

Western Australian Integrated Marine Observing System (WAIMOS)

Western Australian Integrated **Marine Observing System** (WAIMOS) Node **Science and Implementation** Plan 2015-25



An Australian Governn

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.



nt Initiative National Collaborative Research Infrastructure Strategy

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Date: 13 October 2014

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1. Executive Summary

Marine environments of northern and western Australia are strongly influenced by oceanic boundary currents off the coast. The longest and most unique of these is the Leeuwin Current that originates from the northern region of Australia, extends over 8000km to the south, influencing more than 2/3 of the continental slope and shelf regions of Australia as far as Tasmania. The response of the equatorial Pacific to El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation is transmitted from the western Pacific Ocean to the northern and then western Australian coast via the equatorial and coastal waveguides, so that the Western Australian marine environments are very sensitive to climate variability in the Indo-Pacific region. Over the past 6 years, the Western Australian IMOS (WAIMOS) Node has been implemented to observe, monitor, simulate, and understand climate impacts through the variability of the oceanic boundary currents of northern and western Australia, and their influences on the continental shelf and coastal environments, marine ecosystems and biodiversity.

In WAIMOS, the oceanic boundary currents are monitored at a number of shelf locations along the waveguide-path: at the Indonesian Throughflow Line extending from Joseph Bonaparte Gulf to the Timor Trench, and on transects across the continental shelf and over the slope off the Kimberley coast, off Pilbara, and off the Two Rocks transect of the south-west coast. The Node has also been supported by measurements at the National Reference Stations at Darwin, Ningaloo, Rottnest, and Esperance from north to south. The WAIMOS observing system (Figure 1) comprises of shelf moorings, ocean gliders, HF radar systems, habitat mapping through AUV's, acoustic tagging and passive acoustic monitoring of fish and cetaceans. Together these platforms provide data streams of ocean temperature, salinity, ocean current and water quality parameters in the water column and related biological observations. The Rottnest National Reference Station has extended the time series from a 50-year CSIRO Station since 1950s. The WAIMOS science is also supported by the IMOS Bluewater and Climate Node, especially in the observations of Indonesian Throughflow, and satellite remote sensing, Argo and XBT data streams.



Figure 1: Existing WAIMOS observation platforms [http://portal.aodn.org.au/aodn/].

The WAIMOS data streams have supported a number of high profile research topics in Western Australia. The Two Rocks shelf mooring array, Argo Float, and the National Reference Stations captured the rise and

fall of the evolution of the 2011 marine heatwave known as the Ningaloo Nino phenomenon, and the associated ocean dynamics. Changes in biota were documented through the AUV program that recorded marine heatwave impacts and subsequent recovery of coral and kelp communities from Rottnest Island, central West Coast and Abrolhos Islands. These achievements clearly demonstrated the value of integrated long term oceanographic and marine ecological observing programs in West Australia.

Over the last couple of years, the WAIMOS data streams have also helped us to describe the sub-mesoscale eddies and how these physical processes influence the pelagic ecosystems and whale activity along the west coast. Similarly, observations of dense water cascades of the continental shelf off the south-west coast suggest a major influence on deeper water biota. IMOS mooring data from the north-west coast also provides our first description of the ocean boundary current off the coast, and will contribute to understanding the biology of an as yet poorly studied but biologically diverse region. In hindsight, without the WAIMOS observing system in place, we would not have adequate data to be able to describe physical phenomena and ecosystem responses as they occur. Maintaining a sustained ocean observing system is vital to the interests of the region in establishing long term fundamental data to answer the science questions posed here but also those questions about future predictions that have not yet been thought of.

At this stage the key science-questions are concerned with:

- Multi-decadal variation, it's regional structure, mechanisms, impact on the Leeuwin Current and ecosystems (see specific questions in section 3.1)
- Interannual climate variation and weather extremes (such as Ningaloo Niño), local versus remote forcing of the marine environment and ecosystems and regional feedback-dynamics, if it exists (see section 3.2)
- Dynamical studies of the Leeuwin Current, its relationship to El Niño Southern Oscillation, its eddy-field and connectivity to inter-basin flows (Indonesian Throughflow and the Indo-Pacific supergyre) (see section 3.3).
- Continental shelf and coastal processes, the relationship of shelf waters to offshore circulation (Holloway Current, Ningaloo Current, Capes Current, continental shelf waves and tides) (see section 3.4).
- Ecosystem studies focussed on key species linked to exotic higher trophic level biota (e.g. krill in Perth canyon linked to Blue whales; small prey near Abrolhos Islands linked to nesting birds; larvae in the Leeuwin Current linked to juvenile bluefin tuna), drivers of water quality and benthic ecology, and their impacts of iconic fisheries and ecosystems (see section 3.5).

In the next 10 years, the WAIMOS is dedicated to monitor the ocean boundary current systems off the northern and western Australian coast on the decadal timescale, along with the impacts on the continental shelf processes. The observing system will be prioritised to focus on regions that have the largest footprint on a decadal time scale, applying new cost effective technologies to monitor physical and biogeochemical properties along the coastline. Knowledge gaps need to be addressed particularly in the data sparse south coast and the biologically abundant Kimberley regions to maximise the social and economic benefits to Western Australia and the Northern Territory, serving both the coastal and offshore marine industry and marine conservation.

Imminent changes to the observation infrastructure deployed in WA will lead to large gaps in the continuity of data around vast expanses of the coastline. The infrastructure in the Kimberley and Pilbara regions co-funded by the WA State Government from 2011-2014 is at risk and already the National Reference Stations

at Ningaloo and Esperance have been terminated, leaving only the Darwin and Rottnest NRS sites still operational. The potential loss of the transects over the northwest shelf will leave the entire tropical northwest region of West Australia void of IMOS observations. The resource rich region is of huge economic significance nationally and also harbours immeasurable richness in biodiversity whilst contributing vast volumes of water carried south to envelop more than half of the Australian coastline. Similarly on the south and southwest coasts, observations do not extend south beyond Rottnest adjacent to Perth. A serious challenge for WAIMOS is to find the resources needed to meet the most critical of the outstanding knowledge gaps identified in this NSIP to establish sustained ocean observations.

The Indian Ocean is increasingly important politically, strategically and scientifically for Australia. Some of Australia's most important trading partners including China and India are increasingly concerned about the climate and maritime impacts of Indian Ocean variability, as well as the flow of energy and free passage of oil along the shipping lanes. WAIMOS intends to better integrate with the broad, multinational second International Indian Ocean Expedition (IIOE-2); the Eastern Indian Ocean Upwelling Research Initiative (EIOURI) and the Challenger Glider Mission initiatives. The IMOS observing system in WA will become an integral part of the EIOURI, an international collaboration in oceanography and climate, as well as the biology and chemistry research in the eastern Indian Ocean as part of the IIOE-2. The IMOS complement of the initiative is to use the observing platforms from the Kimberley, Pilbara, west and south-west coasts to understand the dynamics of coastal upwelling, and to explore how the interannual variations induced by the Pacific ENSO would affect the upwelling processes and marine ecosystems. Leadership of the EIOURI resides in China and Japan, again important trading partners for Australia.

This document aims to provide a science review for WAIMOS, with a focus on recent progress of the IMOS program in Western Australia and the Northern Territory, and to provide the scientific, social, and economic contexts for the implementation plans of IMOS in WA and NT in the next 10 years.

13 October 2014

2. Socio-economic context

Australia is a 'marine nation' with the third largest ocean territory on earth. This marine estate is much larger than the terrestrial landmass, and more than 70% of Australian territory lies beneath the ocean. However Australia has a relatively small population, making stewardship of this large marine estate both a grand opportunity, and a grand challenge. Australia extracts huge economic benefit from its ocean territory, through industries such as offshore oil and gas, marine tourism, shipping, fishing and aquaculture, much of it off the coast of Western Australia.

The Western Australian economy is dominated by its rich resources sector and largely driven by the extraction and export of minerals (iron ore, gold, bauxite and alumina), petroleum products, liquefied natural gas (LNG) and agricultural commodities (wheat, wool, live animals). It provides almost half of Australia's exports and has had sustained economic growth well above the national average in meeting increasing global demand for its primary commodities. The state's ongoing prosperity is closely aligned to the transformative economic growth of Asia's largest nations. In the marine sector, rock lobsters are key to wild caught fisheries in WA, with strong demand from Asian markets, however in recent years supply has been reduced due to management responses to concerns over stock abundance in the Western Australian rock lobster fishery (ABARE 2010),

The area covered by the WAIMOS node (Figure 2) includes the marine waters off Western Australia and the Northern Territory accounting for over 40% of the nation's coastline, bordering the Indian Ocean to the west, Timor Sea and Arafura Sea in the north, and in the southwest the Southern Ocean.



Figure 2: IMOS regional nodes

The Indian Ocean, vital to world trade, is the least studied of the world's oceans and is also one of the most biodiverse (with many endemic species). Australia's Indian Ocean boundary represents the largest maritime jurisdiction of the 48 independent littoral and island countries of the Indian Ocean

region. This western boundary of Australia boasts the longest coastal current and anomalous eastern boundary current, the Leeuwin current, that transports water poleward, rather than toward the equator as is evident in most other southern hemisphere ocean gyres. In the tropical north the Indonesian Throughflow (Figure 3) is unique in that it links the Pacific to the Indian Ocean and is an important source of heat transport from the equator. The Indian Ocean meets the Southern Ocean at Cape Leeuwin, so that the south coast of WA is influenced by the added energy of the Roaring Forties and the northern extent of the Antarctic circumpolar current.



Figure 3: Currents in the Indian, Pacific and Southern Ocean (CSIRO)

The socio-economic context covered by the WAIMOS node includes:

- The geographic interface with the Indian Ocean and key SE Asian nations with associated strategic economic and security implications
- Two of Australia's four marine based World Heritage areas
- Three of Australia's five marine bioregions
- The combined State and Commonwealth marine park area second only to Antarctica
- The largest offshore oil and gas resources developments in Australia including new frontiers in FLNG a significant determinant of future Australian energy security
- The strategically complex resource fields of the Timor sea
- The most valuable individual species fishery in Australia in the lower west coast of WA
- Rapid coastal urban development areas particularly in the south-west corner and along the northwest Pilbara coast
- The largest ports throughput in Australia with key mineral resources export from the Pilbara and Darwin

• The highest proportion of shark attacks and fatalities in any state in Australia with seven fatal attacks recorded in the past three years.

Given the expanse and particular resources in this region, a substantial proportion of the future national 'blue economy' described in the *Marine Nation 2025* document can be apportioned to the WAIMOS node area.

Since WAIMOS extends from tropical through to subtropical zones the following sections give a regional description of the socio-economic drivers for ocean observing broadly based on the regional divisions (Figure 4) established by the Regional Development Commissions Act 1993.



Figure 4: The nine Regional Development Commissions Act regions of WA

2.1 Tropical North

Regionally, the tropical north has a high concentration of Australia's essential resources - energy, mining and biodiversity. Attendant with that are high level risks and vulnerabilities from accidents and natural disasters. The region is both vast and remote. In the tropical north the WAIMOS node includes the offshore waters of the Northern Territory and the Kimberley region of Western Australia.

2.1 Northern Territory

The Indonesian Throughflow (ITF) is a system of currents linking the Pacific and Indian Oceans transporting large amounts of warm and fresh water to the Indian Ocean. The transported eggs and larvae of the Indo-Pacific marine life also bring an abundance of species into this area of northern Australia. Linked to El Niño and Asian monsoons the ITF impacts the heat content and SST of the Indian Ocean and the WA coastline.

Illegal, unreported and unregulated (IUU) fishing has been increasing over the last two decades in Northern Australia and may lead to domestic productivity losses, reduced stocks and changes in the ecosystem. Incursions of fishers from Indonesia and PNG target shark, reef fish, rock lobster and trepang (AFMA 2014).

The Ichthys Project is a JV between INPEX and TOTAL located in the Browse Basin off the northwest coast of WA and approximately 820km southwest of Darwin (see Figure 5). Condensate is processed on an FPSO but the remaining gas will be transported through a subsea pipeline over 885km to an LNG processing plant in Darwin. Dredging operations for this project have made extensive use of the IMOS NRS mooring in Beagle Gulf for wave height and water quality monitoring (Cardno reports, 2013-2014).



Figure 5: Ichthys Project in the Browse Basin of northwest Western Australia with pipeline to Darwin LNG processing plant

2.2 Kimberley

The Kimberley, one of the last remaining true wilderness areas on the planet, has the most pristine coastline in the Indian Ocean and hosts a raft of marine parks with strong connection between State marine parks and Commonwealth marine reserves. The MarineParks for subtidal waters of Camden Sound and Eighty Mile Beach have been established and agreements are currently being sought to include intertidal waters in these parks. Planning for further proposals at Roebuck Bay, Horizontal Falls, North Kimberley and extension to the WA/NT border are proceeding. Further research¹ is already underway to identify if zoning could be improved.

¹ The State Government granted WAMSI \$12million to build the baseline understanding of Kimberley marine systems

The Kimberley sits on vast reserves of natural energy and mineral resources (Figure 6). There is increasing investment by multinational corporations in the exploration and development of hydrocarbon resources which are ~ 200km from the coast, adjacent to deep water reefs and atolls. The Brecknock, Calliance and Torosa fields, collectively known as the Browse Basin, are estimated to contain about 15 trillion cubic feet of dry gas and over 440 million barrels of condensate which will deliver billions of dollars in government revenue during its expected 50 year operations cycle. There remains uncertainty about hydrocarbon risk to local and remote environments rich in coral reefs and biodiversity (known habitat for marine turtles, whale nursery, dugongs and seabirds) and other industries (eg fishing, fish farming, tourism). As the extraction of hydrocarbon progresses into deep water reserves, floating facilities anchored to the seabed are beginning to replace more traditional fixed platforms.

The Shell Prelude FLNG project is a world first that will operate a floating LNG plant in the East Browse Basin near to the INPEX Ichthys platform off the Kimberley coast from 2016. In September 2013 Woodside announced the use of the Shell FLNG technology as the development concept for the Basis of Design on their Browse gas fields. Such floating plants are likely to become standardised and operational in Kimberley waters in the term of this NSIP. Once operating, billions of litres of wastewater will be returned to the ocean annually. INPEX and Shell have also announced a joint project to lay about 2000km of subsea cable to provide high speed data and voice communications services linking their Browse Basin offshore structures (Shell floating gas hub and the INPEX platform) with Port Hedland and Darwin.

