projects, Principal Investigators, 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
The Marine Flora and Fauna of Esperance, WA	Western Australian Museum, Department of Fisheries WA	Dr Fred Wells
Assistance to Staff Members of the Western Australian Museum to Participate in the Biological Cruise of the Southern Surveyor off Western Australia in 2005	Western Australian Museum	Dr Jane Fromont
Funds to Facilitate Student Research Projects at the Abrolhos Islands	Department of Fisheries WA	Mr Kim Nardi
Baseline Biodiversity Monitoring in the Proposed Jurien Bay Marine Park – survey 3	Department of Conservation and Land Management	Dr Chris Simpson
WA Marine Algae: Taxonomic Studies and Identification Guide	Department of Conservation and Land Management Murdoch University	Dr Chris Simpson Dr John Huisman
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
Supplemental Grant for Seagrass Responses to Light Availability (*note: no report required*)	Edith Cowan University Through Department of Environment	Dr Paul Lavery Dr Ray Masini
Consequences of Reduced Light availability in Seagrass Meadows for Fauna and Fisheries	Edith Cowan University Through Department of Environment	Dr Kathryn McMahon Dr Ray Masini

SRFME Core Projects

The largest component of SRFME was the SRFME Core Projects. These were established to address the priorities established in the SRFME Framework and 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. This was to be achieved by relocating and recruiting 20 CSIRO marine research staff to Western Australia.

Development of the SRFME Core Projects

Core Project outlines were developed by CSIRO and considered by the SRFME 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 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 the extent that they were broadly consistent with the strategic priorities for the WA Government priorities within the SRFME framework and could deliver a strong CSIRO research capability into Western Australia which complemented rather than duplicated existing capability. The process of developing the SRFME Core Projects was completed on 22 May 2001 and the resultant three SRFME Core Projects were carried out over five years between 2002 and 2006 at a cost of $15.3 million.

Biophysical Oceanography Core Project

The Biophysical Oceanography project sought 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.

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.

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 anthropogenic change.

Synopsis of Findings from the SRFME Core Projects

Introduction

The Core Projects in the Strategic Research Fund for the Marine Environment (SRFME) have contributed significantly to our understanding of the marine environment of south-western Australia. Combining physical and biological oceanography with marine chemistry, biology and ecology, this research, and the future studies and publications that arise from it, will better inform decisions in managing, developing and protecting the WA marine environment.

This section provides an overview of the research conducted in the SRFME Core Projects by CSIRO and its collaborators in WA Universities and State government agencies. The detail of this research in each of the three Core Projects has been integrated and is reported on in Volume 2 of the SRFME Final Report.

The Leeuwin Current

In structuring this overview, we start with the physical oceanographic influences on the Western Australian marine ecosystems before moving on to examine the biogeochemical components of the pelagic and benthic parts of the ecosystem, including aspects of their dynamics and ecological interactions. Western Australian marine ecosystems are directly, and measurably, affected by hydrodynamic processes at a wide range of scales, from the circulation in the Pacific and Indian Oceans, down to turbulence from individual waves crossing the reefs. Time-scales range from the seconds associated with breaking waves up to the decades associated with climate change. Research in SRFME has increased our understanding of the oceanography at all of these scales. At decadal to century time-scales, the water temperature at coastal stations in the region has risen by around 0.017 ºC per year over the last 50 years, consistent with the global temperature rise attributed to climate change. At the same time, salinity off the WA coast has also increased. Sea-level at Fremantle is rising at about 1.5 mm per year. There is also a clear suggestion of a lengthening warm season. As in other parts of the world, Western Australia will need to determine how it will respond to a changed climate, and marine studies will be vital to ensure that industry and the community have adequate time and information to adapt. How the Western Australian marine environment will change as a result of climate change remains a great unknown.

The Leeuwin Current is profoundly influential on the marine ecosystems of Western Australia. As one of very few poleward-flowing eastern boundary currents in the world, it has been the subject of much research. SRFME studies have quantified both the annual and ENSO-related interannual variations of the Leeuwin Current, and the relationship between the Fremantle sea level and the strength (volume transport) of the Current. These results justify the usage of the Fremantle sea-level as an index for the Leeuwin Current, that has been widely used in fisheries management in Western Australia, especially for predicting western rock lobster recruitment. The Leeuwin Current is about 40% stronger during a La Nina year than during an El Nino. The Current responds as well to a smaller signal called the Pacific Decadal Oscillation, which can also be monitored by the Fremantle sea-level.

