IMOS Integrated Marine Observing System

New South Wales Integrated Marine
Observing System (NSW-IMOS)

# New South Wales Integrated Marine Observing System (NSW-IMOS) Node Science and Implementation Plan

## 2015-25

An Australian Government Initiative
National Collaborative Research Infrastructure Strategy

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

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**The current authors would like to acknowledge the tremendous effort put in by the team who generated the previous NSW node plan in 2010. We thank them for their endeavour. This work is based on the previous plan for both content and organization and is meant to be read as an updated, self-contained snapshot of this node's current state and future plans.**

**Edited by: Robin Robertson,**

**Date: 25 September 2014**

# Table of Contents

Table of Contents ..... 3

1 Executive Summary ..... 5

2 Socio-economic context ..... 11

3 Scientific Background, by Major Research Theme ..... 18

3.1 Multi-decadal ocean change ..... 18

3.1.1 Science Questions ..... 18

3.1.2 Notable gaps and future priorities ..... 19

3.2 Climate variability and weather extremes ..... 21

3.2.1 Interannual Climate Variability ..... 21

3.2.2 Intra-seasonal variability and severe weather ..... 21

3.2.3 Modes of variability in a changing climate ..... 21

3.2.4 Science Questions ..... 21

3.2.5 Notable gaps and future priorities ..... 22

3.3 Major boundary currents and inter-basin flows ..... 23

3.3.1 East Australian Current (EAC) system (including Tasman Outflow, Flinders Current and Hiri Currents) ..... 23

3.3.2 Eddy Processes in boundary currents. ..... 24

3.3.3 Science questions ..... 24

3.3.4 Notable gaps and future priorities ..... 26

3.4 Continental Shelf and Coastal Processes ..... 27

3.4.1 Boundary current eddy –shelf interactions ..... 27

3.4.2 Upwelling and downwelling ..... 28

3.4.3 Wave climate, including internal and coastally trapped waves. ..... 29

3.4.4 Science questions ..... 30

3.4.5 Notable gaps and future priorities ..... 31

3.5 Ecosystem Responses ..... 34

3.5.1 Ocean Chemistry – Nutrients ..... 35

3.5.2 Ocean Chemistry – Carbon and acidification ..... 36

3.5.3 Plankton ..... 36

3.5.4 Mid Tropic Levels (Nekton) ..... 37

3.5.5 Top Predators ..... 40

3.5.6 Benthos ........ 40
3.5.7 Science questions ........ 41
3.5.8 Notable gaps and future priorities ........ 42
4 How will the data provided by IMOS be taken up and used? ........ 44
5 Regional, national and global impacts of IMOS observations ........ 54
6 Governance, structure and funding ........ 56
7 References ........ 61

# 1 Executive Summary

Due to its broad geographical reach, the East Australian Current (EAC) influences the climate and marine economies of nearly half the Australian population, from Brisbane to Sydney, Melbourne, and Hobart. The poleward flowing EAC brings warm water down the NSW coast modulating the region's climate as well as the composition, organisation and function of marine ecosystems. The EAC and the eddy field it produces dominate the marine environment on the narrow, NSW continental shelf. Off northern NSW, the EAC starts as a strong western boundary current until it separates from the coast between 29-33 $^{o}$S (Ridgway and Dunn 2003). South of its separation zone, part of the current moves offshore, retroflecting northward and back into the EAC, part flows east into the Tasman Sea, and a third portion develops into a "river of eddies".

Although most of this flow is off the continental shelf, the strong flow of the EAC impacts the coastal region in several ways. The strong current sporadically stimulates upwelling, which induces cross-shelf transport and increases primary productivity. The EAC transports the resulting phytoplankton blooms and larvae along the coast or into the Tasman Sea. EAC-generated eddies also draw coastal waters offshore. These form highly productive cold-core eddies which act as nurseries for fish larvae. In addition to the EAC, smaller scale processes such as internal tides and waves contribute to mixing, cross-shelf transports, and nutrient replenishment, which influence biological productivity.

