Bluewater & Climate Node Science and Implementation Plan 2015-25

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.

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1 Executive Summary

The Bluewater and Climate Node (BCN) provides the scientific rationale for the collection of observations from the open ocean region surrounding Australia and Australia's Antarctic territories. The Science and Implementation Plan of the Bluewater and Climate Node represents a community-wide view of the key scientific questions and the sustained observations needed to address them. The plan covers the period 2015 to 2025.

Observations from the open ocean are essential for improving understanding of the ocean's role in climate and for tracking the evolution of climate change on decadal time-scales. Australia's highly variable climate is sensitive to conditions in the surrounding oceans and measurements of the open ocean provide the primary source of information used to anticipate floods and droughts associated with climate modes like El Niño and the Indian Ocean Dipole. Bluewater observations are also critical for ocean prediction on time-scales of days to weeks. Continental shelf and coastal waters are strongly influenced by offshore conditions and open ocean observations are therefore also needed to support the regional nodes of IMOS.

Sustained observations of the open ocean have traditionally been limited to physical variables like temperature, salinity and currents. There is growing recognition, however, that understanding climate change and its impacts requires measurements of a wide range of biogeochemical and ecological variables. The Node Plan articulates a strategy for an integrated sustained observing system to provide these measurements.

The science challenges identified by the node span time-scales from days to decades, space-scales from 10 to 10,000 km, and a geographical domain extending from the tropics to Antarctica and from the central Indian to the central Pacific Ocean.

The Science and Implementation Plan is targeted to address issues highlighted in national priority-setting documents including the National Framework for Climate Change Science, Marine Nation 2025, the Australian Antarctic Science Strategic Plan, and the Australian Strategic Research Priorities such as "Living in a Changing Environment" and "Managing our Food and Water Assets."

The four major areas of research driving the Bluewater observing system design are:

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

The Bluewater and Climate Node research community includes Australian scientists tackling a wide range of issues of direct relevance to the nation, including: climate change and its impacts; sea-level rise; changes in the global water cycle; seasonal-to-interannual climate variability; ocean carbon uptake and acidification; biodiversity; and management of marine resources and ecosystems. The BCN is closely integrated with national and international research efforts; in particular, the open ocean observations collected by IMOS are the primary data streams used by Australia's climate and ocean circulation research communities. Co-investment by a wide range of national and international stakeholders results in substantial leverage of the Commonwealth investment in IMOS infrastructure.

The BCN Science and Implementation Plan should be read in conjunction with the IMOS National Science and Implementation Plan 2015-25. In particular, the National Plan includes more detailed information on the status of the IMOS bluewater observing system and a summary of implementation plans for each of the IMOS Facilities that provide data to the BCN node. To allow the BCN Node Plan to stand alone, some of the scientific background is repeated in the two documents.

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2 Introduction

As an island continent, Australia's climate, environment, economy and communities are strongly influenced by the surrounding oceans. The Integrated Marine Observing System (IMOS) provides infrastructure needed by researchers to observe, understand and predict Australia's oceans. The Bluewater and Climate Node takes responsibility for articulating the science needs and observing system design driving IMOS investment in the open ocean, beyond the coastal and shelf seas that are the domain of the regional nodes. The open ocean domain of relevance to IMOS extends from the tropics to Antarctica and from the central Indian Ocean to the central Pacific Ocean.

The Science and Implementation Plan is organised as follows. The socio-economic context motivating investment in open ocean observations is summarised in Section 3. Section 4 provides an overview of the scientific background for six themes of research of relevance to the Bluewater and Climate Node: ocean change on time-scales of decades and longer; climate variability and weather extremes; boundary currents and inter-basin flows; continental shelf and coastal processes; ecosystem responses; and ocean prediction. The discussion of each research theme concludes with a summary of the status, gaps, opportunities and priorities for future enhancement of the IMOS infrastructure relevant to each theme. Usage of IMOS data by the Bluewater and Climate Node is discussed in Section 6. Section 7 provides an overview of major achievements and impacts of Bluewater and Climate Node science using IMOS data. The governance, structure and support for the node is described in Section 8.

3 Socio-economic context

The Bluewater and Climate Node has the task of determining a comprehensive, integrated and multi-disciplinary set of observations designed to address some of the major science questions relating to Australia's oceanic environment. A summary of the main socio-economic drivers of these questions is included in the following sections.

3.1 Managing a Variable and Uncertain Climate

The strong variability characteristic of Australia's climate is driven by interaction between the atmosphere and the surrounding oceans, in particular the western Pacific, eastern Indian and Southern Oceans. Due to our reliance on commodity exports and our large agricultural sector, Australia has a climate sensitive economy. For example, many areas of the economy are adversely impacted by climate variability with a $10B (1.6%) decrease in GDP associated with droughts, while in regional Australia the impact is much larger at 10% (Adams et al., 2002). Drought conditions also impact on water supplies to our cities, causing disruption and hardship for citizens and industries. Improved climate prediction on seasonal timescales can help mitigate these impacts in the natural terrestrial environment, agricultural sector, water management and health and disaster mitigation systems (e.g. bushfire risk). Many of these sectors already utilise seasonal climate forecasts, both from national and international operational centres. Improved predictions will immediately benefit these sectors. Even modest predictive skill can greatly benefit farming systems (McIntosh et al., 2005). The science of seasonal climate forecasting relies on timely and accurate ocean data streams and enhanced understanding of upper ocean processes and atmosphere/ocean coupling.

3.2 Rising Sea Levels, Warming and Aridification under Climate Change

As a continent located largely in the latitudes of the 'desert belt' (downwelling limb of the atmospheric Hadley circulation), the most populous and agriculturally productive regions of the Australian continent are likely to experience substantial warming and drying over the next decades due to anthropogenic climate change. On a continental scale, the widely predicted poleward migration of the Hadley Circulation suggests that the temperate zone will move out over the ocean, aridifying southern Australia. Australia is also a coastal nation: 86% of the population lives within 50 km of the coast along with much of our infrastructure. Australians are thus highly vulnerable to sea level rise. The 2009 House of Representatives standing committee on climate change report emphasised the importance of sea level rise, extreme sea level events and regional variations in sea level rise, and specifically recommended increased investment from the Australian Government across these areas (Commonwealth of Australia, 2009).

Australian policy makers and the public require more thorough and timely global and regional assessments of ongoing changes in our climate, oceans, ice-sheets and terrestrial systems. Improved projections are also needed to underpin adaption. However, much more regionally detailed information is required, as well as better information on the rates of change. This remains a huge challenge to the global climate research community, as coupled modelling systems do not agree on regional responses (particularly in the tropics and for rainfall). Unresolved natural decadal variability and poorly modelled ocean processes play a role in this uncertainty.

Even with truly quantitative predictions, an adaptive approach to managing risk is needed, guided by timely observations of how the system is responding to changes in forcing.

Thus, monitoring is required for

- early detection of large or rapid shifts in the climate and marine ecosystems
- developing climate change mitigation and adaptation policies
- tracking the effectiveness of national and international policy interventions

As one of the few Southern Hemisphere nations with the required technical and scientific capacity, Australia has a responsibility and is well positioned to monitor key aspects of the Southern Hemisphere climate system and its impacts on the marine ecosystem. Without this knowledge, climate change assessments will be biased towards the Northern Hemisphere (as is true for the current Intergovernmental Panel on Climate Change (IPCC) assessments). It is imperative that we monitor climate responses in our region and develop an observational capability to support the development of parameterizations and model testing. Further, our climate change assessments are biased towards observing physical systems on land and in the atmosphere. The biogeochemical and ecological responses and feedbacks in the ocean have been, to varying extents, overlooked (Richardson and Poloczanska, 2008).

3.3 Stewardship and Conservation of Biodiversity

Under the United Nations Convention on the Law of the Sea (UNCLOS), Australia has one of the largest marine jurisdictional zones in the world (Figure 2.1). This zone comprises about 16 million km^2, excluding Antarctica, is double the Australian landmass and includes some 4.4% of the global ocean area. The UNCLOS allows nations to claim territorial seas (which extend 12 nm from the coastal baseline), a 200 nm exclusive economic zone (EEZ) and a legal continental shelf. In some places, Australia's continental margin extends further out than the 200 nm limit. Australia’s marine area includes about 12,000 islands and some of these islands have an important role in extending Australia’s EEZ, and hence our marine responsibilities. Australia shares maritime borders with six other nations - Indonesia, Papua New Guinea, Solomon Islands, New Zealand, Timor Leste and France (New Caledonia).

Figure 2.1: Australia’s Exclusive Economic Zone (EEZ).

Australia has a long history of leadership in Antarctica and the Southern Ocean. Australia’s influence in the Antarctic Treaty system is to a large degree founded on the quality of its science in Antarctica and the Southern Ocean. Sustained observations of the Australian sector of the Southern Ocean are one means of demonstrating the physical presence and stewardship needed to support Australia’s sovereignty in the region. Fisheries in the Southern Ocean are managed under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), with Australia playing a key role in research and southern ocean fisheries management. Australia plays a leading role in the International Whaling Commission’s (IWC) assessment of Southern Ocean whale stocks and in managing these stocks within the IWC framework. There are large and longstanding Australian research programs in stock assessment, biological studies and management for Southern Ocean pinniped populations.

Australia's ocean domain includes all five of the world's ocean temperature zones - tropical, subtropical, temperate, subpolar and polar. These habitats contain a wealth of fauna and flora, most of which are unique to Australia. Under the Environmental Protection and Biodiversity Conservation (EPBC) 1999 Act, Australia has a responsibility to not only protect marine biodiversity but to have inventories of what is there and its ecological role.

Given the high endemism of marine species in Australian temperate waters and the fact that our tropical species from the Indo-West Pacific are sometimes a last refuge for some species affected by degrading environments in neighbouring countries, it is imperative that Australia have long-term baselines to know how our marine biodiversity is being affected by climate change (e.g. Pittock 2003; Poloczanska et al., 2007). It is thus imperative that we not only observe the physical and chemical changes in the marine environment, but also the biological changes that will have ecological and socio-economic consequences, and will also influence the pace and extent of climate change itself.

3.4 Sustainable Use of Marine Resources:

Australian policy requires that we maintain healthy and properly functioning ecosystems, and that this is best achieved by managing the marine ecosystem in an integrated way (Australia's Oceans Policy 2000). Data that quantify the response of ocean physics, chemistry and biology to climate variability is needed as part of this integrated ecosystem based management. Examples include ecosystem based fisheries management (EBFM) and in the planning for Bluewater Marine Protected Areas (MPAs).

Marine ecosystems also provide major economic and social values through commercial and recreational fishing and marine aquaculture. The Australian Fishing Zone is the third largest in the world, covering nearly nine million square kilometres. Australia has more than 20 Commonwealth fisheries worth ~ $320 million in production value alone, generating more than 45,000 tonnes of catch. The gross value for the entire Australian fisheries production including state fisheries and aquaculture is about $2.23 billion in 20010-011 (Skirtun et al., 2013). Climate change is expected to have dramatic impacts on fisheries and aquaculture through changes in temperature, ocean currents, winds, nutrient supply, rainfall, ocean chemistry, and extreme weather conditions (Denman et al. 1996, Cox et al. 2000, Bopp et al. 2001, Boyd and Doney 2002).

3.5 Defence and Security:

Australia's defence and security rely on the ability to operate in the maritime environment of the Australian region, and specifically to defend the air and sea approaches to Australia. The physical oceanography of our region is extraordinarily complex: the highly dynamic East Australian Current and Leeuwin Current dominate the east and west coasts, respectively; the poorly-understood Indonesian Throughflow affects the waters to our north; extreme tidal variation occurs in the Timor and Arafura Seas, and on the North West Shelf; upwelling events take place in some coastal regions; and internal waves dominate the physical oceanography of the North West Shelf and the Coral Sea. The Australian Government's Defence White Paper 2009 (Defending Australia in the Asia Pacific

Century: Force 2030[1]) lays out a vision for a large and capable submarine force, and greatly improved Anti-Submarine Warfare (ASW) capability for the Royal Australian Navy (RAN). A deep understanding of the oceanography of the Australian region (ranging from physical circulation, to production of sedimentary particle clouds, to biological sources of noise), and an ability to monitor and predict them, will be required to ensure the maximum effectiveness of these new defence capabilities.

[1] http://www.defence.gov.au/whitepaper/docs/defence_white_paper_2009.pdf

4 Scientific Background by Major Research Theme

4.1 Multi-decadal ocean change

The global oceans constitute the primary source of thermal inertia of the climate system and also contain the largest pool of active carbon in our planetary system. Thus, they are a key player in setting the rate at which anthropogenic greenhouse gases build up in the atmosphere and how fast the surface warms in response to the radiative forcing that results. Tracking and understanding the processes by which both carbon and heat are sequestered into the global oceans is therefore essential for monitoring rates of global change and for informing Earth System Models (ESMs) used to project future climate. Australia has a substantial effort in developing an Earth System Modelling capability through the multi-agency ACCESS project (http://www.accessimulator.org.au/). The ACCESS team has used IMOS measurements of sea surface height, ocean heat and salt content, and transport of boundary currents for testing and improving model performance.

4.1.1 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, 2012; Rhein et al., 2013). Tracking changes in ocean heat content is therefore the only way to quantify the global radiation imbalance resulting from the warming action of the long-lived anthropogenic greenhouse gases and the net cooling effect of natural and anthropogenic aerosols (IPCC, 2013). Multi-decadal changes in ocean heat content can be tracked with confidence only in the upper 700 m since 1970 because of a lack of data at deeper depths and from earlier times. Limited sampling of the deep ocean shows evidence for warming between 700 and 2000 m (Levitus et al., 2012) and below 4000 m (Purkey and Johnson, 2010, 2013), suggesting the deep ocean is a significant global heat sink. The global distribution and rate of ocean warming must be known to track the rate of climate change and to inform earth system models – such models will only provide useful projections if they accurately represent the mechanisms and pathways responsible for sequestering heat in the ocean. It is also recognised that the accuracy of observed trends in global and regional sea level are dependent on continued validation of satellite observations (Fu and Haines, 2013).