The average flow rate of the Leeuwin Current, estimated from long-term, ship-based measurements, is about 3.4 x 10^6 m^3s^{-1}. An increase in the flow rate of 1 million m^3s^{-1} is reflected by an increased Fremantle sea-level of about 7.5 cm. The strength of the current varies by about a factor of 2 over the year, being strongest in winter and weakest in summer, when it is opposed by southerly winds. These summertime winds may generate northward coastal currents that have been given local names such as the Capes and Abrolhos Currents.

SRFME research has determined that the extent of influence of the Leeuwin Current is much greater than previously envisaged. During the winter, the Leeuwin Current turns east past Cape Leeuwin, and can be tracked, in satellite images of surface temperature and height, all the way to southern Tasmania, a distance of 5500 km from North West Cape, making it the world's longest current. Its name changes to the South Australian Current, and then the Zeehan Current, over this distance.

Eddies form south of the Abrolhos Islands (29ºS) from meanders of the Leeuwin Current. The eddies are studied primarily from satellite altimetry, and are more intense when the Leeuwin Current is strongest, in the winter and in La Nina years. Warm-core eddies drift from the shelf offshore and may persist for months. Approximately six warm-core eddies form each year, carrying a total volume of water roughly equivalent to flushing the southern shelf twice per year. The eddies are believed to carry nutrients and phytoplankton from inshore waters, significantly enhancing offshore primary production, and probably play a significant role in the advection of larvae. Significant advances in the understanding of these eddies and their importance to the southwestern Australian continental shelf ecosystem have resulted from SRFME studies. This work is described in part in both volumes 1 and 2 of the SRFME Final Report and is to be documented in a special issue of the journal *Deep Sea Research.*

The Leeuwin Current is apparent in images of both sea-surface temperature and sea-surface height. As part of SRFME, an accurate numerical (hydrodynamic) model of the Leeuwin Current has been developed, at 10 km horizontal resolution, by forcing it with the surface observations, and using the model equations to calculate the 3-dimensional current and density fields. The model has been validated against ship-based observations of eddies, and inshore moorings.

Three moorings were deployed across the shelf from Two Rocks in water depths of 20 m, 40 m and 100 m, and maintained for a year, primarily recording currents and water temperature. At the innermost mooring (approx. 5 km offshore), the currents follow the wind direction, principally north in the summer and south in the winter, with the current speed close to 3% of the wind speed. At the 100 m mooring, about 50 km offshore, surface waters tend to follow the wind direction, while waters below 50 m flow south under the influence of the Leeuwin Current. The water is warmer and saltier inshore during the summer, but during the winter the Leeuwin Current keeps the offshore water warmer. In summer, the surface water in 100 m is about 2 ºC warmer than the bottom, but the water is well-mixed during the winter.

Biogeochemistry

Two Rocks was also the base for a major SRFME measurement program along a transect from nearshore to the outer continental shelf (100 m water depth). The transect was occupied monthly from 2002 – 2004, with a quarterly extension 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 the moorings to provide both a cross-sectional description of the physics and productivity, and verification data for the modelling.

The Two Rocks transect data reveal that summer conditions on the shelf and offshore were oligotrophic, characterised 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) layer located between the 0.1% and 1.0% light levels. The DCM was frequently associated with a deep nitracline (between 100 and 150 m water depth). By contrast, in late autumn and winter, the upper mixed layer deepened and stratification weakened, leading to shoaling of the nitracline and DCM. Except within the lagoon, where no clear seasonal cycle was observed, phytoplankton biomass integrated through the water column was generally twice as high from April – September as in the spring and summer (October – February).

Satellite data reveal the spatial extent of the dynamics observed at the transect. Near-surface chlorophyll-*a*, an indicator of phytoplankton biomass, can be inferred from ocean-colour sensors mounted on satellites. Over the continental shelf, phytoplankton production appears to peak during the late autumn and early winter, corresponding to the onset of winter storms and the seasonal strengthening of the Leeuwin Current and its eddy field. Further offshore, the phytoplankton biomass peaks in late winter, assisted by the eddies' transport of both nutrients and phytoplankton from the shelf. Deeper mixing during winter is also likely to enhance nutrient levels. The offshore flux of phytoplankton biomass by the warm-core eddies is estimated as equivalent to about 4×10^5 tonnes of carbon per year.

A relatively simple, one-dimensional, biophysical model has been developed during SRFME to demonstrate the importance of spinup over the shelf for warm-core eddies. The model represents an eddy as a trapped body of water and follows it as it detaches from the Leeuwin current and moves offshore. Given appropriate density and nutrient properties during eddy formation, the model successfully distinguishes between the productivity of the warm and cold-core eddies as they evolve. Cold-core eddies tend to spin up on the low-nutrient, seaward side of the Leeuwin Current.