Opportunities for aquaculture and tidal power schemes for remote communities are being explored in this region. The area includes the valuable wild-caught pearl oyster fishery as well as hatcheryproduced oysters that are used for pearl production.



Figure 6: Oil and gas acreage, 2001 (Geoscience Australia)

Australia is currently experiencing an unprecedented expansion of the offshore Oil and Gas industry in NW Australia. In 2012 the industry delivered a capex investment of \$130bn (Deloitte Access Economics *Advancing Australia*. *Harnessing our Comparative Energy Advantage*). National production of LNG is estimated to increase from 12 mtpa in 2005 to 94 mtpa in 2016, with the majority of new production delivered from offshore NW WA projects. Morgan Stanley (2014 Energy outlook) predicts that Australia will be the world's biggest LNG exporter by 2017. Offshore activity in the NW Shelf and Browse basin is taking place in close proximity to iconic marine systems, notably the Ningaloo World Heritage area, Rowley Shoals and Scott Reef. In response to Recommendation 90 of the Montara Commission of Inquiry, the Australian Government now requires all new offshore oil and gas production facilities to develop environmental and operational and scientific monitoring programs (OSMP) that can be promptly implemented in the event of a spill.

An emerging and increasing need in this region is to investigate and establish baselines for the potential anthropogenic threats resulting from new deep water developments, dredging, fishing and tourism. In order to determine the impact of industry activity and spill events on marine habitats adequate, fit-for-purpose baseline data against which post-spill observations can be compared to determine the extent, severity and persistence of the spill, and assess effectiveness of oil spill

response is necessary, in addition a detailed understanding of oceanographic drivers of spill transport is required in order to model and predict spill trajectory and 'zones of potential impact'.

2.2 Pilbara

The Pilbara, rich in iron ore, gold, copper, salt and offshore petroleum (including a range of hydrocarbons), accounts for 20% of WA land mass but 80% of the total WA resources sector value and a significant contribution to the prosperity of the broader Australian economy (CME WA 2010). The ocean shelf in the region is at once geologically ancient up to 8000yrs old and newly perturbed due to mixing caused by high tidal variation, tropical storms and cyclones and industrial dredging of shipping lanes and extraction infrastructure.

Australian petroleum energy security is largely dependent on this key resources region in the northwest of WA, with the largest oil and gas field in the Carnarvon Basin of the North West Shelf. As consumption of oil, gas (70% of all new electricity generation capacity installed in the decade to 2017 is gas-fired), and LNG increases, so production is increased to meet demand. The oil and gas industry continues to expand with unprecedented growth and enormous investments in projects, construction and greenfields developments off WA. The net present value (NPV) of Australian oil and gas production and exploration over 2012-25 is estimated to be \$429.1b (APPEA State of the Industry 2012). Gas and petroleum exploration is currently being undertaken near and adjacent to the World Heritage Ningaloo reef systems. The risk to these receiving environments is poorly characterised. Sediment transport is also poorly documented on this highly developed and developing shelf and is critical to understanding the impacts of industry and natural events such as tropical cyclones.

Pilbara Cities development plans to build on regional centres and increase populations in the northwest (IPAA 2010). There is a high likelihood of at least 4-5 seasonal tropical cyclones impacting the region every year leading to coastal inundation, infrastructure damage and loss of productivity for industries in the region. The latest IPCC report on climate impacts and vulnerability shows more people will be at risk of flooding as a result of sea level rise. The forecasting and prediction of coupled ocean and atmosphere phenomenon such as the Indian Ocean Dipole (affects the climate of Australia and other countries that surround the Indian Ocean Basin, and is a significant contributor to rainfall variability in this region) and the Madden Julian Oscillation (the major fluctuation in tropical weather on weekly to monthly timescales near the equator) are significantly improved by regular ocean observations at a number of temporal and geographical scales (ie. regionally in northwest Australian waters as well as beyond Commonwealth waters via deep ocean moorings, Argo floats etc). Similarly regular and near real-time observations are critical for operational oceanography and in particular the forecasting and tracking of extreme weather events such as cyclones and storm surges which have the potential to cause significant damage to terrestrial and marine infrastructure and growing populations within the Kimberley and Pilbara regions.

2.3 Midwest and Gascoyne

The warm southward flow of the Leeuwin Current makes the waters on the WA continental shelf warmer throughout the year. This warm tropical water offshore is responsible for the most southerly true corals at the Abrolhos Islands and brings tropical marine species down the west coast and into the Great Australian Bight. The Midwest Gascoyne covers more than one fifth of WA and ranks third

for Gross Regional Product in WA, with mining, agriculture, fishing and tourism as key contributors. The 1500+km of varied coastline includes the World Heritage listed Shark Bay and Ningaloo Reef, the Abrolhos and other offshore islands also taking in the Cocos and Christmas Island Territories. Exmouth Gulf and the coastal shelf to the north are known winter resting grounds for humpback whales from early June to late October every year. Offshore operations and oil and gas exploration are intensifying in this region and affect the marine environment with noise and traffic. Research in WA has involved trials of acoustic monitoring to detect whales approaching offshore sites, ports and vessel corridors (Gavrilov, Curtin Uni pers comm) and the analysis of habitat preference and carrying capacity in light of humpback population growth of at least 10% per year (Braithwaite, PhD submitted 2014).

The region contains the most valuable fisheries off Western Australia, including Western Rock Lobster, prawn, scallop, abalone and western deep water trawl fishery. Recruitment of western rock lobster (*Panulirus Cygnus*) is influenced by a strong Leeuwin Current and warmer water temperatures. Already a multidecadal weakening trend of the LC has been noted between the 1970s-1990s along with persistent warming trends over the last 50 years (Feng and Pearce 2007; Caputi et al. 2009; Feng et al. 2009). Understanding the risk to these fisheries from future extreme events such as heatwaves and long term change is critical to planning and community preparation. Understanding of marine wildlife migration and potential interference is important to the ongoing Marine Stewardship Council (MSC) sustainable fishing certification of these fisheries. The threat of climate change from a warming ocean and extreme weather events associated with La Nina periods are however increasing based on coral core records of the past 215 years (Zinke et al. 2014).

2.4 South West (including Perth Metropolitan Area)

The regions known as Perth, Peel, Wheatbelt and South West carry the majority of the Western Australian population.

Approximately 1 million people are expected to move to the south west of Western Australia over the next 3 decades and there is already substantial development along the Perth to Dunsborough coast. This triggers the need for greater understanding of the impacts of climate change and variability on the sea conditions and coastal processes. Rising sea levels and the changing intensity and frequency of storms impact flooding of coastal communities and eroding coastal infrastructure. Changing coastal and oceanic conditions require need to be understood so that appropriate policies are developed for the protection of the community such as having appropriate setbacks for development along the coastal zone. They also need to be understood for the design of infrastructure such as sea-defences, groynes, boat ramps, marinas, boat harbours where changing sea levels have a critical impact on heights of infrastructure, the materials to be used. Understanding the oceanic and coastal processes and the impact of climate change on these are required to appropriately engineer coastal structures so that coastal communities are kept safe and developments are costed appropriately.

There is also a need for understanding the future risks of inundation from tides and storm events as well as information for planning coastal structures such as groins, marinas. Some 70-80 hotspots requiring coastal management review have been identified in need of action to remedy or retreat with costs estimated in the hundreds of millions (pers comm). Examples of well-known areas

needing coastal protection works and erosion management review include Quinns Beach, Seabird, Geraldton and Geographe Bay. Population increase will exacerbate the demands on coastal living and bring to attention coastal erosion and need for revetment in larger areas.

An increase in shark attacks has resulted in a cull policy response implemented in January 2014 to protect the community. Baited drum lines are to be set off metropolitan Perth and South West beaches annually between September and April to catch great white, tiger and bull sharks greater than 3m. The uncertainty about shark numbers, movements, environmental factors and prey characteristics limits the use of existing information for long term management of this issue. Tagging of undersize animals caught on drumlines could contribute considerable insight into management policies given the extensive acoustic infrastructure placed by the Department of Fisheries along metropolitan beaches and in collaboration with IMOS for the OTN curtain.

Marine based industries include ports, tourism, defence, commercial and recreational fishing and newer developments in desalination and wave energy production. Marine heatwaves and gradual warming of the ocean temperature will impact on the fisheries recruitment and affect the species distribution causing range shift for marine ecosystems further south than ever before.



Figure 7: Inflow into Perth metropolitan dams (Water Corporation 2011)

There are continuing declines in rainfall across the southwest (Figure 7). The water management responses by regulators and water users require better short to medium term forecasting of rainfall. The Water Corporation is currently undertaking a planning study, Water Forever South West, to secure water supplies across the South West to 2060, covering 31 regional towns between Binningup north of Bunbury to Collie in the east and Windy Harbour in the south. The challenges of drying climate, increasing population and minimising environmental impact are key drivers for the region. Climate resilience is a major part of the strategy requiring a balance of reducing water use, increasing the water recycled, and developing additional water sources.

2.5 South Coast WA

There remains community pressure for marine parks to be established along the south coast as well as increasing interest and hydrocarbon exploration off the coast. Increasing interest in wave energy is also a key opportunity for the coastal towns in the region. Across the southwest and south coast, major estuarine systems support local community values and important environments. These estuary systems are likely to change substantially with less catchment runoff and changing water levels. The Southwest Marine Region report produced in 2006 provides an excellent analysis of the socio-economics of marine industries from Kangaroo Island in South Australia around to Shark Bay in WA (Gardner et al 2006).

3. Scientific Background, by Major Research Theme

In keeping with the five major themes defined as research priorities by IMOS, the following sections address each theme in the context of WAIMOS.

3.1 Multi decadal ocean change

Due to the high climate-sensitivity of the ocean boundary current systems off the north and west coasts of Australia, a better understanding of the multi-decadal climate change in the Indo-Pacific Ocean is crucial for understanding regional marine impacts off the coast of Northern Territory and Western Australia. The Indonesian Throughflow transport is known to vary with regime shifts of the Indo-Pacific climate system; and the changes induce heat content anomalies that propagate to the Southwest Indian Ocean, and contributes to mighty decadal changes in sea level near the coast of Australia, such as the multi-decadal weakening of the Leeuwin Current between 1960s and 1990s, and its rebound of the 1990s (Feng et al. 2011b; Han et al. 2014). The rebound of the Leeuwin Current strength since the 1990s appears to be highly related to the more frequent occurrences of the marine heat waves (Ningaloo Niño) over the last decade (Feng et al. 2013).

Multidecadal ocean observing is a necessity as it supplies ecologically relevant physical background data for assessing ecological response to ocean change. In Australia the National Reference Station at Rottnest is one of only three national multidecadal observing points around our coast, and it has captured temperature and salinity change over the past 6 decades (Pearce and Feng 2007). The data has been used to validate oceanographic models and provide valuable long term data sets to assess ecological change on shorter scales. Other multidecadal observing networks include the XBT network in the Indian Ocean over the past three decades and the state govt agencies such as the tide gauge sea level data have been proved to be crucial to our understanding of multidecadal variations of boundary current systems. These observations are supplemented by coral- and otolith-(fish ear bone) proxy data to better quantify the decadal variations of the physical environment and ecosystem (Zinke et al. 2014; Rountrey et al. personal communication). The chemical composition of coral growth bands indicates past sea temperatures and shows how climate variability in the western tropical Pacific Ocean drives changes in winds, sea level and ocean currents in the eastern Indian Ocean (Zinke et al. 2014). The coral cores also revealed that the extreme temperature record off Western Australia in 2011 was unprecedented in the context of the past 215 years. In addition to warming sea surface temperatures, is coral data also show that the Leeuwin Current variability has enhanced since 1980.

An objective of WAIMOS is to create an ocean observing platform for understanding the links in the physics in the system and the biological responses. The main goal is to have scaling from the ocean to the ecological scales. Understanding the physical oceanography is important to inform biologists of the origin and temporal and spatial scales of environmental change to interpret ecological responses (pelagic and benthic) and to mitigate future risks.

The node's science is also well connected to the broader Indian Ocean, through national and international collaborations. The tropical Indian Ocean was one of the most rapidly warming regions

of the global ocean during the 20th century. The surface salinity trend in the tropical Indian Ocean has a spatial pattern resembling that of the mean surface salinity, which is consistent with enhanced hydrological cycle associated with global warming. Interannual variability in the Indian Ocean has strengthened during the 20th century. There is an upward trend of positive Indian Ocean Dipole occurrence since the 1950s, which is attributed to the mean state change associated with global warming (Cai et al. 2013). The Indian Ocean Dipole affects the winter wind patterns off the west coast of Australia, which is highly related to winter storms and fisheries recruitments (Weller et al. 2012). It is still not clear if the Indian Ocean has its own decadal climate mode and how it is manifested (Han et al. 2014).

It is important to understand the influence of the multi-decadal changes of the Pacific trade winds and Walker Circulation of the Indonesian Throughflow volume and heat transport into the southeast Indian Ocean. Their influence on the Leeuwin Current and the regional air-sea coupling (e.g. Marshall et al. 2014) is still a challenge of the climate research in the Indian Ocean.

3.1.1 Science Questions

The WAIMOS data streams focus on regional processes on decadal time scales and therefore provide observations that could capture footprints of the large processes.

The WAIMOS Node observing strategy will contribute to the following high-level science questions from the National Plan:

- 1. What are the vertical structures of the long-term trend in ocean temperatures in the south-east Indian Ocean?
- 2. How do the multi-decadal changes in Indo-Pacific climate affect the Leeuwin Current and regional air sea coupling?
- 3. Do the long term changes of the Indonesian Throughflow, the Leeuwin Current and the wind regimes affect eddy energetics, coastal upwelling, ocean production, and marine ecosystem?