Research over the past decade indicates that poleward extension of the EAC is strengthening, with an increase of over 2 ºC per century at the Maria Island reference station off eastern Tasmania (Ridgway and Hill 2009) and an effective shift of the water masses by ~350 km southwards. These changes are expected to continue, with both an increase in flow and southward shift of the separation location (Matear et al. 2013) and changes in flow within and outside eddies (Heredia, 2014). The EAC, and its changing nature, will impact the climate and weather of NSW, the distribution of marine organisms, and the state's ecological and socio-economic values. Therefore, NSW-IMOS's goal is to understand the variability of its marine ecosystems in this complex oceanographic setting, and interpret and predict their behaviour. This overarching goal is relevant to several grand challenges facing Australia:

- Developing resilient human-natural linked systems which can thrive in a changing environment;
- Optimising food production from marine resources;
- Managing the flow of goods and people across our borders; and
- Increasing productivity and economic growth.

The natural variability of the EAC, driven largely by the mesoscale eddy field, makes it difficult to forecast, and even hindcast, the Tasman Sea currents. BLUElink, the forecasting model of the Bureau of Meteorology (BOM), CSIRO, and the Royal Australian Navy (RAN) shows the least skill in this region (Oke et al., 2012; Woodham, 2013). Much of the variability has its origin in the separation dynamics of the EAC off central New South Wales (NSW), and the subsequent formation of warm and cold core eddies at "Eddy Avenue" (Everett et al. 2012). To fully understand the variability of the EAC and its eddies, longer-term observations are required.

Although satellite estimates of sea surface temperature (SST) readily cover the region and are incorporated into BLUElink, subsurface data is less easily available. The vertical distribution of bio-physical properties is essential for understanding the entire ocean ecosystem. Subsurface processes are usually estimated from remote sensing of the ocean's surface and the implications of and errors associated with this translation are not well understood. Further data on the subsurface is needed to address this shortcoming. The eventual goal is to assimilate the subsurface information (e.g. glider data, temperatures from animal tags, real-time mooring data) into BLUElink and other models (e.g. coupled climate-circulation, ecosystem, and biogeochemical) to improve atmospheric, ocean, ecosystem, fisheries, and sonar forecasts.

NSW IMOS' focus on processes north and south of the separation zone off Coffs Harbour (30 ºS) and Sydney (34 ºS) and complemented by similar observations off Narooma (36 ºS). Observations atMaria Island (43.5 ºS) by Tas-IMOS, and at the full depth EAC monitoring mooring off Stradbroke Island (28 ºS) by Q-IMOS and the Bluewater node also contribute to the understanding of these processes. These observations parallel those made for the poleward Leeuwin Current in Western Australia, to understand common ENSO and SAM phenomena and other teleconnections.

Ocean conditions impact the atmosphere and vice-versa. The EAC eddy field has been related to the sudden intensification of East Coast Lows (ECLs) and severe winter storms. In June 2007 five ECLs led to 10 deaths, the grounding of a ship, severe flooding and coastal erosion. ECLs are also responsible for 10-20% of coastal rainfall and substantial filling of NSW and Victorian reservoirs.

Biological observations are increasingly important as we begin to understand the implications of the strengthening and variable EAC. Furthermore, they represent an important link between physical variability and socioeconomic endpoints. For example, offshore fishing permits are now managed by water mass properties (SST), rather than static latitudinal rules (Hobday and Hartmen 2006). Both warming and urbanization have been attributed as drivers of change in pelagic and temperate reef ecosystems. Declines in the distribution of kelp as well as changes in the distribution of sea urchins along the coast of south-eastern Australia have been observed (Johnson et al. 2011). IMOS is using both water column and deep reef observing to monitor changes in these marine primary producers and critical "ecosystem engineers". The effect of different water masses and eddies of the EAC on phytoplankton and zooplankton diversity and abundance must also be quantified, as these organisms underpin all marine food webs.

Ecosystem impacts are also being tracked at higher trophic levels through observations of benthic habitats and fish. Physical factors and processes at lower trophic levels drive both the movements and distribution of fishes and marine mammals. For example, seasonal variability in coastal oceanography is essential for the spawning and effective dispersal of some fishes. Conversely, deviation from seasonal cycles can have detrimental effects on the success of particular year classes and lead to changes in species distributions.

