Ocean biogeochemistry (incl. carbon cycle, ocean acidification, marine chemistry)

Abstract

Ocean biogeochemical research is central to determining the capacity of Australian regional seas and the Southern Ocean to take up and store carbon, supply oxygen to the deep sea, control biological productivity and biomass, and for determining the sensitivity of these processes to changing climatic conditions. Characterisation of ocean biogeochemistry also provides critical information on the exposure and consequences of ocean acidification for Australia’s marine ecosystems and biodiversity. Considering Australia's vast marine jurisdiction, limited resourcing presents major challenges, resulting in sparse or no data coverage for many regions and limited capacity to assess the impact of changing marine biogeochemistry on ecosystems and marine-based economies.

Background

CSIRO Oceans and Atmosphere has the major group of researchers covering a broad range of observational and modelling capabilities for research into biogeochemical cycling and change. The CSIRO scientists (15+ and teams) are based in Hobart, Brisbane, Perth and Melbourne, with research projects from the Antarctic shelf to the tropics and scales of reef/coastal to open ocean. Their expertise includes observing system development, biogeochemical cycling of carbon, nutrients and oxygen, ocean-atmosphere carbon and oxygen exchanges, coastal-offshore linkages, phytoplankton ecology, satellite oceanography and modelling from coastal to global scales. These researchers work closely with physical oceanographers on observations and modelling of circulation and mixing that can profoundly influence ocean biogeochemical cycling and ecosystem responses.

Expertise in trace element chemistry and micronutrient availability, which limits biological growth in many regions including the Southern Ocean, exists at the Institute for Marine and Antarctic Studies, University of Tasmania and Australian National University (4+ scientists and teams). Groups involved in research on marine primary production, satellite oceanography, and microbial ecology that can influence biological carbon and nutrient cycling are located at the Institute for Marine and Antarctic Studies, CSIRO, Curtin University, Institute of Marine and Antarctic Studies, Australian Antarctic Division, University of Queensland, University Technology Sydney, and University of New South Wales (12+ scientists and teams).

Most of the research in high latitude waters is coordinated through the Antarctic Climate and Ecosystems Cooperative Research Centre (ACECRC), which brings together scientists from Australian Antarctic Division, CSIRO, and the Institute for Marine and Antarctic Studies at the University of Tasmania. Research on biogeochemical cycling in coastal and reef regions is carried out by groups at the

Australian Institute of Marine Sciences, Australian National University, CSIRO, Curtin University, Flinders University, Geosciences Australia, Griffith University, James Cook University, Southern Cross University, University of Sydney, University of Adelaide, University of New South Wales, University of Queensland, Wollongong University, and University of Western Australia.

The funding to support research comes from a variety of sources. The Integrated Marine Observing System (IMOS) funds some sustained biogeochemical observations for Australia in surface and shelf waters, including the Southern Ocean Time Series, and underway and national reference station observations. High latitude research is also supported through the Department of the Environment, Australian Antarctic Division, Australian Research Council, and the Antarctic Climate Ecosystems Cooperative Research Centre. For coastal and tropical waters, the funding is typically through the Australian Research Council, Department of the Environment, state government departments, with some industry funding for research specific to the Great Barrier Reef.

International links substantially enhance the footprint of the Australian research effort through joint observational and modelling programs (e.g. USA, France, UK, Japan, India, Germany, South Africa, and China) and through the provision of satellite based data and products by NASA. Numerous organisations linked to the UNESCO International Oceanographic Commission, Global Ocean Observing System, Scientific Committee of Ocean Research, International Ocean Carbon Coordination Project, Global Ocean Acidification - Observing Network, GEOTRACES (Marine Biogeochemistry of Trace Elements and their Isotopes), and programs within the International Geosphere - Biosphere Program support Australian biogeochemical researchers participation in international science panels and research initiatives.

Access to ships is a critical element of the research effort, and support for limited ship time is provided through competitive proposals for the Australian Marine National Facility and to a lesser degree the Australian Antarctic Division. The new RV *Investigator* operated by the Marine National Facility is capable of supporting coastal to offshore research down to the sea-ice edge. The SRV *Aurora Australis* is the only ship with ice breaking capability needed for Southern Ocean research. Ships of opportunity (e.g. collaboration with industry and overseas research institutions) are availed of where possible. Some institutions have coastal vessels (e.g. AIMS, state government departments), which have limited time available on a user pays basis for researchers outside the vessels home institution. These are typically small coastal vessels that limit the scope of research that can be carried out. The Australian Museum, University of Queensland, James Cook University, and the University of Sydney maintain coastal research stations that provide platforms for shelf-based observational networks.