High-nutrient water below the nutricline is not considered to contribute directly to the shelf, because the Leeuwin Current inhibits upwelling. However, vertical mixing, associated both with storms and the increased intensity of the Leeuwin Current, is thought to bring nutrients locally towards the surface, into the photic zone, during autumn and winter.

The role of vertical mixing on the biogeochemistry was also tested with a simplified one-dimensional biogeochemical model. The model was set up to simulate the upper 200 m at station E, the outermost station on the transect, 85 km offshore and in 1000 m of water, for the year 2003. Vertical mixing due to atmospheric conditions and the Leeuwin Current was simulated by forcing ("relaxing") the vertical temperature and salinity profiles to synTS (a technique which, given the surface height and temperature, derives T and S profiles from historical data sets).

There were only 5 transects to Station E during 2003, providing limited data for comparison. The model appears to predict well (given only 5 comparison points) the measured seasonal cycle of temperature. It predicts the stable summertime nutrient profile with a deep (100 m) chlorophyll maximum, and the transition to a surface bloom in autumn. It failed to predict the deep chlorophyll maximum observed in late winter. The winter observation corresponded to an exceptional cold event (2 °C cooler at 100 m depth), relative to synTS predictions, and may have been associated with an eastward migration of the Leeuwin Current, obviously beyond the scope of a 1-d model.

Thus, the late-autumn and early-winter bloom appears to be at least partially explained by enhanced vertical mixing, and the transport, by eddies, of nutrient-rich water from the shelf. It is also possible that the intensified Leeuwin may entrain nutrients in the north, where the nutricline is shallower, and advect them southward.

One of the main roles of the SRFME hydrodynamic model was to provide the ocean-forcing for a fully 3-dimensional biogeochemical model. The biogeochemical model simulates the cycling of carbon, nitrogen and oxygen through the water column and sediments. Its primary output is phytoplankton biomass, and its key initial challenge is to represent the seasonal cycle of phytoplankton productivity as observed from satellites and measurements from the Two Rocks transect. The model appears to simulate the large-scale variability, with low productivity in the summer and blooms in the late autumn and winter. However, it does not reproduce the high inshore productivity visible in satellite images for autumn and winter.

Nutrient sources remain a significant unknown for the coastal and shelf biogeochemistry. The inshore productivity is assumed to be due to onshore or nearshore sources that are not sufficiently identified or quantified to be included in the model. Nutrients will also be stored in coastal and shelf sediments, and presumably released during high wave and swell conditions. Sensitivity tests with the model indicate the likely importance of nutrient storage in the sediments, but the magnitude of the store is unquantified. Further, the large-scale nutrient distribution, required for both initialising the model, and for its open boundary conditions, is not well established. The hydrodynamic model currently uses temperature and salinity fields predicted from synTS. The model can also access CSIRO's global BLUElink model for initial and open boundary conditions. Equivalent fields for nutrients do not yet exist.

Plankton Ecology

Measurements along the Two Rocks transect indicate that phytoplankton biomass and production integrated through the water column were generally several-fold higher offshore, although maximum volumetric chlorophyll concentrations were observed inshore. Depth-integrated chlorophyll concentrations on the shelf and offshore generally ranged from 20 – 40 mg chl *a* m^{-2}, compared to 5 – 15 mg chl *a* m^{-2} inshore. This difference was considerably reduced in spring and summer, because the seasonal cycle was less pronounced in the lagoon environment. Annual phytoplankton production over the study period was 46 g $C \cdot m^{-2} \cdot yr^{-1}$ inshore and about 115 g $C \cdot m^{-2} \cdot yr^{-1}$ on the shelf and offshore—relatively oligotrophic for a coastal environment. Not unexpectedly, given the nutrient depleted conditions generally observed in the euphotic zone, biomass and production were far greater in the small phytoplankton size fraction (< 5 μm): the median percentage of biomass and primary productivity in the small size fraction was 5 and 12%, respectively. Based on analysis of HPLC pigments, the outer shelf and offshore stations were characterised by high prochlorophyte and unicellular cyanobacteria populations. Small flagellates were most prevalent on the shelf, and periodic blooms of larger diatoms 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.

Microzooplankton biomass peaked in winter, consistent with the winter peak in chlorophyll. Species richness was significantly higher on the shelf and offshore than nearshore, which was ascribed to the generally less stable inshore environment. Dilution experiments indicated that the microzooplankton consumed, on average, 60% of primary production. Growth of the picoplankton was particularly closely coupled with microzooplankton grazing.

