IMOS Integrated Marine Observing System

National Science and Implementation Plan 2015-25

Australian Government
Department of Innovation Industry, Science and Research

IMOS is a national collaborative research infrastructure, supported by Australian Government. It is led by University of Tasmania in partnership with the Australian marine & climate science community.

UTAS

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Available as separate documents...

Bluewater and Climate Node Science and Implementation Plan

WAIMOS Node Science and Implementation Plan

Q-IMOS Node Science and Implementation Plan

NSW-IMOS Node Science and Implementation Plan

SAIMOS Node Science and Implementation Plan

SEA-IMOS Node Science and Implementation Plan

Authorship- The national overview (sections 1 to 9), which draws heavily on the Node plans, has been prepared by the IMOS Director Tim Moltmann and Scientific Officers: Ana Lara-Lopez, Shavawn Donoghue, and Katherine Hill. Authors of the Node Plans are cited on the front page of each Plan. The significant contribution of many people from across the Australian marine and climate science community, and of our international reviewers, is gratefully acknowledged.

1 Executive Summary

The National Science and Implementation Plan has been written to guide the development of Australia's Integrated Marine Observing System (IMOS)[1]. Many researchers from across the Australian marine and climate science community have contributed to it with all key components internationally peer reviewed. It represents a major body of work that will continue to evolve over the life of IMOS, in response to national needs and global trends.

It is important to highlight that this is a science and implementation plan to guide the development of a research infrastructure program. As such, it is not meant to define the research projects that will use the infrastructure, but rather to define the observations and data streams required to address big, strategic, science questions that will underpin a wide variety of current and future research. It is therefore essential that the Plan is well aligned with frameworks guiding Australia's National Innovation System over the longer term. These include the Australian Government's Strategic Science and Research Priorities (Department of Industry, 2013), and the National Marine Science Plan 2015-2025: *Driving the development of Australia's blue economy* (2015).

IMOS has now been funded for its first decade (2006-16). Continuing to articulate a compelling science case is crucial to sustained investment in a comprehensive, national scale in-situ marine observing system for decades to come.

IMOS is designed to assist in delivering critical information over multiple decades on ocean change, climate variability and weather extremes, major boundary currents, continental shelf and coastal processes, and marine ecosystem responses. This information is essential if the Australian marine and climate science community is to meet knowledge needs about our oceans and support evidence-based decision making on issues of national significance, with intergenerational impact.

As data streams develop and grow and long-term time-series of key variables are constructed, there will be opportunities to refine the observing system and address important information gaps. In the open ocean, additional information on the deep ocean, high latitudes (including the sea ice zone), and the tropics will improve our understanding. On the other hand, the coastal zone will benefit greatly by enhancing geographical coverage and spatial resolution. Furthermore, a sustained *in situ* observing program is crucial to underpin ecosystem-based management for Australia's marine environment.

November, 2015

[1] All acronyms used in this document are explained at first use, and again in Attachment 1.

2 Outline

The Plan is structured into seven components – a national overview (this document) and six science Node chapters (separate documents). Together, they provide the rationale for current and ongoing investment in a national scale integrated marine observing system.

In the first sections of the national overview (Sections 3-6), the Plan briefly introduces IMOS, sets the context for sustained ocean observing in Australia, and explains the role and structure of IMOS science Nodes. This is followed by a scientific background section (Section 7), which is divided into five major themes of research: 1) Multi-decadal ocean change, 2) Climate variability and weather extremes, 3) Major boundary currents and inter-basin flows, 4) Continental shelf and coastal processes and 5) Ecosystem responses. In each of the major research themes, the current knowledge and science questions are a summarised from the more detailed Node chapters of this plan. This information sets the context for the observations needed to answer these science questions. The platforms that will deliver these observations are then identified together with gaps in the current observing capability and a list of future priorities is then outlined to address those gaps.

The following section (Section 8) assesses IMOS capabilities using the Framework for Ocean Observations developed and adopted by the Global Ocean Observing System (GOOS). The Framework identifies pathways by which new observing technologies can be brought into the long-term observing system according to their “readiness level”.

Section 9 explains the design of IMOS as an integrated observing system. Here we explain how, where and when the observational resources are deployed and maintained across each of the Nodes. Also given are the primary, secondary and modelling products supported by each facility, and the uses and limitations of the technology. Because IMOS capability is very broad, this section is structured into 3 sub-sections. A national backbone section that describes the IMOS facilities that help interconnect all the other observing platforms and includes the Australian Ocean Data Network (AODN), the Satellite Remote Sensing Facility, and a network of moored National Reference Stations. The next section describes the facilities that collect observations in the open ocean and the last section describes the facilities used to observe coastal and shelf waters.

Section 10 highlights the impact IMOS has had in Australian marine science and lists a selection of the many achievements accomplished to date. It also identifies the many challenges that remain and that IMOS will help to address in the short (5 years) and long (10 to 20 years) terms.

Section 11 is the list of references used for the main document.

The national overview is supported by six Node chapters, which give a more detailed account of the science, future observational needs and achievements for each of the Node regions.

3 Introduction

IMOS is Australia's Integrated Marine Observing System, led by University of Tasmania (UTAS) in partnership with the Australian marine and climate science community. It was established in 2006-7 under the National Collaborative Research Infrastructure Strategy (NCRIS), and has attracted $144M from Australian Government research infrastructure investment programs, and up to $200M in co-investment from partners (i.e. ~$344M in total).

IMOS is currently funded until June 2016. The Australian Government has committed an additional $150 million of NCRIS funding in 2016-17 and IMOS expects to be funded in this period and beyond.

IMOS Facilities deploy a range of observing equipment in Australian oceans, making all of the data freely and openly available through the Australian Ocean Data Network Facility. These data streams represent a national research infrastructure created and developed for the Australian and international marine and climate science community use. These data streams comprise long-term time-series of key physical, chemical and biological variables that are necessary to tackle big, strategic, science questions relevant to the Australian society and international community.

From inception, IMOS was designed to contribute to and benefit from the Global Ocean Observing System (GOOS). It is important to note that since 2009, GOOS has developed and is beginning to implement a new Framework for Ocean Observing (UNESCO, 2012). This Framework aims to better integrate the open-ocean and coastal components of GOOS, and build on traditional strengths in physics to fully encompass biogeochemistry, biology and ecosystems. IMOS has therefore been ideally positioned to establish itself as a world leading national marine observing system that integrates across scales and variables in line with the current thinking of the global community.

At the national level, collaboration with relevant terrestrial, freshwater, geological, cryospheric, and atmospheric observing systems is also being pursued within an earth system science context.

To successfully establish a national collaborative research infrastructure in the form of a sustained in-situ ocean observing system, IMOS engaged the Australian marine and climate research community. A network of science-community-driven 'Nodes' was created to provide the scientific rationale for IMOS, develop the science questions, and thereby identify the need for IMOS Facilities to obtain specific data streams with the appropriate technology platforms.

There are six Nodes, one open-ocean and five regional:

1. Bluewater and Climate (open ocean)
2. Western Australia (WAIMOS)
3. Queensland (Q-IMOS)
4. New South Wales (NSW-IMOS)
5. Southern Australia (SAIMOS)
6. South East Australia IMOS (SEA-IMOS).

The IMOS National Science and Implementation Plan consolidates science planning output from these Nodes over the last seven years, most of which has been benchmarked through international peer review. It provides clear evidence that the Australian marine and climate science community can collectively support a national approach to integrated marine observing, with Node components that reflect regional priorities. Australia is attracting significant international interest and support for this ambitious and exciting approach.

4 The Australian Context

Australia has one of the largest marine jurisdictions on earth, with more than 70% of our territory in the marine realm. At ~14 million km^2, Australia's Exclusive Economic Zone (EEZ) is nearly twice the surface area of the Australian continent (7.69 million km^2), extending from the tropics to high latitudes in Antarctic waters. As an island nation, our borders are maritime. The vast majority of Australians live on or near the coast, with 85% of the population living within 50km of the ocean. Our nation is highly sensitive to ocean-influenced climate and weather, and regularly experiences drought, flood, tropical cyclones and other extreme events. Huge economic benefits are extracted from our oceans and its marine biodiversity is of global conservation significance, with sites such as the Great Barrier Reef, Ningaloo Coast, and sub-Antarctic islands listed as World Heritage Areas. For these reasons, understanding our oceans is a matter of national importance for current and future generations of Australians.

4.1 The need for ocean observing in Australia

Australia is a 'marine nation' - an island continent with the third largest ocean territory on earth (Figure 4.1). However, Australia has a relatively small population, making stewardship of this large marine estate both a grand opportunity and a great challenge.

Huge economic benefits are obtained from our oceans through industries such as offshore oil and gas, marine tourism, shipping, fishing and aquaculture. According to the Australian Institute of Marine Science (AIMS) Index of Marine Industries (Australian Institute of Marine Science, 2012) "*In 2009-10, the total measurable value of economic activity based in the marine environment in Australia was around $42.3 billion…. From 2001-02 to 2009-10, the marine industry value has increased by just under 80 per cent*". It is estimated that by 2025, Australia's marine industries will contribute ~$100 billion annually to our economy (National Marine Science Committee, 2015). Therefore, sustainable development of ocean resources and safe and efficient operation of marine industries, relies on having an adequate level of continuous ocean observations. Moreover, the National Marine Science Plan (National Marine Science Committee, 2015), developed by Australia's best and brightest marine scientists to articulate the science required to address the national marine grand challenges identified in Marine Nation, highlights the need for sustained ocean observations to meet these challenges. They include: marine sovereignty and security, energy security, food security, biodiversity conservation, sustainable coastal development, climate variability and climate change adaptation, and equitable and balanced resource allocation.

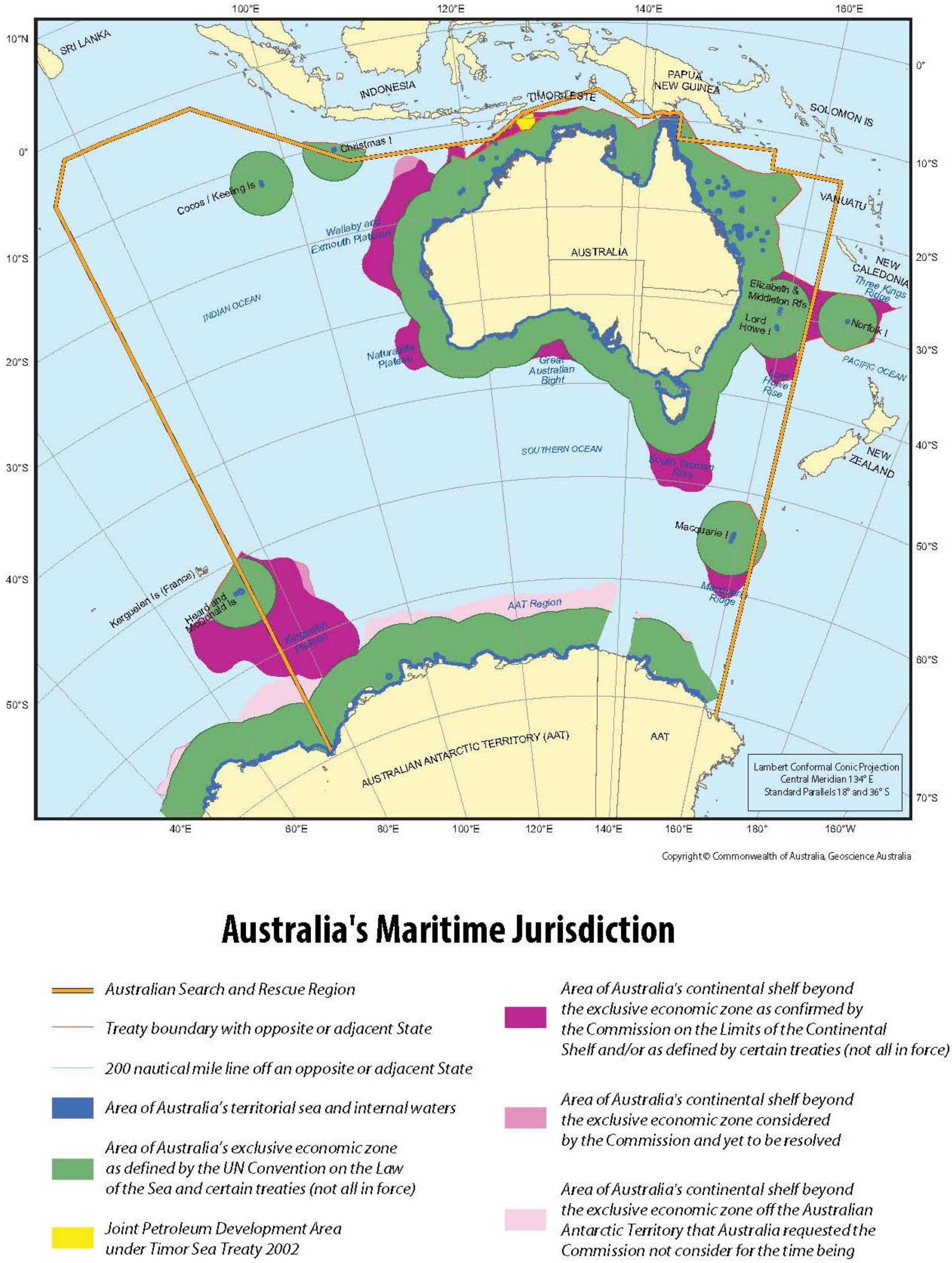

Figure 4.1: Australia's total area of marine responsibility covers 14% of the world's oceans (Australian GovernmentOceans Policy Science Advisory Group, 2013).

Australia's variable climate is strongly influenced by its surrounding oceans (Figure 4.2). Extreme events such as drought, flood, and tropical cyclones are regular occurrences, with large social and economic impacts. Improved understanding of ocean processes has the greatest potential to increase our forecasting ability of these events, thus helping mitigate negative socio-economic consequences.

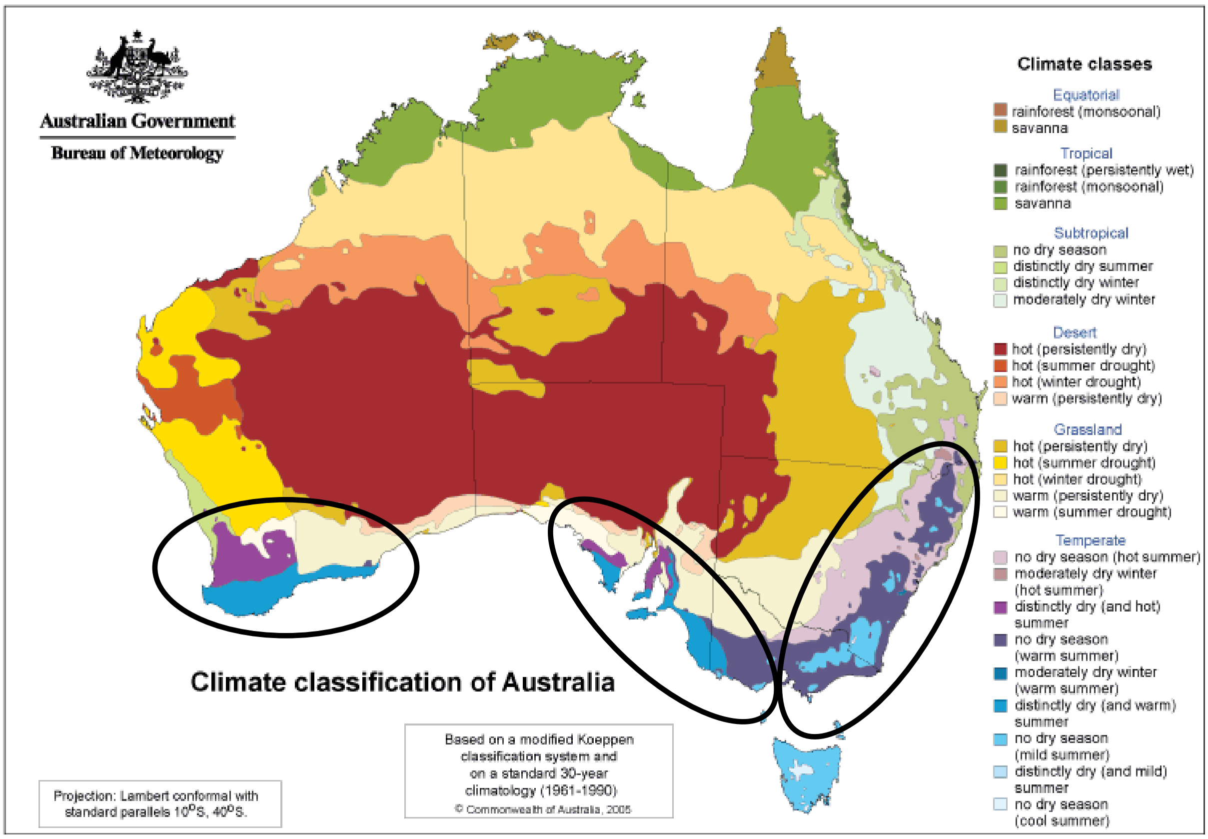

Figure 4.2: Climate classification of Australia (www.bom.gov.au, accessed 8 Jan 2014). The high population centres of the south east and west are highlighted.

With much of Australia's landmass being desert or semi-arid, the population is concentrated in temperate coastal regions of the south east and west (Figure 4.3). This contributes to Australia being one of the most highly-urbanised countries on earth, with 88% of the population living in major cities and surrounding inner-regional areas Australian Bureau of Statistics (Australian Bureau of Statistics, 2013). Coastal oceans are therefore of vital importance to most Australians providing a variety of important ecosystem services. Information about the vulnerability of the coastal regions to extreme events and long-term change (e.g. sea level rise) is therefore critical.

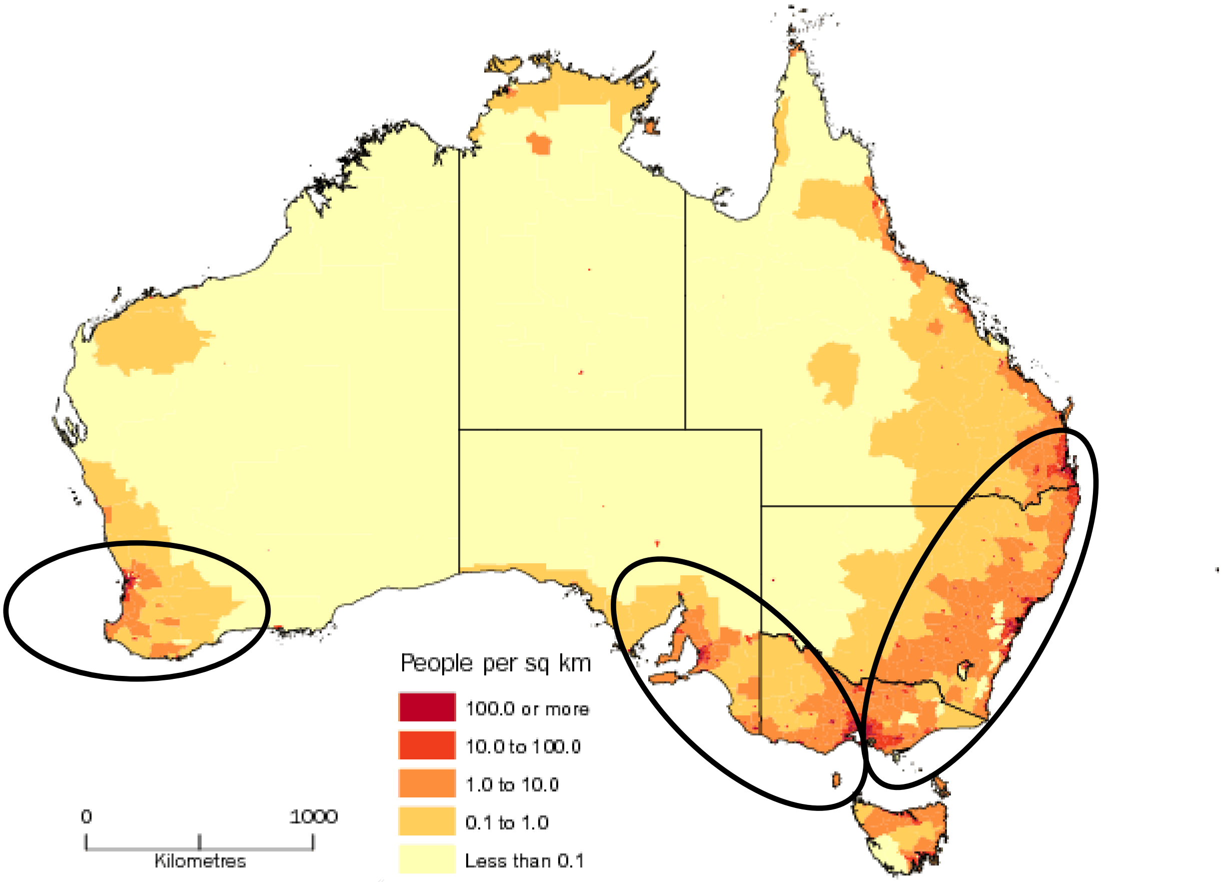

Figure 4.3: Australian population density in June 2012 (Australian GovernmentAustralian Bureau of Statistics, 2013). The high population centres in the south east and west are highlight as in Figure 4.2.

Australia is also the custodian of marine biodiversity assets of global significance, ranging from the high tropics to Antarctica. The global Census of Marine Life determined that marine biodiversity in the Australian region is amongst the highest on earth (Ausubel et al., 2010), with several World Heritage sites such as the Great Barrier Reef (GBR), Shark Bay, Ningaloo Reef, and the coral reefs of the Lord Howe Island Group. In addition, the Australian Government and all coastal State and Territory Governments are currently implementing networks of marine protected areas within a marine bioregional planning context (Figure 4.4). Reserves in Commonwealth waters, three nautical miles off the coast to the edge of Australia's Exclusive Economic Zone (~200 nm), are the responsibility of the Australian Government. Reserves from the low water line along the coast to 3 nautical miles offshore are maintained by State and Territory Governments.

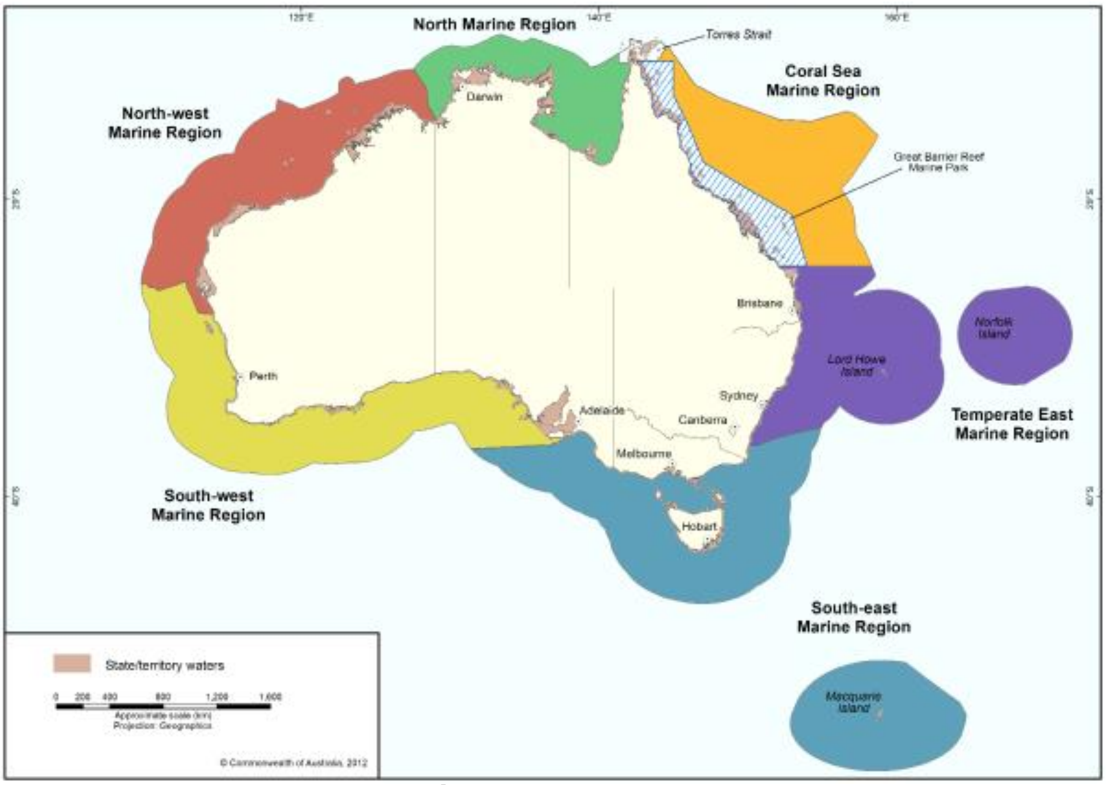

Figure4.4: Australia's marine bioregions (Australian GovernmentDepartment of the Environment, 2012).

The economic benefits and ecosystem services that our ocean provide, its influence on climate and, in particular, the vulnerability of our coasts to extreme weather events, make sustained long-term ocean observation a priority for current and future generations of Australians.

4.2 Australian ocean observing in a global context

Ocean observing is a global enterprise, and international cooperation is fundamental to its success. The majority of the ocean is in the southern hemisphere (~57%) but it is relatively poorly sampled, compared to oceans around the United States, Europe and Japan. Therefore, Australia has a key role to play, as articulated by one eminent reviewer of IMOS Node Science Plans; "*Australia's IMOS, as a contribution to the global ocean observing system for climate, is a major regional step toward satisfying these societal mandates. Moreover, its role is an especially critical one for enabling the global implementation. Australia is the strongest southern hemisphere partner in the global enterprise, with a broad regional perspective in addition to sharing the global one.*" There are significant benefits to Australia in playing this role.

As noted in the 2008 review of the National Innovation System (Cutler and Company Pty Ltd, 2008), Australia's yearly share of new knowledge and innovation to the global R&D is approximately 2%. "*The quality of the 2 percent that we produce and its usefulness to the rest of the world will be important determinants in our ability to access the other 98 percent.*"

As the new Framework for the Global Ocean Observing System is developed and implemented, the role of well integrated national observing systems, such as IMOS and the US Integrated Ocean Observing System (IOOS), is increasingly being recognised as a critical component for the global effort (Figure 4.5) (Unesco, 2012). IMOS is now formally recognised as a GOOS Regional Alliance.

Strong national efforts also contribute to the development of observing systems at ocean basin scales. In the case of IMOS, this manifests through involvement in the Indian Ocean Observing System (IndOOS), the Southern Ocean Observing System (SOOS) and the Tropical Pacific Observing System (TPOSS 2020) evaluation project.

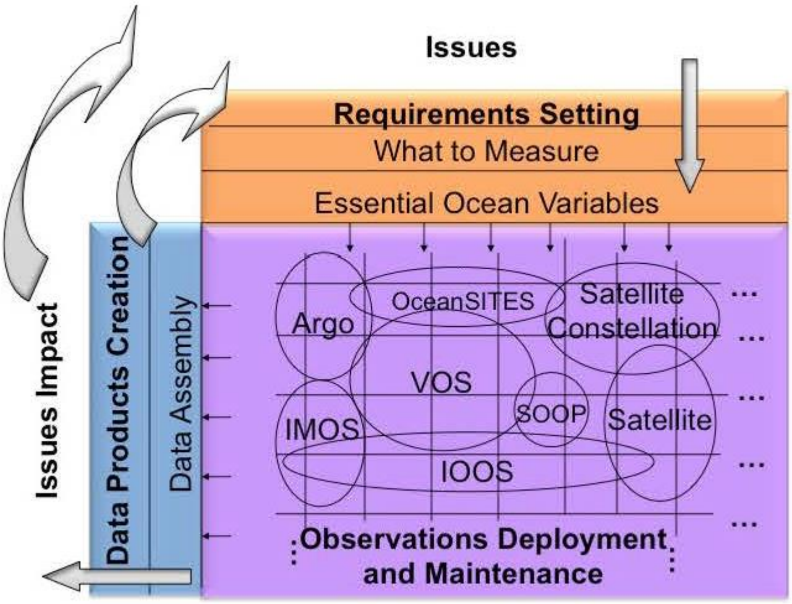

Figure 4.5: Diagram titled 'Structure of the Framework for Ocean Observing (FOO)' from A Framework for Ocean Observing (UNESCO, 2012), with IMOS and US-IOOS used as specific examples, describing how ocean observing activities fit into the system model for the FOO.

By making strategic investments in globally significant ocean research infrastructure, Australia attracts strong international collaboration on issues of national significance, and positions Australian marine and climate science as world class. In this respect, our location in the southern hemisphere places Australian marine and climate science in a key position to monitor important aspects of the Southern Hemisphere climate system and its impacts on the marine ecosystem. Our contribution also helps balancing the knowledge and assessment on climate change, which will otherwise be biased towards the Northern Hemisphere.

4.3 Research and operational observing systems in Australia

IMOS was established under an Australian Government research infrastructure program, to deliver ocean observations to the marine and climate scientists to undertake research of national and international significance. It has not been established as an operational system. However, the broader utility of these research infrastructure investments was recognised in the evaluation of Australia's National Collaborative Research Infrastructure Strategy (NCRIS) (Department of Industry, 2011) - "*It also needs to be recognised that infrastructure is often not exclusively research-focused. In many areas, the infrastructure may have a complementary function for other purposes, such as supporting operation uses and applications.*"

The Bureau of Meteorology (the Bureau, or BOM) is the main Australian Government agency providing marine and oceanographic services to the Australian community. The services include marine weather warnings, forecasts of winds and waves, tide predictions, tsunami warnings, and forecasts of sea surface temperature (SST), salinity, currents, and sea level anomalies, which rely on ocean observations. These services are in addition to the Bureau's responsibilities for weather forecasting (including extreme weather) and climate information (including seasonal prediction), both of which also rely on ocean observations. Therefore, IMOS and the Bureau are close collaborators.

In addition, a number of other Australian Government agencies have operational responsibilities that also rely on ocean observations, such as the Australian Maritime Safety Authority, the Royal Australian Navy, Australian Fisheries Management Authority, the Great Barrier Reef Marine Park Authority, and the Department of the Environment (including for the broader Commonwealth Marine Reserves Network). Various State and Territory Government departments undertake regular monitoring programs in order to manage their responsibilities in coastal waters. Large marine industries such as offshore oil and gas also make significant investments in ocean observing in order to manage and grow their operations, and meet the requirements of environmental and operational regulators.

Operational needs depend on availability of ocean observations in real-time and/or near-real-time (within a few days or minutes of collection). These observations are currently sourced from various national and international programs, with some programs running in an operational setting (e.g. IOC/WMO), and other, like IMOS maintained through research funding.

A key element of IMOS strategy has been to lead the development of a national marine information infrastructure that enables IMOS data and other Australian research and operational ocean data to become discoverable, accessible, usable and reusable for the benefit of the nation as a whole. In this way, valid differences between research and operational needs can be respected, and synergies between research and operational systems fully-exploited. This involved using the marine information infrastructure developed within IMOS to become the Australian Ocean Data Network (AODN), with partnerships that include Australian Government agencies, State and Territory Government agencies, Universities, and private sector companies.

More recently, the inaugural Forum for Operational Oceanography was undertaken with IMOS as an important component of present capabilities in that field.

In summary, it is important to emphasise that Australia needs to invest in both:

- The research infrastructure required to provide sustained ocean observations for the marine and climate science community to address large, long-term questions of national significance, and
- The operational ocean observing systems required for safe and efficient operation of Australian industries and communities on a day to day basis.

4.4 Structure of the Australian marine and climate science community

Providers of Australian marine and climate science include Australian Government agencies, State and Territory Government agencies, Universities, and private sector companies (Figure 4.6). These sectors have different but complementary roles noting that State and Territory Governments are responsible for coastal waters to the three nautical mile limit, while the Australian Government is responsible for the rest of Australia's marine estate.

Universities	Australian Govt	State Govt's	International
1. UTAS	1. CSIRO	1. SARDI**	1. NOAA (US)
2. UNSW*	2. AIMS	2. Queensland Gov	2. Scripps IO (US)
3. USyd*	3. BOM	3. WA Government	3. French Polar Inst.
4. Macquarie*	4. AAD	4. Tasmanian Govt	4. Canadian Govt
5. UTS*	5. ACE CRC	5. NSW Govt	5. St Andrews Uni
6. UWA	6.	6. Sydney Water	6. NIWA (NZ)
7. Curtin	7. GA	7. SA Government	7. NASA
8. Flinders**	8. RAN	8. Darwin Port Corp	8. CNES/EUMETSAT
9. JCU	9. DSTO	9. Victorian Govt	9. Overseas Uni's
10. UQ			
11. Murdoch	10. DoE		
12. Adelaide	11. GBRMPA		
13. Griffith	12. FRDC		
14. CDU			
15. ANU			
16. Deakin University			
17. University of Melbourne			
18.			

* Operating as the Sydney Institute of Marine Science (SIMS)

** Operating through Marine Innovation South Australia (MISA)

Figure 4.6: A list of the research sector organisations that IMOS is currently collaborating with. The shading indicates the primary role each organisation plays, as Facility operator, co-investing Partner, or Node user within IMOS

Australian Government agencies tend to undertake strategic and applied science and include both:

- Research agencies (i.e. AIMS, and the Commonwealth Scientific and Industrial Research organisation, CSIRO), and
- Other government agencies with significant research capacity (i.e. BOM, Australian Antarctic Division (AAD), Geoscience Australia (GA), and Defence Science and Technology Organisation (DSTO).

All Australian coastal States and Territories also have marine and climate science capability. Research tends to focus on applied science often partnering with both Universities and Australian Government agencies. Research organization varies from state by state, but is generally clustered around:

- Environment and natural resources,

- Fisheries/primary industry/economic development, and
- In some cases, climate change.

The University sector's key roles in the marine and climate science are in research, education and training with more basic science focus, whereas private industry tends to be involved with science through commercial application. Of the 39 Universities in Australia, ~23 (or 60%) have a tangible focus on marine and climate science. These include all of the 'Group of Eight' (a coalition of leading Australian Universities), and six of the seven 'Research Intensive' Universities within the sector.

Other users of marine science information and infrastructure include:

- Australian Government departments responsible for Climate Change, Environment, Fisheries & Aquaculture, Defence, Maritime Safety, Resources and Energy, Infrastructure, Tourism, Foreign Affairs and Trade, Science, Research, and Education,
- State and Territory Government departments (with the equivalent responsibilities at State level),
- Marine Industries and other climate-sensitive industries (such as agriculture), and
- the Australian people.

The major centres with marine and climate science capability in Australia are shown in Figure 4.7. IMOS has engaged this diverse and dispersed community through its science Node structure, which is further explained in Section 5.

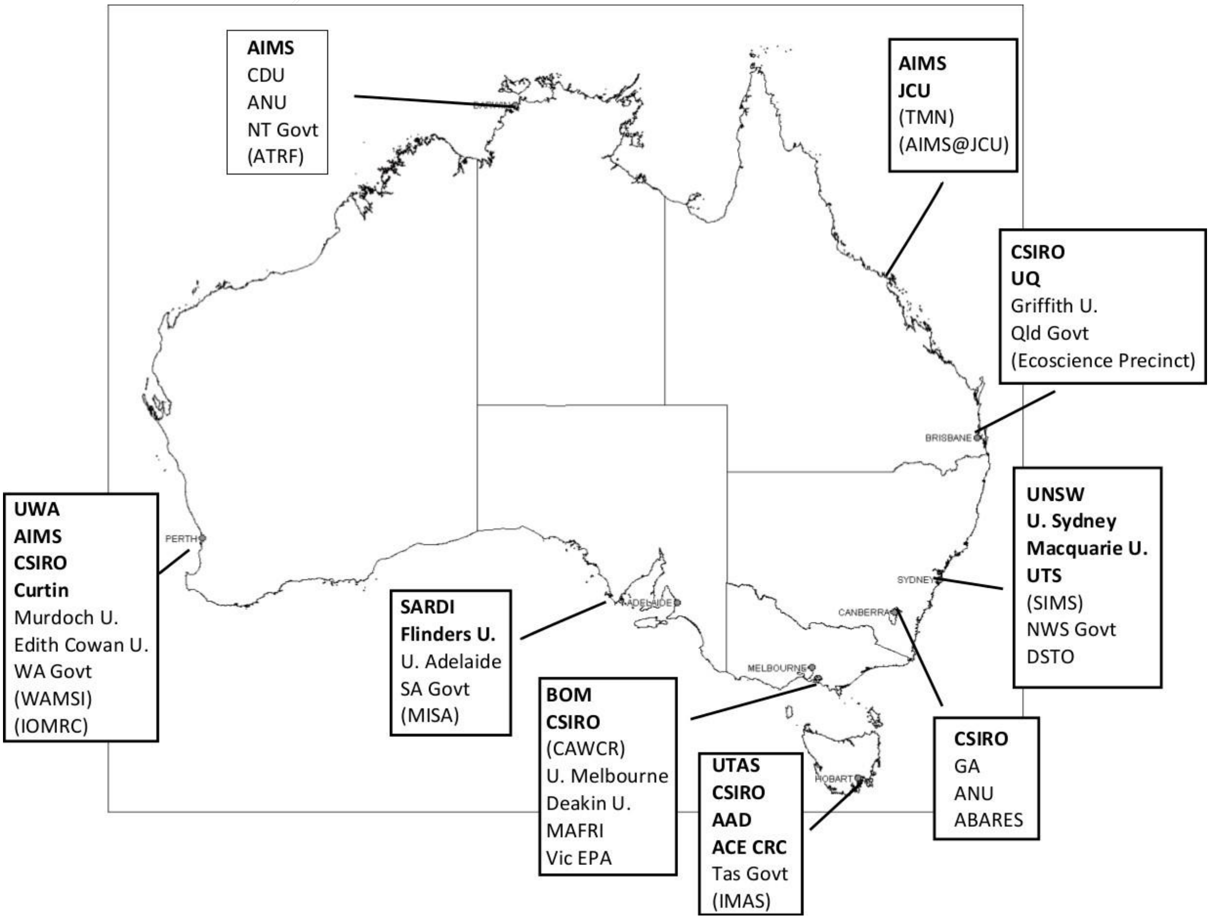

Figure 4.7: Major centres of marine and climate science capability in Australia. Institutions involved in leading IMOS are shown in ***bold*** *and cross-institutional initiatives are shown in (brackets). (Map image – University of Melbourne Map Collection, accessed 8 Jan 2014).*

A key ingredient in this process has been partnering with region-specific collaborations, which have helped shape the IMOS Node structure. The collaborations formed for each region are:

- Bluewater and Climate: the Centre for Australian Weather and Climate Research (CAWCR) involving CSIRO and BOM; and the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) involving UTAS, AAD and CSIRO.
- Western Australia: the multi-institutional Western Australian Marine Science Institution (WAMSI) and Indian Ocean Marine Research Centre (IOMRC) involving AIMS, CSIRO, WA Department of Fisheries and Oceans Institute at University of WA (UWA).
- Queensland: the Tropical Marine Network (TMN) involving University of Sydney (USyd), Australian Museum, University of Queensland (UQ) and James Cook University (JCU); AIMS @JCU (James Cook University); Dutton Park Ecosciences Precinct involving CSIRO and Queensland State Government.
- Northern Territory: the Arafura Timor Research Facility (ATRF) involving the Australian National University (ANU) and AIMS.
- New South Wales: the multi-institutional Sydney Institute of Marine Science (SIMS) involving the University of NSW (UNSW), University of Sydney, Macquarie University and University of Technology Sydney (UTS).
- South Australia: Marine Innovation South Australia (MISA) program involving the South Australian Research and Development Institute (SARDI) in collaboration with Flinders and Adelaide Universities.
- Tasmania: the Institute of Marine and Antarctic Studies (IMAS).

4.5 The position of IMOS in marine and climate science

IMOS is now well recognized as an element of Australia's marine and climate science capability. The Australian Government's 2012 National Research Investment Plan NRIP, (Department of Industry, 2012) recognized that investment in research infrastructure such as IMOS, a world class research facility, is fundamental for Australia's research fabric – "*For Australia's research fabric to remain sustainable it requires funding for national research infrastructure. It is not possible to manage large research facilities with any continuity or efficiency, or to retain specialist expertise that is in high demand around the globe, when the existence of infrastructure funding programs is uncertain, or ceases altogether*". Furthermore, successive Strategic Roadmaps for Australian Research Infrastructure Investment under the NCRIS identified sustained observing of the marine environment, such as IMOS, as a national priority (Department of Industry, 2011).

Through the National Marine Science Plan 2015-2025, Australia's marine science community recommended that one of eight priorities be to "**Sustain and expand the Integrated Marine Observing System to support critical climate change and coastal systems research, including coverage of key estuarine systems**", . The NMSP drew together the knowledge and experience of 23 marine research organisations, universities and government departments and more than 500 scientists.

The fundamental role of IMOS in Australia's national marine and climate research infrastructure is as an *in situ* ocean observing system. However, as a large, national, multi-institutional, multi-disciplinary program, it is uniquely placed to facilitate partnerships with other components (e.g. vessels, satellites, data, and modelling). This has allowed the creation of an even more powerful national infrastructure base for use by the Australian marine and climate science community, its collaborators and stakeholders (Figure 4.8).

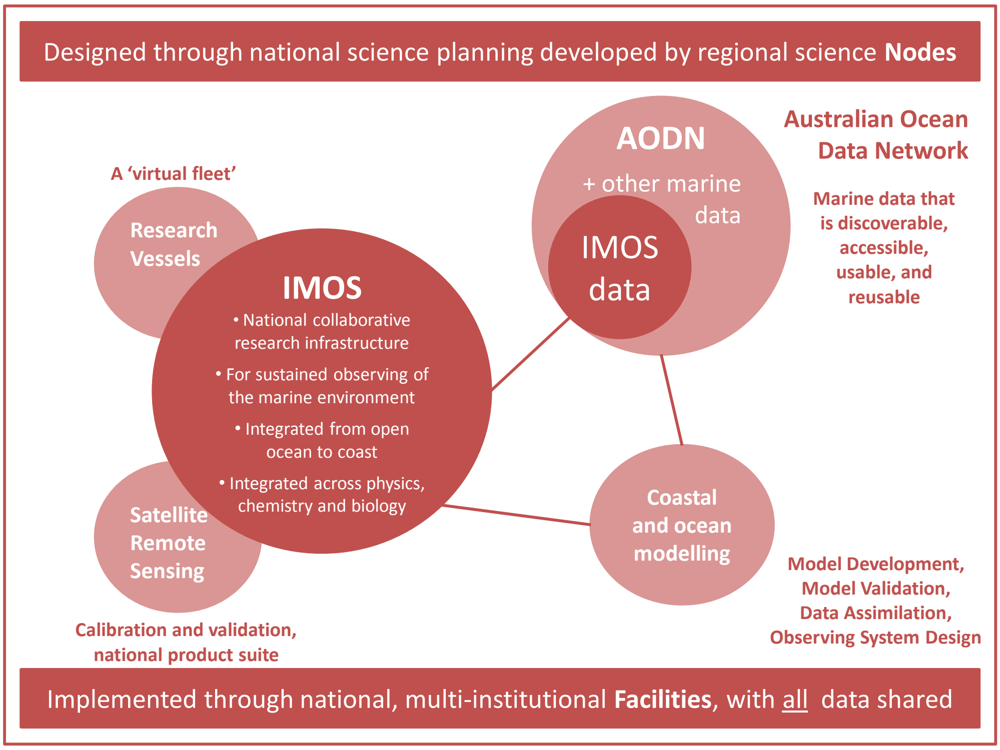

Figure 4.8: Positioning of IMOS relative to other components of the national infrastructure for marine and climate science.

IMOS works in close collaboration with the operators of Australia's research vessel platforms, foreign research vessels operating in our region and commercial vessels as 'ships of opportunity'. By providing common instrumentation and data delivery systems, we have been able to create a single 'virtual fleet' and leverage the observational power of multiple vessel platforms regardless of ownership and management arrangements.

Satellites provide the only means of obtaining continuous, broad scale observations of key ocean variables. Australia is totally reliant on foreign satellites for this information, but through IMOS we contribute high quality *in situ* observations for calibration and validation in our region. In doing so, we are assisting Australian scientists in becoming valued members of international satellite mission science teams.

As noted above, IMOS has taken a 'data centric' approach to research infrastructure development, with all data discoverable and accessible via the Ocean Portal (http://imos.aodn.org.au/imos123/). Further value has been added by expanding the IMOS information infrastructure to create the

Australian Ocean Data Network (AODN), through partnerships with the Australian Federal State and Territory Government agencies, Universities, and private sector companies. Some progress has been made in using this infrastructure to provide access to other marine and coastal data resources, with current efforts in marine data management highly regarded nationally and internationally as the NMSP has pointed out (National Marine Science Committee, 2015).

Close collaboration between marine observing and coastal and ocean modelling is also essential. Modellers require observations for model development, validation, and in some cases data assimilation, providing a major pathway for IMOS data to be taken up and used, thus having broader relevance and impact. In turn, models can be used to run observing system simulation experiments and provide insight into more efficient and effective design for future observing infrastructure. The lack of well-developed links with modelling in the initial phase of IMOS, was the most consistent feedback provided by international reviewers of Node Science and Implementation Plans in 2009. Since then, IMOS has made a determined effort to catalyse national scale engagement between marine observing and coastal and ocean modelling, with three main points of focus. (1) Holding biennial Australian Coastal and Oceans Modelling and Observations (ACOMO) workshops, with the first one held in 2012 and one planned for 2014. (2) Establishment of a Marine Virtual Laboratory (MARVL- http://www.marvl.org.au/) to provide tools that enable scientists to bring together models, observational data and visualisations 'at the desktop'. In collaboration with the National eResearch Collaboration Tools and Resources (NeCTAR) program funding was secured to support this enterprise. (3) Align IMOS observational capability with regional modelling activities in areas such as the Great Barrier Reef, Darwin Harbour, North West Shelf and Great Australian Bight.

The infrastructure base as illustrated in Figure 4.8 is intended to underpin significant education and training activities across the university sector, as well as observational, experimental, and model-based research activities across the marine and climate science community.

Multiple pathways for data uptake and use have been established (see Figure 4.9), with science outputs recorded and reported as a performance indicator for the program.

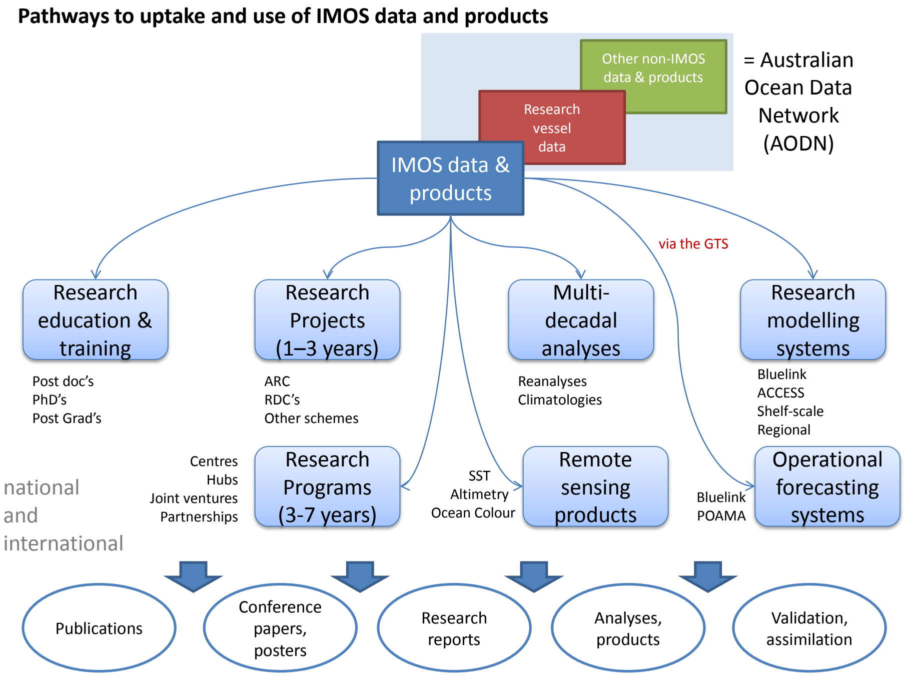

Figure 4.9: Pathways to uptake and use of IMOS data and products.

IMOS has been carefully designed to ensure that the benefits of sustained observing and data access are translated in better economic, social and environmental outcomes (Figure 4.10). It is operated by the most capable marine research institutions in Australia, with strong international collaborators. Making all of the data **openly available** ensures this collective observational power is used to generate a wide range of scientific outputs, from PhD's to ocean forecasts. By aligning with all relevant national and international research and innovation frameworks, IMOS ensures that it is underpinning science, research and education most **relevant** to the grand challenges facing Australia as a 'marine nation'.

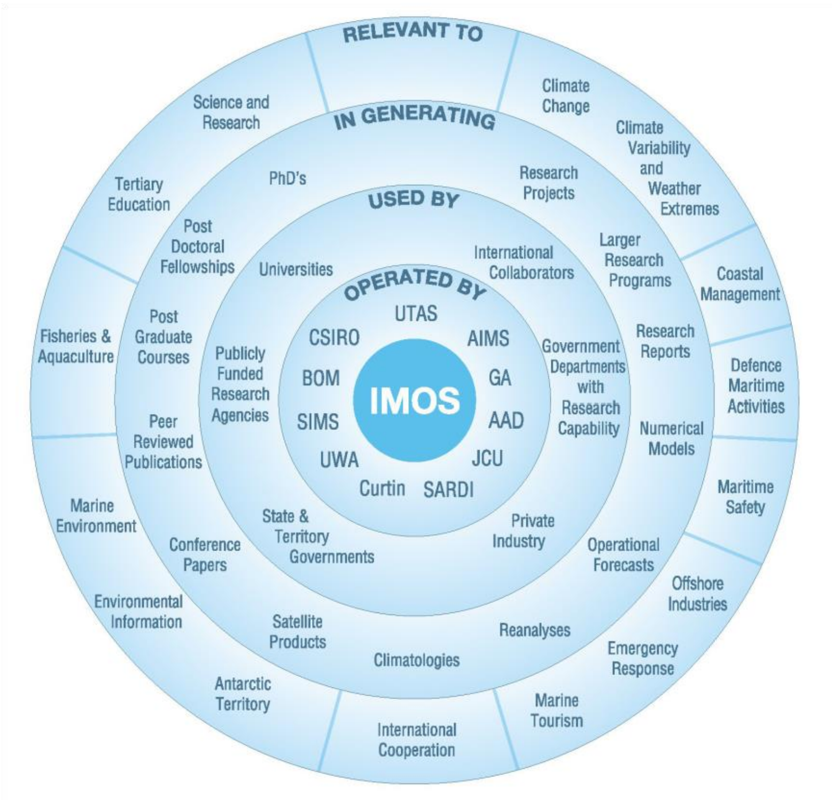

Figure 4.10: The 'circle diagram' (read from inside to out) illustrates how IMOS Facilities operated by institutions can be used by the entire sector, to generate scientific outputs that deliver benefits across all relevant sectors of Australia's economy, society and environment.

5 The role of Node science plans in guiding IMOS investment

One of the most obvious risks in establishing a research infrastructure program like IMOS is the risk of a 'build it and they will come' approach. IMOS is explicitly managing this risk through its Node Science and Implementation Plans. The Node planning process has enabled the Australian marine and climate science community to come together and provide the scientific rationale for a national scale integrated marine observing system. They develop the science questions based on current understanding and knowledge gaps, thereby identifying the need to obtain specific data streams from the appropriate technology platforms. The Node plans have gradually been strengthened since the inception of IMOS, including through international peer review.

Under this model Nodes are not directly funded. However, their Node plans are used to guide investment in technology-based national facilities which are then operated by relevant institutions within the national innovation system. This model helps avoid regional competition and ensures Nodes have the ability to tackle major science questions using multiple technological platforms. In doing so, IMOS ascertains its Facilities are widely utilised thus delivering better value for money.

IMOS has established the following Facilities and Sub-Facilities (with Operating Institutions noted):

Facility	Sub-Facility
1. **Argo Floats** (CSIRO)	
2. **Ships of Opportunity - SOOP** (CSIRO)	• XBT and Biogeochemical (CSIRO) • Continuous Plankton Recorder Survey (UQ/CSIRO and AAD) • Sensors on Tropical Research Vessels (AIMS) • Sea Surface Temperature (BOM) • Real-Time Air-Sea Fluxes (BOM) • Bioacoustics (CSIRO) • Temperate Merchant Vessels
3. **Deep Water Moorings** (UTAS/CSIRO)	• Air-Sea Flux Stations (BOM) • Southern Ocean Time Series (UTAS/CSIRO) • Deepwater Arrays (CSIRO)
4. **Ocean Gliders** (UWA)	
5. **Autonomous Underwater Vehicle - AUV** (SIMS)	
6. **National Mooring Network** (CSIRO)	• Queensland and Northern Australia (AIMS) • New South Wales (SIMS) • Southern Australia (SARDI) • Western Australia (CSIRO) • Passive acoustic Observatories (Curtin University) • National Reference Stations (CSIRO, AIMS, SIMS, SARDI) • Ocean Carbon and Acidification (CSIRO)
7. **Ocean Radar** (UWA)	
8. **Animal Tagging and Monitoring** (SIMS)	
9. **Wireless Sensor Networks** (AIMS)	
10. **Satellite Remote Sensing - SRS** (CSIRO)	• Sea Surface Temperature (BOM) • Ocean Colour (CSIRO) • Altimetry Calibration/Validation (UTAS)
11. **e-Marine Information Infrastructure** (UTAS)	• Australian Ocean Data Network (UTAS) • OceanCurrent (CSIRO)

The profile of IMOS core investment by Facility is shown in Figure 4.1. These figures are based on total investment. To give some indication of scale of investment, each 10% 'share' equates to an average of ~$4M per annum over the period.

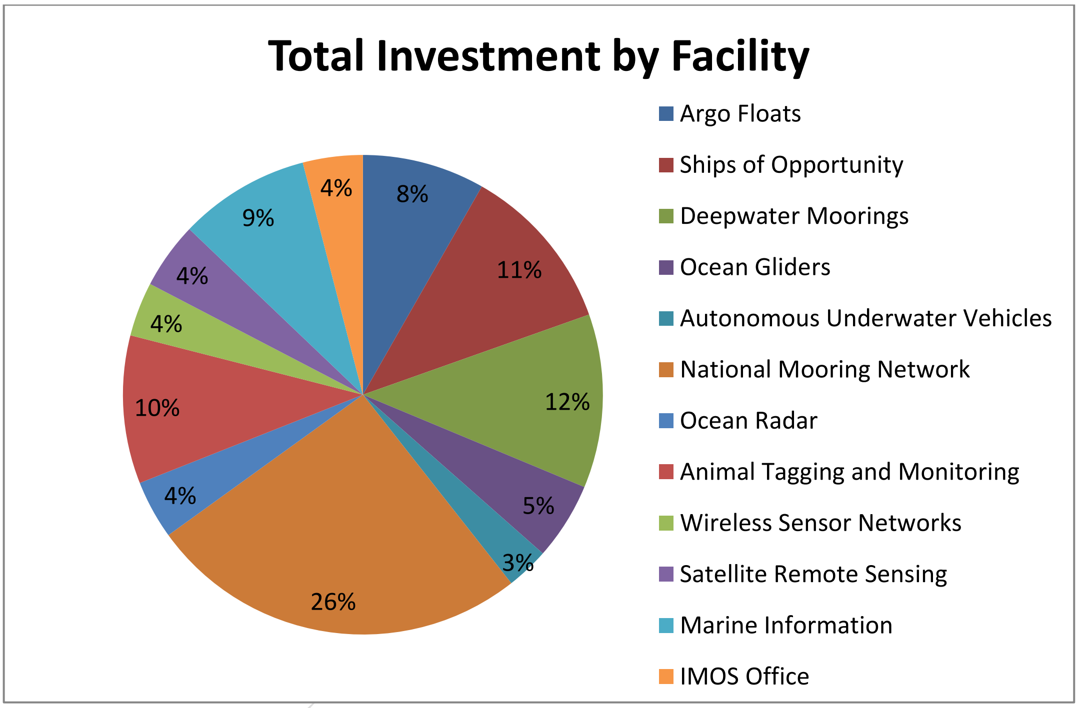

Figure 4.1: Spread of total IMOS Investment across Facilities

Most Facilities deliver across multiple Nodes, and all Nodes draw from multiple Facilities as shown in Figure 4.2.

	Bluewater & Climate	WA	QLD	NSW	SA	SEA
Argo	P	S	S	S	S	S
SOOP	P	P	P	S	S	S
Deepwater moorings	P	S	S	S		S
Ocean gliders	S	P	P	P	P	P
AUV		P	P	P		P
Shelf Moorings	P	P	P	P	P	P
Ocean Radar		P	P	P	P	
Animal	P	P	P	P	P	P

Tagging						
Sensor networks			P			
SRS	P	P	P	P	P	P
AODN	P	P	P	P	P	P

Figure 4.2: How IMOS Facilities deliver to the Nodes. P = primary relationship and s = secondary relationship

For IMOS to operate at its current scale, co-investment by partners has been fundamental. Approximately 57% of the total resources required come from co-investment by partner institutions, related Australian Government programs, State Governments and international collaborators. The breakdown of total investment is shown in Figure 4.3.

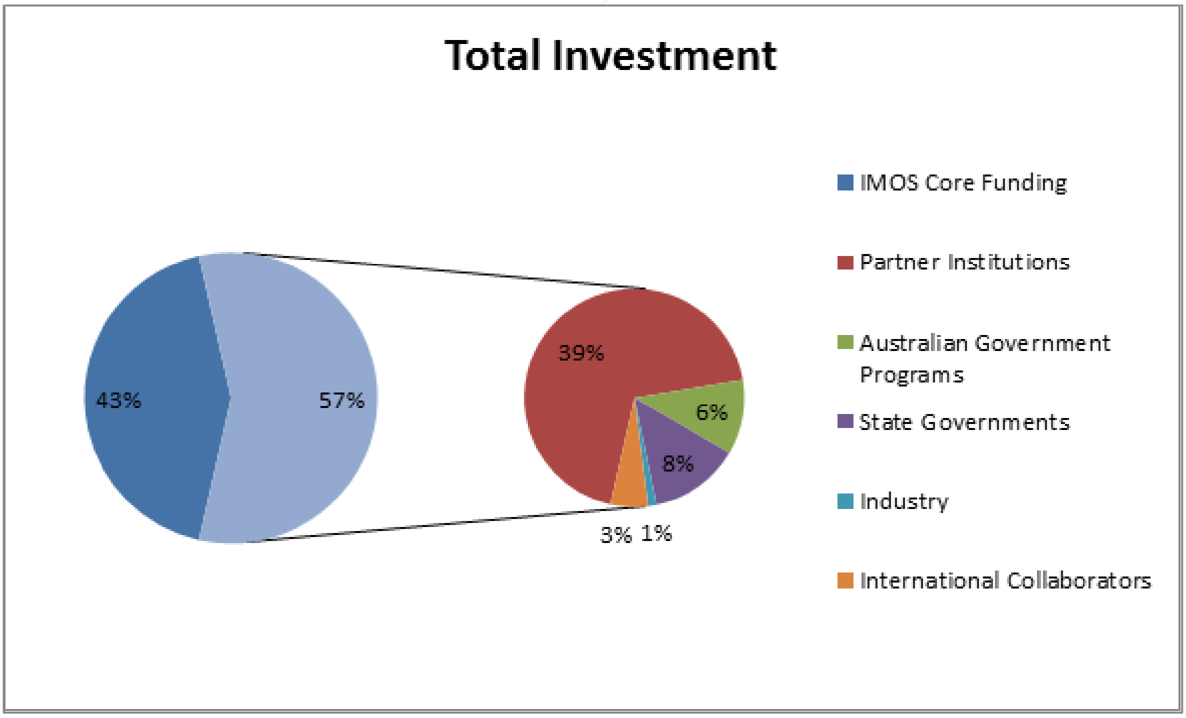

Figure 4.3: Sources of total investment in IMOS split between core funding from Australian Government and co-investment by various partners

Significant additional leverage is gained through Australia's participation in international collaborative programs. In most cases this is not accounted for in the above co-investment figures, but can be measured in terms of data delivered through the IMOS Ocean Portal. Examples include:

- A doubling of Argo floats in the Australian region through international partners,
- NOAA surface drifting buoys containing the tracks of surface drifting buoys in the Australasian region deployed as part of the Global Drifter Program (GDP), and
- Access to satellite remote sensing data and products, for sea surface temperature, ocean surface topography, and ocean colour.

6 The IMOS Science Nodes

IMOS has been designed with linked open-ocean and shelf/coastal components. The open ocean component (Bluewater and Climate Node) provides the scientific underpinning for the collection of ocean observations in the open ocean surrounding Australia. This Node is firmly embedded in relevant international programs.

The shelf/coastal component comprises a series of regional nodes which collectively cover Australia's coastal oceans - Western Australia (WA-IMOS), Queensland (Q-IMOS), New South Wales (NSW-IMOS), Southern Australia (SA-IMOS) and South East Australia (SEA-IMOS) (Figure 5.1).