3.1.2 Notable gaps and future priorities

WAIMOS identified the following gaps and future priorities for multi-decadal ocean change:

Notable gaps:

Biochemistry properties of the Indonesian Throughflow , air-sea fluxes in the south-east Indian Ocean, longshore variations of thermocline structures at the shelf break following the coastal waveguide

Future priorities:

- Support Bluewater node initiative on surface flux mooring in the extended Timor sea northwest of WA;
- Mooring array along 200 m isobath from the Kimberley to north-west Australia to monitor the thermal structure of the upper ocean on interannual and decadal time scales
- Support the nutrient sampling at the Indonesian Throughflow mooring locations

3.2 Climate variability and weather extremes

IMOS physical oceanographic data supports our understanding of climate change (BoM marine strategy 2014-19, State of the Climate CSIRO, Marine Nation 2025). Shelf circulation and marine environment off the coast of northwest, west, and south coasts of Australia are strongly influenced by climate variability in the Indo-Pacific Ocean, ranging from intraseasonal, interannual, and decadal time scales.

3.2.1 Interannual Climate Variability El Niño –Southern Oscillation (ENSO)

Due to the existence of equatorial and coastal waveguides, interannual variations of sea levels and thermocline depths along the northern and western coast of Australia are strongly influenced by climate variability in the equatorial western Pacific that are induced by El Niño Southern Oscillation (Figure 8; Pearce and Phillips 1988; Clarke and Liu 1994; Meyers 1996; Wijffels et al. 2008; Hendon and Wang 2009) and Pacific Decadal Oscillation/Inter-Decadal Pacific Oscillation (Feng et al. 2004).

The ENSO related upper ocean variations propagate poleward as coastal Kelvin waves along the northwest to west WA coasts (Meyers 1996; Feng et al. 2003). The waves transmit high coastal sea levels (deep thermocline) and induce strong Leeuwin Current transports (4.2 Sv) during the La Niña years, and transmit low sea levels (shallow thermocline) and induce weak Leeuwin Current transports (3 Sv) during the El Niño years (Feng et al. 2003). A significant linear relationship between the Fremantle sea level and the volume transport of the Leeuwin Current across 32°S on the annual and interannual time scales can be derived. There is also a strong association between ENSO and the altimeter derived eddy energetics, $\frac{1}{2}(u^2+v^2)$, averaged between Abrolhos and Perth (Feng et al. 2005; 2009), demonstrating the strong sensitivity of the Leeuwin Current system to ENSO. The Leeuwin Current processes the strongest eddy energetics among all mid-latitude eastern boundary current systems (Feng et al. 2005).

Another important feature of the physical environment in the Leeuwin Current is the strong surface heat loss along the southward flowing warm current. The heat loss is mostly due to the evaporative cooling (latent heat flux) when warm sea surface temperature in the Leeuwin Current meets the cold air temperature in the south and the frequent occurrence of winter storms originated from the Southern Ocean. The evaporative cooling is strong during austral winter, when the Leeuwin Current transport is strong. There are also consistent ENSO-related interannual variations in the surface heat loss – the heat loss is stronger during the La Niña years and weaker during the El Niño years (Feng et al. 2009).





Indian Ocean Dipole (IOD)

Off the Western Australia coast, interannual variations of wind regime during the austral winter and spring are significantly correlated with the Indian Ocean dipole (IOD) variability (Weller et al. 2012). Atmospheric general circulation model experiments forced by an idealized IOD sea surface temperature anomaly field suggest that the IOD-generated deep atmospheric convection anomalies trigger a Rossby wave train in the upper troposphere that propagates into the southern extratropics and induces positive geopotential height anomalies over southern Australia. The positive geopotential height anomalies over southern Australia. The positive geopotential height anomalies off the Western Australia coast and a reduction of the high-frequency synoptic storm events that deliver the majority of southwest Australia rainfall during austral winter and spring. In the marine environment, the wind anomalies and reduction of storm events may hamper the western rock lobster recruitment process.

Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) has been identified to strengthen the local cyclonic atmospheric circulation off the west coast of Australia and enhance the southward advection of the Leeuwin Current and associated heat transport (Kataoka et al. 2013).

3.2.2 Intra-seasonal Variability and Severe Weather The Madden-Julian Oscillation (MJO)

Marshall and Hendon (2013) demonstrate that the intra-seasonal variability in the Leeuwin Current is associated with the direct forcing of the Madden-Julian Oscillation (MJO), through southward-propagating coastal trapped wave that is forced on the NW shelf through Ekman-induced vertical advection and surface heat fluxes in the easterly phase of the MJO.

Tropical Cyclones

The intensity and frequency of tropical cyclones off NW Australia appears to be related to upper ocean heat content off the NW Shelf, being higher during La Nina events, while lower during El Nino years. IMOS mooring and glider transects have been used to research the impacts of TCs on mixed layer processes and biogeochemistry (McDonald, H., personal communications).

Ningaloo Nino and Marine heat waves

During the February/March 2011 Ningaloo Nino – marine heat wave, nearshore water temperatures along the Gascoyne and mid-west coast exceeded 5°C above the long-term average for that time of year. This has been attributed to both a very strong Leeuwin Current (anomalously high coastal sea levels) during an intense La Niña period and anomalously high air-sea heat flux entering the ocean (Pearce and Feng 2013; Feng et al. 2013). Strong easterlies anomalies in the equatorial western Pacific and low sea level pressure anomalies off the west coast of Australia have been identified to be important to cause the local wind and Leeuwin Current anomalies in early 2011, resulting in the peak of the Ningaloo Nino events (Figures 9 and 10; Feng et al. 2013). Historical occurrences of the Ningaloo Nino events are found to be associated with La Nina in the Pacific, positive phase of the Southern Annular Mode, Australian monsoon, as well as local air-sea coupling (Katoaka et al. 2013; Marshall et al. 2014).

Effects of the Ningaloo Nino (marine heat wave) on the marine biota were devastating, with massive mortality in some areas (Weinberg et al. 2012). There were also sightings of tropical species (including some iconic megafauna) well south of their normal ranges (Pearce et al. 2011a). Unusually warm water was also encountered during the summers of 2011/12 and 2012/13, and their effects on WA fisheries are rather severe (Caputi et al. 2014b). Interannual and decadal predictions of the Leeuwin Current system are essential for marine environment off the WA coast. The near-record strength of the Leeuwin Current and Ningaloo Nino in the austral summer of 2010-11, driven by one of the strongest La Niña events, appears to be closely associated with the phase shift of the Pacific Decadal Oscillation/Inter-Decadal Pacific Oscillation in late 1990's (Feng et al. 2013).



Figure 9: Sea surface temperature anomalies at the peak of the 2010-2011 Ningaloo Nino in February-March 2011 (Feng et al. 2013)



Figure 10: Temperature evolution at the 200m Two Rocks mooring in early 2011, and the comparison with climatology temperature in the surface layer (adapted from Feng et al. 2013).

3.2.3 Decadal Variations

The long-term trend of the Leeuwin Current is essentially driven by the variations and changes of Pacific equatorial easterly winds: the Leeuwin Current has experienced a strengthening trend during the past two decades, which has almost reversed the weakening trend during 1960's to early 1990's (Feng et al. 2010b; 2011b), associated with the phase transition of the Pacific Decadal Oscillation/Inter-Decadal Pacific Oscillation in the late 1990's. There has been an acceleration of the rising trend in the past two decades, at about 5 mm per year. The acceleration is closely associated with a relatively high global sea level rising trend (~ 3 mm per year) and the rebound of the strength of the Leeuwin Current during the past two decades.

3.2.4 Interactions between modes of Variability

The near-record strength of the Leeuwin Current and Ningaloo Nino in the austral summer of 2010-11, driven by one of the strongest La Niña events, appears to be closely associated with the phase shift of the Pacific Decadal Oscillation/Inter-Decadal Pacific Oscillation in late 1990's (Feng et al. 2013). The phase transition of the PDO/IPO is also likely responsible for the more recent marine heat wave events during the summer of 2011-12 and 2012-13, coupled with intraseasonal variations associated with MJO.

3.2.5 Modes of variability in a changing climate

The strong seasonal, interannual and decadal variations of the current system off northwest Australia indicate that it is sensitive to climate change (Pattiaratchi and Woo 2009). There has been a rapid warming of the waters off Western Australia for several decades (Pearce and Feng 2007). A weakening of the ITF has been observed during 1960's to 1990's (Wainwright et al. 2008)

and there is preliminary evidence that the Leeuwin Current has weakened over the same period (Feng et al. 2004). Both the Indonesian Throughflow and the Leeuwin Current have strong rebound since late 1990s (Feng et al. 2011b). Currently, most climate models project a weakening trend of the Pacific trade winds and a reduction of the Leeuwin Current strength in response to greenhouse gas forcing (Sun et al. 2012). Whereas the greenhouse gas forcing induced changes may be obvious in the long-time climate projection, e.g. 2100, for assessment of short-term climate projection, e.g. 2030's, natural decadal climate variations still need to be taken into account.

3.2.6 Science Questions

The following high-level science questions will guide the Western Australian Node observing strategy:

- What are the relative roles of local and remote forcing driving the seasonal, inter-annual, and decadal variability of the ocean boundary current systems off WA?
- What drives the upper ocean heat and freshwater balance in the ocean boundary current systems?
- What are drivers of the extreme Leeuwin Current strength and marine heat wave (Ningaloo Nino) off the coast of WA and what is the predictability of Ningaloo Nino? What is the nature of local and/or regional Indian Ocean air-sea coupling and feedback?
- How do decadal climate variations and climate change affect the marine extreme events (e.g. Ningaloo Nino) off the coast?
- How will the climate variability in the Indo Pacific affect coastal upwelling off the Western Australia coast, and subsequently the marine ecosystem?

3.2.7 Notable gaps and future priorities

For WAIMOS, it is crucial to continue to monitor the strength of the Leeuwin Current and the associated temperature and salinity properties off the northern and Western Australian coast at key locations along the coast on decadal time scale, to capture the full spectrum of the variability of the ocean boundary current. It is important to maintain the mooring observations to continue to monitor the Leeuwin Current strength off the Two Rocks transect. The WA node of IMOS will continue to monitor physical and biogeochemical properties at observed Rottnest national reference station. It is highly desirable to extend the Two Rocks transect to cover the full width of the Leeuwin Current. Ocean gliders and HF radar observations are also good supplement to the mooring and national reference station observations.

It is also crucial to be able to link the shelf measurements with offshore observations such as Argo floats and XBTs, in order to understand both remote and local large scale climatic drivers. It is also important to understand the ecosystem responses of extreme climatic events such as Ningaloo Nino on the continental shelf of Australia.

Notable gaps:

- Increase the coverage of the coastline with better spaced national reference stations
- More frequent biogeochemical sampling at NRS
- Understand the onshore impacts of the climate variability and extreme events;
- Understand the ecosystem responses of extreme climatic events such as Ningaloo Niño on the continental shelf of Australia;

• Establish natural variability of key ecology indicators in key coastal regions

Future priorities:

- Continue to monitor physical and biogeochemical properties at the Rottnest National Reference Station and associated shelf mooring sites;
- Maintain a footprint in the Kimberley coastal region;
- Re-establish the Ningaloo National Reference Station as a high priority;
- It is also highly desirable to re-establish the national reference station at Esperance;
- Ocean gliders and HF radar observations in Perth Basin;
- Support offshore observations such as Argo floats and XBTs, in order to understand both remote and local large scale climatic drivers of extreme climatic events

3.3 Major boundary currents and inter-basin flows

The south-eastern Indian Ocean has a complex structure of major currents (Figure 11) that have direct impacts on marine ecosystems and climate in Northern and Western Australia. The Indonesian Throughflow is a critical "choke-point" in the distribution of heat on a global scale, and hence has an impact on global and regional climate. The transmission of Pacific properties (mean state and interannual variation) by Rossby and Kelvin waves through the Timor Passage and along the Australian northwest shelf affects climate and regional ecosystems. Further south, the Leeuwin Current is an anomalous eastern boundary current that brings warm, lower salinity tropical waters southward along the west coast of Australia modulating the marine ecosystem. The other boundary current systems include the Holloway Current, the seasonal south-westward flow along the northwest coast of Australia; the Leeuwin Undercurrent, the continuation of the Tasman Outflow and the Flinders Current. Sustained regional observations are required to describe, understand and model the interplay of variability and change in regional currents and the cascade of scales from ocean-basins to local ecosystems.



Figure 11: Major ocean currents off the west coast of Australia (Waite et al 2007)

3.3.1 The Leeuwin Current (LC) system

The existence of the Leeuwin Current is due to the meridional steric height gradient in the southeast Indian Ocean and associated eastward currents flowing toward northwest and west coast Australia. The current turns southward approaching the coast and flows poleward down the pressure gradient along the whole length of Western Australia past Cape Leeuwin. It is a shallow (< 300 m) and narrow band (< 100 km wide) of relatively warm, lower salinity water of tropical origin that flows southward, mainly above the continental slope from Exmouth to Cape Leeuwin (Smith et al. 1991; Ridgway and Condie 2004). The maximum flow of the current is located at about the 500m isobath. At Cape Leeuwin it pivots eastward, spreads onto the continental shelf and flows towards the Great Australian Bight. It is now accepted that the Leeuwin Current signature extends from North West Cape to Tasmania as the longest boundary current in the world (Ridgway and Condie, 2004).

The LC also is highly variable on seasonal and interannual timescales (Feng et al. 2003; Feng et al. 2008). The strong seasonal cycle enhances fresher and warmer tropical waters along the west Australian coast when its poleward flow is at maximum in the austral autumn (Cresswell and Golding 1980; Smith et al. 1991). The seasonal cycle of the Leeuwin current is driven by a combination of pressure gradient and wind stress, which reinforce one another (Godfrey and Ridgway 1985; Feng et al. 2003). During October to March the Leeuwin Current is weaker as it flows against the maximum southerly winds resulting in transports of +1.5 Sv, whereas between April and August the Current is stronger as the southerly winds are weaker resulting in transports of up to 7Sv (Godfrey and Ridgway 1985, Smith et al. 1991). The mean volume transport is estimated to be 3.4 Sv (Feng et al. 2003). The location of the 'core' of the current also changes seasonally – in winter the core of the current located close to 200m contour whilst under the action of the southerly wind stress, the Current is pushed offshore.