Ocean warming and its associated thermal expansion is a major contributor to sea level rise (Cazenave et al., 2009; Church et al., 2013). While global rates reflect both ocean thermal expansion and land ice melt, regional sea level is affected by ocean circulation and processes like subduction that control the distribution of heat in the ocean. Recent progress on closing the multidecadal sea level budget underscores again the important role of both upper and deep ocean warming in driving sea level rise (Figure 4.1)

Figure 4.1: 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 [From Domingues et al., 2008].

4.1.2 The global ocean circulation

The primary means by which the ocean sequesters and transports heat and carbon is through the mean ocean circulation – both the shallow subduction systems and associated western boundary currents operating in ocean subtropical gyres and the deeper reaching global overturning circulation (GOC). While monitoring large-scale changes in storage of heat and other properties is already challenging, measuring the low frequency ocean circulation is even more difficult. Some aspects of the mean ocean circulation and its role in the climate system were quantified during the World Ocean Circulation Experiment (Siedler et al, 2001), but major currents and water mass conversion rates remain poorly constrained. In addition, the role of eddy property fluxes in sustaining the mean state is still poorly understood (see below).

How the ocean circulation will change in the future and impact its ability to sequester and transport heat and carbon is a critical question. ESM's suggest that some limbs of the GOC will weaken, such as the North Atlantic Conveyor belt (IPCC, 2013). This has resulted in a huge effort to monitor this limb of the GOC. Less attention has been focussed on the Southern Hemisphere component of the

GOC, which is of equal climatic importance (Sloyan and Rintoul, 2001; Rintoul et al, 2001). Trends in the GOC in ESMs require stringent validation as they impact on their ability to confidently project future climate. Such measurements are seen as key in validating decadal prediction systems (Latif et al, 2009).

4.1.3 The global hydrological cycle (salinity)

In addition to warming, changes to the global hydrological cycle (patterns and rates of precipitation and evaporation) driven by anthropogenic greenhouse gases will have serious societal impacts. The current generation of climate models shows less agreement on the patterns and rates of precipitation changes compared to those for temperature (IPCC, 2013). Historical measurements of precipitation and evaporation on a global scale are inadequate for constraining model 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. The ocean salinity field, however, integrates spatially and temporally the major hydrological fluxes through the atmosphere. Thus, changes in the ocean salinity field can be used to quantify changes in precipitation - evaporation. Estimates of surface salinity changes to date captured in historical archives (Wong et al., 1999) and based on comparing Argo data with historical archives (Roemmich and Gilson, 2009; Hosoda et al, 2009; Durack and Wijffels, 2010; Helm et al., 2010; Durack et al., 2012) suggest large and coherent changes are already underway. These changes are consonant with amplification of the global hydrological cycle over past decades, in qualitative agreement with ESM results. Deep ocean salinity changes, in particular the warming and freshening of Antarctic Bottom Waters (Rintoul, 2007; Purkey and Johnson, 2013; van Wijk and Rintoul, 2014) may also track changes associated with melting ice sheets. The change in the production rate of these bottom waters impacts on deep ocean ventilation rates, deep oxygen levels and the efficacy of the deep ocean in sequestering heat and carbon.

4.1.4 The global carbon cycle (Inventory, air sea fluxes, physical and biological controls)

The oceans play a key role in the global carbon budget, taking up the equivalent of about 30% of annual anthropogenic CO_2 emissions (Doney et al, 2009; Ciais et al, 2013). The subtropical to sub-Antarctic band has the largest zonal inventory of anthropogenic carbon, with the Southern Ocean being the single most important uptake region of the oceans (Figure 4.2, Sabine et al., 2004), accounting for 40% of the total ocean uptake (Khatiwala et al, 2009, 2013). The uptake of anthropogenic carbon is largely driven by the overturning circulation, which also influences the oxygenation of the deep ocean.

The current ocean carbon uptake is used to constrain terrestrial uptake and resolve the global carbon budget (Wanninkhof et al, 2013; Le Quéré et al, 2014). The influence of climate change on the physical and biological processes that control ocean carbon uptake and storage is an important consideration in determining global carbon budgets and the rate of increase in atmospheric CO_2 (Séférian et al, 2013). The same processes can also influence the oxygenation of the deep ocean (Gruber, 2011). Changes in ocean stratification, warming, winds and the buffering capacity of the ocean all have the capacity to change the ocean uptake. The same processes could also influence the biological export of carbon and carbonate production providing biological feedback to the air-sea exchange of CO_2 that could be positive or negative (e.g. Gruber et al, 2004). These potential feedbacks between the natural carbon cycle and anthropogenic changes are now being introduced into ESMs via the inclusion of an active ocean carbon model. Australia's ACCESS initiative is building such a capability. These models require high quality validation data sets on ocean carbon storage and cycling.

Figure 4.2: The column inventory of anthropogenic CO_2 for the oceans (Sabine et al., 2004).

Fundamental questions remain about the mean and seasonal distributions of the natural air-sea CO_2 fluxes. Measurements since the early 1960's have been combined to provide a seasonal and annual climatology of surface CO_2 fluxes (Takahashi et al 2009). However, the 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 surface CO_2 and the air-sea CO_2 flux has also been identified for the equatorial Pacific (Feely et al, 2006) and North Atlantic (Thomas et al, 2008) that are linked to ENSO and the North Atlantic Oscillation (NAO), respectively. For the Southern Ocean, model-data comparisons show widespread discrepancies at seasonal and regional scales, and interannual variability is to a large degree uncharacterised (Lenton et al, 2013). LeQuere et al (2007) suggested that an increased upwelling of CO_2 rich deep waters due to more intense westerlies (SAM response) has reduced the efficiency of the Southern Ocean uptake in recent decades. The change has potential to alter the amount of CO_2 that accumulates in the atmosphere (Canadell et al, 2007). The evidence for a decline in the Southern Ocean sink efficiency has relied primarily on carbon models and atmospheric observations and remains controversial (Böning et al, 2008). A shift to an increasingly efficient sink suggested for recent years due to surface mixed layer cooling overwhelms the influence of the upwelling of CO_2-rich waters (Majkut et al, 2014). Continuing and enhanced ocean observations are required to 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. This effort will be aided by the development of uniformly quality-controlled global datasets for ocean CO_2 (Bakker et al., 2014; Sabine et al., 2010; Lo Monaco et al., 2010) and the collection of a consistent set of essential variables across international observing systems (GOOS, 2014).

4.1.5 Science Questions and variables needed to address them

The following high-level science questions will guide the Bluewater & Climate Node observing strategy:

Ocean Heat Content:

- *How are the global energy balance and the broadscale ocean temperature patterns changing? What is the impact on regional sea level rise?*
- *How are open ocean temperature changes related to temperature changes on the shelf?*
- *How does ocean heat content vary with time, location, and depth? Do earth system models capture the evolution of ocean heat content, and if not, why not?*

Global Ocean Circulation:

- *How is the overturning circulation of the Southern Ocean changing with time?*
- *How and why are the major current systems in Australian waters (including the East Australian Current, Indonesian Throughflow, Leeuwin Current and Antarctic Circumpolar Current) changing?*

Global hydrological cycle:

- *How is ocean salinity changing and what do changes in salinity tell us about the response of the global hydrological cycle to climate change?*
- *How is the salinity of the deep ocean changing and what do these changes say about ocean – ice shelf interaction and/or changes in high latitude precipitation?*

Global carbon budget:

- *What is the global ocean carbon inventory and how is it changing on decadal timescales?*
- *What is the seasonal through interannual variability in air-sea CO_2 fluxes for Australian shelves and regional seas and the Southern Ocean?*
- *What are the key biological and physical processes driving air-sea CO_2 exchange in the Southern Ocean and Australian region and how sensitive are they to climate change?*

Observations needed:

Broad-scale measurements of temperature, salinity and carbon are needed, throughout the full ocean depth and with sufficient temporal and spatial resolution to resolve the primary modes of climate variability. Tracking and understanding the processes by which heat and carbon are sequestered into the global oceans is essential for the detection, interpretation and projection of climate change. Measurements of ocean salinity provide information about changes in the global hydrological cycle as well as changes in the atmospheric drivers of variability in ocean circulation. Knowledge of regional and global ocean circulation throughout the full ocean depth is needed to determine where and for how long heat and carbon are sequestered in the ocean. A major impediment to understanding and modelling of the Southern Ocean is the large uncertainty in present estimates of air-sea fluxes of heat, momentum and freshwater; direct high-quality measurements such as those provided by the Southern Ocean Flux Station (SOFS) are critical to identify biases in flux products derived from models and remote sensing. Observations of the evolving inventory of heat, freshwater and carbon are also compared to model simulations to quantify the human contribution to observed ocean change.

4.1.6 Status, gaps, opportunities and priorities for future enhancements

Status:

IMOS uses a number of platforms to collect the observations needed to track multi-decadal change in Australia's oceans. IMOS facilities are providing broad-scale observations of temperature, salinity, velocity (and increasingly oxygen and chlorophyll) from Argo floats (Argo facility) and sensors deployed on marine mammals (AATAMS); physical and biogeochemical sampling of the upper ocean along ship of opportunity lines (SOOP); and deepwater moorings deployed in key boundary currents and interbasin exchanges in the Indonesian Throughflow, the East Australian Current, and Antarctic polynyas. The time series of atmospheric, physical oceanographic and biogeochemical variables provided by the Southern Ocean Flux Station (SOFS) and Southern Ocean Time Series (SOTS) stations are uniquely valuable (DEEP WATER MOORINGS) because they provide the only high-quality, continuous observations of these properties in the Southern Ocean. BWCN scientists also rely heavily on satellite remote sensing of sea surface temperature, salinity, ocean colour and sea surface height provided by the SRS facility (the altimeter calibration sites operated by IMOS, the only such sites in the southern hemisphere, are particularly important to ensure the highest quality altimeter data). (More detail on the status and plans for IMOS facilities delivering these data streams can be found in the IMOS National Plan and on the IMOS web site). In addition, the Node relies heavily on non-IMOS infrastructure such as repeat deep hydrography to track multi-decadal change in the deep ocean, tide gauges for sea level measurements, and the Global Tropical Moored Buoy Array for well-resolved time series in the tropics and at 25°S off Western Australia.

Gaps:

The Research Infrastructure Road Map identifies two key gaps in IMOS that influence our ability to track multi-decadal change: the deep ocean and the sea ice zone (including both the sea ice and the ocean beneath the ice). Indeed, these regions remain gaps in global ocean observing efforts. IMOS makes measurements below 2000 m only on a handful of moorings. To date, IMOS makes no measurements of sea ice. Oceanographic tags on seals, a limited number of ice-capable floats, and the Polynya moorings provide sparse measurements of the ocean beneath the sea ice.

Opportunities:

New technologies are being developed that can help fill the gaps identified in IMOS infrastructure for tracking multi-decadal change. Pilot deployments are underway of profiling floats capable of sampling the full ocean depth ("deep Argo"). When proven, deep Argo floats promise to revolutionise study of the deep ocean in the same way that Argo has done for the upper 2 km of the ocean.

New biogeochemical sensors suitable for deployment on profiling floats are now coming on-line. The recently-funded Southern Ocean Climate and Carbon Observations and Modelling (SOCCOM) project will deploy ~200 floats with pH and nitrate sensors in the Southern Ocean. Bio-optical sensors are also being developed for floats. These new sensors will provide year-round, broad-scale measurements of chemical and biological fields for the first time.

Acoustic techniques hold promise for navigation of oceanographic vehicles under sea ice and ice shelves. Argo floats have been tracked under ice with acoustics in the Weddell Sea for several years. Acoustic navigation of under-ice gliders has been successful in the Arctic and will be trialled by Australian and US investigators in the Antarctic in 2015. New sound sources, receivers and signal processing techniques are likely to allow for expansion of acoustic navigation of autonomous platforms to other regions in the coming years, as articulated in recent community White Paper on Under-Ice Observing in the Southern Ocean, coordinated by the Southern Ocean Observing System (SOOS) office hosted by IMOS (http://www.soos.aq/science/under-ice).

These technological developments provide a means to fill gaps identified in IMOS infrastructure over the coming decade.

Priorities for Future Enhancements:

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, and satellite remote sensing of sea surface height, sea surface temperature and ocean colour. Priority enhancements, when resources allow, include:

- Deep Argo to determine changes in heat and freshwater content throughout the full ocean depth
- Profiling floats with biogeochemical and bio-optical sensors (pH, oxygen, nutrients, optical parameters), with an emphasis on coordination with new international initiatives like SOCCOM.
- 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).
- Add pH, macronutrient and bio-optical sensors to ships of opportunity and use new observing infrastructure like wave gliders for improved coverage.
- Expansion of climate and carbon cycle measurements to include the sea ice zone, where the response to climate forcing is complex and where biological productivity is often much higher than in the open Southern Ocean. Establish a high latitude CO_2/acidification mooring in the region where overturning circulation and global CO_2 outgassing changes are under debate. No such measurements exist yet in the Southern Ocean including the critical winter months. This could be done with yearly servicing of a DART mooring as already used for the CO2 measurements around Australia, providing reliable data collection with daily satellite transmission of data. These moorings are small and proven work in the high latitude North Atlantic Ocean. International collaboration should be explored for sharing the effort in servicing the mooring.

4.2 Climate variability and weather extremes

Three major coupled ocean-atmosphere modes 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 globally dominant mode with strong impacts on Australia. The key role of the ocean for ENSO was recognised more than 40 years ago (Bjerknes, 1966). The international Tropical Ocean Global Atmosphere (TOGA) programme (1985-1995) greatly advanced the description and understanding of coupled ocean-atmosphere behaviour and produced a legacy of dynamical prediction models as well as the ENSO observing system in the Pacific Ocean. These observations were recognised as an essential part of the prediction system to initialise coupled ocean-atmosphere models (McPhaden et al. 1998). The IOD was documented as a coupled climate mode more than a decade ago (Saji et al., 1999). Its impacts on Australia are beginning to be recognised. The SAM has been identified largely in atmospheric observations; however a possible role for oceanic circulation in the South Pacific and Indian Oceans, in particular in the Tasman Sea, has been suggested by climate models (Cai et al. 2005). It also impacts the large scale circulation and eddy properties of the Southern Ocean (Farneti et al. 2010)), with consequences for ocean biogeochemistry (Ayers and Strutton, 2013).