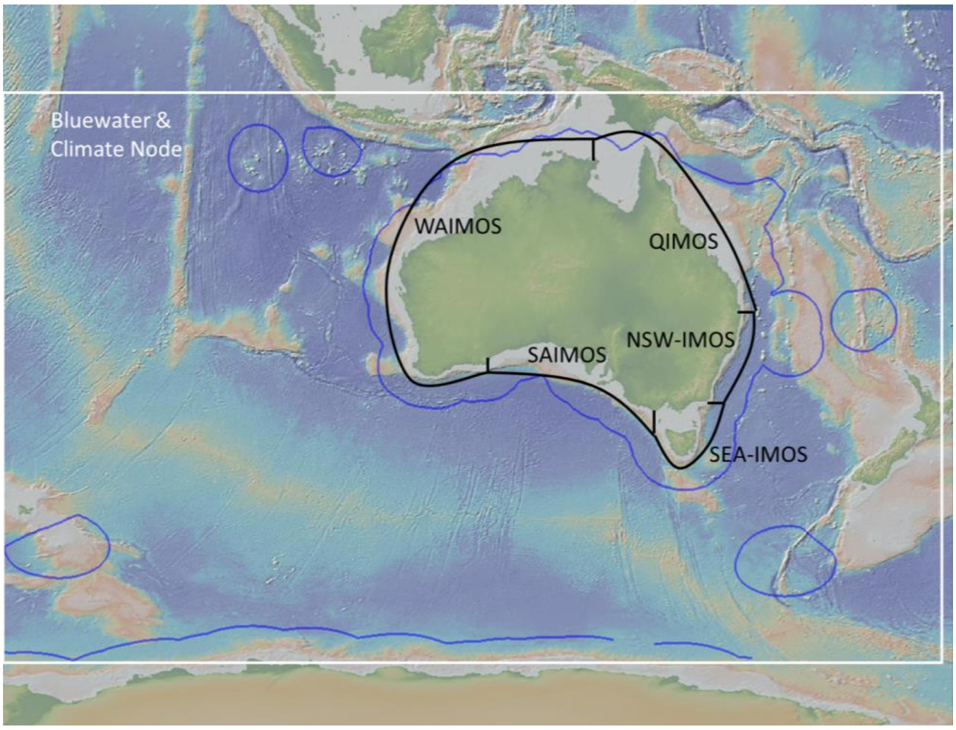

Figure 5.1: Regions of interest for the IMOS Nodes and the conceptual framework applied to Australia's ocean territory, with the blue lines indicating the boundaries of Australia's Exclusive Economic Zone (EEZ), and the white and black lines showing regions of interest for each IMOS Node.

All Nodes are connected by a 'national backbone' which includes the Australian Ocean Data Network (AODN), the Satellite Remote Sensing Facility, and a network of moored coastal Reference Stations. The infrastructure also includes the coordination of regional mooring deployments, and deployment planning of ocean gliders, AUVs and acoustic tracking arrays.

At the coastal/shelf level, essential collaboration with the terrestrial, freshwater, geological and atmospheric science communities will be pursued by IMOS through its regional Nodes, with particular attention to information and modelling. Priorities will include:

1. Working with the coastal ecosystems facility of Australia's Terrestrial Ecosystem Research Network (TERN), established under the same Australian Government program as IMOS
2. Partnering with relevant national programs, such as BOM's coastal information component of the National Plan for Environmental Information, the National Environmental Science Programme (NESP), previously the National Environmental Research Program (NERP), through their Marine Biodiversity, Earth Systems and Tropical Water Quality Hubs, as well as the Commonwealth Marine Reserve (CMR) networks.
3. Partnering with relevant regional initiatives, such as the Great Barrier Reef Integrated Monitoring Framework, SEQ Healthy Waterways Partnership, and Derwent Estuary Program.

6.1 Bluewater and Climate Node

The Bluewater and Climate Node research interests are in the open ocean region surrounding Australia. Four major areas of research have been the focus of this Node:

1) Multi-decadal ocean change: identifying the nature, causes and consequences of multi-decadal changes in ocean climate
2) Climate variability: understanding and predicting the major modes and drivers of climate variability in the Australian region
3) Ocean prediction: improving the understanding and prediction of ocean currents and the links between the open ocean and shelf waters
4) Biogeochemistry and Ecosystems: understanding the impact of changes in the physical environment on biogeochemical cycles and ecosystems

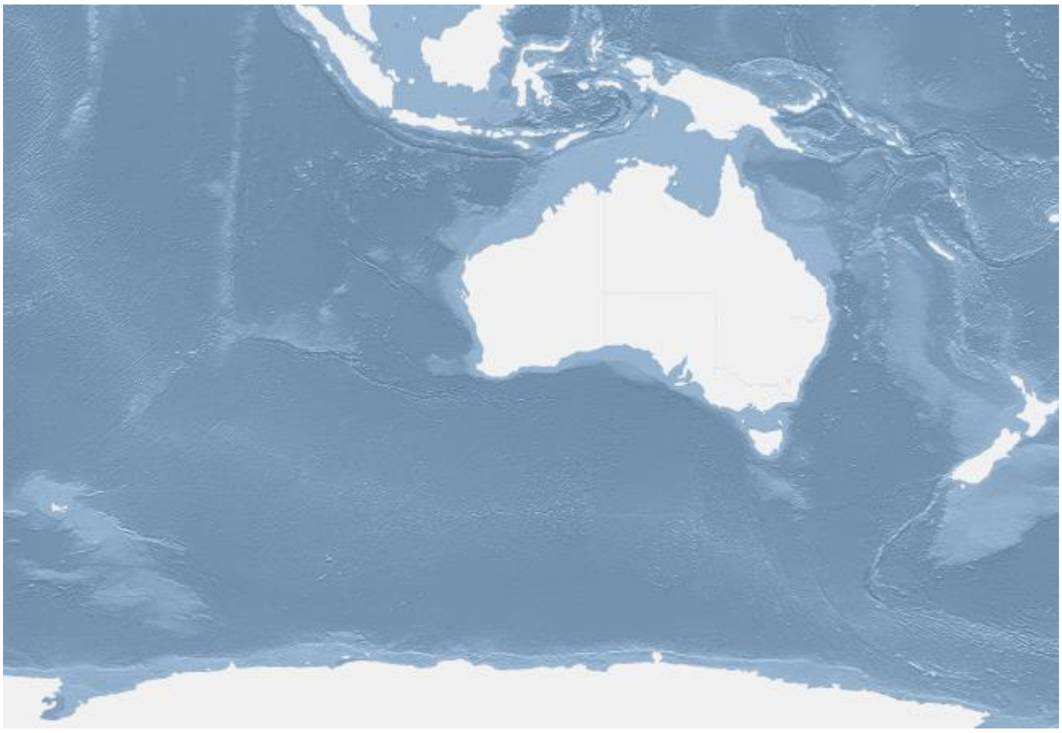

Figure 5.2 Bluewater & Climate Node area of interest

6.2 Regional Nodes

Establishing a series of regional coastal Nodes that are integrated with the open ocean and which together take a truly national perspective was a major challenge for a large nation such as Australia. This challenge was well-articulated by one distinguished reviewer of IMOS Node Science Plans who recommended a national planning process for the coastal ocean – "*There is a tendency in large nations for coastal observing systems to be designed piecemeal, as the sum of what the participating coastal institutions would each like to do in their patch... There needs to be first a carefully articulated national vision of the requirements for coastal observations, including the transitions from coastal to blue water zones. Regional planning should be a recognizable application of the national plan to the local setting using local knowledge and expertise.*"

In addressing this challenge, IMOS considered:

- Key regional features of Australia's coastal oceans,
- The nature of Australia's coastal States and territories, and
- Locations of multi-institutional strength in Australian marine and climate science community with the capability to both operate and use a national scale observing system.

6.2.1 Regional features

At least five distinct regions in Australia's coastal oceans can be identified considering factors such as the continental shelf and slope's topography, boundary currents - shelf interactions, phytoplankton provinces, and marine bioregions (i.e. Australia's 'large marine ecosystems'). These regions are the tropical north, GBR lagoon, south east, south west, and south central (Figure 5.3).

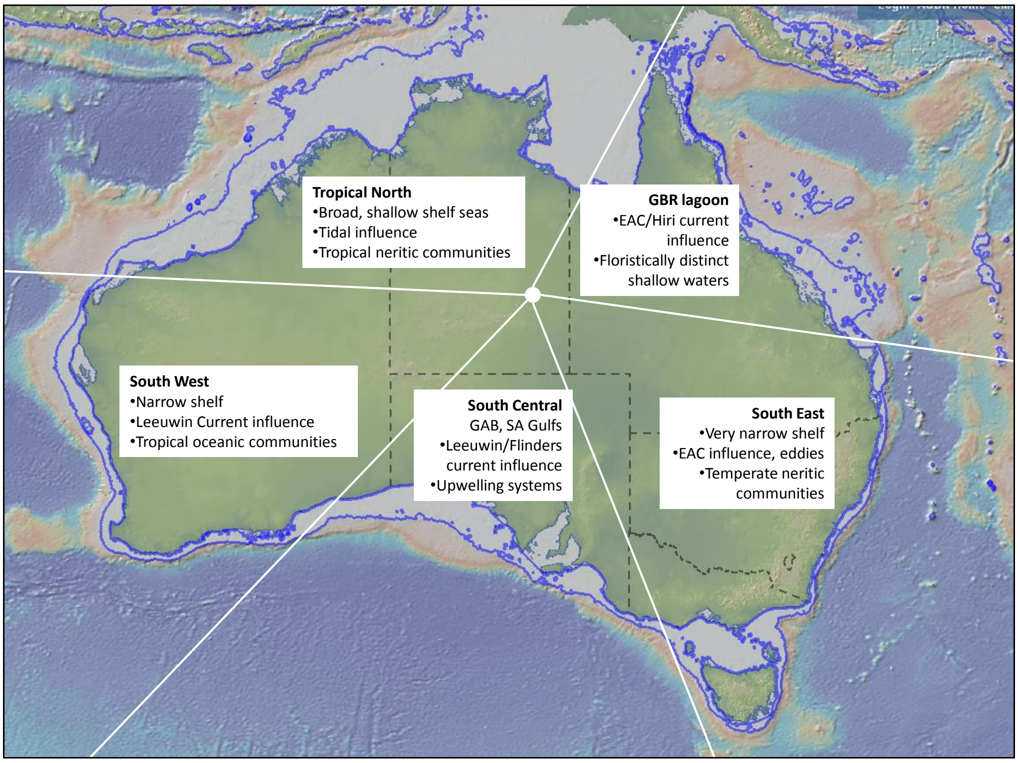

Figure 5.3: IMOS has identified five distinct regions of Australia's coastal oceans - Tropical North, GBR lagoon, South East, South West, and South Central - and their key characteristics.

6.2.2 Coastal States and Territories

Australia's government is a federal system with powers divided between a central government and regional governments. There are six States, and three mainland Territories in Australia. States retain the power to make their own laws over matters not controlled by the central government (Commonwealth), and each has its own constitution and a structure of legislature, executive and judiciary. Two mainland Territories have been granted a right of self-government in a similar manner to a State.

All States and two Territories are adjacent to the coast. Some of their key physical, demographic and economic information are shown in Table 5.1.

Table 5.1: Physical, demographic and economic data for the Australian States and Territories (reference??).

	Percent of coast (excl. offshore islands)	Percent of Australian population	Percent of total Gross State Product (GSP)
Western Australia	35.9	10.9	16.2
Queensland	19.4	20.1	19.3
Northern Territory	15.2	1	1.3
South Australia	10.6	7.2	6.2
Tasmania	7.9	2.2	1.6
New South Wales	5.2	32	30.9
Victoria	5.6	24.8	22.3
Jervis Bay Territory	0.2		

Points to note include the size of WA's coastline and its above average GSP per head of population, and the concentration of population and related economic activity in the south east (NSW and Victoria).

6.2.3 Science capability

Concentration of -Australian institutions with strength in marine and climate science are outlined in Section 4.4. In summary, there is significant existing capability and substantial new investment (marine laboratories and region-specific research programs) in Townsville and Brisbane (Queensland), Sydney (NSW), Hobart (Tasmania), Perth (WA), and Adelaide (SA).

6.2.4 IMOS regional coastal Nodes

Consideration of regional features, coastal states and territories and science capacity has led IMOS to establish five regional coastal Nodes with the following key characteristics (Figure 5.4):

1. **Western Australia (WAIMOS)** – Strong focus on the Leeuwin Boundary Current system and related climate variability. Emphasis has increased in the tropical northwest where massive regional development is planned over the coming decade. It includes Northern Territory waters. It is linked to the Bluewater and Climate and SAIMOS Nodes' interests through research of the Indo-Pacific Throughflow and Leeuwin Boundary Current.
2. **Queensland (Q-IMOS)** – Strong focus on oceanic influences from the western Pacific on the Great Barrier Reef. Emphasis has increased on the flow of the East Australian Current (EAC) into South East Queensland. There is a longer-term plan to also consider northerly flow including exchange through Torres Strait and into the Gulf of Carpentaria. Integration with Bluewater and Climate and NSW-IMOS Nodes' interests is through research of the tropical and western Pacific including the Coral Sea, and the EAC.

3. **New South Wales (NSW-IMOS)** – Strong focus on the EAC separation zone and eddy field along the narrow continental shelf of NSW. Integration with Bluewater and Climate, Q-IMOS and SEA-IMOS Nodes' interests is through research of the EAC.
4. **Southern Australia (SAIMOS)** – Strong focus on highly-productive upwelling zones along the coast of South Australia to the border of Victoria, and the Great Australian Bight. Integration with Bluewater and Climate, WAIMOS and SEA-IMOS Nodes' interests is through research of the Southern Ocean, Leeuwin Current and EAC .
5. **South East Australia (SEA-IMOS)** – Strong focus on the south east of Australia including Tasmania and Victoria, which is one of the most populated areas of Australia with significant and ongoing coastal development, significant commercial and recreational fisheries and major marine industries. Integration with Bluewater and Climate, NSW-IMOS and SA-IMOS Nodes' interests is through research of the EAC, Southern Ocean and Leeuwin currents.

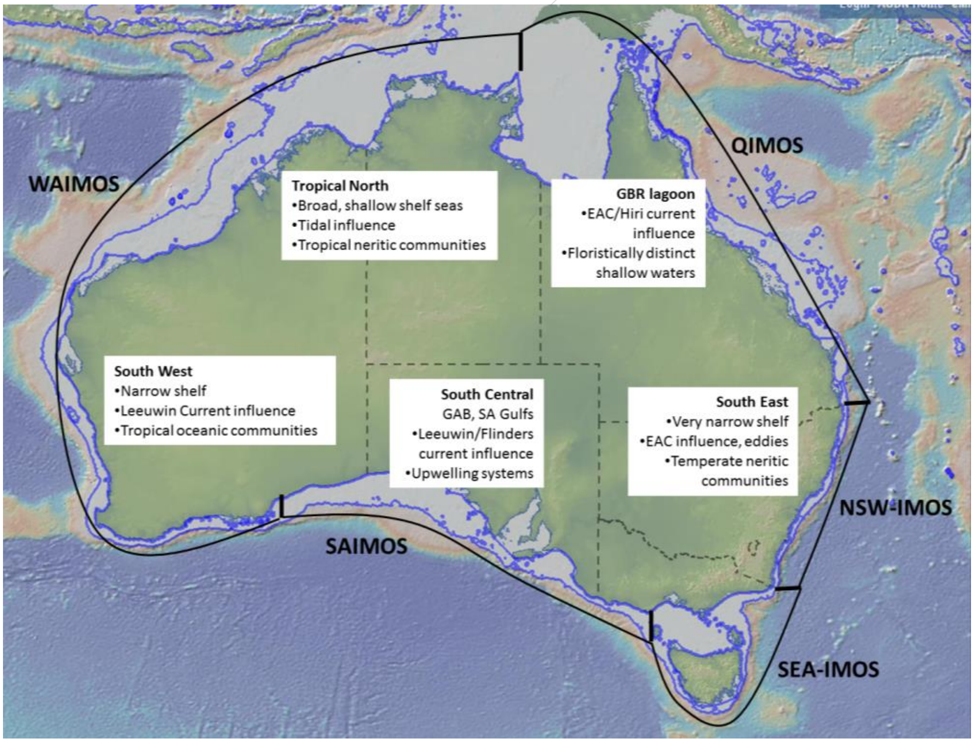

Figure 5.4: The five regional IMOS Nodes cover Australia's coastal oceans

However it is important to note that a number of sub-regional gaps that will need to be considered have been identified by the Nodes:

- WAIMOS: the Kimberley and Pilbara regions, Arafura Sea
- QIMOS: in Torres Strait and the Gulf of Carpentaria
- NSW-IMOS: in Stockton Bight
- SAIMOS: along the Bonney and Otway coasts
- SEA-IMOS: Bass Strait

In situ observations provided by IMOS are relatively sparse across Australia's large ocean region. Therefore, to ensure that the national observing system delivers meaningful information to the regions, it has been imperative that the Nodes work together to make optimal use of the national backbone, develop and populate the AODN, and strengthen integration between the observing system and relevant modelling frameworks.

6.3 Node governance

The IMOS Node structure is governed by processes that draw on the strengths of the Australian marine and climate science community. Each Node has a pair of elected leaders (leader and deputy, or co-leaders) (Table 5.2), and an institutional sponsor. The Node leaders, along with the IMOS Director, IMOS Scientific Officer and AODN Director, form a National Steering Committee that oversees the national science planning process. Each Node also has a more broadly-based scientific reference group that assists with science plan development, and meets periodically to review progress (see Node plans for current reference group lists). In addition, Nodes have a larger membership base that is kept informed of developments and provides a catchment for wider uptake and use of IMOS observations and data.

Table 5.2: The current (2014) IMOS Node elected leadership.

Node	Leadership	
Bluewater & Climate	Steve Rintoul (CSIRO)	Peter Strutton (IMAS/UTAS)
WAIMOS	Gary Kendrick (UWA)	Ming Feng (CSIRO)
Q-IMOS	Richard Brinkman (AIMS)	Russ Babcock (CSIRO)
NSW-IMOS	Martina Doblin (UTS)	Robin Robertson (UNSW/ADFA) Tim Ingleton (NSW OEH)
SAIMOS	Simon Goldsworthy (SARDI)	Sophie Leterme (Flinders University)
SEA-IMOS	Mark Baird (CSIRO)	Vanessa Lucieer (IMAS/UTAS) Daniel Ierodiaconou

The current Node leadership is drawn from nine different institutions across the Australian marine and climate science community – two Australian Government research agencies (CSIRO and AIMS), five Universities (UWA, UNSW, UTS, Flinders and UTAS) and two State Government agencies (SARDI and NSW OEH). There is also a good mix of broader-scale and regional expertise as well as disciplinary breadth, from physics to biology.

International peer review was undertaken in 2009-10 in order to improve the quality and coherence of IMOS science planning across Nodes. Bluewater and Climate and WAIMOS were reviewed in late 2009, and Q-IMOS, NSW-IMOS, SAIMOS and TasIMOS in late 2010. Feedback from reviewers has been incorporated into this national science plan as appropriate. The TasIMOS Node has been repositioned as South East Australia IMOS (SEA-IMOS) and a new Node plan is incorporated into the National Plan.

6.4 Major research themes that integrate across Nodes

Perhaps the most important mechanism used to drive national science planning within IMOS has been developing major research themes that cut across the Nodes, integrating Node-specific science questions into a larger framework, linking the open ocean and shelf/coastal components, and linking across the physics, chemistry and biology.

Five major research themes have been identified (Figure 5.6):

1. Multi-decadal ocean change;
2. Climate variability and weather extremes;
3. Major boundary currents and interbasin flows;
4. Continental shelf and coastal processes; and
5. Ecosystem responses (productivity, abundance and distribution).

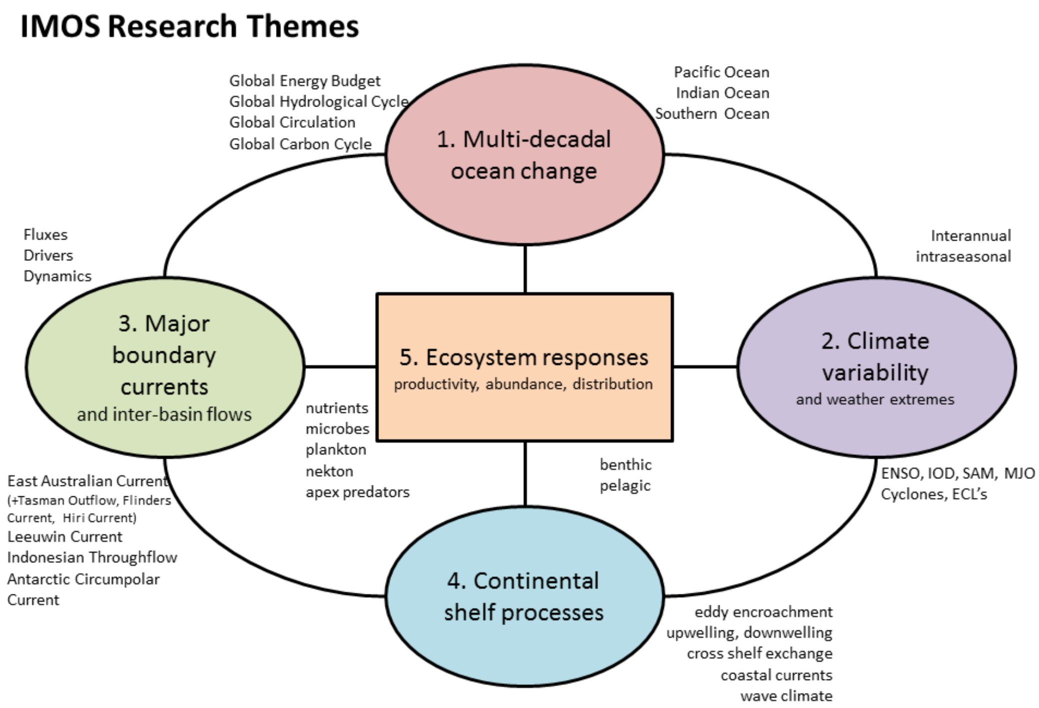

Figure 5.6: The five major research themes identified by the Australian marine and science community.

The theme of **multi-decadal ocean change** sets the broad scale context for tracking and understanding the processes by which both carbon and heat are sequestered into the global oceans at a multi-decadal scale. Questions under this theme are related to the Australian region but in a global context.

The theme of **climate variability and weather extremes** looks at improving understanding and modelling of seasonal and intra-seasonal climate and severe weather patterns by resolving and simulating ocean-atmosphere fluxes and upper ocean responses. Questions under this theme are related to coupled ocean-atmosphere modes of climate variability that most affect Australia such as El Nino/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Southern Annular Mode (SAM), and Madden-Julian Oscillation (MJO).

The theme of **major boundary currents and inter-basin flows** aims at understanding how major boundary ocean currents around Australia vary temporally and their interaction with the shelf/slope regions in Australia. This theme is a significant integrator within IMOS, linking large-scale, offshore, remotely-driven variability and responses with regional scale responses and variability.

The theme of **continental shelf and coastal processes** allows us to tailor questions about Australia's large and varied continental shelf and coastal environment, as relevant to regional priorities.

The theme of **ecosystem responses** brings together understanding of physical and chemical processes at various scales with biological observations across trophic levels in order to answer questions about productivity in marine ecosystems, and abundance and distribution of marine organisms.

In the following section, the scientific background for each of these major research themes is elaborated at a national scale and linked to the more detailed science and implementation plans for each Node.

6.5 Collaboration with other nationally significant programs

While the central component driving the national science planning within IMOS is the Nodes science planning structure, in alignment with the National Marine Science Plan to meet the grand challenges faced by Australia, IMOS also collaborates with other nationally significant programs. The Australian Government's National Environmental Science Programme (NESP), previously the National Environmental Research Program (NERP), is one example. The program provides scientific information and advice to support the Department of the Environment (DoTE) in decision making for the marine environment in areas like National State of the Environment (SoE) reporting, the developing Essential Environmental Measures program and Commonwealth Marine Reserves (CMR) network management.

The SoE reports provide information about environmental and heritage conditions, trends and pressures for the Australian continent, surrounding seas and Australia's external territories. Under the Environment Protection and Biodiversity Conservation Act 1999, the Minister for Environment Protection, Heritage and the Arts is required to table a report in Parliament every five years on the SoE. The intent of this report is to capture and present key information on the state of the 'environment' in terms of: its current condition and trend; the pressures on it and the drivers of those pressures; management initiatives in place to address environmental concerns, and the impacts of those initiatives. SOE reporting has previously acknowledged the lack of quantitative long-term time-series data. The Essential Environmental Measures program has been designed to help to address this issue so that by 2021 SoE reporting will be able to access at any time, from one location, up-to-date useable data and summary reports on the Essential Environmental Measures being developed by the programme. Over time it is anticipated that the Essential Environmental Measures programme will become a core component of the evidence used to inform SoE reporting. Identifying the EEMs is now starting.

Key ecological features (KEFs) around Australia's oceans have been identified by the DoTE through its marine bioregional planning process (Fig. 5.7). These KEFs were selected based on the importance of their ecological role, high productivity and/or high biological diversity and were used as foci for developing environmental indicators. The NESP Marine Biodiversity Hub is developing a Marine Monitoring Blueprint (the blueprint) to provide direction and options for using these indicators to inform future SoE reports directly and through the Essential Environmental Measures Program.

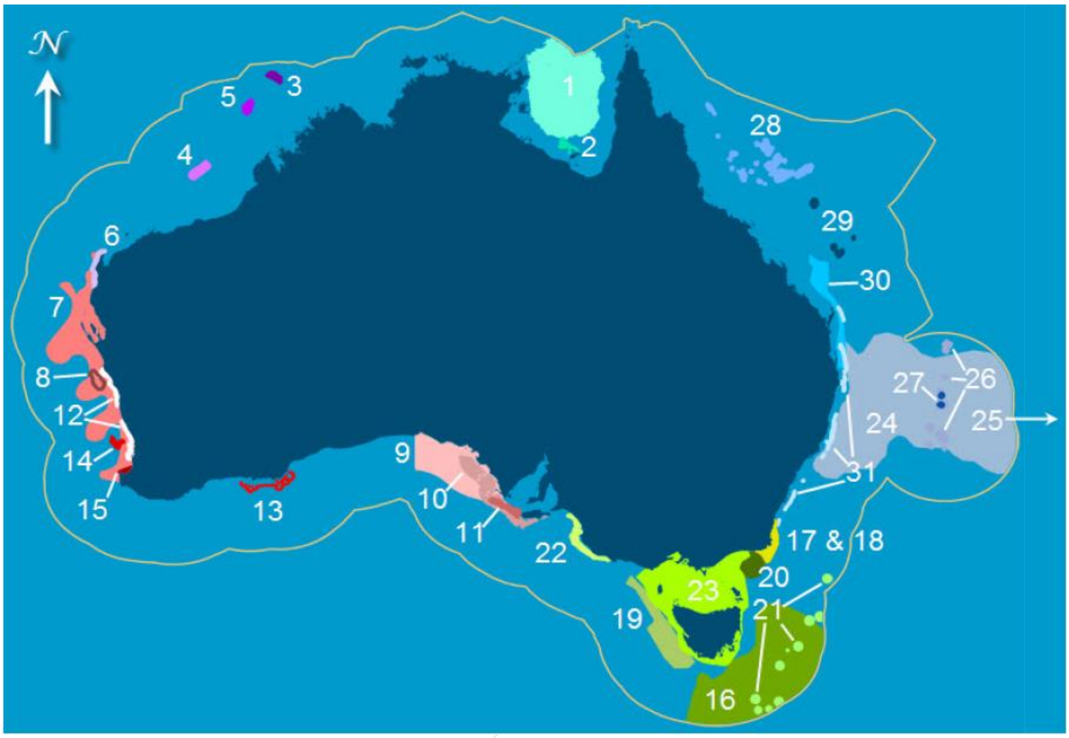

Figure 5.7. Key ecological features (KEFs) identified by DoTE for which qualitative models were developed and ecological indicators identified (Dambacher et al., 2012).

The Australian Government has also established a network of CMRs (Fig.5.8) under Australian environment law to protect and conserve marine biodiversity and other values in our oceans. Parks Australia is developing CMR management plans which have a maximum life of 10 years and set out how the reserves are to be managed including what activities are allowed. CMR network research and monitoring strategies will be developed to increase understanding of the biodiversity and values of the reserve, provide for ongoing reporting of their condition and support the decadal reviews. The NESP Marine Biodiversity Hub is also working with Parks Australia to develop the approach to monitor CMRs that draws on and complements the Marine Monitoring Blueprint.

To this end, IMOS is now sufficiently well established as an integrated marine observing system to be of significant and ongoing relevance to the Australian Government's SoE reporting needs and CMR monitoring. It should be anticipated that IMOS will be a major contributor to the developing Essential Environmental Measures program. IMOS has the capacity to routinely produce quality controlled observations of a wide range of essential ocean variables (physical, chemical and biological), at a range of time and space scales, using a multiple sensors and platforms. For example, a total of 56 KEF's was identified by the DoTE, with 31 modelled by the NESP Marine Biodiversity Hub to identify ecological and pressure indicators. From these 31 KEFs, IMOS observing platforms currently have the capacity to collect ecosystem indicator data in 20 KEFs (Table 5.3). Further work is required to organise and report this scientific data so that it provides information at an appropriate level and focus to support national environmental reporting initiatives.

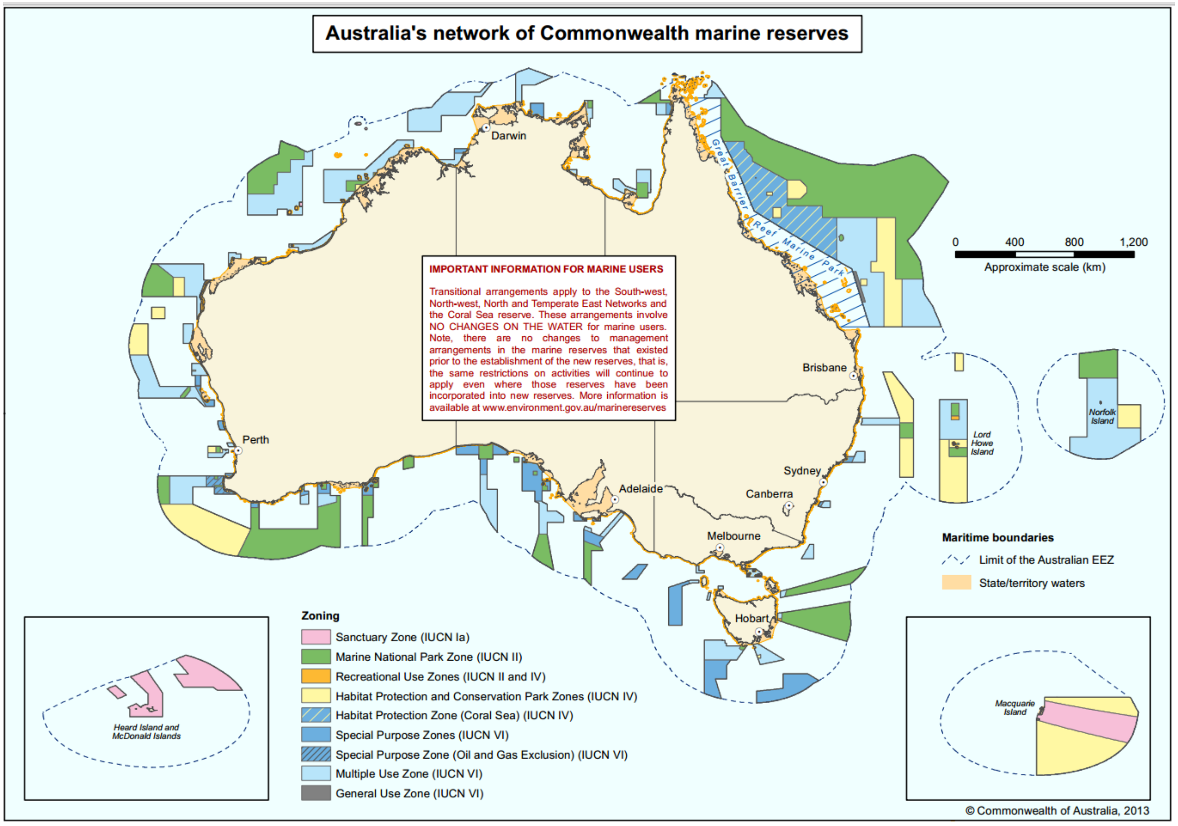

Figure 5.8. Map of Australia's network of Commonwealth marine reserves (http://www.environment.gov.au/topics/marine/marine-reserves).

In addition, our leading role in developing the Australian Ocean Data Network (AODN), an interoperable, online network of marine and coastal data resources to make data accessible to as wide a community as possible, puts IMOS in a position to influence availability of 'non-IMOS' data collected by other agencies, including: direct visual census such as Reef Life Survey, and fisheries catch, which will benefit agencies such as DoTE especially through the Essential Environmental Measures program. Furthermore, collaboration with other relevant agencies helped the development of the MARine Virtual Laboratory (MARVL), which comprises a suite of complex models (e.g. ocean circulation, waves, water quality, and marine biogeochemistry), a network of observing sensors, and a host of value-adding tools that can underpin research to understand the dynamics, interactions, and connectivity of different marine regions.

Table 5.3. Key Ecological Features (KEFs) where IMOS is currently collecting data.

Marine Region	KEF	IMOS Nodes	IMOS Facilities/ Sub-Facilities
North	1. Gulf of Carpentaria Basin	X	
	2. Submerged reefs of GoC	X	
North West	3. Ashmore Reef Cartier Island	X	
	4. Mermaid Reef Rowley Shoals	WAIMOS	AUV, Tagging (Acoustic)
	5. Seringapatam/Scott Reef	WAIMOS	AUV, Tagging (Acoustic)
	6. Ningaloo Reef	WAIMOS	AUV, Tagging (Acoustic)
South West	7. Meso-Scale Eddies (Leeuwin Current)	WAIMOS	Remote Sensing, Gliders, Radar
	8. Houtman Abrolhos Islands	WAIMOS	AUV, SOOP CPR
	9. Benthic communities eastern GAB	SAIMOS	
	10. Kangaroo Island	SAIMOS	NRS, Tagging (Biologging), Radar
	11. Small Pelagic Fish (off SA Gulfs)	SAIMOS	
	12. Adjacent to West Coast inshore lagoons	WAIMOS	
	13. Recherche Archipelago	WAIMOS	NRS
	14. Perth Canyon	WAIMOS	Moorings (phys, passive acoustic), Gliders, Radar
	15. Geographe Bay	WAIMOS	
South East	16. E. Tas Subtropical convergence zone	X	
	17. Bass Cascade	NSW IMOS	Gliders
	18. Upwelling East of Eden	NSW IMOS	SOOP CPR
	19. West Tasmanian Canyons	X	
	20. Big Horsehoe Canyon	SEA IMOS	
	21. Seamounts S and E of Tasmania	X	
	22. Bonney Coast Upwelling	SAIMOS	Gliders, Radar, SOOP CPR, Tagging (Acoustic),
	23. Shelf Rocky Reefs/Hard Substrate (Bass St)	SEA IMOS	SOOP Merchant vessel
East	24. Tasman Front and Eddy Field	NSW IMOS	Remote Sensing, SOOP XBT, Gliders.
	25. Norfolk Ridge	X	
	26. Lord Howe Seamount Chain	X	
	27. Elizabeth and Middleton Reefs	X	
	28. Queensland Plateau	X	
	29. Marion Plateau	X	
	30. Upwelling off Fraser Island	QIMOS	Gliders, SOOP CPR
	31. Reefs/Canyons/Seamounts E. Cont Shelf	NSW IMOS	

7 Scientific Background, by Major Research Theme

The five major research themes previously mentioned, unify the IMOS Node science plans and related observations. The aim of this section is to provide the scientific background and rationale for a sustained observing system that is globally and regionally integrated and that collects information of multiple ocean variables across several spatial and temporal scales. It provides information of recent research outcomes and identifies gaps and priorities with high level science questions developed for each theme in order to guide the national science implementation plan within IMOS.

7.1 Multi-decadal ocean change

The global oceans are the main source of thermal inertia in the climate system moderating our climate on diurnal, seasonal and multi-decadal timescales. They also contain the largest pool of active carbon in the planetary system and influence the hydrological cycle, with most precipitation and evaporation occurring over the ocean surface. Therefore, they are a key player in setting the rate at which anthropogenic gases build up in the atmosphere, how fast the surface of the planet warms in response to the radiative forcing that results, and are the main source of rainfall. In addition, as the upper layers of the global oceans warm, the thermal expansion can forced a slow rise in sea levels. Tracking and understanding the processes by which carbon and heat are sequestered into the global oceans is therefore essential for monitoring rates of global change.

7.1.1 The global energy balance (temperature) and sea level budget

The oceans absorb over 90% of the extra heat trapped in our climate system due to the build-up of greenhouse gases (Levitus et al., 2005). Current estimates of multi-decadal ocean heat content changes are limited to the upper 700m over the past four decades, and down to 2000m (the sampling depth of Argo) over the last 10 years. Warming below 2000 m has also been detected (Johnson and Doney, 2006, Johnson et al., 2007, Johnson et al., 2008, Johnson and Purkey, 2009, Purkey and Johnson, 2010, 2013) suggesting the deep ocean is a significant global heat sink. Therefore to track the rate of climate change, it is necessary to know the global patterns and rates of ocean warming, which are also needed to inform ESMs – particularly to test their ability to predict accurately heat sequestration and distribution in the global oceans.

Sea surface temperatures around Australia have increased by about 0.6-0.74°C over the past century (Lough and Hobday, 2011, Lough et al., 2012). However, south eastern Australian waters experienced warming three to four times the global average, becoming a global hot spot for ocean temperature change. Sea surface temperature in the region has been warming at a rate of 2.3 ^{o}C century^{-1} off Tasmania (Ridgway, 2007b), and 0.75 ^{o}C century^{-1} at Port Hacking (Thompson et al., 2011). Average SSTs of the GBR have also warmed significantly since the end of the 19th century with average temperatures for the most recent 30 years (1976 to 2005) 0.4°C warmer than the earliest instrumental 30 years (Lough, 2007). Likewise, in Western Australian water has been rapidly warming for several decades, with sea temperature rising by ~0.6-1 °C along the south-western Australian continental shelf over the past 50 years (Pearce and Feng, 2007). Information of these regional variations will be important in understanding the impact of increased temperatures on both Australian climate and weather patterns, and impacts on regional ecosystems.

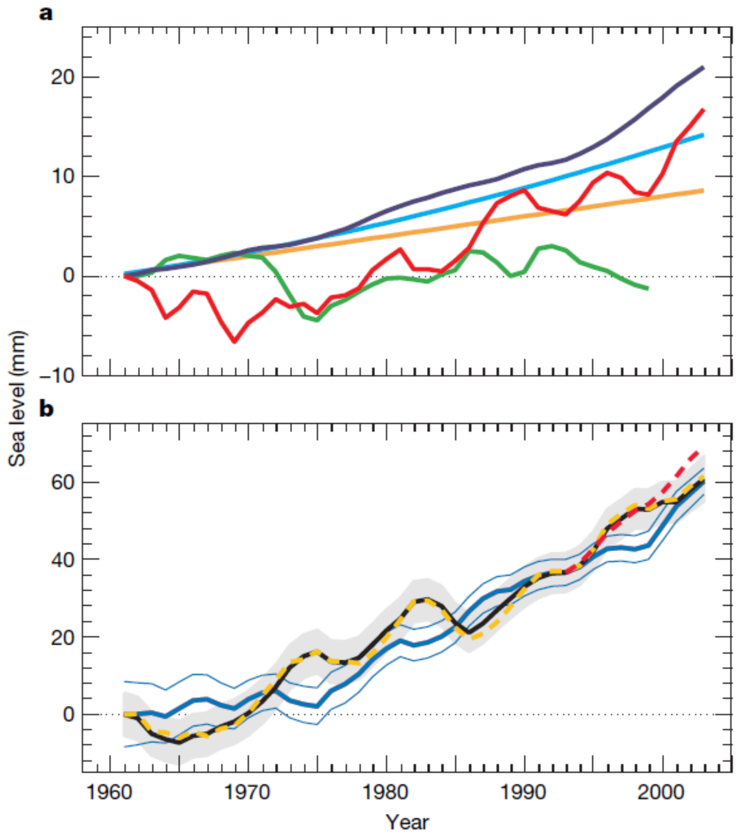

Figure 7.1: Total observed sea-level rise and its components. A, The components are thermal expansion in the upper 700m (red), thermal expansion in the deep ocean (orange), the ice sheets of Antarctica and Greenland (cyan), glaciers and ice caps (dark blue) and terrestrial storage (green). B, The estimated sea levels are indicated by the black line (this study), the yellow dotted line from Jevrejeva et al., (2006) and the red dotted line (from satellite altimeter observations). The sum of the contributions is shown by the blue line. Estimates of one standard deviation error for the sea level are indicated by the grey shading. For the sum of components, we include our rigorous estimates of one standard deviation error for upper-ocean thermal expansion; these are shown by the thin blue lines. All time series were smoothed with a three-year running average and are relative to 1961 (Domingues et al., 2008).

Ocean warming and its associated thermal expansion is also a key contributor to both the global rate and regional patterns of sea level rise (Cazenave et al., 2009). While global rates reflect both ocean thermal expansion and land ice melt, regional rates are affected by ocean processes distributing heat, such as subduction and wind changes. Recent progress on closing the multi-decal sea level budget underscores the important role of both upper and deep ocean warming driving sea level rise (Figure 7.1). Sea level rise is not uniform from place to place. Accurate estimates of regional sea level variability and change is essential to assess the impacts on coastal regions, and these estimates are available from satellite altimeters and tide gauges. The regional pattern depends on ocean surface fluxes, interior conditions and ocean circulation. The largest trends in relative sea level rise has been observed in the north and west of Australia, sea levels have risen from 8-9mm per year since 1993 (Figure 7.2).

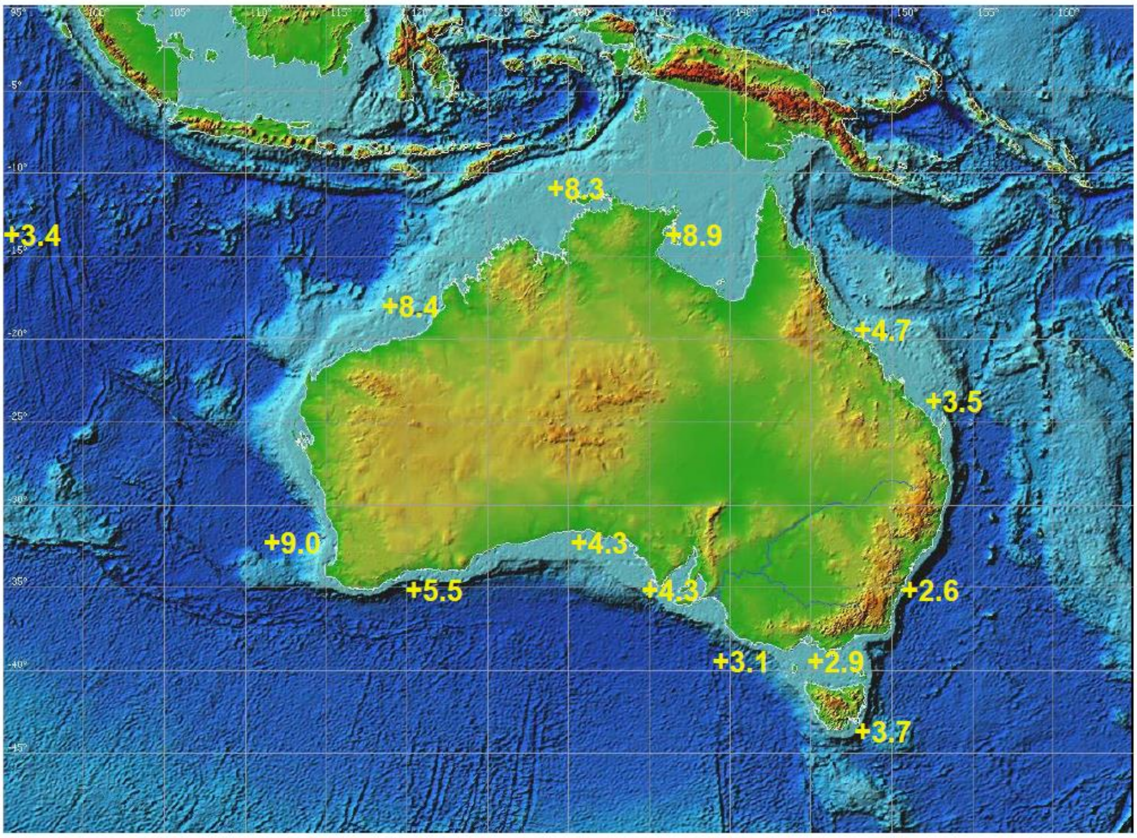

Figure 7.2: Sea level rise (mm/yr) from 1993 to June 2011 (source: http://www.bom.gov.au/ntc/IDO60202/IDO60202.2011.pdf)

7.1.2 The global ocean circulation

The global oceans sequester and transport heat and carbon primarily through the mean ocean circulation – both the shallow subduction systems and associated western boundary currents operating in ocean subtropical gyres (such as the EAC) and the deeper reaching density driven global overturning circulation (GOC). While it has been challenging to monitor large scale changes in storage of heat and other properties, measuring the low frequency variability in ocean circulation has proved to be even more difficult. Major inter-basin fluxes such as the Indonesian Throughflow (ITF) and Tasman Outflow, (TO) and water mass conversion rates remain poorly constrained (Figure 7.3), and there is still little understanding in the role of eddy property fluxes in sustaining the mean state.

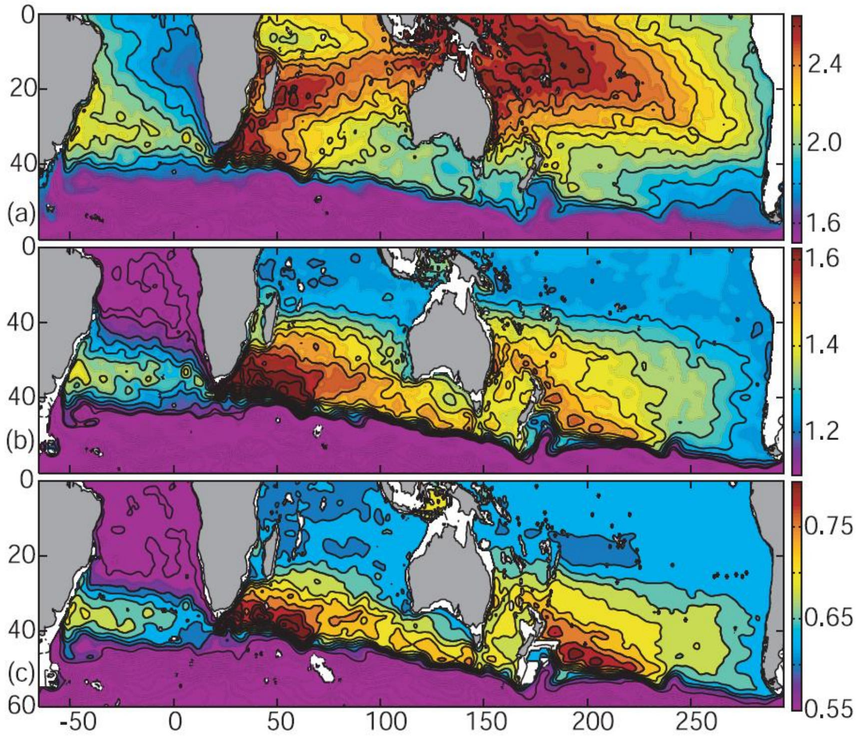

Figure 7.3. The interbasin gyre system for the Pacific and Indian Oceans as shown by the mean steric height, (a) h0/2000 (contour interval 0.02-m), (b) h400/2000 (contour interval 0.01-m), and (c) h1000/2000 (contour interval 0.01-m) (Ridgway and Dunn, 2003)

How the ocean circulation will change in the future and impact its ability to sequester and transport heat and carbon is a critical question. Evidence suggests that both surface and deep circulation patterns are changing. Recent studies show that the South Pacific subtropical gyre is projected to spin up by about 25% in response to surface heat and freshwater fluxes and surface wind stress changes, with a poleward shift of Southern Hemisphere westerly winds (Cai et al., 2005, Roemmich et al., 2007, Zhang et al., 2013). The response of the other Southern Hemisphere subtropical gyres is still being explored. One consequence of this trend is the intensification of the heat transport from the tropics to the poles via the western boundary currents such as the East Australian Current (EAC). Furthermore, evidence from models suggests a southward shift and broadening of the South Equatorial Current (Ganachaud et al., 2009, Zhang et al., 2013), which is expected to intensify the EAC (see section 7.3.1). On the western side, the long-term trend of the Leeuwin Current (LC) is driven by variations and changes of Pacific equatorial easterly winds and together with the Indonesia Throughflow(ITF), variations are coherent with the Pacific subtropical cells (STC)(Feng et al., 2010). The LC has experienced a strengthening trend during the past two decades, reversing the weakening trend of 1960’s to early 1990’s (Feng et al., 2010, 2011), and is associated with the phase transition of the Pacific Decadal Oscillation in the late 1990’s. Currently most climate models project a weakening trend of the Pacific trade winds and a reduction of the LC strength in response to greenhouse gas forcing (Sun et al., 2012).

ESM’s suggest that some limbs of the GOC will weaken. However, attention has been less focussed in the Southern Hemisphere component of the GOC, compared to the northern counterpart. The Southern Ocean (SO) is important to climate partly because the overturning circulation in this region transfers large amounts of heat and carbon dioxide from the atmosphere to the deep ocean (Rintoul et al., 2001, Marshall and Speer, 2012). Antarctic Bottom Water (AABW) forms around the Antarctic continental margin, feeding the deep limb of the GOC in the SO and ventilating the abyssal layers of the eastern Indian and Pacific basins (Mantyla and Reid, 1995, Orsi et al., 1999, Nakano and Suginohara, 2002). Observations and analysis from repeat hydrographic data suggest that the AABW is warming, freshening, contracting and become less dense in most ocean basins over the last four decades (Purkey and Johnson, 2010, 2012, 2013, Van Wijk and Rintoul, 2014). Freshening of ocean waters in the high latitudes has the potential of changing the thermohaline circulation thus driving abrupt changes in the climate (Alley et al., 2003, Rintoul, 2007). In addition, these bottom water changes may also impact the efficacy of the deep ocean in sequestering heat and carbon. Changes in bottom water formation can be detected by measurements of change in temperature, salinity and oxygen of bottom waters (Purkey and Johnson, 2010, 2012, 2013, Van Wijk and Rintoul, 2014) and by direct measurements of the sinking of bottom water near Antarctica and in the boundary currents that carry bottom water north (Fukamachi et al., 2010). Important deep boundary currents in the Australian region include the Kerguelen Deep Western Boundary Current and the deep flows into the Perth Basin.

7.1.3 The global hydrological cycle (salinity)

Besides warming, changes to the global hydrological cycle (patterns and rates of precipitation and evaporation) driven by anthropogenic greenhouse gases is a major source of concern and likely to have serious societal impacts. The water cycle is expected to strengthen expecting an increase of ~7% in atmospheric moisture content due to the ability of warmer air to hold moisture (Held and Soden, 2006, Durack et al., 2012). The current generation of ESM's show little agreement on the patterns and rates of precipitation changes compared to those for temperature (Solomon et al., 2007). Historical measurements of precipitation and evaporation on a global scale are also inadequate for constraining ESM behaviour– most of the hydrological cycle occurs over the ocean surface where few historical observations are available. In addition precipitation is both sporadic in space and time, making it difficult to extrapolate point time series into spatial integrals. However, global evaporation and precipitation spatial pattern is highly correlated with the sea surface salinity spatial pattern (Durack et al., 2012). Thus the ocean's salinity field integrates spatially and temporally the major hydrological fluxes through the atmosphere and these changes in ocean salinity can be used to test and constrain the hydrological response of ESMs. Estimates of surface salinity changes to date based on comparing Argo data with historical archives suggest large and coherent changes already underway (Hosoda et al., 2009, Durack and Wijffels, 2010). These changes are consistent with an amplification of the global hydrological cycle over past decades (i.e. wet areas are getting wetter and dry areas are getting dryer), which is in qualitative agreement with ESM results.

The hydrological cycle in Australia is highly variable, in eastern Australia rainfall and temperature is strongly associated with ENSO, with reductions in rainfall during the warm El Niño phase and enhanced rainfall during the cool La Niña phase (Verdon et al., 2004). There is also evidence of the existence of multidecadal variability in modulation of ENSO impacts such as the Interdecadal Pacific Oscillation (IPO) (Power et al., 1999, Kiem et al., 2003, Kiem and Franks, 2004). It is apparent that the effects of El Niño and La Niña across Australia are stronger and more predictable during the negative phase of the IPO, increasing the magnitude and variability of rainfall, with greater effects on NSW and QLD (Verdon et al., 2004). Changes in the water cycle and redistribution of rainfall can have serious consequences to human societies, where multidecadal modulation of the magnitude of

ENSO can have marked consequences on multidecadal flood and drought risk in Australia, affecting food availability, stability, access and utilization.

7.1.4 The global carbon cycle (Inventory, air sea fluxes, physical controls)

The oceans play a key role in the global carbon budget, taking up the equivalent of about 30% of annual anthropogenic carbon dioxide (CO_2) emissions (Doney et al., 2009, Le Quere et al., 2013). The subtropical to sub-Antarctic band has the largest zonal inventory of anthropogenic CO_2, with the Southern Ocean being the single most important uptake region of the oceans, accounting for ~ 40% of the total ocean uptake (Sabine et al., 2004, Khatiwala et al., 2009, Khatiwala et al., 2013).

Changes in ocean stratification, warming, winds and the buffering capacity of the ocean all have the capacity to change the ocean uptake of carbon. The same processes could also influence the biological export of carbon and carbonate production providing positive or negative biological feedback to the air-sea exchange of CO_2 (e.g. Gruber et al., 2004). Many ESMs are including an active ocean carbon model – Australia's ACCESS initiative is building such a capability. These models require key data sets on ocean carbon storage and cycling for tuning and validation.

Fundamental questions remain about the mean and seasonal distributions of the natural air-sea CO_2 fluxes. Available climatology is coarse resolution (4 x 5 degrees) and the shelves and large areas of the ocean, including waters around most of Australia, contain little or no data. Interannual variability in CO_2 has been described for the equatorial and subtropical Pacific (Feely et al., 2002, Dore et al., 2003, Brix et al., 2004, Borges et al., 2008) and North Atlantic (Gruber et al., 2002, Thomas et al., 2008). For the Southern Ocean, LeQuere et al. (2007) suggested that Southern Ocean carbon uptake has reduced due to more intense westerlies (in response to the Southern Annular Mode) and an increased upwelling of CO_2 rich deep waters. However, this estimate is based on carbon models and atmospheric observations, and remains controversial (Böning et al., 2008).

Variability in the partial pressure of CO_2 (pCO_2) in coastal regions has been observed, with changes in carbon flows disproportionately higher in the coast compared to the open ocean (Borges, 2011). Inadequate spatial and/or temporal coverage of CO_2 can bias the estimates of air-sea fluxes in coastal environments. Enhanced coastal upwelling, increased stratification, expanding ocean minimum zones, ice retreat and changes in the hydrological cycle due to climate change have the capacity to change CO_2 air-sea fluxes (Borges, 2011). There is evidence of inter-annual variation in CO_2 air-sea fluxes modulated by variations of wind speed that affects the gas transfer velocity and the intensity of the air-sea CO_2 flux south of Tasmania (Borges et al., 2008). In addition, seasonality in mixed layer carbon has been found to exist in the Southern Ocean, with biological processes playing the main role while mixing and sea-air exchange playing a smaller role (Mcneil and Tilbrook, 2009). Continuous ocean observations are required to resolve spatial and temporal patterns in air-sea pCO_2 fluxes and storage to help understand the role of the ocean in buffering the greenhouse effect and to inform assessments of the knock on effect on vulnerable ecosystems. A quantitative description of the air-sea carbon flux is a key data set for carbon model development and validation. The development of uniformly quality-controlled global datasets for ocean CO2 (Lo Monaco et al., 2010, Sabine et al., 2010, Bakker et al., 2014) and the collection of a consistent set of essential variables across international observing systems will help resolve if a change in ocean carbon uptake is occurring, and if it is a transient, or a long-term shift driven by climate change.

7.1.5 Spatial and temporal scales

The four components of multi-decal ocean change described above have spatial scales from 50km to 10,00km and temporal scales from decades to 100s of years, with the need to resolve interannual variability to avoid aliasing of these signals to the low-frequency signal (Figure 7.4).

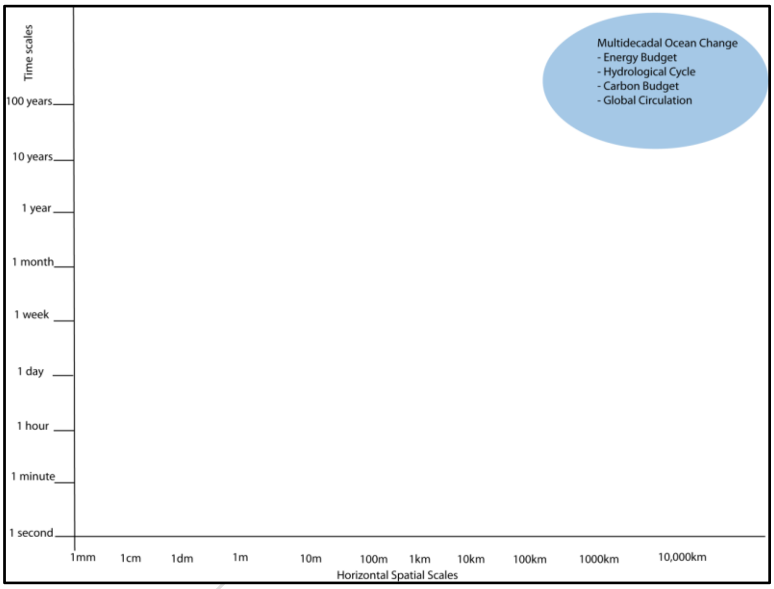

Figure 7.4. A Stommel diagram illustrating the spatial and temporal scales of Multidecadal Ocean Change processes.

7.1.6 Modelling Activities

Global coupled climate and Earth System Models (ESMs) are used to make projections of future climate and global change scenarios, and are contributed to the Climate Model Intercomparison Project phase 5 (CMIP5). The CMIP5 contributions are assessed as part of the Intergovernmental Panel on Climate Change (IPCC) process. The Australian Community Climate and Earth System Simulator (ACCESS) is Australia's new contribution to CMIP5, developed by BOM and CSIRO. Two versions have been submitted to CMIP5: CSIRO-BOM ACCESS1.0 and ACCESS1.3. In order to have confidence in future climate projections, models are benchmarked against the observational record, for example to check the horizontal and vertical distribution of ocean warming.

With respect to multidecadal ocean changes, ESMs are used to represent the mechanisms and pathways responsible for sequestering heat in the ocean, project future climate and predict changes in the hydrological cycle and carbon cycle. ESMs require key data sets on ocean temperature and salinity changes, carbon storage and cycling for tuning and validation.

7.1.7 Science Questions

The high-level science questions that will guide the IMOS observing strategy in this area are related to:

Ocean Heat content

- Spatial and temporal changes in temperature and ocean heat content across all regions around Australia, including coastal and open ocean
- Impacts of temperature on sea level rise across all regions around Australia

Global Ocean Circulation:

- Temporal changes in the overturning circulation
- Mass and heat transport across all regions around Australia, including coastal and open ocean

Global hydrological cycle:

- Spatial and temporal changes in salinity across all regions around Australia, including coastal and open ocean, and how does this reflect changes in the hydrological cycle due to climate change
- Temporal changes in river outflow and its impact on salinity patterns
- Changes on deep ocean salinity and how does this reflect ice-shelf interaction and changes in high latitude precipitation

Global carbon budget:

- Global and regional carbon inventory and changes in decadal timescales
- Biological and physical processes involved in CO_2 air-sea fluxes in the open ocean and regional areas across Australia
- Evolution of CO_2 fluxes on the Australian shelf and regional seas and their relationship with the open ocean and major circulation features

7.1.8 Variables required to address science questions

Tracking and understanding the processes by which heat and carbon are sequestered into the global oceans is essential for monitoring rates of global change and informing ESM used to predict future climate.

Temperature observations at a broader and local scale are necessary to understand and answer the science questions pertaining ocean heat content and thermal expansion around Australia at both open-ocean and regional scales. Observations of ocean salinity are essential for monitoring changes in the global hydrological cycle, as precipitation and evaporation can be derived from ocean salinity data.

Surface and subsurface temperatures, salinity, and velocity will improve our knowledge of regional and global ocean circulation throughout the full ocean depth and will help determine where and for how long heat and carbon are sequestered in the ocean. Continuous ocean observations of pCO_2 are required to resolve spatial and temporal patterns in pCO_2 air-sea fluxes and storage to help understand the role of the ocean in buffering greenhouse impacts and inform assessments of the knock on effects on vulnerable ecosystems (Table 7.1).