The interannual variation in depth of the thermocline associated with ENSO propagates poleward along the coastal waveguide, affecting the entire West Australian coast and into the Great Australian Bight (Pariwono et al. 1986; Pearce and Phillips 1988; Clarke 1991; Feng et al. 2003). Higher sea level anomalies, warmer sea surface temperatures, and deeper thermocline, and a stronger Leeuwin Current are expected along the coast during La Niña years and vice–versa during El Niños. The Two Rocks mooring and glider transects were designed to monitor the interannual variability of the LC on the shelf (Figures 12 and 13). Note that in the new IMOS plan during 2013 – 2015, only the 100 m, 200 m, and 500 m moorings will be maintained. In Perth canyon, only the 200 m mooring will be maintained.



Figure 12: WAIMOS shelf mooring array at Two Rocks and Perth Canyon



Figure 13: Mooring observations include thermistor chains, ADCP, and water quality

3.3.2 The Leeuwin Undercurrent (LUC)

Initial studies by Thompson (1984, 1987) indicated that there was an equatorward undercurrent flowing beneath the Leeuwin Current (Figure 9). Current meter data from the Leeuwin Current Interdisciplinary Experiment (LUCIE) (Smith et al. 1991) confirmed the observations of Thompson (1987) and indicated that

the equatorward undercurrent was narrow and situated between 250 m and 450 m depth contours, adjacent to the continental slope.

The LUC is driven by an equatorward geopotential gradient located at the depth of the Undercurrent (Thompson 1984; Woo and Pattiaratchi 2008). The LUC is closely associated with the subantarctic mode water (SAMW) formed in the region to the south of Australia. A feature of this water mass, resulting from convection, is high dissolved oxygen concentration; thus the core of the LUC can be identified from the dissolved oxygen distribution: a dissolved oxygen maximum (252 μ M/L) centred at a depth of approximately 400 m (Woo and Pattiaratchi 2008). From a recent model analysis, the Leeuwin Undercurrent appears to be drawing water from the Tasman Outflow, forming the southern branch of the inter-basin connection between the Pacific and the Indian Ocean (van Sebille et al. 2014).

3.3.3 The Indonesian Throughflow (ITF)

The ITF is generated by the wind field over the Pacific Ocean, primarily the Trade Winds, which pile up water on the western side of the ocean creating a pressure gradient from the Pacific toward the Indian Ocean. The ITF transport is sensitive in particular to the zonal wind anomalies over the equator in the Pacific and Indian Ocean. The current divides in the Indonesian Seas into a system of currents flowing through the passages in the Indonesian Archipelago, and between Timor Leste and northwest Australia (Wijffels et al. 2008). The largest single component of ITF flows in the narrow passage between Darwin and Timor Leste (Sprintall et al. 2009). While its net volume transport is moderate (10-15 x $10^6 \text{ m}^3 \text{s}^{-1}$ or 10-15 Sv), the current transports a significant amount of heat because it is the only location in the global ocean where warm tropical water flows from one basin to another, and ultimately has to be replaced by cold water at higher latitudes in the South Pacific.

The ITF is highly variable on seasonal, interannual and decadal time scales (Meyers et al. 1995; Meyers 1996; Wijffels and Meyers 2004; Wainwright et al. 2008; Sprintall et al. 2009, and many more listed in Sprintall et al.). The largest and most persistent mode of variation is associated with the El Nino Southern Oscillation (ENSO) phenomenon. The confluence of coastal and equatorial waveguides in the Indonesian Seas allows large perturbations in depth of the thermocline during the ENSO cycle to propagate into the Indian Ocean and down the West Australia coast. The heat content in the deep ocean off northwest Australia is highly predictable out to one year in advance as a consequence of the oceanic signal from the western Pacific (Hendon and Wang, 2009). The heat content anomalies in that region are one of the driving forces of the Leeuwin Current variability. In recent years, the ITF has strengthened and become shallower in vertical structure (Gordon et al. 2012), however, the downstream impacts on the ocean boundary currents off the northern and Western Australia coast have not been studied.

3.3.4 Eddy Processes in boundary currents.

The LC has the strongest eddy energy among the mid-latitude eastern boundary current systems (Figure 14; Feng et al. 2005). The interannual variations of the Leeuwin Current and its eddy field respond to the El Nino/Southern Oscillation (ENSO). The eddy energetics of the west coast of Australia is mostly derived from the instability of the Leeuwin Current. The eddies are important to redistribute the Leeuwin Current heat transport offshore. The Leeuwin Current eddy field has vital influences on the marine pelagic production off the west coast of WA (e.g. Hanson et al. 2005a; Feng et al. 2007; Koslow et al. 2008) and many of the fisheries recruitments (Caputi et al. 1995).

The Leeuwin current becomes unstable as it interacts with changes in the bathymetry and offshore water of different densities, to generate eddies which propagate offshore—in particular, off Shark Bay, the Abrolhos Islands, Jurien Bay, Rottnest Island, and Cape Leeuwin. On the seasonal cycle, the LC eddy field is strong during the austral winter and weak during the austral summer, such that the peak eddy energy occurs about 1 month later (July) compared to that of the peak Leeuwin Current transport. This would be expected since the eddy field draws its energy from the instability of the Leeuwin Current. Mesoscale eddies from the Leeuwin Current can drive significant cross-shelf nutrient exchanges off the west coast of WA (Paterson et al, 2008), and enhanced concentration of surface chlorophyll a tend to be observed in the warm-core eddies off the west coast, associated with increases in primary production (Waite et al. 2007; Thompson et al. 2007) and larval transport (Waite et al. 2007; Muhling et al. 2007). Once they detach from the shelf, the Leeuwin Current eddies tend to have deep expression through the water column to depths of 2500 m (Fieux et al. 2005; Meuleners et al. 2007).

The Leeuwin Current eddies might be able to explain the poorly understood supply of nutrient to surface waters in this region. The phytoplankton here blooms in late autumn and winter, coinciding with the period of strongest Leeuwin flow, in contrast to the usual spring bloom in most open ocean areas. A unique feature of the LC and offshore region is the existence of anticyclonic eddies that generally have higher chlorophyll concentrations than cyclonic eddies. Off Western Australia, this anomalous behaviour is related to the seeding of anticyclonic eddies with higher chlorophyll from shelf water and the retention of chlorophyll in these eddies. Further off-shore, a recent study by Gaube et al. (2013) suggested that eddy-induced Ekman divergences/upwelling could be responsible for that behaviour. Looking at satellite chlorophyll, sea surface height and wind data, Gaube et al. (2013) proposed that eddy-induced Ekman upwelling (reaching order 10 cm/day) sustains enhanced chlorophyll concentration in the Leeuwin Current anticyclonic eddies throughout their life cycle while propagating in the South Indian Ocean. This novel mechanism is seasonal and higher concentrations of surface chlorophyll within the anticyclonic eddy interiors are observed in winter only (Gaube et al. 2013).

Dufois et al. (submitted) however suggests that multiple mechanisms could induce the unusual eddy/chlorophyll relationship observed in the South Indian Ocean. Based on Argo float data, they postulate that the unusual relationship may be partly related to a slight modulation of the chlorophyll seasonal cycle within eddies. Deeper mixing (and mixed layer depth) in anticyclonic eddies is expected to enhance the nutrient supply to the mixed layer, while shallower mixing in cyclonic eddies is expected to reduce it. This could lead to the winter surface chlorophyll bloom being stronger, starting earlier and lasting longer in anticyclonic eddies than in cyclonic eddies.

Those later hypotheses will be further investigated as part of an Australia-India Strategic Research Fund project. Several robotic profiling floats equipped with novel bio-optical and biogeochemical sensors (Bio-Argo) will be deployed in eddies in the South Indian Ocean in 2014 and 2015 to investigate the productivity of these ecosystems. Understanding the supply of nutrient to surface waters is critical for management of the biological impacts of climate variation and change.



Figure 14: Long-term mean surface eddy kinetic energy derived from satellite altimeter data (left panel), seasonal cycle of Fremantle sea level, LC transport and surface eddy kinetic energy between Abrolhos and Perth (derived from Feng et al. 2003, 2005 and 2009)

3.3.5 Science questions

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

- What is the nature of ENSO signals propagating along the NW, west, and SW coasts of Australia? How much energy is transmitted from the Pacific versus generated by forcing in the Indian Ocean?
- What are the relative roles of local and remote forcing driving the seasonal, inter-annual, and decadal variability of the Leeuwin Current, its eddy fields and its relationship to the Indonesian Throughflow?
- > What is the role of topography in the generation of Leeuwin Current eddies?

- > What are the mechanisms by which the Leeuwin Current and its mesoscale eddies drive the alongshore, cross-shelf exchanges?
- What drives the upper ocean heat and freshwater balances in the ocean boundary current systems off WA?
- What are drivers of the extreme Leeuwin Current strength and marine heat wave (Ningaloo Nino) off the coast of WA
- > What is the predictability of Ningaloo Nino and other climate extreme events in WA?
- What offshore mechanisms dominate the supply of nutrient to surface waters over the continental shelf, in the Leeuwin Current and offshore?

3.3.6 Notable gaps and future priorities

The WAIMOS will continue to support the monitoring of the Indonesian Throughflow, in collaboration with the Bluewater node. It is also important to monitor how the Kimberley coast and the North-West Shelf are influenced by the variability of the Indonesian Throughflow. As part of the eastern Indian Ocean upwelling initiative, the biogeochemical properties of the Indonesian Throughflow waters should also be monitored.

To monitor of variability of the Leeuwin Current is the core of the WAIMOS plan. The Two Rocks Transect is at the centre of our plan. Currently, the Two Rocks Transect is not a full current resolving array, and only covers part of the Leeuwin Undercurrent. It is highly desirable to extend the transect into deep water, in terms of both mooring and glider observations. HF radar will provide complementary information of ocean surface current. The Rottnest National Reference Station (NRS) will continue to provide data to determine the onshore influence of the Leeuwin Current water. It is also desirable to monitor the Leeuwin Current at multi-locations along the coast.

Notable gaps:

- Capture the whole width of the Leeuwin Current using moorings and glider survey;
- Currently, the Two Rocks Transect is not a full current resolving array, and only covers part of the Leeuwin Undercurrent;
- It is also important to monitor how the Kimberley coast and the North-West Shelf are influenced by the variability of the Indonesian Throughflow/Holloway Current.

Future priorities:

- To monitor of variability of the Leeuwin Current is the core of the WAIMOS plan. The Two Rocks Transect is at the centre of our plan. It is highly desirable to extend the Two Rocks transect to cover the full width of the Leeuwin Current. Thus, it is highly desirable to extend the Two Rocks mooring transect both into deep water, and to the nearshore region.
- Improve the coverage of glider observations of the Leeuwin Current variability off Two Rocks/Perth.
- HF radar will provide complementary information of ocean surface current.

- It is also desirable to monitor the Leeuwin Current at multi-locations along the coast, such as the Kimberley and Pilbara lines; alternatively, an alongshore mooring array, assisted by data assimilating numerical models, will also help ocean boundary current monitoring in the region.
- Continue to support the Indonesian Throughflow mooring array.
- As part of the eastern Indian Ocean upwelling initiative, the biogeochemical properties of the Indonesian Throughflow waters should also be monitored.

3.4 Continental Shelf and Coastal Processes

Partly because of the vast extent of Western Australia ranging from the tropics to the Southern Ocean as well as the varying orientation of the coastline, there are distinctly different oceanographic regimes around the continental shelf from north to south. This review accordingly summarises the dominant circulation processes and water properties in three regions: Northwest Shelf (Section 3.4.1), the west coast (Ningaloo to Cape Leeuwin – Section 3.4.2) and the south coast (Cape Leeuwin to Eucla, Section 3.4.3). While some extensive oceanographic studies have been undertaken along the Northwest Shelf for the oil industry (with inherent limitations of data distribution), by far the majority of current and temperature measurements have been made along the west coast between the Abrolhos Islands and Geographe Bay. Very little is known about shelf processes along the south coast.

3.4.1 Northwest Shelf

The circulation on the broad continental shelf northeast of Exmouth is complex and poorly understood. Early analyses of current measurements along the southern portion of the shelf led Holloway and Nye (1985) and Holloway (1995) to conclude that the Leeuwin Current flows southwestward along the shelf parallel to the coast, at least in late summer through to winter. A recent review of the now extensive current mooring data, however, suggests that this may be viewed as a more regional flow driven by the steric height gradient and potentially contributing to the Leeuwin Current (D'Adamo et al. 2009); the authors named this largely autumn flow the Holloway Current.

The Holloway Current is a surface layer poleward flowing ocean current that brings water perhaps from as far north as the Banda and Arafura seas, southward over the continental shelf of northwest Australia at the end of the northwest monsoon (D'Adamo et al. 2009). A simple view of the generating mechanism is the seasonal south-westerly wind piles up water in the Arafura Sea and Gulf of Carpentaria during the peak of the Australian monsoon, and the current flows southward as the wind relaxes during the monsoon transition. This is seen clearly in results from a high resolution ocean model (Figure 15) and satellite altimetry data (Ridgway, personal communication, Fig. 16). However, detailed analysis and modelling indicate that the impact of seasonal heating on sea level adds to the overall force balance to generate the full strength of the current (Godfrey and Mansbridge 2000; Kronborg 2004; D'Adamo et al. 2009). The Holloway Current is particularly important because of its proximity to coastal ecosystems and its potential to provide a mechanism of along-shore bio-physical connectivity along a region of the world that has both high biodiversity conservation value (largely to be explored) and strong economic claims in oil and gas exploration/production. The existence of the seasonal Holloway current and the strong seasonal variations are the shelf circulation has been confirmed by a data assimilating numerical model (Figure 15; Schiller 2011).



Figure 15: Schematic of near surface circulation in January and July derived from a numerical model. Dotted arrows indicate either weak currents (Gulf of Carpentaria and Arafura Sea) or interactions between the ITF and coastal currents (Timor Sea), Schiller 2011


Figure 16: Monthly mean sea level observed by satellite. Figure provided by Ken Ridgway CSIRO (personal communication)

The IMOS Kimberley Array comprising 4 moorings at depth of 50, 100, 200 and 400m were aligned under a satellite altimeter track (# 038) that spans the continental shelf that intersects with coastline around James Price Point and Broome. The array was first deployed in early 2012 and is located between the southern Pilbara array and a northern Indonesian Throughflow array that is also aligned along a satellite altimeter track (Figure 17). The current location is thought to be representative of the mid northwest shelf region and acts as the gateway to the Kimberley shelf itself. The innermost mooring (KIM050) however is still a significant distance from the coast and so there is limited ability to tie in with coastal observations.