Relevance

Ocean biogeochemistry links physical and biological systems from coasts to offshore. The research provides data to assess ocean acidification change, the role of the ocean as the major long-term sink for anthropogenic carbon dioxide, and the ocean roles in regulating the oxygenation of the deep-ocean, nutrient cycling, and productivity. Biogeochemical observations and models also provide diagnostic tracers to determine how ecosystems are functioning and ecosystem responses to a changing environment, including the response to ocean acidification.

Government, intergovernmental agencies, and the research community are major users of the research output, including input to the Intergovernmental Panel on Climate Change (Rhein et al, 2013). Measurements of ocean carbon and related tracers contribute to the essential ocean variables listed by the United Nations Framework Convention on Climate Change and to the national Australian plan for implementing climate science (Australian Government, 2012). There is a growing awareness of the threat of ocean acidification to marine ecosystems (Hennige et al., 2014) and biodiversity (Secretariat of the Convention on Biological Diversity, 2014). The need to develop policy options related to detection of ocean acidification change and evaluation of mitigation and adaptation strategies is increasingly being recognised (Herr et al., 2014). United Nations initiatives such as Blue Planet (GEO, 2014) also identify the need for ocean carbon and acidification monitoring.

The capacity of science to inform government on threats to ecosystem structure and biodiversity relies on understanding biogeochemical cycles and the sensitivity to changes in environmental conditions. Ocean acidification is recognised as a significant threat to the long-term health of marine ecosystems in Australia's marine jurisdiction (e.g. Great Barrier Reef Marine Park Authority, 2014). Analyses aimed at informing policy makers of biogeochemical change, including ocean acidification, and the likely consequences for ecosystems are emerging (ACECRC, 2008a; Howard et al., 2012), as are inputs to government on the efficacy of modifying biogeochemical cycles through geo-engineering as a way to manage or enhance ocean carbon sinks (e.g. iron fertilisation; ACECRC, 2008b, coastal carbon storage; Fourqurean et al., 2012). Government departments such as the Department of the Environment benefit as the agency responsible for managing Commonwealth Marine Reserves by receiving science products that promote awareness and understanding of threats to marine ecosystems and help to support the setting of priorities for the management of reserves.

The threat of ocean acidification and other stressors, such as ocean warming and hypoxia to ecosystems requires determination of the complex physical-chemical-biological interactions that will influence the response, adaptive capacity, and connectivity of ecosystems to the changes. Integrated biogeochemical modelling and sustained observations can be used to quantify these interactions and provide a foundation for the development of management strategies. The biogeochemical tracers also provide the means to diagnose how ecosystems are responding to change. The application of marine biogeochemistry will become increasingly important for addressing economic and societal concerns, for example, in detection and prediction of shifts or tipping points in coral reef ecosystems from conditions of net growth to net loss of reef, changes in ocean carbon storage efficiency, the potential for altered productivity of our seas, and in determining if changes in acidification could impact commercial food production (Cooley et al., 2012; Narita et al., 2012; Waldbusser et al 2013; Mathis et al., 2014).

Australia currently has a lead role in marine biogeochemistry research for the Southern Hemisphere, including the assessment of ocean acidification change relevant to neighbouring island countries (Australian Bureau of Meteorology and CSIRO, 2011). Unfortunately, the coverage for the Australian region remains sparse and infrequent. Other nations with rapidly growing research efforts in marine biogeochemistry in the Southern Hemisphere (e.g. China, India, Japan, Korea and the USA) may provide some future coverage of the seas around Australia and the waters of the Australian Antarctic Territories. However, these other nations are unlikely to prioritise Australian interests and research needs above their own interests. An active and leading effort by Australia will be needed to ensure proper coverage and an understanding of the consequences of biogeochemical change in its own region.