The impact of grazing of mesozooplankton on the phytoplankton was generally low, but the impact on the microzooplankton increased with distance offshore. Incubation experiments showed that increased densities of mesozooplankton grazed down an increased proportion of the microzooplankton, which led to a decrease in grazing on phytoplankton.

Particularly clear trends in onshore-offshore and seasonal assemblages were seen in the ichthyoplankton. These trends were related to water mass structure and the seasonal characteristics of spawning in the region. The inshore region was characterized by reef fishes, such as gobies, clinids, blennies and tripterygiids, whereas pelagic fishes, such as clupeids and carangids, dominated over the shelf. Oceanic fishes, such as myctophids, phosichthyids and gonostomatids dominated the ichthyoplankton at the shelf break and over the slope. However the changing seasonal dynamics of the Leeuwin and Capes Currents were clearly reflected in the ichthyofauna assemblages.

Benthic Ecology

Towards the coastline, the seabed falls within the photic layer, and macrophyte productivity begins to dominate phytoplankton productivity. SRFME made significant advances in our knowledge of the patterns found in the benthic components of Western Australia's marine ecosystems and the underlying processes and dynamics that give rise to these patterns and the variability exhibited in benthic communities. Western Australia is unusual in possessing high-biomass, high-productivity benthic ecosystems despite the relatively low-nutrient levels that result from the low-rainfall climate and the influence of the Leeuwin Current.

SRFME focused on improving understanding of one major habitat type – coastal rocky reefs – that had previously received relatively little attention. Rocky reefs are an important habitat type in nearshore coastal waters, supporting a diverse assemblage of benthic macroalgae and associated fish and invertebrates. The rocky reef communities are a key component of coastal productivity, provide habitat and food for marine fauna, contribute to biogeochemical cycles, and can exert influence over nearby habitats such as seagrass meadows. Despite their recognised importance, comparatively little is known of the ecology of rocky reef habitats along the lower west coast of Western Australia.

SRFME research incorporated the first quantitative, broad-scale investigations of several key ecological processes on the reef benthos of south-western Australia. Major findings were that spatial gradients in wave exposure were significantly correlated with spatial patterns in the species richness and composition of macroalgae, that the rates of some ecological processes (e.g. algal productivity) and the abundances of both mobile and sessile fauna vary significantly between inshore and offshore reefs, and that consumers (including humans) exert a significant influence on some reef-associated biota. The understanding of both pattern and process is essential to achieving the ultimate goal of modelling the coastal ecosystem and gaining the ability to predict ecosystem behaviour.

The benthic field sites were categorized into 3 "regions" – Jurien, Perth and Geographe Bay – within each of which there were two "locations" – Green Head and Jurien Bay, Two Rocks and Marmion, and Bunbury and Cape Naturaliste, respectively. Each location had two measurement "sites", within which quadrats were sampled.

There is a strong seasonal signal in algal biomass in all regions, but processes underlying this pattern varied for different locations, or for particular sites within locations depending on the dominant algal habitat type. Most locations (e.g. Jurien Bay, Marmion, Two Rocks and Bunbury) showed lowest biomass in winter. The proximal factors that drive these variations also differ among locations. Erosion of biomass is most likely to be driving changes in *Ecklonia*-dominated sites (Marmion, Two Rocks, Perth) while light-limitation is likely to be a major factor at Bunbury. Here, seasonal resuspension of particulate matter and sediment by winter and spring storms and swell appears to affect the entire algal community, which is largely made up of foliose red and brown algae. At sites where *Sargassum* dominates (Green Head), there is a summer minimum in biomass because of the algal phenology. In contrast to the pattern for biomass, algal community structure showed no seasonal trend.

Among the study regions, the overall number of algal species recorded was similar. In all the regions, by far the largest contribution to overall species diversity was made by the red algae. While variations in species richness were not large, more species were recorded at the lower latitude sites, and fewer recorded in the Perth region. This may be explained by variation in the relative dominance of large brown algae in the different regions, since there is an inverse relationship between *Ecklonia* biomass and that of red algae. The highest densities of *Ecklonia* were found at reefs in the Perth region.

Macroalgal community structure varied at all the spatial scales we examined, but was strongest at the site level. In fact, at the site level, the differences between sites, even within locations, was greater than the differences between sites at the most widely separated regions. This strongly suggests that, for algal community structure, processes operating or varying across relatively small scales may be responsible for much of the observed variation observed. Assemblages not dominated by *Ecklonia* or other canopy species were most often composed of a diverse mixture of medium to small sized foliose algae, mainly red and brown, although green algae were occasionally dominant. Our study has shown that these habitats can on average form almost 50% of all algal communities, and are likely to be of greater importance than previously assumed in WA.