Figure 17: Northern WAIMOS mooring arrays comprise Pilbara (PIL050, PIL100, PIL200), Kimberley (KIM050, KIM100, KIM200, KIM400) and the ITF Shelf array. These arrays are bookended by the Ningaloo NRS in the south (now removed) and the Darwin NRS to the north

There was evidence from more recent observational data of a south-westward seasonal current, the Holloway current, that strengthens in autumn when the west southwest monsoon wind stress "weakens" before the commencement of weak to moderate east southeast trade winds. The ITF shelf, Kimberley and Pilbara arrays have for the first time enabled extensive concurrent cross and along-shelf observations of the Holloway current (Figure 18). The planned longer term observations will allow for at least 3 annual cycle opportunities to observe inter-annual variability of the onset, strength, character and cessation of the seasonal current. Recirculation of Indonesian Throughflow waters contributes to surface flows off the shelf break, the slope and over the abyss in the northwest region. The deep water array is integrated with the AIMS operated ITF shelf line, allowing estimates of the inter-basin exchange to include the transport of very warm waters across the Australian North West Shelf. It is likely that the ITF has an impact on shelf ecosystems however virtually nothing is known about the impact at present. All moorings in the Timor Passage are located along a high precision swath line of the TOPEX/Jason satellite altimeter missions. These data will shed light on how best to exploit altimetric data over our shallow northern shelves, especially in data assimilating models.



Figure 18: Progressive vector diagrams from Pilbara (PIL) and Kimberley (KIM) arrays from the 2012 deployment. Note length scales change for each plot (adapted from Pattiaratchi pers. comm.)

Internal tides are internal waves with the tidal periods, and are generated by interaction of tides and topography in stratified ocean (Garret and Kunze 2007). Large-amplitude internal tides propagate across the North West Shelf (NWS) particularly in summer (Holloway 1983), when the water column is strongly stratified due to intense solar insolation. Internal tides on the NWS are typically generated on the shelf slope, and subsequently propagate onto the shelf (Holloway 1994, 2001; Holloway et al. 2001); however, existence of offshore reefs and inner shelf could make the wave field more complex (Rayson et al. 2011). Internal tides may evolve nonlinearly to form internal bores and/or to degenerate into high-frequency internal waves, such as solitary-like waves (Holloway 1987). IMOS data has been used to confirm that coastal internal tides are largely unpredictable (Nash et al. 2012).

Internal tides and their nonlinear evolution on the NWS are important from engineering and ecological points of view. These internal waves increase peak near-bottom currents, enhance vertical shear, and modify near-surface currents, which are crucial for designing offshore structures,

daily operation, and emergency response of oil and gas industry on the NWS. These internal waves also enhance mixing (Holloway 2001; Holloway et al. 2001; Katsumata 2006), and are considered to bring nutrient-rich offshore deep water onto the NWS (Holloway and Nye 1985). It is not known how the large climate driven fluctuations in the depth of the thermocline in the coastal waveguide affect thermal structure and internal tides on the continental shelf.

Long-term monitoring of temperature, salinity, and currents provide valuable baseline data to fill gaps in our understanding of internal tide dynamics on the NWS. Long-term monitoring data are important in understanding what control the linear and nonlinear tidal responses, which are not phase-locked to the neap-spring cycle (Holloway 1983; Holloway et al. 2001; Bluteau et al. 2011). Temporally high-resolution data are valuable to estimate the contribution of internal tides on nutrient fluxes, and validate models' skill in simulating nonlinear evolution of internal tides on the NWS (Holloway et al. 1999), challenges remaining till today. Long-term monitoring data, combined with satellite and glider data, also provide publicly available, accurate background stratification on the NWS, which is lacking due to very limited continuous monitoring and ARGO floats on the NWS. Background stratification not only provides essential input data for hydrodynamic modelling of the NWS and biogeochemical modelling that uses currents from a hydrodynamic model, but also improve reanalysis products, such as Bluelink reanalysis (Schiller et al. 2008), in the future.

The high evaporation along the Pilbara coast and the high freshwater input along the Kimberley coast result in cross-shelf density gradients which are also capable of influencing cross-shore exchange. High evaporation together with winter cooling results in higher density water (cooler more saline water) along the coast which results in a high density gravity current along the sea bed – this is termed 'shelf dense water cascade' and results in nearshore waters being advected offshore. The dynamics of such flows were documented by Brink et al. (2008) along the Pilbara coast. Along the Kimberley coast, freshwater discharge results in lower density water closer to the coast. This region is defined as 'ROFI – regions of freshwater influence' globally and well known similar regions include Liverpool Bay (UK) and the Rhine outflow (Dutch coastline). In ROFI regions the alongshore density gradients together with the tidal action results in a residual circulation similar to that of estuaries where the lower density surface water flows offshore with the higher density water flows onshore near the sea bed (gravitational circulation). Tidal straining may result in the de-stratification during the flood tide which is modulated by the spring-neap cycle. Detailed observations of this complex process will be needed to validate models of the region, particularly as the BLUElink model moves progressively inshore by downscaling.

3.4.2 West coast (Exmouth to Cape Leeuwin)

Regional current measurements along segments of the continental shelf between Ningaloo and Cape Leeuwin over the past 4 decades have clearly demonstrated the seasonally reversing nature of the alongshore current system on the shelf, with typically southward flow during the winter months, influenced by the Leeuwin Current, and northward counter-currents in summer, driven by alongshore wind (Figure 19; Steedman and Associates 1981; Boland et al. 1988, Cresswell et al. 1989, Smith et al. 1991, Pattiaratchi et al. 1995, Fandry et al. 2006, Keesing et al. 2006, Zaker et al. 2007, Cresswell 2009). These somewhat sporadic historical measurements have recently been supplemented by the longer-term and more systematic IMOS/ANMN ADCP moorings off Two Rocks and HF radar (ROT and TURQ) which are providing (for the first time) valuable insights into the crossshelf and vertical structure of the flow over a range of time-scales from hours to inter-annual.

Figure 19: Satellite images off south-west WA showing SST (left) and chlorophyll concentration (right), depicting the upwelling of cold water into the Capes Current with the associated high chlorophyll concentration



Recent reviews of the Leeuwin Current and shelf circulation along the west coast were presented by Woo and Pattiaratchi (2008) and Pattiaratchi and Woo (2009). Because the Leeuwin Current typically flows along the edge of the continental shelf (albeit with periodic mesoscale meanders and eddies looping the flow away from the shelf), the currents along the outer shelf have a generally southward tendency (squares in Figure 20a, updated from Pearce et al. 2011b). By contrast, the shallow nearshore waters (triangles in Figure 20a) are largely driven by the prevailing wind regime, resulting in almost exclusively northward flow between October and February in response to the dominantly southerly wind stress prevailing during the summer months (e.g. Steedman and Associates 1981, Zaker et al. 2007), and dominantly southward currents in winter.





The summer counter-currents have been regionally named the Ningaloo Current (flows between Shark Bay and Northwest Cape, and probably further north; Taylor and Pearce 1999, Woo et al 2006a, Rossi et al. 2013a) and the Capes Current (Shark Bay to Cape Leeuwin; Pearce and Pattiaratchi 1999, Gersbach et al. 1999). Recent current measurements (Lowe et al. 2012) have suggested that the Ningaloo Current may in fact be a more transient (rather than seasonal) flow which can occur in any season, so may not always be evident (Woo et al. 2006a). The Capes Current has been identified as a potential vector of some commercially important fish species (Lenanton et al. 2009).

The cross-shelf flow is complex with little evidence of any seasonal cycle (Figure 20b) as onshore and offshore flows apparently occur throughout the year. Bearing in mind the differing depths, distances offshore and localities of the various current measurements, there are a number of possible reasons for this (which are not further explored here) including distance from the coast, vertical shear in the water column, regional small-scale topographic effects, the near-bottom offshore cascade of dense

shelf water largely during autumn and winter (Pattiaratchi et al. 2011, Pearce et al. 2006), and Leeuwin Current meanders penetrating across the shelf (Mills et al. 1996, Gaughan 2007). Although the monthly mean onshore-offshore current speeds are largely between 5 and 10 cm/s (Figure 1b), maximum hourly cross-shelf component speeds exceed 50 cm/s; Lowe et al. (2012) found similar high bursts of current off Ningaloo Reef.

Superimposed on the seasonal cycle are frequent short-term current reversals generally (but not universally) driven by the wind fluctuations with periods of a few days (e.g. Cresswell et al. 1989, Zaker et al. 2007, Cresswell 2009). The cross-shelf transition from the wind-forced nearshore zone out to the Leeuwin Current-dominated outer shelf has clear implications for the dispersal of fish eggs and larvae hatching at different distances offshore, while the observed pulses of strong cross-shelf flow represent an active mechanism for the exchange of larvae (and other materials) between the Leeuwin Current and the nearshore waters. It may be noted in passing that tidal currents along the southwestern coast are effectively negligible due to the microtidal regime.

Due to the warm Leeuwin Current, the shelf waters off south-western Australia are some 4°C warmer than in the corresponding eastern boundary current (EBC) regions off the west coasts of southern Africa (the Benguela Current system) and South America (Humboldt Current system) (Pearce 1991). Despite the strong southerly winds occurring in all 3 EBC regions, the seasonal, cool nutrient-rich upwellings which lead to the highly productive fisheries in the Benguela and Humboldt Current regions do not occur off Western Australia (Lenanton et al. 1991, Rossi et al. 2013b). Localised short-term upwelling, however, does occur sporadically where the continental shelf is narrow such as at the Capes (Gersbach et al. 1999, Hanson et al. 2005b) and Ningaloo (Hanson et al. 2005a, Woo et al. 2006b, Rossi et al. 2013b) as well as north of Rottnest Island due to flow curvature of the Capes Current around the western end of the Island (Alaee et al. 2007).

Largely because of the southward flow in the Leeuwin Current and the generally strong winds that promote vertical mixing along the Western Australian coast, the mixed layer over the continental shelf is comparatively deep and the shelf water column effectively unstratified for much of the time (Lourey et al. 2006, Pearce et al. 2006).

Along the south-western continental shelf, there is a seasonally-varying cross-shelf temperature gradient. Along the outer shelf, monthly mean water temperatures peak at 22-23°C between March and May when the Leeuwin Current is strengthening, and the temperature falls to 19-20°C in August-September (Hodgkin and Phillips 1969, Cresswell and Golding 1980, Pearce et al. 2006). Close inshore, water temperatures reach their 22-23°C peak in January-February but winter temperatures drop sharply to ~16°C in July-August (Hodgkin and Phillips 1969, Pearce et al. 1999) as the shallow water loses heat to the atmosphere, resulting in a 3-4°C temperature rise from the coast out to the shelf break. The offshore seasonal cycle lags that near the coast by 1 to 2 months and the mean annual temperature range offshore is some 3°C compared with almost double that near the coast. Similar conditions apply at the Houtman Abrolhos Islands off Geraldton although the temperatures are about 1°C warmer (Pearce 1997). One of the consequences of the nearshore winter cooling is the formation of a band of high density water along the coast which then cascades offshore across the seabed (Pattiaratchi et al. 2011).

In addition to the strong seasonal signal, longer-term datasets have shown that there is some considerable inter-annual temperature variability along the continental shelf (Feng et al. 2003; Pearce and Feng 2007, Caputi et al. 2010) superimposed on a general warming trend of about 0.6°C between the late 1950s and 2003 (Pearce and Feng 2007). Record high temperatures were experienced along the Western Australian continental shelf during the "marine heat wave" in early 2011, when nearshore temperatures were briefly >5°C above the long-term average summer temperature as a result of both an extremely (and unseasonally) strong Leeuwin Current and anomalously high heat flux into the ocean (Pearce and Feng 2013, Feng et al. 2012, Feng et al. 2013). These unprecedented temperatures, which in fact extended well offshore and were monitored along the IMOS/ANMN mooring transect off Two Rocks, resulted in some localised fish and invertebrate mortality (for more detail, refer to section Ningaloo Nino – marine heat wave and references therein). The summers of 2012 and 2013 also saw abnormally high temperatures although not as extreme as in 2011. The temperature measurements along the IMOS/ANMN transect off Two Rocks will become increasingly valuable as the data length extends over time.

There are strong cross-shelf gradients in salinity during the summer months when evaporation can raise the nearshore salinity to over 36.4 psu compared with ~35.8 psu along the outer shelf. In winter, on the other hand, salinities are typically ~35.2 psu (Cresswell and Golding 1980, Zaker et al. 2007) to 35.6 psu (Pearce et al. 2006) across the shelf.

Because of the strong seasonality of the wind regime off southwestern Australia, the wave climate also has a pronounced seasonal cycle. Superimposed on the background swell from the Southern Ocean which is experienced throughout the year, moderate seas are generated by the sea breeze system in summer and heavy seas and swell accompany winter storms (Lemm et al. 1999).

3.4.3 South coast

Apart from a short-term mid-shelf mooring southwest of Cape Leeuwin in spring 1986 (Boland et al. 1988, Smith et al. 1991), the only current meter mooring on the south coast was a year-long ADCP deployment in 80 m water depth off Esperance in 2000/2001 reported by Cresswell and Domingues (2009). At both locations, the currents were generally towards the east (with some topographic steering from nearby islands in the Recherche Archipelago), indicative of the Leeuwin Current running along the shelf and on occasion flooding across the shelf to the coast (Cresswell and Domingues 2009). The flow was strongest in winter and weakest between November and February when some appreciable wind-related current reversals occurred.

3.4.4 Upwelling

Coastal upwelling is a key process that links the physical environment to marine ecosystems.