The tropical upper ocean thermal distribution is the largest source of predictability at seasonal timescales for all coupled modes due to the large ocean thermal inertia and its predictable dynamics (Kelvin and Rossby waves). The first dynamical ENSO prediction systems took only the Pacific Ocean into account, but the leading systems are now based on coupled, global models. Improved predictions partly hinge on better initialising the ocean component using global ocean observations. Improved predictions also depend on better understanding (and parameterisation) of the coupled and oceanic processes involved, which also require global observations. While widely distributed and intermittent observations (e.g. Argo) are required for global initialisation, continuous time series are required in the tropical oceans to observe the fast intraseasonal variability (such as Madden Julian Oscillation (MJO), see below). Improved prediction of MJO is recognised now as one of the most promising approaches to providing seasonal climate information to the public. The observations needed are:

- global measurements of the large scale upper ocean temperature and salinity structure on seasonal timescales, particularly in the tropics and subtropics
- well resolved time-series of atmospheric and oceanographic variables in the equatorial oceans
- global wind, air-sea flux and sea level measurements
- air-sea flux time series stations, like the IMOS SOFS mooring in the Southern Ocean and the RAMA and TAO arrays in the tropics, are critical for validation of flux products derived from atmospheric reanalyses and remote sensing

4.2.1 Interannual Climate Variability

4.2.1.1 El Niño –Southern Oscillation (ENSO)

The El-Nino-Southern Oscillation (ENSO) is a combined atmospheric-oceanic cycle which involves warming and cooling of surface waters in the tropical eastern Pacific Ocean, and changes in surface pressure in the tropical western Pacific (Fig 4.3).

Due to the implementation of the ENSO Observing system in the late 1980's - primarily comprised of the Pacific TAO/TRITON/TOA 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. However, key research questions around ENSO and ocean processes remain. For example, the role of higher-frequency variability (like the MJO) in triggering ENSO events is still in debate. Also, 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.

(a)

(b)

(c)

Figure 4.3: Schematic showing the oceanic and atmospheric state during (a) normal, (b) El Nino and (c) La Nina conditions in the Pacific Ocean SST

Figure 4.4: IOD pattern during September–November. (a) Regression of 20°C isotherm depth (Z20; shades in m) and surface wind velocity (m/s) upon the first principal component of Z20 and (b) correlation of precipitation (shades) and SST (contoured at 0.3, 0.6, and 0.9 with zero omitted and negative dashed) with the first principal component of Z20 [from Saji et al., 2006a].

4.2.1.2 Indian Ocean Dipole (IOD)

The Indian Ocean Dipole (IOD) is a coupled ocean and atmosphere phenomenon in the equatorial Indian Ocean that affects the climate of countries that surround the Indian Ocean basin, including Australia (Figures 4.4 and 4.5). Its positive phase is characterized by cool SSTs in the eastern Indian Ocean in the region affected by seasonal upwelling along the coasts of Java and Sumatra. Shoaling of the thermocline, anomalous easterly wind and low rainfall are associated with the SST anomaly (Fig 3.4a). Anomalies of opposite sign develop in the western Indian Ocean. The negative phase tends to be weaker with reversed signs of all the anomalies throughout the eastern and western Indian Ocean. Both observations and models show that the IOD is a natural mode of the Indian Ocean coupled system, which either can be externally triggered, by ENSO, or can self-generate (Saji et al., 1999; Schott et al., 2009).

The skill of predicting IOD is considerably less than the skill of predicting ENSO. This may be due to insufficient observations to initialize the model, inadequate data assimilation methods, incorrect physics (or parameterizations) in the model, or inherently more chaotic behaviour of the Indian Ocean. The interactions of IOD with MJO are not well understood. IOD remains an active area of international research, with challenges in observing, describing, understanding, modelling and prediction. An improved understanding of the IOD and improving its simulation in the Australian seasonal climate prediction model are Australian research priorities.

Figure 4.5: 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.

4.2.1.3 Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) is the leading mode of climate variability over the mid- to high-latitude Southern Hemisphere. In its positive phase, which has dominated the last few decades, the SAM is associated with lighter winds over southern Australian latitudes, and stronger, poleward contracting westerlies in the Southern Ocean.

The positive mode also moves low pressure systems southward, reducing winter rainfall over southwest WA, Tasmania, Victoria and South Australia (Hendon et al. 2007). The mechanisms associated with these climate linkages remain uncertain. While natural variability in the SAM is observed, both greenhouse gas increases and polar stratospheric ozone depletion are driving the SAM toward a positive phase (Figure 4.6), reducing rainfall over the southern margins of the continent (Cai, 2006).

Figure 4.6: The long term trend in the Southern Annular Mode, from Hogg et al., 2014.

4.2.2 Intra-seasonal variability and severe weather

4.2.2.1 The Madden-Julian Oscillation (MJO)

While the previous three modes are drivers of seasonal climate variability, at intra-seasonal timescales the MJO is the most prominent mode. The MJO is a key phenomenon for both weather and climate forecasting science, and it spans and links the areas in the Indian and Pacific Oceans that have greatest impact on Australian climate. It is a propagating coupled convective disturbance that migrates from the central western tropical Indian Ocean eastwards across the maritime continent and out to near the dateline in the Pacific Ocean (Zhang, 2005). Having a dominant time period near 50 days, and embedded in the seasonally migrating inter-tropical convergence zones, the MJO is suggested to play a role in the initiation and evolution of ENSO and IOD events (McPhaden et al., 2006), modulation of the Indonesian Throughflow (Sprintall et al, 2009), and partly accounts for the dry break events within the monsoons (Wheeler and McBride 2005).

Improved representation of intraseasonal variability is a high priority in development of the Australian seasonal prediction model POAMA. At present, coupled models do not capture this 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 increased process understanding to improve model simulation of this phenomena.

A fundamental aspect of observing, describing, understanding and modelling the MJO is better knowledge of the fluxes of momentum, heat and freshwater at the sea surface. In situ ‘climate quality’ flux observations are scarce and are therefore a valuable means for validating and improving flux products (from NWP and satellites) that provide the required spatial and temporal coverage to understand ocean dynamics, the ocean’s role in climate variability and change, investigate forcing of the atmosphere and ocean and assess the realism of data-assimilative ocean models and coupled ocean-atmosphere models. The lack of in situ flux observations in the oceans around Australia, and particularly the Southern Ocean, is evident in the disagreement between flux fields from different sources. The IMOS Southern Ocean Flux Study mooring (SOFS) helps to address this need for the Subantarctic Ocean.

Prediction and understanding of the MJO, and many other processes related to tropical climate modes requires high temporal resolution (hourly) monitoring of tropical heat, freshwater and momentum fluxes, and the upper ocean temperature, salinity and velocity structure.

4.2.2.2 Tropical Cyclones and East Coast Lows

Tropical cyclones impact much of the northern Australian coast. Tropical cyclones gain energy from warm waters and require sea surface temperatures greater than 26°C to form. Cyclones reaching the Queensland coast generally intensify over the warm waters of the Coral Sea. Understanding of ocean temperatures and atmospheric conditions at and following formation is required for accurate prediction of cyclone track and intensity.

East Coast Lows are short-lived weather systems that form close to the coast. They are most common along the coast of New South Wales and southern Queensland in winter and, while not as intense as tropical cyclones, are associated with significant flooding and coastal erosion. Recent research suggests that sea surface temperatures may influence the development of ECLs, in particular the temperature gradient between coastal waters and the East Australian Current offshore (Leslie et al., 1987; Speer and Leslie, 2000).

The sensitivity of tropical cyclones and East Coast Lows to ocean temperatures indicates that improved observations and understanding of open ocean temperatures can contribute to better forecasting of extreme weather events.

4.2.3 Interactions between modes of variability

Interaction of the Pacific and Indian basins and their modes of variability, ENSO and IOD, is a topic of active research. The two basins are connected through atmospheric teleconnections and the Indonesian Throughflow. The dynamics of IOD and ENSO may be coupled to some extent. These interactions may not be well-represented in seasonal forecasting models. For example, most such models are of low spatial resolution, and thus suffer biases in their representation of the magnitude, pathways and variability of the Indonesian Throughflow, which is filamented by the complex topography of the Indonesian Seas. The possibility that neither ENSO nor IOD can be fully understood when considered in isolation, and evidence that ocean circulation couples the Indian and Pacific basins, highlights the need for broad-scale observations of ocean temperature, salinity and currents in both the tropical Indian and Pacific and for direct measurements of the Indonesian Throughflow.

4.2.4 Modes of variability in a changing climate

Of particular importance to Australia is how the modes of variability will change in a warming world. ESMs suggest an intensification of the SAM is being driven by both reduced ozone levels and greenhouse forcing (Cai et al., 2005; Cai, 2006), driving a poleward shift in the circumpolar westerly winds (Gillett and Thompson, 2003). Recent studies document a decadal spin-up and southward shift of the Southern Hemisphere subtropical ocean circulation (Roemmich et al, 2007). Hill et al. (2008) showed how both a trend and decadal variations may be driven by low-frequency wind variability over the South Pacific gyre (Figure 4.7). Observations indicate that regional responses to these gyre changes include a southward extension of the EAC and intensification of its flow past Tasmania

(Ridgway, 2007) and a large scale warming of the thermocline in the mid-latitude region of the Indian Ocean (Alory et al, 2007).

Figure 4.7: Low-pass filtered (a) sea surface temperature off coastal eastern Tasmania, (b) surface salinity off coastal eastern Tasmania. (c) South Pacific regional mean wind stress curl (20–50°S, 180–280°E), (d) net transport through the Tasman Sea, calculated using the Island Rule [Godfrey, 1989]. Black dashed lines show the linear trend. Green dashed lines illustrate the time lag between the Maria Island time series and South Pacific winds/Tasman Sea transports [from Hill et al, 2008].

In contrast to the observations, coupled climate models give little guidance on how ENSO will evolve in a warmer world. More detailed observations of coupled ocean-atmosphere behaviour across the global, tropical oceans are required to constrain the models. In the Indian Ocean, 21st century simulations suggest that the mean is shifting to a more positive IOD state – that is a cooler and dryer eastern Indian Ocean (and thus dryer Australia – Cai, et al, 2009; Ummenhoffer et al, 2009). Weakening of both equatorial westerly winds and eastward oceanic currents in association with a faster warming in the western than the eastern equatorial Indian Ocean is predicted to lead to more frequent extreme positive IOD events, increasing the frequency of extreme climate and weather events in Australia (Cai et al. 2014).

While much of the observational data required to support research on seasonal climate variability in Australia comes from international networks, there has been a lack of sustained, well-resolved time series data from bluewater moorings in our region. The IMOS mooring array in the Indonesian Throughflow, and the deployment of the RAMA 25°S, 100°E mooring are important steps forward. The Indian Ocean RAMA array (McPhaden et al., 2009), part of the Global Tropical Moored Buoy Array, provides freely available, near-real-time observations of atmospheric fluxes and upper ocean variability. Australia has so far contributed to the moored arrays in the tropical Indian and Pacific oceans, only by providing ship time for two deployments of the RAMA 25°S mooring. The future of these arrays is being actively discussed by the international community.

4.2.5 Science Questions

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

Major weather patterns can also be strongly influenced by ocean conditions, as they draw energy from the ocean. Variability in the number and magnitude of weather events like cyclones and east coast lows are linked to coupled climate modes like ENSO.

The following high-level science questions are primarily aimed at improving dynamical understanding in support of climate modelling and seasonal forecasting. Sustained observations are needed to guide the development of more effective parameterisations of unresolved physical processes in models. Observations are also essential for assimilation by and initialisation of seasonal forecasting models.

Interannual:

- *How does exchange of heat, moisture and momentum between the atmosphere and the ocean surface layer affect modes of climate variability?*
- *Can we improve dynamical understanding of ENSO (e.g. subtropical-tropical interaction through oceanic pathways, heat transport by tropical instability waves, dynamics of the different flavours of ENSO) and use this understanding to improve seasonal forecasts and projections of ENSO in a future climate?*
- *Can we improve dynamical understanding of IOD, including the possibility of coupling between IOD and ENSO?*
-

Intraseasonal:

- *How does the Madden Julian Oscillation (MJO) interact with other climate processes, such as ENSO, IOD and the Australian monsoon?*
- *What role does air-sea interaction play in the dynamics of the MJO?*
- *How is the development of weather events like tropical cyclones and East Coast Lows influenced by ocean variability such as sea surface temperature?*

4.2.6 Status, gaps, opportunities and priorities for future enhancements

Status:

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 similar. Observations are needed of upper ocean temperature and salinity on broad scales, well resolved time-series in the equatorial oceans, air-sea exchange of heat and momentum (wind stress), and sea level. Direct measurements of air-sea fluxes are of particular importance to this theme, such as those routinely collected, and made publicly available, by the Global Tropical Moored Buoy Array. Satellite measurements of wind stress, sea level, and sea surface temperature are also relevant to this theme.

Several IMOS facilities are delivering data streams relevant to climate variability. Argo is providing broad-scale measurements of temperature and salinity in the upper ocean. Measurements of atmospheric and oceanographic variables from ships of opportunity (SOOP) contribute to this theme. Satellite remote sensing of wind stress, sea surface temperature, and sea surface height are also used by BWCN scientists investigating climate variability and weather extremes. Air-sea fluxes measured at the SOFS site south of Tasmania are helping to improve understanding of air-sea interaction south of Australia. Australian scientists have relied heavily on the Global Tropical Moored Buoy Array and have assisted with deployment of a mooring at 25S, 100E as part of the RAMA program.

Gaps:

The recent decline in data provided by the tropical moored arrays is a potentially serious issue for studies of Australian climate variability, given the sensitivity of Australian climate to the tropical Indian and Pacific Oceans. 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.

Opportunities:

The tropical ocean observing system is presently being reviewed by the international community. The findings of this review will be useful for IMOS as it considers the infrastructure needed to support Australian research into climate variability over the next decade.