Since the nature of this variation was often associated with clear qualitative differences in community structure, for example, the presence or absence of a canopy, we developed a method to classify algal communities based on a semi-quantitative mix of structural and taxonomic attributes. The system was accurate in 75% of cases and offers a means of classifying algal assemblages for use in higher-level analysis of patterns at the landscape scale, and as a rapid system for visual quantification of habitats for mapping and ground-truthing (for example, in hyperspectral mapping).

A statistical model relating algal-assemblage structure to physical environmental variables in the Jurien region showed that the two factors most strongly associated with community structure were seabed roughness at the 1 m and 10 m scales, and modelled seabed orbital velocity. Wave-generated water movement across the seabed and small-scale seabed topography interact very strongly, further reinforcing the conclusion that small scale variations in ecological processes are likely to be of prime importance in determining the structure of benthic reef assemblages. Processes controlled by interactions of topography and water motion include physical disturbance (dislodgement), diffusive processes (gas and nutrient exchange) and sediment transport (scour and burial). It is important for us to understand this small scale variation in algal assemblages, as a basis for future work and for scaling up results to larger areas.

For invertebrates, weaker patterns in community structure were present, particularly for the algal-associated epifauna. Some pattern was present in the larger sessile and solitary fauna, but levels of similarity/dissimilarity did not vary markedly across scales. The lack of pattern suggests that the spatial scales encompassed in the sampling (regions, locations, sites), which was designed primarily to quantify algal assemblages, did not adequately capturing variation in the invertebrate assemblages.

However, informative patterns did emerge at different spatial scales. Species number varied according to the algal habitat type with epifaunal invertebrate species richness (at the scale of 0.25 m^2 quadrats) higher for turf habitats, followed by *Caulerpa*, *Ecklonia* forest, *Sargassum*, low algae, red foliose and mixed brown habitats. A higher number of solitary and sessile invertebrates (1 m^2 quadrat) were found to be associated with low algae and red foliose habitats, followed by mixed brown, turf, *Sargassum*, *Ecklonia* forest and *Caulerpa* habitats. As for the algae, the highest number of invertebrate species was recorded at Jurien, and Perth had the lowest numbers of species although numbers were only marginally greater at Geographe Bay. While the magnitude of the differences is relatively small, it is once again interesting that the region with the most *Ecklonia*-dominated sites had the lowest number of species.

For larger sessile invertebrates, belt transects revealed strong trends for coral and sponge abundance, within low algae and red foliose algal habitat types. Brown algal dominated habitats totalled 53% of habitats covered by transects at Marmion, yet within these transects only 22% of sponges and 7% of corals were recorded. These patterns essentially reflect algal habitat structure and coverage, and its patchiness or variability, not just at the site level but within sites. Interestingly a coral species (*Plesiastrea*) was one of the taxa most responsible for dissimilarity among sessile and solitary invertebrate assemblages at the site level. Sessile invertebrates such as corals and sponges may achieve a higher larval settlement rate, and/or higher subsequent survival and growth, in habitat that is lower and more sparsely covered by algae, in contrast to the typically dense, canopy forming brown algae species.

At the scale of individual quadrats, there were significant patterns in the overall abundance of mobile invertebrates, particularly molluscs and crustaceans. Most of these animals are relatively small and likely to be key contributors to secondary production in the reef ecosystem. This pattern resulted from a significant negative correlation between invertebrate abundance and the biomass of *Ecklonia radiata*, that has a key indirect influence on invertebrate assemblages.

Fish assemblages showed a contrasting pattern to those of algae and invertebrates, with a high level of variation among assemblages at the regional level and virtually none at the location level. However, at the site level there was once again significant variation in fish assemblages. We attribute this consistent variation at the site level to the association of fish assemblages with definable algal habitat types that tend to dominate at particular sites. While large brown algal assemblages dominated at just over half the sites, nearly as many sites were instead characterized by a diverse assemblage of foliose and filamentous red and brown algae.

At small scales across all three major groups we have studied, algae, invertebrates and fish, we see the importance, even dominance, of processes operating at distances of metres to tens of metres for structuring variation in benthic assemblages. This variation has important implications for understanding which ecological processes structure these communities. As noted, analysis of algal community structure strongly suggests that some aspect of wave action, coupled with the nature of the substratum, interact to determine the characteristics of the algal community. The characteristics of the algal community in turn appear to strongly determine the nature of invertebrate assemblages. For fish, these aspects of habitat also appear to be important, although in their case there may also be stronger large-scale biogeographic factors influencing distribution across the west coast region.