The existence of coastal upwelling along the Northwest Shelf of Australia was first suggested by Schott (1933) and Wyrtki (1962). Holloway and Nye (1985) showed that weak upwelling events occurred, both in the summer and winter months, along the Northwest Shelf when the currents were flowing north-east and suggested that this north-east flow occurred when the south-west winds were sufficiently strong to overcome the steric height gradient and thus to reverse the dominant south-west flow. The associated seasonal cycle of vertical upwelling from June to August south of 8.5 degrees S and between 124 degrees E and 137.5 degrees E exceeds $1.5 \times 10^6 \text{ m}^3/\text{s}$ across 40 m depth (Schiller 2011). Off the west coast of Australia, localised short-term upwelling

occur sporadically where the continental shelf is narrow such as at the Capes (Gersbach et al. 1999, Hanson et al. 2005b) and Ningaloo (Hanson et al. 2005a, Woo et al. 2006b, Rossi et al. 2013) as well as north of Rottnest Island due to flow curvature of the Capes Current around the western end of the Island (Alaee et al. 2007). These upwelling predominantly occurred during the austral summer, due to the prevailing southerly wind. Rossi et al. (2013) pointed out that upwelling can also occur due to the interaction between the onshore geostrophic flow and the shelf bottom bathymetry during other seasons. It has also been found that the interactions between the Leeuwin Current meander/eddies and the shelf bathymetry can also drive localised upwelling events (Koslow et al. 2008).

3.4.5 Science questions

- What is the influence of ITF waters on continental shelf and coastal regions of the Kimberley and Pilbara?
- Is the Holloway Current a major feature of the regional circulation in north-west Australia and if present, is it driven by alongshore and/or cross-shore pressure gradients? What generates the pressure gradients? Does interannual variation modulate the seasonal cycle?
- What is the northward extent of the Ningaloo Current and the response of the regional currents?
- > What are main the interactions between Capes and Leeuwin Current?
- > What is the hydraulic connectivity and variability between the different regions in the northern, north-west and south-west of Australia?
- > What are the main driving forces (seasonal?) of shelf currents in the region?
- What is the relative importance of Coastally Trapped Waves on driving continental shelf circulation?
- What is the tidal regime in the region? In particular, the tides in deeper water in the northern region of Australia
- What are the roles of alongshore density gradients generated by (1) freshwater inputs and (2) evaporation in cross shore exchange through baroclinic forcing? What is the role of wind on cross-shore exchange?
- > What are the roles of currents and upwelling in the supply of nutrients to shelf ecosystems?
- > What are the key processes in the region which needs to be included in numerical models?
- > What data streams are required for model forcing, validation, and assimilation?
- > How can we facilitate the use of Bluelink and in particular, improve accuracy and resolution?
- How can we develop data assimilating hydrodynamic models (ultimately) to as to extrapolate observations and improve observing system design?

3.4.6 Notable gaps and future priorities

To address these challenges, it is crucial to maintain the two rocks transect and the Rottnest national reference station, as well as related glider operations and HF radar off Perth, and the Perth Canyon mooring. It is important to develop data assimilation in numerical models in order to integrate these observations with ocean dynamics.

It is important to maintain the footprint of IMOS off north-west Australia. It has been proposed that to shelf moorings will be maintained off the Kimberley coast for better integration with the WAMSI and WA state government long term coastal initiative. The original intent of the array will be preserved as it will remain on a similar across shelf transect but advantaged by being more central to the Kimberley region that bisects Camden Sound allowing investigation of the limits of the growing field of coastal altimetry in this macro-tidal area.

Notable gaps:

Nearshore measurements of wind, surface wave and ocean current along the whole coast

Future priorities:

Enhanced national reference stations measurements; improve HF radar coverage and the data QC. Specifically:

- It is crucial to maintain the complementary two rocks mooring transect and the Rottnest national reference station, as well as related glider operations and HF radar off Perth and the Perth Canyon mooring.
- Extend the Two rocks mooring array to measure inshore current.
- Maintain the footprint of mooring observations off the Kimberley coast.
- Use bio-logger technology to monitor the coastal environment off Esperance and south-west coast in general.
- Re-assess the footprints analysis of National Reference Stations and shelf moorings using higher resolution model.

3.5 Ecosystem Responses

WAIMOS addresses marine observing around over a third of Australia's continental shelf and coastal oceans. Here we present our understanding of the pelagic and benthic ecosystem processes and the knowledge generated from existing IMOS platforms that address these needs. We then propose future research priorities.

3.5.1 Coupling of pelagic ecosystems to physical oceanography: West Coast

Pelagic ecosystems are relatively poorly understood off the western coast of the Australia, especially how they are influenced by the physical oceanography. However, over the past few years there have been some investigations that have provided insights into this domain. Using the Bluelink re-analysis product (BRAN), Feng et al. (2010a) examined retention and dispersal of shelf waters influenced by interactions of the Leeuwin Current and coastal geography and identified some high retention areas and others with particularly low retention rates. Pearce et al. (2011b) showed southward dispersal potential of larvae of tropical fishes from the coral reefs of the Abrolhos Islands to Rottnest Island by means of the Leeuwin Current.

The major voyage to study the Leeuwin Current in 2007 has provided increased understanding of how the physical oceanography during peak flow of the Leeuwin Current is linked to the availability of nutrients, primary production levels, larval fishes assemblages and other macro-zooplankton (Weller et al. 2011; Thompson et al. 2011; Lourey et al. 2013; Holliday et al. 2012). For example, the unexpected occurrence of pre-flexion larvae of coastal, tropical anchovies in oceanic water at 27°S was backtracked using BRAN (Figure 21) and shown to be derived from coastal water near Ningaloo that had been advected offshore during eddy formation (Holliday et al. 2012).

The Leeuwin Current is known to have the highest eddy kinetic energy of all mid-latitude boundary currents especially in the region between the Abrolhos islands (28°-29°S) and Rottnest Island (32°S) (Feng et al. 2005). A detailed study of an evolving eddy as it formed from a meander in the Leeuwin Current identified mixing between coastal water and Leeuwin Current water (Patterson et al. 2008). It also showed that coastal fish larvae could be entrained and then, when the eddy detached from the main flow, they were trapped in the mesoscale feature with no return pathway to the coast (Holliday et al. 2011a). As there is considerable cross-shelf transport, the Leeuwin Current eddy field may temporarily disrupt long-shore connectivity (Holliday et al. 2012).

The ecology of the planktonic larval phase of the western rock lobster in relation to physical oceanography and the prey field in the south-east Indian Ocean has been examined in recent years (Saunders et al. 2012; Säwstrom et al. in review). Indications are that meanders of the Leeuwin Current can set up strong fronts where the warm tropical water meets the cooler subtropical waters resulting in strong onshore flow which is potentially linked to transport of phyllosoma and settlement success. Sampling in both anti-cyclonic warm-core eddies and cyclonic cold-core eddies have shown that although phyllosoma are more abundant in anti-cyclonic eddies, their condition is better in the cyclonic eddies where the mixed layer depth is generally less than in the warm core eddies (Wang et al. in press).



Figure 21: Results of a Lagrangian particle-backtracking model showing particles in a developing anticyclonic eddy (red ellipse) in the late austral autumn, May 2007. Particle tracks for a) 2weeks, b) one month after release (Holliday et al. 2012)

Ningaloo Reef in NW Australia has also been the subject of recent biological and oceanographic studies (Rousseaux et al. 2012, Wyatt et al. 2012, Rossi et al. 2013). Nitrogen fixation over temperate to tropical oligotrophic oceanic waters has been investigated in the SE Indian Ocean (Waite et al. 2013). Considerable work is now being focused on the biological oceanography of the macro-tidal waters off the coast of the Kimberley in NW Australia and preliminary papers on phytoplankton (Thompson and Bonham 2010) and macro-zooplankton (Holliday et al. 2011b) have been published.

3.5.2 WAIMOS and Fisheries Management

Understanding how environmental factors contribute to the variation in annual recruitment of fish and invertebrate fisheries is a key component of the fisheries stock assessment process. This has become more important under climate change and the lower west coast of Western Australia has been identified as a climate change hotspot in the Indian Ocean (Pearce and Feng 2007, Feng et al. 2012). Understanding how these environmental factors affect fisheries requires long-term time series of environmental data. This highlights the value of the monitoring projects such as those undertaken by IMOS and their use in oceanographic modelling.

The value of these environmental long-term data sets has been illustrated by downturn over seven years (2006/07 to 2012/13) of the puerulus (post larval stage) settlement of the western rock lobster fishery (Figure 22). The variation in the abundance of this settlement is important as it provides a reliable predictor to the recruitment to the fishery 3-4 years later. Long-term environmental data and associated oceanographic modelling played a vital role in understanding the cause of this downturn in lobster abundance (Feng et al. 2011a, Caputi et al. 2014a).

The marine heat wave event in the Gascoyne and mid-west region of WA during the summer of 2010/11 (section 3.2, Pearce and Feng 2013) provides an example of an extreme event that has had

significant implications in the management of a number of fisheries. The event affected the marine environment and marine community (e.g. seagrass, algae, coral, fish assemblages) with a number of fisheries requiring a re-assessment of the stocks and significant fisheries management interventions, including closures (Caputi et al. 2014b). From an oceanographic perspective the key question was whether the marine heat wave could be viewed as a rare event that was unlikely to reoccur in the near future or whether is it likely to become more common as the climate changes. From a fisheries perspective there were short-term (1-2 mo.) and longer-term (6-24 mo.) effects that have been identified in the years since the heat wave. The short-term effects were fish kills in the mid-west and Abrolhos regions with the 99% mortality of Roei abalone in the Kalbarri region being most significant. There were also short-term (and some longer-term) range extensions of a number of tropical species. However the longer-term effects have been very significant on the recruitment and adult survival of a number of important fisheries for short-lived species such as crabs and scallops in Shark Bay and scallops at the Abrolhos Is. These fisheries were shut during 2012 due to low abundance.



Figure 22: Annual average puerulus settlement of western rock lobster (from the Department of Fisheries, WA, website)

3.5.3 Continental Shelf Benthic Ecosystems under global warming

In Western and Northern Australia IMOS platforms are working towards full continental shelf coverage through radar, mooring arrays, gliders, AUVs, and animal tracking facilities. The offshore and outer continental shelf IMOS facilities need to be linked more closely with other research presently underway in nearshore areas that have recently demonstrated phase shifts and loss of ecosystem resilience. This will demonstrate the importance of understanding regional oceanographic events and their impacts on benthic continental shelf ecosystems.

In the last decade or so, quantitative information on the distributions and ecology of macroalgae, echinoderms, molluscs, historical and extant reef corals and fish (have been collected from various locations along the temperate latitudinal gradient (~35-28°S) (e.g. Smale et al. 2010). While these studies have substantially contributed to our knowledge of the benthic system, they are spatially limited as they were all conducted by SCUBA divers in shallow water (i.e. < 20 m depth). However, only ~5 % of the total area of WA's continental shelf lies at depths of < 20 m, whereas ~70% of the entire shelf lies in depths of 20-100 m (Kendrick, unpublished data). Thus, the majority of the shelf habitat has been greatly under-sampled.

Extreme events cause phase shifts to terrestrial and marine environments. These phase shifts can cause extreme shifts in the functioning of ecosystems. The 2011 marine heat wave coined the 'Ningaloo Niño" impacted the length of the west coast of Western Australia for weeks during February and March 2011 (Feng et al. 2013). Temperature of shelf waters were 2-4 degrees higher than previous late summer water temperatures recorded from Ningaloo Reef to Cape Naturaliste, Western Australia. Impacts to marine biota were extreme and included the following events:

- Bleaching of corals from Ningaloo to Rottnest (Smale and Wernberg 2012, Abdo et al. 2012)
- Defoliation of large areas of seagrass in Shark Bay and Houtmans Abrolhos (Thomson et al. submitted, Fraser et al. submitted)
- Loss of large brown algae from Kalbarri to Jurien Bay (Wernberg et al. 2013, Smale and Wernberg 2013)

The National IMOS AUV program has been instrumental in monitoring both loss and recovery of kelps and corals along temperate Western Australia. Losses of both kelps and corals were extreme (Smale et al. 2012) and recovery of these ecosystems have shown kelps and corals have not recovered two years after the event (Figure 23).



Figure 23: Change in cover of major benthos; the kelp Ecklonia, red Foliose algae, hard corals between 2010 and 2013 showing timing of loss and recovery around the 2011 marine heatwave in WA

3.5.4 Pelagic Ecosystems

Although detailed biological oceanographic studies off the region along the southern NWS, off North West Cape, have been undertaken by the Australian Institute of Marine Science (AIMS), processes that regulate phytoplankton growth and transfer of productivity to higher trophic levels are relatively unknown in the wider NWS region, although it is now the focus of research under the WAMSI II Kimberley node 2013-2017.

The influence of tropical cyclones on the primary productivity was demonstrated by Holloway et and Nye (1985) and McKinnon et al. (2003). The NWS from North West Cape to Broome is one of the most productive fishing areas in Australia, with extraordinarily high biodiversity, yet the source of nutrients remains poorly explained (Holloway and Nye1985; Tranter and Leech 1987). It is clear that neither river runoff nor persistent upwelling is the source. The existence of upwelling on the NWS, however, has been under speculation since it was first suggested by Schott (1933). However, it appears that the source of the nutrients are from the deeper ocean due to episodic events resulting from the Leeuwin Current weakening during El Nino events and cold, nutrient-rich slope waters from the Indian Ocean moving onto the shelf. These waters are then mixed by the strong tides. Thus primary productivity tends to be concentrated below the shallow surface layer, but still within the photic zone, and perhaps supported by nutrients from below (Condie et al., 2003). Brewer et al. (2007) in a review of trophic systems in the North-West shelf marine region concluded that key information gaps exist in the continental slope and shelf break region on the mechanisms, and variability, of nutrient delivery mechanisms onto the continental shelf region. Further, the ecology and connectivity of planktonic larval stages of biota such as fishes remain undescribed for this oceanographically complex region. Further, the ecology and connectivity of planktonic larval stages of biota such as fishes remain undescribed.

A review of scientific literature for the region shows the biological oceanography of the region is extremely poorly studied. For time series or significant spatial coverage we are completely dependent upon satellites. Preliminary assessment of chlorophyll *a* from satellite data suggests a strong cross-shelf gradient with influence from tropical rivers and a range of offshore features (Figure 24). There is considerable temporal variability in chlorophyll *a* (Figure 25), but a strong seasonal cycle is apparent in the monthly chlorophyll *a* averages (Figure 26). Some contamination of the Chlorophyll signal by suspended sediments is possible. High phytoplankton biomass is observed off the coast during March-June when the shelf waters flow south- westward. This region, however, is also known to have a deep chlorophyll maximum at about 75-100 m (Furnas 2007). Different mechanisms have been proposed to explain the nutrient input into the euphotic zone including: cross-shelf exchanges at the shelf break; vertical mixing due to tropical cyclones; benthic- pelagic coupling or riverine inputs. Physical processes that create vertical movement of nutrients into the euphotic zone are poorly resolved (Holloway and Nye 1985). The role of N₂ fixation in this region is important in biogeochemical cycling (Montoya et al. 2004).