Table 7.1 The variables required to address Multidecadal Ocean Change science questions

Table 7.1: The variables required to address Multidecadal Ocean Change science questions.	Temperature - Surface	Temperature – subsurface	Salinity	Velocity	Sea Surface Height	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total Inorg. Carbon	Alkalinity	Macronutrient concentration	Pigment concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass	Detritus (flux)	Precipitation
Energy Balance																			

Hydrological Cycle																			
Carbon Budget																			
Global Circulation																			

7.1.9 Platforms required to deliver observations

Monitoring multi-decadal ocean change requires long-term data sets with sustained repeating operations. IMOS uses a number of platforms to collect these data sets needed to track multi-decadal change in Australia's oceans. Key data streams include (Table 7.2):

- Observations of temperature, salinity, velocity and (in some cases) oxygen provided by Argo floats profiling in the upper 2000 m of the ocean
- Physical and biogeochemical samples of the upper ocean along ship of opportunity lines using XBT's in the upper 700m and surface CO_2 dissolved gas sensor and CO_2 atmospheric gas analysers.
- Deepwater arrays that consist of moorings deployed in key boundary currents and interbasin exchanges, including the ITF, the EAC and the Antarctic polynyas and Southern Ocean time series
- Ocean gliders, bio-loggers (oceanographic sensors) deployed on marine mammals
- Satellite remote sensing of SST, ocean colour and sea surface height

In addition, non-IMOS infrastructure such as repeat deep hydrography and tide gauges for sea level measurements are also used to track multi-decadal change in the deep ocean.

Table 7.2: How variables required to address the high-level Multidecadal Ocean Change science questions are delivered at required scales by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived; Green = relative derived estimate.

		Temperature – surface	Temperature – Subsurface	Salinity	Velocity	Sea Surface Height	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total Inorg. Carbon	Alkalinity	Macronutrient concentration	Chlorophyll a concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass	Detritus (flux)	Primary productivity
Argo		Blue	Blue	Blue	Orange	Orange			Blue											
Ships of Opportunity (SOOP)	XBT	Blue	Blue																	
	Sea Surface Temperature	Blue																		
	Air-Sea Fluxes	Blue					Red	Red												
	Biochemistry (pCO2)	Blue		Red						Blue										
Deep water Moorings	Air-sea fluxes	Blue					Red	Red	Blue	Blue										
	Deep water arrays		Blue	Blue	Blue															
	Southern Ocean Timeseries		Blue	Red					Blue	Blue	Red	Blue	Blue	Blue	Red	Red	Blue	Green	Blue	
Ocean Gliders	Seagliders	Blue	Blue	Red	Red				Blue						Red	Red				
Moorings	Acidification Moorings	Blue		Red					Blue	Blue	Red									
	Shelf array		Blue	Red	Blue				Blue											
Animal tagging	Biologging	Blue	Blue	Red																
Satellite Remote Sensing	Sea Surface Temperature	Blue																		
	Sea Surface Height				Red	Blue														
	Ocean Colour														Red	Red		Red		Green
Non-IMOS Infrastructure																				
	Repeat Hydrography	Blue	Blue	Blue	Red				Blue	Red	Blue	Blue	Blue	Blue	Red					
	Tide Gauges					Blue														

Notable gaps:

The Research Infrastructure Road Map identifies the following gaps in the current observing capability that would address multi-decadal ocean change:

- The deep ocean and the cryosphere (including both the sea ice and the ocean beneath it), with measurements currently collected mostly above 2000 m, with the deep water moorings being the exception and no sea ice measurements available and sparse measurements under the ice available through oceanographic tags on seals, limited number of ice-capable floats, and the Polynya moorings.
- Oxygen data in the Coral Sea
- Gap in the data from the deep water moorings monitoring the EAC.
- Biogechemistry properties of Indonensian Throughflow
- Insufficient spatial coverage on the shelf
- Observations in Bass Strait

Future priorities:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.
- Investigate and evaluate the use of Deep Argo to determine changes in heat and freshwater content throughout the full ocean depth and Ice capable Argo to observe the sea ice zone
- Expand pCO2 network, including CO2 measurements at high latitude where overturning circulation and global CO2 outgassing changes are under debate. Measurements at low latitude are also needed, including a surface flux mooring in the extended Timor sea north-west of WA.
- Additional sites for altimeter calibration at Lorne (VIC) and Darwin (NT) to be considered, or reconfiguration of existing sites to facilitate calibration of new missions (e.g. ESA Sentinel-3).
- Evaluate the oxygen enabled Argo pilot program and expand coverage in the Coral Sea or use gliders if not possible to use Argo
- Evaluate new sensor technologies for pH, nutrients, and bio-optics that could be considered to be ready for piloting at broad scale, on Argo, SOOP, gliders etc.
- Evaluate costing of mooring array along 200 m isobath from the Kimberley to north-west Australia to monitor the thermal structure of the upper ocean on interannual and decadal time scales
- Evaluate new observing infrastructure like wave gliders for improved coverage.
- Develop partnership opportunities for sustained moored bio physical data in Bass Strait

7.2 Climate variability and weather extremes

There are three major well described coupled ocean atmospheric modes which account for a significant portion of Australian seasonal climate variability – El Niño/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM), with centres of action in the equatorial Pacific, equatorial Indian, and Southern Oceans, respectively (Risbey et al., 2009). ENSO is the strongest mode both globally and in terms of impact on Australia. Impacts of the IOD in Australia are beginning to be recognised, while impact of SAM in oceanic circulation in the South Pacific and Indian Oceans and large scale circulation and eddy properties of the Southern Ocean has been suggested (Cai et al., 2005, Farnetti and Delworth, 2010). In addition, the intraseasonal atmospheric wave mode in the tropics known as the Madden Julian Oscillation is seen as increasingly important in terms of its role in monsoon rain patterns, but also it is thought to have an influence on coupled modes such as the IOD.

Major weather patterns are strongly influenced by ocean conditions; tropical cyclones and east coast lows (in southern Queensland and NSW coast) draw energy from surface ocean temperatures, and temperature patterns may also influence storm paths. Hence, the frequency and intensity of these storms are linked to couple climate modes such as ENSO.

7.2.1 Interannual Climate Variability

7.2.1.1 El Niño –Southern Oscillation (ENSO)

ENSO is a coupled ocean-atmospheric mode with a timescale of 2-7 years, centred on the tropical Pacific. A characteristic of ENSO is the associated pattern of sea surface temperature (SST) variation in the eastern tropical Pacific Ocean, which alternates between a warm phase (El Niño) and a cold phase (La Niña). El Niño phase is related to weak trade winds over the Pacific and warmer than normal ocean temperatures in the eastern tropical Pacific, while La Niña is related to strong trade winds and colder than normal ocean temperatures (Figure 7.5). It is the dominant climate mode globally on inter-annual timescales, with worldwide environmental and socioeconomic impacts. In Australia, ENSO has a strong influence on regional rainfall patterns with El Niño (La Niña) events associated with droughts (heavy rainfall) across much of Australia.

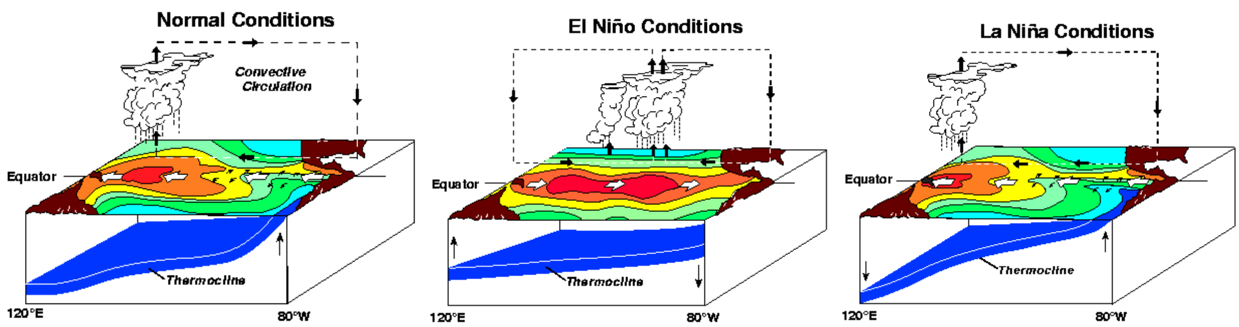

Figure 7.5. Schematic showing the oceanic and atmospheric state during (a) normal, (b) El Nino and (c) La Nina conditions in the Pacific Ocean SST (http://www.pmel.noaa.gov/tao/proj_over/diagrams/index.html).

The key role of the ocean in ENSO was recognised more than 40 years ago (Bjerknes, 1966). Due to the implementation of the ENSO Observing system in the late 1980's, primarily comprised of the Pacific TAO/TRITON/TOA tropical Pacific Array and the TOGA repeat XBT lines, a large and active research community is focussed on ENSO prediction, with mature prediction systems being trained and tested on the 30 year data sets supplied by this network. Nevertheless, key research questions around ENSO and ocean processes remain and it is currently unclear how this important climate mode can be affected by anthropogenic climate change (Collins et al., 2010, Vecchi and Wittenberg, 2010, Newman, 2013).

A lower frequency (~30 years) variation that influences sea surface temperatures, sea level pressure, and surface winds in a similar way to ENSO was identified as the Pacific Decadal Oscillation (Fig. 7.6). This low frequency mode of variability appears to have a modulating effect on the climate patterns resulting from ENSO, i.e. when PDO and ENSO are in phase (El Niño–warm PDO, La Niña–cold PDO), the ENSO climate signal is stronger while out-of-phase PDO and ENSO (El Niño–cold PDO, La Niña–warm PDO) results in a weaker climate signal (Gershunov and Barnett, 1998). However, the underlying mechanism of the PDO is still unclear and its complex relationship with ENSO is still a matter of debate (Goodrich, 2007).

In Australia, ENSO is known to have a significant effect in the west coast affecting the intensity of the Leeuwin Current (LC) and shelf slope currents (Feng et al., 2003, Clarke and Li, 2004, Holbrook et al., 2009), with the LC weakening (strengthening) during El Niño (La Niña). In the southern coastline El Niño (La Niña) events lead to lower (higher) than normal sea surface height (SSH) (Clarke and Li, 2004), with enhanced upwelling effects along the south coast during El Niño (Middleton et al., 2009).

On the east coast of Australia there is some evidence of ENSO directly or indirectly affecting the Coral and Tasman Seas (Holbrook et al., 2009), however, there have been only a few studies where evidence of ENSO effect in the EAC has been observed (Hsieh and Hamon, 1991, Burrage et al., 1994, Holbrook et al., 2005a, b). It appears that variations in the subtropical gyre circulation strength, including the EAC, are consistent with one of ENSO propagating modes (Holbrook et al., 2005a, b, Holbrook et al., 2009), likely due to the influence of Rossby waves (Holbrook et al., 2009). However, ENSO variability along Australia's east coast appears to be weaker than along Australia's west coast.

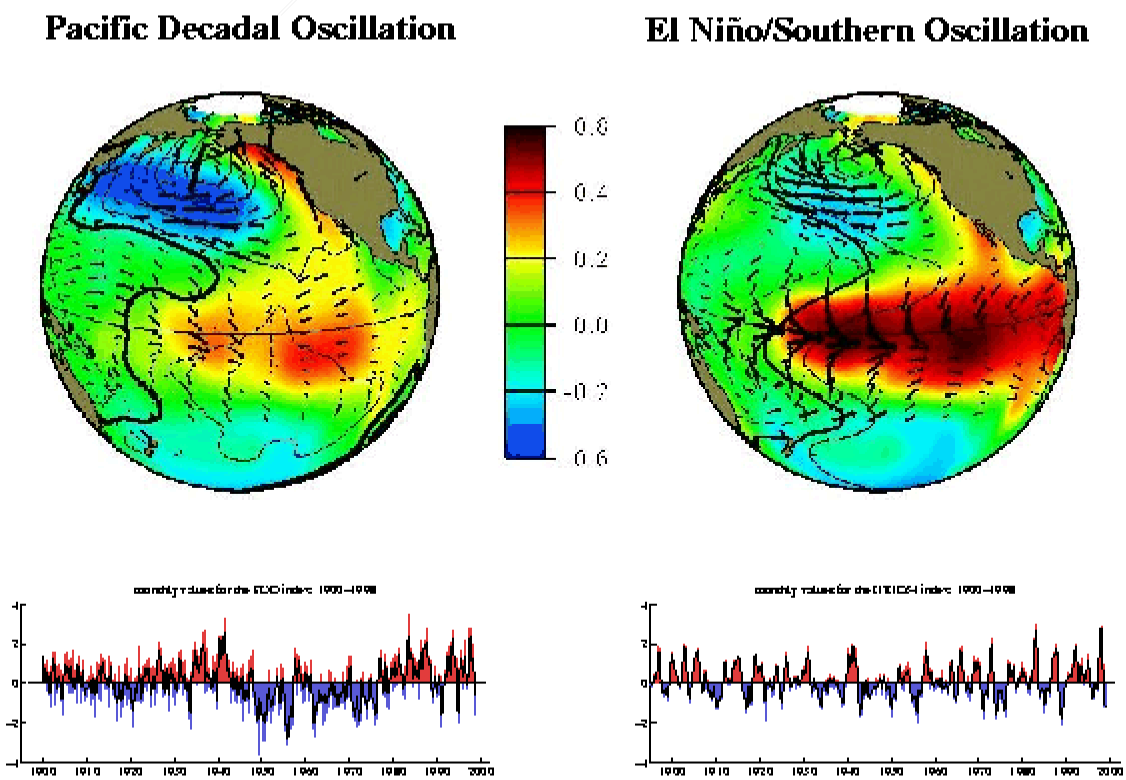

Figure 7.6. Comparing the spatial and temporal patterns of the Pacific Decadal Oscillation and the El Nino-Southern Oscillation (http://jisao.washington.edu/static/pdo/img/pdo_enso_comp.gif).

7.2.1.2 Indian Ocean Dipole (IOD)

Inter-annual variability in the tropical Indian Ocean has been recognised as a factor in global and Australian seasonal climate variability after an intensive decade of research on the IOD (Schott et al., 2009). A positive IOD phase is characterised by cooler waters in the tropical eastern Indian Ocean, and warmer waters in the tropical west. On the other hand, the negative IOD phase is characterised by warmer waters in the east and cooler waters in the west of the tropical Indian Ocean (Figure 7.7). Shoaling of the thermocline, anomalous easterly winds and low rainfall in the eastern Indian Ocean are associated to positive IOD, while the negative phase is weaker with reversed signs of all the anomalies in the same region. IOD events are seasonally phase locked and reach the peak in autumn (Schott et al., 2009).

The origin of IOD events are not clear, it appears that sometimes the seasonal timing of El Niño onset is essential for IOD development, but it is also apparent that IOD events impact the life cycle of ENSO (Schott et al., 2009). However, IOD development can also happen in the absence of ENSO (Saji and Yamagata, 2003). Recently, research on the influence of IOD and ENSO on the southeast Australian rainfall showed that the influence of ENSO is restricted to the subtropics during winter and spring, and that a positive IOD plays a major role in the droughts in the southeastern Australia, with El Niño playing a lesser role (Pepler et al., 2014 and refs. within). However, the interaction between ENSO and the IOD is complex, with strongest rainfall anomalies observed in years where both drivers co-occur (Ummenhofer et al., 2009, Pepler et al., 2014).

Improved understanding of IOD and improving its simulation in the Australian seasonal climate prediction models are research-priorities. IOD predictability appears to be much less than ENSO's, probably due to inadequate representation of its slow physics in models, inadequate observations in the Indian Ocean (CLIVAR-GOOS Indian Ocean Panel Clivar, 2006), and/or inherently more chaotic physics. The IOD remains an active area of international research, with challenges in the observation, description, understanding and prediction.

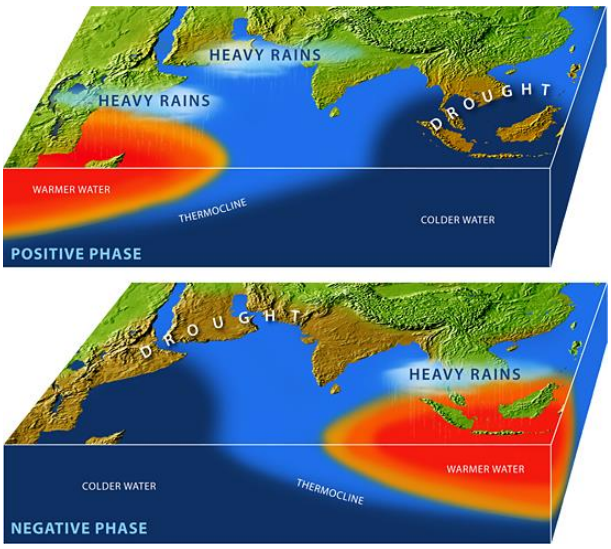

Figure 7.7. Upper panel shows the positive phase of the IOD, with warm water in the western Indian Ocean and increased rainfall in the region. The lower panel shows the negative phase with the warm water in the east

and associated increased regional precipitation (Illustration by E. Paul Oberlander, ©Woods Hole Oceanographic Institution, https://www2.ucar.edu/news/backgrounders/weather-maker-patterns-map-text-version).

7.2.1.3 Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) describes the north–south movement of the westerly wind belt that circles Antarctica. It dominates the middle to higher latitudes of the southern hemisphere and it is the leading mode of climate variability in the southern mid to high latitudes. In the pressure field, it is characterized by north-south shifts in atmospheric mass between the polar region and the middle latitudes (Thompson and Solomon, 2002). The changing position of the westerly wind belt influences the strength and position of cold fronts and mid-latitude storm systems, and is an important driver of rainfall variability in southern Australia. Variations occur on timescales of 10 days or longer and exert a dynamic influence over ocean circulation, water-mass formation and the distribution of heat and energy around the entire planet (Figure 7.8) (Sen Gupta and England, 2006).

In its positive mode, the belt of strong westerly winds contracts towards Antarctica, resulting in lighter westerly winds and higher pressures over southern Australian latitudes. Conversely, a negative SAM shows an expansion of the belt of strong westerly winds towards the equator, resulting in more or stronger storms and low pressure systems over southern Australia.

From an Australian perspective the positive phase of SAM shifts low pressure systems southwards reducing rainfall over southwest Western Australia (WA), Tasmania, Victoria and South Australia (Hendon et al., 2007). It has also been identified to strengthen the local cyclonic atmospheric circulation off the WA and enhance the southward advection of the Leeuwin Current and associated heat transport (Kataoka et al., 2013). In addition, SAM positive phase is associated with increase in daily rainfall on the southeast coast as a result of an increase occurrence of moist upslope flow from the Tasman Sea, explaining 10-15% of weekly rainfall variability during spring and summer in the southwest and southeast coasts (Hendon et al., 2007). There is also strong evidence that the SAM positive trend has driven a spin up and southward shift of the south Pacific subtropical gyre (Cai, 2006, Roemmich et al., 2007, Hill et al., 2008) resulting in a shift in the distribution of certain marine species (e.g. an expansion of a mainland sea urchin species, C. rodgersii, to Tasmania, (Ling et al., 2009). In the Southern Ocean (SO), early models showed that the higher index state of SAM is associated with the strengthening of the circumpolar wind stress, which results in an increase of the Antarctic Circumpolar Current (ACC) transport, a change in its position and the intensification of the SO eddy field with a lag of 2-3 years (Meredith and Hogg, 2006). However, in recent eddy-resolving models, a doubling of the wind stress increase the overturning circulation by 70% but the ACC transport remained nearly unaltered (Meredith et al., 2012, Morrison and Hogg, 2013). Given that the SO is a major sink for anthropogenic CO_2 and source for natural upwelled CO_2, understanding changes in the overturning circulation is of great importance to know how CO_2 concentrations will evolve into the future.

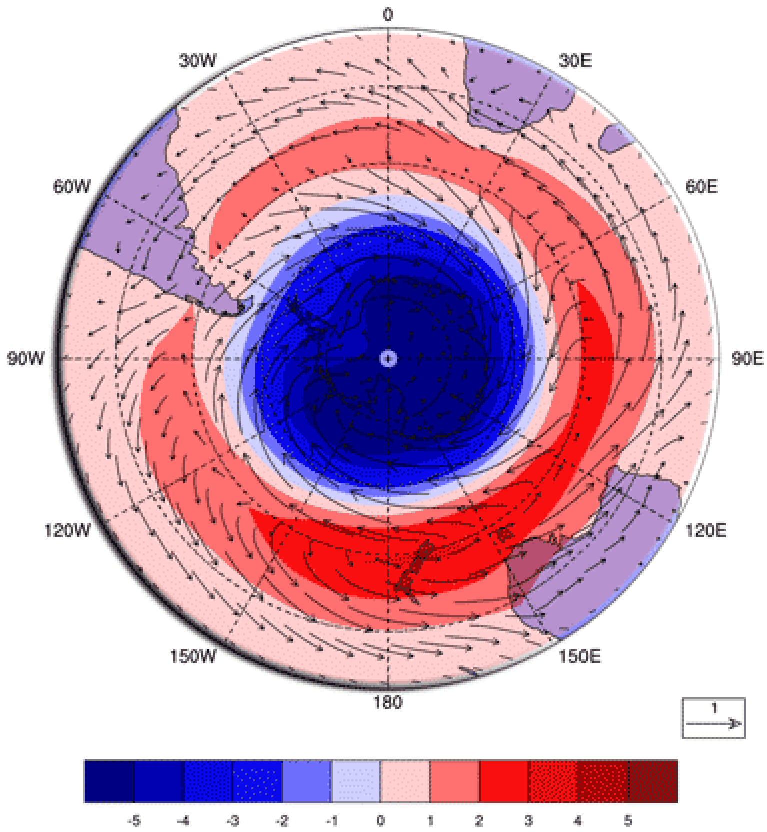

Figure 7.8. Regression of sea level pressure (colour bar) and wind vectors (1m/s shown) from a climate model onto the SAM index (Sen Gupta et al., 2006)

Annular modes appear to be sensitive to increasing greenhouse gases (Shindell et al., 1999, Hendon et al., 2007 and ref. within), and SAM has exhibited trends that are consistent with the forcing by the Antarctic ozone hole (Thompson and Solomon, 2002, Gillet and Thompson, 2003, Shindell and Schmidt, 2004). A number of studies have noted that the positive trend in the SAM since the 1970s (during the summer-autumn seasons) may be attributed primarily to ozone depletion and is consistent with enhanced greenhouse forcing (Arblaster and Meehl, 2006 and references within). However, uncertainty remains regarding the influence of stratospheric ozone recovery on the future evolution of the SAM trend (Son et al., 2008).

7.2.2 Intra-seasonal variability and severe weather

7.2.2.1 The Madden-Julian Oscillation (MJO)

The MJO is a large scale coupling between the atmospheric circulation and tropical deep convection that slowly (~5 ms^{-1}) propagates eastward from the Indian to the Pacific Ocean where the sea surface is warm (Zhang, 2005). It is the dominant component of the intraseasonal (30-90 days) variability in the tropical atmosphere (Zhang, 2005) that can enhance or suppress convective activity and lead to burst and breaks in the Northern Australian summer monsoon (Wheeler et al., 2009). It is suggested that the MJO plays a role in the initiation and evolution of ENSO and IOD events

(Mcphaden et al., 2006), modulation of the ITF (Sprintall et al., 2009) and is a useful indicator of the timing of potential rainfall events across much of tropical Australia.

The MJO is classified into eight phases based on the pattern of convection and zonal winds near equatorial latitudes. Its phase is tracked in near-real time by the Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/). Passage of the MJO not only affects rainfall but also can lead to surface water cooling or warming at critical times for thermal stress events; thus influencing the risk of coral bleaching. During winter, the rainfall response along the Queensland coast co-varies with the MJO phase due to modulation of the SE trade winds. In the west of Australia, the intra-seasonal variability in the LC is associated with the direct forcing of the MJO through southward-propagating coastal trapped waves forced on the NW shelf through Ekman-induced vertical advection and surface heat fluxes in the easterly phase of the MJO (Marshall and Hendon, 2014). Recognition of the importance of the MJO for both numerical weather prediction and seasonal climate forecasting is driving a demand for observing systems which resolve these phenomena and increased process understanding to improve model simulations.

7.2.2.2 Tropical Cyclones

Tropical cyclones are low pressure systems that form over tropical waters and have gale force winds extending more than half-way around near the centre and persisting for at least six hours. They derive their energy from the tropical oceans requiring sea surface temperatures (SST) higher than 26°C to form and can persist for many days sometimes following quite erratic paths (Bureau of Meteorology). Tropical Cyclones impact much of the Northern Australian coast (Figure 7.9). They induce strong mixing of warm, surface layer water with colder, denser water from the upper thermocline (Korty et al., 2008). This mixing leads to large reductions of SSTs observed in the wake of tropical cyclones (Leipper, 1967, Price, 1981). It has been suggested that mixing induced by tropical cyclones may also drive a substantial portion of the oceans' observed heat flux (Emanuel, 2001).

Differences in the strength of summer monsoon circulation over northern Australia associated with ENSO events result in strong interannual variability in tropical cyclone activity. During El Niño the cyclone season is less active in the western Pacific, when the tropical warm pool has receded to the east, while during La Niña the activity is enhanced (Lough, 1994). Cyclones impacting the Queensland coast generally undergo a period of intensification over the Coral Sea, gathering energy from the warm waters. The cumulative exposure to cyclones since 1985 has been responsible for approximately half of the observed decline in coral cover (De'ath et al., 2012) across the whole Great Barrier Reef (GBR) with more severe decline in the southern GBR. In the NW of Australia, the intensity and frequency of tropical cyclones appears to be related to upper ocean heat content off the NW Shelf, being higher during La Niña events and lower during El Niño years. Research shows that an understanding of the ocean temperatures and atmospheric conditions during and following cyclone formation is required for accurate prediction of track and intensity; which requires tracking these systems and the associated ocean and atmospheric conditions throughout their lifetime or longer.

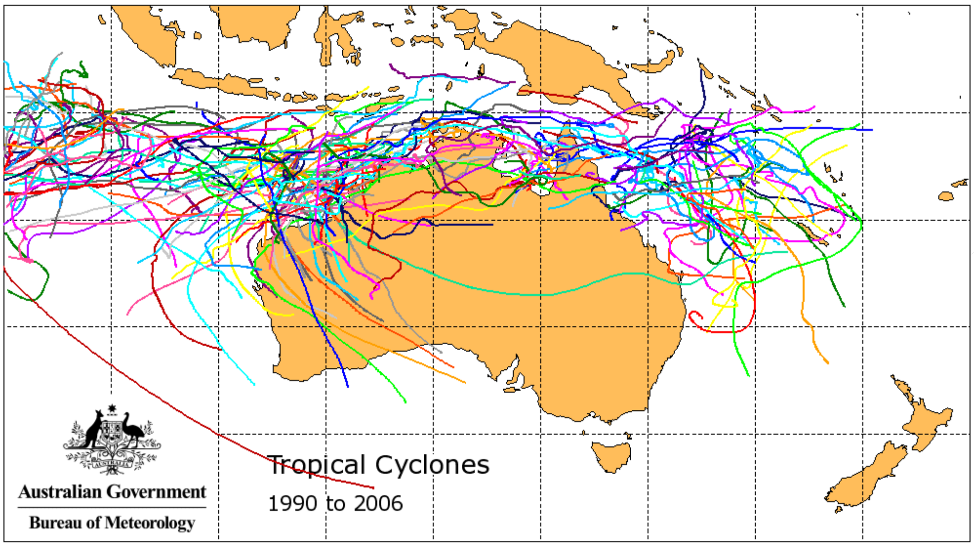

Figure. 7.9. Tracks of tropical cyclones in the Australian region from 1990 to 2007 (source: BOM).

7.2.2.3 East Coast Lows (ECL's)

ECLs are short lived intense low-pressure systems that occur on average several times each year over the Australian east coast approximately between 25 and 40ºS (Holland et al., 1987). Although they can occur at any time of the year, they are more common during Autumn and Winter with a maximum frequency in June (Bureau of Meteorology). ECLs may form in a variety of weather situations; in summer they can be ex-tropical cyclones, at other times of the year they will most often develop rapidly just offshore within a pre-existing trough of low pressure due to favourable conditions in the upper atmosphere. They can also develop in the wake of a cold front moving across from Victoria into the Tasman Sea. Although they are most common on the coastline of New South Wales adjacent to the offshore eddy field produced by the separation of the EAC from the coast, ECLs manifest every few years in southern Queensland. Unlike cyclones, ECLs are driven by temperature gradients in the upper atmosphere colliding near the coast. The SST gradient between the coast and the EAC offshore also appears to be critical in the evolution of coastal low pressure and trough systems (Holland et al., 1987, Leslie et al., 1987, Speer and Leslie, 2000). The significance of ECLs is their rapid intensification (most often overnight) that can produce highly energetic systems (of local to meso-scale size) capable of producing gale force winds and large waves on the adjacent coast. They can have severe consequences such as flash flooding and damaging winds and seas, but also beneficial consequences such as being responsible for heavy rainfall events that contribute significantly to total rainfall and runoff around the region (Dowdy et al., 2011).

7.2.2.4 Ningaloo Niño

Ningaloo Niño is a marine heatwave that raises the temperature in nearshore waters. This heat wave is associated with La Niña in the Pacific, a positive phase of SAM, the Australian monsoon, as well as local air-sea coupling (Kataoka et al., 2013, Marshall and Hendon, 2014). During the February/March 2011 Ningaloo Niño temperatures along the Gascoyne and mid-west coast exceeded 5°C above the long-term average for that time of year. This has been attributed to both a very strong LC (anomalously high coastal sea levels) during an intense La Niña period and anomalously high air-sea heat flux entering the ocean (Feng et al., 2013, Pearce and Feng, 2013). Strong easterlies anomalies in the equatorial western Pacific and low sea level pressure anomalies off the west coast of Australia have been identified to be also important to cause the local wind and LC anomalies in early 2011, resulting in the peak of the Ningaloo Niño event (Feng et al., 2013). Effects of the Ningaloo Niño (marine heat wave) on the marine biota can be devastating, with severe effects on WA fisheries (Caputi et al., 2014).

7.2.3 Modes of variability in a changing climate

The impact of modes of variability on the Australian region has been discussed above. Less is known about how these modes will change in a warming world. Observations and ESMs suggest a continuing trend towards a more positive SAM, driven by both reduced ozone levels and greenhouse gas forcing (Cai et al., 2005, Cai, 2006), driving a pole-ward shift and intensification in the circumpolar westerly winds, (Gillet and Thompson, 2003) and a trend towards reduced rainfall across Southern Australia.

There is less certainty about how ENSO will evolve in a warmer world. Low frequency variability in the Pacific Basin related to ENSO means that long time-series are needed to separate out variability from change (Collins et al., 2010). Despite progress in our understanding of the effects of climate change in various processes that contribute to ENSO variability, we do not have yet the ability to predict if ENSO activity will be enhanced or damped, or it the frequency of events will change in a warming climate (Guilyardi et al., 2012).

In the Indian Ocean, 21st Century simulations suggest that the mean is shifting towards a more positive IOD; that is a cooler dryer eastern Indian Ocean and thus a dryer Australia (Cai et al., 2009, Ummenhofer et al., 2009). These modes also feed back into the ocean circulation. Both the trend in the SAM and decadal ENSO variability have been related to a long term positive trend and decadal variability in the South Pacific Gyre strength and circulation pattern (see Section 7.3).

7.2.4 Spatial and temporal scales

Within the long-term trends and cycles of climate, critical variations in oceanic processes occur at inter- and intra-annual scales. Typically length and space scales of these different phenomena are correlated and this range defines the spectrum from high frequency cycles in climate to extreme events in the weather band. The contributors to climate variability and weather extremes span spatial scales of 10 to 10,000 km and temporal scales from a few days to 100s of years. ENSO, SAM, IOD and other climate modes vary on longer scales from multiple years to decades and impact scales from 100s of km to 10,000 km. ECLs and tropical cyclones on the other hand are ephemeral events that regardless of their magnitude are typically measured in days and their major impact is restricted to areas measured in hundreds of kilometres.

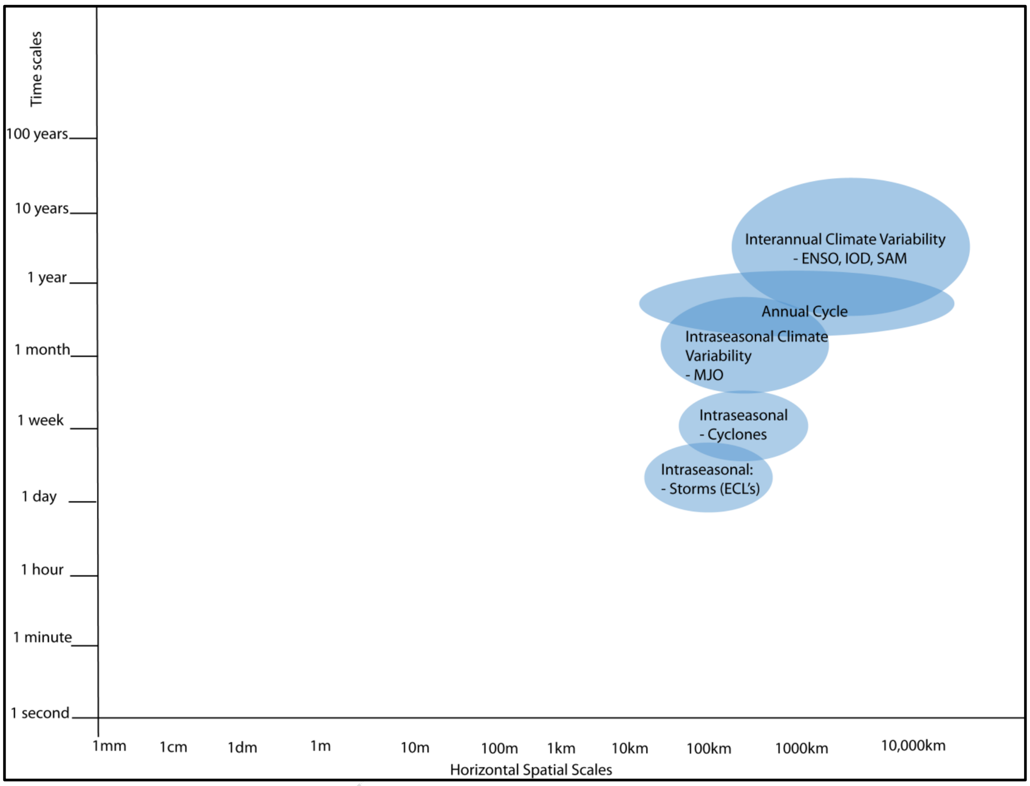

Figure 7.10: A Stommel diagram of the spatial and temporal scales of climate variability processes.

7.2.5 Modelling activities

Australia's climate is uniquely connected to the processes in the surrounding ocean; modes of variability such as ENSO and IOD determine seasonal rainfall patterns. The tropical upper ocean thermal distribution is the largest source of predictability at seasonal timescales for coupled modes such as ENSO. The present day coupled models do not simulate the mean state of the ocean well (e.g. the Pacific equatorial cold tongue), indicating that much remains to be understood about parameterisation of key processes, such as ENSO. Comprehensive coupled general circulation models, such as those used in the phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), have become powerful tools for examining ENSO behaviour, dynamics and potential changes in ENSO mean state and variability (Meehl et al., 2007, Randall et al., 2007, Sriver et al., 2014). However, challenges remain in simulating key statistical features of ENSO, given biases in the current generation of these models. Seasonal forecast systems such as the Predictive Ocean-Atmosphere Model for Australia (POAMA) run by the BOM, show skill in predicting the onset of an event such as an El Niño, but not its magnitude or timing. Improved understanding of these modes of variability and how they interact is essential for improving both Earth System models and seasonal forecast systems.

On the other hand, current coupled models do not capture intra-seasonal variability very realistically (Lin et al., 2006). Recognition of the importance of the MJO for both numerical weather prediction (Hendon et al., 1999) and seasonal climate forecasting is driving a demand for observing systems which resolve these phenomena and increase process understanding to improve their model simulation. Relatively rapid intra-seasonal variability (e.g. the MJO) affects the evolution and predictability of seasonal signals. Improved representation of this type of variability is of high priority in development of POAMA.

However, progress on improving model simulation partly hinges on better initialising the ocean component of prediction systems using ocean observations and parameterisation of the coupled ocean processes involved. Recognition of the importance of intra-seasonal variability such as the MJO, for both numerical weather prediction and seasonal climate forecasting is driving a demand for continuous observing systems which can resolve these phenomena and increased process understanding to improve model simulations.

7.2.6 Science Questions

The following questions are primarily aimed at improving dynamical understanding in support of climate modelling and seasonal forecasting, e.g. correcting errors in the representation and parameterisation of physical processes in dynamical models. Observations will also be aimed at improving the data assimilation and initialisation for seasonal forecasting.

The high-level science questions that will guide the IMOS observing strategy in this area are related to:

Interannual:

- Effects of interactions between the atmosphere and the ocean surface layer,(e.g. the exchange of heat and moisture), on climate processes
- Improvement of dynamical understanding of ENSO in the open ocean and regional areas and its effect on coastal waters and boundary currents around Australia
- Improvement of seasonal forecast and projections of ENSO in future climate
- Improve dynamical understanding of IOD, the possibility of coupling between ENSO and IOD and its effects in the open ocean and regional areas
- Effect of SAM in coastal waters

Intraseasonal:

- MJO interaction with other recurrent climate processes, such as ENSO, IOD and the Australian monsoon, and its incorporation into predictive models
- The role of air-sea interaction in the dynamics of the MJO
- Influence of ocean variability such as sea surface temperature, in the development of weather events like tropical cyclones and East Coast Lows, marine heat waves (Ningaloo Niño),their genesis and their effects in coastal areas

7.2.7 Variables required to address science questions

Three major, coupled ocean-atmospheric modes account for a significant portion of Australian seasonal climate variability – El Nino/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). Upper ocean temperature distribution is the largest source of predictability due to the large thermal inertia of the ocean and its predictable dynamics.

Major weather patterns are strongly influenced by ocean conditions drawing energy form the ocean. Cyclones and east coast low have inter seasonal variability with strong links to coupled modes like ENSO.

While climate variability operates on inter-annual timescales, and weather extremes operate on shorter space and time scales, the observations needed to understand them are the same (Table 7.3). To characterize the climate variability and the weather extremes observations are needed of upper ocean temperature and salinity, air-sea exchange heat, gases and momentum (wind stress), sea level measurements, dissolved oxygen and pCO_2 and velocities.

Table 7.3: The variables required to address Climate Variability and Weather Extremes science questions.

	Temperature - Surface	Temperature – subsurface	Salinity	Velocity	Sea Surface Height	Internal waves	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2
Inter-annual (ENSO, IOD, SAM)										
Intra-seasonal (MJO, Cyclones, ECL's)										

7.2.8 Platforms required to deliver observations

Monitoring climate variability and weather extremes requires observations drawn from the same platforms as those for the larger scaled multi-decal ocean change theme. The major additional requirement is the need for surface air-sea fluxes from Ships of Opportunity, which are of particular importance to this theme, to measure the magnitude and variability of air-sea heat, freshwater and carbon exchange. Satellite measurements of wind stress, SST and altimetry are also relevant to this theme. Velocities, sea surface height, and subsurface temperatures from moorings, ocean gliders, Argo floats and XBT transects will also be used for this theme (Table 7.4).

Table 7.4: How variables required to address the high-level Climate Variability and Weather Extremes science questions are delivered at required scales by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived; Green = relative derived estimate.

		Temperature – surface	Temperature- Subsurface	Salinity	Velocity	Sea Surface Height	Internal waves	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH
	Argo	Blue	Blue	Blue	Orange	Orange				Blue		
Ships of Opportunity (SOOP)	XBT	Blue	Blue									
	Sea Surface Temperature	Blue										
	Air-Sea Fluxes	Blue						Red	Red			
	Biochemistry (pCO2)	Blue		Red							Blue	
	Tropical RV	Blue		Red								
Shelf Moorings	National Reference Stations	Blue	Blue	Blue	Blue			Orange	Red	Blue		
	Shelf arrays		Blue	Red	Blue		Orange			Blue		
	Acidification Moorings	Blue		Red							Blue	Red
	Temperature loggers	Blue										
Deep water Moorings	Air-sea fluxes	Blue						Red	Red	Blue	Blue	
	Deep water arrays		Blue	Blue	Blue		Orange					
Satellite Remote Sensing	Sea Surface Temperature	Blue										
	Sea Surface Height				Red	Blue	Orange					
Ocean gliders	Sea Gliders	Blue	Blue	Red	Red		Orange			Blue		
	Slocum gliders	Blue	Blue	Red			Orange			Blue		
	Wireless sensor networks	Blue	Blue	Red				Orange	Red			

Notable gaps:

The Research Infrastructure Road Map identifies the following gaps in the current observing capability that would address climate variability and weather extremes:

- Lack of direct air-sea flux measurements in the tropical oceans north of Australia limits understanding of phenomena like the MJO and IOD and their influence on Australian climate.
- Spatial and temporal coverage of current measurements are insufficient and it is important to understand effects of extreme climatic events.
- Oxygen data is only measured in oceanic water and needs to be matched by data streams from the shelf, particularly to monitor after extreme weather events.
- Gap in the data from the deep water moorings monitoring the EAC.

Future priorities:

- Maintain and enhance the IMOS infrastructure that is presently in place and increase spatial and temporal coverage, if it can be done efficiently and economically.
- Maintaining the SOFS air-sea flux mooring remains the highest priority Australia.

- Look for opportunities to fill the gap in air-sea flux measurements north (e.g. in regions relevant to MJO) and south of the continent (e.g. south of the SOFS site, to sample fluxes at higher latitude). Past collaborations with JAMSTEC in Japan and NOAA/PMEL in the USA may be built on in the future to allow this to proceed. Extending the air-sea flux network from Ships of Opportunity could also help address these gaps.
- Increase deployment of slocum and/or sea gliders on repeated cross-shelf transects in Qld, NSW, WA and SA and SEA with additional taskable deployments to specific impacted regions during and after extreme events.
- Maintain a footprint in the Kimberley coastal region.
- Support and maintain offshore observations such as Argo floats and XBTs, in order to understand both remote and local large scale climatic drivers of extreme climatic events.

7.3 Major boundary currents and inter-basin flows

The waters around Australia form a complex intersection of the Pacific and Indian Oceans (Figure 7.11). The main large-scale influences on this ocean region arise from the two major subtropical gyre systems; the South Pacific in the east and the Indian Ocean in the west. These ‘gyres’ are the pathway followed by the flow in each ocean basin. Australia is therefore influenced by two major boundary current systems: the EAC, which forms the western boundary current of the South Pacific gyre, and the LC, a unique poleward-flowing eastern boundary current of the Indian Ocean gyre. There are also two major ‘gateways’ or inter-basin flows between these ocean regions; the Indonesian Throughflow (ITF), an ocean pathway through the deep channels connecting the western Pacific and the northeast Indian Ocean, and the Tasman Outflow (TO) which provides a trajectory around Tasmania for the residue of EAC to penetrate into the Indian Ocean (Ridgway and Dunn, 2007), thus connecting the Pacific and Indian Ocean subtropical gyres. To the south of Australia, is the northern extent of the Antarctic Circumpolar Current, the world’s largest ocean current. The southern Australian coast, and particularly Tasmania also have a complex interaction between the EAC from the east (stronger in summer), the Leeuwin Current/Zeehan Current from the west (stronger in winter), and the subtropical front (STF) to the south.

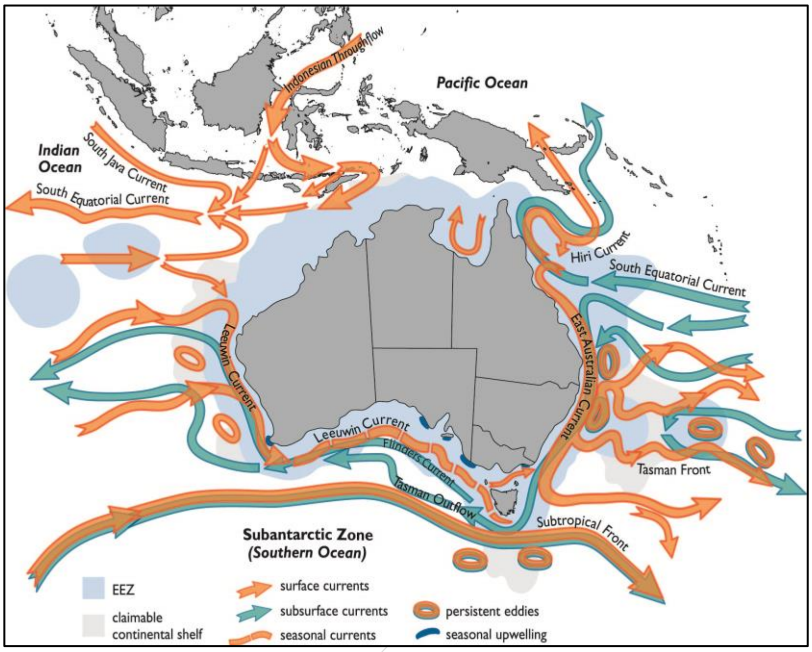

Figure 7.11: Boundary Currents in the Australian region (image provided by CSIRO).

In this section, the main boundary currents and interbasin flows in the Australian region are described. While the major boundary currents have their own unique features, the high level questions are focussed around the boundary current fluxes of heat mass and salt, drivers of variability and change in boundary currents and the dynamics of boundary current key features such as separation/bifurcation zones, and eddy generation/fate.

7.3.1 East Australian Current (EAC) system (including Tasman Outflow, Flinders Current and Gulf of Papua Currents)

East Australian Current

The EAC is the major western boundary current of the South Pacific subtropical gyre. As the South Equatorial Current (SEC) reaches the Australian shelf in the Coral Sea it bifurcates to form a northward limb called the Gulf of Papua Current, while the southward limb forms the EAC. The flow of the EAC along Australia's east coast has been described to occur in four stages: 1) formation in the south Coral Sea (15-24ºS); 2) intensification of the current off northern NSW (22-35ºS); 3) separation stage from the coast (31-33 ºS); and 4) declining to eddies and coastal fingers off southern NSW, eastern Victoria and Tasmania (38ºS) (Ridgway and Dunn, 2003). The portion that continues south past the separation is referred to as the EAC Extension which flows south to Tasmania, either turning eastward as part of the southern limb of the subtropical gyre or westward as the Tasman Outflow, which feeds into the Flinders Current, and is thought to form the Leeuwin Undercurrent (LUC). The EAC is also Australia's largest current, typically 30 km wide and 200 m deep and it plays a critical role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Roemmich et al., 2005). This heat transfer is a dominant environmental influence on regional climate and fisheries production along the eastern seaboard (Poloczanska et al., 2007). The EAC is complex and highly energetic travelling up to 4 knots (2 ms^{-1}), with a mean transport estimated as 20-32 Sv (Ridgway and Godfrey, 1994, Mata et al., 2000). However, its seasonal cycle is large compared to the mean flow, with estimates of transport ranging from a maximum of 36.3 Sv in summer and a minimum of 27.4 Sv in winter (Ridgway and Godfrey, 1997). The EAC has ~5 fold greater volume transport than the seasonally flowing LC on the west coast.

Off NSW the variability of the EAC is so large, as a result of the separation from the coast, that very often a single continuous current cannot be identified, with large mesoscale eddies dominating the flow (Bowen et al., 2005, Mata et al., 2007). The separation has been ascribed to various sources: wind stress, coastal geometry (i.e. the westward retraction of the coast), bottom topography, or the interruption of the basin circulation by New Zealand (Ridgway and Dunn, 2003). The current is generally known to separate anywhere between 29 and 32°S, however, recent work shows a bi-modal separation pattern with a distinct preference for separation either at 29°S or 31-32°S (Cetina Heredia et al. in prep). The largest of the EAC eddies are 200-300 km in diameter and 2-3 of these warm-core eddies are generated annually with lifetimes often exceeding a year (Nilsson and Cresswell, 1981, Bowen et al., 2005). They follow variable southward trajectories, but are generally constrained within the deep basin just offshore from the EAC extension. Cold-core eddies are also embedded in this flow.

Long-term observations from an ocean reference site in Tasmania (Maria Island) have shown warming trends much greater than the average global ocean trend: 2.3°C vs 0.6°C respectively over the past 100 years (Ridgway, 2007b). This temperature increase in Tasmanian waters has been ascribed to the EAC, with the long-term record indicating a poleward advance of this boundary current. This intensification of the EAC near its southern limits has been attributed to mid-latitude changes in ocean circulation driven by changes in wind stress and curl. There is also evidence that the SAM positive trend has driven a spin up and southward shift of the south Pacific subtropical gyre (Cai, 2006, Roemmich et al., 2007, Hill et al., 2008) and thus the intensification and poleward movement of the EAC into the Tasman Sea. The impact of ENSO on the EAC remains an active area of research. Ridgway (2007b) suggests that ENSO has very little impact on the EAC, as the signal follows the waveguide through the Indonesian archipelago and continues down the west coast of Australia. However, on decadal timescales, the strength of the EAC Extension and the Tasman Front are anti-correlated, representing two gyre scale circulation states. This has been related to decadal ENSO variability projecting onto the South Pacific westerly winds (Hill et al., 2011).

<u>Gulf of Papua Current</u>

As the northern part of the South Equatorial Current (SEC) encounters the continental margin of Australia, an equatorward western boundary current system is formed. At depth, northerly flow starts as far south as 22°S (Fig. 7.12) which results in the subsurface Great Barrier Reef Undercurrent (GBRUC). When the GBRUC merges with the surface flow north of about 15°S the North Queensland Current (NQC) is formed. The easterly flow of the NQC detected south of the Louisiade Archipelago that has been labelled the Hiri Current (Qu and Lindstrom, 2002). All three regional currents are parts of what is argued to be a single system referred to as the Gulf of Papua Current (Burrage et al., 2012).

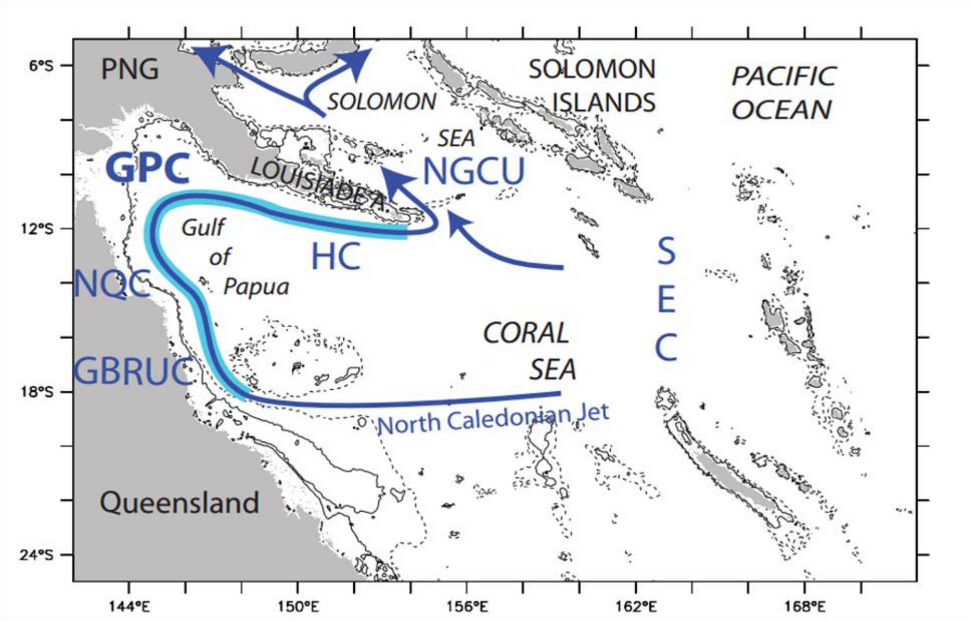

Figure 7.12. The component currents (GBRUC, NQC, HC) forming the Gulf of Papua Current (Source Ganachaud 2012).

Tasman Outflow

The Tasman Outflow derives from the EAC Extension flowing westward around southern Tasmania mainly at intermediate depths between 500 and 1200 m. It can be traced to the eastern Indian Ocean with an important impact on the global ocean circulation, connecting the gyre systems in the Pacific and Indian Oceans (Ridgway and Dunn, 2007), and forming a third element of the global thermohaline circulation (Speich et al., 2002). The Tasman Outflow, together with the EAC, provides a mechanism driving the variability in the eastern Subantarctic Zone.

Flinders Current

The Flinders current (FC) is a slope current which flows along Australia's southern shelves and it is fed by the Tasman Outflow (Ridgway and Dunn, 2007). This westward subsurface boundary flow is also partially forced by Southern Ocean Sverdrup dynamics (Middleton and Cirano, 2005). It is an upwelling favourable flow with enhanced onshore nutrient exchange (Middleton and Bye, 2007). The FC intensifies as it moves westward and provides source waters for the Leeuwin Undercurrent (LUC) once rounding Cape Leeuwin. The FC appears to be implicated in cross-shelf exchange and is important to the ecosystems of the region, with the upwelling favourable bottom boundary layer enhancing onshore exchange of nutrients.

7.3.2 The Leeuwin Current (LC) system (including the Zeehan Current)

The Leeuwin Current (LC) originates off the North West Cape and flows down the Western Australian coast in winter, bringing warm, relatively fresh water. The LC is generated by the meridional steric height gradient in the southeast Indian Ocean and associated eastward currents flowing toward northwest and west coast of Australia (Godfrey and Ridgway, 1985). The LC current turns southward approaching the coast (under dynamic control of the poleward Kelvin wave guide), and flows down the pressure gradient along the whole length of Western Australia past Cape Leeuwin. It is the only subtropical poleward flowing boundary current on the eastern side of an ocean in the world (Ridgway and Condie, 2004). It is a shallow (< 300 m) and narrow band (< 100 km wide) of relatively warm, lower salinity water of tropical origin that flows southward, mainly above the continental slope from Exmouth to Cape Leeuwin (Smith et al., 1991, Ridgway and Condie, 2004). The maximum flow of the current is located at about the 500m isobath. At Cape Leeuwin it pivots eastward, spreads onto the continental shelf and flows towards the Great Australian Bight extending along the south coast of Australia as a shelf current and down the west coast of Tasmania as the Zeehan Current. This represents a 5500km path, the longest continuous ocean current system in the world.

The source of the LC water is from the west tropical/subtropical Indian Ocean and the northeast continental shelf. The southeast Trade Winds, in the Pacific Ocean, drive the SEC westwards advecting warm surface waters towards Indonesia. This results in the flow of warm, low salinity water from the western Pacific Ocean through the Indonesian Archipelago into tropical regions of the Indian Ocean, which feed into the LC. It is highly unstable with mesoscale eddies regularly generated along its path. The eddy energy associated with it is higher than any other eastern boundary current system (Feng et al., 2005). The heat budget in the LC is dominantly balanced by the LC heat transport and the heat released through the air-sea interface (Feng et al., 2008).

The LC has a strong seasonal cycle, being strongest during winter when opposing equatorward winds weaken (Smith et al., 1991, Feng et al., 2003). The underlying source of this seasonality remains uncertain. In late autumn/early winter, the LC accelerates and rounds Cape Leeuwin off the southwest coast of WA to enter waters south of Australia, and continues as an eastward shelf current (the South Australian Current) along that coast (Ridgway and Condie, 2004, Middleton and Bye, 2007). During the summer season, sporadic wind-driven northward inshore currents and coastal upwelling events occur in limited shelf regions off the west coast, while wind-driven upwelling is more persistent off the southern coast of Australia. The location of the ‘core’ of the current also changes seasonally, with the core of the current located close to the 200 m contour in winter whilst under the action of the southerly wind stress.

On interannual timescales, variation in the depth of the thermocline associated with ENSO propagates through the Indonesian archipelago in the equatorial waveguide, and then poleward in the coastal waveguide, affecting the entire WA coast and into the Great Australian Bight (GAB). Higher sea level anomalies, warmer sea surface temperatures, and deeper thermocline, and a dose stronger Leeuwin Current are expected along the coast during La Niña years and vice versa during El Niño. Observations suggest that the LC has been getting gradually weaker over the last 60 years, but recent research suggests that this trend reversed in the early 1990’s (Feng et al., 2010).

Initial studies by Thompson (1984, 1987) indicated that there was an equatorward undercurrent flowing beneath the Leeuwin Current. Termed the Leeuwin Undercurrent (LUC), this undercurrent is narrow and is located between 250 m and 450 m depth contours, adjacent to the continental slope (Smith et al., 1991), driven by an equatoward geopotential gradient located at the same depth of the undercurrent (Thompson, 1984, Woo and Pattiaratchi, 2008). The LUC is closely associated with the subantarctic mode water (SAMW) formed in the region to the south of Australia. From a recent model analysis, the Leeuwin Undercurrent appears to be drawing water from the Tasman Outflow, forming the southern branch of the interbasin connection between the Pacific and the Indian Ocean (Van Sebille et al., 2014).

The Zeehan Current (ZC) is a current that runs southeastward along the continental shelf edge of western Bass Strait and western Tasmania throughout the year. Its maximum speed is about 1 knot and it is strongest in winter and weakest in summer. In winter the ZC rounds southern Tasmania and proceeds as far north as Schouten Island, where it is entrained and carried away to the southeast by the remnants of the EAC. In summer the ZC only reaches the southern end of Tasmania before it is wrapped into the EAC, which reaches further southward in summer (~ 200 km or more south of Tasmania) (http://www.marine.csiro.au/~lband/yacht_races/yyzeecur.html). The ZC is the final stage of a continuous southeastward flow from NW Australia to Tasmania (Ridgway and Condie, 2004).

7.3.3 The Indonesian Throughflow (ITF)

The ITF is an ocean current that flows between the Pacific and Indian Oceans through the Indonesian archipelago (Figure 7.13). This flow has a major influence on both the climate of the Indian Ocean and the global oceans. The ITF is generated by the wind field over the Pacific Ocean, primarily the Trade Winds, which pile up water on the western side of the ocean creating a pressure gradient from the Pacific toward the Indian Ocean. The ITF transport is particularly sensitive to the zonal wind anomalies over the equator in the Pacific and Indian Ocean, with the largest single component flowing in the narrow passage between Darwin and Timor Leste (Sprintall et al., 2009). While its net mass (volume) transport is moderate (~10 Sv), the current transports a significant amount of heat because it is the only location in the global ocean where warm tropical water flows from one basin to another, and ultimately has to be replaced by cold water at higher latitudes.

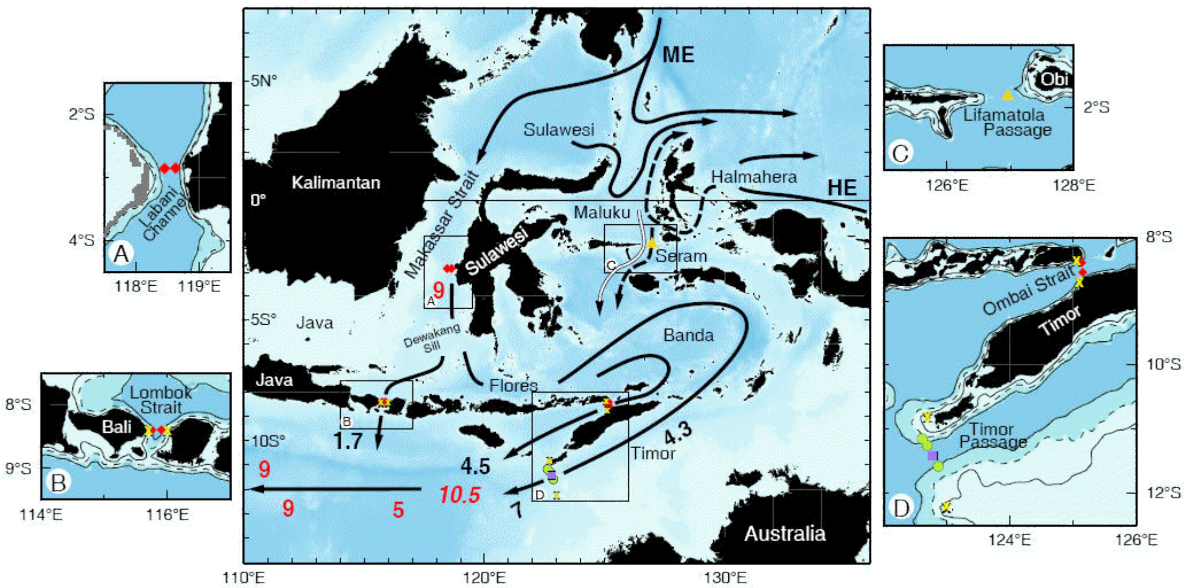

Figure 7.13. A map of the ITF, showing observations made during the INSTANT process study (2003-2006) (Gordon 2001).