Priorities for future enhancements:

For the Bluewater and Climate Node, the highest priority is to maintain and enhance the IMOS infrastructure that is presently in place, including Argo, SOOP, SOFS and remote sensing. These data streams are targeted at the key variables of most relevance to climate variability research: measurements of upper ocean temperature and salinity and of air-sea fluxes. The upper ocean temperature and salinity measurements need to be sustained for the long term. Air-sea flux sites need to be sustained for a sufficient period to sample multiple seasonal cycles and different phases of the major modes of climate variability (e.g. ENSO and SAM).

- While maintaining the SOFS air-sea flux mooring remains the highest priority, Australia should 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.

4.3 Major boundary currents and inter-basin flows

As an island nation, Australia's climate and coastal environment is strongly controlled by the complex network of currents in the surrounding ocean (Figure 4.8). Each of the large ocean domains surrounding the continent – the Indian and Pacific subtropical gyres, the tropical oceans and Indonesian Seas, and the Southern Ocean – has a distinct but inter-connected influence on Australian climate variability and change. Continental shelf and coastal waters reflect conditions offshore, in particular the impact of the system of boundary currents illustrated in Figure 4.8. Furthermore, Australia lies at an oceanic "crossroads" between currents that provide the primary means of exchange between the ocean basins and therefore have a large influence on global ocean circulation and climate, such as the Indonesian Throughflow and Antarctic Circumpolar Current. Sustained observations of the boundary currents and interbasin flows in Australia's bluewater domain are critical for improved understanding of Australian and global climate and the factors controlling Australia's marine environment.

Figure 4.8: The circulation in the oceans around Australia. The surface currents are shown in orange and subsurface currents in green.

The major current systems in Australia's oceans include the East Australian Current and Leeuwin Current, carrying warm water poleward along the eastern and western boundaries of the continent, respectively; the Indonesian Throughflow providing a warm water pathway from the Pacific to the Indian Basins; the Antarctic Circumpolar Current, the largest current in the world ocean, flowing from west to east between Australia and Antarctica. Each of these current systems, and their influence on Australia, are discussed in this section.

4.3.1 East Australian Current (EAC) system (including Tasman Outflow, Flinders Current and Hiri Currents)

The East Australian Current (EAC) is a complex and highly energetic western boundary current in the south-western Pacific off eastern Australia (Ridgway and Dunn 2003). Although its mean flow is relatively weak (Ridgway and Godfrey 1994) it is known to be a highly variable system with large mesoscale eddies dominating the flow (Bowen et al., 2005; Mata et al., 2007). The EAC has an important role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Roemmich et al, 2005). It has a major influence within the Tasman/Coral Sea basin, which is an ocean region of importance to Australia, being adjacent to large population centres, encompassing major shipping lanes, and including regions of environmental significance. The EAC is also the dominant environmental influence on offshore pelagic fisheries in the region (Hobday and Hartmann, 2006). A central driver of key species such as southern bluefin tuna (SBT) is the seasonal changes of subsurface properties within the EAC system.

The EAC provides both the western boundary of the South Pacific Gyre, a connection with the equatorial region and a linking element between the Pacific and Indian Ocean gyres (Speich et al. 2002). It is fed by the westward flow of the South Equatorial Current (SEC) which flows between the Solomon Islands and New Caledonia (Wyrtki, 1962, 200-800-m) and is split into a series of narrow jets by the complex island and reef systems as it approaches the east Australian coast (Webb, 2000). At the coastal boundary the flow bifurcates into northern and southern components (Church 1987). This bifurcation location moves southward with increasing depth (from 15°S at the surface to 19°S at 500-m depth) such that over the first 300-km the there is an undercurrent which only extends to the surface at ~ 15°S (Church and Boland, 1983; Ridgway and Dunn, 2003). Beyond the northern end of the GBR (15°S) the coastal Hiri Current is steered in a clockwise trajectory around the shelf-edge connecting northern Queensland to southern PNG. Some of this flow recirculates back to the Queensland coast, while the remainder turns northwards around the southeastern tip of PNG and through Vitiaz Strait (Qu and Lindstrom, 2002).

The southern component of the current is accelerated poleward along the coastal boundary, to form the main EAC transport. It then separates into northeastward (Subtropical Counter Current), eastward (Tasman Front) and residual southward (EAC Extension) components at around 31°S (Figure 3.8, Ridgway and Dunn 2003). Between 18° to 35°S, the southward transport ranges from 25 to 37 Sv, the latter value includes a significant recirculation feature. A portion of the Tasman Front re-attaches to the northern coast of New Zealand, forming the East Auckland Current and a sequence of semi-permanent eddies. The EAC Extension is the residue of the EAC transport which continues southward along the Australian coast as far as Tasmania. The EAC flow varies seasonally - it is strongest in summer, and the separation location also migrates up and down the coast with season (Ridgway and Godfrey, 1997). The seasonal amplitude is also large compared to the mean flow, with a minimum observed southward flow of 27.4 Sv in winter, and a maximum of 36.3 Sv in summer (Ridgway & Godfrey, 1997). While changes in heat flux within the EAC are controlled by advective processes (Roemmich et al, 2005), how the relative contributions of advection and heat storage to the surface heat flux vary on interannnual to decadal timescales is unknown.

The EAC Extension turns westward into the eastern Indian Ocean (Tasman Outflow) with an important impact on the global ocean circulation (Speich et al. 2002). The Tasman Outflow occurs mainly at intermediate depths between 500 and 1200 m. As well as connecting the gyre systems in the Pacific and Indian Oceans (Figure 4.9; Ridgway and Dunn, 2007) this current forms a third element of the global thermohaline circulation (Speich et al, 2002). The Tasman Outflow subsequently feeds the Flinders Current (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 once rounding Cape Leeuwin.

Figure 3.9: The interbasin gyre system for the Pacific and Indian Oceans as shown by the flow at the (a) surface (the main connection is the Indonesian Throughflow) and (b) 900-m level (Tasman Outflow). Figure adapted from Ridgway and Dunn (2007).

The impact of ENSO on the EAC remains an active area of research. Ridgway and Dunn (2007) suggests that ENSO has little impact on the EAC, as the ENSO signal predominantly 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 states of the South Pacific gyre. This has been related to decadal ENSO variability projecting onto the westerly winds of the South Pacific basin (Hill et al., 2011).

A variety of observational evidence suggests the EAC and South Pacific gyres have strengthened in recent decades in response to changes in wind stress (e.g. Cai et al., 2005; Hill et al., 2008; Roemmich et al., 2007). In particular, the EAC Extension seems to be extending further south along the east coast of Tasmania. The increased strength of the EAC extension is impacting Tasmanian ecosystems by carrying warm water and new species further south (Johnson et al., 2011). Models suggest that the EAC and EAC Extension are likely to strengthen further in response to greenhouse warming (Cai et al., 2005).

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

The Leeuwin Current (LC) is a warm, poleward flowing ocean boundary current off the west and south coasts of Australia driven by a large-scale meridional pressure gradient in the southeast Indian Ocean, established by the Indonesian Throughflow and thermohaline forcing (Godfrey and Golding, 1981; Godfrey and Ridgway 1985; McCreary et al. 1986). The pressure gradient drives an eastward, onshore geostrophic transport, which overwhelms local wind-driven offshore Ekman transport and feeds the Leeuwin Current (Feng et al. 2003; Furue et al., 2013; Benthuysen et al., 2014). The eastward flows extend across the entire South Indian Ocean (Menezes et al., 2013; Menezes et al., 2014), and include recirculation of Indonesian Throughflow Water by the Eastern Gyral Current (Feng et al., 2003, Domingues et al. 2007). The LC is highly unstable and mesoscale eddies are regularly generated along its path. In fact, the eddy energy associated with the LC is higher than any other eastern boundary current system (Feng, 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 Western Australia to enter waters south of Australia, and continues as an eastward shelf current (the South Australian Current) along the southern coast of Australia (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. Limited observations of a precursor to the LC, show a seasonal southward flow on the North West Shelf, the Holloway Current (Holloway and Nye, 1985).

On inter-annual 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. In this way ENSO influences the entire West Australian coast and into the Great Australian Bight. La Niña events are associated with a stronger LC. The particularly strong 2010 La Niña event, and the associate record strength LC, generated SST anomalies along the WA coast from 3 to 5°C, spanning Ningaloo (22°S) to Cape Leeuwin (34°S). Ecological impacts included fish kills and temporary southward range extensions of tropical species

As well as influencing the regional climate along its path, the LC transports many tropical organisms into southern Australia (Maxwell and Cresswell, 1981). Many of the biological processes are strongly influenced by climate variability off the west coast. A notable example is that high recruitment of the western rock lobster (*Panulirus cygnus*) are driven by higher water temperatures, a stronger LC, and stronger westerly winds in winter (Caputi et al. 2001). This correlation is used in management of the lobster fishery. The LC is also is a central influence on the late autumn – early winter phytoplankton bloom along the oligotrophic coast (Feng et al. 2009). The LC is able to carry passive organisms many hundreds of kilometres. For example, it is likely to be responsible for the distribution of dinoflagellates from southwest Australia to Tasmania (Maxwell and Cresswell, 1981). It is probable though not established that species such as Southern Bluefin Tuna, Australian Salmon and herring utilize the current to transport eggs, larvae and juveniles along its path.

4.3.3 The Indonesian Throughflow (ITF)

The Indonesian Throughflow (ITF) is an ocean current that transports upper ocean water between the Pacific Ocean and the Indian Ocean through the Indonesian archipelago. The current enters the Indonesian seas through the Makassar Strait and Malacca Straits, and exits through the Lombok Strait, Ombai Strait and Timor Passage. The ITF is concentrated in the upper 300m but extends to 1250m, the maximum sill depth of the main Indonesian passages. The ITF flow varies seasonally in response to the monsoons, and is also correlated with interannual variations in the Pacific (El Nino/Southern Oscillation). Variations in the ITF affect the properties, and climate of both the Indian and Pacific Oceans, and may also feedback and influence ENSO (Sprintall et al., 2014), and as just described, the ITF is closely coupled to the Leeuwin, and was one of the major drivers of the 2010-11 marine heat wave off WA, known as the Ningaloo Nino (Feng et al. 2013).

Prior to the current IMOS efforts in the ITF region, there was one multi-year field effort that attempted to measure the volume fluxes through the three major straits, called the International Nusantara Stratification and Transport program (INSTANT; Figure 4.10). This program did indeed quantify interannual variability in the ITF that was correlated with variability in the IOD and ENSO (Sprintall et al 2009). Continued observations of the kind being funded by IMOS will further clarify the relationships between modes of climate variability and ITF fluxes. The physical data are also forming the basis of investigations into the total magnitude and variability of nutrient fluxes to the Indian Ocean through the ITF (Ayers et al., 2014).

Figure 4.10: The Indonesian seas, with an inset showing the three straits (Lombok, Ombai and Timor) where INSTANT moorings were deployed. The colours indicate climatological annual mean surface nitrate from CARS. Figure from Ayers et al. (2014).

4.3.4 Antarctic Circumpolar Current

The dominant feature of the Southern Ocean circulation is the Antarctic Circumpolar Current (ACC). The ACC is the largest current in the world ocean, carrying about 150 x $10^6 m^3 s^{-1}$ to the east between Australia and Antarctica (Rintoul and Sokolov, 2001). By connecting the ocean basins, the strong flow of the ACC has a profound impact on the global ocean circulation and climate (Rintoul et al., 2001). Australian climate is also sensitive to changes to the south of the continent, with drying in southern Australia in recent decades linked to a poleward shift of the westerly winds and associated winter storms.

The flow of the ACC occurs along a number of narrow jets or fronts; water mass properties change abruptly across each of the fronts, while in the zones between the fronts the water properties are relatively uniform (Orsi et al, 1995; Sokolov and Rintoul, 2007). From north to south, the fronts and zones of the Southern Ocean are: the Subtropical Front, the Subantarctic Zone, the Subantarctic Front, the Polar Frontal Zone, the Polar Front, and the Antarctic Zone. The ACC fronts extend throughout the water column and are clearly evident in maps of sea surface height (Sokolov and Rintoul, 2007; 2009a,b). In contrast, the Subtropical Front is restricted to the upper 400 m and has only a weak dynamic signature (Ridgway and Dunn, 2007).

The response of the ACC to changes in wind forcing remains a topic of active debate. Observations suggest the ACC has shifted south, along with a southward shift of the westerly winds over the Southern Ocean (Gille, 2008; Böning et al., 2008; Sokolov and Rintoul, 2009b). However, the link between changes in wind forcing and the response of the ACC remains unclear. In coarse resolution models, which do not resolve mesoscale eddies, stronger wind forcing drives stronger ACC transport and a southward shift of the current. Eddy-resolving models tend to suggest that stronger winds drive a stronger eddy field, with little change in transport (Straub, 1993; Hogg et al., 2008; Farnetti and Delworth, 2010; Rintoul and Naveira Garabato, 2013).

The fronts of the ACC are important biogeographic boundaries and define the limits of distinct biological communities (Sokolov and Rintoul, 2007). For example, throughout the year the Antarctic Zone is rich in major nutrients such as silicate, nitrate, and phosphate, allowing diatoms to dominate the phytoplankton community. In contrast, Subantarctic Zone waters are low in silicate year-round and populated by a more diverse mix of smaller phytoplankton, including cyanobacteria, dinoflagellates, coccolithophorids, and small diatoms. Primary production throughout most of the Southern Ocean (with coastal and boundary current waters being notable exceptions0 is limited by lack of trace nutrients such as iron.

4.3.5 Southern Ocean overturning circulation

The Southern Ocean is important to climate in part because the overturning circulation transfers large amounts of heat and carbon dioxide from the atmosphere to the deep ocean (Rintoul et al., 2001; Marshall and Speer, 2012) (Figure 4.11). Deep water spreads south and shoals across the Southern Ocean. Water that upwells near Antarctica is transformed into dense bottom water by atmospheric cooling and brine added during sea ice formation (shown in white). Deep water that upwells further north is transformed into lighter mode and intermediate waters by atmospheric heating and precipitation. The two counter-rotating circulation cells that result from the poleward flow of deep water and the equatorward flow of mode, intermediate and bottom water form the Southern Ocean overturning circulation. As a result of the vigorous overturning circulation, the Southern Ocean stores more anthropogenic carbon dioxide and heat than any other latitude band (Khatiwala et al., 2009, 2013; Levitus et al., 2012). Upwelling of deep water also returns nutrients from the deep ocean to the surface ocean. Export of these nutrients to lower latitudes in mode and intermediate water ultimately supports 75% of global marine primary production north of 30°S (Sarmiento et al., 2003). Recent studies have used IMOS Argo data to quantify the upper limb of the overturning circulation and its carbon transport for the first time (Sallée et al., 2010, 2012).