Science needs

Marine biogeochemistry is intimately linked to physical and biological processes and provides a unique perspective on how these processes are changing. Important insights into the evolution of the coupled physical and biological system are generated by marine biogeochemistry. Research in this area can address three important science needs:

1. Quantification of the role of the ocean in the global biogeochemical cycles and carbon-climate feedback. Large-scale changes in biogeochemistry of the ocean are occurring (Gruber, 2011). The ocean is an important sink for anthropogenic CO_2, accounting for uptake of about 25% of annual emissions and about 40% of the ocean uptake occurs in the Southern Ocean (Sabine et al., 2004; Khatiwala et al., 2009). Changes in processes that regulate the size of the ocean sink and the rate of ocean carbon uptake could significantly alter the global carbon budget with important implications for world climate (e.g. Zhang et al., 2014). Major vulnerabilities in the future behaviour of the ocean-carbon-climate system include the effects of ocean warming, enhanced vertical stratification, strengthening and shifts of westerly winds in the Southern Ocean, and shifts in the biological carbon pump and ecosystem functioning that could alter carbon and nutrient cycling (Doney et al., 2009).

2. Detecting ocean acidification change and the impact on marine ecosystems. The uptake of carbon dioxide by the ocean and the resulting change in ocean acidity and carbon chemistry can impact a range of biological processes including calcification, dissolution, production, respiration, larval development, and even the behaviour and survivability of fish. The changes have potential to cause widespread disruption of marine ecosystems and marine-based economies (Tribollet et al., 2006; Moy et al., 2009; Wild et al., 2011; Hoegh-Guldberg and Andrefouet, 2011, Nilsson et al., 2013; Mathis et al., 2014). Baseline conditions from coastal to offshore regions for ocean acidification are needed to determine the exposure and vulnerability of marine ecosystems and to detect ecosystem responses.

3. Assessing food security and marine ecosystem resilience. Marine biogeochemical cycles are influenced by changes in the physical environment as well as influencing how the biology responds to environmental change (Matear and Lenton, 2014). Evidence of changes in large-scale biogeochemical fields (e.g. de-oxygenation of the deep-sea waters, nutrient and trace element availability, and ocean acidification) could result in changes in ecosystem function, biodiversity, and primary productivity (e.g. Boyd et al., 2007; Bopp et al., 2013; Matear et al., 2013; Matear et al., 2014; Moore et al., 2013). Evaluation of food security and ecosystem resilience will increasingly require an understanding of the linkages between ocean biogeochemistry and the structure and function of marine ecosystems (Cooley et al., 2012; Waldbusser et al., 2013; Mathis et al., 2014).

Key gaps/challenges

To address the science needs in marine biogeochemistry there are a number of gaps to overcome:

1. The development of a more comprehensive biogeochemical observing system to detect and attribute change in biogeochemical cycling is a primary need. Vast areas of Australian coastal to offshore regional seas and the Southern Ocean are unsampled. High-quality biogeochemical measurements including the use of new measurement technologies on sensor-equipped profiling floats, gliders and moorings can substantially enhance the existing ship and satellite based observations. This will provide a major step change in the capacity to deliver sustained biogeochemical observations needed to characterise variability and detect trends, and to develop satellite remote sensing products specific to the Southern Ocean and Australian regional seas. The observing system should be integrated with the delivery of data products for a range of parameters (ocean acidification change, calibrated satellite products, carbon, oxygen, nutrient and trace element distributions, primary productivity and biomass) in order to establish baseline conditions. These parameters are themselves sensitive indicators of global change and ecosystem response, and are the foundation of assessing vulnerability and resilience of marine ecosystems to change. The integration of marine biogeochemistry with ecological research on the distribution of indicator species (e.g. pteropods and deep-sea corals) and on other ecosystem markers like sediment carbonate mineralogy can provide further links to understand ecosystem responses to changes in the biogeochemistry.

2. Process understanding needs to be developed to model and quantify the consequences of environmental change on key biogeochemical processes, marine biota and ecosystems. A large number of these processes are likely to be sensitive to changing environmental conditions, and in order to predict changes in the system, studies of physical and biological drivers are required across a broad range of biogeochemical domains from the Southern Ocean to the tropical seas.