The ITF is highly variable on seasonal, interannual and decadal time scales (Meyers et al., 1995, Meyers, 1996, Wijffels and Meyers, 2004, Sprintall et al., 2009 and references within Sprintall et al). The largest and most persistent mode of variation in the ITF is associated with the ENSO phenomenon. This signal, as far as it is observed at this stage, is largely consistent with linear dynamical theory. The coastal (Kelvin) wave guide off WA runs northward (following the 200m depth contour) to a point off northeastern Papua New Guinea where it joins the Pacific equatorial (Rossby) wave guide. The confluence of waveguides allows large perturbations in depth of the thermocline during the ENSO cycle to propagate into the Indian Ocean and down the WA coast. ITF has strengthened and become shallower in vertical structure (Gordon et al., 2012), however, the downstream impacts on the ocean boundary currents off the northern and Western Australia coast have not been studied. There is evidence that the ITF may play an important role in connecting the IOD with ENSO one year later. Numerical simulations using a hierarchy of ocean models and climate coupled models have shown that the interannual sea level depressions in the southeast Indian Ocean during IOD force enhanced ITF to transport warm water of the Pacific warm pool to the Indian Ocean, producing cold subsurface temperature anomalies, which propagate to the eastern equatorial Pacific, inducing significant coupled ocean atmosphere evolution (Yuan et al., 2013).

7.3.4 Antarctic Circumpolar Current and Antarctic Circumpolar Wave

The Antarctic Circumpolar Current (ACC) is the largest current in the world, carrying 150 Sv eastward around the Southern Ocean (SO), and has a major influence on Earth's climate and ocean circulation. It is closely coupled to the SO overturning circulation and therefore critical for this region (Marshall and Radko, 2003). The ACC thermally isolates Antarctica, with much of the flow occurring along narrow jets or fronts. Water properties across fronts change dramatically while between the fronts they are relatively uniform (Fig. 7.14) (Orsi et al., 1995, Sokolov and Rintoul, 2007). From north to south, the fronts and zones of the SO are: the Subtropical Front, the Subantarctic Zone, the Subantarctic Front, the Polar Frontal Zone, the Polar Front, and the Antarctic Zone. The ACC subpolar fronts extend throughout the water column and are clearly evident in maps of sea surface height (Sokolov and Rintoul, 2007, 2009b, a). In contrast, the Subtropical Front is restricted to the upper 400 m and has only a weak dynamic signature (Ridgway and Dunn, 2007).

The ACC transport varies on timescales from days to years (Aoki, 2002, Hughes et al., 2003, Meredith et al., 2004) in response to westerly winds on the SO. On decadal time scales it has been suggested that there has been only a small change in ACC transport despite the fact that westerly winds have increased over the SO (Böning et al., 2008). Recent research has focussed on whether the ACC will shift south and increase in strength with the strengthening and southward contraction of the southern hemisphere westerly winds associated with SAM. Although a shift south has been observed (Böning et al., 2008, Gille, 2008, Sokolov and Rintoul, 2009b), the link to changes in winds from observations is not conclusive. Whether or not the ACC is spinning up in response to increased winds is also a topic of active debate. IPCC class models, which are not eddy resolving, suggest the ACC will spin up due to stronger wind forcing, driving stronger transport. However, eddy-resolving models tend to suggest the ACC exhibits an "eddy saturated state" where increases in wind enhance the eddy field rather than increase the circumpolar transport significantly (Straub, 1993, Hogg et al., 2008, Farnetti and Delworth, 2010, Rintoul and Naveira Garabato, 2013). A convergence of the Ekman transport on the northern side of the ACC leads to downwelling in that side while and the divergence leads to the upwelling on the southern side. Therefore the ACC in maintained through the geostrophic balance driven by Ekman pumping combining with buoyancy forcing (Wang et al., 2011).

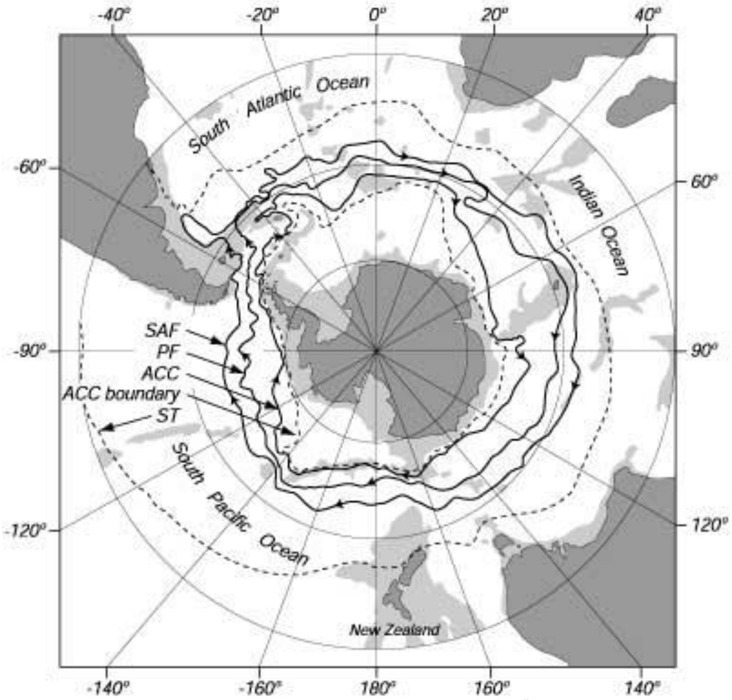

Figure 7.14. The main fronts of the Southern Ocean; The Subtropical Front (ST), the Subantarctic Front (SAF), the Antarctic Polar Front (PF and the Australian Circumpolar Current (ACC). .From Orsi et al (1995).

The Antarctic Circumpolar Wave (ACW) is thought to propagate around the Antarctic with a period of four years exposing boundary currents to with temperature changes of up to 1^{o}C along Australia's southern shelves. The ACW is postulated to result from an interaction of the oceanic and atmospheric boundary layers, has a four year period and amplitude of 0.5 ^{o}C off South Australia (White and Peterson, 1996, Baldwin and Thompson, 2009), and may be tied to the ENSO cycle(Middleton and Bye, 2007). The impact of this wave on shelf and slope circulation off southern Australia is not known.

7.3.5 Eddy Processes in boundary currents.

The ocean is a very turbulent environment, with variability dominated by mesoscale eddies over periods of days to weeks. There are very energetic regions of mesoscale eddies associated with the major current systems: the EAC, the ACC and to a lesser extent the LC (Figure 7.15).

Eddies play an important role in the dynamical and heat balances of the major current systems, acting to modulate the strength of the mean currents and their regional temperature footprint. They also flux heat and nutrients across current systems and isobaths. Along the Australian shelf break, the eddy field likely mediates the transport of these quantities between the offshore and shelf environments. Eddies also feed back into regional weather patterns, and are thought to influence the path of East Coast Lows (see Section 7.2.2.3).

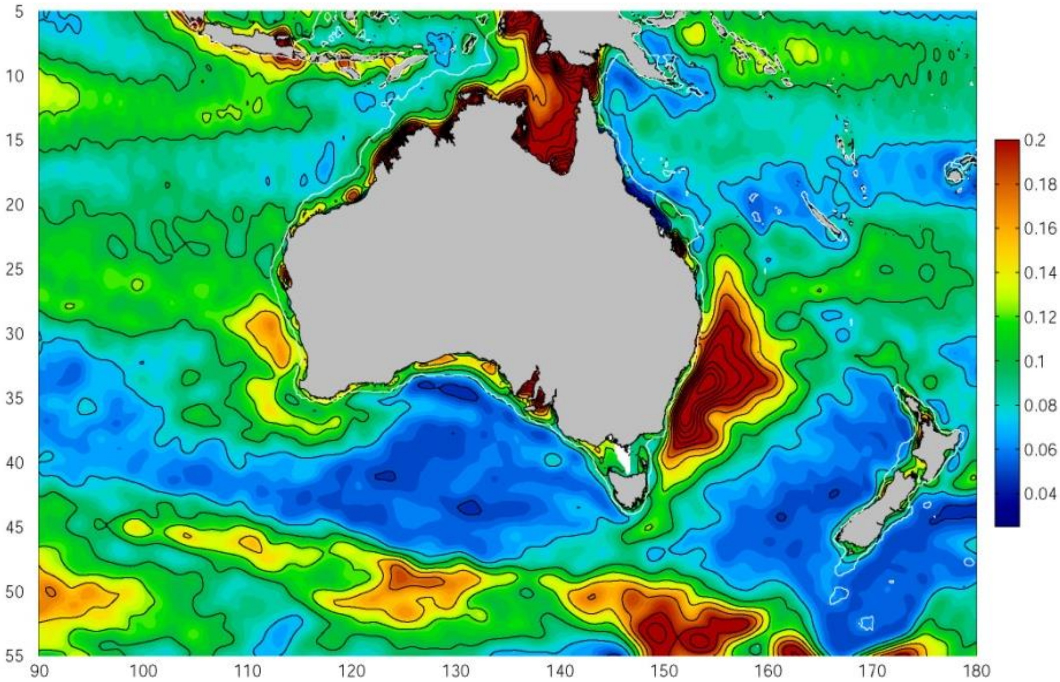

Figure 7.15. The RMS (root mean square) variability of sea surface height determined from satellite altimetry data 1992-2006. Data from the Collecte, Localization, Satellites (CLS)/Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) ''Mean Sea Level Anomaly'' (MSLA) maps, which are produced by mapping data from several satellite altimeters [Le Traon et al., 1998].

7.3.6 Spatial and temporal scales

Our understanding of how these current systems vary on interannnual and longer timescales is far from complete and remains a major research challenge. What is clear, however, is that the major modes of variability identified previously have important influences on these current systems.

For example, on interannual time scale (Figure 7.16), ENSO in the tropical Pacific induces strong responses in the LC off the west and south coasts of Australia, due to the existence of equatorial and coastal waveguides. During the La Niña (El Niño) events, deep (shallow) anomalies in thermocline depth are transmitted along the west and south Australian coasts, inducing high (low) sea level anomalies, strengthened (weakened) LC volume transport, eddy energetics, and poleward transport of warm waters (Pearce and Phillips, 1988, Feng et al., 2003, Clarke and Li, 2004, Wijffels and Meyers, 2004, Feng et al., 2005, Middleton and Bye, 2007, Feng et al., 2008). In contrast, on the east coast, there is little evidence of any ENSO influence on the EAC system (Ridgway, 2007b).

Multi-decadal variations in the tropical Pacific (e.g. Pacific Decadal Oscillation, PDO) have also been found to influence the low-frequency variability of the Fremantle coastal sea level, an index of the strength of the LC (Feng et al., 2004). The strength of the EAC Extension is negatively correlated with the Tasman Front on decadal timescales, which suggests that there is a gating between these two currents (Hill et al., 2011). This is due to enhanced wind stress curl in the South Pacific, which favours the EAC extension pathway over the Tasman Front, and is related to decadal ENSO variability. Decadal warming (cooling) in the tropical Pacific is associated with a weaker (stronger) South Pacific wind stress curl maximum, a weaker (stronger) EAC Extension, and a stronger (weaker) Tasman Front (Sasaki et al., 2008, Hill et al., 2011).

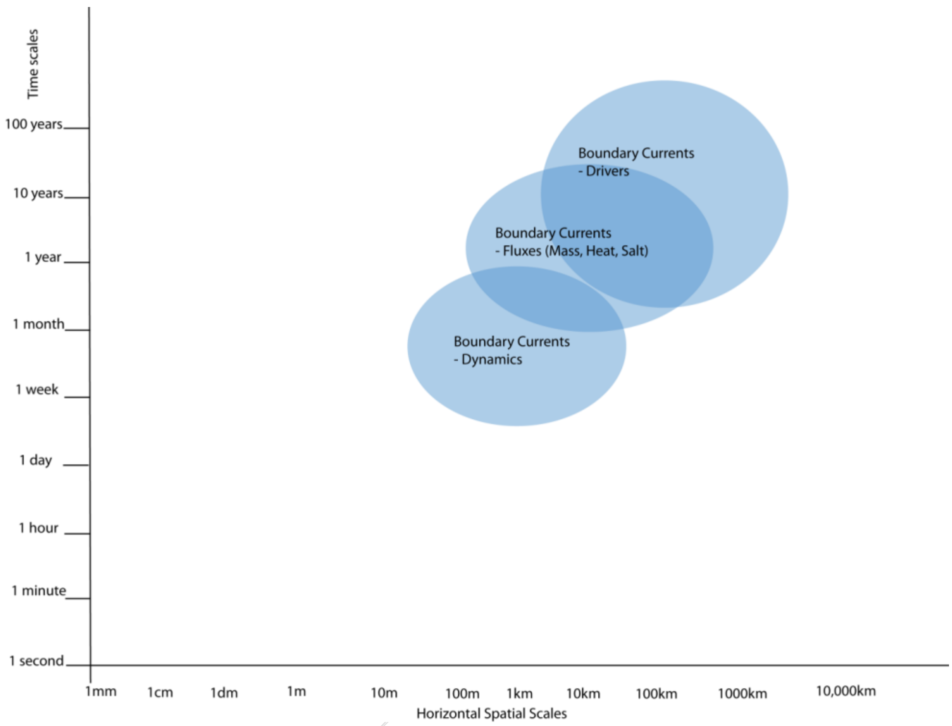

Figure 7.16: A Stommel diagram of the spatial and temporal scales of boundary current processes.

7.3.7 Modelling activities

BLUElink is Australia's Ocean Forecasting Project, delivered through a partnership between CSIRO, BOM and the Royal Australian Navy and produces 10 day ocean forecasts. Now in its third iteration, BLUELink includes three components:

- OceanMAPS, a near-global data assimilating and forecasting model is currently based on a nested grid with 1/10° horizontal resolution around Australia and coarser resolution elsewhere. This version will be replaced within the next two years by an operational model with a near-global grid of 1/10° horizontal resolution;
- ROAM, a Relocatable Ocean-Atmosphere Model which is based on the CSIRO developed Sparse Hydrodynamic Ocean Code (SHOC) Code, and is designed to nest inside OceanMAPS at user-specified spatial resolution;
- LOMS; a Littoral Ocean Modelling System, which runs a wave-current-sediment model (Xbeach).

The ROAM and LOMS models are designed to be easily configured to support Navy operations.

Modelling boundary currents poses challenges, they are difficult to approximate in the coarse (0.5-1 degree). IPCC class Earth System Model ocean component has a grid spacing of half a degree and as a result, boundary currents are generally broader and weaker, and lack frontal structure. Eddy permitting ocean models, such as Australia's BLUELink, provide more accurate representation of boundary currents (Smith et al., 2000). The resolution and prediction of the eddy field and its impacts on the structure of the mean ocean flow is a key research challenge.

7.3.8 Science questions

To understand boundary currents, their drivers and dynamics, observations are required at basin (1000’s km) to eddy (10km) scales.

The high-level science questions that will guide the IMOS observing strategy in this area are related to:

Fluxes:

- Seasonal, interannual and multidecadal variation in mass, heat and salt transport of Australian boundary currents and inter-basin flows
- Feedback of boundary currents into regional climate
- Relative contribution of air-sea fluxes, mean flow, and eddies to the regional heat and freshwater budget of Australia’s oceans

Drivers:

- Cause of variation in current strength
- Mechanisms that drive seasonal cycles of boundary currents
- Amount and type of change in boundary currents attributable to human drivers
- Relationship between boundary currents and modes of climate variability

Dynamics:

- Dynamical connection between boundary currents, interbasin flows and gyres in the Australian region
- Dynamics associated with temporal and spatial changes in boundary currents, such as the bifurcation of the South Equatorial Current and the separation of the EAC from the coast
- Processes that control variations in the strength of the eddy field associated with major Australian current systems

7.3.9 Variables required to address science questions

The waters around Australia form a complex intersection of the Pacific and Indian Oceans, strongly influenced by the boundary currents (EAC, LC), interbasin flows (ITF, Tasman Outflow) and regional current systems (GPC, ACC, FC, ZC) surrounding the continent. These current systems have a central role in transferring heat, salt and nutrients into the coastal region. They vary on inter-annual and longer timescales, influenced by the major modes of climate variability (e.g. ENSO), and can also feedback into the climate system. The boundary current systems are therefore crucial to understanding local manifestations of global ocean processes and their influence on regional marine ecosystems. Therefore, to understand boundary currents, their drivers, and their dynamics, observations of temperature, salinity, velocity, fluxes, sea surface height and wind stress are required at basin scales (1000’s km) to eddy scales (10km) (Table 7.5).

Table 7.5: The variables required to address Boundary Currents and Interbasin Flow science questions.

	Temperature - Surface	Temperature – subsurface	Salinity	Velocity	Sea Surface Height	Internal waves	Wind velocity (stress)
Fluxes (Mass, Heat, Salt)	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Drivers	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Dynamics	Blue	Blue	Blue	Blue	Blue	Blue	Blue

7.3.10 Platforms required to deliver observations

Monitoring boundary currents and determining their heat, mass and salt fluxes demands multiple observational techniques within IMOS (Table 7.6). Shelf and deep water Moorings are being deployed in the narrowest and most coherent sections of the ITF and EAC. Ocean Gliders, Ocean Radars and National Reference Station Moorings are being used to look at boundary current dynamics and their interaction with circulation on the continental shelf. Argo Floats and Ships of Opportunity are providing broad scale context and drivers, with Satellite altimetry and SST providing broad spatial and temporal resolution. Observations required under the previous themes will also be used to resolve boundary current drivers, basin-scale flow and broad spatial and temporal resolution.

Table 7.6: How variables required to address the high-level Boundary Currents and Interbasin Flow science questions are delivered at required scales by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived.

		Temperature– surface	Temperature- Subsurface	Salinity	Velocity	Sea Surface Height	Waves – internal	Wind velocity (stress)
	Argo	Blue	Blue	Blue	Orange	Orange		
Ships of Opportunity (SOOP)	XBT	Blue	Blue					
	Sea Surface Temperature	Blue						
	Air-Sea Fluxes	Blue						Orange
Deep water Moorings	Air-Sea Fluxes	Blue						Red
	Deep water arrays		Blue	Blue	Blue		Orange	
Ocean Gliders	Seagliders	Blue	Blue	Red	Red		Orange	
Moorings	National Reference Stations	Blue	Blue	Blue	Blue		Orange	Red
	Shelf Arrays		Blue	Red	Blue		Orange	

Ocean Radar	WERA							
	CODAR							
Animal Tagging	Biologging							
Satellite Remote Sensing	Sea Surface Temperature							
	Sea Surface Height							

Notable gaps:

The Research Infrastructure Roadmap identifies the following gaps in the current observing capability that would address major boundary currents and interbasin flows:

- Regions with very limited infrastructure and/or observations such as the Gulf of Carpentaria, Timor Sea, Torres Strait, Bass Strait and South East Qld
- Lack of sustained observations in several boundary and shelf currents around Australia.
- Gap in the data from the deep water moorings monitoring the EAC.

Future priorities:

- The highest priority is to maintain the EAC and ITF arrays, which are providing the first long time series from Australia's major boundary currents and inter-basin flows.
- Design and test a strategy for boundary current monitoring using gliders. The reinstatement of the EAC Deep Water Mooring to test the feasibility of gliders to monitor boundary and shelf currents provides the opportunity to test it
- Collect nutrient samples from the ITF and EAC arrays
- It is highly desirable to extend the Two Rocks transect to cover the full width of the Leeuwin Current, i.e. extend the Two Rocks mooring transect both into deep water, and to the nearshore region.
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve and expand coverage of sea gliders in Qld, SA, WA and NSW.

7.4 Continental Shelf and Coastal Processes

Australia's coastal oceanography is dominated by the influence of boundary currents discussed in Section 7.3. These current systems transfer heat, salt and nutrients onto the continental shelf and into the coastal region. It is at the interface between the currents and the shelf that the large scale climate patterns such as ENSO, PDO, and the SAM undergo regional modulation through the interaction of the currents, eddies, local coastal flows. These manifestations are distinct regional features which have become the focal points of coastal Node activities and are the focus of a range of regional modelling activities, which go hand in hand with the observing system. The broad, shallow shelf seas of the tropical northwest are influenced by the ITF. These shelf waters mix with tropical/sub-tropical Indian Ocean waters forming the LC off Northwest Cape in WA. The LC uniquely poleward-flow prevents WA from having a large upwelling driven ecosystem like other eastern boundaries. It also brings tropical species to relatively high latitudes down the coast of Western Australia. Mesoscale eddies formed within the LC drive cross-shelf exchanges off the WA coast with enhanced concentrations of chlorophyll are observed in the warm-core eddies (Feng et al., 2007).

The Great Barrier Reef (GBR) dominates the physical, chemical and biological processes along Australia's northeast shelf region. The prevailing onshore currents interact with the outer GBR, which then determines how these waters interact with the GBR lagoon and vice versa.

The New South Wales coast has an extremely narrow shelf, combined with a very dynamic and eddy driven EAC flowing southward along the shelf edge. The separation of the EAC from the coast spawns eddies which impinge on the continental shelf. They have a strong influence on shelf processes, nutrient inputs and ocean productivity.

Tasmanian waters form a dynamically interesting confluence of subtropical and subantarctic influences; the EAC Extension travels down the east coast and is dominant in summer, the Zeehan current flows down the west coast and is dominant in winter, and the subtropical front vacillates to the south.

The upwelling zones in the GAB feed some of the most productive fisheries in Australia. These upwelling zones are strongly moderated by seasonal variability in opposing shelf and slope currents; the eastward Leeuwin Current on the shelf (stronger in winter) and the westward Flinders current on the slope (stronger in summer). Both the Kangaroo Island-Eyre Peninsular and the Bonney coast upwelling systems are stronger in summer. In winter, there is a combination of downwelling favourable conditions, a stronger Leeuwin Current and local wind forcing.

While there are regional variations in the characteristics of the continental shelf, there are some key processes which are prominent throughout much of Australia's coastline, and ultimately determine biological productivity on the shelf. These include boundary currents – particularly eddy-shelf interactions, upwelling and downwelling, coastal currents, and wave climate (including internal waves and tides).

7.4.1 Boundary current eddy –shelf interactions

Along the temperate east and west coasts, eddies formed in the boundary current regions transport heat, nutrients and other properties between the open ocean and the shelf. This is a two way process with outflows of freshwater and nutrients also being entrained from the shelf into deep currents, in addition to the encroachment of boundary currents and associated eddies onto the shelf. It is at the interface between the currents and the shelf that large-scale climate variations such as ENSO and SAM undergo regional modulation through the interactions of currents, eddies and local coastal flows. Hence, these very local manifestations of global processes are crucial in determining their influence on regional marine ecosystems. Observations are required in the boundary currents and across the shelf to determine the nature of this current/shelf connection.

On the east coast of Australia, from southern Queensland down to Tasmania, the combination of a strong eddy field and a narrow shelf means that eddies have a strong influence on shelf processes and the cross shelf exchange of properties (see Figure 7.11). Eddies are formed about 3 or 4 times per year (Marchesiello and Middleton, 2000). On separation from the coast, the EAC sheds anti-cyclonic (warm core) eddies which transport heat into the Tasman Sea, or turn northeast and coalesce back into the main current. Cyclonic (cold core) eddies can be generated as the EAC meanders and separates along the northern NSW coast, sometimes entraining coastal waters, and it is thought this process might be important in larval recruitment. In the north of Queensland, the circulation reveals the SEC filamented as jets as it bifurcates when it meets the Queensland continental shelf. Embedded within these jets are large eddies that can be cyclonic or anti-cyclonic. As eddies move toward the shelf, their momentum squeezes waters from depth up onto the shelf, producing a cross shelf flow that results in warm surface Coral Sea waters impinging on the shelf. However, it also drives cooler water from depth along the seafloor toward the shelf. The shelf break and outer reef topography can also produce instabilities in the flow forming smaller scale eddies between the main boundary current flow and the reef, enhancing mixing and cross shelf components of flow. Shear instabilities also occur along the shelf break where there are significant density changes between outer shelf waters and the Coral Sea.

On the west coast, eddies form due to the interaction of the LC with topography (Figure 7.17). The eddy field is strongest in winter, when the LC is strongest. Eddies form and propagate offshore, driving cross shelf exchange of heat, nutrients and larvae (Domingues et al., 2006, Moore Ii et al., 2007, Waite et al., 2007). Warm core eddies have been associated with increases in primary production, as they entrain nutrient rich shelf waters. In the northwest shelf, ITF waters flood the shelf via the offshore pathway (the Eastern Gyral Current) and the Holloway Current, with local eddies and internal tides affecting cross-shelf transport and modifying water properties through vertical mixing.

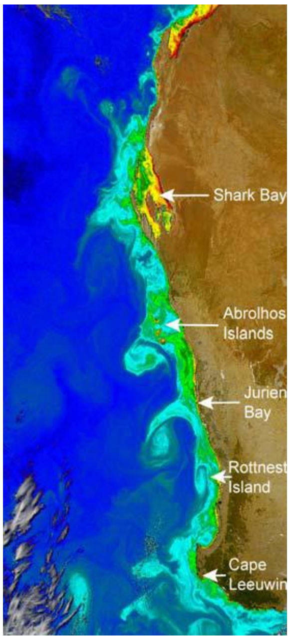

Figure 7.17. Ocean colour image showing the eddy structure of the Leeuwin Current. The higher chlorophyll water is located on the shelf and is entrained into the Leeuwin Current and its eddies.

The interaction of boundary currents with the shelf/slope region off South Australia is highly seasonal, being forced by both the Leeuwin (shelf) and Flinders (subsurface, offshore) currents. Dense waters formed in the Spencer Gulf are entrained in offshore currents (Middleton and Bye, 2007).

The surface flow of the EAC and LC current systems come into direct contact off south eastern Australia, in addition to the subtropical front, which is just to the south. The differences in forcing mechanisms, water masses and seasonal expression directly influence shelf/slope exchanges around Tasmania (Ridgway, 2007a).

7.4.2 Upwelling and downwelling

The classic wind driven upwelling systems seen on the west coasts of major continents (i.e. California Current, Benguela Current, etc) are not seen in Australian waters. While upwelling occurs at locations on the west, south and east coasts, it is strongly modulated (or driven) by boundary current processes and current interactions with bathymetry.

Wind driven upwelling

In South Australia, summer wind driven upwelling is found in the Kangaroo Island-Eyre Peninsula region and along the Bonney and Otway Coasts towards the South Australian/Victorian border. On the Bonney Coast, a surface temperature signature for upwelling is found to the west of Portland, Victoria but not to the east. This "Bonney Upwelling" is the most predictable and intense upwelling off southern Australia (Butler et al., 2002, Nieblas et al., 2009) and enhances daily primary productivity, which can be comparable to levels seen in the Benguela and Humboldt boundary current systems (Van Ruth et al., 2010a).

Observations suggest that summer upwelling along the Kangaroo-Eyre Peninsular originates south-southeast of Kangaroo Island and is largely subsurface, directed along the 100m isobath to the north and northwest (Figure 7.18). Along isobath currents are too weak or infrequent to transport upwelled water to the surface, causing subsurface nutrient enrichment below the mixed layer. However, upwelling does not always occur when the winds are upwelling favourable, and significant reductions in wind forced Ekman upwelling can occur where the offshore Ekman transport is provided by a divergence in the alongshore currents (Middleton and Platov, 2003, Middleton and Leth, 2004). In winter, winds become downwelling favourable.

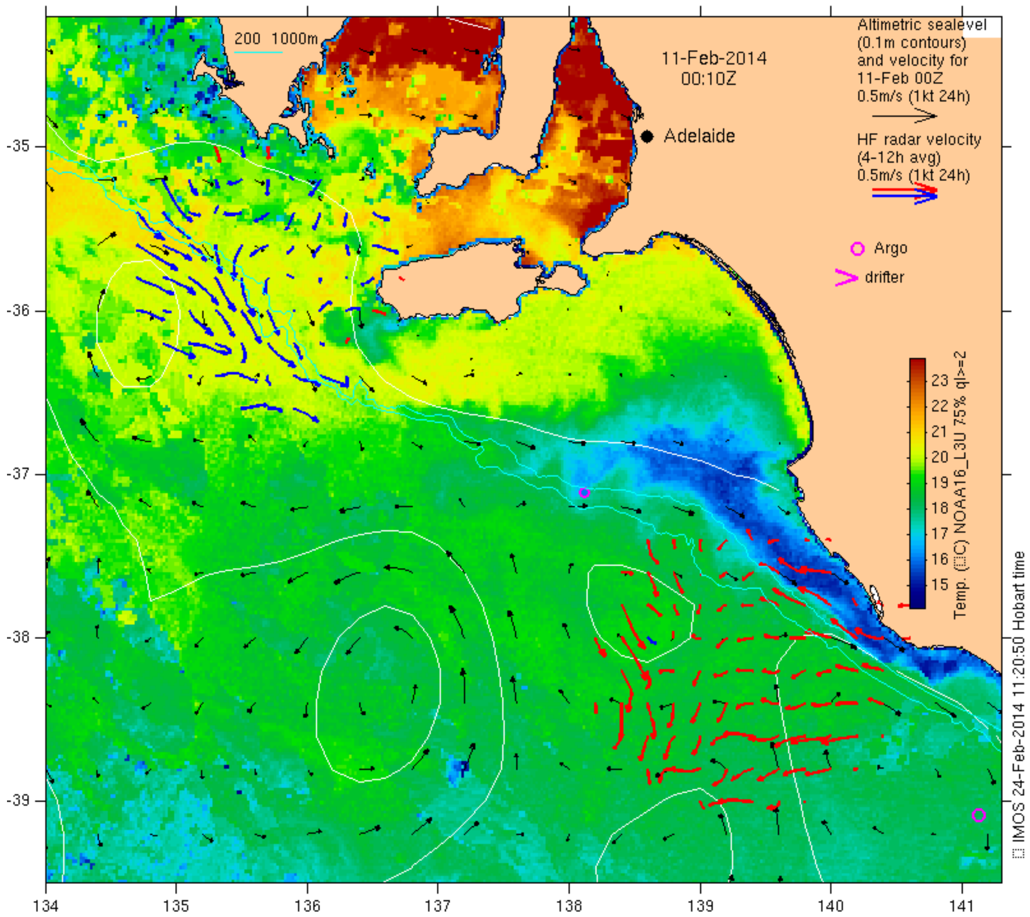

Figure 7.18: The summertime SST (February 2014) for the SAIMOS region. Arrows denote estimated surface velocities from radar(blue and red arrows) and altimetry (black arrows) (OceanCurrent map from http://oceancurrent.imos.org.au/index.htm).

In the west coast of Australia, the LC suppresses upwelling, however, conditions are conducive to upwelling in the summer when the LC is weaker. Strong southerly winds become established in summer which overwhelms the pressure gradient on the inner shelf between Cape Leeuwin and Cape Naturaliste, moving surface waters offshore, and upwelling colder water onto the continental shelf and pushing the LC offshore (Pearce and Pattiaratchi, 1999). The Leeuwin current then strengthens in winter and in the absence of the southerly wind stress, it migrates back inshore. Along the northwest shelf, prevailing winds during summer are upwelling favourable.

Off the coast of NSW, it has been observed that while the winds are generally downwelling favourable, up to 10 upwelling favourable days per month can occur in the spring-summer period (Rossi et al., 2014).

Boundary current upwelling

Variations in strength of boundary currents can cause variations in the depth of the thermocline and therefore variations in the water properties available for transport onto the shelf. Off the east coast, interaction of the EAC and its eddies with the topography of the shelf can stimulate periodic upwelling of cool, nutrient-rich water, resulting in phytoplankton blooms (Roughan and Middleton, 2002). A strong southerly boundary current along the lower GBR should produce upwelling favourable conditions, lifting isotherms along the slope through Ekman transport, although topographic steering and tidal pumping may be more significant at the local scale in drawing deeper waters onto the shelf. Between 17-19°S, however, where the reef matrix is more open, there is evidence of oceanic water being forced into the GBR Lagoon; possibly by eddy encroachment of the EAC onto the shelf (Roughan and Middleton, 2002). South of the Great Barrier Reef there is evidence of some form of upwelling, although the mechanisms are unknown, some suggestions include encroachment of the EAC onto the shelf and topographic effects on flow (Oke and Middleton, 2000), and flow separations from the shelf break (Roughan and Middleton, 2002). Off NSW, the current-driven upwelling by the EAC dominates the classic wind-driven upwelling (Oke and Middleton, 2000, Schaeffer et al., 2013). The EAC accelerates off northern NSW where the continental shelf off Smoky Cape (~31ºS) narrows in less than 0.5º latitude to just 16 km wide. This acceleration sporadically generates upwelling of cooler water, rich in nitrate and phosphate, particularly during the summer. In addition, the separation point can generate sporadic upwelling events; particularly during the summer when the EAC is strongest.

On the west coast interaction of boundary currents with submarine canyons can also drive upwelling, e.g. in the Perth Canyon (Rennie et al., 2009). In addition, eddy-induced Ekman pumping in the LC anticyclonic eddies could be also responsible for upwelling, sustaining enhanced chlorophyll concentrations throughout their life cycle, while propagating in the South Indian Ocean (Gaube et al., 2013).

The FC in the south can cause deep upwelling from depths of around 600m through bottom boundary layer transport, and possibly allow nutrient rich cold water to entrain onto the shelf. This appears more likely to occur in the western GAB where the FC appears to be stronger in magnitude.

Canyon/topographic upwelling

At some locations around the coast, topographic features such as canyons combined with currents help create conditions conducive to upwelling producing productivity hotspots. In the case of the Perth Canyon in WA, the LUC creates cyclonic eddies in the presence of the canyon, driving deep nutrient rich waters to the surface through the canyon (Rennie et al., 2009).

In South Australia, interactions between the FC, coastally trapped waves and submarine canyons may also be conducive to localised deep upwelling in the eastern GAB according to theoretical studies (Kaempf, 2006, 2007).

Evidence suggests that there are regions of persistent upwelling on the Great Barrier Reef driven by a combination of mechanisms. In the southern GBR, the southward flowing EAC provides favourable upwelling conditions due to a shallower thermocline at the shelf break. In addition, in the dense reef structure between 19 and 22°S, strong tidal mixing forces swift exchange through deep reef passages, providing nutrient enrichment Between 22 and 24°S abrupt contraction of the shelf width and steepening of shelf bathymetry produces upwelling favourable quasi-stable recirculation features (Burrage et al., 1996). Similar topography along the east coast south of the GBR suggests similar phenomena may occur more generally along the east coast but their existence and importance has yet to be established.

Dense shelf outflows

Dense shelf outflows are formed when dense inner shelf water created by a decrease in temperature or an increase in salinity is transported near the sea bed across the continental shelf. Off the west coast of Australia, high evaporation along the Pilbara coast and the high freshwater input along the Kimberley coast result in cross-shelf density gradients which are capable of influencing cross-shore exchange. High evaporation together with winter cooling results in higher density water (cooler more saline water) along the coast which results in a high density gravity current along the sea bed and results in nearshore waters being advected offshore (Brink et al., 2007). In the southwest, the formation of dense water inshore and its transport across the shelf as a near bed gravity current is a regular occurrence, during autumn and winter months (Pattiaratchi et al., 2011). In the south coast, winter winds become downwelling favourable, and in association with coastal cooling, water generally becomes well mixed over the shelf down to depths of 200-300 m (Middleton and Bye, 2007). However, it is also known that the cold, salty, dense water formed in Spencer Gulf during winter can cascade out onto the shelf forming a series of low pressure (salty) and high pressure (fresh) eddies of around 20km in diameter (Teixiera, 2010).

On the Australian east coast, there is evidence of water outwelling from mangrove forests in the Great Sandy Strait separating Fraser Island (Middleton et al., 1994), characterized by low temperature, low dissolved oxygen, and high dissolved nutrients. In Hervey Bay, low freshwater input and high evaporation created a hypersaline zone which results in a baroclinic gradient that produces a slow cyclonic circulation within the bay (Grawe et al., 2010). In the Capricorn Channel, evidence of a dense water cascade across the shelf in the vicinity of Cape Clinton was found. This cascade appears to originate from hypersaline water escaping the Broad Sound despite the strong tidal mixing experienced in this region.

Further south, dense waters that flow into the Tasman Sea are generated in Bass Strait (Godfrey et al., 1980). In Bass Strait the waters are affected by both regions the Great Australian Bight and Tasman Sea waters, and these water masses mix within the confines of Bass Strait through tides and wind action. During winter and spring Bass Strait waters are well mixed with little to no stratification (Baines and Fandry, 1983, Tomczak, 1985, Middleton and Black, 1994) and water temperature is lower and itssalinity higher than the adjacent Tasman Sea at the same depth. As a consequence Bass Strait water downwells at the continental slope to a depth of similar density where it turns left following the shelf edge in a narrow northward flowing stream that created high salinity intrusions at ~ 300--400 m depth (Tomczak, 1985). This downwelling process occurs at several locations along the eastern shelf break, with the largest flux (Bass Strait Cascade) occurring in the vicinity of Bass Canyon (Tomczak, 1985, 1987, Luick et al., 1994) and can be advected as far north as the Coral Sea (Sandery and Kämpf, 2005)

7.4.3 Shelf Currents

The continental shelf of Australia varies from the very narrow shelf off eastern Australia, to the extensive reef lagoon environment of the Great Barrier Reef, to the very broad continental shelves in northern Australia, which is characterised by extreme tides. The boundary currents and interbasin flows abutting the continental shelf have a strong influence on these shelf circulation systems. Shelf currents occur around most of the shelf of Australia, except in the temperate east, where the continental shelf is too narrow.

The Great Barrier Reef dominates shelf processes in the north east region, with the reef separated from the coast by a shallow lagoon. Communication between the open ocean and the lagoon is defined by narrow passages through the reef. Ocean currents in the form of the SEC jets are predominantly onshore in this region and are steered by complex topography in the Coral Sea before reaching the outer GBR. Ultimately, these waters either travel north to form the Hiri Current, or South to form the EAC. The complexity of this shelf topography means that empirical observations of currents are only possible in certain locations.

In northwestern Australia, the seasonal Holloway Current is a surface layer poleward flowing ocean current that brings water perhaps from as far north as the Banda and Arafura seas, southward over the continental shelf of northwest Australia at the end of the northwest monsoon (D'adamo et al., 2009). The generating mechanism is the seasonal south-westerly wind piling up water in the Arafura Sea and Gulf of Carpentaria during the peak of the Australian monsoon, and the current flowing southward as the wind relaxes during the monsoon transition. In the west coast, the Ningaloo Current runs inshore and counter to the LC from Shark Bay to Northwest Cape. Similarly in the south, the Capes Current originates between Cape Leeuwin and Cape Naturaliste in summer and flows north counter to the LC (Pearce and Pattiaratchi, 1999) (Figure 7.19). Both are driven by strong southerly wind stress. As the LC turns the corner and flows east along the south coast of Australia, it also becomes a shelf current with flows of 20cm/s eastward in winter; 2-3 times that found in summer, when currents on the shelf flow westward.

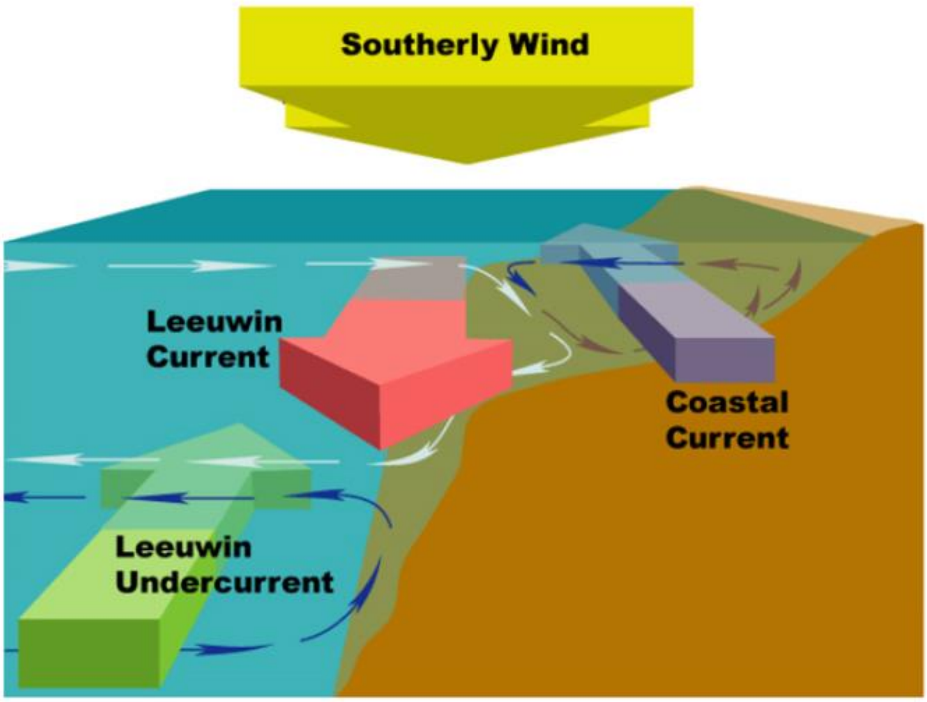

Figure 7.19: Schematic illustrating the flow patterns on the continental margin of SW Australia (Woo and Pattiaratchi, 2008).

Due to narrow shelves on its east and west coasts, Tasmania does not have defined shelf currents. However, the interaction between the Zeehan Current, EAC, and STF makes for a dynamic shelf environment at the confluence of 3 different systems. The Bass Strait connects Tasmania to the mainland. At 80m deep, it is much shallower than surrounding waters. There is also evidence to suggest that the LC encroaches into the Bass Strait adding to the dynamic nature of this region.

7.4.4 Wave climate, including internal and coastally trapped waves.

Coastally trapped waves (CTWs) are the primary mechanism by which the ENSO signal is transmitted around the coast of Australia and at a global scale climate change has a significant effect on surface wave climate (Young et al., 2011). Below the surface, internal waves are a ubiquitous feature of the world's oceans; typically generated by oscillating tidal flow of stratified water over steep topography. Such waves have large wavelengths (10's of kms) and amplitudes equivalent to a significant proportion of the total water depth. Internal waves interact with shelf currents and drive mixing. The wave environment on the continental slope and shelf is influenced, in turn, by the circulation and stratification of open ocean waters adjacent to the boundary.

In the northeast of Australia, coastally trapped waves propagate northwards from south of Fraser Island and are associated with significant vertical motion of the thermocline which appears to modulate both upwelling at the shelf break, and the magnitude of shelf currents in the southern GBR (Griffin and Middleton, 1986). In addition, observational data suggest the existence of very large (+100 m peak to trough) semidiurnal internal waves along the outer GBR (Wolanski, 1986) that modify variability in thermocline depth, however, their impact is limited to the outer margin of the GBR shelf.

Although internal tides and waves off NSW are smaller than those off the North West shelf of Australia, measureable internal tides and waves do occur in the coastal waters off eastern Australia. It is, in fact, thought that internal waves generated off the southern portion of New Zealand impact the Australian coast off southern NSW and/or Tasmania (personal communication L. Rainville 2012). While the nutrient replenishment may be small in comparison to upwelling events, tidal pumping is a regular, event in the NSW region. Along with internal waves, CTWs generated as far away as the North West Shelf by events such as tropical cyclones propagate along the NSW coast (Hamon, 1962, Freeland et al., 1986, Maiwa et al., 2010, Woodham et al., 2013).

In the south coast of Australia, the shelf currents are also modulated by intense CTWs that enter the GAB from Cape Leeuwin and by those locally generated by intense storms. On the shelf, water is advected back and forth along isobaths with periods of 5-20 days, and can be important to cross-shelf exchange. The waves generated along the southern shelves drive CTWs within Bass Strait and on the NSW shelf (Middleton and Black, 1994). The CTWs can also be important to setting the degree of upwelling (Middleton and Leth, 2004) through the set-up (or otherwise) of alongshore divergence of the shelf velocity field. Such divergence can "feed" the offshore surface Ekman transport and shut-down upwelling over the slope. The role of CTWs in setting the degree of upwelling off southern Australia remains to be determined. In addition, the open southern Australian coast faces the highest energy surface waves in the world (Short, 1988). Deep water waves of the Southern Ocean normally exceed 5 m (Chelton et al., 1981) but are attenuated across the wide continental shelf in the GAB (Provis and Steedman, 1985), resulting in diverse landforms of high and low wave-energy environments occurring along the southern Australian coast. Internal waves may also be important in vertical mixing as found on the northwest shelf slope.

On the other hand, northern Australia experiences a macro-tidal environment; particularly in the northwest, which has the largest tidal range for a coastline facing an open ocean (Figure 7.20). Large-amplitude internal tides propagate across the North West Shelf (NWS) particularly in summer (Holloway, 1983), when the water column is strongly stratified due to intense solar insolation. Internal tides may evolve nonlinearly to form internal bores and/or to degenerate into high-frequency internal waves, such as solitary-like waves (Holloway, 1987). Their nonlinear evolution on the NWS is important from engineering and ecological points of view, as they increase peak near-bottom currents, enhance vertical shear, and modify near-surface currents, which are crucial for designing offshore structures, daily operation, and emergency response of oil and gas industry on the NWS. They also enhance mixing (Holloway et al., 2001, Holloway, 2001, Katsumata, 2006), and are considered to bring nutrient-rich offshore deep water onto the NWS (Holloway et al., 1985).

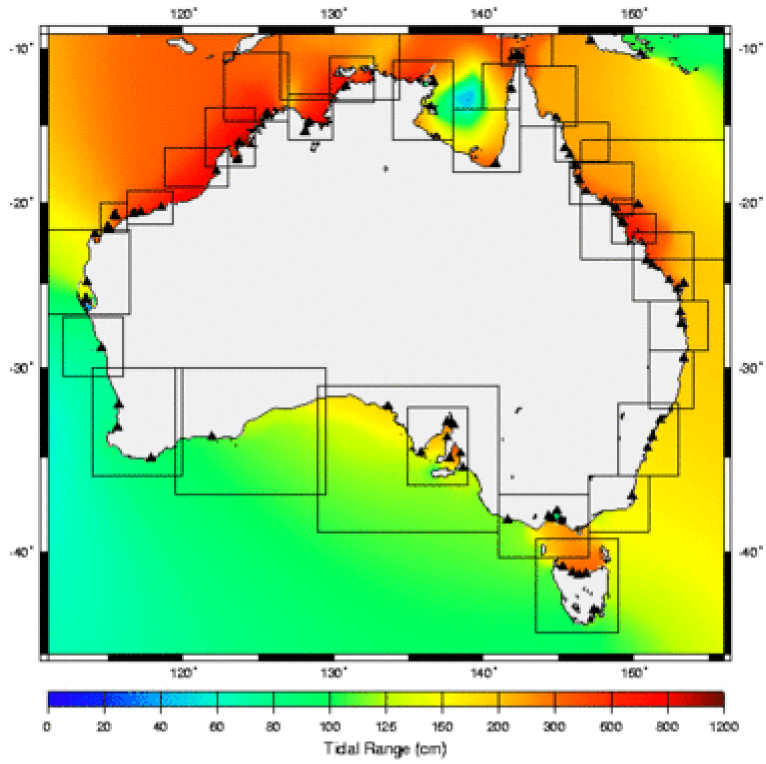

Figure 7.20: Highest Astronomical Tide (HAT) in Australian waters. Bureau of Meteorology 2012

7.4.5 Spatial and temporal scales

Continental shelf and coastal processes are restricted in the scales they cover by the size of the continental shelf. However, many of the processes are smaller scale. For example, surface waves have periods of a few seconds, but change on time scales of hours. Their spatial scales range from the Bragg scatterers (wave heights of a few mm and wavelengths of ~1 cm) that affect radar to storm waves with wave heights of 10s of m and wavelengths of 100's of m.

The various shelf and coastal processes described above operate at a range of space and time scales as shown in Figure 7.21.

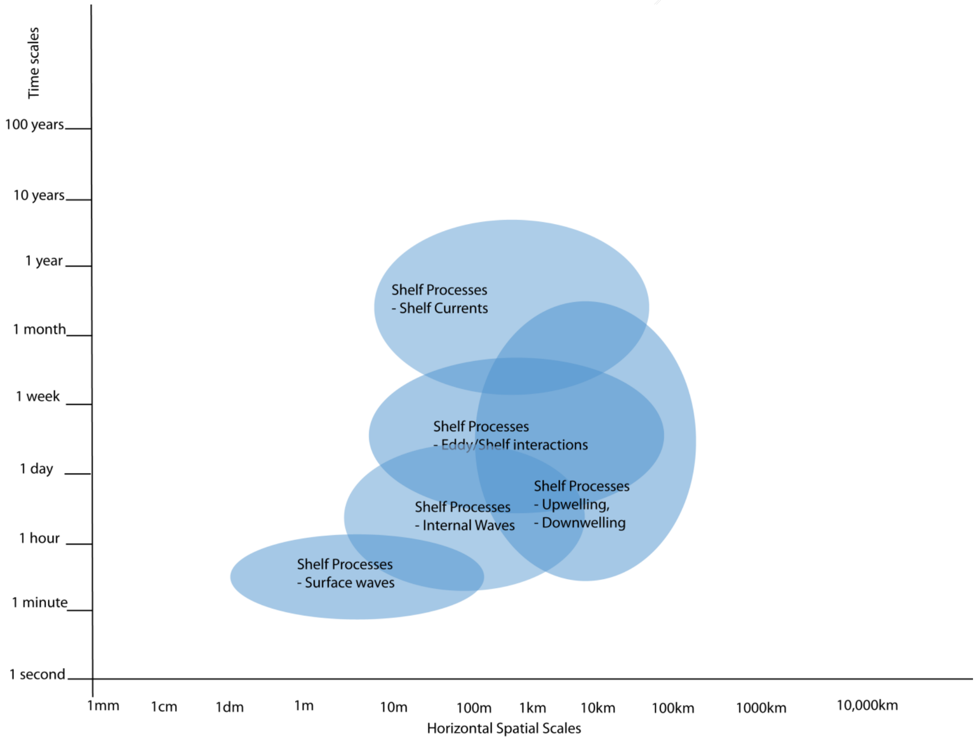

Figure 7.21: A Stommel diagram of the spatial and temporal scales of continental shelf and coastal processes.

7.4.6 Modelling activities

There are two approaches to coastal modelling which are generally used in Australian Waters.

The Regional Ocean Modelling System (ROMS) is an open source code which is generally favoured by university researchers for regional studies and process modelling. Currently footprints include northwest and southwest Western Australia, South Australia, and NSW (Figure 3.11). Observations are used to validate the models. Data assimilation is available in the code, but is currently an aspiration for Australian applications.

A new opportunity in model-data synthesis is emerging through the Marine Virtual Laboratory (MARVL), being developed as part of the national research infrastructure. It brings together the flexibility of Relocatable Ocean-Atmosphere Model (ROAM) with the search and discovery capability of the Integrated Marine Observing System (IMOS) to provide the research community with a powerful tool to conduct regional process studies. MARVL is extending ROAM by the incorporation of additional models and providing the user with an observation data access capability for assimilation and/or validation. Through a companion project, the MARVL Information System (MARVLIS), tools to synthesise models and observations are being developed to support marine management decision making.

The SHOC model developed by CSIRO underpins regional hydrodynamic models which are being developed to deliver to management applications. Footprints currently include the Great Barrier Reef (eReefs project) and the Southern Tasmania (INFORMD project).

In Queensland, the complexity of the continental shelf bathymetry and inflows around the GBR means that synoptic views can only be realised in hydrodynamic models. The main role of empirical observations on velocity is calibration and validation of these models, which must incorporate realistic forcing from the oceanic open boundary to produce accurate results. For computational reasons, most past models of the GBR have truncated the model domain at 14°S and only limited direct observations have been made on shelf currents above this latitude. The latest and most sophisticated hydrodynamic model of the GBR region is an integrated modelling suite known as eReefs (Schiller et al., 2013) that is designed to become a real-time forecasting system operated by the Australian Bureau of Meteorology. In the marine space, eReefs is a 3-D baroclinic model that includes all of the essential forcing functions (winds, tides, atmospheric coupling, bathymetry, etc). It is resolved at 1km grid resolution on the continental shelf and nested within 4km and 10km models at larger scales to obtain accurate oceanic forcing from global models. The domain of the 4km grid extends from Papua New Guinea to the NSW border (encompassing the east coast of Queensland) and encompasses all of the shallow bathymetry on the Coral Sea. In the vertical, the eReefs model tracks 47 layers and is being trained against IMOS observations in four dimensions. A surface wave model for the QLD shelf is also under development as part of the eReefs project with the aim to simulate information on wave data (significant wave height and period, orbital bottom velocity) which then can be used to run the sediment transport and biogeochemistry sub-models. Wave models applied through eReefs include Wavewatch III (v4.11) implemented using source term physics (Ardhuin et al., 2010) and applied on the GBR4 hydrodynamic model grid.

In NSW, SEAROMS focusses on simulating the EAC, it's eddy field and upwelling processes (e.g Macdonald et al 2013a,2013b,2013c). The simulations are complemented by extensive observational studies focused on slope water intrusion dynamics on the continental shelf.

In the south of Australia, a hydrodynamic, wave and biogeochemical modelling facility was established in 2007 building on SAIMOS oceanographic data streams. A suite of ROMS based models were developed; the South Australian Regional Ocean Model (SAROM), and a nested high resolution Spencer Gulf model (SGM). These models were developed to help deliver sustainable growth and management of aquaculture, fisheries and marine resources in SA.

The INFORMD project is designed to address improved delivery of modelling products for management of the coastal marine environment. South-East Tasmania was chosen for the test site of this project and aims to provide near real-time hydrodynamic modelling of the south-east Tasmania, including the Huon and Derwent Estuaries, D'Entrecasreaux Channel and Storm Bay. The hydrodynamic model is forced by global and regional data, which is readily available in real-time. The model domain includes an IMOS measuring station near Maria Island, and it is nested directly into the global model, which resolves the Australasian region at 10 km, and supplies sea level, temperature and salinity on the open boundaries. The model is forced with river flow from the Huon and Derwent Rivers, and uses MesoLAPS atmospheric products for surface flux specification. A high resolution model is nested within this larger scale model, capable of supplying output at ~100 m resolution within the estuaries and increasing to ~2 km offshore.

In the west of Australia, both field measurements, from moorings and ship based transects, and numerical modelling using ROMS are used to conduct the first detailed physical oceanographic study to quantify transient upwelling and the associated dynamics controlling the Ningaloo Current system. In the northwest shelf integration of field observations, of both mean and turbulent flows, and the development and application of numerical ocean circulations model are used to understand processes in the scales from regional ocean flows down to small scale turbulent mixing and to quantify the influence of the complex topography on circulation, ocean mixing and hence the exchange and flushing of material. In addition, field observations are being used to develop and apply a fully non-hydrostatic circulation model (SUNTANS) to predict the intensity and extent of internal wave driven dynamics in the region.

7.4.7 Science questions

The following high-level science questions will guide the IMOS observing strategy in this area:

Boundary Current/shelf interactions

- Influence of large scale circulation (boundary currents, gyres and interbasin flows) on the shelf and coastal environments

Upwelling and Downwelling

- Frequency, magnitude and drivers of upwelling/downwelling processes and slope water intrusions, and their influence in cross shelf properties exchange
- Boundary currents role on the strength, extent and variability of upwelling/downwelling
- Seasonal and interannual dynamics of upwelling in regional areas
- Distribution, variability and drivers of dense shelf outflows

Shelf Currents

- Magnitude and drivers of shelf currents
- Interaction of boundary currents and shelf currents

Wave Processes

- Role of internal and coastally trapped waves in continental shelf processes (circulation and stratification)
- Tidal regimes around Australia and influence on shelf processes
- Influence of wind on wave climate and cross-shore exchange

7.4.8 Variables required to address science questions

Australia has a large and varied continental shelf and coastal environment; broad and shallow in the tropical north and narrow on the sub-tropical east and west coasts. There are key processes occurring across this environment that provide a focus for observing connections, trends and variability between global ocean processes, boundary currents and biological responses on the continental shelf. These include encroachment of warm and cold-core eddies, upwelling and down-welling systems, coastal currents, and wave climates.

The IMOS observing strategy for continent shelf and coastal processes is to provide an extensive national backbone around the continental shelf, and more intensive observations in regions of socio-economic and ecological significance e.g. coral reefs, biodiversity hotspots, population centres, and regional development hubs. To understand continental shelf and coastal processes observations are needed of temperature, salinity, velocity and also biogeochemistry at regional scales (metres to hundreds of metres) and timescales from minutes to years (Table 7.7).

Table 7.7: The variables required to address Continental Shelf and Coastal Processes science questions.

	Temperature - Surface	Temperature – subsurface	Salinity	Velocity	Sea Surface Height	Surface waves – amplitude	Surface waves – spectrum	Internal waves	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total Inorg. Carbon	Alkalinity	Macronutrient concentration	Pigment concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass
Eddy-Shelf interactions	■	■	■	■	■			■	■											
Upwelling/ Downwelling	■	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■
Shelf Currents	■	■	■	■	■			■	■											
Wave Processes		■	■	■	■	■	■	■	■											

7.4.9 Platforms required to deliver observations

IMOS national backbone around the continental shelf comprises a network of National Reference Station Moorings, national access to Satellite remote sensing products (Table 7.8) and the Australian Ocean Data Network (AODN). The more intensive, region-specific observations that IMOS provides include a combination of Shelf Moorings, coastal Ocean Gliders, Ocean Radar (for currents and waves), and Wireless Sensor Networks (on the Great Barrier Reef).

The AODN is particularly important for continental shelf/coastal regions of Australia, as the historical track record of discoverability, accessibility, usability and interoperability of data has been very poor. IMOS is seeking to change the national marine and climate information culture by leveraging its existing infrastructure into a full Australian Ocean Data Network (AODN).

Strong integration between the observing system and the relevant modelling frameworks is also particularly important in this context. Development of coastal, shelf and national scale hydrodynamic modelling needs to be tightly coupled with the IMOS national backbone and regional observing strategies, for the purposes of validation and model development, data assimilation, and observing system design.

Table 7.8: How variables required to address the high-level Continental Shelf and Coastal Processes science questions are delivered at required scales by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived Green = relative derived estimate.

		Temperature – surface	Temperature- Subsurface	Salinity	Velocity	Sea Surface Height	Surface waves – amplitude	Surface waves – spectrum	Internal waves	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total .Inorg. Carbon	Alkalinity	Macronutrient concentration	Chlorophyll concentration	CDOM and backscatter	Total suspended solids	Phytoplankton species	Phytoplankton Biomass
Ships of Opportunity	Tropical RV/Temperate MV	Blue		Red														Red	Red			
Ocean Gliders	Slocum Gliders	Blue	Blue	Red	Red				Orange			Blue						Red	Red			
	Auto. Underwater Vehicle		Blue	Red														Red				
Moorings	National Reference Stations	Blue	Blue	Blue	Blue					Orange	Red	Blue		Red	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
	Shelf Arrays		Blue	Red	Blue		Blue	Red	Orange			Blue										
	Acidification Moorings	Blue		Red								Blue	Blue	Red								
	Temperature loggers	Blue	Blue																			
Ocean Radar	WERA				Red			Orange	Orange	Orange												
	CODAR				Red				Orange													
Animal tagging	Biologging	Blue	Blue	Red																		
	Wireless Sensor Networks	Blue	Blue	Red						Orange	Red											
Remote Sensing	Sea Surface Temperature	Blue																				
	Sea Surface Height				Red	Blue			Orange													
	Ocean Colour																	Red	Red			Red

Notable gaps:

Research Infrastructure Roadmap identifies the following gaps in the current observing capability that would address continental shelf and coastal zone questions:

- Inadequate spatial coverage in the near coastal zone. Although IMOS, TERN, ALA and AuScope all provide infrastructure in the coastal zone, the Roadmap points out that the combined investment is inadequate for the scale of the coastal zone research and management/policy challenges (Strategic Roadmap –Australian Government, 2011). For example there is no instrumentation in The Gulf St Vincent, which borders the Adelaide Metropolitan Coast, to provide accurate sea state conditions on a regular basis.
- Inadequate spatial coverage in the shelf, for example there is negligible data streams (e.g. water column temperature, salinity and current structure) that could be used for calibration and validation of the eReefs model on the shelf north of 14°30'S or south of 23°30'S.
- Wave, windstress and turbulence measurements in the nearshore areas along the coast.

Future priorities:

- Engage in ongoing discussions to establish observing strategies and monitoring frameworks that can assess whether a more adequate shelf/coastal observing system can be implemented through partnership.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW, GAB in SA and Bass Strait in SEA)
- Re-assess the footprints analysis of National Reference Stations and shelf moorings using higher resolution model
- Evaluate the value and use of near real time data form coastal moorings and based on needs consider transitioning or transferring real time data acquisition where it is more needed
- Redesign the EAC mooring and consider the inclusion of the SEQ shelf moorings at the expense of one of the slope moorings as there may be some redundancy in this part of the array
- Expand CO2 network on national reference station to ensure ocean acidification progress is quantified for representative coastal habitats. SOOP BGC could be an alternative
- It is highly desirable to extend the Two Rocks transect to cover the full width of the Leeuwin Current, i.e. extend the Two Rocks mooring transect both into deep water, and to the nearshore region.
- Maintain the footprint of mooring observations off the Kimberley coast.

7.5 Ecosystem Responses

Australia's large ocean territory encompasses a diverse range of marine ecosystems that extend from the tropics to the Antarctic. In this section we identify the key features and drivers of marine ecosystems and our state of understanding, and we begin to integrate this information to build a picture of variability and change in the marine ecosystems. Key knowledge gaps include understanding how organisms at different trophic levels and water affinities will respond to climate change and variability, productivity drivers and the direct impacts of climate change on the distribution and abundance variability of organisms.