Figure 4.11: A schematic view of the Southern Ocean overturning circulation, north to the left, Antarctica to the right (from Rintoul (2000)). The dashed yellow lines and purple arrows indicate the strong, deep-reaching flow of the Antarctic Circumpolar Current. The broad arrows indicate the spreading paths of major water masses (see text).

As for the Antarctic Circumpolar Current, the response of the Southern Ocean overturning circulation to climate change is a topic of active research (Meredith et al., 2012; Rintoul and Naveira Garabato, 2013). The central issue is the extent to which changes in wind-driven transport are compensated by eddy-driven circulations. Resolving this issue is important for climate projections: if stronger winds mean stronger overturning, this might change the ability of the Southern Ocean to absorb heat and carbon dioxide and thereby slow the rate of climate change. Several types of observations are needed to improve understanding of the sensitivity of the overturning circulation to changes in forcing. Changes in bottom water formation can be detected by measurements of change in temperature, salinity and oxygen of bottom waters (e.g. Purkey and Johnson, 2009, 2012, 2013; van Wijk and Rintoul, 2014) and by direct measurements of the sinking of bottom water near

Antarctica (as done in IMOS with the Polynya mooring program) 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 (Figure 4.12). Changes in the upper cell of the overturning circulation can be measured using Argo floats in conjunction with satellite data and ship-based observations. Improved measurements of air-sea fluxes of heat, freshwater and momentum over the Southern Ocean are also required to investigate the sensitivity of the overturning circulation to changes in forcing. The IMOS Southern Ocean flux mooring (SOFS) is an important step toward this goal.

Figure 4.12: A schematic of the system of deep boundary currents carrying Antarctic BottomWater (black arrows) through the Australian Antarctic Basin (van Wijk and Rintoul, 2014). The Kerguelen Deep Western Boundary Current is labelled DWBC near 80°E. The large arrowhead near 110°E, 35°E indicates the deep flow into the Perth Basin. Text labels indicate the sources of AABW (i.e., ALBW=Adélie Land Bottom Water and RSBW=Ross Sea Bottom Water) and the hydrographic sections used in this study; P11S at 150°E, SR3 at 140°E, I9 at 115°E, I8 deep western boundary current (DWBC) at 84°E, and I8 Princess Elizabeth Trough (PET) at 80°E. Station locations are indicated by year (colored symbols). Decadal rates of change in AABW core properties averaged over the bottom 300m are shown by the insets at each section; salinity change (ΔS, blue bars) and potential temperature change (Δϑ, red bars).

4.3.6 Eddy Processes in boundary currents.

The ocean is also a very turbulent environment - over periods of days to weeks the variability is dominated by mesoscale eddies, which have a strong signature in surface pressure and thus sea level. There are very energetic regions of mesoscale eddies associated with the major current systems: the EAC, the ACC and the LC (Figure 4.13).

Figure 4.13: The root mean square (RMS) variability of the sea surface height as determined from satellite altimetry data from 1992-2006. This variability is used as a proxy for eddy activity, or abundance. 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].

These 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. The resolution and prediction of the eddy field and its impacts on the structure of the mean ocean flow is a key research challenge.

Within the abyssal basin adjacent to the coast, the EAC is associated with a highly energetic eddy field. These eddies are 200-300 km in diameter and 2-3 eddies are generated annually and have lifetimes often exceeding a year (Nilsson and Cresswell 1981; Bowen et al. 2005). They are likely to derive from a mixed barotropic/baroclinic instability of the mean flow (Mata et al, 2007). They follow complex southward trajectories, but are generally constrained within the deep basin. These eddies exhibit a westward vertical tilt with increasing depth indicating that they are actively fluxing heat poleward (Oke and Griffin, 2009).

In the Leeuwin Current, eddies grow at the expense of the mean current and bleed momentum offshore playing a fundamental role in balancing the pressure gradient accelerating the current (Feng, 2005) and balancing the warm poleward advection of heat by transferring warm water offshore (Domingues, et al, 2006).

In the Antarctic Circumpolar Current, eddies also extract energy from the mean flow and act to balance the powerful acceleration of the Circumpolar westerlies by fluxing momentum to the sea floor where it is dissipated (Marshall and Radko, 2003). Meridional eddy heat fluxes across the ACC are also crucial to the heat balance of the Southern Ocean, and they play a crucial role in setting the rates and characteristics of the subduction of one of the most important global water masses, the Subantarctic Mode Waters (Sallée et al, 2008). The structure of the ACC itself, a set of multiple semi-permanent narrow jets (Sokolov and Rintoul, 2007) is likely sustained by non-linear aspects of eddy behaviour that are not well understood.

Indeed, narrow zonal jets or striations of the zonal flow are being discovered in all ocean basins (Maximenko et al, 2005) – but are more easily detected in regions of weaker mean flow such as those associated with eastern boundary current systems. Theory suggests these jets are the result of a non-linear energy cascade through eddy-mean flow interactions (Berloff et al, 2009) or that they could be due to mesoscale eddies following preferred paths. Some aspects of these jets are captured by 10km resolution ocean models (Maximenko et al, 2008; Divakaran and Brassington, 2011), but their location, spatial scales and tilts can be incorrectly simulated.

4.3.7 Science questions

Both the climate and marine environment of Australia are strongly influenced by the boundary currents and interbasin flows surrounding the continent. These current systems include the East Australian Current, the Leeuwin Current, the Indonesian Throughflow, the Antarctic Circumpolar Current, and various regional current systems. 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 on 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.

As the boundary currents are themselves part of basin- and global-scale circulation systems, broadscale observations are needed in addition to focused measurements of the boundary currents themselves. The major goal with regard to boundary currents is to quantify the mean flows and the time scales and magnitudes of variability. The following high-level science questions will guide the Bluewater & Climate observing strategy in this area:

Fluxes:

- *How do the mass, heat, and salt transport of Australian boundary currents and inter-basin flows vary on seasonal, interannual and multidecadal timescales?*
- *How do boundary current transports respond to and influence regional climate?*
- *What are the relative contributions of air-sea fluxes, the mean flow, and eddies to the regional heat and freshwater budget of Australia's oceans?*

Drivers:

- *What is the cause of variations in current strength?*
- *How much of the change observed can be attributed to human drivers?*
- *What is the relationship between boundary currents and modes of climate variability?*

Dynamics:

- *What is the dynamical connection between boundary currents, interbasin flows and gyres in the Australian region?*

- *What are the dynamics associated with temporal changes in boundary current bifurcations, such as the bifurcation of the South Equatorial Current and the separation of the EAC from the coast?*
- *What controls variations in the strength of the eddy field associated with major Australian current systems?*

4.3.8 Status, gaps, opportunities and priorities for future enhancements

Status:

IMOS has deployed arrays of current meter moorings to measure the transport of the Indonesian Throughflow, the EAC, and outflow of dense water from an Antarctic polynya. These measurements of major deep-reaching currents are complemented by glider, radar and coastal mooring measurements made on the continental shelf by the regional nodes. As the boundary currents and inter-basin flows are part of the large-scale general circulation of the oceans, the Node relies on broad-scale measurements of the open ocean collected by Argo, SOOP and well-validated satellite remote sensing to study changes in these current systems. SOOP XBT lines have been used to derive accurate transport estimates for the EAC,ACC and ITF. Transport estimates from major current systems like those provided by IMOS are some of the most valuable and widely used metrics available for testing of ocean and earth system models.

The Southern Ocean Flux Station (SOFS) represents a rare validation point in the Southern Ocean for satellites and flux products and for the representation of large-scale currents in climate models. SOFS' location in the subantarctic zone (the only global flux site south of 30°S) facilitates monitoring of interannual climate variability forced by ENSO and SAM. This requires observations on approximately 4-year timescale to measure single events, and a 12-year time-series to confidently observe phenomena on this scale. It is a key observing platform for the air-sea flux component of SOOS.

Opportunities:

Arrays of instruments anchored on the sea floor have been to date the only means for reliable sampling of strong boundary currents. Such arrays are resource-intensive, both in terms of equipment and ship time needed for deployment and recovery. Overseas groups have begun to have some success with the use of autonomous gliders for boundary current monitoring. IMOS should explore the opportunity to use the re-deployment of the EAC array to test the glider approach in EAC waters. Simultaneous deployment of gliders and moorings would allow a robust assessment of gliders as a cost-effective approach to boundary current measurements. Inverted echo-sounders (IES) also provide a cost-effective alternative to traditional tall moorings and should be evaluated for their use in Australian boundary currents.

The original target for the Antarctic polynya moorings was the Mertz Polynya near 143E. This area is a primary source of Antarctic Bottom Water and therefore a high priority for sustained observations. However, calving of the Mertz Glacier Tongue in 2010 has altered the regional ice-scape in such a way that the original polynya mooring site is now usually covered by sea ice and no longer logistically viable. This provides an opportunity to re-assess how best to deploy IMOS assets to study the key issue of bottom water formation and the Southern Ocean overturning circulation. One possibility is to focus on a polynya near the Totten Glacier, the most rapidly-thinning glacier system in East Antarctica. A pilot deployment from January 2014 to January 2015 will provide data with which to assess the value and feasibility of sustained moorings in this location.

Gaps:

A number of important boundary current systems around Australia are not yet measured in a sustained way. These include the Leeuwin Current, the Tasman Outflow, the Kerguelen Deep Western Boundary Current, the Perth Basin, and the boundary currents in the Coral Sea and western tropical Pacific. Support for these arrays is beyond the scope of IMOS in its present form but the node should explore opportunities to leverage support from others to allow these important boundary current systems to be measured in the future.

Priorities for future enhancements:

The establishment of moored arrays at the Indonesian Throughflow and East Australian Current is a major achievement of IMOS. The highest priority is to maintain these arrays, which are providing the first long time series from Australia's major boundary currents and inter-basin flows. Sustained measurements of polynya and bottom water formation processes remains high priority, but as discussed above the IMOS strategy in this area needs revision as a result of changes in ice conditions.

- Design and test a strategy for boundary current monitoring using gliders and/or inverted echo sounders, as a lower cost alternative to tall current meter moorings.
- Sustained measurements of key boundary currents and inter-basin flows that are not yet sampled, such as the Leeuwin Current, the Tasman Outflow, the Kerguelen Deep Western Boundary Current, and the Perth Basin, using moorings or alternative cost-effective technologies.

4.4 Continental Shelf and Coastal Processes

The boundary 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, and local coastal flows. Furthermore, the exchanges between the deepwater systems and the shelf are a two-way process, with outflows of freshwater and nutrients also spreading from the shelf to the deep ocean. Identifying local manifestations of these global phenomena is crucial to understanding the drivers of variability on the continental shelf and their influence on regional marine ecosystems.

EAC eddies frequently move onto the continental shelf and close inshore and influence the local circulation patterns. At prominent coastal features the EAC moves away from the coast, driving upwelling that draws nutrient-rich water from a depth of 200-m or more. However, while the EAC may drive nutrient-rich water onto the shelf, upwelling-favourable winds (northerly) bring the water to the surface (Rochford, 1984; Cresswell, 1994; Church and Craig, 1998). Mesoscale eddies formed within the LC drive cross-shelf exchanges off the WA coast – enhanced concentrations of chlorophyll are observed in the warm-core eddies (Waite et al, 2007).

On the continental shelf, local seasonal wind-driven flows are observed off the west coast. For example, in summer the Capes Current (CC) originates between Capes Leeuwin and Naturaliste (34S) flowing northward as far as the Abrolhos Islands. The CC is present on the inner shelf and bounded offshore by the LC. In the frontal system between the two currents, warmer, lower salinity LC water interacts with the cooler, more saline CC creating intense mixing. Similar systems have been observed off Ningaloo and Esperance.

The interaction of the boundary currents with the shelf/slope region off Southern Australia is highly seasonal and forced by both the Flinders and Leeuwin Currents (Middleton and Bye, 2007). Dense water formed in shallow waters within the Great Australian Bight and Spencer Gulf intrudes into the offshore currents. Upwelling favourable winds and coastal-trapped waves can lead to deep upwelling events off Kangaroo Island and the Bonney Coast that occur over 3–10 days and some 2–4 times a season (Middleton and Bye, 2007).

The surface flow of the EAC and LC come into direct contact off southeastern Tasmania. The differences in forcing mechanisms, water masses, and seasonal expression directly influence shelf/slope exchanges around Tasmania (Ridgway, 2007).

The connection between variability on and off the continental shelf means that sustained observations of the open ocean are needed to understand the drivers, dynamics and impacts of change on the shelf. The node plans for each of the regional nodes address aspects of onshore – offshore exchange relevant to their region in more detail.

4.4.1 Boundary current eddy –shelf interactions

Along the temperate east and west coasts, eddies formed in the boundary currents transport heat, nutrients and other properties between the open ocean and the shelf. Large-scale climate modes such as ENSO and SAM can influence the nature of the boundary currents and hence the exchange of properties across the shelf break. Eddies are particularly important off the narrow shelf regions on the temperate east and west coast of Australia. The eddy field in the Leeuwin Current is strongest in winter and contributes to cross-shelf exchange of heat, nutrients and larvae (Domingues et al., 2006; Moore et al., 2007; Waite et al., 2007).

4.4.2 Upwelling and downwelling

Wind-driven upwelling is uncommon around the Australian coast. In many locations, the predominant wind direction is not upwelling-favourable. Upwelling of waters onto the continental shelf can be both inhibited or enhanced by offshore boundary currents and their eddy field. For example, the Leeuwin Current tends to suppress upwelling and therefore upwelling is more likely in summer when the current is weaker. Moreover, surface eastward flows feeding the Leeuwin Current are believed to downwell at the coast and return offshore at deeper levels (Domingues et al., 2007). 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). Interaction of boundary currents with submarine canyons can also drive upwelling, e.g. in the Perth Canyon (Rennie et al., 2009) and off the South Australian coast (Kaempf, 2006, 2007). Intrusion of open-ocean waters through gaps in the GBR act as a source of nutrients to the reef lagoon (Andrews and Furnas, 1986). Variations in strength of the boundary currents cause variations in the depth of the thermocline and therefore variations in the water properties available for transport onto the shelf. These examples illustrate how an understanding of upwelling onto the Australian continental shelf depends on knowledge of the offshore conditions.