3. The third major requirement for the research is greater integration of observations and models. The system is a complex and it is not possible to observe and model all processes. Eddy-resolving and high-resolution nested biogeochemical models linking coastal-shelf-offshore waters will deliver better representations of the level of biological and physical complexity needed to characterise potential impacts for many regions. Data assimilating biogeochemical models provide a novel way to integrate observations into modelling. This will require an adequate observing system with quantification of observation errors and the assimilation of data actually measured (e.g. radiance rather than chlorophyll derived from ocean colour). The data assimilating models will benefit from the enhanced exploitation of remotely sensed data and has the potential to deliver products that are difficult to measure directly (e.g. secondary production). The required level of sophistication necessary to represent the physics and biology in models will need to be informed through observational and process study research. Here, key questions are:

> a) What is the adequate spatial resolution required to simulate biogeochemical cycling in the ocean (e.g. are eddy resolving or higher resolution biogeochemical simulations required?
> b) What level of biological complexity is required to characterize potential impacts of environmental variability and change (e.g. is it necessary to couple the food web to the BGC models?).

Key Outcomes:

The research will deliver a range of outputs designed to improve understanding of marine biogeochemical cycling and projections of the human impact on these cycles to guide and contribute to sustainable management and exploitation of marine resources and ecosystems.

- Data products to quantify the variability and long-term trends in biogeochemical properties (e.g. carbon, oxygen, nutrients, trace elements) from around Australia and the Southern Ocean, including satellite products calibrated and tested against data from the region.

- Detection of ocean acidification and the quantification of the processes driving change across coastal-shelf-offshore scales and ranging from tropical to high-latitude shelf systems.

- Global carbon budgets have more certainty through the quantification of the ocean sink, which, used in combination with anthropogenic emission estimates and atmospheric measurements, is the primary method for estimating the size of the land biosphere sink and how it is changing.

- Quantification of the role of Australian regional seas and the Southern Ocean in the uptake and storage of anthropogenic CO_2, and the processes driving shifts in the uptake efficiency that may alter the rate of accumulation of CO_2 in the atmosphere and the future climate.

- Determinations of the role of the major current systems around Australia (i.e. East Australian Current, Leeuwin Current, Antarctic Circumpolar Current) in controlling carbon uptake and the potential for change.

- Improved understanding of controls on productivity and biological carbon export from the surface ocean, and the sensitivity to changing environmental conditions.

- Assessments of the role of the Southern Ocean in oxygenating the deep-sea and supplying nutrients to support primary production in tropical and subtropical regions.

- Improved understanding of coast-offshore interaction and the role of shelf processes and feedbacks in influencing biogeochemical cycles.

- A biogeochemical modelling system working across multiple domains (coastal, reef, shelf, offshore, atmosphere and land) for a range of time and space scales to diagnose controls on biogeochemical cycling and predict future change.

- Improved projections by employing better models guided by new process understanding and observations.

- Better assessment of the risk of ocean acidification to ecosystem services and marine ecosystems, including mapping regions of risk at a national scale that can be used to guide the development of adaptation and management strategies.

- An integrated system to examine and test mitigation options to reduce future impacts of climate change and ocean acidification on marine systems.

- Australia maintains a leadership role on Southern Hemisphere biogeochemistry research with input to global programs through covering regions of importance to Australia and immediate neighbours (e.g. Great Barrier Reef, SW Pacific, and Southern Ocean).

Perspective

Priorities

- **Implement a sustained biogeochemical observing system capable of detecting seasonal through interannual variability and long-term trends in biogeochemical cycles, ocean acidification and the feedbacks in carbon uptake**. Long-term time series and other sustained measurements of biogeochemical variables are critical to establishing baseline conditions in order to detect emerging trends that signal shifts in biogeochemical cycles and ecosystem functioning. Without Australia taking a lead in its own jurisdiction, vast ocean areas relevant to Australia will remain uncovered. The observing system should include repeat ocean sections, underway measurements from ships, and sustained time-series stations that can build on existing IMOS infrastructure. Profiling floats with nutrient, pH, oxygen and bio-optical sensors are a cost-effective approach for some parameters and permit year round coverage to enhance more traditional measurements needed for calibration of the autonomous sensors. Observations should be directly linked to synthesis of these data and the delivery of data products to maximise use of outputs and accessibility. The observing system needs to cover the coastal to offshore regions from the tropics to the high latitude waters of the Southern Ocean, which has such an important role the global carbon budget and the ventilation of the deep sea. The observing system also needs to conform to internationally agreed measurement protocols for core essential ocean variables being defined by the GOOS Biogeochemistry Panel (GOOS, 2014), with additional parameters considered to meet research needs (e.g. essential variables of GOOS Biology Panel). Data reporting standards and quality control procedures established by groups like the International Ocean Carbon Coordination Project (http://www.ioccp.org) should be followed rigorously to allow data sharing and incorporation into the global observing system databases (e.g. GEOTRACES; Schlitzer (2012), Carbon Dioxide Information Analysis Centre; http://cdiac.ornl.gov/oceans). The generation of data products like the Surface Ocean CO_2 Atlas (Bakker et al., 2013), and synthesis products including anthropogenic carbon storage (Sabine et al., 2004), air-sea CO_2 flux (Takahashi et al., 2009), and global carbon budgets (Le Quéré et al., 2014) provide mechanisms to translate the observations into outputs for use in earth system modelling, and assessing the impact of changes on ecosystems and food security.