The ocean's ability to take up large amounts of heat and carbon help to buffer our climate system, however, this also has widespread impacts on marine ecosystems. The effect of rising ocean temperatures, changes in stratification and acidification are of particular concern.

Marine ecosystems are comprised of pelagic and benthic components, each with multiple trophic levels and variability over space and time. However, the dynamics of pelagic ecosystems can vary over shorter time scales compared to benthic ecosystems, due to their amenability to physical forcing. On the other hand, benthic ecosystems can be buffered against physical and chemical changes in the overlying water column, but resident organisms have limited capacity to migrate. These fundamental differences between these components of the marine ecosystems will therefore influence the type of observations that are needed to understand the ecosystems' response to climate variability and change.

In Australia, the two major poleward flowing boundary currents, i.e. the EAC and the LC, play a vital role in regulating the productivity of pelagic and benthic ecosystems. These warm boundary currents are nutrient poor with only patchy upwelling which lead to low productivity marine systems. However, nutrient enrichment processes that include cold-core eddies, shelf-edge upwelling, atmospheric dust inputs and topographic upwelling near capes can cause localised peaks in productivity. These productivity hotspots are critical to supporting diverse fisheries, as well as seabirds, marine mammals and sea turtle populations. Boundary current systems also play a key role in transporting marine organisms, influencing the connectivity of ecosystems. The strengthening of the EAC has seen a wide variety of species with warm water affinity extend their range down the east coast of Australia, with many tropical and subtropical species able to exist at relatively high latitudes due to an increase in temperatures (Johnson et al., 2011).

Another key area around Australia is the Southern Ocean (SO), a highly dynamic system, with temporal and spatial variability that has a number of Areas of Ecological Significance (AES). Seasonal changes in circulation, stratification and ice cover boost ecosystem production which makes the SO one of Australia's richest pelagic ecosystems, supporting the greatest density and biomass of apex predators to be found in Australian waters. SO ecosystems are affected by changes in its circulation and sea-ice cover, and it is thought to be a sensitive early indicator of global climate change (Houghton et al., 2001). Despite the fact that the SO plays a central role in the global climate system (Busalacchi, 2004) and increasingly supports human activities such as commercial fishing, the nature of the interactions between physical and biological processes is poorly understood. The SO is warming faster than other oceans (Gillet and Thompson, 2003, Böning et al., 2008, Gille, 2008) and Antarctic sea ice is predicted to reduce 30% by 2100 (Bracegirdle et al., 2008). This will affect circulation patterns and reduce habitat for the biota, especially for keystone species such as krill. Increased wind speed is affecting the ACC and richer CO_2 water is being circulated to the upper layers, which may reduce the effectiveness of the SO as a CO_2 sink (Le Quere et al., 2007). With the SO biota adapted to this extreme environment, they are highly vulnerable to shifts in climate. Changes in phytoplankton are expected to have flow on effects through the entire food web, impacting the survival of higher predators, krill and finfish. Understanding the response of marine biota to climate forcing is therefore vital for the management of the marine environment and its resources.

An integrated approach is needed whereby observations ranging from biogeochemistry through to all trophic levels are undertaken across systems. These observations should encompass variability on spatial scales that range from broad (national/ocean basin) to regional (i.e. boundary currents) and local (i.e. bio-region) and timescales that range from multi-decadal to intra-seasonal. In addition, the observing system needs to develop hand in hand with a range of ecosystem modelling activities, with observations used to test the relationships identified in qualitative models, inform the design of an ecosystem monitoring system, or provide data for fully quantitative, data hungry ecosystem models such as Atlantis.

7.5.1 Ocean Chemistry – Nutrients

About 50% of the global primary production occurs in the oceans providing a major sink for carbon and a huge supply of oxygen to the global atmosphere. Primary production in the oceans is limited by nutrient concentrations and light availability. The elements that are most often limiting to phytoplankton growth or biomass are: C, N, P, Si and Fe. Therefore these elements and their biogeochemistry are very important to the functioning of our ecosystems. However, observations in Australian regional seas are patchy for macronutrients such as N, P, and Si (Figure 7.22), and sparse for important micronutrients such as Fe. On the continental shelf, ecosystems are largely supplied with nutrients from two external sources: terrestrial run-off from coastal catchments and marine upwelling from the adjacent ocean. Other nutrient sources include rainwater and nitrogen fixation by cyanobacteria. Nutrient inventories around the Australian continent show generally low nitrate concentrations, particularly along the western and eastern coastlines which are both strongly influenced by poleward flowing boundary currents. Upwelling adds additional loads of dissolved nutrients to subsurface waters and signatures of upwelling (cold SST, high Chl-a) have been identified around the east coast and south of Australia. Other processes that seemed to be involved in nutrient supply around Tasmania and the west coast of Australia are associated with wind patterns and water mass variation, or cross-shelf exchanges at the shelf break and vertical mixing due to tropical cyclones, respectively. Relative to dissolved inorganic N and Si, the phosphate concentrations are high and do not suggest an ecosystem where P is limiting. Si concentrations off the coast of NSW and Tasmania on the other hand, have shown a decline in the past 30 years, perhaps in response to variation in the SOI and the strengthening of the EAC (Thompson et al., 2009). In the case of Fe, phytoplankton growth in large areas of the world's oceans has been shown to be limited by this nutrient. In the Australian and Tasmanian regions the main source of Fe is 90ioinfo dust (Mackie et al., 2008), with delivery that depends on the distribution of drought. Whether the availability of Fe limits the primary production in Australian coastal waters is an area of active investigation.

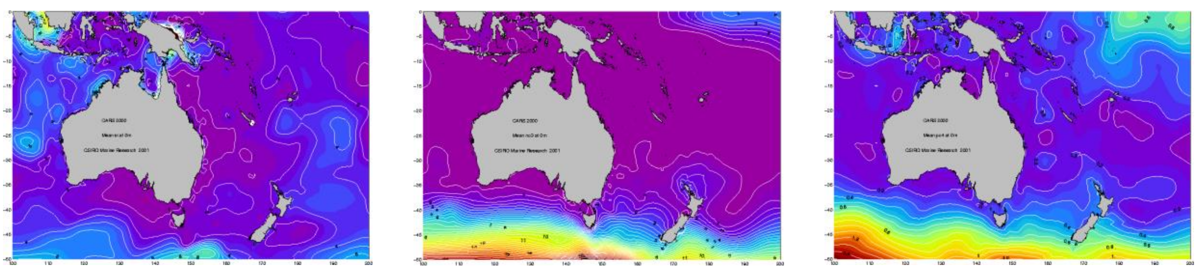

Figure 7.22: Regional nutrients: Analysis of all CSIRO surface (0m) data for silicate (left panel), nitrate (middle panel) and phosphate (right panel). Concentrations are given on the major contours.

7.5.2 Ocean Chemistry – Carbon and acidification

The oceans absorb approximately one third of atmospheric CO_2, derived primarily from anthropogenic activities. As a consequence, pH in the ocean has decreased (increasing acidity) and its chemical balance altered reducing the concentrations of dissolved carbonate ions (Feely et al., 2004), a component essential for many marine organisms. The lower carbonate ion concentrations cause a decrease in the saturation state of major calcium carbonate forms that are precipitated by marine calcifying organisms (Fabry et al., 2008). The upper ocean pH has declined by about 0.1 since preindustrial times and will decline by 0.4 if atmospheric CO_2 concentrations reach 800ppm by the end of this century (Caldeira and Wickett, 2003). The SO is predicted to cross a threshold where aragonite, a form of carbonate produced by many important marine calcifiers, will be undersaturated by about the middle of this century (Fig. 7.23) with profound effects to high latitude ecosystems (Orr et al., 2005).

Calcification rates of coral reef builders are predicted to decline significantly during this century (Kleypas et al., 1999, Langdon and Atkinson, 2005, Hoegh-Guldberg et al., 2007), with ocean acidification steadily eroding reef resilience, in part by increasing vulnerability to bioerosion and cyclone damage (Anthony et al., 2011b), but also by reducing capacity for recovery through impaired recruitment and growth. In the GBR, there is already evidence of changes occurring in the skeletal structure of organisms and the chemistry of this important marine ecosystem. However, projections for ocean acidification are based mainly on the exchange of carbon between atmosphere and oceanic surface waters (Caldeira and Wickett, 2003, Gledhill et al., 2008) and do not consider carbon exchange between seawater and benthic communities (Duarte et al., 2013). Recent work has demonstrated that small changes in benthic composition can alter seawater carbon chemistry patterns at the local scale and modify the risks coming from the Coral Sea in both directions (Anthony et al., 2011a, Anthony et al., 2013). Communities dominated by corals and crustose coralline algae (CCAs) amplify acidification risk, while communities dominated by algae and sand can partly ameliorate ocean acidification at the local scale. The net result of these additive effects depends most critically on water depth, residence time, and the mix of primary producers and calcifiers. To fully understand the risk of ocean acidification in Australian marine ecosystems, it is necessary to investigate the biological processes driving carbon chemistry variation in coastal and shelf waters, the oceanographic processes linking open ocean to coastal systems, and the interactions with ocean warming and changes in other factors such as salinity, nutrients and turbidity.

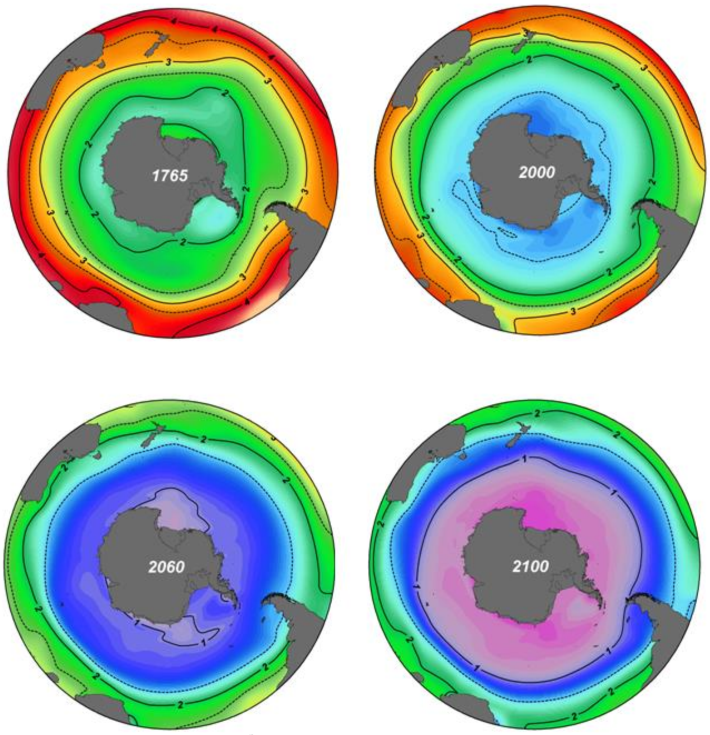

Figure 7.23: Changes in the saturation state of aragonite for surface waters from the preindustrial era, represented by the year 1765, until year 2100. Values below one are undersaturated. The saturation states were modelled using the CSIRO carbon cycle model. Changes after the year 2000 are based on the IS92a emission scenario are now being exceeded (Canadell et al., 2007), indicating a more rapid approach to undersaturation. Note the lowered saturation near Antarctic and the declines in saturation state further north. (Figure generated from CSIRO BGC model using the model simulations of Orr et al., 2005).

7.5.3 Microbial community

Microorganisms are a major player in controlling the function of marine environments. They comprise up to 90% of the total ocean biomass, are the foundation of the marine food-web, and the engine-room of the ocean's major chemical cycles (C, N, P, Si). The composition and biogeochemical functionality of these microbial assemblages underpins the ecology of marine ecosystems and mediates the ocean-atmosphere exchange of climatically important gases.

The genetic diversity of microbial organisms in the oceans is an emerging research area. Metagenomic analysis provides an opportunity to undertake large-scale, spatially-explicit analyses to quantify and map patterns of microbial biodiversity (Fig. 7.24). This information will improve our understanding of the distribution of functional groups in relation to essential metabolic processes such as photosynthesis, nitrogen fixation, and denitrification. High resolution microbial oceanography integrates high spatial and temporal resolution observations of microbial community composition with biogeochemical and oceanographic observations, which allows the identification of the links between them.

The Australian Marine Microbial Biodiversity Initiative (AMMBI) program started in 2012with a one year pilot to test the feasibility of including microbial sampling in the routine, monthly biogeochemical and oceanographic observation of the IMOS National Reference Stations. The pilot study was undertaken at three NRS along the EAC and was expanded to all NRS in the 2014-2015 period. This program is now part of a new project, led by Bioplatforms Australia, that will use

AMMBI observations and apply its genomics network to perform DNA sequencing to generate the large-scale datasets scientists require to understand fundamental marine processes.

The aim of AMMBI is to build a marine microbial biodiversity map of Australia that could be integrated with data on physical environment, biogeochemical cycles, microbial biodiversity and patterns of human activities.

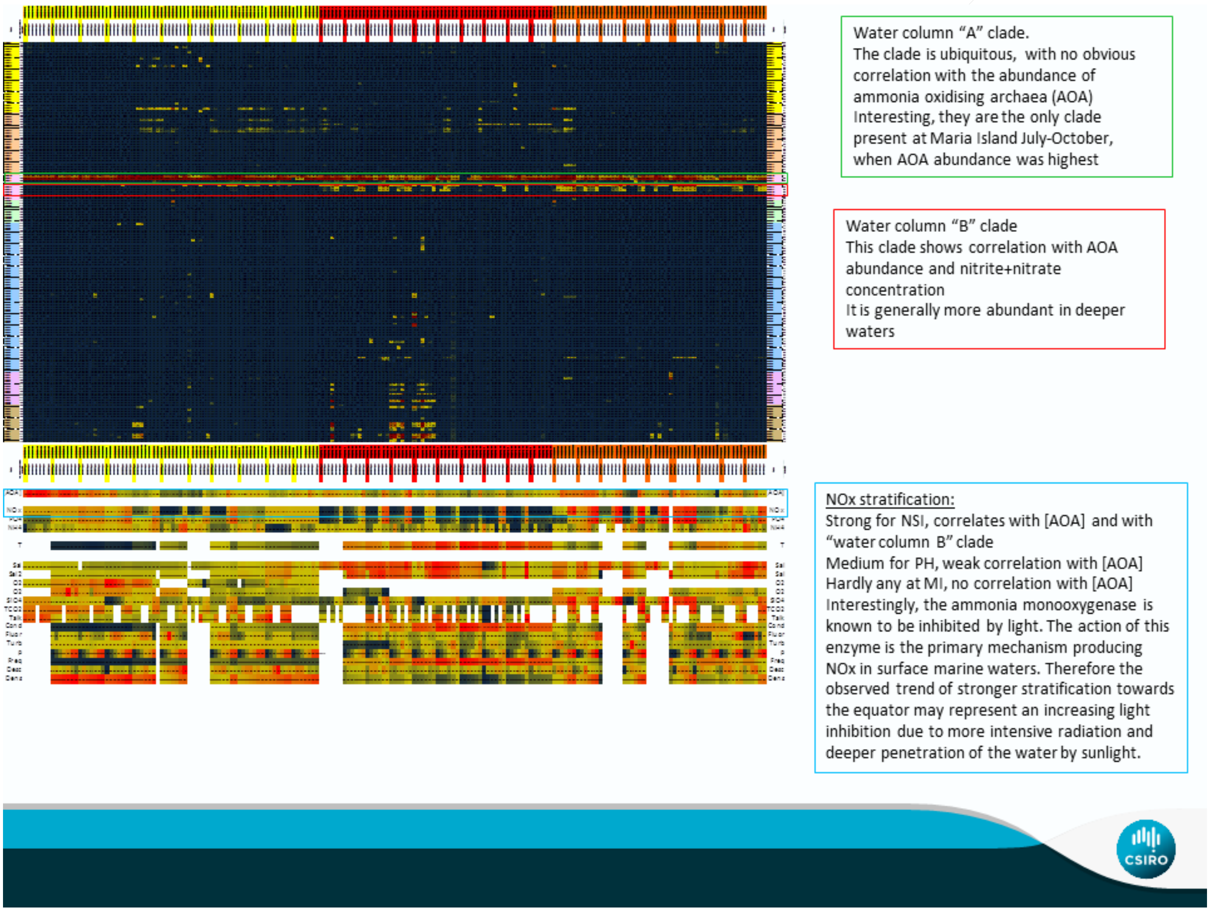

Figure 7.24. Preliminary results of genomic analysis of the community structure of ammonia 93ioinform archaea, using a microarray, targeting the gene encoding for one subunit of the ammonia monooxygenase gene. The microarray detects different varieties of the gene, carried by different archaeal ammonia oxidizers. The main block depicts a heatmap of the results, with each column representing one sample and each row representing one clade of archaeal ammonia oxidizers. The bottom block shows contextual data as individual heat strips. The first strip within the blue square shows the abundance of ammonia oxidizing archaea (per mL of seawater), and the second shows the concentration of nitrite + nitrate (per mL seawater) (L. Boddrossy, unpublished data).

7.5.4 Pelagic: Plankton

<u>Phytoplankton</u>

A critical gap limiting the predictive capability of our ecosystem models is our lack of knowledge on how the plankton community will respond to climate change. This uncertainty in the biological carbon pump needs to be resolved before we can be confident that our models of future climate change are robust. The biological pump encompasses the phytoplankton and their consumers. Phytoplankton contributes half of the primary production on earth, and while the "standing biomass" of phytoplankton is small compared to the terrestrial ecosystems, the rate of primary production is about equivalent due to their rapid lifecycles. They also underpin the entire pelagic food-web, with variations in primary and secondary productivity related to variations in meteorology and oceanography in the region and temperature and stratification of the surface ocean being key determinants of phytoplankton community composition and production. Predicting the response of phytoplankton productivity and community structure to climate change is complex, with some modelling studies (Bopp et al., 2001, Boyd and Doney, 2002, Le Quéré et al., 2003, Bopp et al., 2005) suggesting a global decline in phytoplankton biomass in a warmer world.

In Australia the two poleward warm boundary currents are nutrient poor leading to low productivity marine systems. However, high rates of primary productivity are found in the south coast of Australia, particularly of the eastern GAB, due to the influence of upwelled water mass, and are comparable to levels reported for the highly productive upwelling systems of the Benguela Current off southern Africa, and the Humboldt Current off the coast of Chile (Van Ruth et al., 2010a, b). Highest phytoplankton abundances in the region associated with the upwelled water mass is composed by >5 µm phytoplankton dominated by diatoms and dinoflagellates, with small flagellates present but much less abundant (Van Ruth, 2009). In the east of Australia, there is evidence of phytoplankton species communities changing with diverse consequences to the local ecosystems. Warm water species are moving southward along the east coast, perhaps associated to the strengthening of the EAC paving the way for the apparent range extension of warm-water organism into Tasmanian waters. There is concern that some of these species could be toxic or harmful with potential blooms causing a shutdown of fisheries and aquaculture operations in the region. In the northern seas of Australia massive blooms of what could be coccolithophorids have been observed, and are of sufficient size to have considerable impact on the carbonate chemistry of the regional seas, potentially increasing the ocean acidity in the region. Around the GBR phytoplankton community composition typically shows smaller size phytoplankton (pico- and nanoplankton) offshore and larger size inshore (microplankton, e.g. diatoms). Recent studies of flood plumes show that fast-growing microplankton compete for spikes of nutrients producing ephemeral blooms that persist until their zooplankton predators adjust their population sizes (Mckinnon and Thorrold, 1993). This upwards shift in the size spectrum of the phytoplankton community may advantage some meroplankton that does not feed efficiently on the small cells normally dominant in shelf waters and this change is thought to be the trigger for the explosive expansion of the coral-eating starfish (Fabricius et al., 2010, Furnas et al., 2013).

Ocean colour satellites are the best way to observe large scale changes in phytoplankton abundance and distribution. The marine and climate science community has highlighted the need for a consistent, well calibrated time series of ocean colour products to assess primary productivity and phytoplankton biomass for the Australia's regional seas and the Southern Ocean. However phytoplankton community composition records are sparse with good long-time series available off NSW but not elsewhere.

<u>Zooplankton</u>

Zooplankton are heterotrophic organisms with limited swimming ability relative to the strength of ambient currents and are distributed throughout all marine environments. Zooplankton can fall into distinctive categories according to their use of the water column. The biggest distinction is between the 'holoplankton', where all life history stages are planktonic, and the 'meroplankton', which is composed predominantly from the early life history stages of pelagic and benthic species. They are the most numerous multicellular animals on earth and the main secondary producers in the oceans, transferring energy from primary producers to higher trophic levels and playing an important role in the biological carbon pump. Zooplankton are good indicators of climate change since most species are short lived leading to a tight coupling between environmental change and population dynamics and can therefore show a fast response to changes in temperature and oceanic currents by expanding or contracting their ranges (Hobday et al., 2006). In addition, recent evidence suggests that zooplankton could be a more sensitive indicator of change than environmental variables due to the amplification of their nonlinear response to environmental perturbations (Hobday et al., 2006). Known general responses of zooplankton to increasing temperature include poleward expansions in the distribution of individual species and of assemblages, earlier timing of important life cycle events (phenology), and changes in abundance and community structure.

In Australia, there is evidence that warm-water "signature" species are moving southward into Tasmania (Johnson et al., 2011). Some of these changes in the zooplankton communities are associated with changes in nutrient conditions forced by wind-driven circulation (Harris et al., 1991, Harris et al., 1992), incursion of the EAC, increased water column stability and reduced biological production (Johnson et al., 2011). The phenomenon of "tropicalization" of temperate plankton communities has potentially important ecosystem consequences. The reduced nutrient availability in warm years has led to reduced production and a shift to smaller phytoplankton species, resulting in a drastic reduction of large zooplankton biomass, particularly krill (*Nyctiphanes australis*) which has seen a reduction of its population since the 1980s (Johnson et al., 2011). Another indication of this "tropicalization" is the expansion of the calanoid copepod *Parvocalanus crassirostris* which is primarily a tropical and subtropical species. This shift will have flow on effect over the entire food-web and will ultimately impact fisheries production. In addition to the temperature effects driving redistribution, coastal eutrophication has also been shown to change the size spectrum of zooplankton assemblages (Uye, 1994).

7.5.5 Pelagic: Nekton

Marine nekton are the swimmers of the oceans, it includes fishes, cephalopods, seabirds, marine mammals, reptiles and crustaceans that inhabit all the ecological zones of the ocean from the epipelagic to the deep sea (Pearcy and Brodeur, 2009).

<u>Micro-nekton</u>

Micro-nekton plays a pivotal role in the ecosystem, connecting plankton at the base of the food web to the higher trophic levels. The group comprises the larger zooplankton and smaller nekton (2-20 cm) which includes adult krill, small fish, crustaceans, squids and gelatinous species. They may account for a significant fraction of the ocean's biota, however, accurate estimates are difficult to obtain as their distributions are patchy in time and space and thus are a poorly studied faunal group. Many are carnivorous and some are herbivores and are important prey for seabirds, larger fishes and marine mammals. Krill are especially important as prey for many marine species and are a major source of food for whales, penguins and some pinnipeds in the SO. Recent coupled ocean-biogeochemical-population models have identified a gap in knowledge on the distribution, biomass and energetics of mid-trophic level organisms such as this one (Fulton et al., 2005, Lehodey et al., 2010). These observations are needed at a shelf and basin scale for ecosystem models to validate predictions but there have been limited observations in the southern hemisphere (May and Blaber, 1989, Koslow et al., 1997, Young et al., 2001, Mcclatchie and Dunford, 2003). Micro-nekton biomass at an ocean basin scale has been estimated at 29 g m^{-2} off eastern Australia using a combination of net samples and multifrequency acoustic methods (Kloser et al., 2009). In the nearshore, other important components of micro-nekton that dominate the biomass in Australia are fish species such as anchovies and sardines (Ward et al., 2006). The Australian sardine supports Australia's largest commercial fishery by weight (i.e. the South Australian Sardine Fishery) with its life history and population size/dynamics relatively well understood (Ward et al., 2001a, Ward et al., 2001b, Ward and Staunton-Smith, 2002, Ward et al., 2006, Rogers and Ward, 2007, Strong and Ward, 2009, Ward et al., 2011). Expected impacts of climate change will modify the distribution and abundance of some of these species, with the range of many warm water species potentially expanding south and replacing species with cold water affinities, while an increase in upwelling favourable conditions could see populations of species living near upwelling regions, such as sardines, benefit (Hobday et al., 2006). There is already evidence of species replacement around Tasmania, with the cold-water jack mackerel replaced by the warm-water redbait, which is consistent with the warming trend on the east coast of Australia and Tasmania (Hobday et al., 2006). However, the sparse observations that come from a variety of sampling devices are of limited spatial and temporal extent, making it difficult to compare biomass estimates or to establish trends. Developing a synoptic dataset through time on these mid-trophic groups would fill an essential gap between the abundant observations available at the physical scale from satellites and modelled data, and the higher trophic levels via fisheries data and electronic tagging of top predators.

Large fishes

High trophic level fishes such as tuna, billfish and some species of sharks often act as integrators of the oceanic ecosystem. They are sensitive to changes in the distribution and abundance of their prey, which in turn respond to changes in lower trophic levels and the physical environment. In general, most of the information on distribution and abundance of pelagic species comes from fishery dependent records where the species are exploited (Worm et al., 2003, Zainuddin et al., 2006). Fishery-independent data on the distribution of the larger pelagic species has been gathered by electronic tags that record the location of the fish and some environmental information such as temperature and depth (Arnold and Dewar, 2001, Gunn and Block, 2001, Block et al., 2003, Schaefer and Fuller, 2003). These records have shown that many of these species are constantly on the move at ocean basin scales possibly in search of food or migrating to common spawning areas. Pelagic predators focus their foraging in areas of relatively high food availability and therefore they can be used to identify areas of ecological significance (AES, also known as "hot-spots"). Observing AESs can provide information on the spatial and temporal variability of their prey and the influence of mesoscale features such as fronts and eddies. However, a complete understanding of upper trophic level processes requires measurements over long time frames and integration across trophic levels and ocean physics.

The effect that climate change may have on large pelagic species will be on their distribution. For example, change in ocean temperature can impact the distribution of Southern 96ioinfo tuna, which are restricted to the cooler waters south of the EAC and expand further north when the current contracts up the NSW coast (Majkowski et al., 1981). Therefore, their population could be restricted further south if Tasman Sea warming continues. Preliminary analyses indicate that changes may have already occurred, with fewer fish moving to the east coast in the Austral winter (Polacheck et al., 2006). On the other hand, the increased southward penetration of the EAC may increase the suitable habitat for species such as yellowfin and bigeye tuna.

The decline of krill, *Nyctiphanes australis*, from the shelf ecosystem of eastern Tasmania would also have a profound effect on cephalopods (Hobday et al., 2006), seabirds (Bunce, 2004) and small pelagic fish and tunas (Young et al., 1993), which depend on krill as prey. However, the overall impact on large fish populations due to climate change is still highly uncertain.

Sea turtles

There are 7 species of sea turtles worldwide of which 6 species can be found in Australian waters. They can be herbivorous (e.g. green turtle *Chelonia mydas*), planktivorous (e.g. leatherback turtle *Dermochelys coriacea*) or carnivorous (e.g. loggerhead turtle *Caretta caretta*). All sea turtles, with the exception of the flatback turtle, are listed in the IUCN 2004 Red List of threatened species. Of the species found in Australian waters many nest on Australian tropical and subtropical mainland and island beaches, with flatbacks nesting exclusively on Australian beaches. Major rookeries of international significance for loggerhead, green and flatback turtles are located in Queensland and the Torres Strait (Limpus et al., 1989, Parmenter and Limpus, 1995, Gyuris and Limpus, 1998).

Green turtles are one of the largest herbivores in Australian coastal waters playing an important role in structuring sea grass communities and thus enhancing seagrass biodiversity and productivity through selective cropping (Brand-Gardner et al., 1999, Aragones, 2000, Aragones and Marsh, 2000, André et al., 2005, Moran and Bjorndal, 2005).

Climate change and in particular temperature increases are likely to be a major threat to sea turtles as all stages of their life cycle are strongly influenced by temperature. Gender of embryos is determined by the ambient nest temperature and a small increase in temperature could bias the sex ratio of hatchlings towards females, potentially eliminating the production of males in certain regions. Climate change is also likely to influence phenology and distributions of all species. There is already evidence that turtles are nesting earlier in response to warming and that their ranges are extending or shifting poleward. Increases in sea level will also lead to a substantial loss of nesting sites and inshore foraging habitats for marine turtles. However, the greatest threat to turtles is likely to come from climate-induced changes of their food supply in critical habitats. While little is known about the pelagic stage of turtles life cycles some species forage in surface and subsurface waters around oceanic fronts for mainly gelatinous plankton that tend to concentrate along them (Carr, 1987, Witherington, 2002, Ferraroli et al., 2004, Polovina et al., 2004). Therefore, alterations of primary productivity driven by changes in mixed layer depth will impact food availability for turtles in the open oceans.

In Australia, evidence of climate change effects on turtle reproduction has been observed on green turtles with an increase in their population in the southern GBR linked to an increase in the frequency of ENSO anomalies (Chaloupka and Limpus, 2001). Satellite tags on turtles have revealed long distance movements in the GBR and Torres Strait during normal foraging (Hamann unpubl. Data). Leatherback turtles from a nesting beach in the western Strait (Waral Kawa) have been tracked to extensive feeding grounds on the North West Shelf or lost after entering Indonesian waters. Flatback turtles that breed on beaches in the southern GBR make long reproductive migrations restricted to the continental shelf, with some turtles tagged at rookeries in southern Queensland being recaptured more than 1300 km from their nesting beach (Limpus et al., 1983).

<u>Seabirds</u>

Seabirds are highly visible, charismatic animals in marine ecosystems that feed exclusively at sea, in either nearshore, offshore or pelagic waters. They are efficient integrators of ecosystem health, as many feed on small pelagic fish and zooplankton and thus are sensitive to changes at lower trophic levels. In Australia, a diverse seabird fauna breeds on mainland and island coastlines. The world's largest colony of crested terns (*Sterna bergii*) occurs in the Gulf of Carpentaria in Australia's north (Walker, 1992), and almost a quarter of all albatross species have nesting sites on islands around Tasmania and Macquarie Island. Some species of seabirds are highly valued by coastal indigenous communities for their cultural and spiritual significance and may also be hunted for food. They also benefit local economies through ecotourism, such as with the colonies of little penguins on Phillip Island and Tasmania.

Seabirds are frequently used as indicators of the state of the marine environment as their demographics and reproductive parameters are strongly linked to changing oceanographic and trophic conditions (Congdon et al., 2007), with prey abundance and seabird reproductive biology significantly correlated (Anderson et al., 1982, Burger and J.F., 1990). Therefore, understanding how changing oceanographic conditions impact seabird population dynamics and reproductive ecology can give an insight of potential future impacts of climate change, not only on seabirds, but on other important components of tropical marine ecosystems. Climate change is likely to influence phenology and distributions of seabird species, with evidence of seabird populations nesting earlier in response to warming and distribution ranges changing globally (Hobday et al., 2006). Increases in sea level can also lead to substantial loss of important nesting sites and inshore foraging habitats for some species. However, the greatest threat to seabirds is likely to come from climate induced changes of food resources in their critical habitats.

Around Australia, the Australasian gannet populations are increasing, possibly due to the increase frequency of ENSO anomalies favouring food availability. However, for other species, such as the wedge-tailed shearwater in the GBR, reproductive success will decline as warming reduces their prey supply. Changes in prey availability will ultimately affect distributions, abundance, migration patterns and community structure of these higher trophic levels.

<u>Marine Mammals</u>

Marine mammals are found in all of the world's oceans with Australia recognised as a hotspot of marine mammal species richness (Pompa et al., 2011). There are currently 52 recognised marine mammal species around Australia's coast with at least seven species considered threatened according to the IUCN red list (IUCN 2011). However, due to insufficient data, the conservation status of 25 cetacean species is still unknown (Schumann et al., 2012). Marine mammals can be found at different trophic levels, these include herbivores such as dugongs, mid-trophic levels such as baleen whales and high trophic levels such as pinnipeds and most species of cetaceans (Pauly et al., 1998). The majority of research on Australian marine mammals has been focused on accessible species such as seals, coastal dolphin species or whales which appear in seasonally predictable near-shore regions.

There is currently a low level of confidence in the predicted effects that climate change may exert on Australian marine mammals due to a lack of information on most species, particularly of the distributions, population sizes or ecologies of many species. Therefore, the adaptive capacity of marine mammals to climate change in Australia is poorly known (Schumann et al., 2012). However, non-climatic stressors such as fishing activities, harvesting, boat strikes, coastal development and degradation and acoustic pollution, among others, are thought to exacerbate the vulnerability of marine mammals by acting in synergy with climatic impacts (Schumann et al., 2012). The paucity of data on Australian marine mammals and consequently, the long- term cumulative impacts of human activities and climate change on marine mammals are not well understood. It is evident that the primary climatic influence on many marine mammals appears to be food availability and distribution, which is linked to ocean temperature (Neuman, 2001, Leaper et al., 2006). Therefore, sea surface temperature (SST) is commonly used as a proxy for biological productivity (Bradshaw et al., 2004), with many marine mammals selecting particular SST in which to forage. There is also some evidence that several species may modify their physiological responses to increasing temperatures or alter their foraging locations, behaviour or diet in response to changes in prey availability and distribution (Schumann et al., 2012). It is expected there will be changes in distribution with warm-water species expanding south, and cold-water species contracting. However, the impact on community structure and dynamics remains unknown. Climatic changes may also result in changes in their reproductive success with changes in the extent of suitable breeding and feeding habitat.

To improve our understanding of potential impacts of climate change on Australian marine mammals, research into population trends and critical habitats dynamics, energetics and distribution patterns is required. The use of acoustic technology, satellite tags and biologgers to monitor coastal and oceanic movements of marine mammals will help in the understanding of the effects of climate change in marine mammal populations in Australian coasts and the SO. The deployment of sea noise loggers is also providing acoustic observations of marine mammals to study their abundance and migration patterns. This technology has helped reveal the presence of several whale species in WA waters, such as Bryde’s whales which are found all year round in the NWS, Southern right whales present over winter as far north as Perth Canyon, sperm whales regularly detected in waters offshore Exmouth and the Joseph Bonaparte Gulf and fin whales present regularly in Perth Canyon around September. In addition, marine mammals, such as seals, are being fitted with bio-loggers providing oceanographic observations within the SO throughout the Antarctic winter, data previously unavailable but essential for oceanographic and climate studies, and information on their biology and ecology.

7.5.6 . Benthos

Benthic ecosystems are particularly vulnerable to environmental change due to the sessile or near-stationary nature of most benthic flora and fauna, and some of these ecosystems such as those characterised by coral reefs and kelp forests are one of the most diverse habitats in the world. When these habitat-forming dominants such as corals and kelp disappear there is a huge collateral loss of other biodiversity, catastrophic decline in the local transfer of energy and materials, and potential downstream impacts on fisheries.

Seagrasses

Australia has the highest diversity of seagrasses and most extensive seagrass beds in the world, they are found in shallow coastal waters, generally on soft sediments. They are considered ecosystem engineers, acting as a buffer between terrestrial and oceanic systems, playing a vital role in nutrient cycling and acting as an important CO_2 sink. Seagrass beds provide important nursery habitat for many economically valuable species of fish and crustaceans and support internationally important populations of marine turtles and dugongs. Temperature and water clarity are the major factors controlling the biogeographic distributions of seagrasses in Australian waters. Erosion and flooding due to sea level rise will increase turbidity of coastal waters impacting the survival of seagrasses. On the other hand, increase in CO_2 may favour seagrass productivity increasing its depth limit and enhancing its role in carbon and nutrient cycling (Hobday et al., 2006).

The macro and micro-algal epiphyte community growing on seagrasses beds are an important component of the seagrass ecosystems, contributing to productivity and nutrient recycling (Van Montfrans et al., 1984, Jernakoff et al., 1996, Moncreiff and Sullivan, 2001, Smit et al., 2005). Seagrass ecosystems also have a high numbers of benthic invertebrates which contribute significantly to coastal nutrient dynamics (Edgar 1990), they function as nursery habitats for a wide range of fauna providing protection from predation and a high abundance of food resources (Heck et al. 2003), are important nursery and foraging habitat for many economically valuable species of fish and crustaceans (Coles et al., 1993, Gray et al., 1998, Rotherham and West, 2002, Smith and Sinerchia, 2004). Furthermore, a number of commercially exploited species of fish, crustaceans and molluscs, have been linked to seagrass beds (Jackson et al., 2001).

In tropical Australia the largest contiguous seagrass meadow is located in the Torres Strait, and it could be at risk from changes in water quality, likely due to industrialisation, deforestation, and human development occurring in Papua New Guinea and Irian Jaya. Extensive areas of seagrass habitat have already been lost in Australia in the last 50 years mainly through increased anthropogenic inputs to coastal waters reducing water quality. However, global climate change is expected to have a big impact on seagrasses in the near future (Hobday et al., 2006).

Kelp forests

Of particular importance are the so-called ‘ecosystem engineers’ that have a disproportionate effect by either creating habitat for myriad other species (Jones et al., 1994, 1997) or destroying habitat critical for other species (Johnson et al., 2005, Ling, 2008). The impacts of climate change on habitat-forming ecosystem engineers is particularly important as these species are generally facultative, and form the basis of communities that are hierarchically organised through positive interactions (Bruno and Bertness, 2001, Bruno et al., 2003). Kelp species comprise a small proportion of marine macroalgae, but they are ecosystem engineers in their habitats forming large floating canopies up to 30 metres above the sea floor in the form of ‘kelp forests’ which are inhabited by diverse assemblages of animals and plants that depend on them. They provide extensive three dimensional structures with a variety of micro-habitats, refugia and food for large amounts of coastal fish species and invertebrates, produce very large amounts of phytal detritus (Gerard, 1976) stimulating high secondary production which in turn support higher trophic levels (Duggins et al., 1989). Kelp species are distributed throughout the southern half of Australia wherever there is persistent hard substrata with enough light and they exhibit unusually high endemism and diversity (Womersley, 1990, Phillips, 2001). Southern Australia contains by far the highest diversity of brown algae (140 species per 100 km section) of all the rich kelp areas of the world, with the distributions of some individual kelp species limited to areas such as the South Eastern and South Western Large Marine Domains.

Kelp forest ecosystems are vulnerable to potential climate changes because they are sensitive to increase in temperatures and turbidity, decrease in nutrients and light penetration, and outbreaks of herbivores due to depletion of predators. The ramifications that changes in the density, distribution, or production of canopy-forming algae will have to the structure and functioning of these important seaweed-based communities are likely to be widespread (Dayton and Tegner, 1984, Reed and Foster, 1984, Johnson and Mann, 1988, Schiel, 1988). For example, the kelp *Ecklonia radiate* has a larger depth (4-40+ m) and latitudinal (~27.5-43.5 ^{o}S) range than any other canopy-forming brown seaweed in the region. It extends as far north as south east Queensland where it is found in deeper water (20+ m), apparently able to survive because of thermal stratification and local upwelling of cold and relatively nutrient-rich water over the shelf break. *Ecklonia* dominated habitats are highly biodiverse (Edgar, 1983, 1984, Ling, 2008), and in Tasmanian waters these forests support economically important abalone, rock lobster and scale fish fisheries. *E. radiate* forests are being impacted on two fronts: an increase in temperature shifting south its northern limit and the arrival of warm water species such as the spiny sea urchin *Centrostephanus rodgersii*, which is associated with the destruction of kelp and the formation of urchin barrens along the east coast of Tasmania. It is thought that the southward movement of *C. rodgersii* is related to a strengthened EAC transporting their larvae, which in combination with rising east coast temperatures provide a suitable environment for them. The expansion of extensive areas of 'urchin barrens' habitat in the north east, and 'incipient' barrens over many other areas of the east coast, represent an important threat to the integrity and biodiversity of nearshore reefs and associated valuable fisheries in the region (Johnson et al., 2005, Ling, 2008).

Reefs

Reef-building corals have the ability to form extensive skeletons of calcium that over time transform into vast reef structures that may be easily seen from space. They are considered ecosystem engineers providing critical habitat for a huge diversity of fauna and flora that in Australia includes over 400 species of corals, 4000 species of molluscs and over 1500 species of fish (Hoegh-Guldberg, 2006). Major coral reefs stretch along both coastlines of the Australian continent, from Frazer Island to Torres Strait on the east coast, and from the Houtman Abrolhos reefs across the northwest coast of Australia to the western edge of the Gulf of Carpentaria on the western side of Australia. These reefs show a large variety of structures that range from poorly developed reefs that fringe inshore regions to extensive carbonate barrier reefs offshore. Efficient reef-building is dependent on an intimate symbiosis between an animal host (the coral polyp) and internal unicellular dinoflagellates (the symbionts) known as zooxanthellae. The symbionts capture energy via photosynthesis and provide the animal host with nutrition. In return, the dinoflagellate symbionts gain access to a rich supply of inorganic nitrogen and phosphorus from the host, which supports the primary productivity of the dinoflagellate under the otherwise low-nutrient environment. This energetic contribution from the plant-like zooanthellae accounts for the ability of scleractinian corals to build coral reefs. Natural selection has resulted in symbioses that operate most efficiently near the upper thermal tolerance of the local combination of coral and zooxanthellae genotypes. As a result of this fine balance, the coral-algal symbioses can be destabilised by several external stresses including thermal stress (Berkelmans et al., 2004, 2010), excess light (Lesser and Farrell, 2004), low salinity waters (Kerswell and Jones, 2003, Fabricius, 2005, Berkelmans et al., 2012) and excess nutrients (Wooldridge, 2009). When placed under stress, the animal host ejects its endosymbionts and the loss of their pigments results in colonies of bleached appearance. If the corals remain in a bleached state for more than a few days, the coral animal starves and dies. In addition, ocean acidification has the potential to tip the balance from coral calcification to erosion and severely compromise coral viability. Changes in intensity and frequency of storms, increased aridity leading to greater sediment load on reefs, and sea level rise are also likely to act in synergy with temperature increases and acidification in reducing coral populations. However, it is long-term changes in temperature associated with global warming that are considered the greatest threat to the survival of coral reefs in the next 100 years (Hoegh-Guldberg, 1999) because the animal-plant symbiosis responsible for reef building is destabilised by temperature anomalies as little as 1^{o}C. Corals have not yet shown any great ability to adapt to thermal stress, and current rates of global warming are considered much too fast to anticipate an evolutionary response. Therefore, the risk of catastrophic change to an iconic system like the GBR justifies the need for detailed information about the thermal environments around coral reefs. Based on current coral physiology, a 1-2°C increase in water temperature in the tropical and subtropical regions in Australia could lead to annual bleaching and regular large-scale mortality events. The role of coral reefs in underpinning coastal economies in Australia is becoming increasingly recognised with the GBR tourism industry alone contributing around the $6 billion AUD per annum to the Australian economy (Hoegh-Guldberg et al., 2007). The reduction of coral reefs growth and survival will therefore have not only major consequences for Australia's coastal biodiversity but also economic and social consequences. Coral bleaching can be currently forecast by tracking anomalies in the ambient heat load, and web-based warning systems are now operational for the GBR (ReefTemp) and global reef systems (Coral Reef Watch). These products are based on satellite remote sensing and have required *in situ* observations of bulk temperature to calibrate and validate algorithms for tropical atmospheric conditions.

Deep sea cold-water corals are found globally and in Australian waters. These corals are presently known only from sites around south and southeast Australia. Similar to tropical coral reefs, deep sea cold-water coral reefs are essential fish habitat and are considered "hotspots" for biodiversity. However, unlike their tropical shallow water counterparts, deep sea corals lack the symbiotic algae and are found down to depths of over 1000 meters below sea level. These ecosystems can have large aggregations of fish, such as the commercially important orange roughy (*Hoplostethus atlanticus*) found on some seamounts, providing shelter, feeding grounds, spawning grounds and nursery areas (Bull et al., 2001, Dower and Perry, 2001, Reed, 2002). The unique hydrological characteristics of seamounts together with their biological isolation gives these ecosystems a high level of species endemism and could be important centres of speciation (Richer De Forges et al., 2000, Koslow et al., 2001). However, knowledge of the ecology, population dynamics, distribution and ecosystem functioning of deep-sea corals is sparse. In addition, these reefs are long-lived, slow-growing and susceptible to physical disturbance, making them extremely slow to recover from it (Morgan, 2005). The three major threats to cold water corals are bottom trawl fishing, ocean acidification and seabed mining. They are highly vulnerable to rapidly declining aragonite saturation associated with rising CO2 and declining pH making seamount habitats off South Australia become inhospitable for cold water corals below a few hundred metres as a consequence. Since these deep sea corals are foundation species, their disappearance will have dramatic consequences for the entire ecosystem sustained by them.

<u>Benthic invertebrates and fish</u>

Invertebrates such as crabs, bivalves, prawns, and worm assemblages are extremely diverse in Australia due to the subtle diversity and vast extent of soft sediment habitats in Australia's marine environment with some regions of very high faunal density, biomass, and diversity. These soft sediment fauna play a key role in recycling a considerable portion of the overall energy through the detrital food web. They are important in helping support and mediate the production and maintenance of Australia's marine ecosystems and link the production originating from primary producers with the production that relies on detritus. Human activities such as bottom trawling modify the structure and functions of soft sediment ecosystems while changes in sea temperature and factors that affect productivity such as rainfall and coastal runoff are likely to influence soft sediment communities strongly. Acidification may also drive strong changes as well, but this is less certain.

The benthic and demersal fishes of Australia include teleost and elasmobranchs (sharks, rays, and chimaeras) that inhabit the ocean floor. These fishes play an important role shaping many aspects of Australia's marine biological communities through predation on secondary producers, as forage for other fishes, vertebrates, and scavengers; and sometimes through bioturbation (Hobday et al 2009). These species are also valuable commercial and recreational fisheries in Australia. It is expected that temperate species will continue to shift south in response to increase temperatures as the EAC and the LC continue to strengthen. This will result in the decline of their populations and biomasses, as well as their functional roles in the ecosystem. However, tropical species are likely to expand their ranges and increase their overall biomass in certain areas of Australia's marine realm. Major readjustments could have significant economic and social costs to the commercial and/or recreational sectors of the fishing industry. There is already evidence in the decline of several commercially-important benthic and demersal fish species in response the climate-related changes. Projected climate changes such as warming, increase in the strength of EAC, and decrease in productivity are likely to decrease the overall abundance, biomass, productivity, and diversity of benthic and demersal fish species in Australian marine waters.

7.5.7 Modelling activities

There are two different efforts in biogeochemical (BGC) modelling, one looking at open ocean BGC modelling and the other focused on BGC at a coastal scale.

At an open ocean scale, a model that includes nitrate, phytoplankton, zooplankton and detritus components (NZP), plus the iron, oxygen and carbon cycles (Whole Ocean Model with Biogeochemistry and Trophic Dynamics, WOMBAT) has been developed and included in both ACCESS and BLUELink 3 models to enable the simulation of phytoplankton and carbon. The model is being developed for both climate variability and change simulations, and well as for data assimilation studies.

Coastal modelling capability is being developed by CSIRO in a platform termed the coastal Environmental Modelling Suite and consists of a set of component models that encompass:

1. The hydrodynamic model SHOC for predicting 3-dimensional advection, mixing and tracer transport in coastal systems;
2. The sediment model (MecoSED), which is a multilayered sediment model and represents the physical exchange of particulate and dissolved tracers between the water column and the bed. This model is particularly suitable for representing fine sediment dynamics, including resuspension and transport of biogeochemical particles;
3. A biogeochemical module, which provides a sophisticated representation of the cycling of carbon and nutrients through coupled pelagic-benthic ecosystems. This model has been coupled to a transport model to facilitate simulation of biogeochemical dynamics over fine-scale and computationally large model grids (Wild-Allen 2008). The ecological model water column is organised in 3 'zones': pelagic, epibenthic and sediment, and non-conservative biogeochemical processes are organized into pelagic processes of phytoplankton and zooplankton growth and mortality, detritus remineralisation and fluxes of dissolved oxygen, nitrogen and phosphorus; epibenthic processes of growth and mortality of macroalgae and seagrass, and sediment based processes of phytoplankton mortality, microphytobenthos growth, detrital remineralisation and fluxes of dissolved substances.

This EMS operation suite is being used in programs like eReefs, a coupled system for the GBR that spans hydrodynamics through to biogeochemistry (http://ftp.marine.csiro.au/pub/BGC%20model%20description/EMS.doc).

BGC data assimilation is being tested in eReefs and WOMBAT projects. However, at this stage data assimilation in BGC is used in hindcasts to test model errors and identify the best algorithms that can improve the models. The Bluelink 3 effort will use the data streams generated by IMOS to assimilate into the model and assess BGC model simulations. The data streams include, coastal BGC reference sites, argo drifters, ocean colour products, gliders and moorings. Similarly, multi decadal reanalysis products will be generated for ACCESS (Matear et al., 2012). Currently, remote sensing data such as water leaving radiance from MODIS are being used for data assimilation, and exploration of other data streams is underway to identify the observations required to constrain BGC models.

In ecosystem modelling there is a spectrum of approaches with varying levels of complexity and completeness. These include, single species and fisheries modelling, qualitative modelling and quantitative (end to end) ecosystem modelling.

Single species and fisheries models operated on species or individuals and included models of distribution and movement, demographic processes, habitat selection, behaviour and gene-flow and ecophysiology, among others. However, resource management is moving towards the use of Management Strategy Evaluation (MSE) simulations, which involves the assessment of management strategies consequences or options. In a MSE simulation, multiple candidate models are put forward to evaluate alternate hypotheses and it is done using quantitative or semi-quantitative simulations that contain sub-models for each of the main steps in the adaptive management cycle. At the core of these simulations is a "system state" model that represents the dynamics of the resource.

These "system state" models have been evolving from single species fisheries models (e.g. IWC 1992), or single species with habitat considerations (Mapstone et al., 2004) towards multispecies and more recently ecosystem based management models (http://www.cmar.csiro.au/research/mse/) Atlantis and InVitro are ecosystem based management models developed in CSIRO.

Atlantis is a deterministic biogeochemical whole of ecosystem model based on the MSE approach that considers all parts of marine ecosystems – biophysical, economic and social. The core of the model is a deterministic biophysical sub-model, coarsely spatially-resolved in three dimensions, tracking nutrient flows through the main biological groups in the system. The primary ecological processes modelled are consumption, production, waste production, migration, predation, recruitment, habitat dependency, and mortality, with trophic resolution at the functional group level. Invertebrates are represented as biomass pools, while vertebrates are represented using an explicit age-structured formulation. The physical environment is also represented explicitly, via a set of polygons matched to the major geographical and bioregional features of the simulated marine system, with biological model components replicated in each depth layer of each of these polygons and movement between the polygons by advective transfer or directed movement (http://www.cmar.csiro.au/research/mse/atlantis.htm). Data requirements for Atlantis include: abundance per age class per area, consumption rates, diets, individual growth rates, max age, age-at-maturity, habitat preferences, among others. The Atlantis model has been used in several regions of Australia, particularly in the temperate region, such as Southeast Australia, Westernport, Eastern Tasmania and New South Wales shelf, among others.

The InVitro model has aspects of both aggregate state (Silvert, 1981, Jørgensen, 1994) and individual based models. In the InVitro model, aggregate state models are treated as agents within the system, which in turn are seen as a subset of the set of all individual state models (Mcdonald et al., 2006). In this model system agents can operate at time and space scales appropriate to the nature of the processes in question, and within it there are submodels that reflect the bio-physical and anthropogenic activity in a coastal ecosystem, such as biophysical interactions, fishing, shipping, industrial/coastal development and contaminants. To date, this modelling framework has been used in the Northwest shelf of Australia (Gray et al., 2006, Little et al., 2006) and the Ningaloo region (http://www.cmar.csiro.au/research/mse/invitro.htm).

7.5.8 Spatial and temporal scales

Regional features support distinct ecosystems; such as the GBR, Ningaloo Reef, Bonny Upwelling and Perth Canyon. Observations are tuned to the spatial and temporal variability of drivers in those systems as well as the nature of the ecosystems they support.

Measuring spatial and temporal changes in productivity, distribution and abundance of species is vital for determining their response to climate change and how anthropogenic activities will impact on natural resources, biodiversity and ecosystem services (Figure 7. 24). In marine ecosystems, observing natural and anthropogenic change is more complex in the biological realm than in the physical or chemical realms, with some trophic levels more difficult to observe than others at the necessary spatial/temporal scales. Measuring all trophic levels at the same time over large areas is not feasible. This conundrum has led to the development of methods that provide sustainable observations at specific trophic levels that may then be considered individually or synergistically in ecosystem models.

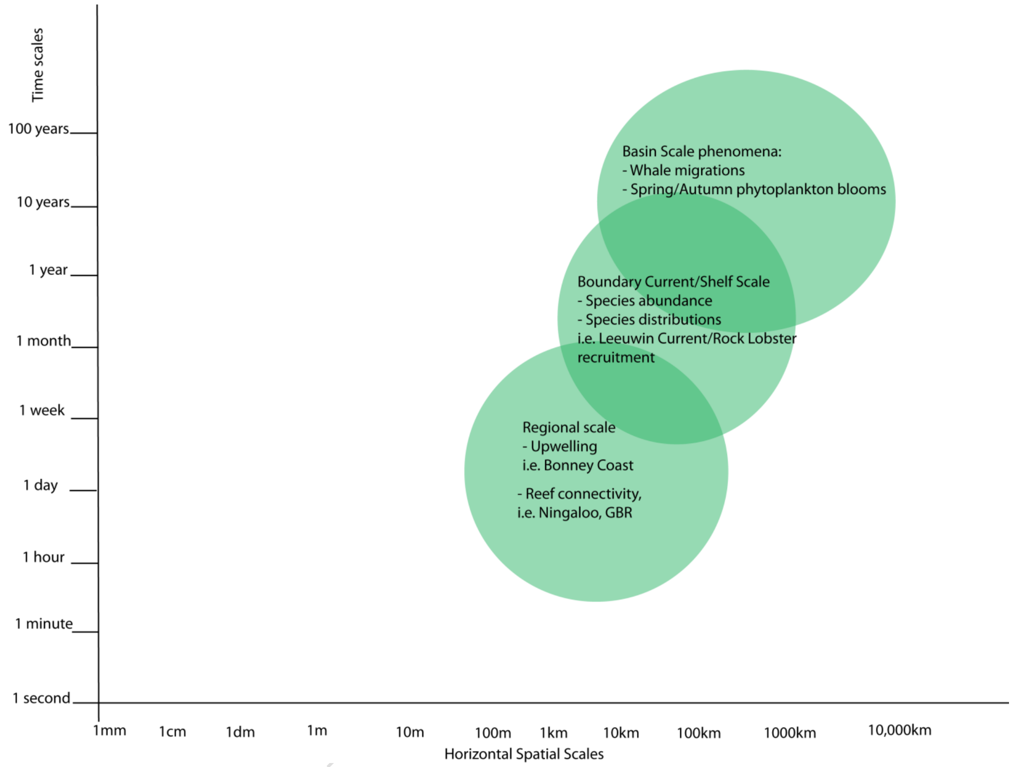

Figure 7.24: A Stommel diagram showing the scales at of key ecosystem processes

7.5.9 Science questions

The ecosystem science questions are formulated around using observations of carbon chemistry and nutrients, phytoplankton and zooplankton, nekton and benthic flora and fauna to understand ecosystem function and response to climate change. The high-level science questions that will guide the IMOS observing strategy in this area relate to:

Productivity:

- Productivity drivers (physical, chemical and biological) and mechanisms, variation and key productive regions (upwelling zones, fronts, canyons)
- Biological and physicochemical drivers of pH and carbon chemistry variation in the oceans, and risks of climate change in key ecosystems (coasts, coral reefs, shelves, SO)
- Effects of environmental forcing and climate change on food-web dynamics, trophic connectivity and biological communities
- Climate change effects on the structure and function (energy, water, nutrient cycling) of ecosystems
- Effects of climate change on ecosystem processes and species life cycles
- Relationship among biodiversity, structure, function, and stability of marine ecosystems
- Identification of vulnerable ecosystems and species (either particularly sensitive or unable to adapt) to changing environmental factors
- Identification of ecosystem health indicators

Distribution and Abundance:

- Distribution and abundance of organisms by species/trophic/functional group level, and variation in space and time

- Environmental and biological drivers of temporal and spatial variation in abundance and distribution of organisms (including animal migrations)
- Implications of climate change and extreme climate events on the status, distribution and abundance of marine communities
- Interconnection of marine populations

7.5.10 Variables required to address science questions

Australia has a large ocean territory that ranges from the tropics to the Antarctic, encompassing a diverse range of marine ecosystems. These ecosystems experience significant perturbations due to modes of climate variability such as ENSO, IOD and SAM, fluctuations in the dynamics of the boundary currents and climate change. Continental shelf processes also play a vital role in regulating the productivity, abundance, and distribution of marine ecosystems, both in the water column (pelagic) and on the sea floor (benthic). Ocean acidification and warming are also likely to impact the productivity of lower trophic levels, with consequences for fisheries and apex predators. To assess the variability and change in ecosystems it is important that we understand the drivers of productivity and all trophic level interactions if we are to predict and mitigate future change. To achieve that, an integrated approach is sought whereby measurements ranging from biogeochemistry through to higher trophic levels are undertaken to provide information of productivity, abundance and distributions at different space and time scales which encompass broad/basin-wide and bioregional scales, along shelf scales and regional-across shelf scales (Table 7.9).

Table 7.9: The variables required to address Ecosystem Responses science questions.

Variables	Temperature	Salinity	Oxygen	pCO2	pH	Total Inorg. Carbon	Alkalinity	Macronutrient concentration	Pigment concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass	Zooplankton Species	Zooplankton Biomass	Nekton Species	Nekton Biomass	Top Predators species	Top predators – population	Benthos (% coverage of species)	Detritus (flux))	Rates of primary production	Rates of secondary production
Circulation and nutrient fluxes	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Productivity	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Trophic connections			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Abundance and distribution	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

7.5.11 Platforms required to deliver observations

IMOS is observing ecosystem responses through an extensive national backbone comprised of Ships of Opportunity, a network of National Reference Station (NRS) Moorings, and national access to Satellite information, along with the IMOS national information infrastructure. More intensive, region-specific observations include a combination of Animal Tagging and Monitoring (acoustic arrays and satellite tagging), Autonomous Underwater Vehicles (AUV) undertaking benthic surveys, deep water and shelf Moorings (Southern Ocean Time Series, acidification moorings, noise loggers), Ocean Gliders, and Wireless Sensor Networks.

Ecosystem processes can arguably operate at a range of spatial and temporal scales that span large spatial and long temporal scales to small spatial and short temporal scales, thus observations need to be adjusted accordingly. At the basin-scale, systems chosen for integration are the Southern Ocean and Tasman Sea. Basin-scale monitoring is carried out from Ships of Opportunity (SOOP) taking pCO_2, Continuous Plankton Recorder (CPR) and bio-acoustics observations, deepwater moorings, animal tagging, and Satellite derived ocean colour. Regional observations are undertaken in regions with distinct features; such as Ningaloo and Great Barrier Reefs, and Bonny Coast Upwelling. The platforms used to collect the observations include SOOP, ocean gliders, AUV, national Mooring Network, animal tagging, Wireless Sensor Network and satellite derive ocean colour (Table 7.10).

Integration between the observing system and the relevant modelling frameworks is also important, though more challenging than with the physical modelling. IMOS has a strategy for engagement with various groups developing coastal, shelf and national scale biogeochemical, trophodynamic, and ecosystem models to further develop this relationship.

Table 7.10: How variables required to address the high-level Ecosystem Responses science questions at Basin Scales are delivered at required scales by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived; Green = could derive a relative estimate.

Ecosystem Responses		Temperature	Salinity	Oxygen	pCO2	pH	Total. Inorg. Carbon	Alkalinity	Macronutrient concentration	Chlorophyll a concentration	CDOM and backscatter	Total suspended solids	Microbial biomass	Phytoplankton species	Phytoplankton Biomass	Zooplankton Species	Zooplankton Biomass	Nekton Species	Nekton Biomass	Top Predators species	Top predators – population	Benthos (% coverage of species)	Detritus (flux)	Rate of primary productivity	Rate of secondary productivity
All scales																									
Argo		Blue	Blue	Blue																					
Ships of Opportunity (SOOP)	Biochemistry (pCO2)	Blue	Red		Blue																				
	Cont. Plankton Recorder									Green				Blue	Green	Blue	Green								
	Tropical RV/Temperate MV	Blue	Red							Red															
Moorings	National Reference Stations	Blue	Blue	Blue		Red	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue								
	Acidification Moorings	Blue	Red	Blue	Blue	Red																			
	Passive Acoustics																			Orange	Green				
	Temperature loggers	Blue		Blue	Blue																				
Animal Tagging	Biologging	Blue	Red																	Blue	Orange				
	Acoustic tagging																	Blue		Blue	Orange				
Remote Sensing	Ocean Colour									Red	Red				Red									Green	
Basin scale																									
SOOP	Bioacoustics																Orange		Orange						
Deep water Moorings	Southern Ocean Timeseries	Blue	Red	Blue	Blue	Red	Blue	Blue	Blue	Red	Red			Blue	Green	Blue	Green						Blue		
Boundary current/shelf and regional scales																									
Ocean gliders	Seagliders	Blue	Red	Blue						Red	Red														
	Slocum gliders	Blue	Red	Blue						Red	Red														
	Auto. Underwater Vehicle	Blue	Red							Red												Red			
	Wireless Sensor Network	Blue	Red																						

Notable gaps

- Primary production is not currently measured by IMOS observational programs, with data streams focussed on spatial and temporal variations in plankton biomass (net community productivity). Routine measurements of primary and secondary productivity via flourometry, stable/radioactive isotope, and biochemical studies, are necessary to address this knowledge gap.
- Another significant gap is lack of integration of data streams. For many scientific questions of interest, simultaneous measurements of a variety of physical, chemical and biological variables are needed. The logistical challenges in achieving this can be great. But IMOS should continue to push for the truly integrated data streams needed to assess ecosystem responses to environmental change.
- Spatial and temporal coverage and some of the more detailed species data at all levels. For example, satellite ocean colour data provide excellent spatial coverage of surface chlorophyll, but these data are difficult to translate into any meaningful information on phytoplankton species composition. The CPR on the other hand does provide species information – again mostly near surface – but the transects are still relatively sparse in space and time.
- Broad coverage of coupled data that document both carbon chemistry and how the distribution or abundance of calcifiers might be changing in important regions such as the Southern Ocean.
- Long-term sensitive indicators such as top predator demographic changes and population dynamics are significant gaps.
- Benthic observations in several regions to improve our understanding of these ecosystems
- Sustained observing for the higher trophic levels
- Insufficient data streams on the shelf north of 14o30'S or south of 23o30'S in Queensland and south eastern shelves and central-western GAB in SA and also in Bass Strait.