4.4.3 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 are characterised by extreme tides. The boundary currents and inter-basin flows abutting the continental shelf have a strong influence on these shelf circulation systems. For example, the waters of the GBR are influenced by the onshore flow of the SEC jets; in northwestern Australia, the Holloway Current transports waters from the Indonesian Throughflow southward to feed the Leeuwin Current; and the eastward extension of the Leeuwin Current in winter contributes to the shelf currents in the Great Australian Bight.

4.4.4 Wave climate, including internal and coastally trapped waves.

Coastally trapped waves are the primary mechanism by which the ENSO signal is transmitted around the coast of Australia, where it influences the strength of the Leeuwin Current and other shelf current systems (Wijffels and Meyers, 2004; Feng et al., 2005). 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.

4.4.5 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 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.

Evidence for a strong connection between conditions on and off the shelf suggests that observations that span both domains are needed to understand variability on the continental shelf. In the IMOS context, this means close integration between the bluewater node and each of the regional nodes.

The following high-level science questions will guide the Bluewater & Climate Node observing strategy in this area:

Boundary Current/shelf interactions

- *How does the large-scale circulation (boundary currents, gyres, eddies and interbasin flows) affect the shelf and coastal environment?*

Upwelling and Downwelling

- *How do boundary currents moderate the strength, extent and variability of upwelling and downwelling?*

Shelf Currents

- *How do offshore flows interact with shelf currents?*

Wave Processes

- *How does the large-scale circulation and stratification affect the wave environment (e.g. internal waves and coastally trapped waves) on the continental shelf?*

4.4.6 Status, gaps, opportunities and priorities for future enhancement

Status:

The IMOS observing strategy for continental 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. (See the National and Regional Node plans for details). The contribution of the BCN node to this area of research is to identify and quantify the open ocean processes that drive variability in shelf and coastal waters. The observations discussed above contribute to them, in particular Argo, boundary current arrays, ship of opportunity measurements, and satellite remote sensing. In many cases, IMOS measurements on the continental shelf and in the deep ocean have been coordinated to exploit the synergy between them (e.g. extension of the EAC and ITF mooring arrays over the continental shelf).

Gaps:

IMOS measurements of Australia's vast continental shelf remain sparse and widely distributed.

Opportunities:

Research conducted by the bluewater and coastal/shelf communities in Australia could be better integrated to ensure we are taking maximum advantage of the IMOS data streams. Profiling floats are being developed for sampling on the continental shelves. These instruments offer the potential for broad-scale sampling of shelf waters for the first time.

Priorities for future enhancements:

- Expand CO_2 network on national reference station to ensure ocean acidification progress is quantified for representative coastal habitats.

4.5 Ecosystem Responses

Ecosystem change is anticipated via climate change impacts on temperature, the hydrologic cycle, and ocean circulation, and the influences of these changes on biogeochemical properties such as nutrient delivery and oxygen levels. Direct forcing is also expected from the ocean acidification accompanying anthropogenic CO_2 emissions. Attention to the role of boundary currents and the overturning circulation provides a unifying approach for the assessment of what are likely to be diverse and complex impacts.

The two major poleward flowing boundary currents around Australia, the East Australian Current and the Leeuwin Current, play a vital role in regulating the productivity of pelagic and benthic ecosystems. The warm boundary currents are generally nutrient poor with only patchy upwelling, leading to marine systems of low productivity. Tropical and subtropical species can exist in relatively high latitudes, especially as the East Australian Current has increased in strength over the past 60 years (Ridgway 2007). However, nutrient enrichment processes including cold-core eddies, shelf-edge upwelling, atmospheric dust inputs and topographic upwelling near capes, cause localised peaks in productivity. These productivity hotspots are critical to supporting diverse fisheries, seabirds, marine mammals and sea turtles. Key knowledge gaps include understanding how lower trophic levels will respond to climate change, how this will influence the higher trophic levels, and the direct impacts of climate change on the distribution and abundance of higher trophic levels.

Another key area around Australia is the Southern Ocean. Changes in Southern Ocean circulation and sea-ice cover can be thought of as sensitive early indicators of global climate changes (Houghton et al 2001), which also affect the Southern Ocean ecosystem. Despite the fact that the Southern Ocean 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 Southern Ocean is warming faster than other oceans (Gille 2002, 2008; Böning et al. 2008) and Antarctic sea ice is predicted to reduce by 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 Antarctic Circumpolar Current (ACC), and richer CO_2 water is being circulated to the upper layers and may be reducing the effectiveness of the Southern Ocean as a CO_2 sink (Le Quere et al., 2007), although this is still a matter of debate. The biota of the region are uniquely adapted to the extreme environments in which they exist, and thus vulnerable to shifts in climate. Changes in phytoplankton will be expected to have a flow on effect through the rest of the food web, impacting the survival of higher predators, krill and finfish. This highly dynamic system, with temporal and spatial variability in primary production produces a number of "hot-spots" or Areas of Ecological Significance (AES). Seasonal oceanography and ice cover boosts ecosystem production, making it one of Australia's richest pelagic ecosystems. This supports the greatest density and biomass of apex predators to be found in Australian waters. Understanding the response of marine biota to climate forcing is vital both for climate and for management of marine resources. In this context, the Subantarctic Zone is notable owing to its role in defining the upper limb of the overturning circulation which determines the export of nutrients to waters outside the Southern Ocean, its proximity to Australia, connections to the Leeuwin and East Australia currents, and recognition as the region with the largest accumulation of anthropogenic CO_2 in the southern hemisphere.

In the sections that follow, we address these issues using an approach that builds up from the environment (physical and chemical) towards the impacts on key trophic levels.

4.5.1 Ocean Chemistry – Nutrients

Primary production in the ocean is limited by regional patterns of light and nutrients. Background nutrient levels are controlled by the large-scale ocean circulation. The response of nutrients to changes in ocean circulation is key to understanding how the productivity in Australian waters will change. However, observations in Australian regional seas are patchy for macronutrients N, P and Si, but especially for micronutrients such as iron. Except in a few locations (e.g. the work of Thompson et al., 2009 at Maria Island, Tas; and the high resolution seasonal observations recently achieved at the Southern Ocean Time Series), the best nutrient data sets available are climatological annual cycles from the CSIRO Atlas of Regional Seas (CARS; Figure 4.14).

Figure 3.14: Global nutrients: CARS surface (0m) data for silicate (top panel), nitrate (middle panel) and phosphate (bottom panel). Concentrations in mmol m^{-3} are given on the colour bars. Figures are from http://www.marine.csiro.au/~dunn/cars2009/plots_index.html.

The very limited distribution of nutrient measurements, mostly obtained from voyages of research vessels, is likely to be skewing and aliasing nutrient climatologies (both spatially and temporally). Underway mapping of nutrients from SOOP vessels would help to resolve these inadequacies, but possibly the most promising avenue for increased nutrient coverage is on next generation Argo floats, which capture the depth structure and not just surface distributions. Currently, international programs are developing that capability that aims at deploying~ 200 Argo floats equipped with pH, nitrate, bio-optics and oxygen into the Southern Ocean. Such increased information on nutrient dynamics will become particularly useful when it is matched with the simultaneous collection of phytoplankton data.

4.5.2 Ocean Chemistry – Carbon and acidification

The uptake and storage of CO_2 in the oceans causes ocean acidification, where pH and upper-ocean carbonate ion concentrations decrease (Orr et al, 2005). The lower carbonate ion concentrations cause a decrease in the seawater saturation state of major calcium carbonate forms that are precipitated by marine calcifying organisms (Feely et al 2004). Current CO_2 emission trajectories indicate the upper ocean will undergo a shift in carbonate chemistry in this century that is profound. 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, 2005; Figure 4.15). All regions of the ocean will show a decline in calcium carbonate saturation states. The Southern Ocean 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 (Orr et al., 2005). In high latitude shelf environments, natural processes can lead to significant changes in ocean carbonate chemistry compared to large-scale model projections. For example, off Davis Base, Antarctica, decadal shifts in ocean acidification were almost twice as large as expected due to the uptake of atmospheric CO_2 (Roden et al, 2013). In contrast, enhanced biological production associated with the break-off of the Mertz Glacier tongue in 2010 reversed the predicted ocean acidification change in the Mertz Polynya region (Shadwick et al., 2014).

Figure 3.15: 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 based on the IS92a emission scenario have now been 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.)

The ecosystem response to acidification is not well understood and is an area of intense international research. Incubations of corals and other marine calcifying species grown at elevated CO_2 do show reduced rates of calcification (Langdon and Atkinson, 2005; Gazeau et al 2007; Riebesell et al, 2000), although the response varies among species (Iglesias-Rodriguez et al 2008). Multiple stressors like warming can also affect the acidification response (Byrne et al 2013). Non- calcifying species may be impacted in ways that could alter ecosystem dynamics and nutrient availability (e.g. Boyd and Doney, 2003 and Hutchins et al, 2007). The potential for impact on fish populations and larval survival is undetermined. The changes to calcifying organisms are predicted to have a major impact on the health and sustainability of reef and perhaps planktonic ecosystems (e.g. Hoegh-Guldberg et al, 2008, Riebesell et al 2000). Evidence of decreased calcification for high latitude foraminifera, South of Australia (Moy et al, 2009), and in corals on the Great Barrier Reef (De'ath et al, 2008) are broadly consistent with an acidification response. However, a lack of data on the change in carbonate chemistry in these environments makes a definite link difficult to establish. The changes in and drivers of carbonate chemistry need to be measured to determine the exposure of ecosystems to acidification and to evaluate the likely ecosystem response to the change. The SOTS is making progress for the Southern Ocean in resolving the carbonate system characteristics with the required seasonal resolution for biomass poor waters in the Subantarctic Zone , but additional effort is needed to provide comparison to biomass rich waters and for waters further south in the Antarctic Zone. Relocation of the SOTS infrastructure is one option, although international experience at sites such as HOT for the central Pacific and BATS for the north Atlantic suggests that ongoing commitment to a single site provides an important focus for national efforts and has special value given the almost complete absence of multi-decadal ocean records.

4.5.3 Phytoplankton and Zooplankton

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. Specific groups of interest include , diatoms (as the dominant taxa for the Antarctic Zone), calcifiers (owing to expected impacts from ocean acidification), and zooplankton (as the greatest unknown in terms of converting readily available satellite observations of phytoplankton biomass into more useful understanding of ocean productivity.

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 Australia's regional seas and the Southern Ocean. The former is beginning to be tackled through IMOS-funded efforts led by the bio-optical working group, to accumulate Australia's in situ pigment data and provide them to NASA's databases. These pigment data sets of course include valuable and ongoing IMOS data streams such as the plankton sampling at the National Reference Stations. The latter was recently addressed by Johnson et al. (2013), who improved the existing Southern Ocean algorithms to correct pervasive underestimates. The reprocessed SeaWiFS and MODIS data archives are now hosted by IMOS.

Observations of calcifiers are currently best achieved by two IMOS facilities: the continuous plankton recorder (CPR) facility and the SOTS Southern Ocean sediment trap moorings. The CPR spans both coastal Australia and the Southern Ocean, so together these observational tools are providing important information on changes potentially associated with ocean acidification spanning the tropics to Antarctica. The CPR also samples zooplankton, and an important potential area of IMOS science in the coming decade will be the closer coupling of zooplankton CPR observations with phytoplankton data from the CPR, concurrent underway systems (for example on Aurora Australis) and ocean colour remote sensing. The SOTS SAZ sediment trap mooring has provided samples that have advanced understanding of plankton community structure and ecological responses to ocean acidification (see the Highlights section below for details), and along with the SOTS Pulse biogeochemistry mooring now offers the best sample collection for study of the links between phytoplankton community structure and environmental conditions.

4.5.4 Mid Trophic Levels (Micronekton)

The water column comprises more than 90% of the Earth's living space, and its deep water inhabitants are the largest and least-known major faunal group on Earth. Mid-trophic animals (meso-zooplankton and micronekton ~2 to 20 cm length including small fish, crustaceans, squids and gelatinous species) probably account for the bulk of global ocean biomass. This ecological system is under threat from a broad range of influences, including climate change, acidification and fishing (Robison, 2009).

Mid-trophic organisms that occupy this enormous pelagic realm have a pivotal role in the functioning of ecosystems, linking biogeochemistry to the distribution and abundance of predators. However, coupled ocean-biogeochemical-population models have identified a lack of data on their distribution, biomass and energetics (Fulton et al. 2005, Lehodey et al 2010). Models need observations on the distribution and abundance of these micro-nekton at shelf and basin scale to validate predictions, but there are very few observations in Southern Hemisphere waters. These sparse observations come from a variety of sampling devices of limited spatial and temporal extent, making it difficult to compare biomass estimates or 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 top trophic levels via fisheries data and electronic tagging of top predators. SOTS has made first steps to address this issue, with the deployment of a four-frequency acoustic water column profiler to map seasonal changes in small fish and large zooplankton, paired with CPR deployments. New bioacoustic capabilities of the RV Investigator are expected to allow further advances.

4.5.5 Top Predators

The importance of upper trophic levels in structuring marine communities due to their role as predators is now clear (Estes et al. 1998; Myers and Worm 2003). At the same time, the significance of transport of nutrients across and within the water column by upper trophic level predators is becoming increasingly recognised (Smetacek and Cloern 2008). However a complete understanding of upper trophic level processes requires measurements over long time frames and integration across all trophic levels and with ocean physics. Marine apex predators 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. Zooplankton, fish and squid remain the most difficult aspect of the ocean ecosystem to monitor, and predator movements (Figure 4.16) are one of the most effective means of inferring basic distribution and abundance data for these animals (Nicol et al. 2008).