At the regional level, some locations have physical characteristics that mean larger-scale processes play a more important role. Variation in water quality in eastern Geographe Bay creates conditions that result in a seasonal change in algal biomass, quite distinct from other parts of the west coast. The implications of this unusual pattern merit further exploration. It is possible that elevated nitrogen levels in Perth metropolitan waters are linked in some way to the abundance of *Ecklonia*-dominated habitats at Marmion. For most of the coast, smaller-scale studies focused on the impact of environmental factors at the site, or even quadrat, scale are likely to lead to a broader general understanding of key ecological processes across the coastal ecosystem as a whole. The role of such small-scale processes, and of nutrients in coastal reef systems, remains an important area of research yet to be fully explored.

In December 2005, 4 acoustic doppler velocimeters, capable of measuring wave orbital velocities, were deployed across the Marmion reef to measure the cross-shore change in wave signature. The amplitude diminished by up to 1/3 as the waves travelled 1500 m across the reef. This behaviour was reproduced by a standard wave model (SWAN), but with enhanced bottom friction attributed to the reef roughness.

In these shallower waters, the water movement tends to be dominated by the effect of surface waves. The 20-m mooring on the Two Rocks transect included a pressure sensor to measure waves, and an acoustic doppler current profiler, which could be used to infer the sediment suspended from the seabed by the waves. The data were used to calibrate a sediment-transport model. They show that, at this inshore location, the waves are sufficiently energetic to keep medium-sized sand mobile most of the time.

South and north of Perth, the sediment mobility was examined by nesting a local wave model (SWAN) inside a global model (WAVEWATCH 3). The modelling suggests high levels of sand mobility (>60% of the time) in Geographe Bay throughout the year, with an increase (to 80%) in the winter. There is a small area in the lee of Cape Naturaliste where the mobility is much reduced. Mobility rates are also similar off Geraldton.

Exposure to waves affects the distribution of macroalgal species on the reefs. For Jurien Bay, the wave model was used to estimate exposure to large wave events at the 26 sites sampled during the benthic field program. The species diversity at the sites was positively correlated with wave disturbance; that is, the more exposed the site to large wave events, the higher the diversity. Presumably, the breakage and removal of plants by big waves increases opportunities for new species to establish. There is a suggestion that, at the highest exposure, diversity begins to diminish again, presumably because only the hardiest species survive under the most extreme conditions. This increase, and subsequent decrease in species diversity with increasing disturbance rate is a well-documented phenomenon, generally known as the *intermediate disturbance hypothesis.*

Accumulated wave exposure over an 8 year period provided a significantly better explanation of species richness patterns than wave-energy over a single year. This suggests that species richness of macroalgae might be the result of integration of processes occurring over years, rather than the result of short-term responses to disturbance.

The consequences of wave action for an individual alga include detachment from the substrate on which it grows. Our research showed that, once detached, kelps may drift for many kilometres. Substantial accumulations of detached reef algae occurred at an inshore reef, coinciding with high densities of sea urchins, which eat mainly detached fragments of algae. Analyses of the morphology of individual kelps at this location indicate that a large proportion originate from reefs several kilometres further offshore. These results demonstrate large-scale trophic linkages across the lagoon that are a result of wave action.

Trophic linkages such as these are likely to have profound implications for the function of WA's coastal ecosystems at broad scales. For example, differences between inshore and offshore reefs were observed for densities of sea urchins (higher densities inshore) and grazing on drift kelp by sea urchins (higher inshore), as well as for algal productivity and diversity. This overall trend might be a result of the gradient in wave action, and gradients in ecological processes that occur due to physical disturbance by waves, such as detachment and export of reef algae. Our measurements of rates of recruitment to collectors indicated that while rates were higher inshore, they were also highly variable. This suggests that densities of adult urchins inshore were not due to higher recruitment, but to the higher availability of food (drifting fragments of algae).