Future priorities:

- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.
- Assess the feasibility of obtaining routine coupled CPR and carbon chemistry transect data on platforms such as Aurora Australis.
- Collaborate with international partners to advance the deployment of bio-Argo floats, particularly in the Southern Ocean.
- Evaluate if ATAAMS acoustic receiver's existing locations suit the Nodes' needs to address science questions
- Evaluate new sensor technologies for pH, nutrients, and bio-optics that could be considered to be ready for piloting at broad scale, on Argo, SOOP, gliders etc.
- Maintain the SOTS observations and augment them with a high latitude mooring based on small profile CO2/acidification moorings or expand the SOOP BGC network to track biological and physical controls on the carbon cycle in the Southern Ocean.
- Given the importance of the bulk chlorophyll signal to shelf processes and ecosystem performance, the Ocean Colour product from satellite remote sensing needs comprehensive

ground 111ioinfor in shelf waters using platforms that can support these data collection such as slocum gliders and expanding current collection of bio-optical and biogeochemical data

- Increase deployment of gliders in QLD, NSW, WA and SEA
- Expand AUV coverage to visit more sites and at more frequent time intervals to increase our understanding of the spatial and temporal variability within benthic communities.

7.6 Summary

In order to monitor, predict and simulate ocean processes it is necessary to examine a range of phenomena at different temporal and spatial scales. The challenge is to identify the observations needed to define and study the interactions of forcing and processes at the appropriate spatio-temporal scales to understand the oceanic system.

In the case of IMOS, the spatial and temporal scales which govern key science questions determines the design of the observing system; i.e. what is the optimum combination of instruments and platforms that will provide observations on the appropriate scales to study the processes and phenomena of interest . The scales of processes and phenomena in the ocean naturally cascade in scale from large scale (Multidecadal Ocean Change) to meso- and small scale (Continental Shelf Processes), (Figure 7.25).

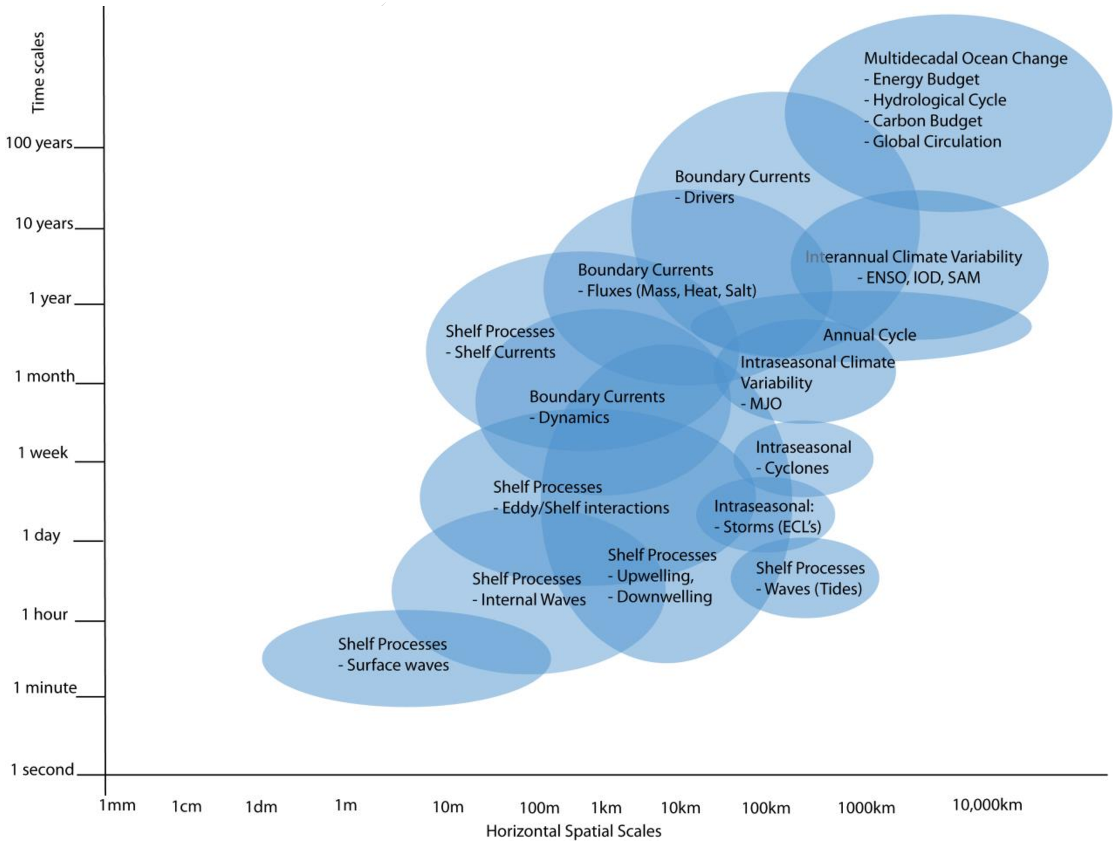

Figure 7.25: A Stommel Diagram showing spatial and temporal scales of physical key processes identified in IMOS Science Questions.

Applying this logic to biological systems is more challenging, as there is a need to observe nutrient concentration and distribution as well as the productivity, abundance, distribution and tropho-dynamics of all organisms at all spatio-temporal scales (see Fig. 7.24).

Capturing this range of scales from all five themes involves a diversity of data sets collected from ships, moorings, drifters, gliders, autonomous vehicles, and satellites. A summary of the variables (Table 7.11) required to address scientific questions and platforms required to deliver those observations (Table 7.12) on all five themes are included below. The similarity of variables required across each theme suggests that most of IMOS infrastructure and platforms can be used to address science questions at the different spatio-temporal scales (Fig. 7.26), which also includes specialised instrumentation to address more specific questions, such as productivity variability and ecosystem response questions.

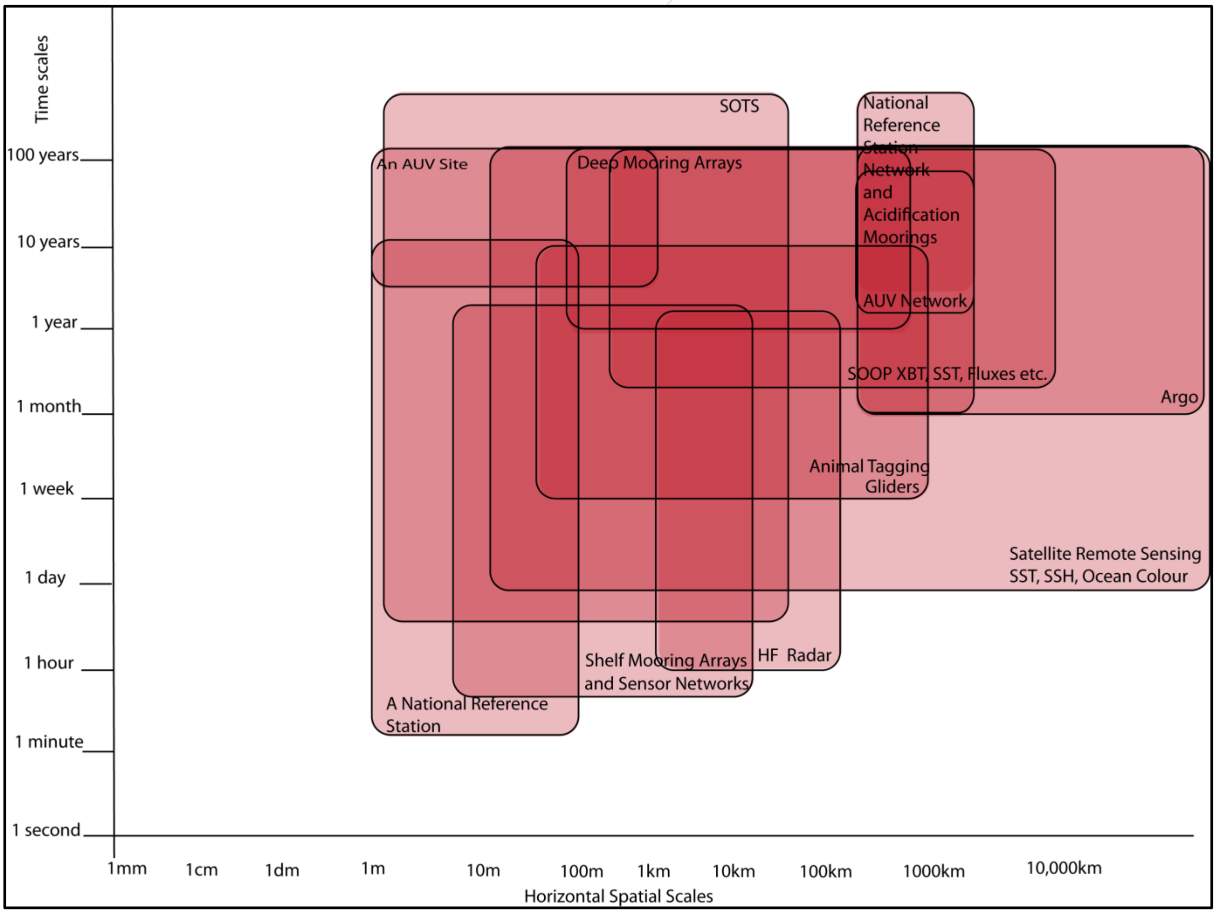

Figure 7.26: A Stommel diagram showing the spatial and temporal scales at which IMOS platforms are able to take observations.

Table 7.11: The variables required to address key science questions across IMOS.

Science themes	Variables	Temperature - Surface	Temperature – subsurface	Salinity	Velocity	Sea Surface Height	Surface waves – amplitude	Surface waves – spectrum	Internal waves	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total Inorg. Carbon	Alkalinity	Macronutrient concentration	Chlorophyll a concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass	Zooplankton Species	Zooplankton Biomass	Nekton Species	Nekton Biomass	Top Predators species	Top predators – population	Benthos (% coverage of species)	Detritus (flux)	Primary productivity
Multidecadal Ocean Change	Global Energy Balance	■	■	■	■	■				■	■																			
	Global Hydrological Cycle	■	■	■		■					■																			
	Carbon Budget	■	■	■	■					■	■	■	■	■	■	■	■	■	■	■	■								■	
	Global Circulation	■	■	■	■	■				■		■																		
Climate Variability and Weather	Inter-annual (ENSO, IOD)	■	■	■	■	■			■	■	■	■	■																	
	Intra-seasonal (MJO, Cyclones, ECL's)	■	■	■	■	■			■	■	■	■	■																	
Boundary Currents and Inter-basin Flows	Fluxes (Mass, Heat, Salt)	■	■	■	■	■			■	■																				
	Drivers	■	■	■	■	■			■	■																				
	Dynamics	■	■	■	■	■			■	■																				
Continental Shelf Processes	Eddy-Shelf interactions	■	■	■	■	■			■	■																				
	Upwelling/ Downwelling	■	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■									
	Shelf Currents	■	■	■	■	■			■	■																				
	Wave Processes				■	■	■	■	■	■																				
Ecosystem Responses	Circulation and nutrient fluxes	■	■	■								■	■	■	■	■	■	■	■	■	■	■	■							■
	Productivity	■	■	■								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Trophic connections											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Distribution and abundance	■	■	■								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 7.12: How variables required to IMOS science questions are delivered by IMOS facilities. Blue = directly measured variable; Red = derived variable; Orange = could be derived; Green = relative estimate.

How facilities deliver variables across IMOS		Temperature- surface	Temperature- Subsurface	Salinity	Velocity	Sea Surface Height	Surface waves – amplitude	Surface waves – spectrum	Waves – internal	Wind velocity (stress)	Air-sea fluxes	Oxygen	pCO2	pH	Total. Inorg. Carbon	Alkalinity	Total Suspended solids	Macronutrient concentration	Chlorophyll a concentration	CDOM and Backscatter.	Phytoplankton species	Phytoplankton Biomass	Zooplankton Species	Zooplankton Biomass	Nekton Species	Nekton Biomass	Top Predators species	Top predators – population	Benthos (% coverage of species)	Detritus (flux)	Primary Productivity
	Argo	Blue	Blue	Red	Orange	Orange						Blue																			
Ships of Opportunity (SOOP)	XBT	Blue	Blue																												
	Sea Surface Temperature	Blue																													
	Air-Sea Fluxes	Blue								Red	Red																				
	Biochemistry (pCO2)	Blue		Red									Blue																		
	Cont. Plankton Recorder																		Green		Blue	Green	Blue	Green							
	Bioacoustics																							Orange		Orange					
	Tropical RV/Temperate MV	Blue		Red															Red												
Deep water Moorings	Air-sea fluxes	Blue					Blue			Red	Red	Blue	Blue																		
	Deep water arrays		Blue	Blue	Blue				Orange																						
	Southern Ocean Timeseries		Blue	Red			Blue					Blue	Blue	Red	Blue	Blue		Blue	Red	Red	Blue	Green	Blue	Green						Blue	
Ocean Gliders	Seagliders	Blue	Blue	Red	Red				Orange			Blue							Red	Red											
	Slocum Gliders	Blue	Blue	Red	Red				Orange			Blue							Red	Red											
	Auto. Underwater Vehicle		Blue	Red															Red										Red		
Moorings	National Reference Stations	Blue	Blue	Blue	Blue		Blue			Orange	Red	Blue		Red	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue							
	Shelf Arrays		Blue	Red	Blue		Blue	Red	Orange			Blue																			
	Acidification Moorings	Blue		Red								Blue	Blue	Red																	

	Passive Acoustics																														
Ocean Radar	WERA																														
	CODAR																														
Animal Tagging	Acoustic Tagging																										?				
	Biologging																										?				
	Wireless Sensor Networks																														
Satellite Remote Sensing	Sea Surface Temperature																														
	Sea Surface Height																														
	Ocean Colour																														
	Non- IMOS Observations																														
	Repeat Hydrography																														
	Tide Gauges																														
	Wave buoys																														

8 Assessing the readiness of observing system components

Considering the timescales of ocean variability, IMOS needs to be sustained for decades to deliver the information required. Technologies and methods used need to routinely deliver consistent information on these timescales, while new approaches need to be tested and review before they can be brought into the sustained observing system. The Framework for Ocean Observations identifies a pathway by which new observing technologies can be brought into the long-term observing system according to their "readiness level" (Figure 7.1).

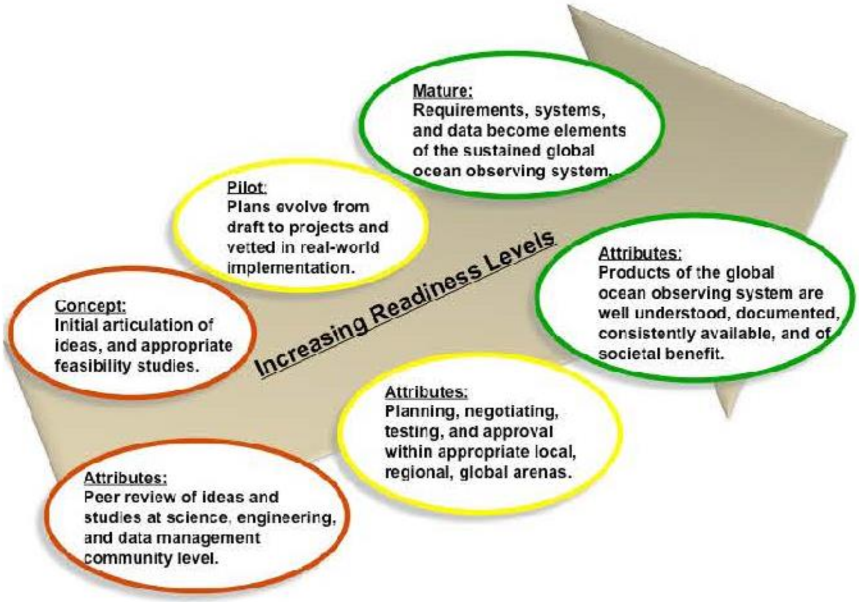

Figure 8.1: The Concept of Readiness Levels. How ocean observing activities will be assessed for inclusion in the Framework for Ocean Observing. The scale and scope of activities at each readiness level will vary according to the needs of a particular EOV (Unesco, 2012).

With IMOS's strong focus on national community level science planning, this readiness concept can be adapted to incorporate:

- The scientific and technical maturity of the observing system components, i.e. whether the science and hence observation requirements are well understood or whether there is a conceptual model of a system that requires validation.
- The technical maturity of observing technologies that range from well established, such as Argo floats and many Ships of Opportunity components, to new technologies where deployment plans needs refining such as Gliders.

Plotted against each other, these categories provide four quadrants; three of which are appropriate space for IMOS to invest in (Figure 8.2).

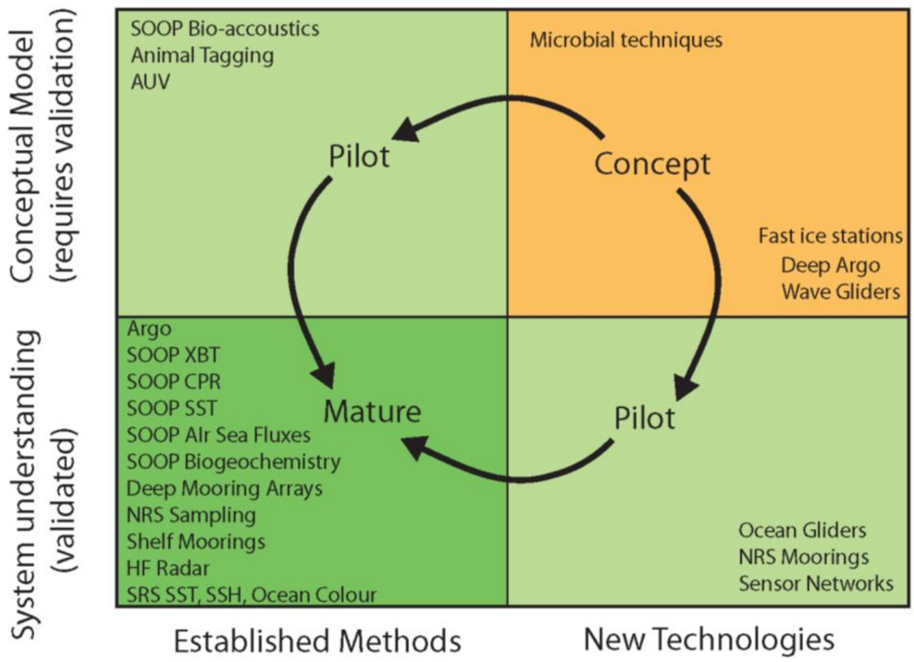

Figure 8.2: Assessing the "readiness" of observations to be brought into the IMOS system.

As a sustained *in situ* observing system, IMOS needs to invest in proven technologies. The range of potential observations available to address the science questions and their delivery at the scales required is therefore quite well known. However, as a national scale observing system it is appropriate for IMOS to take a 'portfolio' approach to its strategy; building on established global strengths but also pushing the boundaries in terms of integration from open-ocean to coastal and from physics to biology.

Accordingly, some elements of IMOS will be very mature and have an established role in the global ocean observing system, while other elements will be new to global observing systems exploring new regions or using new technologies.

8.1.1 Mature

Mature components of the observing system are those where there is good understanding of the system trying to be measured including the variables and scales of observations required. There is also knowledge on how to measure it using mature technology that has been tested and tried in observing systems.

Many of the data streams from IMOS that are of most importance to the science goals of the Nodes come from mature components and are the foundation of global ocean observing systems. These include Argo, ship of opportunity programs, deep and shelf moorings, biologging, radar and satellite measurements of surface temperature, surface height and ocean colour.

For very mature components of the observing system, it will be important to consider the potential for operationalising them, such as Argo, a technology that is mature enough for consideration. The operationalization of technology will need to be discussed with agencies such as the Bureau of Meteorology and develop a framework that could enable transition of observational data streams from the research environment to the operational environment, where justified.

It is noted that there are observing system components already in used which are considered mature, but are not part of IMOS; such as:

- Repeat Hydrography (implemented through the Marine National Facility and collaboration with international Partners)
- Surface Drifters (deployed by the Bureau of Meteorology)
- Tide gauges (funded by the Bureau of Meteorology and State Governments)

8.1.2 Pilot – System understanding, new technology

This component of the observing system is where there is understanding of the system, as well as the spatial and temporal scales of variability and variables required to measure the system. However, new technologies are used to take measurements and needs refinement in the context of sustained observing systems. These technologies include ocean gliders, wireless sensor networks and enhanced sensor suites to measure bio-optics, oxygen, pH and nitrate for Argo floats.

In the case of Gliders, observations need to transition from discovery (where we are seeing features at a resolution not delivered before now) to sustained mode, where we can deduce changes and variability in the system using the data in the context of other regional observations.

Wireless sensor networks, installed around the four island research stations on the Great Barrier Reef, have demonstrated their reliability as a way of obtaining real-time observations. The challenge for this technology is expansion to ocean variables beyond temperature, which can be collected at much lower cost albeit in delayed mode using loggers.

Based on current momentum, it seems inevitable that within the next 5-10 years there will be a large coordinated effort to deploy Argo floats with biochemical sensors in the Southern Ocean. Australian scientists could contribute to such a program by deploying floats and providing initial *in situ* validation data.

8.1.3 Pilot – Conceptual model of system, mature technology

This component of the observing system is where there is only a conceptual idea of how a system works, but the methods for taking measurements are well established. For example a number of tested mature technologies for observing sea ice and ice – ocean interaction already exist such as ice-tethered profilers, ice-capable profiling floats and ice mass balance buoys. However, they remain "pilot" component for IMOS in the sense that their role in a sustained observing system for Antarctic sea ice has not yet been articulated as a comprehensive strategy for IMOS observations in the sea ice zone.

Another example is observations being made at key trophic levels (e.g. SOOP bio-acoustics, passive acoustic arrays and animal tagging) or particular ecosystems (AUV deployed in deep regions) which will be used to improve system understanding and hence feed back into refining the suite of observations and design of the observing system.

A near-term goal for IMOS will be to aim for better integration of existing data streams to facilitate study of the coupled system (i.e. simultaneous, coincident measurements of physical, chemical and biological parameters are needed) and articulate a comprehensive strategy to expand sustain observing in regions with little information such as the Antarctic sea ice zone.

8.1.4 Concept

Concept components are new technology and methods that require further field testing and/or demonstrated application to science requirements before being brought into the sustained observing system.

Many of new technologies of relevance to IMOS are presently transitioning from Concept to Pilot stage. These include deep Argo floats capable of sampling the full ocean depth. A pilot experiment, with involvement of IMOS personnel, will be carried out off New Zealand to test the capability of several deep Argo designs, with the intention of Deep Argo becoming a standard tool of the global ocean observing system in a few years.

Monitoring of microbial indicators using metagenomic approaches are being tested with samples collected at the East Coast NRS. It is expected that microbial monitoring will expand to all NRS stations in the coming year. However, to be a useful tool for sustained observations, further technological developments are needed for sample collection and analysis, requiring both the molecular and the 119ioinformatics components of the analysis to become cheaper and more automated.

While the use of marine animals as platforms for oceanographic observations is well established, the use of sea turtles as platforms for acoustic receiver/transmitters that could provide data on their own movements and also those of other tagged animals could be a new concept to collect data.

Technology to transfer data from moored sensors in a cost effective manner, such as acoustic downloads to passing ships or data pods that surface periodically to transmit data is in development. This technological advance will be advantageous to Australia given the size and remoteness of most of its marine territory.

9 Facilities implementation plan

The design of the observing system is based around the concept of whole of system approach and the ability to maximise the benefit of each of the individual measurements. The IMOS infrastructure is operated by different institutions within the national Innovation Systems. Each facility is funded to deploy equipment and deliver data streams for use by the entire Australian marine and climate science community and its international collaborators.

To give the observing system a national context and provide the means to integrate sparse ocean in situ measurements across Australia's ocean region, IMOS facilities are interconnected by a 'national backbone' which includes the Australian Ocean Data Network (AODN), the Satellite Remote Sensing Facility, and a network of moored National Reference Stations. More intensive observations are then focused on continental shelf and coastal processes observations and regions of socio-economic and ecological significance.

The following sections look at how, where and when the observational resources are to be deployed and maintained for each of the five coastal node and the open ocean node. Also given are the primary, secondary and modelling products produced by each facility and the uses and limitations of technology.

9.1 The National Backbone

9.1.1 Australian Ocean Data Network (AODN)

The AODN is the key element of IMOS strategy enabling IMOS data and other Australian research and operational ocean data to become discoverable, accessible, usable and reusable for the benefit of the nation as a whole.

Marine data and information are the main products of IMOS, and data management is therefore a central element to the project's success. All IMOS facilities deliver the observations and associated metadata to the AODN which, through controlled workflow processes, conducts assessment and archival, and provides infrastructure for the discovery of and access to the data by the research community and the public. The AODN works with the Facilities to make all IMOS observations easily discoverable, accessible and usable. Inherent in this goal is the aim to provide consistency in data quality, formats, metadata, and interoperability with other programs and data sources. In addition, the AODN is an interoperable, online network of marine and coastal data resources that connects the major marine data holdings of Australia and serves them to support Australia's science, education, environmental management and policy needs.

IMOS supports the AODN through partnerships with the Australian Federal, State and Territory Government agencies, Universities, and private sector companies. The main objectives of the AODN are:

- to populate the AODN with publicly funded data and to make this accessible to as wide a community as possible;
- to encourage, and develop, the culture of data sharing across the marine science community of Australia

The AODN provides a single integrative framework for data and information management to allow discovery and access of the data. It specifically provides:

- The standards, protocols and systems to integrate the data and related information into a number of conformal frameworks, and provides the tools to access and utilise the data.
- Data products as web services and web features for processing, integration and visualisation for some of the data.
- The ability to integrate data from sources outside IMOS into IMOS data products, and to export IMOS data to international programs.

Feedback from the user community led the AODN facility to re-design the look and feel of the portal, with the intention to make it easier to search for, display and download data. All metadata and non-gridded IMOS data will be input to a database to enable the faceted search to be fully exploited, including gridded components.

Nature of IMOS Infrastructure

The AODN is based at the University of Tasmania, located in Hobart, Tasmania. AODN staff co-ordinate the handling of IMOS data and organise its storage, accessibility, discoverability and means of visualisation. Among the activities that this facility undertakes are hardening the infrastructure, improve discovery and access to data, map-based filtering of data for viewing and download, develop a controlled vocabulary service, improve data citation including Digital Object Identifier (DOI) usage and improving access to data through extensions to the Matlab Toolbox and a user code library. The AODN's Ocean Data Portal includes data from six Commonwealth Agencies with responsibilities in the Australian marine jurisdiction (AAD, AIMS, BOM, CSIRO, GA and RAN).

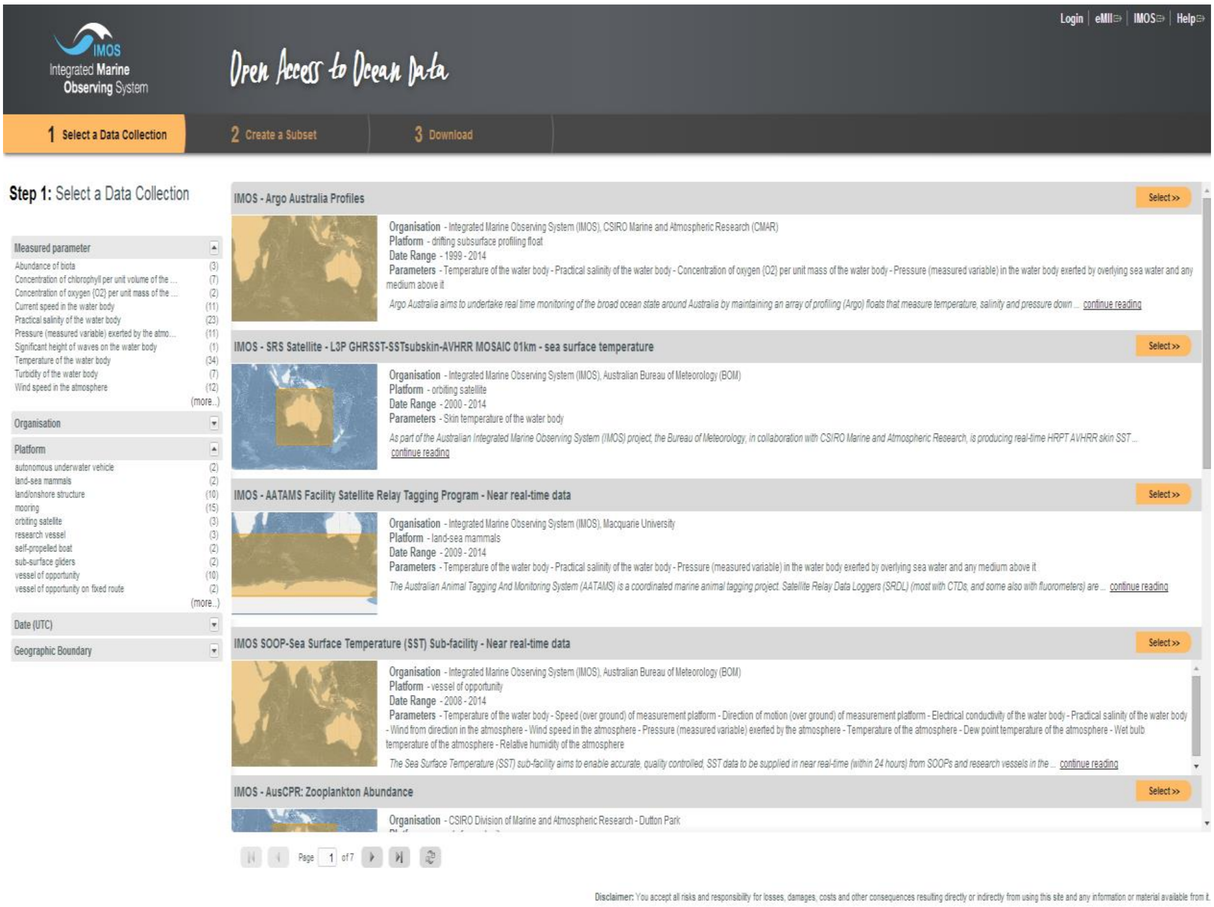

Fig. 9.1. IMOS Ocean Portal launched on February 2014

Primary products

The delivery of data streams through the IMOS ocean portal http://imos.aodn.org.au/imos123/

Secondary products

Go Go Duck middleware system which provides advanced capabilities to query, subset and download remote sensing and other gridded data sets. The system is deployed by AODN as part of the Ocean Data Portal to provide user access to gridded data sets.

Modelling application

In collaboration with the University of Tasmania, CSIRO, UNSW, SARDI, AIMS, UWA, BoM and NCI the MARine Virtual Laboratory (MARVL) has been developed, with the aim to provide necessary tools to construct a virtual environment of a region of interest. MARVL comprises a suite of complex models (e.g. ocean circulation, waves, water quality, and marine biogeochemistry), a network of

observing sensors, and a host of value-adding tools that can underpin research to understand the dynamics, interactions, and connectivity of an estuarine/coastal region, continental shelf region, or open ocean domain.
The MARVL infrastructure created and developed though a NeCTAR project will be used to explore scenarios, and demonstrate how a Virtual Laboratory can enable underpinning science in support of marine management in a specific regional context.

Future priorities identified by the nodes for this facility:

- IMOS and AODN to look into developing workflows that ensure we can deliver 'model ready' data on an ongoing basis

9.1.2 Satellite Remote Sensing

Three key satellite data-streams are the focus of IMOS investment. Australia does not have satellites, but we contribute data to aid in the calibration and validation of satellite data in the Australian region, and products are also developed from raw satellite data.

9.1.2.1 Sea Surface Temperature (SST)

Satellite sea surface temperature (SST) helps identify different bodies of water (or water masses) and their distribution associated with ocean currents. The sea surface temperature (along with wind speed) also dictates the nature of the interaction between the ocean and atmosphere, and hence the feedback of changes in ocean currents and heat content on our climate. This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes

Satellites measure SST by measuring either the infra-red, or microwave radiation emitted from the ocean surface. Satellite SST product development is part of the international Group for High Resolution Sea Surface Temperature (GHRSST) international program, which is working towards the development of high quality multi-platform products with consistent error flagging. The Australian Bureau of Meteorology (BoM) produces 1 km resolution sea surface temperature (SST) products in real time from data from the Advanced Very High Resolution Radiometer (AVHRR) sensors on board NOAA polar orbiter platforms received at the Bureau's satellite reception facilities. As part of the IMOS the BoM upgraded its SST processing system to comply with the GHRSST (Fig. 9.2). The significant components include the use of regional rather than global buoy SSTs for satellite SST calibration, noise resistant methods of SST coefficient estimation, the development of a match-up database (MDB), calculation of single sensor error statistics (SSES), an improvement in cloud identification, an analysis of quality level in terms of km rather than pixels, stitching of overlapping raw AVHRR data from several ground stations and the generation and distribution of SST products in GHRSST L2P and L3C formats.

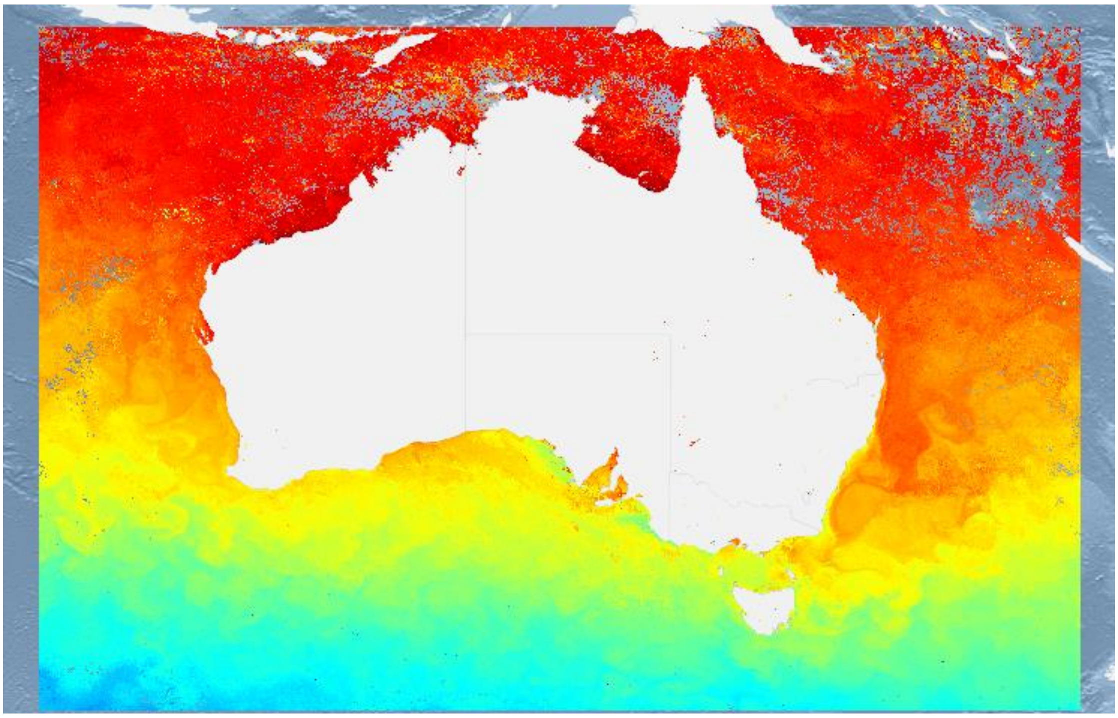

Figure 9.2: Sea Surface Temperature L3P GHRSST-SSTsubskin-AVHRR MOSAIC 01km.

Nature of IMOS Infrastructure

IMOS support for system improvements, data processing, data management and validation of the existing IMOS satellite sea surface temperature (SST) single swath ("L2P") and composite ("L3U", "L3C" and "L3S") products derived from Advanced Very High Resolution Radiometer (AVHRR) sensors on NOAA polar-orbiting satellites. Web-based validation of IMOS satellite SST products also use drifting buoys and IMOS *in situ* SST data from SOOP and Argo floats (see sections below).

Primary products:

High-resolution (1 km x 1 km) satellite sea surface temperature (SST) products over the Australian region produced by the BoM designed to suit a range of operational and research applications.

Secondary products:

- IMOS OceanCurrent
- Operational SST analyses (RAMSSA, GAMSSA)
- Short-term and seasonal weather prediction systems and the GHRSST Multi-Product Ensemble
- ReefTemp NextGen coral bleaching prediction system

Modelling application:

Satellite sea surface temperature is a core dataset for assimilation into ocean state estimates and for initialisation of seasonal and ocean forecasts such as those described below:

- Operational numerical weather prediction (BoM), with IMOS data used as the boundary condition for all operational numerical weather prediction models at the Bureau

- Seasonal Prediction (BoM), with IMOS data feeding into GAMSSA to initialise the Bureau's seasonal prediction model, POAMA-2.
- GHRSST Tropical Warm Pool Diurnal Variability (TWP+) Project using IMOS data to quantify diurnal warming of the surface ocean and validate SST diurnal variation models over the Tropical Warm Pool
- GHRSST Multi-Product Ensemble Project uses IMOS data through GAMSSA to produce a daily near real-time global 0.1 degree resolution SST analysis as a median of 10 global SST analyses (http://ghrsst-pp.metoffice.com/pages/latest_analysis/sst_monitor/daily/ens/index.html)

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.

Uses	Limitations
- Systematic global measurements of sea surface temperature every ~10 days. - Can be used to identify currents, fonts and meso-scale ocean features - Data assimilated into models for weather and ocean prediction - SST defines the nature of the interaction between the ocean and the atmosphere	- Cloud contamination is a problem; especially in the Southern Ocean. - Satellites can't see below the sea surface. Or below sea ice

9.1.2.2 Sea Surface Height (SSH)

Altimetry sensors measure the height of the surface of the ocean. The sea surface height (SSH) signal is made up of the underlying topography of the oceans and as such has become the tool of choice for scientists to measure sea level rise at regional and global scales as well as for giving information about ocean currents and large and small-scale variability. The determination of changes in global mean sea level is of fundamental importance in understanding the response of the ocean to a continuing warming climate, both through thermal expansion of the ocean, melting of the major ice sheets of Greenland and Antarctica, and mountain glaciers, and redistribution of water over the continents and atmosphere. As with all scientific observations calibration and validation are an important component and IMOS provides the sole southern hemisphere ***in situ*** calibration site with ongoing calibration and validation data streaming directly to the international (NASA and CNES sponsored) Ocean Surface Topography Science Team (OSTST). This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes

Figure 9.3: The IMOS satellite altimetry calibration/validation sites at Bass Strait and Storm Bay.

Nature of IMOS Infrastructure

The Australian calibration site includes two comparison points, Bass Strait and Storm Bay (Fig. 9.3), where *in situ* data is compared against the altimeter. These two locations lie on descending (N -> S) pass 088 of the satellite altimeter, and thus share similar satellite orbit characteristics. The use of these two sites allows detailed investigation into the accuracy of the altimeter over two different wave climates. The average significant wave height at Storm Bay is approximately double that observed at the comparatively sheltered Bass Strait location.

Primary products:

Two data streams are generated, the "absolute bias" stream and the "bias drift" data stream, which are feed directly to the international (NASA and CNES sponsored) Ocean Surface Topography Science Team (OSTST).

Secondary products:

- Production and improvement of the Gridded Sea Level Anomaly (GSLA) data set, which access data from at least two ocean-optimised altimeters
- OceanCurrent website where altimetry data, along with many other forms of IMOS data, are shown in graphical form for immediate interpretation by a wide range of users.

Modelling applications:

Satellite SSH is a core data-stream for assimilation into ocean state estimates and for initialisation of seasonal and ocean forecasts such as Bluelink project.

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.
- Additional sites for altimeter calibration at Lorne (VIC) and Darwin (NT) to be considered, or reconfiguration of existing sites to facilitate calibration of new missions (e.g. ESA Sentinel-3).

Uses	Limitations
- Provide accurate, systematic estimates of Sea Surface Height - Provide information on mesoscale ocean dynamics - Constrain most ocean state estimates and initialise ocean forecasting systems - Provides a tool to measure sea level rise and detect changes due to ocean warming	- Surface only estimates - Not accurate in coastal regions.

9.1.2.3 Ocean Colour

Satellite observation and quantification of ocean colour can provide estimates of phytoplankton concentration due to the fact that the colour in the visible light region, (wavelengths of 400-700 nm) varies with the concentration of chlorophyll and other plant pigments present in the water in most of the world's oceans. Therefore, ocean colour can be used to estimate the spatial variability of phytoplankton biomass (ocean colour) and activity (primary production) in the surface ocean. However, ***in situ*** bio-optical datasets are needed to calibrate and validate ocean colour sensors to increase the reliability and precision of satellite measurements for applications such as water quality monitoring. This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change
- Continental shelf and coastal processes
- Ecosystem responses

IMOS collects measurements of ocean colour for calibration and validation in a number of ways including coastal observatories of water radiance and in water optical properties, vessel mounted spectro radiometers. It also created a bio-optical database to consolidate historical bio-optical measurements made around Australia.

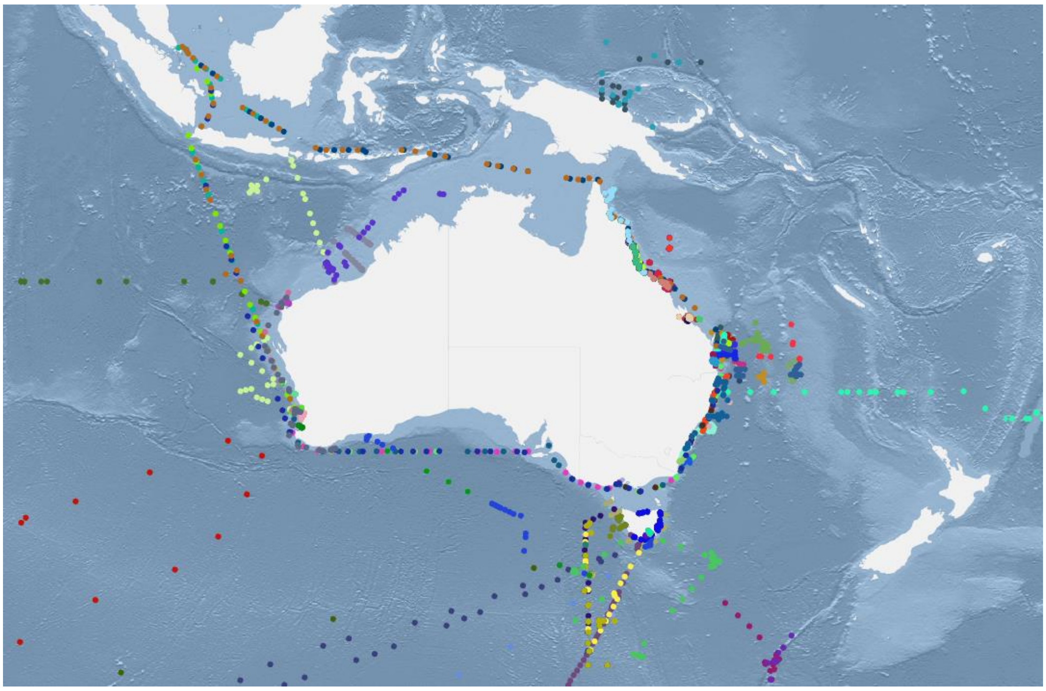

Figure 9.4. The Bio-optlcal database to date in the IMOS Portal.

Nature of IMOS Infrastructure

The Lucinda Jetty Coastal Observatory which collects two different data streams: above water measurements of the water radiance and in water measurements of the optical properties. The observatory aims to become the preeminent source of measurements for the validation of coastal-ocean colour radiometric products applied to biogeochemistry and climate studies in Australia.

Spectro-radiometers installed on board three research vessels (RVs Southern Surveyor, Solander and Investigator) to enhance the continental coverage of the radiometry dataset.

Bio-Optical Data Base (Fig. 9.4), which bring together bio-optical data from the research community to enhance its holdings. This data base contributes to NASA and ESA and used by the international community for calibration and validation of ocean colour sensors.

Primary products

Match-up database of bio-geochemical and bio-optical data. Lucinda Jetty measures in situ bio-optical data in real time and delayed mode. Radiometers collect quality controlled delayed mode bio-optical and skin SST data along ship tracks. The Bio-Optical DataBase delivers data in delayed mode and it is served via the IMOS portal. All radiometry data after calibration is uploaded within 2 weeks of each voyage, while quality controlled radiometry data (ready for satellite matchup analysis) is uploaded within 4/6 weeks of each voyage.

Secondary products

Regionally validated ocean colour products of gridded satellite data

MODIS ocean colour products at daily temporal resolution and at 1x1 km spatial resolution

MODIS Chlorophyll products for use in the OceanCurrent website and other projects

Experimental phytoplankton functional type (PFT) products derived from the MODIS data sets, which are being used to test PFT algorithms globally by the IOCCG and for Australian ecological modelling activities.

Modelling applications

Ocean colour data (reflectance) is being assimilated into biogeochemical models such as WOMBAT and other ecological models such as eReefs.

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.

Uses	Limitations
- Qualitatively shows spatial variability in primary production in the ocean. - Provide global, systematic, repeat measurements of photosynthetic pigments providing a broad-level indication of phytoplankton composition. - Skin SST from radiometers used for cal/val of satellite SST.	- Data in open ocean waters require calibration with in situ measurements. - The accurate characterisation of coastal waters is still a major research activity. - Ocean colour is not an estimate of primary productivity

9.1.3 National Mooring Network (ANMN)

The National Mooring network measures physical and biological parameters of Australian coastal waters, and consists of a number of components;

- A network of National Reference Stations (NRS)
- regional arrays of shelf moorings
- CO_2 moorings and passive acoustic observatories.

9.1.3.1 National Reference Stations (NRS)

Long-term observations are critical for defining key components of climate change and associated responses of ocean ecosystems. Within the Australian marine system, geographically comprehensive long-term monitoring programs are challenging given the large size of the Nation’s ocean territory and extensive continental coastline. To address a general lack of sustained ocean observations essential for documenting long term time-series against which more spatially replicated short term studies can be referenced, IMOS in collaboration with marine institutional partners developed a network of National Reference Stations.

Currently seven NRS are in operation around the continent, building on three long-term locations (Maria Island, TAS; Rottnest Island, WA; Port Hacking, NSW), where monthly water sampling for physical and biological parameters have been in operation since the 1940's. All seven sites fully instrumented with *in situ* moored ocean sensors (Fig. 9.2) and include an enhanced monthly sampling regime for nutrients, microbes (from 2012), phytoplankton, small zooplankton and environmental factors. This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes
- Ecosystem responses

This co-ordinated network of sites is unique for a coastal monitoring system deployed at a continental scale. A rationale, design and implementation plan developed for the NRS Network to provide a sound scientific foundation and operational basis for long term investment in the NRS network can be found at http://imos.org.au/fileadmin/user_upload/shared/ANMN/NRS_rationale_and_implementation_100811.pdf.

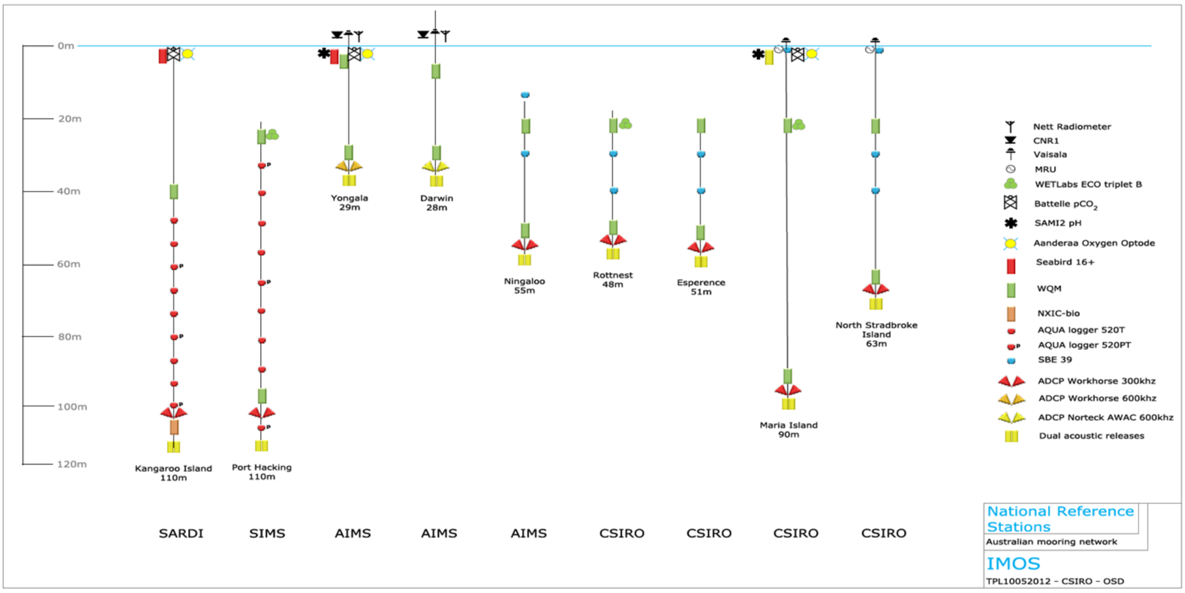

Figure 9.2: Current NRS instrumented array schematic

Nature of IMOS Infrastructure

- NRS that will continue operations are located at Maria Island (TAS), Port Hacking (NSW), North Stradbroke Island and Yongala (QLD), Darwin (NT), Rottenest Island (WA), and Kangaroo Island, (SA). Ningaloo and Esperance (WA) stations will cease to operate this year (Fig. 9.3).

- Near real time and quality controlled delayed mode data is collected from Maria and North Stradbroke Islands, Darwin and Yongala stations.
- Quality controlled delayed mode data is collected at Port Hacking, Ningaloo, Rottnest, Esperance and Kangaroo stations.

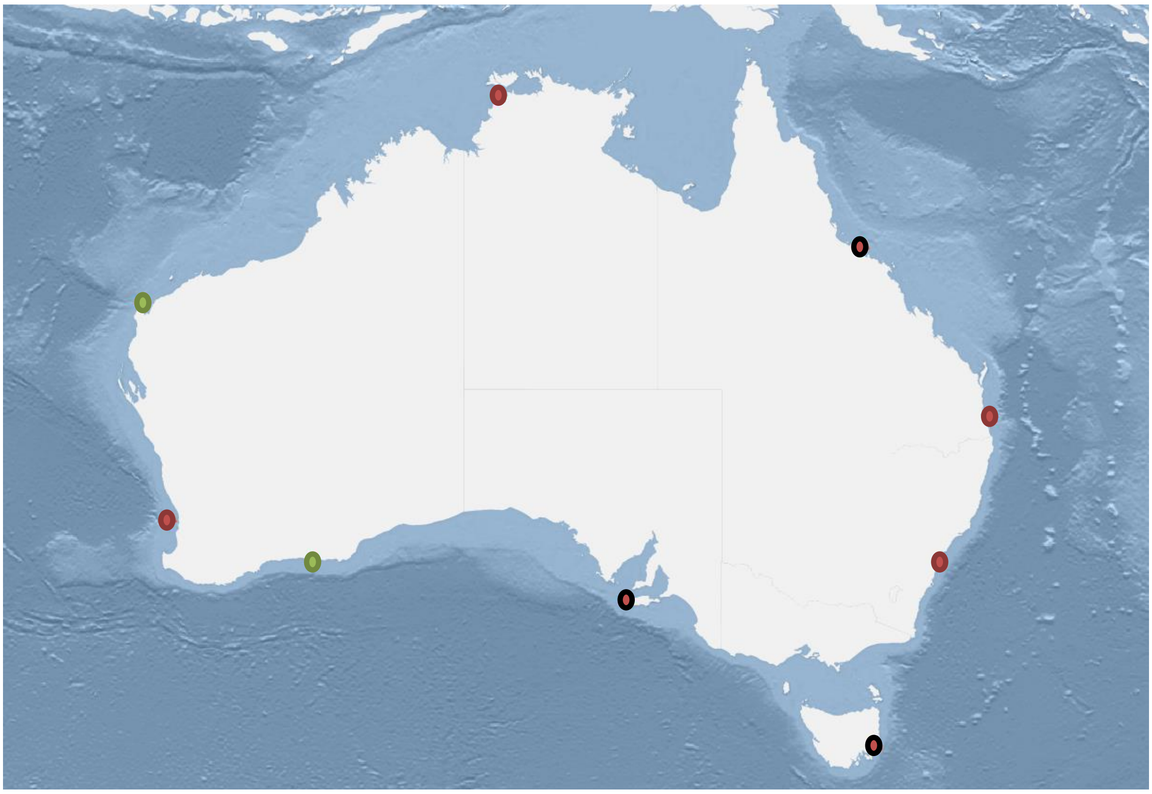

Figure 9.3: NRS stations currently operating (red circles), NRS stations that include CO_2 moorings (red with black outline) and NRS stations to be decommissioned (green circles). Note: the Yongala CO_2 mooring has been relocated to Heron Island in 2015.

Primary products:

In total 58 data streams are delivered by the NRS and include temperature, salinity, dissolved oxygen, nutrients, turbidity, carbon, biological parameters for both phytoplankton and zooplankton and an optical proxy for chlorophyll a. Near real time parameters from the stations include all those delivered by the water quality monitor (WQM) sensors as well meteorological data from the Visalia WXT520 weather station. Additional near real time data include sea surface temperature and for NRS MAI and NSI significant wave height.

Secondary products:

All the data collected at the NRS sites intends to provide integration of long-term time-series observations to more spatially-distributed and intensive shorter-term studies, a coastal information infrastructure through development of national data standards and calibration and validation of coastal remote sensing.

At a regional scale provides focal points within regional Nodes for integrating with observations of other IMOS ‘coastal ocean’ facilities, modelling of coastal processes and linking coastal processes with offshore processes.

***Modelling applications**:*

Sensor and sampling data are used to validate coastal and biogeochemical models.

Future priorities identified by the nodes for this facility:

- Re-assess the footprints analysis of National Reference Stations and shelf moorings using higher resolution model
- Evaluate the value and use of near real time data form coastal moorings and based on needs consider transitioning or transferring real time data acquisition where is more needed
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.
- Consider measurements of rates of primary and secondary productivity via fluorometry, stable/radioactive isotope such as triple oxygen isotope method, or biochemical studies.
- Maria Island NRS. The Maria Island NRS is one of the longest time series of ocean temperature, and is placed in a hotspot for warming. Its record must continue

Uses	Limitations
- Consistent long term monitoring at representative sites gives insights into broad scale low frequency variability in the context of climate change. - Some sites are representative of changes and variability in boundary currents. - Broad suite of measurements allows relationships between physical changes, nutrients and ecosystem responses to be identified.	- Monthly sampling may not be fit for all purposes i.e. monitoring nutrient enrichment from periodic upwelling. - Expensive to maintain - Telemetry only at four sites - Require regular servicing

9.1.3.2 Regional Mooring Arrays

Shelf moorings (Figure 9.4) are deployed in a wide range of configurations (cross shelf arrays, mooring pairs and single moorings), and are designed to characterise and monitor regional processes on the continental shelf. In some places, shelf moorings are linked to deep water transport arrays. This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change

- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes
- Ecosystem responses

Parameters measured include oceanographic data, i.e. WQM and current velocity from ADCPs, with some moorings collecting biogeochemical data as well.

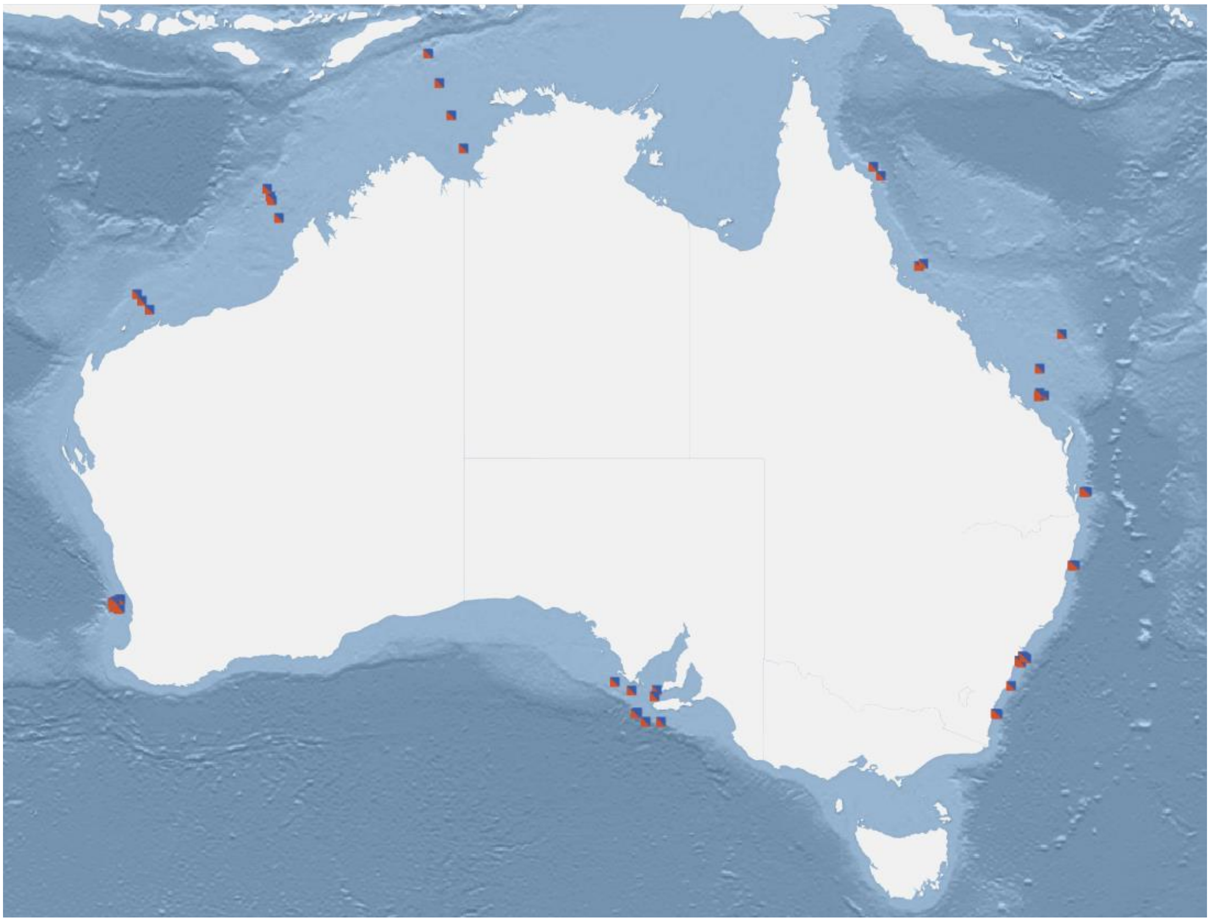

Figure 9.4: Location of the shelf arrays around Australia

Nature of IMOS Infrastructure

Shelf arrays are maintained at:

- Two Rocks, Perth Canyon, Indonesia Throughflow, Kimberley and Pilbara (WA);
- GBR (north , central, south) (QLD);
- Beagle Gulf (NT);
- Sydney, Coffs Harbour and Bateman's Bay;
- Spencer Gulf and Coffin Bay and mid slope and deep slope moorings (SA).
  Moorings at Batemans Bay, Lizard Shelf, Slope and Elusive Reef, Kimberly and Pilbara will be discontinued this year.

Primary products:

Temperature, conductivity, fluorescence and current velocity data on all locations, above water weather parameters including air temperature, humidity, barometric pressure, wind speed and direction where available and chlorophyll, turbidity, dissolved oxygen and waves data also available at some sites. Delayed mode data are delivered to eMII to be placed onto the data portal. Real-time data are also available from some regional moorings, as well as cruise based biogeochemical and CTD data from SA.