Pelagic apex predators focus their foraging in areas of relatively high food availability; accordingly they can be used to identify areas of ecological significance (AES, also known as "hot-spots"). Observing AESs will provide information on the spatial and temporal variability of their prey and the influence of mesoscale features such as fronts and eddies. The response of predators to fluctuations in prey availability can initially be manifested as changes in their foraging locations or foraging success, and subsequently as demographic changes in survival, breeding success and eventually abundance. Each of these parameters are readily measurable with appropriate instruments and methodologies. Observing a suite of such parameters across a range of predator species and sites, in concert with monitoring of other biological and physical parameters at similar spatial and temporal scales, provides a basis for assessing changes in oceanic ecosystem and the demographic consequences of those changes on select iconic apex predators (Raymond et al., 2014). Apex predators have been clearly established as sensitive indicators of climatic perturbations in the Southern Ocean (Lea et al. 2006, Jenouvrier et al. 2009). Australian scientists are key players in international conventions governing the management of Southern Ocean apex predators (e.g. CCAMLR, SCAR, Antarctic Treaty).

Figure 4.16: Summary map of at-sea predator locations from ARGOS platform transmitters illustrating the extent of spatial coverage that can be obtained from this form of sampling (IMOS data portal - http://imos.aodn.org.au/imos123/home#).

4.5.6 Science questions

Marine ecosystems underpin major economic activity in Australia's regional seas and the Southern Ocean. These ecosystems experience significant perturbations due to modes of climate variability such as ENSO, IOD and SAM, fluctuations in the dynamics of the Australian boundary currents and climate change. Ocean acidification and warming are also likely to impact the productivity of lower trophic levels, with consequences for fisheries and apex predators. It is important that we understand the bottom up drivers of ecosystem productivity and trophic level interactions if we are to predict and mitigate future change.

The goals of the ecosystem science questions are to determine the links between ocean circulation, biogeochemical fluxes (including nutrients) and ecosystem function. The umbrella term ecosystem function includes the productivity, distribution and abundance of species, but also connections in space and between trophic levels.

The ecosystem science questions are formulated around using observations of carbon chemistry and nutrients, phytoplankton and zooplankton, mid-trophic animals and apex predators to understand ecosystem function and response to climate change.

Circulation and nutrient fluxes:

- *How does the large scale circulation control the links between the physical, chemical and biological environment?*
- *What controls the temporal variation in biogeochemical fluxes of the ocean and how will they respond to climate variability?*

Productivity:

- *What is the relationship between rapid mixed-layer dynamics in the Southern Ocean, plankton production and carbon transports*?
- *How do the changes in boundary currents (EAC and LC) and associated eddy fields influence ecosystem productivity?*
- *How do cross-shelf exchange processes (boundary currents and shelf regions) influence coastal productivity and ecosystem connectivity?*
- *How do changes in ocean acidification influence key vulnerable ecosystem components such as Southern Ocean calcifiers?*

Trophic connections:

- *How do the different trophic levels respond to climate variability?*
- *How are trophic levels connected and how might these connections be altered under a changing climate?*
- *What are the most vulnerable regions and species (either particularly sensitive or unable to adapt) to changing environmental factors?*

4.5.7 Status, gaps, opportunities and priorities for future enhancements

Status:

At the level of biogeochemistry and primary productivity, the national reference stations and SOTS/SOFS provide comprehensive data sets for detecting change in parameters including nutrients, air-sea CO_2 fluxes, deep carbon export and phytoplankton/zooplankton communities. Repeat hydrography campaigns also provide perhaps the best data at ocean basin scales for detecting processes such as ocean acidification. Future sensor developments might see observations of comparable quality made on Argo floats. High quality data on both phytoplankton and zooplankton are collected from the continuous plankton recorder on ships of opportunity around Australia and on the Aurora Australis in the Southern Ocean. Passive acoustics and animal tagging are the primary IMOS data streams relevant to higher trophic levels.

Gaps:

The major gaps in data coverage for the BCN ecosystem questions relate to spatial and temporal coverage and some of the more detailed species data. 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. We are also lacking 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.

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.

Opportunities:

There are opportunities to add value to individual data streams through more effective integration. For example, simultaneous measurements of mixed layer depth, stratification, phytoplankton pigments, pCO_2, nutrients, zooplankton (from CPR and acoustics) and higher trophic levels (e.g. from AATAMS) would provide an extremely powerful data set for understanding coupling between physical and biological systems. Even partial achievement of this ideal system would be a major step forward. Wave gliders are now becoming more or less standard oceanographic equipment, but are not yet used in Australia. They offer the potential for more cost-effective monitoring and their larger payload allows use of sensors too big for floats or gliders.

Priorities for future enhancement:

- 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.
- Apply new sensing platforms like wave gliders to improve coverage for biogeochemical and bio-acoustic sensing technologies.
- Maintain the SOTS observations and augment them with a high latitude mooring based on small profile CO_2/acidification moorings to track biological and physical controls on the carbon cycle in the Southern Ocean.
- Assess the feasibility of deploying new integrated pH and oxygen sensors in Antarctic shelf waters to track acidification change.

4.6 Ocean Prediction

The development of numerical models with sufficient resolution to resolve the mesoscale ocean circulation, and with the ability to assimilate ocean observations, now allows for true ocean prediction, akin to weather forecasts in the atmosphere. Ocean forecasts are being used for a wide variety of applications, including defence, search and rescue, ocean energy assessments, offshore engineering, oil spill response, shipping, weather forecasting, climate variability, and management of fisheries. In Australia, ocean predictions are provided by the BLUElink system (see http://www.csiro.au/Outcomes/Oceans/Oceans-and-climate/BLUElink.aspx and http://www.bom.gov.au/oceanography/forecasts/). A number of IMOS data streams are assimilated by the BLUElink models, including Argo, SOOP and satellite remote sensing data. Other IMOS observations like coastal radar data have been used for validation of model performance and are increasingly being used to initialise and constrain coastal models.

Examples of the use of IMOS data streams and ocean forecasts/hindcasts include the response to the Montera oil spill, the search for Malaysian Airlines flight MH370, cost-effective scheduling of drilling operations, and real-time adaptive management of the tuna and billfish fisheries off Australia's east coast.

Data assimilation is also increasingly being used in seasonal climate prediction systems (e.g. Yin et al., 2011), as discussed in the climate variability and weather extremes theme above.

Status, gaps, opportunities and priorities for future enhancements:

Status:

The most important data streams for assimilation into large-scale ocean prediction systems are satellite measurements (of sea level, sea surface temperature and winds) and Argo profiles of temperature and salinity. The status of these observing systems is discussed above. While broad-scale measurements like these are most valuable for assimilation into global or basin-scale models, local measurements from moorings, coastal radars and gliders are important for model testing and for assimilation into high resolution limited-area models (For example, coastal radar data was used to identify a bias in a new version of the BLUElink model). Ocean prediction systems have also been used to guide and assess the design of observing systems like IMOS (e.g. Oke et al., 2009; Oke and Sakov, 2012; Lea et al., 2012). These studies demonstrate that the individual components of the observing system (e.g. Argo, XBTs, and satellite altimetry) are highly complementary and none are redundant. By contrast, recent studies have indicated that enhancements to each component of the Global Ocean Observing System – particularly Argo and satellite altimetry, may lead to significant improvements in our ability to forecast the ocean on time scales of weeks to months (e.g., Fujii et al. 2014 – submitted TPOS paper to QJRMS).

Gaps:

To date, many IMOS data streams have been used only to assess ocean predictions and reanalyses. This is an important function, but there is an opportunity for even greater impact if IMOS observations could be exposed to the operational ocean forecasting community over the World Meteorological Organisation's Global Telecommunication System (GTS). This would deliver IMOS observations to WMO endorsed agencies for ingestion into their operational ocean forecasts. This would include all nations – not just Australia – and would help improve the quality of ocean forecasts in the Australian region world-wide. This activity is best done in consultation with the BoM.

Australia's core capabilities in ocean prediction have been developed mostly under the Bluelink partnership between CSIRO, BoM, and RAN. The Bluelink capabilities are currently still the only Australian capabilities that can assimilate observations to initialise forecasts and reanalyses of the mesoscale ocean circulation. However, the Bluelink global model is 1/10° resolution around Australia, does not explicitly resolve tides, and does not routinely include marine biogeochemistry. Much of Australia's marine industry operates on our continental shelves, where tidal flow is important, and where the scales of variability are short – with the submesoscale playing an important role. Our community does not currently have any capability to reliably model, predict, or hindcast the submesoscale ocean circulation around Australia. An initiative called the Australian National Shelf Reanalysis (ANSR) has begun to develop a strategy to fill this gap. The ANSR will ultimately seek to develop a national, high-resolution (2-4 km), tide-resolving ocean model that can realistically simulate the submesoscale variability around Australia, and can synthesise all shelf and open-ocean observations through data assimilation – ultimately yielding a realistic picture of the three-dimensional, time-varying submesoscale circulation around Australia for the last 5+ years. This activity – currently at the planning stage – is likely to take several years to mature, and will draw on expertise from Australia's coastal oceanography community – bringing together large-scale and coastal ocean modellers, and open-ocean and coastal observational oceanographers. The end goal is to produce a reanalysis of Austrralia's coastal and shelf circulation, akin to atmospheric reanalyses such as ERA-Interim and JRA-55.

The Bluelink forecast and reanalysis has demonstrated steady improvement over its 10-year partnership. But with the constant evolution of the GOOS – with new observation platforms coming on-line (e.g., SMOS, Aquarius; Altika and soon SWOT), the efforts to continually assimilate more observation types more accurately must be sustained.

The Bluelink forecasting capabilities are not global – with the latest Bluelink "global" ocean model only extending between the latitudes of 75S and 75N. This neglects the important contributions of high-latitude processes, including sea-ice. Efforts towards the development of a truly global eddy-resolving ocean forecast system are underway – but the Bluelink team has not yet received a clear mandate from funders or decision –makers that have allowed this development to be undertaken at the level it requires to succeed.

Opportunities:

As ocean prediction systems aim to simulate ocean conditions at increasingly fine spatial scales, the data needs for both assimilation and validation change. There is an opportunity to more fully exploit IMOS data streams in regional/local ocean prediction. Ultimately, this may be achieved under ANSR – but recall that at the time of writing, ANSR is only in the planning stage.

Exposure of IMOS observations to the WMO GTS would result in immediate improvements to ocean forecasts by many national centers (e.g., Australia, US, UK, French) in the Australian region. Many commercial met-ocean service providers routinely access forecasts from all available international forecasts to support various Australian maritime industries.

5 How is IMOS data being used?

There has been wide uptake and use of IMOS data by Australian scientists and stakeholders contributing to the Bluewater and Climate Node. The vast majority of Australian scientists studying large-scale ocean circulation, climate change and variability, biogeochemical cycles, and ecosystem processes use IMOS data streams in their research (Table 5.1). The investment in IMOS infrastructure allows Australian researchers to play lead roles in major international climate research programs, such as those of the World Climate Research Program. In turn, co-investment by users of IMOS data has resulted in substantial leverage of the investment in IMOS.

Stakeholder use of IMOS research is both direct and indirect. Direct uses of IMOS data include use by scientists to publish scientific papers, by modellers to test and improve circulation models, and use in a large number of Australians PhD projects. Indirect uses include a wide variety of applications. International assessments like those of the Intergovernmental Panel on Climate Change are based on studies that rely on the global data streams of IMOS and its international partners. Ocean forecasts based on models that assimilate IMOS data streams are routinely used for search and rescue, emergency response and defence (e.g during the Montera oil spill and the search for Malaysian Airlines flight MH370). Seasonal outlooks and warnings for extreme weather events are underpinned by IMOS data. Managers of marine resources use products based on IMOS data to set catch limits and manage stocks. IMOS data also underpins national assessments of the marine environment including "report cards' and state of the environment reports. IMOS data streams like Argo have been used as a teaching tool at levels from primary school to university.

Table 5.1: How IMOS Facilities deliver to the Nodes. P = primary relationship and s = secondary relationship

	Bluewater & Climate	WA	QLD	NSW	SA	TAS
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
eMII/AODN	P	P	P	P	P	P

*there exists great potential for glider deployments to answer BCN questions in the boundary currents and Southern Ocean if operational issues can be addressed.

5.1 Recent highlights of research using IMOS data streams

IMOS data have already been used to study a diverse range of scientific questions of direct relevance to Australia.

- IMOS data streams like Argo played a prominent role in many of the analyses assessed by the Intertgovernmental Panel on Climate Change 5th Assessment Report, in particular the chapters on ocean change (Rhein et al., 2013) and sea level (Church et al., 2013).
- Argo profiles have been used to extend ocean heat content records to 2000 m, revealing a significant but elusive heat sink for part of the Earth's energy budget that had been previously unaccounted for in some climate models (Abraham et al., 2013), to demonstrate that ocean warming can be attributed to human activities (Gleckler et al., 2013), and to constrain estimates of ocean heat content, sea level rise and the planetary energy budget (Gregory et al., 2013; Otto et al., 2013).
- Argo data has also been used to show that changes in ocean salinity indicate that the global water cycle has intensified in recent decades, consistent with expectations in a warming world (Durack et al., 2012).
- By combining Argo data with a climatology of carbon dioxide observations, scientists from the BWCN quantified the uptake of anthropogenic carbon dioxide by the Southern Ocean for the first time from observations (Sallée et al., 2012).
- IMOS data have provided new insights into the air-sea interactions involved in the Madden-Julien Oscillation (Drushka et al., 2012), the Indian Ocean Dipole (Qiu et al., 2012; Cai and Qiu, 2013) and the seasonal cycle of mixed layer depth in the Coral Sea (Jaffres, 2013).
- Argo and satellite altimeter observations have documented changes in ocean circulation patterns relevant to Australian and global climate, including the Tasman Outflow (Fieschi et al., 2013) and the global subtropical western boundary currents (Wu et al., 2012).
- Particle- export samples and data generated by the Southern Ocean Time Series (SOTS) and its predecessor sediment-trap collections in the Subantarctic Zone southwest of Tasmania constitutes the longest series of its type in the Southern Ocean, and has provided invaluable data on the response of plankton ecosystems to decadal-scale changes in the ocean and on

the validation of biotic and isotopic tracers for palaeoclimate reconstructions (King and Howard, 2003, 2005). In particular this site has provided the first published evidence of a biological response to ocean acidification in nature (Moy et al., 2009; Howard et al., 2009), as well as baseline data on calcareous plankton export against which future acidification response may be measured (Roberts et al., 2008).