Primary productivity of *Ecklonia* was greater at Jurien than in the Perth Region. In addition, productivity was higher offshore at Jurien, but not in the Perth Region. These results suggest that nitrogen *per se* might not be limiting for growth of macroalgae on this coast since these productivity patterns are directly opposite to the C:N trends found in *Ecklonia* plants from these sites. The C:N values were far lower at Perth, than at Jurien — yet production was higher at Jurien. There is potential for anthropogenic nitrogen sources in the Perth region to enhance the growth of macroalgae which is worthy of further investigation. Nutrient levels offshore from Perth seem to be elevated and to carry a high level of $\delta^{15}N$, a sign of terrestrial effluent origins for this nitrogen. In addition, C:N ratios of kelps from both regions were lower inshore than offshore — yet production tended to be higher offshore, at least at Jurien. The most common paradigm for marine algae of all types is that their growth is nitrogen limited, yet our data contradict this assumption. The suggestion that availability of nitrogen might not be limiting growth of *Ecklonia* on the WA coast requires investigation through controlled experiments. Other potential influences on the rate of N uptake, such as light availability, and the role of wave-driven turbulence, must also be investigated.

Little of the *Ecklonia* primary productivity was directly consumed. The only direct grazing was by herbivorous fish. However, densities of herbivorous fish, and rates of grazing by herbivorous fishes, varied from reef to reef, and showed no broad trends. The highest rates of consumption of tethered kelps were on drifting fragments, and mainly by sea urchins. Similar observations have also been made in seagrass and intertidal habitats in the region. It is clear that detached macroalgae are ubiquitously important in sustaining coastal food webs on the Western Australian coast.

Humans can exert a strong influence on the structure of communities through harvesting of key species. For example, in several parts of the world, hunting and fishing has reduced predators of sea urchins to ecologically trivial abundances, resulting in increases in sea urchin density and landscape-scale decreases in canopy-forming primary producers due to grazing. Similar processes are possible in WA, and are a potential explanation for variation in the structure of assemblages of reef algae. SRFME research included the first assessment of the effects of a 16-year fishing closure (the Kingston Sanctuary at Rottnest Island) on assemblages of fish and invertebrates. The overall abundance of fish, abundance of predatory fish and western rock lobster (*Panulirus cygnus*) was higher inside the Kingston Sanctuary than at adjacent fished reefs. For fish, two popular angling species and four by-catch species were more abundant inside the sanctuary, while some bycatch species showed opposite patterns.

The differences in abundance of predatory fishes and lobsters were reflected by experimental predation rates on small and medium size invertebrates. The intensity of predation on tethered sea urchins was higher in the sanctuary. However, there were no simple trends in the abundance of prey: the abundance of one species of sea urchin (*Heliocidaris erythrogramma*) was lower in the area protected from fishing, consistent with the pattern predicted if predation was a strong influence, but the abundance of a second species (*Centrostephanus tenuispinus*) was higher. There was also no evidence of trophic-cascade effects outside the protected area as a result of lower abundance of predators, with no difference in assemblages of macroalgae between the sanctuary and fished areas.

The correlation between wave energy and both algal diversity, and community structure, plus the patchy nature of macroalgal assemblages, suggests that physical disturbance may have much more pervasive and important influences on benthic communities of WA coastal reefs than do top-down effects resulting from variations in predation. Curiously, bottom-up effects (supply of nutrients) also appear to have less influence on the structure of benthic assemblages than might be predicted in what has been assumed to be a nutrient-limited coastal ecosystem. The dynamics of patches and the influence of varying nutrient availability require more detailed investigation before we can be certain of their impact on the dynamics of WA coastal ecosystems.

Data Storage and Access

As a by-product of its research, SRFME has set high standards in the archiving and documentation of data collected and has developed innovative tools for the visualisation and analysis of data and model outputs.

The SRFME field and model data have been stored in standard formats (mostly NetCDF and ASCII column-files) in a data repository that is accessible for visualisation by the software DIVE (Data Interrogation and Visualisation Environment). DIVE enables data from different sources (such as models, vessels, moorings and diving), to be overlaid and compared in up to 4 dimensions. The DIVE software has been supplied to State Agencies to give them direct access to the SRFME data set.

DIVE is supplemented by other software tools developed during SRFME. WebOLIVE is a web-based visualisation program for regularly gridded data such as model output and climatology. WebOLIVE is installed on the SRFME website. Aus-Connie (The Australian Connectivity Interface, *http://www.per.marine.csiro.au/aus-connie*) allows users to investigate large-scale patterns of spatial connectivity around Australia. It provides estimates of the probability that any two regions are connected by ocean circulation. Meanwhile, the Argo website (*http://www.per.marine.csiro.au/argo*) provides an interactive data explorer to display tracks and vertical profiles from over 100 Argo vertical profiling floats which have been deployed in the Indian and Southern Oceans.