Modelling applications*:* Shelf mooring arrays provide the backbone validation data for regional/coastal models; i.e. eReefs on the GBR, and SAROM in South Australia. Through the BP project in the GAB, extensive hydrodynamic models will be developed for that region and will be validated against SAIMOS and IMOS data.

Future priorities identified by the nodes for this facility:

- Evaluate costing of mooring array along 200 m isobath from the Kimberley to north-west Australia to monitor the thermal structure of the upper ocean on interannual and decadal time scales
- Maintain and enhance the IMOS infrastructure that is presently in place to increase spatial and temporal coverage, if it can be done efficiently and economically. Maintaining the SOFS air-sea flux mooring is particularly important
- Maintain a footprint in the Kimberley coastal region;
- It is highly desirable to extend the Two Rocks transect to cover the full width of the Leeuwin Current, i.e. extend the Two Rocks mooring transect both into deep water, and to the nearshore region.
- Engage in ongoing discussions to establish observing strategies and monitoring frameworks that can assess whether a more adequate shelf/coastal observing system can be implemented through partnership.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)
- Re-assess the footprints analysis of National Reference Stations and shelf moorings using higher resolution model
- Evaluate the value and use of near real time data form coastal moorings and based on needs consider transitioning or transferring real time data acquisition where is more needed
- Redesign the EAC mooring and consider the inclusion of the SEQ shelf moorings at the expense of one of the slope moorings as there may be some redundancy in this part of the array
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.
- Consider measurements of rates of primary and secondary productivity via fluorometry, stable/radioactive isotope such as triple oxygen isotope method, or biochemical studies.

Uses	Limitations
- Continuous time series of variables at regional scale that allows validation for	- Sparse spatial coverage - Difficult to identify optimal locations of

coastal remote sensing - Arrays of shelf moorings linked to deep water transport arrays allow the influence of offshore processes on the shelf to be identified.	single moorings. - High cost - Require regular (3-6 month) servicing which can be difficult for remote regions.

9.1.3.3 CO_2 Moorings

CO_2 moorings (Figure 9.4) are collocated at some NRS sites to collect the full suite of parameters needed to characterise the concentration of CO_2 in the water and provide key observations to help us understand and address the problem of increasing ocean acidification. This sub-facility delivers observations relevant to the following major research themes:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes
- Ecosystem responses

These are the only IMOS high-frequency shelf moorings for the measurement of CO_2 parameters and complement the 1-2 monthly coverage from the Ships Of Opportunity Program (SOOP) BGC measurements. The sites contribute to national and international research priorities, delivering to international data bases and UNFCCC core variable measurements, the new international Global Ocean Acidification Observing Network, and they also help meet priority measurement requirements identified in the Australia's National Framework Climate Change Science plan. The combined moorings and SOOP vastly improve temporal and spatial coverage in Australia.

Nature of IMOS Infrastructure

- CO_2 moorings were located originally at the Maria Island (temperate), Yongala (tropical/GBR) and Kangaroo Island (upwelling) NRS sites. The Yongala mooring was discontinued after cyclone damage and was moved to Heron Island on the Great Barrier Reef. The Kangaroo and Maria Island moorings remain in place. Each mooring is equipped with surface CO_2 systems, using proven and robust technology. Three sensors determine surface CO_2, temperature, salinity and oxygen. In addition, the hydrochemistry sampling at the NRS also provide total alkalinity data, while future pH sensors on the moorings will allow for a complete determination of the carbonate system and pH.

Primary products: Data is available to eMII in near real-time and delayed mode data are submitted within six months of sensor recovery and download of the complete data set stored on the sensors.

Secondary products: Time series of calcite/aragonite saturation depths. Reanalyses products such as the Surface Ocean Carbon Atlas (SOCAT) version updates in 2014+ Carbon Dioxide Information Analysis Center Ocean CO_2 data.

***Modelling Applications*:** pCO_2 data can be used to tune reef-scale model runs and will be used to tune the eReefs model.

Future priorities identified by the nodes for this facility:

- Expand pCO2 network, including CO2 measurements at high latitude where overturning circulation and global CO2 outgassing changes are under debate. Measurements at low latitude are also needed.
- Expand CO2 network on national reference station to ensure ocean acidification progress is quantified for representative coastal habitats. SOOP BGC could be an alternative.

Uses	**Limitations**
- Accurate estimates of temporal variability of CO_2 concentrations in the ocean	- Restricted to point measurements

9.1.3.4 Passive Acoustic Moorings

The Acoustic Observatories sub-facility has deployed 3 arrays of acoustic listening stations (Fig. 9.5) that passively record sounds from the ocean. The stations provide baseline data on ambient oceanic noise, detection of fish and mammal vocalizations linked to ocean productivity, monitoring of multiple species of whales and detection of underwater events. This sub-facility delivers observations relevant to the following major research themes:

- Ecosystem responses

Examples of information available on physical sea noise sources includes: seasonal and climate driven inter-annual changes in rainfall over large ocean areas; calculating the size and propagation speed of seafloor ruptures due to earthquakes; deriving long term trends in seismic activity in subsea fault zones; or monitoring Antarctic ice calving. It is the only system with publicly available data in world

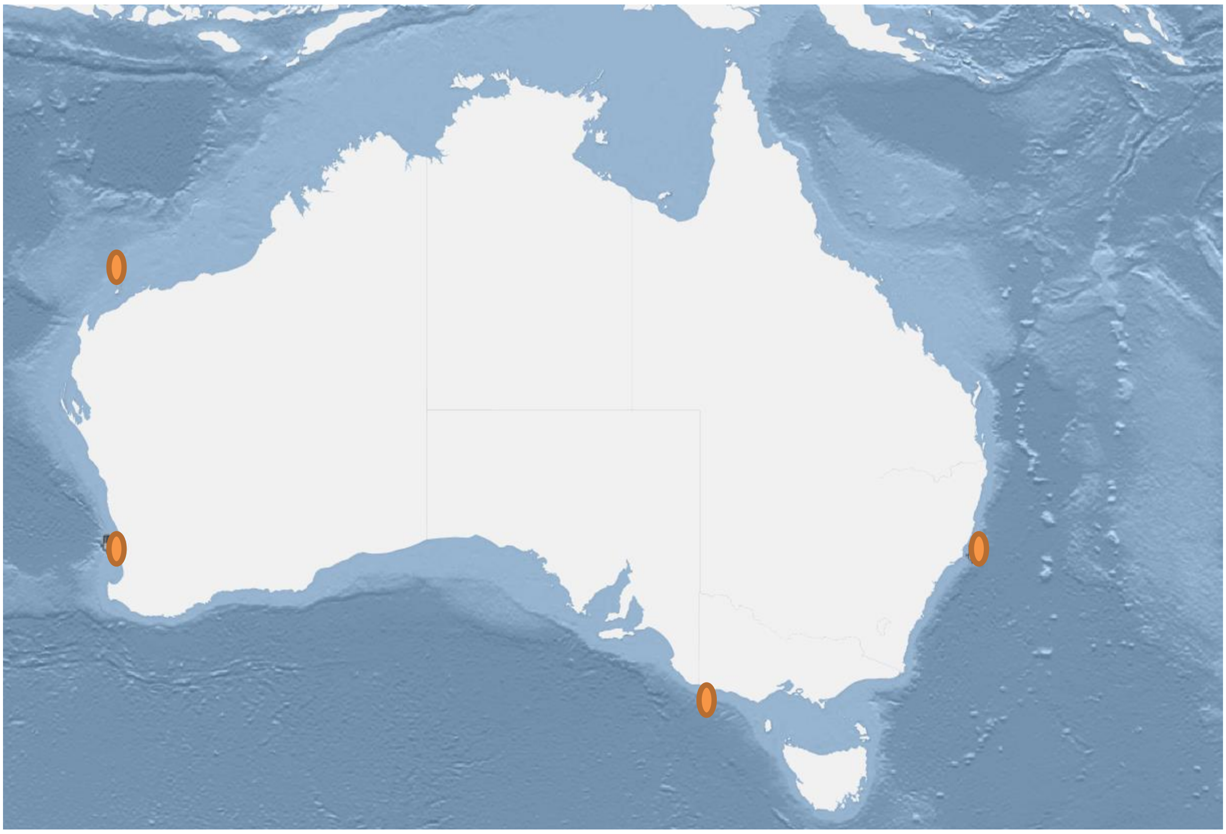

Figure 9.5. Passive Acoustic Observatories on the Ocean Portal.

Nature of IMOS Infrastructure

Arrays are located in Perth Canyon (WA), Portland (VIC) and Forster/Tuncurry (NSW). These sites have been chosen for their biological interests. Perth Canyon is a focal feeding area for pygmy blue whales *Balaenoptera musculus brevicauda*, with the station operating since 2000. This array is also closely matched to the moorings being deployed in the canyon by the Western Australian sub-facility, allowing for multidisciplinary correlations between the acoustic data and the oceanographic physical and chemical data. In addition, there are two passive acoustic observatories in the Pilbara/Kimberley co-invested by WA Government, with emphasis on analysis and use of data from WA, SA/Victoria and NSW.

***Primary products**:* Delayed mode raw acoustic records from all listening stations and QC data delivered within 6 months of collection.

Secondary products: IMOS Acoustic Data Viewer, which enables visualisation and downloading of raw data.

Modelling applications: Additional distribution and abundance estimates for use in ecological models.

Uses	**Limitations**

- Acoustic data contains a broad range of useful information, which is difficult to get from other sources.	- Large amounts of data which is difficult to store/distribute/analyse - Significant amount of post-processing required to get scientifically useful indices.

9.2 Open Ocean Facilities

9.2.1 Argo

Argo floats are autonomous profiling floats which drift around the ocean delivering high quality temperature and salinity data in real time and delayed mode, down to 2000m. The Australian Argo program contributes to a global array of ~ 3600 floats (Figure 9.5). Australia is a key player in the southern hemisphere observing effort, and the second largest partner in the global Argo program. The Argo program has been deploying floats since 1999. It is the first worldwide in situ ocean observation network that produces data in near real time. The primary goal of the Argo program is to maintain a global array of autonomous profiling floats integrated with other elements of the climate observing system.

The specific aims are to:

- detect climate variability over seasonal to decadal time-scales including changes in the large-scale distribution of temperature and salinity and in the transport of these properties by large-scale ocean circulation.
- provide information needed for the calibration of satellite measurements.
- deliver data for the initialisation and constraint of climate models.

Recent developments in Argo floats include ice capable floats (either programmed with ice avoiding algorithms, or ruggedized antennae to withstand ice), the development of bio-optical sensors for measuring dissolved oxygen, and most recently Deep Argo floats operating to depths of 3500m. Other developments in sensor technology that have not been incorporated into the core Argo mission include; Bio-Argo, which can measure bio-optical and bio-geochemical properties and Carbon Explorers, which measure particulate organic and inorganic carbon to a depth of 2000m.

This facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Ecosystem responses

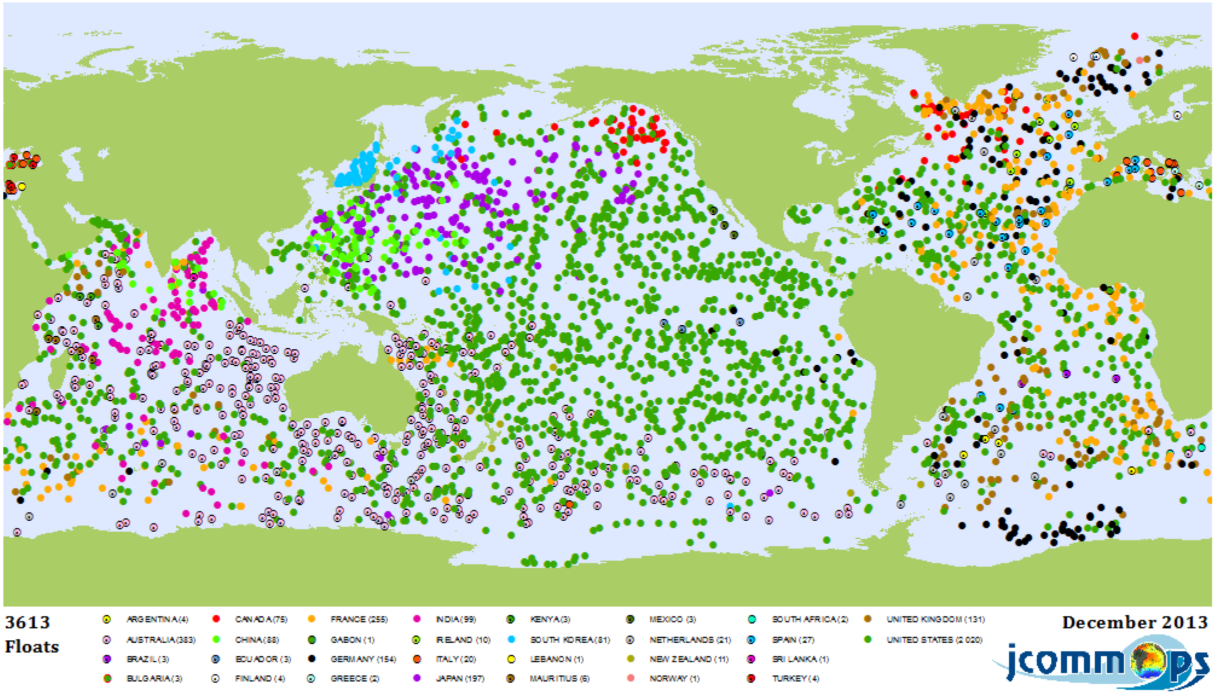

Figure 9.5: Argo float deployed globally with Australia contributing 383 floats (pink circles)

Nature of IMOS Infrastructure

- An active array of around 383 profiling Argo floats in the oceans around Australia, contributing to an international array of > 3600 active floats A total of 95 floats will be purchased, tested and prepared for deployment in collaboration with CSIRO, BoM and ACE CRC within the next 2 years and 40 floats acquired previously will be deployed, particularly in the South Pacific Ocean.
- Assistance to international Argo partners in deployments in remote regions of the south Indian, Pacific and Southern Oceans.
- Priority area for coverage is 90°E -180°E, equator to southern winter sea ice edge. Secondary priority is some deployments (5-10 per year) in the seasonal ice zone.

Primary products

Over 9000 (750) ocean profiles per month delivered globally (Argo Australia) of temperature (Fig. 9.6), salinity and pressure to near 2000m depth, distributed in real time (< 24 hours) and delayed mode (< 1 year). Oxygen data is also collected from approximately 45 active floats.

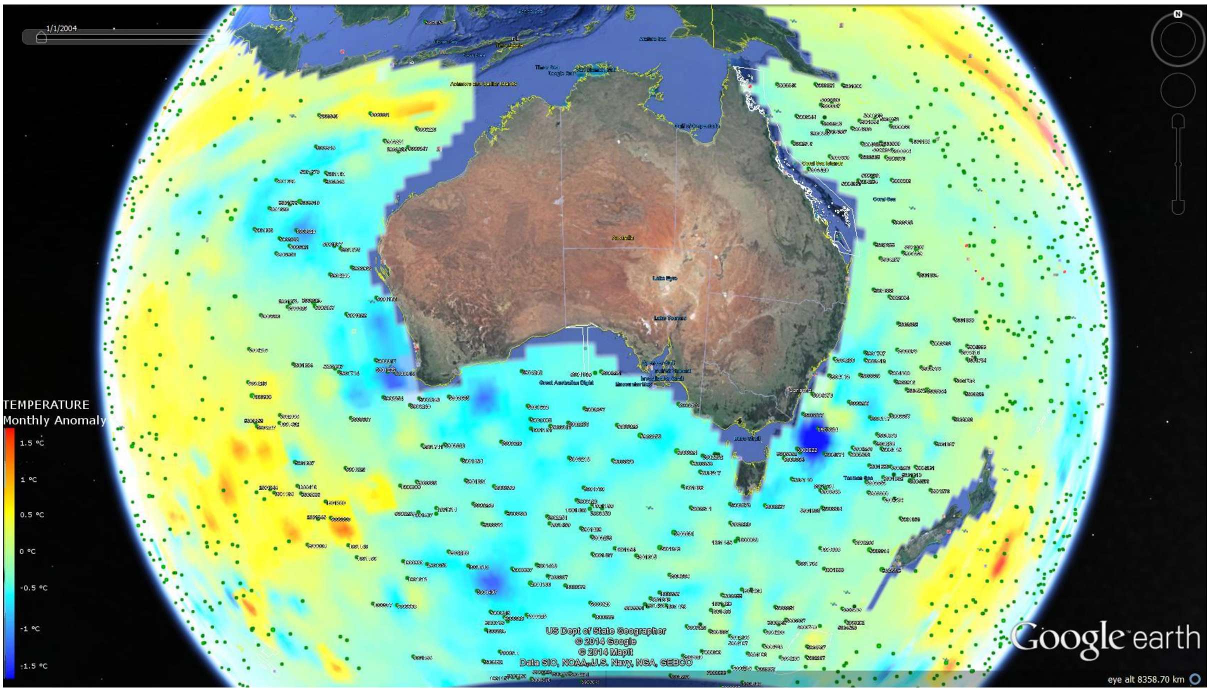

Figure 9.6: Active Argo floats deployed around Australia showing monthly temperature anomaly at 2.5m (Data from http://wo.jcommops.org/cgi-bin/WebObjects/Argo.woa/1/wo/2tlGuKw97gg1X1bDyJPUb0/9.0.30.19.1.5)

Modelling applications

The Argo array provides a global dataset of broad-scale subsurface temperature and salinity in near real time and delayed mode. Near real-time Argo data are a core dataset for seasonal and ocean forecast initial conditions. Delayed-mode Argo data are assimilated into ocean state estimate models such as BlueLink, and are used to validate the distribution of temperature and salinity with depth in the oceans. All ocean reanalyses ingest Argo profile data – the 14 systems comprising OceanView GODAE can be found at https://www.godae-oceanview.org/science/ocean-forecasting-systems/. The CSIRO has completed a new 10km ocean reanalysis around Australia (BRAN3) which will be available in mid-2013.

Future priorities identified by the nodes for this facility:

- Investigate and evaluate the use of Deep Argo to determine changes in heat and freshwater content throughout the full ocean depth and Ice capable Argo to observe the sea ice zone
- Evaluate the oxygen enabled Argo pilot program and expand coverage in the Coral Sea or use gliders if not possible to use Argo
- Evaluate new sensor technologies for pH, nutrients, and bio-optics that could be considered to be ready for piloting at broad scale, on Argo, SOOP, gliders etc.
- Support offshore observations such as Argo floats and XBTs, in order to understand both remote and local large scale climatic drivers of extreme climatic events
- Collaborate with international partners to advance the deployment of bio-Argo floats, particularly in the Southern Ocean.
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived

from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.

Uses	Limitations
- Global broad-scale coverage of temperature salinity and pressure data down to 2000m. Some floats include oxygen data as well - Delivered in real time, - High quality (robust instrumentation, rigorous QA/QC)	- Does not cover deep ocean (below 2000m) - Not suitable for shallow shelf areas. - Does not resolve mesoscale processes such as eddies. - Limited ability to deliver observations in the sea ice zone. - Limited ability to deliver observations in BGC variables.

9.2.2 Ships of Opportunity

Ships Of Opportunity Program (SOOP) is an international effort that implements a network of cargo, ferries and research vessels to deploy scientific instruments that collect ocean observations and Australia is one of the largest contributor to this program. Due to the high cost of chartered research vessels, the use of volunteer merchant vessels as oceanographic platforms while underway is an important and cost-effective way to collect observations. These vessels are fitted with a variety of sampling instruments that collect data along fixed, pre-established transects, such as the shipping routes undertaken by merchant vessels or ferries.

The IMOS SOOP program uses ferries, tankers, and supply ships on repeating lines and those that have a broad coverage such as fishing and research vessels.

9.2.2.1 Expendable Bathythermographs (XBT's)

Expendable Bathythermograph (XBTs) is a probe that is dropped from a ship to measure temperature from the sea surface to 850m as it falls through the water. Data is transmitted to the vessel by a thin wire where it is recorded for later analysis. XBTs provide a quick and inexpensive means of collecting temperature data at pre-established transects that are repeated at least 4 times a year. Data from XBT observations are focused on, but not limited to:

a) variability of surface, subsurface, currents and undercurrents,
b) meridional heat transport,
c) thermal temporal variability along fixed transects

The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows

There are currently several sections sampled around Australia, which are generally high resolution (eddy resolving) and/or frequently repeated (monthly occupied) transects (Figure 9.7). On average 25,000 XBTs are deployed each year by the XBT global program, with some time series that are approximately 30 years in some. Australia's XBT operations started in 1983.

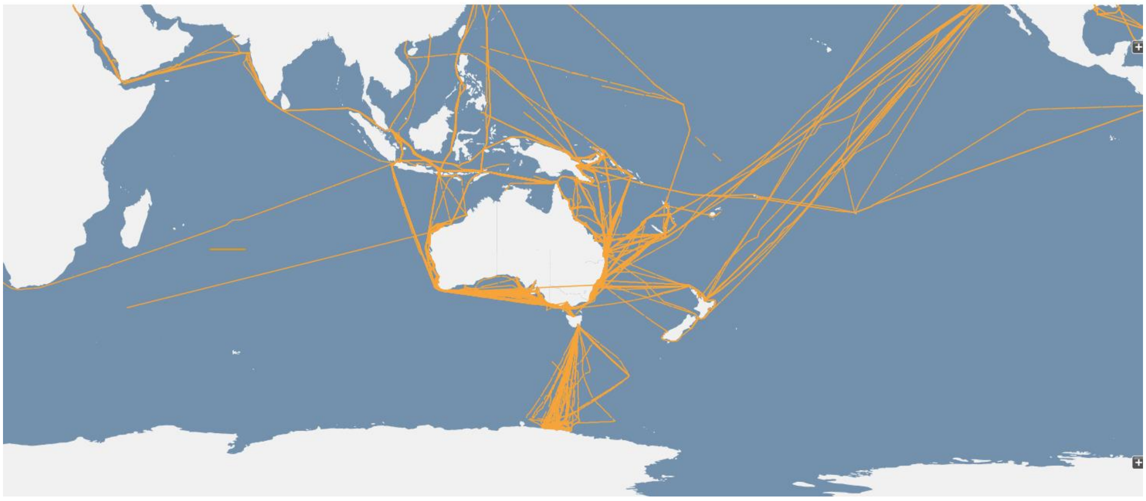

Figure 9.7: SOOP XBT sections available in the Ocean Portal.

Nature of IMOS Infrastructure

- Repeat and sustained collection of frequently repeated or high density temperature sections along shipping lanes, including:
  - Undertake 8 'high density' XBT sections per year on each line: Brisbane to Fiji and Sydney to Wellington
  - Undertake 2 'high density' XBT sections from Fiji to New Zealand and South Africa to Perth 4 times a year (co-investment with Scripps)
  - Undertake 12 'high density' XBT sections from Hobart – Dumont d'Urville
  - Australia to South Africa – assist in operations by Scripps Institution of Oceanography
  - Bi-weekly sections from Perth to Singapore and monthly from Singapore east across the Banda Sea (co-investment with BoM)

Primary Products

High quality, scientifically QC'd upper ocean temperature data collected along high resolution sections bounding the Tasman Sea and crossing the Southern Ocean to Antarctica.

High resolution sections bounding the Tasman Sea and Southern Indian Ocean collected under co-investment by Scripps.

Secondary products

XBT lines surrounding Australia cut across critical currents and provide data important to our understanding of climate variability and change in our region.

Ocean transport time-series to track major regional boundary current changes, used to document and track decadal changes in the Tasman Sea

Modelling applications

Near real-time XBT data are a core dataset for seasonal and ocean forecast initial conditions. Delayed-mode XBT data are assimilated into ocean state estimates, and are used to validate heat fluxes (both net basin and boundary currents) in ESM's. XBT data contributes in real-time (via GTS) to several operational ocean assimilation systems including 'OCEANMAPS' and global ocean climatologies (including CARS).

Future priorities identified by the nodes for this facility:

- Support offshore observations such as Argo floats and XBTs, in order to understand both remote and local large scale climatic drivers of extreme climatic events
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)

Uses	**Limitations**
- Eddy resolving - Supplement other platforms to assess the upper ocean heat content. - Subsurface data (down to 850m) - Repeat observations along same lines. - 20 year timeseries already exists on many lines.	- Confined to main shipping routes (hence less coverage in the southern hemisphere) - Measures temperature only - Depth estimate has errors (based on fall rate) - Changes in shipping schedules or routes disrupt the time series

9.2.2.2 Ocean Surface C02 (or Biogeochemical (BGC))

Biogeochemical sensors are used to collect high quality partial pressure of CO_2 (pCO_2) and fugacity of carbon dioxide (fCO_2) measured in surface seawaters. Observations in pCO_2 in the atmosphere and ocean surface are used to infer the flux of CO_2 across the air-sea interface. pCO_2 is measured from platforms that are wither on a repeat transect (e.g. the Antarctic resupply vessels- L'Astrolabe) or from research vessels operating in Australian waters (Figure 9.8). The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows

- Continental shelf and coastal processes
- Ecosystem responses

Data collected are used to track the size and variability of the ocean carbon sink in Australian regional seas and the Southern Ocean, and to determine the extent and controls on ocean acidification that results from the ocean uptake of CO_2. The data contribute to international efforts and databases used to track the ocean carbon sink, providing information in the Australian region that would not otherwise be covered. They are also helping to address the need for measurement of essential climate variables (surface CO2) identified by the UNFCCC and in the Australian Government National Framework Climate Change Science Plan.

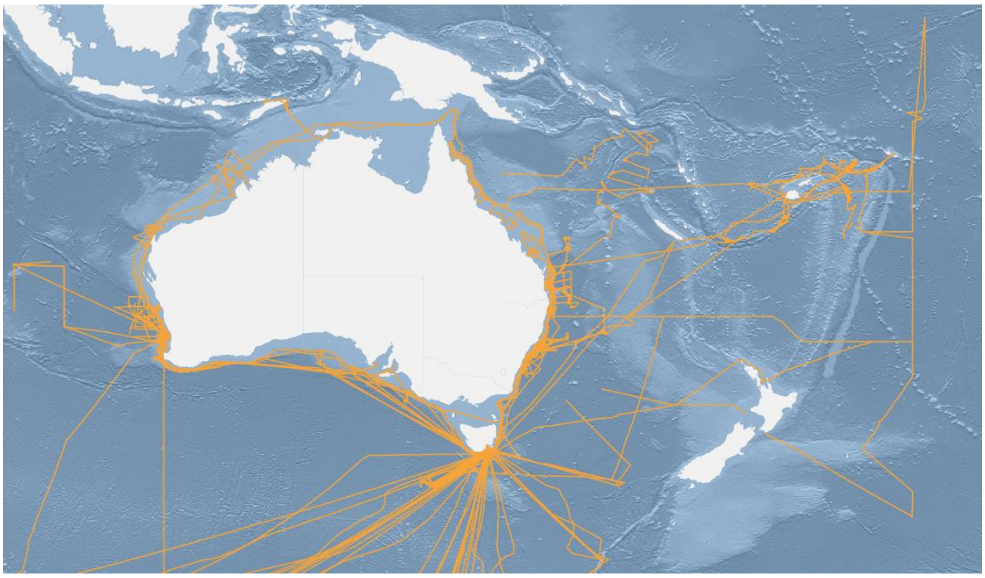

Figure 9.8: SOOP CO_2 data available in the Ocean Portal.

Nature of IMOS Infrastructure

Surface underway biogeochemical instrumentation on ships of opportunity to measure ocean CO_2 and related parameters. The Aurora Australis provides valuable data on surface ocean CO_2 for the Southern Ocean, while the Southern Surveyor and its replacement RV Investigator, cover shelf and offshore waters around Australia. Data are delivered in near real-time (daily) with final quality controlled data delivered within six months of cruise completion, provided ancillary ship's data are available.

Primary products

Data on surface CO_2 measurements (time, position, pCO2, temperature, salinity) are delivered in near real-time when Aurora Australis and Southern Surveyor/Investigator are operating. Final quality controlled data is submitted within six months of completion of voyages or wherever possible.

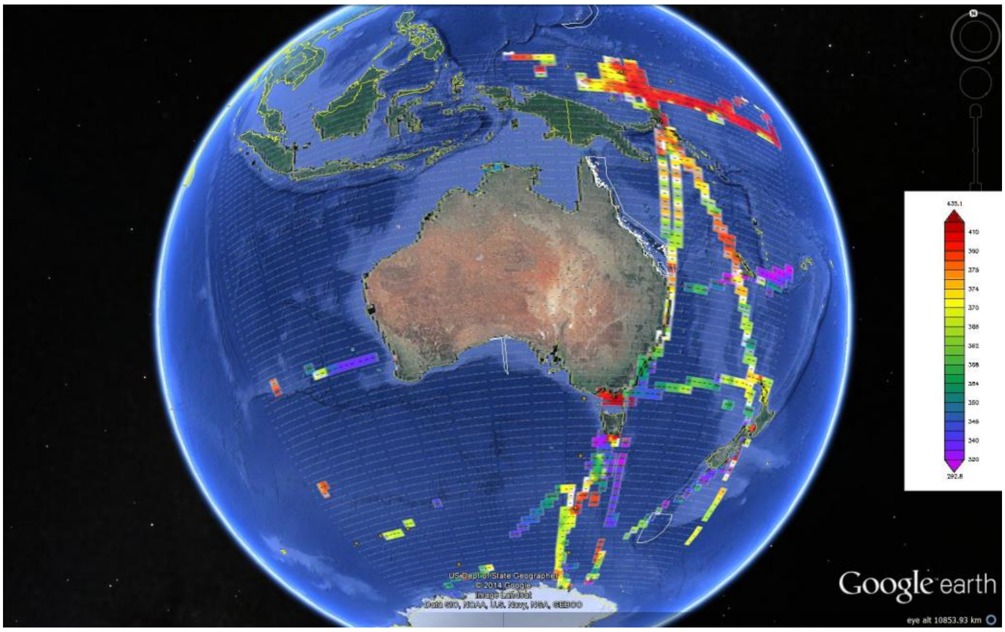

Figure 9.9: SOCAT (V2) 12 month climatology 1x1 gridded showing mean fCO2 (uatm) weighted per cruise

Secondary products:
Surface Ocean Carbon Atlas (SOCAT) gridded product (Fig. 9.9).

Modelling applications:

These data are used to test ocean biogeochemical models and provide baseline information used to help establish the vulnerability of marine ecosystems to ocean acidification. Data is currently used for validation of CO_2 fluxes in WOMBAT biogeochemical model, and will potentially be used for assimilation in the future.

Future priorities identified by the nodes for this facility:

- Expand pCO2 network, including CO2 measurements at high latitude where overturning circulation and global CO2 outgassing changes are under debate. Measurements at low latitude are also needed.
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)
- Expand CO2 network on national reference station to ensure ocean acidification progress is quantified for representative coastal habitats. SOOP BGC could be an alternative

- Assess the feasibility of obtaining routine coupled CPR and carbon chemistry transect data on platforms such as Aurora Australis.

Uses	Limitations
- Provides broad spatial coverage around Australia and in the Southern Ocean to fill gaps in the seasonal climatology of surface fluxes. - Provides repeat coverage across the Southern Ocean, to monitor seasonal and interannual variability in fluxes across major fronts.	- Systems require expert technical support; hence are only deployed on research vessels. - Observations in the Southern Ocean are biased towards summer - Confined to shipping routes - Changes in shipping schedules or routes disrupt the time series

9.2.2.3 Continuous Plankton Recorder (CPR)

Historically, Australia has few zooplankton time series compared to other countries which at least have 15 years or more. Plankton are short-lived and respond rapidly to changes in ocean conditions, making them valuable sentinels of environmental change such as global warming. Given the diversity of Australia's marine habitats and the economic and social importance of fishing, Australia needs information on environmental changes and long-term zooplankton datasets have the ability to provide this information. The Australian CPR project is helping addressed this situation by providing estimates of plankton diversity and distribution along the east coast of Australia and it is complemented by tows made between Australia and Antarctica (Figure 9.10). The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Ecosystem responses

The CPR is a device which collects underway samples of plankton, by trapping them on a spool of silk as it is towed through the water. The samples are then analysed to give information on the biodiversity and distribution of different species of phytoplankton and zooplankton.

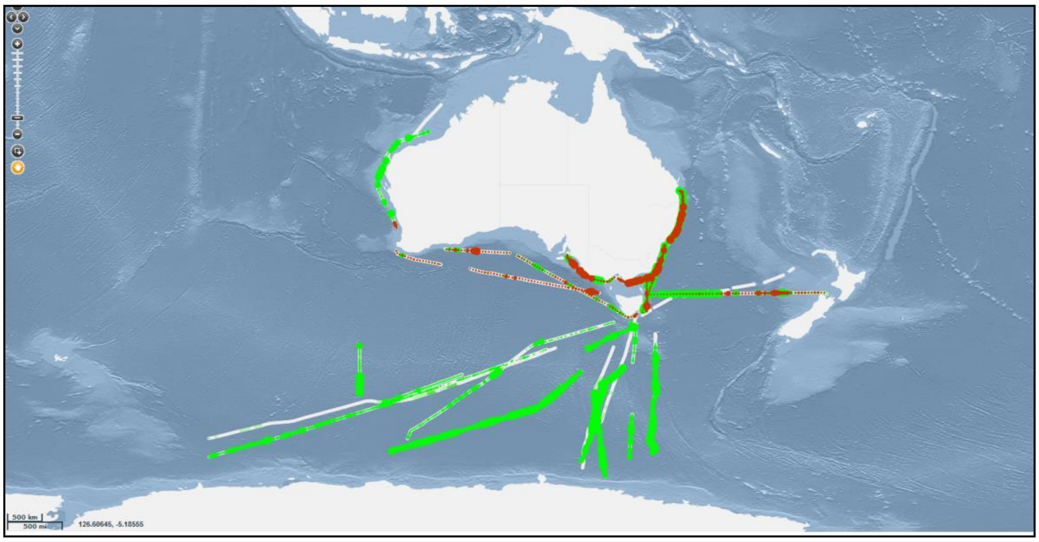

Figure 9.10: SOOP CPR Data available in the Portal. Phytoplankton relative abundance indicated by size of green dots and zooplankton by red dots, and CPR Plankton Colour index data.

Nature of IMOS Infrastructure

Phytoplankton and zooplankton species-level data for regular routes between Brisbane and Adelaide (seasonally), the GBR (seasonally), NW WA (ad hoc), across the Tasman Sea (annually) and in the Southern Ocean from the *Aurora Australis* (over summer) with additional 20 tows per annum in Southern Ocean between about September/October to March/April. All data is made available to AODN.

Primary Products

Quality controlled physical, chemical, plankton and zooplankton data along ships tracks. Calculate phytoplankton biomass for each sample along route.

Secondary Products:

Website for identifying zooplankton:

Australian Marine Zooplankton: a taxonomic guide and atlas. Version 1.0 February 2013 (Swadling et al 2013) and Australian Marine Zooplankton: Taxonomic Sheets (Richardson et al, 2013) (Fig. 9.11)

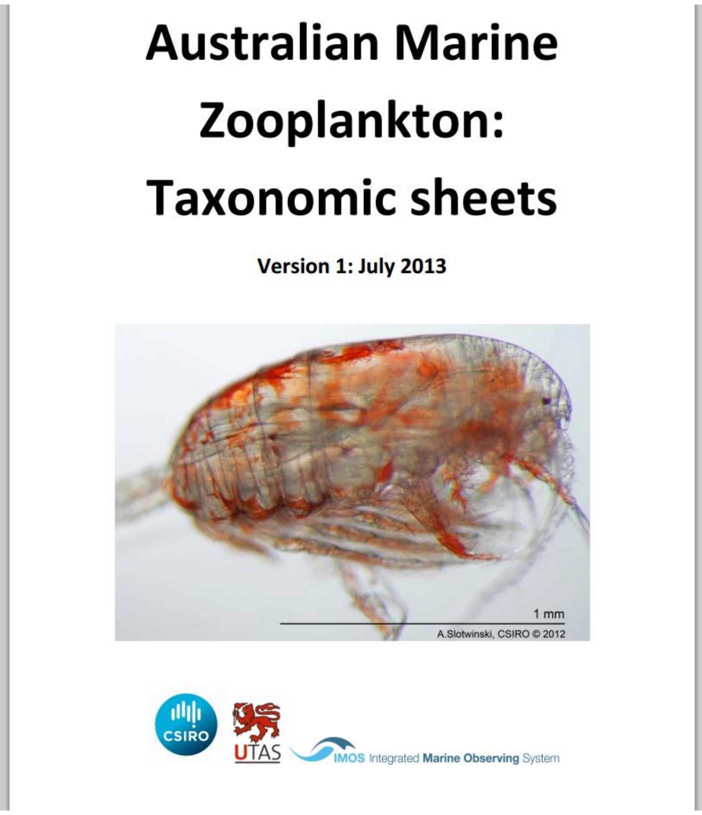

Figure 9.11: Australian Marine Zooplankton Taxonomic sheets available online http://www.imas.utas.edu.au/__data/assets/pdf_file/0009/396477/AtlasAustralianZooplanktonGuide_Introduction.pdf

Modelling applications: CPR data can be used to validate biogeochemical (i.e. WOMBAT) and ecosystem (i.e. ATLANTIS) models, providing information on size fraction of plankton, functional groups, etc. This data is currently not assimilated.

Future priorities identified by the nodes for this facility:

- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)
- Assess the feasibility of routine coupled CPR and carbon chemistry transect data on platforms such as R/V Aurora Australis
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.

Uses	**Limitations**
- The only systematic approach to collecting information on phytoplankton and zooplankton species distribution - Information for marine environmental management issues such as harmful algal blooms, pollution, climate change and fisheries - Validate satellite remote sensing	- Analysis of samples is very labour intensive - Underestimates some plankton components - Changes in shipping schedules or routes disrupt the time series - Confined to shipping routes

9.2.2.4 Surface underway data

Tropical Research vessels (AIMS) and some merchant vessels (Spirit of Tasmania) carry out a suite of underway measurements utilising temperature, salinity, chlorophyll and turbidity sensors to record temperature, salinity, turbidity and chlorophyll (Figure 9.12). The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows

- Continental shelf and coastal processes
- Ecosystem responses

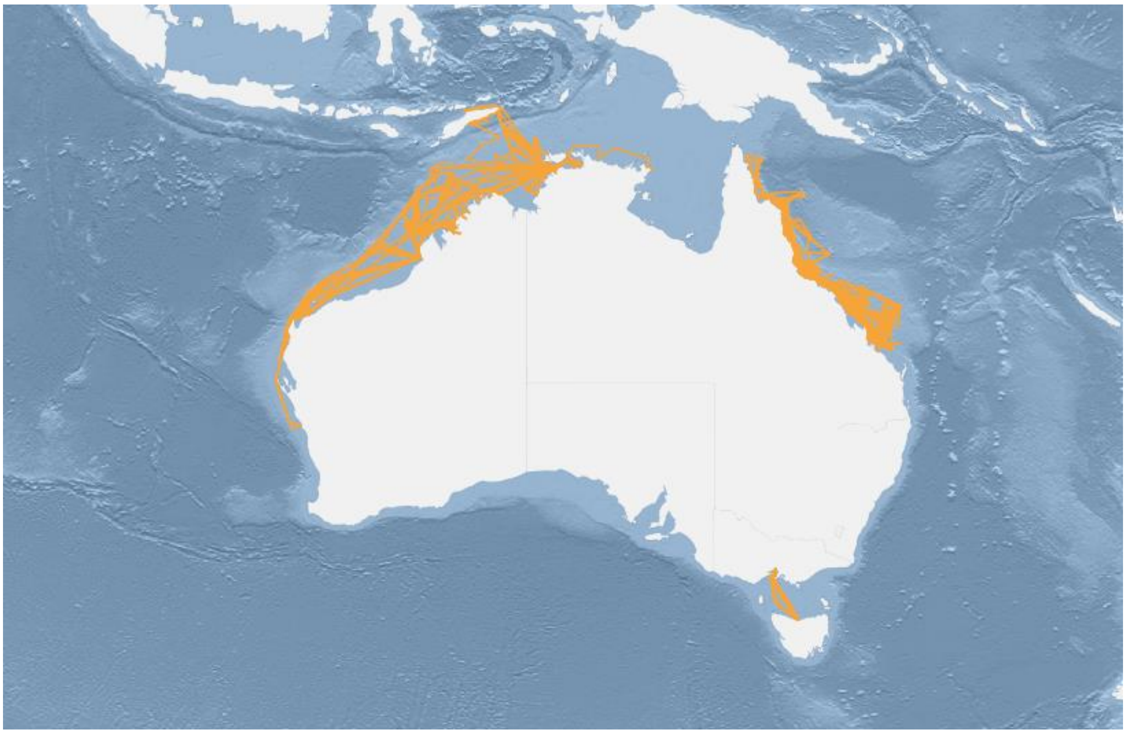

Figure 9.12: SOOP Tropical Research and Temperate Merchant Vessels data available in the Ocean Portal.

Nature of IMOS Infrastructure

- Collect temperature, salinity, turbidity, chlorophyll data across tropical Australia from two vessels:
    - *RV Cape Ferguson*, full width of the Queensland shelf from 14^0S to 23^0S as well as at least two cruises per annum into the Coral Sea (AIMS).
    - *RV Solander*, along the north east coast between Darwin and North West Cape (AIMS).
- Collect temperature, salinity and turbidity data across Bass Strait form the *Spirit of Tasmania* (Vic Govt).

Primary products

Raw and QC'd data records and validation data within 3 months of collection. Data streams from the tropical research vessels are currently being used in projects such as Reef Rescue Marine Monitoring Program (GBRMPA-funded), Coral Sea Connections Project (AIMS), Kimberley Oceanography (AIMS and WAMSI funded) and GBR bathymetry project (JCU). .

Modelling applications

Data streams used for validation of satellite sea surface temperature (SST) maps by the BoM and will be used to validate the eReefs model.

Future priorities identified by the nodes for this facility:

- Evaluate new sensor technologies for pH, nutrients, and bio-optics that could be considered to be ready for piloting at broad scale, on Argo, SOOP, gliders etc.
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)
- SOOP Bass Strait transect. The four year record of surface temperature, salinity and fluorescence is showing both seasonal and inter-annual trends. It should continue

Uses	Limitations
- Provide multidisciplinary measurements, filling in key gaps in Bass Strait (repeat observations) and Northern Australia waters (broad scale)	- Only measure surface data through engine intake system - Confined to ship routes - Require technical support

9.2.2.5 Sea Surface Temperature (SST)

SST measurements are made using hull contact SST sensors on a broad range of platforms. The high quality ***in situ*** near real time SST observations are collected on a number of vessels operating in Australian waters (Figure 9.13). These measurements are augmented by observations made by the SOOP air-sea flux platforms (see Section 9.2.2.6) and skin SST from radiometers (see Section 9.1.2.1). The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes

The SOOP SST observations are also used to validate satellite SST and ocean models in the Australian region.

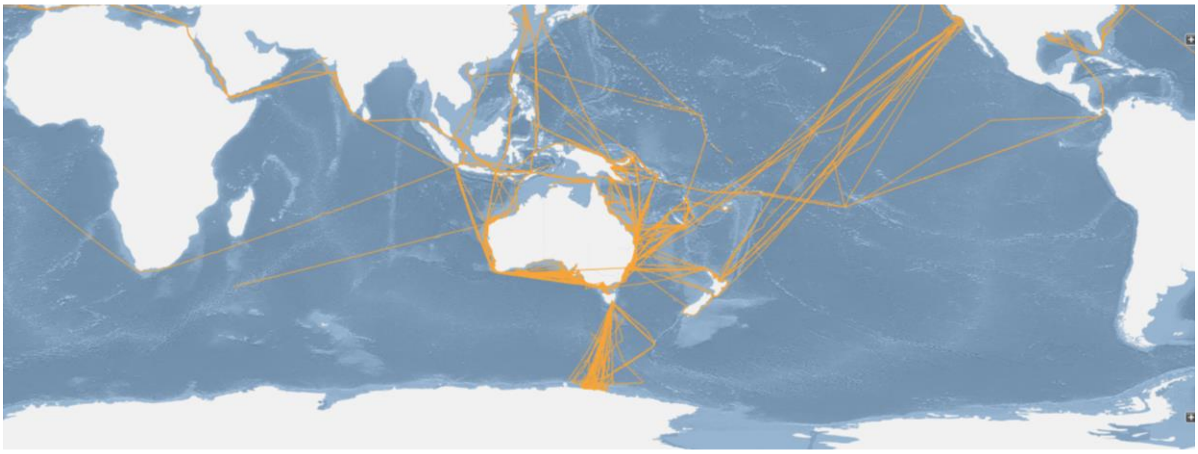

Figure 9.13. SOOP SST data available in the Ocean Portal from commercial vessels (blue) and SOOP flux (yellow and black) and TRV (light blue) research vessels that collected SOOP SST.

Nature of IMOS Infrastructure:

SST data from 7 research vessels and 2 tourist ferries collected and reported every minute to the GTS and data from 9 commercial vessels collected and reported every hour to the GTS. Half of these vessels report the data to a much higher resolution than previously available and the data streams are significantly more accurate (~1/4 the error) than non-IMOS ship SST reported to the GTS in the Australian region.

Primary products:

Near real-time SST (and where available salinity and meteorological) data automatically quality controlled and supplied to eMII in IMOS netCDF format and to the GTS in SHIP or Trackob format.

Secondary products:

SST data from SOOPs are used in several reanalyses products around the world such as: Global Ocean Surface Underway Data Project (GOSUD) which to collect, process, archive and disseminate in real time and delayed mode sea surface salinity and other variables collected by SOOP, iQUAM for satellite SST validation, Shiptrack web site which provides a snapshot of current weather conditions at sea, worldwide, WMO VOS Program which provides high-quality marine meteorological data to support global climate studies.

Modelling applications:

SOOP SST data is primarily used to produce high quality (GHRSST) Sea Surface Temperature Products, which in turn are a core dataset for data assimilation.

Future priorities identified by the nodes for this facility:

- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.

- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)

Uses	Limitations
- Accurate bulk SST measurements - Broad coverage in Australian region - Good timeliness, special and temporal coverage	- Confined to ship routes

9.2.2.6 Air-Sea Fluxes

The SOOP Ship Flux facility collects rare meteorological and surface ocean observations for bulk flux measurements of heat, mass and momentum in data sparse regions of the ocean. The instrumentation operates in an autonomous underway configuration on three ships of opportunity giving broad spatial coverage in Australian and Southern Ocean waters (Figure 9.14) and thus filling the gaps in the global seasonal climatology of air sea fluxes. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows

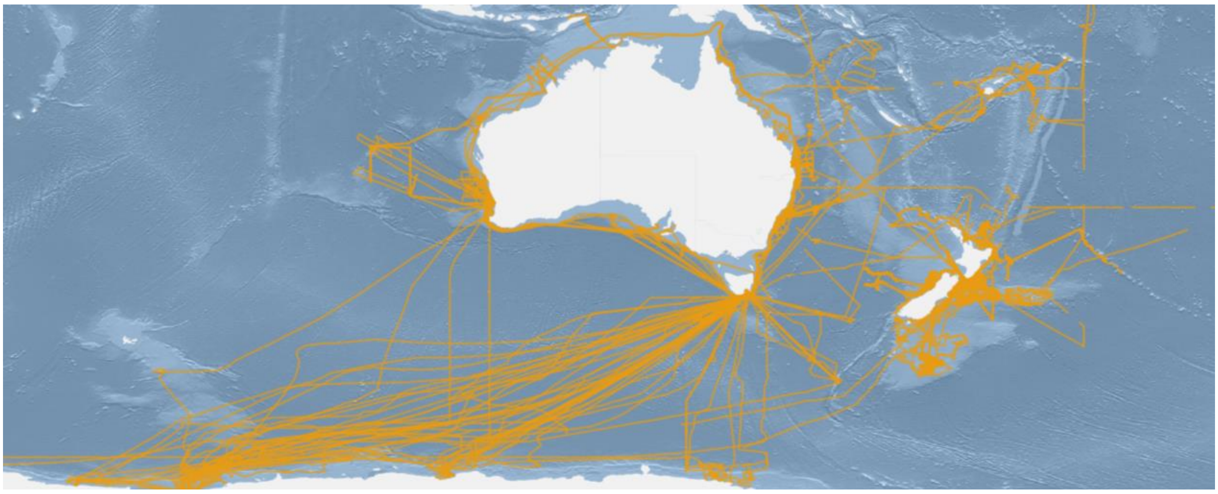

Figure 9.14: SOOP Air Sea Flux data available in the Ocean Portal.

Nature of IMOS Infrastructure

- RV *Southern Surveyor* – non-repeating, but operates in the broad region around Australia

- RSV *Aurora Australia:* Summer sampling Hobart – eastern Antarctica (wide area)
- *RV Tangaroa* – non-repeat sampling in broad region around New Zealand.
- *RV Investigator* – non-repeating, but operates in the broad region around Australia (replaces the Southern Surveyor).

Primary products

Observations collected on the vessels are delivered in near real-time (hourly to daily transmissions of 1-minute averaged data). Bulk air-sea fluxes of momentum, heat and mass are computed, with data automatically quality controlled and sent to the IMOS ocean portal. Meteorological observations are also put onto the GTS as the contribution to the Australian Volunteer Observing Fleet. Observations collected while at sea include, near-real-time wind speed and direction, Air temperature, air humidity, air pressure, precipitation, solar radiation (down welling short-wave), infrared radiation (down welling long-wave), sea surface temperature (at 1m depth), sea surface salinity and bulk fluxes of heat, mass and momentum.

Modelling applications*:*

Used for validation of atmospheric models (NCEP) and to improve ocean surface heat flux estimates using satellite observations and numerical modelling.

Future priorities identified by the nodes for this facility:

- Look for opportunities to fill the gap in air-sea flux measurements north (e.g. in regions relevant to MJO) and south of the continent (e.g. south of the SOFS site, to sample fluxes at higher latitude). Past collaborations with JAMSTEC in Japan and NOAA/PMEL in the USA may be built on in the future to allow this to proceed. Extending the air-sea flux network from Ships of Opportunity could also help address these gaps.
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)

Uses	**Limitations**
- Provides broadscale spatial coverage of the complete range of air-sea flux variables - Provides important data from the southern hemisphere where data is sparse	- Temporal resolution poor, as do not repeat tracks regularly.

9.2.2.7 Bio-acoustics (BA)

Bio-acoustics (BA) involves the use of echosounders, at single and multiple frequencies, on research vessels and large fishing and cargo vessels to estimate mid-trophic level organism distribution and abundance around the Australian Exclusive Economic Zone (EEZ) shelf, slope and oceanic environments. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Ecosystem responses

These mid-trophic bio-acoustic data will complement data collected through the biogeochemistry, phytoplankton and CPR programs for distribution and abundance of surface chemistry, plankton and zooplankton and AATAMS. The bio-acoustic sampling is targeted on vessels operating in areas of high importance due to predicted impacts from climate change or of ecological significance such as the Tasman Sea and the EAC region (Figure 9.15). Southern and Indian Ocean waters are also part of the Sentinel and SOOS initiatives.

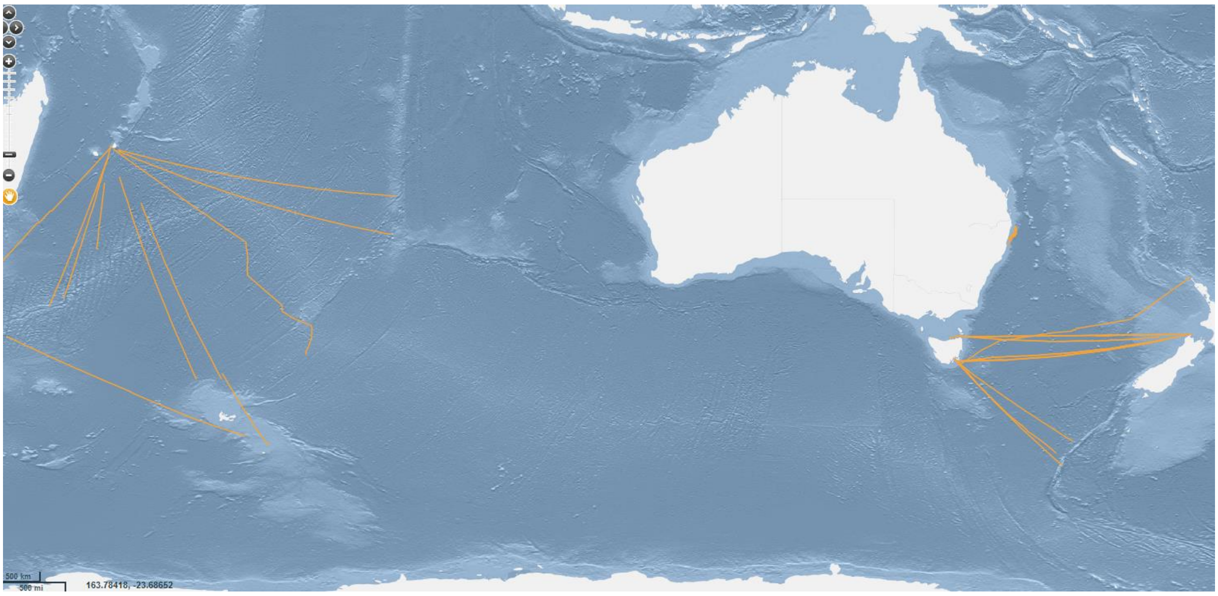

Figure 9.15: SOOP Bioacoustics data available in the Portal.

Nature of IMOS Infrastructure

Collection of quality controlled delayed mode bio-acoustic data at single (38 kHz) and multiple frequencies (12, 38 and 120 kHz) from existing vessel infrastructure (research and fishing) annually within season on transit over regions of high regional, ecological and oceanic importance.

Primary products

Delayed mode data of calibrated acoustic volume backscatter at 38 kHz (as well as 12, 18, 120 and 200 kHz on some routes) at a spatial resolution of 10 m depth by 1 km long, down to a nominal depth of 1000 m.

Secondary products

Trans-Tasman index reported in the scientific literature for a decade of sampling.
Posting of multi-frequency data and indices developed for pelagic habitat surrogacy for MNF Investigator and other vessels with multi-frequencies.

Modelling applications

Mid-trophic level organisms are identified as a key knowledge gap/uncertainty in ecosystem models; bio-acoustic estimates of mid trophic level biomass are used in ecosystem models such as SEPODYM and APECOSM-E.

Future priorities identified by the nodes for this facility:

- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)
- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.

Uses	**Limitations**
- Cost effective method to obtain quantitative information about biomass of mid-trophic level organisms, currently a major uncertainty in ecosystem models - Ability to integrate with physical and chemical properties, and measurements of phytoplankton and zooplankton taken along CPR transects - Higher spatial resolution compared to other sampling methods	- Unproven in a sustained observing context - Small direct user community in Australia, making integration with other data streams and engagement with the modelling community more important for uptake and use - Species identification is not possible unless ground truth with other sampling methods (nets, video) - Expert technical support for calibration and post-processing of data - Confined to shipping routes

9.2.3 Deep Water Moorings

Deep water moorings are used to obtain data on the deep ocean, generally at either single timeseries sites or as arrays at “choke points” to measure key current systems. The moorings are located in Antarctic, sub-Antarctic and Tropical open ocean waters around Australia. The instrumentation for each mooring depends on the desired variables and local conditions at each site.

9.2.3.1 Air Sea Flux Station Time series

Air sea flux moorings measure key atmospheric and surface ocean variables continuously. The Southern Ocean Time Series (SOTS) program maintains 3 moorings to measure of heat, moisture, CO_2 and oxygen exchanges between the ocean and the atmosphere. The Southern Ocean Flux Station (SOFS) mooring is tasked with building a climate record in the Southern Ocean measuring near real time meteorological and oceanographic conditions at the sea surface, essential for climate change research. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter-basin flows

SOFS is located in the Sub-Antarctic Zone, approximately 350 nautical miles southwest of Tasmania (46.75S, 142E) (Figure 9.16). This mooring is deployed in concert with other SOTS mooring forming one of the few comprehensive Southern Ocean sites and contributing to the understanding of ocean controls on climate and carbon cycling.

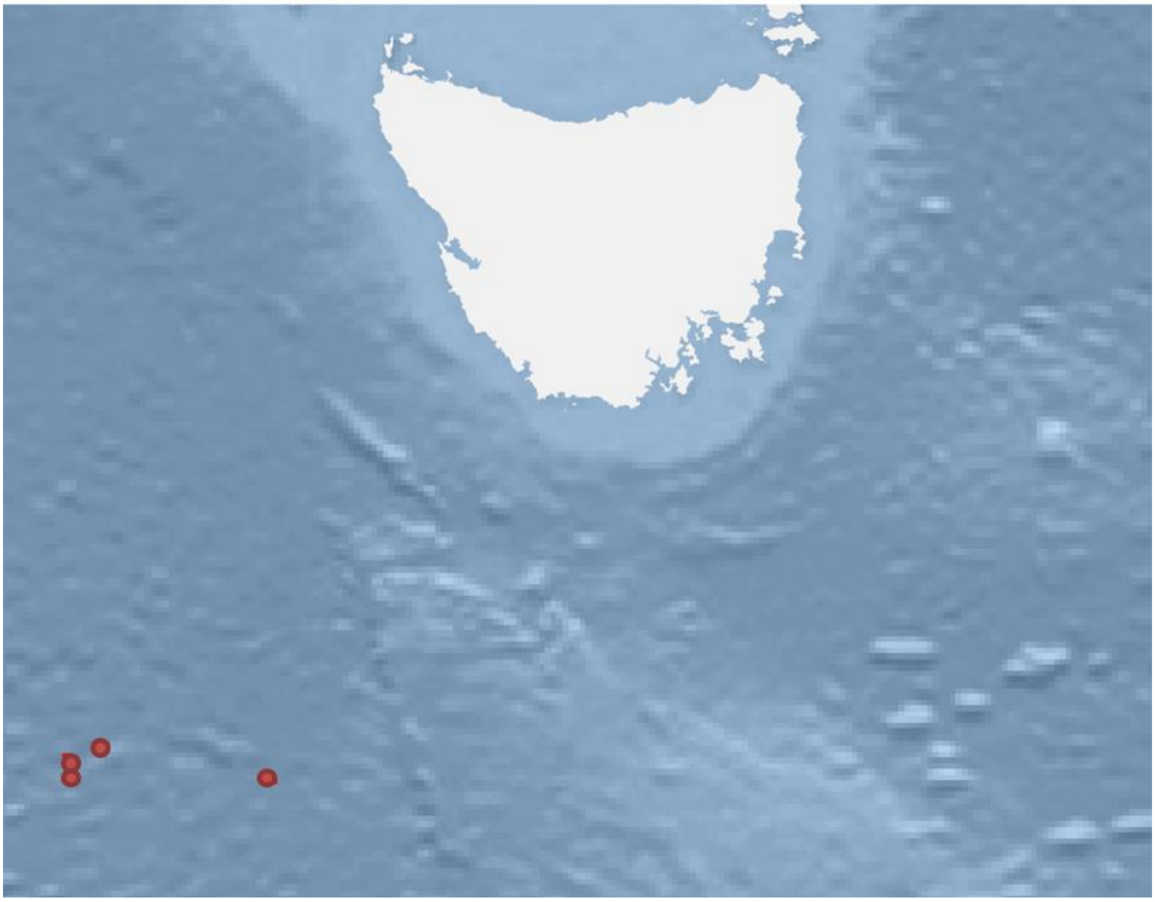

Figure 9.16: Locations of SOTS mooring infrastructure.

Nature of IMOS Infrastructure

The SOFS mooring is equipped with two Air-Sea Interaction METeorology (ASIMET) systems, along with Iridium modems. SOFS observations are collected on the buoy on 1-minute averages, telemetered as spot measurements and 1-hourly averages every hour. Most meteorological instruments are duplicated (some triple) for redundancy). The mooring is currently turned around six-monthly. Significant piggy-back observations are also collected including pCO2 (PMEL/NOAA), a partial replicate of the Pulse observations (Utas/CSIRO), waves, and ocean currents and turbulence (Swinburne Uni. & CSIRO).

Primary products

Near real time data that is quality controlled by an automated system and available on a daily basis. Delayed mode data is available around 3 months after mooring recovery and delayed-mode quality controlled data is available around 15 months after mooring recovery. Data available near real time include: wind speed and direction, air temperature, air humidity, air pressure, precipitation, solar radiation (down welling short-wave), infrared radiation (down welling long-wave), SST, sea surface salinity, pCO2, wave motion. Data available in delayed mode include: photosynthetically active radiation in air (PAR), dissolved oxygen, dissolved gases, phytoplankton fluorescence, particle backscatter, currents: profiles and point measurements, ocean turbulence, ocean temperature, salinity & pressure

Secondary products

Contributes to gridded air-sea fluxes products.

Modelling applications

Data contributes to the Bluelink project, use for validation of NCEP atmospheric model marine fluxes over the Southern Ocean and of Oceansat-2 winds using an array of moored buoys

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.