- SOTS also provided an independent estimate of anthropogenic carbon dioxide penetration in the Southern Ocean mixed layer through stable carbon isotopic measurements in sediment-trap foraminiferal shells referenced to pre-industrial levels recorded in Holocene sediments in the region (King and Howard, 2004).

- The Southern Ocean Flux Study (SOFS) has provided the first direct measurements of air-sea fluxes of heat and momentum in the Southern Ocean (Schulz at al., 2012). These observations are being used to identify biases in air-sea flux products derived from atmospheric reanalyses and satellite measurements.

- IMOS CO_2 data are making valuable contributions to an international program on constraining global and regional CO_2 uptake and determining the acidification of the oceans that is coordinated through the International Ocean Carbon Coordinated Project. The sustained observations span Australia's regional seas and the Southern Ocean and provide the keystone data to evaluate ecosystem responses to acidification. IMOS is a major contributor to the Surface Ocean CO_2 Atlas, which is a uniformly quality-controlled data product of all high quality data collected in the oceans since 1968 (Bakker et al, 2014). The atlas is a product used widely for detecting changes in ocean CO_2 uptake and resolving the global carbon budget (e.g. Le Quéré et al, 2014; Sarma et al., 2013; Lenton et al., 2013).

- The CPR program is mapping marine biodiversity, understanding climate variability, documenting climate change impacts (e.g. Constable et al., 2014), validating ecosystem models and remote sensing products, providing indices of ecosystem health, harmful algal blooms (e.g. McLeod et al., 2012) and for fisheries management, understanding trophic linkages, measuring marine plastic pollution, and monitoring impacts of ephemeral events such as dust storms or oil spills.

- A new sea surface temperature (SST) data set developed with IMOS support has revealed patterns of variability over the past 20 years (Foster et al., 2014). Enhancements to ship of opportunity measurements of SST were identified (Beggs et al., 2012) and IMOS was active in an international assessment of SST products (Dash et al., 2012).

- IMOS data have been assimilated in a variety of ocean models that have been used for a wide range of applications, including: to determine the circulation of the Tasman and Coral Seas (Oke et al., 2012); to downscale climate change scenarios for Australia's boundary currents (Chaojiao et al., 2012) for use in impact assessments (Hobday et al., 2013); for global eddy-resolving simulations (Oke et al., 2013); and to assess the footprint of the IMOS observing system (Oke and Sakov, 2012).

- Handegard, NO, du Buisson, L, Brehmer, P, Chalmers, SJ, De. Robertis, A, Huse, G, Kloser, R, Macaulay, G, Maury, O, Ressler, PH, Stenseth, NC, Godo, OR 2013, Towards an acoustic-based coupled observation and modelling system for monitoring and predicting ecosystem dynamics of the open ocean, Fish and Fisheries, vol. 14, no. 4, pp. 605-615, doi:10.1111/J.1467-2979.2012.00480.X

- IMOS has developed new, more accurate algorithms to estimate chlorophyll from satellite measurements of ocean colour (Johnson et al., 2013).
- Oceanographic sensors deployed on seals have provided new insights into the foraging patterns of seals and other animals (e.g. Bestley et al., 2013; Cleeland et al., 2014). Oceanographic profiles collected by the seals have revealed new sources of Antarctic Bottom water (Ohshima et al., 2013; Kitade et al., 2014) and been used to improve the representation of mixed layer properties and circulation patterns in models of the Southern Ocean (Roquet et al., 2013).

5.2 Australian Blue Water and Climate Research Community

Nationally, the climate and oceans research community is growing, as policy demands from this area are increasing, which in turn strengthens the need for marine observations. A process of consolidation and increased cooperation has also continued in this community, with IMOS playing a key role in stimulating national coordination and discussions.

To aid an understanding of the user community the Node comprises, the primary agencies, centres and major projects are briefly summarised below. Where appropriate, use of IMOS data streams by these large projects and teams is noted.

The Australian Centre for Weather and Climate Research (CAWCR) (http://www.cawcr.gov.au
Many of the Node scientists work in CAWCR, a partnership formed by the Bureau of Meteorology Research Centre and CSIRO's Marine and Atmospheric Research oceans and climate capability. CAWCR scientists use IMOS data for a wide range of research, including climate change, climate variability, ocean forecasting, biogeochemical cycles, and ecosystem processes. This centre hosts the three major modelling/data assimilation capabilities of importance to the Node: ACCESS, POAMA and BlueLink.

ACCESS (http://www.accessimulator.org.au/) – Australian Community Climate and Earth System Simulator- aims to cover modelling and prediction across all time scales from those of weather through to climate change. In the Earth System Modelling (ESM) realm, ACCESS includes ocean, land and sea-ice modelling, plus both land and ocean carbon models. ACCESS will supply Australia's contribution to the next IPCC assessment report. ACCESS developers utilise IMOS physical and carbon/BGC data streams in model tuning and testing parameterisation schemes, and in model validation.

In the longer-term, many international groups and possibly the ACCESS team will build a decadal prediction system. Such a system will require full depth ocean physical and carbon data to initialise the model ocean.

POAMA (http://poama.bom.gov.au/) – Australia's dynamical seasonal climate prediction system, comprising a coupled atmospheric/ocean model system, with an initialised ocean component. Dependent on IMOS and global data streams for initialising the ocean model. Utilises IMOS data streams for model validation and process understanding around the MJO.

BlueLink (http://www.cmar.csiro.au/bluelink/) – A CAWCR/Royal Australian Navy (RAN) partnership in ocean state estimation and prediction. BlueLink has been focussed on the offshore region, providing 10km resolution in the Australian region only, with limited resolution and little data assimilation over the shelf. BlueLink is Australia's primary contribution to the GODAE OceanVIew initiative, providing eddy-resolving regional ocean reanalyses back to 1992.

The Bluelink Global Ocean forecasts and hindcasts are both produced by a global ocean model that is forced at the ocean surface by fluxes of heat and momentum. Multi-variate assimilation of satellite observations of sea surface temperature and sea level anomaly, and in situ observations of temperature and salinity are essential for the model to have any useful accuracy at meso-scale (50-

300km) resolution. A rigorous analysis of the input data dependency of the system shows that no data types are redundant in the broad sense. Forecasts are updated twice weekly and require data to be available as soon as possible (ie within a day or two of observation). Hindcasts over long periods (1992-present) are only updated when a new version of the model is released, ie every few years, so delayed-mode delivery of data is acceptable. The horizontal grid of the model is currently 10km x 10km in the Australian region and the assimilation data window is about 10days long, so data sets observing variability over scales greater than ~20km or ~3days are of most value to this particular model.

The Bluelink Relocatable-Ocean Atmosphere Model is a higher-resolution forecast system that is user-nestable within the global system. ROAM is beginning to use IMOS data (e.g. glider, mooring, radar, satellite and other physical oceanographic data) for model testing and improvement; these data may also be assimilated into the model in the future.

National Environmental Science Program (NESP)

NESP follows on from the **Australian Climate Change Science Program (ACCSP)** – a long term (>16 years) research effort which brings together Australian researchers studying climate change and developing models for climate change projections and impacts assessments in fundamental climate science, primarily run through CAWCR, but with some university contributors. The ACCSP supports ACCESS and some IMOS Facilities (Argo, XBT). The recent Framework for Australian Climate Change Science (http://www.climatechange.gov.au/publications/science/cc-science-framework.aspx) recognises the importance of ocean observations and process understanding. ACCSP ocean scientists are heavy users of IMOS data streams including Argo, moored arrays, XBT time series and the carbon network.

UNSW Climate Change Research Centre (CCRC - http://www.ccrc.unsw.edu.au/) and the **Australian Research Council Centre of Excellence for Climate System Science** (http://www.climatescience.org.au/) – house research expertise in the key areas of Earth's climate: atmospheric, oceanic and terrestrial processes, exploring climate dynamics, global climate change, and extremes of weather and climate. Use IMOS data to validate IPCC-type models and further understanding of ocean and atmosphere physics and biogeochemistry.

Australian Research Council Research Network for Earth System Science (ARCNESS - http://www.arcness.mq.edu.au/) – a University led Australian Research Council (ARC) supported initiative to establish a network for scientists working in the general area of earth system sciences. A key focus of ARC-NESS is to integrate Australian University expertise into developing strategies for building and maintaining an Earth System Model. These strategies have recently been merged into ACCESS (the Australian Community Climate and Earth System Simulator). Oceanography researchers comprise around 30% of the network, with an even greater proportion having interests in climate.

The Marine Adaptation Network - comprises a holistic framework of five connecting marine themes (integration; biodiversity and resources; communities; markets; and policy) that cross-cuts climate change risk, marine biodiversity and resources, socio-economics, policy and governance, and includes ecosystems and species from the tropics to Australian Antarctic waters. From 2009 to 2013, the Adaptation Research Network for Marine Biodiversity and Resources (or simply, the Marine Adaptation Network) worked closely with the National Climate Change Adaptation Research Facility to deliver on its vision to build adaptive capacity and adaptive response strategies for the effective management of marine biodiversity and natural marine resources under climate change. The Marine Adaptation Network is hosted within the School of Geography and Environmental Studies at the University of Tasmania and is led by Associate Professor Neil Holbrook (convenor).

The Australian Antarctic Division (AAD - http://www.aad.gov.au/): Broad ranging research of Antarctic ice, ecosystem and climate issues. Most climate related work is housed inside the ACE CRC.

Australian Institute of Marine Science (AIMS - http://www.aims.gov.au/) – focussed primarily on the northern Australian continental shelf, AIMS researchers utilise climate projections, satellite SST and BlueLink products (as an offshore boundary condition for shelf models). The impact of offshore variability on the ocean circulation and ecosystems of the Great Barrier Reef and North Western Shelf is an area of active research, including influence on coral bleaching events. Ocean acidification and its effect on reef and mangrove ecosystem health is also a growing research area. Both the Responding to Climate Change (large scale) and Reef Water Quality Monitoring programs utilize Node data streams to derive a large-scale context for local changes.

The Antarctic Climate and Ecosystem Co-operative Research Centre (ACE-CRC): a long-running collaboration between AAD, CSIRO, University of Tasmania on Antarctic and Southern Ocean Research. The ACE CRC is a heavy user of physical, chemical and ecological data streams from IMOS, as well as a substantial co-investor in IMOS observing systems. The ACE CRC was recently renewed for another five year period (2014-2019).

Western Australian Marine Science Institute (http://www.wamsi.org.au/): multidisciplinary and multi-agency marine research focused on the Western Australian coasts and eastern Indian Ocean. Both the Climate Change and Oceanography themes utilize IMOS data and secondary products (e.g. BlueLink), as the strong impact of remote ocean forcing on this coastline is well recognized.

6 Impacts and deliverables from IMOS in 5 years and in the long-term

1.1 Next five years:

- Vastly improved seasonal climatologies of key large-scale physical oceanographic properties via the phenomenal improvement in data coverage provided by Argo
- Improved climate models as a result of testing with new observations
- Much more accurate monitoring of the planetary energy budget on decadal time scales, allowing the evolution of climate change to be tracked
- More accurate sea level budgets by monitoring the rate and cause of decadal sea level rise
- Increased understanding of the Indian Ocean Dipole as a result of the enhanced Indian Ocean sampling by Argo, and the high quality time-series provided by the RAMA array

- Better-constrained time series of air-sea flux products through validation against the time series observations from SOFS in the Southern Ocean and the Global Tropical Moored Buoy Array, including RAMA in the mid and low latitudes.

- Established ecosystem time-series –annual cycles and interannual variability of plankton in the Southern Ocean at SOTS, off the east coast, and in other regions.

- A 1 km-resolution archive of sea surface temperature extending from the equator to Antarctica, with greatly reduced errors.

- Improved regional calibration and validation of satellite sea surface temperatures using data from the in situ radiometer on the new Marine National Facility, *RV Investigator*

- Improved regional algorithms for satellite chlorophyll and other parameters with sufficient in situ validation data, such as particulate inorganic carbon.

- Accurate transport estimates for major boundary currents and inter-basin flows

- New insights into long-term changes in the global hydrological cycle gained by comparing Argo to historical data

- First maps of biogeography of zooplankton in Australian waters, derived from the IMOS continuous plankton recorder survey

- The passive acoustic listening stations will provide the first publicly available and systematically collected data set of southern ocean sea noise. The data set will enable a long term monitoring program for several southern ocean marine mammal populations to be established.

- Baseline data to constrain process studies of biogeochemical cycling and gridded CO_2 flux and acidification products for model validation

- Via validation against IMOS data, better understanding of the accuracy of high resolution ocean analyses such as BlueLink but also international products

- New insights into the interannual variability of the major Southern Hemisphere gyres via the first multi-year sustained broadscale observing achieved by Argo

1.2 Long-term:

- 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

- Tracking the multidecadal planetary radiation budget to understand whether global greenhouse mitigation measures are effective

- Tracking global and regional sea level rise rates and their cause
- Understanding of how the global overturning circulation is changing and 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.
- Quantification of the seasonal to interdecadal CO_2 uptake in Australian waters and the Southern Ocean

7 Governance, structure and funding

The CSIRO Oceans & Atmosphere Flagship and IMAS/UTas sponsor node leadership and support Node meetings.

A multidisciplinary leadership team has been formed. Two co-leaders are needed to share the coordination and communication load across this large Node.

The Node membership is large, dispersed and spans many disciplines. This makes coordination more challenging. In the future, the Node may choose to create expert groups for each of the science themes.

The Node will meet face-to-face every one to two years, or as needed, preferably at a national marine or climate science meeting. As the only national node in IMOS, the challenges of meeting face-to-face are significantly greater than for the regional nodes, and so email will remain the primary means of communication.

External stakeholders co-invest heavily in IMOS facilities relevant to the Bluewater and Climate Node, as described in Section 5. The Node will continue to help the IMOS office expand the stakeholder base, of both research users and co-investors, to ensure IMOS continues to deliver the sustained observations needed to address national challenges.

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