- **Process studies to improve understanding of biological and physical interactions in key regions**. There is currently little data to assess biogeochemical cycling in the shelf to offshore waters of the Indian Ocean and Northern Australia and large parts of the Southern Ocean. Process studies aimed at characterising/determining the controls and feedbacks on carbon and nutrient cycling at the mesoscale, shelf-offshore interactions, coastal habitats, and in the seasonal sea-ice zone and sub-polar regions would be valuable for quantifying the changes in the ocean carbon uptake. The role of microbial processes in controlling the production, turnover and transport of carbon and nitrogen including nitrogen fixation, are poorly known for most ocean environments in our region. In addition, process studies to better document and understand bio-optics relationships in Australian waters will deliver improved biogeochemical satellite products for the region.

- **Develop improved models including higher resolution with more detailed representation of biological and physical processes, integration of coastal to offshore models, and exploitation of data assimilating technology.** Model-data integration will deliver better assessments of changes in biogeochemical processes and ocean acidification that could influence future climate, food security and ecosystem resilience. A key component of the modelling effort should be to make the model results accessible to the research community and to provide rigorous model-data comparisons like the Regional Carbon Cycle Assessment Project (Lenton et al., 2013) to help guide observational needs and model development.

- **Closer integration of land, ocean and atmosphere carbon cycle research.** Observations and models within each domain can provide valuable insight into the global carbon cycle. For example, surface ocean carbon uptake estimates combined with atmospheric measurements of CO_2 are the main constraints used to determine carbon uptake by the land biosphere. Improved integration of research across these domains will help resolve the global carbon budget, ensure consistency across the three domains and provide new ways to monitor, detect and predict how the global carbon cycle is evolving. The influence of the atmospheric sources of nutrients (e.g. nitrogen and iron) on marine productivity and the cycling and the air-sea exchange of biogenic gases like nitrous oxide and dimethylsulphide are other aspects of ocean-atmosphere coupling that are poorly known in the Australian region. The Australian research ship, RV *Investigator*, provides new capability for integrated ocean-atmosphere research.

- **Develop stronger links across other components of the National Science plan** to deliver improved multidisciplinary science. The biogeochemistry will be important input to link biological and physical processes across the various components of the science plan: Dealing with Climate Change, Biodiversity Conservation and Ecosystem Health, Coastal Environments and Infrastructure.

- **Research priorities vary with regions**:

  - Southern Ocean: carbon uptake and the influence on the global carbon budget, the detection of seasonal through interannual variability and long term trends in carbon uptake and ocean acidification and the drivers, detection of the pathways for anthropogenic carbon transport to the ocean interior, the role of the Southern Ocean in deep-sea oxygenation and nutrient supply, controls on production and biological carbon export including macro and micronutrient availability, the impact of changing environmental conditions (sea ice extent, warming, stratification, winds) on biogeochemical cycling and the biological carbon pump response, ocean acidification change and the drivers for shelf and offshore waters.

- SW Pacific and Indian Ocean, including Southern and Northern Australia: carbon uptake, nutrient cycling and acidification change from coastal to open ocean regions, the role of the major current systems and shelf-offshore interactions in regulating carbon uptake and the biological carbon pump, the potential for changes in warming, stratification, shelf-offshore exchange and major currents to alter biogeochemical cycling, ocean acidification and productivity. The expansion of low oxygen conditions in the subsurface waters of the northern Indian Ocean is a global concern, and is of particular importance to Indian Ocean rim nations.