Uses	**Limitations**
- High temporal resolution - Can use platform to measure complete range of variables to determine the flux of gases in/out of the ocean, the biogeochemical processes within the water column, and the export of organic matter into the deep ocean	- Measurements are only at one site. - Re-deployment depends on vessel availability

9.2.3.2 Biogeochemical Time Series (SOTS)

The Southern Ocean Time Series (SOTS) is based on multiple platforms deployed in the Sub-Antarctic Zone (SAZ) southwest of Tasmania (Figure 9.16) and it a contributor to the international OceanSITES program. The emphasis is on inter-annual variations of upper ocean properties and their influence on exchange with the deep ocean. The program is highly interdisciplinary and includes physical, chemical, and biogeochemical observations. Resolution of high amplitude seasonal variations beyond those achievable from ship-based observations (e.g. via SOOP facility observations) is an important characteristic. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Ecosystem responses

Overall SOTS consists of 3 moorings, and ancillary robotic floats and ship observations. The biogeochemical time series consist of the Pulse biogeochemistry and Sub Antarctic Zone (SAZ) sediment trap moorings, as well as the robotic float and ship observations. The objective is to advance climate and carbon cycle understanding to levels where efficient mitigation, adaptation, and mitigation options can be developed and evaluated.

Nature of IMOS Infrastructure

There are three main components of SOTS:

- ***SAZ deep ocean sediment trap mooring:*** Annual deployments to continue delivery of particulate carbon flux estimates and deep ocean sinking particle samples from the Subantarctic Zone. This platform is wholly sub-surface, and provides data and samples only on recovery. SAZ sensor data streams are collected at ~hourly intervals and include deep ocean currents, deep ocean temperature and salinity. SAZ sample data streams are collected at ~10 day intervals and include sinking mass flux, sinking particulate organic carbon flux, sinking particulate inorganic carbon flux, sinking particulate biogenic silica flux.
- ***Pulse surface mixed layer mooring:*** This mooring delivers upper ocean biogeochemical property measurements. It is equipped with a range of sensors to record waves, currents, temperature, salinity, oxygen, total gas tension, particulate backscatter and PAR. Pulse sensor datastreams are collected at hourly intervals.
- ***Robotic floats:*** These floats collects temperature, salinity oxygen, fluorescence and backscatter data.

Primary Products

Mooring data are delivered in delayed-mode, because the subsurface instruments store data which is only retrieved during the annual service. Pulse and SAZ sensor data are available approximately 3 months after mooring recovery. Pulse and SAZ sample data are available approximately 12 months after mooring recovery. Robotic floats observations – un-calibrated robotic float data for temperature and salinity are delivered in near real time via the Argo facility. Float oxygen, fluorescence, and backscatter are available with approximately 6 months delay.

Secondary products

Information on diatom community structures collected by SOTS SAZ sediment traps and their relation to climate variability and carbon transfer to the deep sea

Modelling applications

SOTS data is used to validate the carbon cycling in the WOMBAT biogeochemical model.

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.

Uses	**Limitations**
- Allow the research community to advance understanding of ocean controls on climate and carbon cycling - Measure processes important to quantifying changes in climate and carbon cycling. - Provides observations in an important region but where there are very little data	- Measurements only at one site. - Regular maintenance needed

9.2.3.3 Transport Arrays

Australia's ocean domain includes all five of the world's ocean temperature zones ranging from tropical to polar. This sub-facility maintains 3 full deep-ocean mooring arrays in three key climate regions in the Australian ocean domain: (1) the Polynya mooring array on the Antarctic continental shelf; (2) the Indonesian Throughflow array in the Timor Passage and Ombai Strait and; (3) the EAC array on the Australian continental slope near Brisbane. These climate monitoring sites provide a full deep-ocean observing system that enables the tracking of multi-decadal climate change and variability, and will improve our understanding and prediction of both climate variability in the Australian region and global climate. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes
- Major boundary currents and inter basin flows

These transport arrays measure temperature, salinity, and current in deep waters that are specifically targeted to monitor formation of Antarctic bottom water, inter-basin exchange, and major boundary currents. They have been ideally located across choke points, or where the current is constrained by topography to measure transport of current systems and to allow heat/salt flux to be calculated (Figure 9.17).

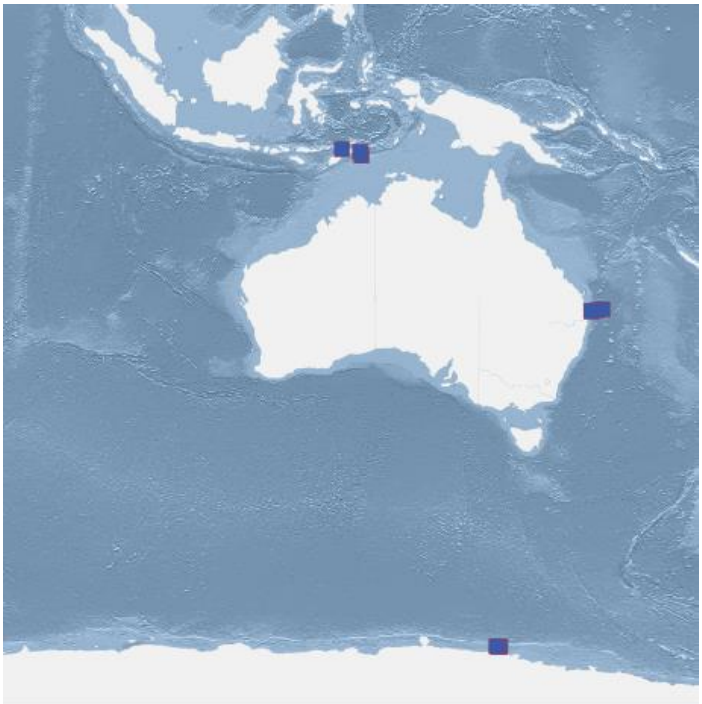

Figure 9.17. Locations of Deepwater Arrays in the IMOS Ocean Portal.

Nature of IMOS Infrastructure

The mooring arrays are placed in three different regions collecting temperature, salinity, current velocity and oxygen (Polynia mooring only).

Polynya Mooring Array: Consists on 3 moorings on the Antarctic continental shelf measuring currents and water properties in a coastal polynya. The program originally targeted the Mertz Polynya. Changes in the regional icescape following calving of the Mertz Glacier Tongue mean that this region is no longer logistically feasible. A one-year pilot deployment in a polynya near the Totten Glacier is underway to assess its suitability for sustained observations.

Indonesian Throughflow Array: Consists on 3 moorings; 2 in Timor Passage and 1 in Ombai Strait. The mooring array monitors ~80% of the interbasin exchange of mass, temperature and salt between the Pacific and Indian Ocean.

The East Australian Current Array: Consists on 5 mooring deployed off Brisbane from the continental slope to the abyssal ocean. This array monitors the strength and variability of the EAC.

***Primary Product*s**

Delayed mode full depth timeseries of temperature, salinity, velocity and oxygen (Polynia only) across boundary currents. Mooring data are delivered in delayed-mode, because the subsurface instruments store data which is only retrieved during the 18 month or 2 year servicing of the arrays.

***Secondary Product*s**

Delayed mode mass, heat, salt fluxes of boundary currents and deepwater formation zones

Estimates of transport mean and variability of the EAC.
Estimates of decadal variability in Australia's major ocean boundary currents if observations are sustained long term.

Modelling applications

Analysis of the INSTANT and IMOS ITF time-series combined with modelling studies to improve understanding of the response of the northern and northwestern Australia continental margin shelf/slope boundary current and Leeuwin Current System to Indonesian Throughflow variability. Validation of key chokepoints in the global circulation in ESMs; delayed mode assimilation into ocean state estimates.

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.
- Maintain the EAC and ITF arrays, which are providing the first long time series from Australia's major boundary currents and inter-basin flows.
- Design and test a strategy for boundary current monitoring using gliders. The reinstatement of the EAC Deep Water Mooring to test the feasibility of gliders to monitor boundary and shelf currents provides the opportunity to test it.
- Collect nutrient samples from the ITF and EAC arrays.
- Redesign the EAC mooring and consider the inclusion of the SEQ shelf moorings at the expense of one of the slope moorings as there may be some redundancy in this part of the array

Uses	Limitations
- Accurate, direct measurements of mass and heat transport. - Continuous timeseries of deep ocean properties at key locations and choke points.	- Expensive. - Difficult to constrain highly dynamic currents (such as the EAC) - Do not provide broadscale coverage of the deep ocean - Deployment dependent on vessel availability

9.3 Shelf and Coastal facilities

9.3.1 Ocean Gliders

Ocean Gliders are state of the art technology for observing the ocean. They are designed to operate in water depths up to 1000 m. By changing its buoyancy, the glider is able to descend and ascend, and have wings which allow them to move laterally. Two different types of gliders are operated under this facility (Fig. 9.18); the Slocum glider which is designed to operate to a maximum depth of 200 m and a maximum endurance of 30 days, and the Seaglider which operates to a maximum depth of 1000 m and a maximum endurance time of up to 6 months. They are able to house a broad suite of sensors; in addition to temperature and salinity, they also measure fluorescence, oxygen, turbidity and depth integrated currents. The facility delivers observations relevant to the following major research themes in IMOS:

- Multi-decadal ocean change
- Climate variability and weather extremes

- Major boundary currents and inter basin flows
- Continental shelf and coastal processes
- Ecosystem responses

Figure 9.18: Slocum glider (yellow) and Seaglider (pink) deployments to date, per the Ocean Portal.

Nature of IMOS Infrastructure

- Multi-open-ocean Seaglider missions for monitoring boundary currents
    - Leeuwin Current system, the Hiri Current, the South Australian Current/Flinders Current and the EAC Extension (NSW eddy field and eastern Tasmania) Tasman Outflow (southern Tasmania), the EAC (Brisbane), sub-Antarctic front (SOTS) and Coral Sea.
- Multi-coastal Slocum glider missions for monitoring continental shelf processes
    - Two Rocks/Perth Canyon, Kimberly and Pilbara transects, Sydney Region, Kangaroo Is/Eyre Peninsula, SE Tasmania

In addition, six glider missions per annum to deliver biologically relevant observations of reef and coastal waters will be conducted in the GBR region to enhanced the data available from Palm Passage real time mooring and help improve real time modelling of the GBR region using eReefs. Operational requirements of this particular programme are driven by the specific needs of the numerical modelling user group.

Primary products

Depth, temperature, salinity, chlorophyll, dissolved organic matter (CDOM) and turbidity data are available in delayed mode and near-real time. The Slocum glider also provides underwater light climate. The near real time data is not quality controlled. For delayed mode data basic quality control for the glider data is provided through the ANFOG standard operating procedures.

Secondary products

The depth averaged velocity is provided as an indirect measurement. Data is also input into global climatology data sets and made available on the GTS

Modelling applications: Near real-time data goes onto the GTS and can be assimilated for ocean and seasonal forecasting initial conditions. Glider data is also being used for validation of coastal models. Bio-optical data is being used to validate biogeochemical models.

The e-reefs GBR modelling project is currently using both the glider and Palm Passage real time mooring data.

Future priorities identified by the nodes for this facility:

- Evaluate new sensor technologies for pH, nutrients, and bio-optics that could be considered to be ready for piloting at broad scale, on Argo, SOOP, gliders etc.
- Evaluate new observing infrastructure like wave gliders for improved coverage.
- Increase deployment of slocum and/or sea gliders on repeat cross-shelf transect in Qld, NSW, WA and SA, but also taskable to specific impacted regions during and after extreme events.
- Design and test a strategy for boundary current monitoring using gliders. The reinstatement of the EAC Deep Water Mooring to test the feasibility of gliders to monitor boundary and shelf currents provides the opportunity to test it.
- Explore potential opportunities to collect data in northern Australia (Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria) by leveraging other infrastructure in this vast and remote region, including infrastructure maintained by AMSA (the maritime safety authority), fishing vessels in the Gulf of Carpentaria, undersea fibre optic cable being laid between Darwin and Port Hedland as part of the Ichthys project etc. The use of slocum gliders, ocean radar and enhanced SOOP could also be alternatives.
- Improve and expand coverage of sea gliders in Qld, SA, WA and NSW.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA).
- Storm Bay glider transects. At their offshore limit these transects are recording the location of the front between boundary currents. Slight reduction of the Storm Bay transects could be considered to allow for the prioritised Bass Strait transect. Summer trans-Bass Strait Slocum glider deployments to observe sub-surface waters of Bass Strait. Late summer provides the best meteorological conditions.

Uses	**Limitations**
- Navigable	- Cannot fight against strong currents

- Multidisciplinary payload of sensors - Can make observations across the shelf - Can make routine repeat sections in more benign areas of the ocean. - Potential for monitoring boundary currents	- Optimal modes of operation still under development - High offshore shipping can present a difficulty

9.3.2 Autonomous Underwater Vehicle (AUV)

The Sirius Autonomous Underwater Vehicle (AUV) is designed for undertaking high resolution benthic stereo optical and acoustic imaging work. The AUV Facility at IMOS provides precisely navigated time series measurements of water column parameters and benthic imagery using AUVs at selected reference stations on Australia's shelf. AUV systems have recently been shown to be effective tools for rapidly and cost-effectively delivering high-resolution, accurately geo-referenced, and precisely targeted optical and acoustic imagery of the seafloor. This capability makes AUVs ideally suited to undertaking repeat surveys that will be necessary to monitor changes in the benthos, particularly beyond diver depths. AUV dive sites have been selected to capture habitats at a variety of depths and latitudes along the East and West coasts (Figure 9.19). The facility delivers observations relevant to the following major research themes in IMOS:

- Ecosystem responses

The general sampling methodology using the AUV is designed to monitor the fundamental reef processes that maintain reef biodiversity and resilience. The sampling design will be optimised using information from existing survey data to designate particular transect sites. The processes of interest occur at a number of spatial scales so a nested hierarchical sampling method will be adopted as appropriate to detect changes at these differing scales.

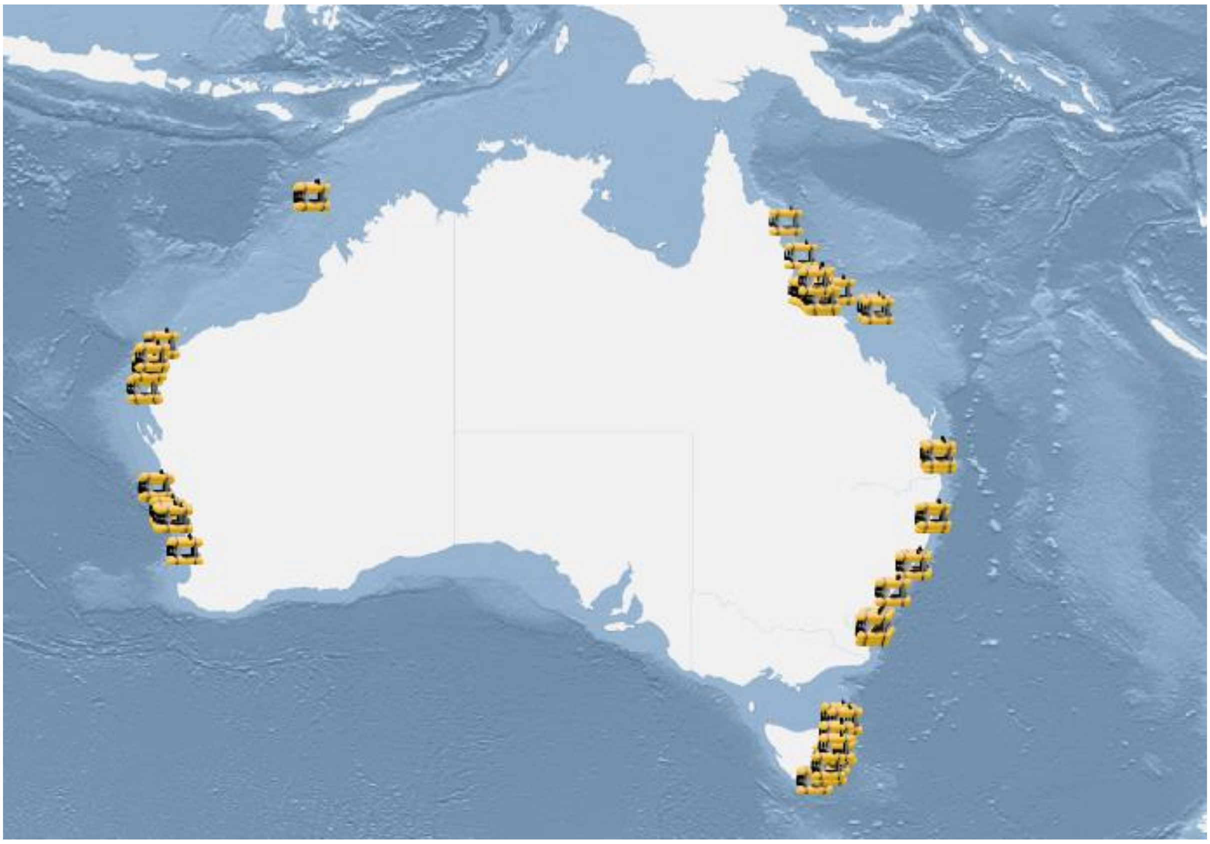

Figure 9.19: AUV Surveys in the Ocean Portal.

Nature of IMOS Infrastructure

The AUV is schedule to undertake up to 8 campaigns per annum, with site surveyed on an annual or bi-annual basis. Observations include associated AUV-based geo-referenced imagery and bathymetry together with measurements of conductivity, temperature, depth, chlorophyll-a, CDOM, backscatter in red and PAR.

A new AUV is currently being built to replace the facility's primary vehicle.

Primary products

All data from the facility will be made available through the IMOS. The data includes images, navigation data, oceanographic measurements and multibeam data when available. This data is collected in the field and then delivered to eMII once the team has returned to Sydney. The volume of data is not practical to be delivered in real time.

Secondary products

Products based on automated pattern recognition are being developed, which identify substrate type; e.g. Mud, Rocky Reef, Sand, Coral, etc.

Habitat mosaics (integration of images with vehicle navigation)

Modelling applications

The data will be used to validate qualitative models as part of the NESP Biodiversity Hub Project.

Future priorities identified by the nodes for this facility:

- Expand AUV capability and coverage
- AUV-based cross-shelf observing of benthic communities along bioregionally-based transects, documenting spatial and temporal trends in biological assemblages and providing CMR monitoring in Southeast Australia region.

Uses	**Limitations**
- Georeferenced, repeatable surveys of the sea bed. - Can work deeper than scuba diver depth - Can be used to detect changes in the benthic habitat - Includes oceanographic and navigation data	- Challenges in storing/interpreting the data. - Small spatial coverage

9.3.3 Ocean Radar (ACORN)

HF Radar stations are deployed in pairs at a number of sites around the country to produce surface current maps over meso-scale areas (Figure 9.20). The facility delivers observations relevant to the following major research themes in IMOS:

- Major boundary currents and inter basin flows
- Continental shelf and coastal processes

Two types of Radar system are being used. The first is a WERA Phased array, which provides data on surface currents; significant wave height; dominant wave height and directional wave spectrum. The second a CODAR-SeaSonde direction finding system, which provides data on surface currents, significant wave height and wind direction.

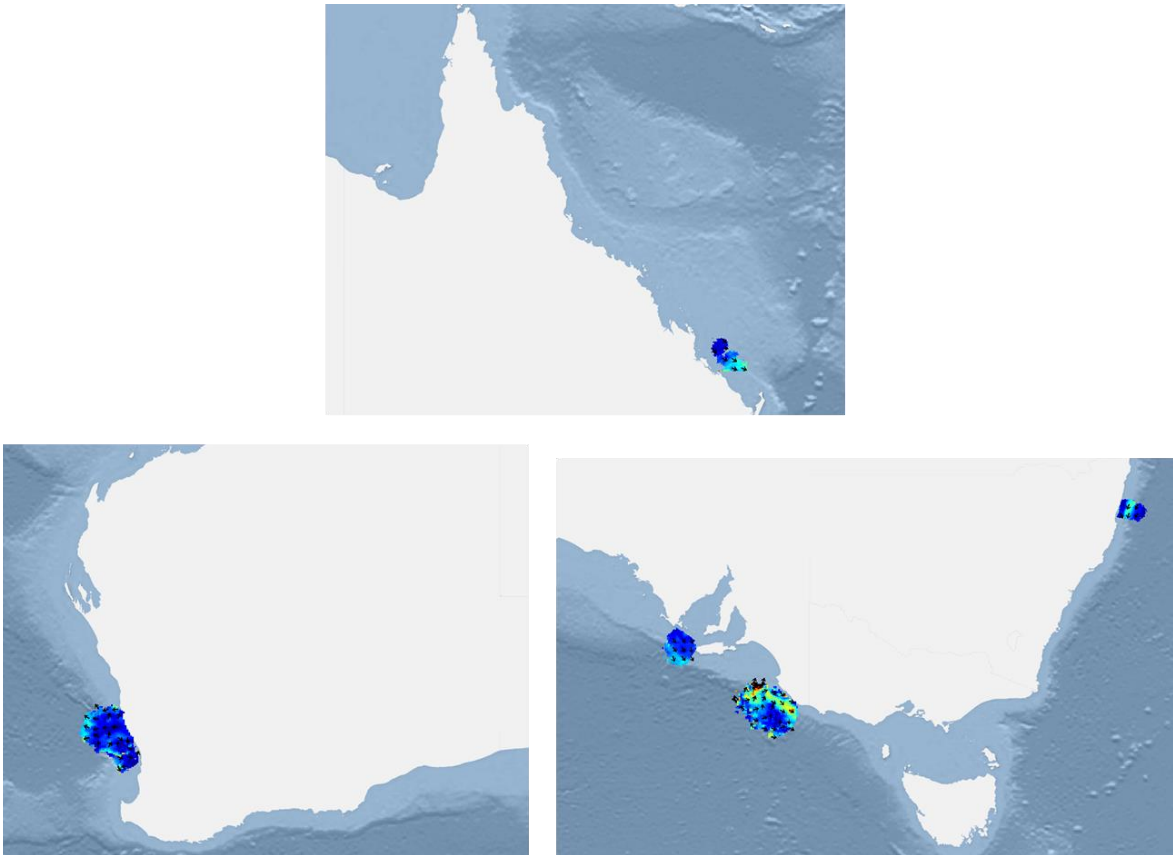

Figure 9.20: Radar locations on the Ocean Portal. The colours indicate sea water velocity measured at each station.

Nature of IMOS Infrastructure

The facility maintains, services and operates 12 radar stations, grouped in pairs, at 6 locations around Australia using two different radar systems: WERA and SeaSonde.

- There are four WERA pairs deployed at Coffs Harbour, NSW, Rottnest Island, WA, South Australian Gulfs, SA and on the southern Great Barrier Reef.
- There are two CODAR pairs deployed at Bonney Coast, SA and Turquoise Coast, WA.

JCU will continue to support this facility to Sept 2014 but cannot continue to commit beyond that date. The radio frequencies of all radars will be changed over the next two years to meet new ACMA and international requirements. An important activity will be to develop a plan for ACORN's sustainable future.

Primary Products:

The radars provide surface currents in near real time delivered to eMII for some additional processing and uploading to the portal. WERA delayed mode QC data are delivered within one month of data disks being recovered from the radar sites. The WERA pairs provide hourly maps of surface currents and one hourly average gridded quality controlled data and non-QC radial and one hourly average gridded data from all six sites. The CODAR pairs provide non-QC radial and one hourly average gridded data from all four sites. Wave and wind data in delayed mode will become available via the portal.

Secondary products:

Data use in Ocean Currents website

eMII will add statistics to hourly averaged current vector files: within hour: max/min/median values, standard deviation and number of values averaged; and include GDOP information and take it into account when producing real-time current vector files

Modelling applications:

BlueLink, eReefs are two models that are currently using radar data, as well as other regional models. There is also interest by the BoM to use radar data to verify coastally trapped waves as part of their OceanMAPS aggregate sea level product work.

Future priorities identified by the nodes for this facility:

- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA)

Uses	**Limitations**
- High resolution, time-resolved maps of surface currents Potential wave height and wind direction data	- Raw data needs significant processing to be useful - Vulnerable to interference

9.3.4 Animal Tagging and Monitoring (AATAMS)

AATAMS represents the higher biological monitoring of the marine environment for the IMOS program. This facility uses acoustic technology, CTD satellite trackers and bio loggers to monitor coastal and oceanic movements of marine animals from the Australian mainland to the sub-Antarctic islands and as far south as the Antarctic continent. Currently a large range of fish, sharks and mammals are collecting a wide range of data. This includes behavioural and physical data such as the depth, temperature, salinity and movement effort of individual marine animals.

9.3.4.1 Acoustic Tagging

Acoustic monitoring is a powerful tool for observing animals in coastal and continental shelf ecosystems. Networks of receivers, allow animals to be monitored over scales 10s of metres to 1000s of kilometres. Tracking animals using these tags has been invaluable for monitoring habitat use, home range size, timing of long-term movements and migratory patterns and examining biotic and abiotic factors that dictate animal distribution and movements. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Continental shelf and coastal processes
- Ecosystem responses

IMOS have deployed an array of submerged receiving stations that form a national network (Fig. 9.21) and also contribute to the Ocean Tracking Network (OTN). The array has been strategically developed to facilitate research on movements of animals in relation to the major boundary currents complementing physical measurements made with other IMOS infrastructure. This has strong ties to over 35 state federal and private research organisations acting as a central point to all. Acoustic tagging is primarily used to monitor the movement of large fish around the continental shelf regions. Fish are tagged with acoustic coded transmitters, which are detected by the underwater acoustic receiver network. The single frequency used in all tags allows all receivers within AATAMS and other users within Australia and elsewhere to recognise our tags.

Figure 9.17. Acoustic curtain locations (circles).

Nature of IMOS Infrastructure

The facility currently maintains arrays and curtains comprising 550 Acoustic receivers distributed in a national network. In addition, it supports over 750 receivers owned by other parties but registered with our network. Over 40 million detections are currently recorded from 2341 individual animals representing all coastal habitats across coastal Australia.

Primary products:

The detection and species identity of tagged individuals at sites in a national network of receivers.

Secondary products:

Development of global networks through international collaborations with Australia's nearest neighbours (e.g. New Zealand).

Animal movements in relation to the major boundary currents.

Modelling applications:

Acoustic data will be used to validate qualitative models as part of the NESP Biodiversity Hub. There is also potential to use this data for models such as Atlantis.

Future priorities identified by the nodes for this facility:

- Increased attention to questions regarding coupling between trophic levels, for example, linking bioacoustics data on meso-zooplankton and micro-nekton to productivity estimates derived from moorings, satellites, and bio-Argo floats. A similar strategy could be taken for linking tagging data from top predators to other trophic levels, in particular new mobile acoustic receiver transmitters deployed on top predators.

- Evaluate if ATAAMS acoustic receiver's existing locations suit the Nodes' needs to address science questions.

Uses	Limitations
- Able to track a range of species (commercial fish, sharks) around the continental shelf region	- Cannot track fish in open ocean (limited to continental shelf) - Hard to close out curtains on broad shelves - Detection of tags from other parties that are not register in the facility (ghost tags)

9.3.4.2 Bio-logging devices

There are two types of location tags used in IMOS (Figure 9.22). Satellite Relay Data Loggers (SRDL) (most with CTDs, and some also with fluorometers) are used to explore how marine mammal behaviour relates to their oceanic environment. These loggers transmit data in near real time via the Argo satellite system. Geolocation archival (GLS) tags are used in seabirds such as the Short-tailed shearwaters (*Puffinus tenuirostris*) and can store data from up to four sensors (e.g. date, time, temperature, and light levels). Unlike GPS tags these tags must be retrieved from their data to be downloaded. The light levels are used to calculate the time of dawn and dusk, which can be used to estimate an approximate daily position of the animal. The sub-facility delivers observations relevant to the following major research themes in IMOS:

- Multidecadal ocean change
- Major boundary currents and inter-basin flows
- Continental shelf and coastal processes
- Ecosystem responses

Miniaturized loggers with high resolutions sensors directly enhances collection of oceanographic data in the Southern Ocean and in Australian boundary currents by providing profiles of temperature and salinity from regions of the Southern Ocean and coastal shelf regions that are difficult to sample by other means (e.g. beneath the winter sea ice for which 45,496 profiles had been collected as at 14 Feb 2013, and across cross shelf currents in southern Australia, 26,000 profiles to date), and by relating predator movements and behaviour to fine-scale ocean structure and variability.

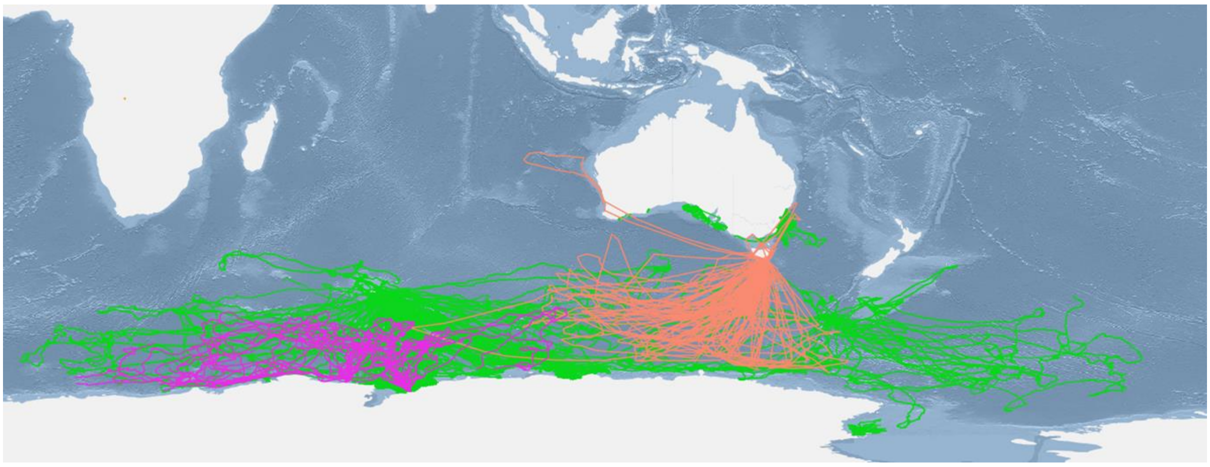

Figure 9.22: Showing tracks of Marine Mammals (green tracks), Emperor penguins(purple tracks) and seabirds(orange tracks).

Nature of IMOS Infrastructure

A total of 123 satellite tags (SRDL) tags will be deployed by 2015 on marine mammals and penguins, including Elephant Seals, Weddell Seals, Australian Fur Seals, Australian Sea Lions, New Zealand Fur Seals and Emperor Penguins. Data is being collected in the Southern Ocean, the Great Australian Bight, and off the South-East Coast of Australia. Parameters measured by SRDL tags on marine mammals include time, conductivity (salinity), temperature, speed, fluorescence (available in the future) and depth. Data from tags in Emperor Penguins do not include CTD data. A total of 230 GLS tags will be deployed by 2015. Currently the records collected were from 21 tagged and recaptured animals, with data presented throughout the Southern Ocean.

Primary Products

Biologging stream collect high quality biotic and abiotic data with in excess of 71,000 CTD profiles collected by seals in the southern ocean and along Australia's southern coasts (SOSS) and with mapping of Areas of Ecological Significance by a suite of top predator species (seabirds and seals). All data represented by this record are presented in delayed mode.

Secondary products

Identification of areas of ecological significance.

Modelling applications

Temperature and salinity profiles are delivered on GTS and assimilated into seasonal/ocean forecasting initial conditions; and ocean state estimates. State/space modelling techniques are used to interpret tagging data.

Future priorities identified by the nodes for this facility:

- The highest priority is to maintain and enhance support for key IMOS infrastructure that exists now, including Argo, oceanographic sensors on marine mammals, boundary current arrays, Southern Ocean time series (SOTS and SOFS), SOOP, satellite remote sensing of sea surface height, sea surface temperature and ocean colour, shelf moorings, etc.
- Improve observation coverage near the coast and shelf by enhancing and/or extending moorings currently deployed, enhance observations from SOOP, maintaining and improving radar

coverage, increase deployments of slocum gliders and use of alternative observing platforms such as biologging along areas with poor observation coverage (Esperance, north GBR, areas in NSW and GAB in SA).

- There are extensive ongoing animal tracking studies across Bass strait (i.e. seals, penguins, gannets) that may provide useful alternatives for data collection in appropriately instrumented through IMOS facilities (i.e CTDs and other sensors through AATAMS) and also an ecological context to the observations observed (i.e. animal movement, foraging ground, prey capture success, health).

Uses	**Limitations**
- Monitor the movements of large predators across open ocean regions - Get incident physical data to elucidate why predators aggregate in certain regions (i.e. Frontal zones) - Get incident physical data in traditionally data sparse regions (i.e. the Southern Ocean in winter) to complement the Argo Array - Distribution of seabirds, marine mammals and penguins - Ability to obtain data at inaccessible regions	- Animals need to be large enough to carry GPS tags. - Seals and penguins moult once a year, and shed the tag. - GLS tags do not transmit data, must be retrieved to download data - Tags can be very expensive - Small sample size can jeopardise the statistical reliability of the data

9.3.5 Wireless Sensor Networks (FAIMMS)

Sensor networks are leading edge technology that is used to provide spatially dense bio-physical data in real-time. The term “sensor network” refers to an array of small interconnected wireless sensors that collectively stream observational data to a central aggregation point. Data is communicated through the “NextG” mobile phone network. The system is “smart” in that the sensors adaptively sample; that is change how they monitor based on the conditions they measure. The communications network is installed, and is available for additional “plug and play” compatible instruments to be integrated into the system. The sensor network is currently located in the Great Barrier Reef (Figure 9.23). The facility delivers observations relevant to the following major research themes in IMOS:

- Climate variability and weather extremes
- Continental shelf and coastal processes
- Ecosystem responses

This facility supports a number of projects including an ARC Linkage project at Heron Island, work being done under two Lizard Island fellowships, pCO2 work being undertaken with CSIRO at Heron Island, real time acoustic tag monitoring in conjunction with the AATAMS Facility (Heron, One Tree and Orpheus Islands) and work on coral health measures with AIMS.

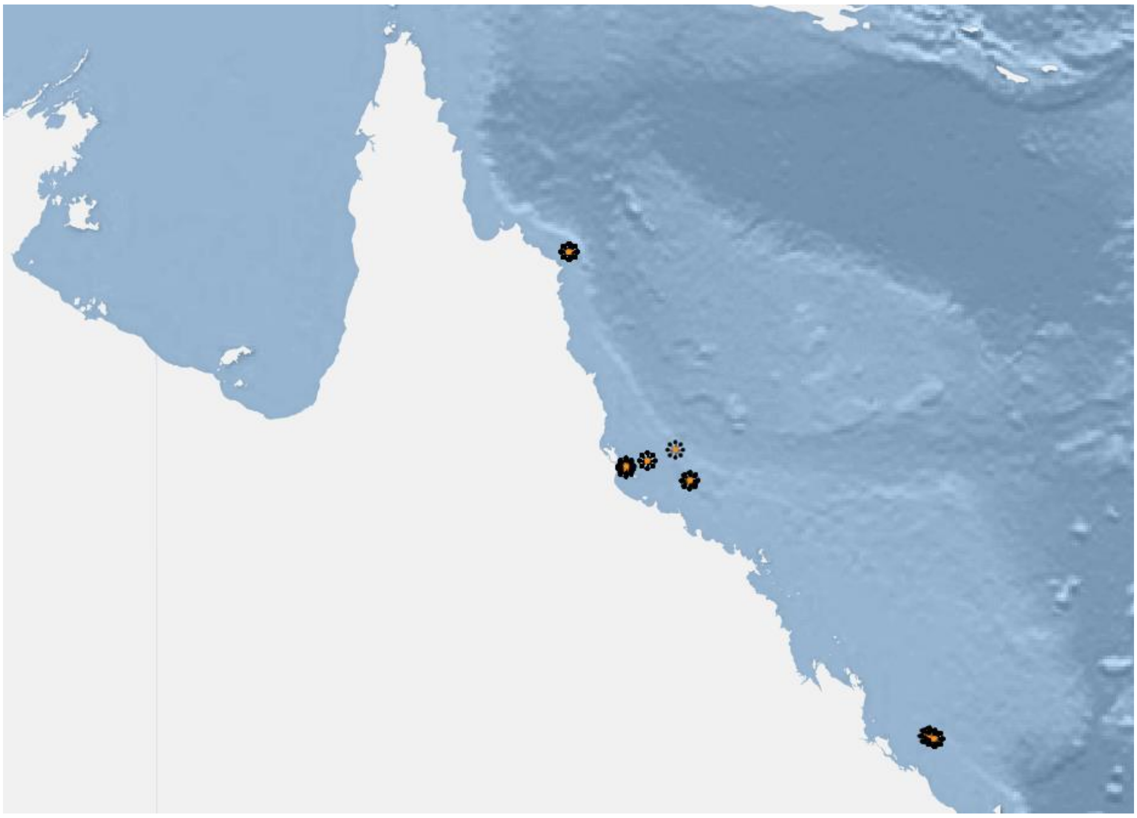

Figure 9.23. Sensor networks locations along the GBR, from the Ocean Portal

Nature of IMOS Infrastructure

The facility supports the maintenance and ongoing development of four Wireless Sensor Network sites along the Great Barrier Reef (GBR) at the Island Research Stations (Lizard Island in the north, Orpheus Island in the central GBR and Heron and One Tree Islands in the south). These sites include 13 sensor poles, ten sensor floats, four weather stations and one camera delivering some 179 data streams (61 from Lizard, 42 from Orpheus, 53 from Heron and 23 from One Tree). Deployment of a range of new sensors was undertaken at Heron Island which includes newly developed pCO2 sensors, coral photosystem sensors and imaging sensors.

The variables measured include: water temperature, salinity, pressure and conductivity; above water weather parameters including air temperature, humidity, barometric pressure, wind speed and direction, light (PAR) and rainfall; above and below water images and video at some sites; below water light as paired measurements to give water clarity / transmission; acoustic animal detections at the real-time detection stations; pCO2 from some sites and chlorophyll and turbidity at some sites.

Primary products:

All data streams are real time with data delivered within 20-30 minutes of the actual measurement NetCDF files are also provided with automated Quality Control (QC) is performed nightly

Secondary Products:

Provide early warning of an imminent bleaching episode and activate an appropriate response by researchers

Development of models of coral health for the four sites based on the real time data

Climatologies and basic coral physiology that will allow for a 'coral health dashboard' to be developed

***Modelling applications*:**

Used for validation/assimilation into the eReefs hydrodynamic/water quality model

Future priorities identified by the nodes for this facility:

- None identified

Uses	Limitations
- Real time data delivery - Spatially dense observations for key regions of interest (i.e. GBR) - Adaptive sampling. i.e. if conditions are changing rapidly, sampling rate can increase.	- Not suitable for observing large areas, and hence much of the Australian coastline - Network does not develop strategically as reliant on individual projects to fund and add sensors.

10 Highlights and Achievements

As policy demands in the marine environment increase nationally, it strengthens the need for marine observations. A process of consolidation and increased cooperation has continued in the marine science community, with IMOS playing a key role in stimulating national coordination and discussions. From inception IMOS has been able to amalgamate the Australian marine science community, a large, diverse and dispersed community, by fostering collaboration among Australia's most important marine science institutions and by providing essential infrastructure and data to undertake marine research.

In addition, IMOS role as a marine observing system has also have an impact internationally, collaborating closely in a number of global initiatives such as the Global Ocean Acidification Observing Network (GOA-ON), Coral Reef Environmental Observatory Network (CREON); OceanSITES; Global Ocean Observing System (GOOS); among many others.

There was been wide uptake and use of IMOS data by Australian scientists and stakeholders with IMOS data streams and facilities contributing to the study of ocean circulation, climate change and variability, biogeochemical cycles, and ecosystem processes. As a fully-integrated, national observing system, it has the capacity to take measurements at ocean-basin and regional scales covering physical, chemical and biological variables.

IMOS has had a great impact in Australian marine science and this is demonstrated by the many achievements accomplished to date. A few examples of these achievements are listed below.

- Provided data that showed evidence that climate change has caused the wet (higher rainfall) areas of the global ocean to get wetter while the dry get drier (Durack et al., 2012).
- Improved estimates of ocean heat content and thermal expansion for the upper ocean for 1950-2003.
- Provided invaluable data on the response of plankton ecosystems to decadal-scale changes in the ocean, the first published evidence of a biological response to ocean acidification in nature (Howard et al., 2009, Moy et al., 2009) and baseline data on calcareous plankton export against which future acidification response may be measured (Roberts et al., 2008) through the SOTS facility.
- Contributing to an international program on constraining global and regional CO_2 uptake and determining the acidification of the oceans, coordinated through the International Ocean Carbon Coordinated Project.
- Releasing of a website for identifying Australian zooplankton (Swadling et al., 2013) and the accompanying taxonomic guide, Australian Marine Zooplankton: Taxonomic Sheets (Richardson et al., 2013) using CPR and zooplankton data from NRS

- Contributing to the validation and data assimilation into near real time forecasting models (BlueLink, eReefs, Darwin Harbour, SAROM and other regional modelling efforts) and products (OceanCurrent).
- Contributing to national initiatives such as: 1)FishTrack www.fishtrack.com web site to advise recreational and commercial fishers on likely fish locations; 2)ReefTemp NextGen (BoM) to report on SST-related factors impacting coral bleaching over the Great Barrier Reef; 3) the Reef Rescue Marine Monitoring Program and eReefs in the GBR, 4) multiple projects examining biological processes in Australian waters, in particular in the Kimberley and Great Australian Bight.
- Assisting with calibration and validation of satellite data for our international partners and serving as back up when their receiving stations are down as was the case with NASA in 2012 when we help with MODIS data acquisition.
- Leading globally on bio-acoustic (passive and active) data provision (we are world first) and providing assistance to other nations to build infrastructure in the active acoustics domain.
- World first to provide a central repository for data from collaborating institutes and researchers from Australia on acoustic tag detections
- Extending the International Nusantara Stratification And Transport (INSTANT, 2003-2006) time series data of the Indonesian Throughflow mass, heat and salt fluxes between the Pacific and Indian Ocean and contributing to the International Eastern Indian Ocean Upwelling Initiative 2015-2020
- Providing unparalleled high-resolution AUV stereo imagery and three-dimensional reconstructions in terms of size (area covered), geo-referencing accuracy, consistency and quality of the imagery and maturity of the data processing pipeline.
- Helping improved modelling tools to better inform the management of the marine environment and fisheries.
- Helping Australia maintain a leadership position in coral reef science.

While the achievements to date are great, there are still many challenges we need to address. Many questions about our oceans are still unanswered, our understanding of ocean processes is in many cases limited, and climate, ocean and ecosystem models need improvement and validation. Providing an Integrated Marine Observing System that is sustained in the long term is therefore essential if we are to meet these challenges.

In the short term it is expected that IMOS will help the marine research community:

- Improve seasonal climatologies and thus climate models
- Improve the monitoring of the oceans energy budget and thus allow the tracking of climate change evolution

- Improve understanding and prediction of climate variability modes such as the Indian Ocean Dipole as well as climate variability and extreme weather events impacting coastal and marine ecosystems which can lead to an enhanced predictive capacity to support preparation for, and response to extreme weather events
- Improve regional algorithms for satellite through in situ validation data
- Improve transport estimates for major boundary currents and inter-basin flows
- Improve understanding of the global hydrological cycle and provide new insights into long-term changes
- Improve the accuracy of high resolution ocean analyses such as BlueLink, ocean circulation models, coastal models, biogeochemical models, ecosystem models and international products by providing data for validation and improve parameterization
- Continue the development of ocean circulation models particularly over the continental shelf region, ranging from hindcasting, nowcasting and forecasting and including improvements of parameterizations such as mixing
- Improve understanding of cross-shelf flows, deep water intrusions, tidal mixing and connectivity between boundary currents and shelf currents
- Improved data products for assimilation into and verification of ocean, wave, climate and weather prediction models
- Enhance models of biophysical coupling through enhanced measurement of mechanistic parameters driving biological variability (e.g. light) and via mapping of biological parameters onto the physical variability
- Improve prediction of climate change impacts on sediment transport, storm surge, coastal erosion, inundation and ecosystem changes.
- Improve understanding of connectivity between physical environment and marine organisms
- Provide a baseline and monitor changes in benthic and planktonic communities
- Improve the modelling tools that inform resource management, regulators and industry
- Provide critical data on populations of apex predators and other mega fauna, their habitat needs, and the oceanographic and ecological factors that underpin the high trophic levels, their foraging ecology and critical foraging areas including those utilised by multiple species (Areas of Ecological Significance)
- Improve understanding of interannual variability of marine ecosystems
- Provide data and context to assess effectiveness of management and conservation strategies for coastal and marine regions

In the longer term, IMOS is expected to help in:

- Providing new insights into decadal variability in the oceans around Australia and its ecological and carbon cycle impacts
- Detection of future anthropogenic impacts on the Southern Ocean planktonic ecosystem and carbon sink
- Providing the ability to track multidecadal planetary radiation budget and assess the effectiveness of global greenhouse mitigation measure
- Providing the ability to track global and regional sea level rise rates and their cause
- Improving understanding of how the global overturning circulation, major boundary currents and shelf currents are changing and the impacting on ocean heat and carbon uptake rates
- Improving the predictions of ENSO and the IOD, giving more accurate seasonal climate forecasts for Australia
- Quantifying acidification rates for major bioregions in shelf and offshore waters, a prerequisite for determining response and resilience of ecosystems to acidification
- Providing the ability to better quantify natural variability vs long-term climate change and its impacts on the marine environment, coastal communities and industry
- Providing the ability to quantify the seasonal to interdecadal CO2 uptake in Australian waters and the Southern Ocean
- Determining long-term trends in climate and ecosystem dynamics, as well as regime shifts in biological communities

The economic, social and environmental benefits we extract from our ocean and the increasing threats faced by it, make it imperative for Australia to invest in research with observation, experimentation and modelling as the three main pillars (OPSAGOceans Policy Science Advisory Group, 2013). IMOS provides the infrastructure required for the science process to move forward, delivering the benefits of a better understanding of our ocean, its processes and dynamics, as well as helping improve the available tools and creating new tools for the effective management of our resources and support evidence-based decision making on issues of national significance with intergenerational impact.

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12 Attachments

12.1 List of Acronyms

Acronym	Full Title
AABW	Ant-Arctic Bottom Water
AAD	Australian Antarctic Division
AARNet	Australian Academic and Research Network
AATAMS	Australian Acoustic Tagging and Monitoring System (Facility 8)

Acronym	Full Title
AATSR	Advanced Along-Track Scanning Radiometer
ABARES	Australian Bureau of Agricultural and Resources Economics and Sciences
DWM	Deep Water Moorings (Facility 3)
ABP	Annual Business Plan
ACC	Antarctic Circumpolar Current
ACCESS	Australian Community Climate and Earth Systems Simulator
ACCSP	Australian Climate Change Science Programme
ACECRC	Antarctic Climate and Ecosystems Collaborative Research Centre
ACEF	Australian Coastal Ecosystems Facility
ACFR	Australian Centre for Field Robotics
ACMA	Australian Communications and Media Authority
ACORN	Australian Coastal Ocean Radar Network (Facility 7)
ADCP	Acoustic Doppler Current Profiler
ADFA	Australian Defence Force Academy
ADO	Australian Defence Organisation
AERONET-OC	A Network for the Validation of Ocean Color Primary Products
AES	Areas of Ecological Significance
AFMA	Australian Fisheries Management Authority
AGU	American Geophysical Union
AIC	Argo Information Centre
AIMS	Australian Institute of Marine Science
ALA	Atlas of Living Australia - NCRIS Capability
Altimetry CalVal	Altimetry Calibration and Validation (Sub-Facility, SRS)
AMC	Australian Maritime College (now UTAS)
AMOS	Australian Meteorology and Oceanography Society
AMSA	Australian Marine Sciences Association
ANDS	Australian National Data Service
ANFOG	Australian National Facility for Ocean Gliders (Facility 4)
ANMN	Australian National Mooring Network (Facility 6)
ANU	Australian National University
ANZLIC	The Spatial Information Council of Australia and New Zealand
AO-DAAC	Australian Oceans [Remote Sensing Data] Distributed Active Archive Centre
AODCJF	Australian Ocean Data Centre Joint Facility
AODN	Australian Ocean Data Network
APEX	Autonomous Profiling Explorer Argo Floats
ARC	Australian Research Council
ARC LIEF	Australian Research Council Linkage Infrastructure, Equipment and Facilities
Argo	Argo Australia (Facility 1)
ASFS	Air-Sea Flux Stations (Sub-Facility, DWM)
ASIMET	Atmospheric Structure Instrument/Meteorology Package
ASTEP	Astrobiology Science and Technology for Exploring Planets
ATRF	Arafura Timor Research Facility

Acronym	**Full Title**
AuScope	NCRIS Capability for a National Earth Science Infrastructure Program
AusCPR	Australian Continuous Plankton Recorder
AUV	Autonomous Underwater Vehicle Facility (Facility 5)
AVHRR	Advanced Very High Resolution Radiometer
AVOF	Australian Volunteer Observing Fleet
AWI	Alfred Wegener Institute for Polar and Marine Research
AWS	Automatic Weather Stations
BA	Bio-Acoustics
BGC	Biogeochemical
BIOS	Basic Input/Output System
BLUElink>	Ocean Forecasting Australia; a project to deliver ocean forecasts for the Australian region
Bluewater	Bluewater and Climate Node
BoM	Bureau of Meteorology
BRAN	BLUElink Reanalysis
CAML	The Census of Antarctic Marine Life
CARS	CSIRO Atlas of Regional Seas
CART	Coastal Acoustic Release Transponder
CAWCR	Centre for Australian Weather and Climate Research
CBIBS	Chesapeake Bay Interpretive Buoy System
CCAMLR	Convention on the Conservation of Antarctic *Marine* Living Resources
CDOM	dissolved organic matter
CDU	Charles Darwin University
CLIVAR	Climate Variability and Predictability (World Climate Research Programme)
CLW	CSIRO Land and Water
CMAR	CSIRO Marine and Atmospheric Research
CMIP	Coupled Model Intercomparison Project
CMST	The Centre for Marine Science and Technology (based at CU)
CNRS	National Centre For Scientific Research France
COAG	Council of Australian Governments
CODAR	Brand name for equipment
CPR	Continuous Plankton Recorder
CPU	Central Processing Unit
CRC	Cooperative Research Centre
CREON	Coral Reef Environmental Observatory Network
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity Temperature Depth
CU	Curtin University
DA	Deepwater Array (Sub-Facility, DWM)
DAAC	Distributed Active Archive Centre
DSTO	Department of Defence (Defence Science and Technology Organisation)
EAC	Eastern Australian Current

Acronym	Full Title
ECL	East Coast Low
ECU	Edith Cowen University
EEZ	Exclusive Economic Zone
EGU	European Geosciences Union
EIF	Education Investment Fund
eMII	electronic Marine Information Infrastructure (Facility 10)
EMS	Environmental Modelling Suite
ENSO	El Niño-Southern Oscillation
EnviSat	Environmental Satellite
EOV	Essential Ocean Variable
EPA Vic	Environment Protection Authority Victoria
EPOC	Ecosystem productivity ocean climate
ERS-2	European Remote-Sensing Satellite-2
eRSA	eResearch South Australia
ESM	Earth System Model
EuroGOOS	European Global Ocean Observing System
FAIMMS	Facility for Automated Intelligent Monitoring of Marine Systems (Facility 9)
FOO	Framework for Ocean Observing
FRDC	Fisheries Research & Development Corporation
ftp	file transfer protocol
GA	Geoscience Australia
GAB	Great Australian Bight
GAMSSA	Global Australian Multi-Sensor SST Analysis
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GCOS	Global Ocean and Climate Observing System
GDACs	Global Data Assembly Centres
GEOBON	Group on Earth Observations Biodiversity Observation Network
GHRSST	Group for High Resolution SST
GLOBEC	Global Ocean Ecosystem Dynamics
GLS	Global Location Sensor
GOC	Global Overturning Circulation
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GOSUD	Global Ocean Surface Underway Data
GPS	Global Positioning System
GSFC	Goddard Space Flight Centre
GTOPP	Global Tagging of Pelagic Predators
GTS	Global Telecommunications System
GTSPP	Global Temperature-Salinity Profile Program
GUI	Graphical User Interface
HF	High Frequency (radar)

Acronym	Full Title
HPC	High Performance Computing
HRPT	High Resolution Picture Transmission
HRX	Hi-density Expendable bathy-thermograph
IAPSO	The International Association for the Physical Sciences of the Oceans
IAST	International Argo Steering Team
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ICON	Integrated Coral Observing Network
IEEE	Institute of Electrical and Electronics Engineers
IFREMER	French national institute of marine research
IGBS	International Geosphere-Biosphere
ILTER	International Longterm Ecological Research
IMAS	Institute of Marine and Antarctic Studies
IMDIS	International Conference on Marine Data and Information Systems
IMOS	Integrated Marine Observing System
INSTANT	International Nusantara Stratification And Transport
IOC	Intergovernmental Oceanographic Commission
IOD	Indian Ocean Dipole
IODE	International Oceanographic Data and Information Exchange
IOMRC	Indian Ocean Marine Research Centre (UWA)
IOOS	Integrated Ocean Observing System – US
IP Camera	Internet protocol camera
IPCC	Intergovernmental Panel on Climate Change
IRF	Indian Ocean Resources Forum
ISO	International Standards Organisation
ISSNIP	Intelligent Sensors, Sensor Networks and Information Processing Network
ITF	Indonesian Through Flow
iVEC	Interactive Virtual Environments Centre
IWC	International Whaling Commission
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JCU	James Cook University
L2P	GHRSST-PP Level-2 Pre-processed data format for satellite sea surface temperature
L3P	GHRSST-PP Level-3 Pre-processed data format for satellite sea surface temperature
LAN	Local Area Network
LC	Leeuwin Current
LJCO	Lucinda Jetty Coastal Observatory (Sub-Facility, SRS)
LNA	Low Noise Amplifier
LOMS	Littoral Ocean Modelling System
LUC	Leeuwin Under Current
MAPSO	Monitoring Apex Predators in the Southern Ocean
MARVL	Marine Virtual Laboratory
MARVLIS	MARVL Information System
MCP	Marine Community Profile

Acronym	Full Title
MECOSED	Model for Estuarine and Coastal SEDiment Transport
MEOP	Marine Mammals Exploring the Oceans Pole to Pole
MEST	Metadata Entry and Search Tool
MHL	Manly Hydraulics Laboratory (NSW)
MICE	Models of Intermediate Complexity
MISA	Marine Innovation SA
MJO	Madden-Julian Oscillation
MNF	Marine National Facility
MODIS	Moderate Resolution Imaging Spectro-radiometer
MOM	Modular Ocean Model
MPA	Marine Protected Area
MQ	Macquarie University
MRU	Motion Reference Unit
MTSAT-1R	Japan's Multi-functional Transport Satellite
MV	Merchant vessel
NASA	National Aeronautics and Space Administration
NAVOCEANO	Naval Oceanographic Office
NCDC	National Climatic Data Centre
NCEP	National Centres for Environmental Prediction
NCRIS	National Collaborative Research Infrastructure Strategy
NDBC	National Data Buoy Centre
NDSF	National Deep Submergence Facility
NERP	National Environmental Research Program
NESP	National Environmental Science Program
netCDF	Network Common Data Form
NIES	National Institute of Environmental Science
NIWA	National Institute of Water and Atmosphere Research, New Zealand
NOAA	National Oceans and Atmospheric Administration (USA)
NOCS	National Oceanography Centre, Southampton (UK)
NODC	National Oceanographic Data Center
NPEI	National Plan for Environmental Information
NPZ	Nutrients Phytoplankton Zooplankton
NQC	North Queensland Current
NRETA	Ningaloo Reef Ecosystem Tracking Array
NRM	National Resource Management
NRS	National Reference Station mooring
NRSMPA	National Representative System of Marine Protected Areas
NSIP	Node Science and Implementation Plan
NSW OEH	New South Wales Office of Environment and Heritage
NSW-IMOS	New South Wales Integrated Marine Observing System (Node)
NWS	National Weather Service
OAS	Obstacle Avoidance Sonar

Acronym	Full Title
OceanMAPS	Ocean Modeling and Prediction System
OceanSITES	Ocean Sustained Interdisciplinary Timeseries Environment observation System
OPeNDAP	Open-source Project for a Network Data Access Protocol
OPSAG	Oceans Policy Science Advisory Group
ORG	Optical Rain Gauge
ORS	Ocean Reference Station
OSD group	Ocean Sensor Deployment group (CMAR)
OSDM	Office of Spatial Data Management
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
OSTST	Ocean Surface Topography Science Team
OTN	Ocean Tracking Network
PAR	Photosynthetically Active Radiation
PDO	Pacific Decadal Oscillation
PFRA	Publicly Funded Research Agency
PIES	Pressure Inverted Echo Sounder
PMEL	Pacific Marine Environmental Laboratory
PO.DAAC	Physical Oceanography Distributed Active Archive Center is located at the NASA Jet Propulsion Laboratory (JPL)
POAMA	Predictive Ocean Atmosphere Model for Australia
POST	Pacific Ocean Shelf Tracking
PULSE	Brand name for equipment
QA	Quality Assurance
QC	Quality Control
QCIF	Queensland Cyber Infrastructure Foundation
QIMOS	Queensland Integrated Marine Observing System (Node)
QMS	Quantitative Marine Science (UTAS postgraduate course)
RAMA	Regional Moored Array for African-Asian-Australian Monsoon Analysis
RAMSSA	Regional Australian Multi–Sensor SST analysis
RAN	Royal Australian Navy (Directorate of Oceanography and Meteorology)
RMS	Root mean square
ROAM	Relocatable Ocean Atmosphere Model
ROMS	Regional Ocean Modelling System
RV	Research Vessel
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SAIMOS	South Australian Integrated Marine Observing System (Node)
SAM	Southern Annular Mode
SAMOS	Shipboard Automated Meteorological and Oceanographic System
SARDI	South Australian Research and Development Institute
SAROM	South Australian Regional Ocean Model
SAZ	Sub-Antarctic Zone
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research

Acronym	Full Title
SEA-IMOS	South East Australian Integrated Marine Observing System (Node)
SEAPODYM	Spatial Ecosystem and Population Dynamics Model
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	South Equatorial Current
SEMAT	Smart Environmental Monitoring and Analysis Technologies
SENSEI	Integrating the Physical with the Digital World of the Network of the Future
SEQ	South East Queensland
SHOC	Sparse Hydrodynamic Ocean Code
SIMS	Sydney Institute of Marine Science
SIO	Scripps Institute of Oceanography (USA)
SLAM	Simultaneous Localization And Mapping
SMHI	Swedish Meteorological and Hydrological Institute
SOCAT	Surface Ocean Carbon Dioxide Atlas
SOFS	Southern Ocean Flux Station Meteorological Mooring
SOLAS	Surface Ocean Lower Atmosphere Study
SOOP	Enhanced Measurement from Ships of Opportunity (Facility 2)
SOOS	Southern Ocean Observing System
SOPAC	Secretariat of the Pacific Islands Applied Geoscience Commission
SOTS	Southern Ocean Time Series (Sub-Facility, DWM)
SPICE	Southwest Pacific ocean circulation and Climate Experiment
SRS	Satellite Remote Sensing (Facility 11)
SSH	Sea Surface Height
SSOS	Southern Seals as Oceanographic Samplers
SST	Sea Surface Temperature
STF	Sub-Tropical Front
T/S	Temperature/Salinity
TAO	Tropical Atmosphere Ocean
TasIMOS	Tasmanian Integrated Marine Observing System (Node)
TERN	Terrestrial Ecosystem Research Network
TERSS	Tasmanian Earth Resources Satellite Station
TMN	Tropical Marine Network
TO	Tasman Outflow
TOGA	Tropical Ocean Global Atmosphere program
TOPP	Tagging of Pacific Predators
TPAC	Tasmanian Partnership for Advanced Computing
TSG	thermosalinograph
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNSW	University of New South Wales
UPS	Uninterruptible Power Source
UQ	University of Queensland
US NODC	United States National Oceanographic Data Center

Acronym	Full Title
US NSF	United States National Science Foundation
USGS	United States Geological Survey
US-IOOS	United States – Integrated Ocean Observing System
USyd	University of Sydney
UTAS	University of Tasmania
UTS	University of Technology Sydney
UWA	University of Western Australia
VOS	Volunteer Observing Ships
VR2W	Submersible, single channel receiver with wireless technology capable of identifying coded transmitters, produced by the company VEMCO
WAIMOS	Western Australia Integrated Marine Observing System (Node)
WALIS	Western Australia Land Information Systems
WAMSI	Western Australia Marine Science Institute
WASTAC	Western Australian Satellite Technology and Applications Consortium
WERA	Brand name for equipment
WHOI	Woods Hole Oceanographic Institute
WMO	World Meteorological Organisation
WMO-GTS	World Meteorological Organisations Global Telecommunications System
WMO-VOS	World Meteorological Organisation Volunteer Observing Ships Programme
WMS	Web Map Services
WOCE	World Ocean Circulation Experiment
WOD	World Ocean Database
WOMBAT	Whole Ocean Model with Biogeochemistry and Trophodynamics
WQM	Water Quality Monitor
XBT	Expendable bathy-thermograph

IMOS Integrated Marine Observing System

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