Figure 24: Long term (January 1998 to December 2012) averaged surface chlorophyll a concentrations



Figure 25: Time series of monthly average chlorophyll a concentrations (SeaWIFS satellite data courtesy NASA) for 8 years from the Kimberley region



Figure 26. Seasonality in SeaWIFS chlorophyll a for Kimberley. Monthly means averaged from 1998 to 2006 ± 1 standard deviation, across region shown in figure above, data courtesy of NASA).

Published work on the phytoplankton community composition for the region is rare. In the early 1980s (Hallegraeff and Jeffrey 1984) collected a few net samples and reported an array of larger cells, especially larger diatoms and dinoflagellates including *Ceratocorys*. More recent samples of pigments showed the presence of relatively high concentrations of divinyl chlorophyll *a* and zeaxanthin suggesting numerical and biomass dominance by the picoplanktors (< 2 microns) *Synechococcus* and *Prochlorococcus* across the Northern Australia (Thompson, pers. comm.). Cell counts from a repeated transect off the NW Cape also support this conclusion (Furnas, pers. com.).

Periodically the Northern Australian seas are determined by satellite sensors to support massive blooms of coccolithophorids, probably *Gephyrocapsa* and *Emiliania*. We have no in situ observations to validate whether these are indeed coccolithophorids blooms or their impact on the ecology or biogeochemistry of the region. These blooms are of sufficient size to have considerable impact on the carbonate chemistry of the regional seas, potentially increasing the ocean acidity considerably.

The regional seas of Northern Australia can be highly impacted by river run off. There exists a strong conceptual framework for plankton ecology in riverine impacted coastal areas that considers the major forcing factors to be light or nutrients (Cloern 1982, 1984, 1987). Even without a riverine influence the shallow seas of northern Australia are characterized by high turbidity that reduces the underwater light and may negate the validity of standard algorithms for remotely sensed products such as chlorophyll *a* or calcite. In high riverine impacted regions the underwater light field in King Sound is likely to be controlled by turbidity (Wolanski and Spagnol 2003) including further offshore areas impacted by resuspension due to the high tidal velocities. Relationships between light penetration, tidal mixing, suspended particulate material and primary production need to be investigated. Increased river flow is known to increase prawn catch in the Gulf of Carpentaria (Loneragan and Bunn 1999), implying some combination of nutrients and/or physics is increasing primary and secondary production in spite of the loss of light due to increased water column turbidity. Large rivers in this region also contribute nutrients and the silicate contribution can be detected all the way down the west coast of Australia past Perth.

Both the Gulf of Carpentaria and the Arafura Sea are highly productive regions which each support significant commercial fisheries, however, there is a paucity of detailed biological oeanographic observations in the region. What data that is available shows very high rates primary productivity in the Arafura Sea of up to 3-7 g C m⁻² 12hr⁻¹ (Gieskes et al, 1990). The mechanisms, and variability, of nutrient delivery and transport through this system are poorly understood and represents a key information gap.

3.5.5 Benthic Ecosystems

Biologically, the nearshore and coastal environments support a diverse array of marine communities including coral reefs, seagrass meadows, mangrove forests and sponge gardens. These communities in turn provide critical habitat, shelter and food resources for specially protected and culturally and commercially important species including marine turtles, cetaceans, dugongs, birds, fishes, and invertebrates.

Coral reefs in the region fall into two general, though distinct groups — the fringing reefs around coastal islands and the mainland shore, and large platform reefs, banks and shelf-edge atolls

offshore. Seagrasses are biologically important for four reasons: (1) as sources of primary production, (2) as habitat for juvenile and adult fauna such as invertebrates and fish, (3) as a food resource, and (4) for their ability to attenuate water movement (waves and currents) and trap sediment.

The IMOS national benthic ecosystem marine observing platform using AUVs is of high value for Commonwealth and State environmental managers and regulators. The AUV data is a yearly snapshot of the condition of benthos and this has been shown to be of high value in the case of the 2011 marine heatwave on the Western Australian continental shelf. Clearly we need closer ties to other platforms to link local benthic change to the broader oceanographic setting. The gap in the IMOS coverage is the central west coast of Australia and we highly recommend some glider cruises as a minimum in this region. Also a calibration exercise of remote temperature logging across institutions will be of great value as Universities, Commonwealth and State Government Departments and fishermen monitor temperature that presently have minimal cross calibration of loggers.

3.5.6 Marine Megafauna

The Western Australian coastline is richly endowed with marine megafauna, these being the larger more obvious fauna such as great whales, various dolphin and toothed whale species, whale sharks, dugong or sea turtles. Many of these species form the basis for substantial tourism industries and are major factors in offshore marine operations given their threatened species status and high public profile as "characteristic megafauna". The species which frequent coastal areas such as whale sharks, dugong, humpback whales and many dolphin species are relatively better known from a scientific perspective than those species which primarily occur offshore, simply as they can be observed more easily. The deployment of sea noise loggers along the WA coast along the shelf break has revealed that WA has a host of offshore great whale and toothed whale species. The sea noise loggers depend on animals vocalising with signatures unique to a species, which most whale species do at rates varying from perhaps 10 to 100% of that species present within the listening range of the receiver. The receiver listening range for great whales may be on the order of tens to a hundred km in shelf or shelf edge depths respectively and depending on species. Western Australia has regular seasonal migrations of great whales detected on the sea noise loggers, notably:

- Humpback whales- migrate north from the Antarctic (80° E to 120° E) to Western Australian waters between Albany and northern WA, with their preferred breeding/calving areas between Exmouth and the southern Kimberley but extending to offshore Kimberley Islands and reefs and further north into the Joseph Bonaparte Gulf. Humpbacks arrive along the WA coast in June and July, then largely depart WA waters by November each year. The WA humpback whale population is large, estimated at near 26,100 whales in 2008 and increasing exponentially at 10-12% (Salgado Kent 2012), thus the population is starting to impose significant management issues relating to collisions, vessel interactions, carcass disposal, fishery interactions etc. Humpback whales generally do not feed while in WA waters
- Pygmy blue whales migrate south, down the WA coast over October to January each year from a northern terminus in Indonesian waters to the equator, spend summers feeding between latitudes of 33-54° S, then migrate north again along the WA coast over March to

August depending on Latitude. The northern migratory leg is slower than the southern leg. Pygmy blue whales tend to keep to shelf break or open ocean waters with the notable exception of southbound animals passing through Geographe Bay which can pass within a few hundred m of the shoreline as they round Cape Naturaliste over October to December each year. Northbound pygmy blue whales stop and feed along the WA coastline, notably in the Perth Canyon but likely along the steep shelf edge between Lancelin and north of the Abrolhos Islands, off Exmouth and possibly near offshore reefs in the Kimberley. These, regularly occurring foraging whales emphasise that there are deep aggregations of suitable prey, krill, along the WA coast of sufficient density to feed great whales for sustained periods (weeks to months in the Perth Canyon).

- Bryde's whales sea noise loggers detect Bryde's whales year round on the North West Shelf. These animals do not appear to migrate thus must be feeding in 'hotspots' on the NW Shelf between Exmouth and the northern Kimberley.
- Minke whales- the two sub species (dwarf and Antarctic forms) are detected seasonally migrating along the WA shelf break from Perth to Scott Reef over winter, returning south in late spring. The dwarf Minke can occur in schools of several hundreds of animals given the call rates encountered.
- Southern right whales appear seasonally on the sea noise loggers over winter, commonly as far north as the Perth Canyon. These animals have been observed feeding over winter in the Perth Canyon.
- Sperm whales occur along the entire WA coast but are little known recently. Sperm whales were a targeted whale fishery up until the 1970's out of Albany with regular, seasonal west bound migrations along the shelf edge observed. It is not known if these animals still frequent southern WA. In northern WA waters sea noise loggers regularly detect sperm whales in waters offshore Exmouth and in the Joseph Bonaparte Gulf, with their appearance coincident with elevated water temperature during the summer monsoon. These are believed to be pods of females although they are poorly studied.
- Fin whales very poorly studied with largely unknown habits in WA, but seem to be a regular visitor to the Perth Canyon in September each year.

The whales listed above represent the more common great whales detected in the sea noise loggers and highlight the diverse and mostly poorly studied nature of the offshore WA megafauna. That many of these whales consistently feed in WA waters (completely in WA for northern Bryde's whales) highlights that at times and in certain places along the coast sufficiently dense aggregations of suitable prey exist for protracted periods.

3.5.7 Biological baselines and ocean observation

Oceanic reefs and shoals in NW WA are dynamic systems where rapidly changing habitat cover and diversity has been observed (Heyward et al. 2012, 2013, Gilmour et al. 2013). In many cases changes in habitats, for instance the loss of sea grass beds at Vulcan shoal (Heyward et al. 2013) have been considered to be the result of physical oceanographic drivers (storms, waves etc.). However, due to

the remote nature of these systems there is a paucity of real time ocean observation data to confirm such assumptions.

Oil spill modelling and prediction of spill trajectory during an event requires real time high resolution surface current velocity and direction information. In addition, this information is critical in developing a fundamental understanding of the potential physical drivers of genetic connectivity between geographically isolated reef and shoal systems, for instance the transport of coral gametes. A potential emerging issue requiring this information is the introduction and transport to oceanic reefs and shoals of marine pests resulting from bulk LNG carriers loading direct from proposed Floating LNG production facilities.

Apart from the cross shelf transport of productivity eddy system do impact more practical activities particularly when the rotational rate of the eddy system is strong. The offshore oil and gas industry and the lobster industry are impacted by strong eddies. It is possible to track eddy system from their formation to depletion using satellite observations and also determine a set of physical attributes including source and destination locations, along track coordinates, rotation direction, rotation rate, eddy diameter, temperature and chlorophyll concentration of the surface waters relative to the background ocean. Such data may be used to build a long term climatology of eddies and establish any trends over at least the past 35 years. Offshore industry has sought eddy climatologies previously. The motivation is that they have recorded severe impacts of a single strong eddy system that has caused the order of \$80 million in lost production and damage to the gas riser and the loading vessel. Of much less costly but operationally important is the fact that eddy systems are able to pull lobster pot floats well below the ocean surface to a depth such that fishermen cannot retrieve their pots. With eddies being slowly drifting features, the delay in retrieving lobster pots and the associated catch can run into 3-5 days. A knowledge of real-time [daily] information on eddy systems off the WA coast [imagery, coordinates, size, strength, drift velocity etc] delivered via web tools would have real benefits to the marine operations, e.g IMOS Ocean Current.

For several years IMOS has been operating the Continuous Phytoplankton Recorder (CPR) program using ships of opportunity. The benefits of a sustained record of the phytoplankton populations is clearly beneficial for understanding a range of issues including climate change impact on the marine system, identification of sensitivity to water quality change, causes and implications of changes to the mix of phytoplankton species. As well as the CPR program satellite products generated by IMOS support the long term study of plankton. As mentioned the CPR program samples just routes of ships of opportunity whereas satellites provide a comprehensive cover of the oceans. An argument is made for extending the satellite program to produce a new product to the am suite - namely phytoplankton functional groups (PFG). This product was reported on favourably by Aikin et al. (2007) but has been further developed and refined in recent years (e.g. Brewin et al. 2010, Alvain et al. 2008) and is now relatively mature. The success of the application of an algorithm in a specific region may depend of the species present. For example, tricodesmium occurs in the warmer tropical waters but would not be a product of interest or that is extracted in the cooler non-tropical waters. A program of PFG mapping using the archive of Australian satellite data would be advantaged because the ship-track CPR data may be used to validate and improve the tuning of satellite algorithms applied to Australasian waters.

3.5.8 Science questions

The following high-level science questions will guide the Western Australian Node observing strategy:

Productivity:

- What is the role of krill in the Perth Canyon where localised upwelling appears to be supporting a blue whale feeding ground?
- How does the Leeuwin Current influence the pelagic ecosystem eg prey availability for pelagic seabirds, especially those that nest on the Abrolhos Islands?
- What is the mechanistic influence of the Leeuwin Current on southward distribution of larvae and juvenile blue fin tuna from the north, as well as, on tailor and herring larvae from spawning areas near Perth?

Distribution and Abundance:

Large scale ocean drivers of variability of water quality (temperature salinity, turbidity, chlorophyll, primary productivity)

- What is the natural variability of water quality (particularly under water light, TSS, temperature, Chlorophyll, primary productivity) in the region?
- > What is the influence of water quality on ecosystems?
- > What are the dynamics of regional nutrient supply associated with production?
- What are the drivers and natural variability of planktonic community structure and primary production?
- > What are the processes driving productivity in LC eddies?
- What is the seasonal variability in carbonate system parameters (pH, pCO2, TA, DIC), hence ocean acidification buffering capacity, in coastal waters?
- > Are WA coastal waters sinks or sources of atmospheric CO2?

Effects of tidal and wave dynamics on marine habitats

- > What is the role of tidal fronts in controlling the biological productivity?
- > What is the role of internal waves on biological productivity?
- > What is the influence of tidal and wave stress on bottom habitats?
- > How are benthic and pelagic systems coupled?

Water column processes.

- What are the mechanisms of alongshore and cross-shelf dispersals of fish larvae and other biota?
- > What is the nature and variability of planktonic ecosystems supported by cross-shelf exchange?

Natural variability of populations and pathways of large marine fauna.

- > What are the migration pathways of mega-fauna in the region?
- Can seasonal patterns of use be determined, or precisely when are they present and what controls this?
- How can we monitor over the long term, trends in mega-fauna populations and link these to physical factors?

How can we use marine vertebrates as platforms to collect oceanographic data and to inform us of where and when regions of high productivity occur?

3.5.9 Notable gaps and future priorities

Linking of physical oceanography to biology in the tropical – temperate transition zone along the central Western Australian coastline

This is one of the fastest changing marine environments in Australia with climate change and the increased frequency of events like the Ningaloo Nino and in storminess and extreme high water levels during winter.