- Coastal and Shelf Seas: The influence of estuaries, sediment-water and coast-shelf-offshore exchanges on biogeochemical cycling, acidification, and carbon storage across major habitats. For example, how do shelf-offshore exchanges of water and local biogeochemical processes interact to regulate acidification change for shelf and coral reef waters? How does ocean acidification influence the dissolution of carbonates for shelf and reef environments? The potential for ocean acidification to shift coral reefs from conditions of net calcification to net dissolution is a major concern (Hoegh-Guldberg and Andrefouet, 2011), both for Australia and for Pacific and Indian Ocean neighbouring states whose economies and food security are reliant on healthy reef ecosystems (SIDS, 2014). The impacts of processes such as ocean dredging, riverine inputs, sedimentation and coastal pollution on biogeochemical cycles at local or coastal scales should be addressed through coordination with the coastal component of the National Marine Science Plan.

- **Encourage more integration of Australian science effort** across universities, commonwealth and state institutions to maximise the use of the research expertise.

- **Leverage international collaborations to share resources and increase the footprint of the research** through:
  - participation in international panels and reports (e.g. IPCC, IGBP SOLAS/IMBER, Global Ocean Acidification - Observing Network, Global Carbon Project, International Ocean Carbon Coordination Project) and location of international project offices in Australia.
  - Australian component of multinational partnerships funded to deliver process studies and observations (e.g. GEOTRACES, Southern Ocean Time Series, underway CO_2 measurements, increased contribution to calibration of international satellite missions).

- encourage multinational research programs and initiatives with nations active in the region (United States, Japan, China, New Zealand, Southwest Pacific Island nations, India, Indonesia, South Africa).
- development of global data products, synthesis efforts and model-data comparisons.

Realisation

- Adequate funding is needed for platforms, technical and research synthesis support for sustained observations, process studies and integrated modelling. The potential impacts of biogeochemical cycle changes encompassing global, regional and local scales and observations directed at these different scales are required. The support needs to cover observations through to data synthesis to maximise efficiency.

- Support for international research initiatives that promote Australia's needs and accelerate the efficient use of new technology and the delivery of cutting edge science. The Southern Ocean Carbon and Climate Observations and Modelling program (SOCCOM) is an example of where investment by Australia can result in high value research outcomes. The US-led SOCCOM program is an initiative to deploy new and proven biogeochemical sensor technology (pH, nutrients, oxygen and bioptics) on profiling floats in the Southern Ocean and is integrated with the development of the latest high-resolution earth system models. Collaboration with SOCCOM through investment in acquiring and deploying floats in the Australian sector of the Southern Ocean and through modelling efforts is an example where Australia can deliver to its own regional priorities for research and at the same time build partnerships with major overseas institutions. Other examples of significant international collaboration are Australian contributions to global biogeochemical programs to map the distribution of trace elements (GEOTRACES) and to determine decadal change in carbon, oxygen and nutrients throughout the ocean (CO_2/CLIVAR). Australian efforts for GEOTRACES and CO_2/CLIVAR cover Southern Hemisphere waters that are of major importance for regulating biogeochemical cycles. Funding for international project offices in Australia (e.g. Southern Ocean Observing System and Global Carbon Project) are a mechanism to strengthen research ties with other nations and develop multinational collaborations.

- Regional-specific biogeochemical research is funded to enhance sustained observations and synthesis efforts and to build research capacity in neighbouring countries. Support for biogeochemistry research in programs such as the Second International Indian Ocean Expedition (IIOE-2) and research on acidification change for coral reefs of our Pacific and Indian Ocean neighbours will deliver research of relevance to Australia and help develop research capacity in the region.

- High performance computing resources are needed to enable state of the art simulations of the carbon climate feedback, projection of ocean acidification, and projection of changes in biogeochemical processes at both the global and regional scales.

- Funding for data storage infrastructure with sufficient computational resources to efficiently share observations and model simulations to enable the analysis and exploitation of these data products by the entire scientific community.

- A better mechanism is needed to link research ship proposals with other funding proposals to avoid the present situation where a proposal for a ship time can be successful and matching funds to support research on the voyage is not successful.

- Improve mechanisms for research ship time to be allocated to proposals for sustained observations are needed in addition to the shorter term process studies favoured by the existing system.

- Establish multidisciplinary research initiatives across universities and institutions to allow research on the impacts of environmental change on marine ecosystems and the economic consequences with more direct links to policy. Regional focus areas similar to Long Term Ecological Research efforts that cover representative areas of relevance to Australia (Antarctic shelf, subpolar waters, coral reef systems, temperate and tropical shelves) will facilitate substantially improved links between observations through to modelling than is currently possible.

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