SRFME also constructed high-resolution climatology for temperature, salinity, nitrate, phosphate, oxygen and silicate off the Western Australian coast. The SRFME-CSIRO Atlas for Regional Seas (CARS) covers the domain 110E-130E, 40S-10S at one-eighth-degree resolution, with data at 56 standard depths. SRFME CARS is available at *http://www.per.marine.csiro.au/SRFME-modelling/olive_atlas.html*

Conclusion

While SRFME has made very significant advances in our understanding of many aspects of Western Australian marine ecosystems, much remains to be done. The area is known for its unique oceanography, productive benthic ecosystems and as a biodiversity “hotspot” worthy of significant conservation measures. However, the area is also one that creates great wealth for Australia through the exploitation of its natural resources and, increasingly, nature-based tourism. Achieving the right balance of these activities and ensuring their sustainability is a major challenge, particularly as the population of Western Australia's coastal regions is growing rapidly. As the coastal population grows, so too will pressures on the coastal region. The range of often competing uses and cumulative impacts has the potential to degrade Western Australia's unique marine environment, if the coasts are not managed with care.

Continued high-quality strategic research like that conducted over the five years of SRFME can ensure that decision-making in the marine environment is based on continually improving knowledge of these marine systems. Thus, while this report closes a successful chapter in marine science in Western Australia, the need for strategic marine science remains as great today as when SRFME began. The chapters in this report outline where SRFME has advanced our knowledge of Western Australian marine ecosystems. In addition, the chapters set out a path for future strategic research to further understanding of these systems. In many cases, the new research needs to test hypotheses that have arisen in SRFME. It should also target our need to describe key processes in the marine environment, to enable us to better predict the response to future anthropogenic change.

Publications

Publications arising from SRFME funded research and related activites

This is the list of the 140 publications, reports and manuscripts which have arisen from SRFME and allied projects to date. While this listing includes some as yet unpublished manuscripts, it is also an as yet incomplete listing of all the publications which will eventually arise from SRFME. More publications will be produced as SRFME students begin to write up more papers from the research included in their theses (Volume 1, Chapter 2). In addition, those yet-to-be-concluded SRFME Collaborative Projects (Volume 1, Chapter 3) will also give rise to more publications as will the research from the SRFME Core Projects described in Volume 2. This list does not include a significant number of conference presentations and milestone reports which are referred to in the main volumes of the SRFME Final Report.

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Acknowledgements

Many people have contributed to the establishment and management of SRFME and the development of its research portfolio. Many more have participated in the many research projects funded by SRFME. In addition to the SRFME research teams, SRFME PhD students and their supervisors whose names are listed with their contributions to each of the two volumes of the SRFME Final Report, we thank the following people who have contributed to the SRFME Joint Venture in a number of ways over the period of 2000 to 2006.

Kim Anderson, Department of Industry and Resources
Simon Allen, CSIRO
Dr Greg Ayers, CSIRO
Arthur Banks, CSIRO
Louise Bell, CSIRO
Pru Bonham, CSIRO
Dr Bernard Bowen, Chairman Marine Research Taskforce
Dr Nan Bray, CSIRO
Dr Alan Butler, CSIRO
Dr Ed Butler, CSIRO
Dr Nick Caputi, Department of Fisheries
Gary Carroll, CSIRO
Celine Chan, CSIRO
Graham Cobby, Department of Industry and Resources
Ian Cook, CSIRO
Dr Scott Condie, CSIRO
Jeff Cordell, CSIRO
Richard Craddock, Department of Industry and Resources
Dr George Cresswell, CSIRO
Lea Crosswell, CSIRO
Dr Nick D'Adamo, Department of Conservation and Land Management
Carl Davies, CSIRO
Peter Dunn, CSIRO
Siobhan Duffy, CSIRO
John Gunn, CSIRO
Peter Green, CSIRO
Kim Grey, CSIRO
Michael Harrison, CSIRO
Dr Tony Haymet, CSIRO
Dr Chad Hewitt, CSIRO
Dr Bruce Hobbs, Department of the Premier and Cabinet
Dr John Huisman, Murdoch University
Tennille Irvine, CSIRO
Neale Johnston, CSIRO
Lucy Kay, CSIRO
Hiski Kippo, CSIRO
Mark Lewis, CSIRO
Craig McCauley, CSIRO
James McLaughlin, CSIRO
Dr Mike Mackie, Department of Fisheries
Dr Ray Masini, Department of the Environment
Dr Sue Meek, Department of Commerce and Trade
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Toni Moate, CSIRO
Tim Mangan, CSIRO
Tim Moltmann, CSIRO
Michael Mulligan, Geraldton Port Authority
Phillip Murray, Department of the Premier and Cabinet
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Dr Fred Wells, WA Museum
Dr Kate Wilson, CSIRO
Dr Jackie Zanetti, CSIRO