Understanding the physical oceanography and biology of the Pilbara and Kimberley continental shelf

WAMSI and DPaW are investing 10s millions of dollars into these regions and IMOS should reassess the importance of deployments in regard to these investments.

Notable gaps:

Support the public and research outcomes of the ~30 marine research offset programs, conservation programs, BoM storm surge modelling trials, and economic development related assessments in the Pilbara by offshore industry.

Future priorities:

- Offshore glider and mooring data linked and calibrated with onshore oceanographic measurements made by other agencies through the IMOS AODN (e.g. Fisheries WA, Wernberg at UWA).
- Addition of Glider deployments north of Perth such that they inform researchers working on AUV deployments of the oceanographic conditions before and after deployments and allow calibration of AUV instrumentation collected over a few hours to diurnal, weekly and monthly changes in physical oceanography in the Houtmans Abrolhos, Leeman, Jurien and Rottnest regions.
- Reinstatement of oceanographic moorings at Ningaloo and either Albany or Esperance to give a broader synopsis of the connectivity in physical oceanography on the Western Australian Tropical-Temperate Transition zone.
- Deployment of spectral equipment on existing moorings to calibrate ocean colour for remote sensing.
- In consulting with the facility, move ATAAMS array to other locations other than Ningaloo on the West Australian coastline to service issues other than shark and fish movement in and outside MPAs. (e.g. green turtle and tiger shark behaviour in Shark Bay with Ecosystem recovery post-2011 marine heat wave);
- Acoustic mooring arrays to monitor whales in Perth Canyon, killer whales off the south coast/Bremer Bay.
- Maintain and extend mooring and glider data from existing transect off Pilbara.
- Develop a mandate to increase radar coverage of the region through collaborations with BOM , state government and industry.

4 How will the data provided by IMOS be taken up and used?

There have been wide uptakes and use of IMOS data by Australian scientists and stakeholders contributing to the WA IMOS Node. In Western Australia, the WAIMOS data streams have to be used to study the ocean boundary currents, shelf circulation, coastal upwelling, Ningaloo Nino and impacts, tropical cyclone impacts, ecosystem response, and fisheries recruitments. The IMOS infrastructure and data streams have become an integrated component of the Indian Ocean Global Ocean Observing System (IOGOOS), allowing Australian researchers to actively engage in international collaborations in the Indian Ocean, especially the recently proposed second International Indian Ocean Expedition and Eastern Indian Ocean upwelling Research Initiative.

The IMOS data have been used by scientists to publish scientific papers, by modellers to test and improve shelf circulation models, and by managers to monitor the marine ecosystem. IMOS data have supported major research projects in Western Australia, such as WAMSI and Net Conservation Benefits, and have also been used by a large number of PhD projects in Western Australia.

	Bluewater & Climate	WA	QLD	NSW	SA	TAS
Argo	Р	S	S	S	S	S
SOOP	Р	Р	Р	S	S	S
Deepwater moorings	Р	S	S	S		S
Ocean gliders	S	Р	Р	Р	Р	Р
AUV		Р	Р	Р		Р
Shelf Moorings	Р	Р	Ρ	Р	Р	Ρ
Ocean Radar		Р	Р	Р	Р	
Animal Tagging	Р	Р	Ρ	Р	Р	Р
Sensor networks			Ρ			
SRS	Р	Р	Р	Р	Р	Р
eMII/AODN	Р	Р	Р	Р	Р	Р

Table 16: How IMOS Facilities deliver to the Nodes. P = primary relationship and s = secondary relationship

The key stakeholders of the West Australian IMOS program include the following agencies, research centres and major projects.

Western Australian Marine Science Institution (WAMSI) is a key stakeholder of IMOS. WAMSI is the leading Australian marine research organisation, representing the collaboration of state, federal, industry and academic entities cooperating to create benchmark research and independent, quality scientific information in Western Australia. It carries out research into climate change, biodiversity, the iconic Ningaloo Marine Park, sustainable fisheries, biotechnology and oceanography. IMOS provides key data streams to validate oceanography and the shelf models in the WAMSI Kimberley research program. IMOS aims to become a key component of the Western Australian Marine Science Blueprint 2050, championed by WAMSI. The blueprint will help identify the most important knowledge gaps in marine research sector in Western Australia in order to provide industry and the Government the right information at the right time for decision making.

CSIRO is a key contributor to the oceanography and climate research in Western Australia. **The University of Western Australia** plays a key role in the understanding of coastal oceanography and marine ecosystems. The Australian Institute of Marine Science (AIMS) is the lead agency for tropical marine research. **The Department of Fisheries** is a leading fisheries research agency in Western Australia. These agencies will form the Indian Ocean Marine Research Centre in the coming years. IMOS infrastructure and data streams will be core portfolio of the new research centre. Researchers from **Curtin University** have also been making use of the IMOS remote 's sensing and shelf mooring data streams.

Department of Parks and Wildlife manages quite a number of marine parks along the West Australian coast, some of those are world heritage sites, which are important for sustained the biodiversity along the coast. IMOS shelf moorings have been used to understand the coastal upwelling processes off the Ningaloo reef and their influences on the coral reefs. In other coastal areas, IMOS does not have a footprint within marine parks, however, IMOS data have been used to understand the offshore physical and biological conditions of the marine parks and sometimes provide validations for the modelling study of the marine parks. A sensor networks concept will likely be attractive to the marine park managers.

Regional models have been used in Western Australia to understand physical and biological processes of the continental shelf and coastal regions and IMOS data streams have been providing a vital role to validate these diverse numerical models. Researchers from CSIRO has been developing a high resolution shelf model off the west coast of Australia, and IMOS shelf mooring data streams have provided the key data sets to validate the model results, with applications in extreme events and fisheries recruitment studies. Researchers from the UWA has been working on the higher resolution models off north-west shelf, to study internal wave generation and propagation, tropical cyclone impacts of shelf environment, and the IMOS data streams from the shelf mooring and glider facilities have provided critical reality check of these models. In the future, IMOS data will also be used to provide validation for regional model efforts in the **Net Conservation Benefits** and WAMSI Kimberley projects, as well as the OzROMS initiative.

Bluelink, the joint CSIRO and Bureau of Meteorology product, is a 10-kilometre resolution global hydrodynamic model that assimilates various open ocean IMOS data streams to deliver historical

reanalysis and short term forecast of ocean circulation. In Western Australia, Bluelink products have been widely used in providing open boundary conditions for regional models and directly in the applications of oceanography, fisheries and ecosystems related research. The Bluelink model does not resolve fine scale processes on the shelf due to its resolution. The next generation Australian shelf and coastal models will have the data assimilating capability, thus the IMOS data streams on the continental shelf and coastal areas are important to be well maintained so that they can be assimilated into these new generation models.

The Australian Government has confirmed its long-term commitment to environment and climate research with funding of \$102 million over four years for the National Environmental Science Programme. The National Environmental Science Programme will assist decision-makers to understand, manage and conserve Australia's environment by funding world-class biodiversity and climate science. A number of research hubs in the program such as climate and biodiversity will rely on sustained data streams on the continental shelf of Australia, and IMOS will be able to play a key role in that demand.

The WAIMOS data streams have supported a number of high profile research topics in Western Australia. The Two Rocks shelf mooring array, Argo Float, and the National Reference Stations captured the rise and fall of the evolution of the 2011 marine heatwave known as **the Ningaloo Niño** phenomenon, and the associated ocean dynamics. Changes in biota were documented through the AUV program that recorded marine heatwave impacts and subsequent recovery of coral and kelp communities from Rottnest Island, central West Coast and Abrolhos Islands. In other areas, data streams from gliders and HF radar have been used to understand the dense shelf water cascades, peddies, and coupled wave and current dynamics. IMOS acoustic observatory have also been used to track whales as well as the missing Malaysian airplane MH370.

In the planning of the second **International Indian Ocean Expedition**, the Two Rocks mooring and glider section has been identified as the end point of a cross-Indian Ocean array to estimate meridional transport in the Indian Ocean. The proposed mooring array in the north-west coast will also enhance our understanding of the ocean circulation and thermal structure in the region, which will contribute to the **East Indian Ocean Upwelling Research Initiative**. These data will also be highly valued by the **offshore industry**, as the variability and change of oceanography conditions in the region is important for the industry operation, to save the operation cost and improve efficiency. These observations will also improve our capability to simulate and predict ocean circulation and extreme climatic conditions off the coast, so as to help **fisheries and marine resources management**, to better prepare for the future climate change.

5 Regional, national and global impacts of IMOS observations

5.1 Next five years

- A greater understanding on the seasonal, inter-annual variability of the processes influencing the Leeuwin Current systems and their relationship to coastal ecosystems.
- Information on Temporal variability of ITF; providing seasonal and inter-annual variability of currents in the northern, western and southern margins of Australia which in turn influence the variability in ecology.
- Information of the Holloway current, better description of the extent and climatology of the Ningaloo
- A greater understanding of the dynamics and variability of the Ningaloo Nino
- A better understanding of the continental shelf processes off Perth/Rottnest
- Validated data sets for use as inputs for improving forecasting models.
- Definition of the long-term and spatial characteristics of exchange of water and nutrients between northwest coastal and offshore waters
- Definition of the tidal regime in the region, particularly spatial variability and distribution of bottom stress
- Elucidation of marine mega-fauna including: migration pathways; links to physical factors such as productivity; inter-annual variability in population; foraging areas identified
- description of the movement and habitat use of keystone species at the scale of thousands of kilometres along the NW coast of WA
- data sets and associated research as important inputs into regional oceanographic studies and modelling such as undertaken through the Indian Ocean Global Ocean Observing System Regional Alliance (IOGOOS) and through the second International Indian Ocean Expedition (IIOE-2)

5.2 Long-term

- Information on natural variability of ocean conditions and their relationship to water quality which will lead to more informed biodiversity conservation and fisheries management
- Availability of scientific data on which decisions on the approvals of coastal and offshore infrastructure be made
- Contribution to the second International Indian Ocean Expedition (IIOE-2) and the Eastern Indian Ocean Upwelling Research Initiative (EIOURI).

6 Governance, structure and funding

6.1 Scope of the WAIMOS Node's responsibilities

The key responsibilities of the WAIMOS Node are:

- To represent the scientific opinion of the broader WA marine research community provide scientific rationale for IMOS, develop research goals and identify the need to obtain specific streams of data and engage the relevant "users" of these data streams to ensure uptake;
- To advise the IMOS Board and Director on the technical implementation of IMOS generally, WA IMOS and the scientific merit of research undertaken with IMOS data;
- To integrate regional research objectives into a national scientific perspective on marineobserving with a focus on researching the major boundary currents;
- To provide advice as part of IMOS strategic reviews, including an assessment of the Node's impact;
- Make nominations for, and approve the membership of the IMOS Advisory Board;
- Promote use of IMOS data streams within the scientific and general user community

6.2 Structure and frequency of meetings of the IMOS Nodes

The Nodes will have a formal structure including a sponsor (one of the Operators or other body that provides funding for meetings, travel for national coordination and possibly other nodeactivity), elected officers (at least a Node Leader and a Node Representative on the IMOS Steering Committee, which may or may not be the same person), a list of members and a documented process (approved by 2/3 of the membership) for making recommendations to the Steering Committee. Nodes will meet at least twice per year, or more frequently if required or desired by the marine community.

The Nodes will be an essential part of the forward planning, development and implementation of IMOS. As such, it is a requirement that the IMOS Director and Executive Officer are invited to all WA IMOS Node meetings. Meetings will generally be face-to-face at a location suitable for the majority of the Node members to attend, however teleconference facilities (or other electronic means) may be used to hold meetings. The Node Leader is responsible for calling of meetings, arranging the venue, taking formal Minutes of meeting and maintaining a list of the Node participants.

6.3 IMOS Steering Committee

The marine community has formed regional Nodes eg. WAIMOS, which provide the scientific rationale and research goals for marine observing. The five Node Leaders, the eMII Director and the IMOS Director form the IMOS Steering Committee, which consolidates scientific thinking in the Nodes and forms a national perspective that guides the preparation of annual business plans for

the facilities. The Steering Committee also assists the IMOS Office in assessment of annual business plans and reports from the Facilities. It is not necessary for the Steering Committee to meet on a regular basis, rather to be available as necessary to discuss issues arising.

6.4 WAIMOS Committee Structure

WAIMOS Membership - includes all those interested in marine science in WA/NT and the membership is not restricted in any way. The WAIMOS community are engaged in IMOS through seminars, workshops and meetings arranged by the Manager of the Node. Communication is via approximately monthly newsletters or as required to advise of key events of interest to the marine science community. The manager makes every effort to introduce potential collaborators across the stakeholder group which includes industry, government, research organisations, consultancy groups and individuals.

WAIMOS Scientific Reference Group – a smaller focussed group, undertaking the detailed science planning and reviewing Node progress against the work plan. The Group is formally required to have 2 meetings per year Normally 3 – 4 meetings of the Scientific Reference Group are held annually. The WAIMOS Node Leader (or the deputy Node Leader) chairs the meetings. The current membership of the WAIMOS Scientific reference group is as follows.

Name	Affliation		
Gary Kendrick	University of Western Australia		
Ming Feng	CSIRO		
Nick D'Adamo	IOC Perth		
Robert McCauley	Curtin University		
Merv Lynch	Curtin University		
David Antoine	Curtin University		
Chari Pattiaratchi	University of Western Australia		
Reena Lowry	Department of Transport (WA)		
Steve Buchan	RPS Metocean Engineers		
Lynnath Beckley	Murdoch University		
Paul Lavery	Edith Cowan University		
Patrick Seares	Western Australia Marine Science Institute		
Nick Caputi	Fisheries WA		
Ray Steedman	Western Australian GOOS		
Alan Kendrick	Department of Parks and Wildlife		
Alan Pearce	Fisheries WA		
Steve Rogers	AIMS		
David Williams	NT / AIMS		

Sub-Groups can be formed for specific tasks, but must always be working under the auspices of the main WAIMOS Group to ensure broad stakeholder buy-in/ ownership of outputs and transparency of decision making. Secretariat support is the responsibility of the Node Leader to provide/ coordinate.

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