**The key research aims pertinent to NSW-IMOS are:**

1) **To contribute to national observations of decadal changes and climate variability of the EAC using common platforms and metrics**.

   i) To determine the variability in EAC strength from its source in the Coral Sea, the temporal and spatial variability in the separation of the EAC from central NSW, and the EAC's southward extension;
   ii) Contribute to the national backbone through the National Reference Station network and the validation of Satellite Remote Sensing products with local data.
   iii) To identify and quantify the elusive EAC undercurrent and its contributions to heat and salt fluxes.

2) **To investigate the EAC, its separation from the coast and the resultant eddy field along the coast of SE Australia**.
   i) To determine the frequency, form and function (horizontal and vertical) of EAC eddies;
   ii) To understand air sea interactions, particularly to determine the development of East Coast Lows and severe winter storms in relation to warm core eddies;
   iii) Quantify the impact of key physical processes such as onshore encroachment of the EAC, slope water intrusions, upwelling, downwelling, internal waves, and interaction of the current with topography.

3) **To quantify oceanographic processes on the continental shelf and slope of SE Australia:**
   i) Examine the coastal wind and wave climate in driving nearshore currents and the northward sediment transport;
   ii) Quantify the biogeochemical cycling of carbon (nutrients and phytoplankton composition);
   iii) Determine the transport and dispersal of passive particles (e.g. larvae, eggs, spores) and the degree of along coast connectivity and trophic linkages.

4) **To integrate the ecosystem response with oceanographic processes:**
   i) Quantify the daily to decadal variation of planktonic communities in relation to oceanographic and climate-driven changes in physical and chemical ocean properties;
   ii) Quantify rocky reef biota variables (kelp distribution and abundance) associated with climate variability, at deep reefs along the NSW to Tasmanian coast;
   iii) Relationship of the EAC, its eddies and oceanographic conditions on fisheries, and movements by fish.

**We are addressing these aims with the following essential observations:**

- Maintaining an array of **oceanographic moorings** north and south of the separation zone: 2 moorings off Coffs Harbour (30ºS) and 4 moorings off Sydney (34ºS) measuring temperature, salinity, dissolved oxygen and velocity; some augmented with bio-optical sensors (turbidity, chlorophyll-a fluorometer) **autonomous ocean glider** deployments and **Satellite Remote Sensing** to support the validation of ocean circulation models, (Aim 1);
- Continued monthly **biogeochemical sampling** (5 years of monthly sampling to Jan 2014) along the National Reference Transect (Port Hacking, near the Sydney Mooring array) for determination of phytoplankton and pigment diversity and concentration, zooplankton abundance and diversity, and suspended particulate matter to maintain one of three of the longest ocean time-series in Australia (Aims 1,4i);
- Use of the **biogeochemical sampling** and concentration of colour dissolved organic matter for bio-optical sensor validation to interpret **Satellite Remote Sensing** products that are cost-effective across large spatial scales (Aim 1ii) ;

- Measuring vertical transports of volume, heat and salt in the EAC and examining the EAC undercurrent and its contribution to heat and salt fluxes using the **EAC deep water array** (Aim 1iii);
- Collection of surface current velocities from **high frequency coastal radar** (WERA) off Coffs Harbour (30 ºS) (22 months of continuous operation) and **waverider buoys** for coastal current and wave climate studies, respectively (Aims 2i, 3i);
- Using **satellite remote sensing** and **waverider buoys**, along with atmospheric data, to identify the precursors to ECL's and aid prediction of these events (Aim 2ii)
- Continued deployment of **autonomous ocean gliders** (24 deployments with successful data acquisition) with bio-optical sensors to facilitate repeated transects along the NSW shelf to examine cross-shelf flows (Aim 2iii);
- Measuring surface and subsurface currents and density-driven flows on the continental shelf using **high frequency coastal radar**, **moorings** and **glider** data to support development of physical circulation and ecological connectivity models (Aims 3ii and 3iii);
- Using **satellite remote sensing** and sustained observations along a Melbourne to Brisbane ship transit using the **continuous plankton recorder** (CPR-SOOP) as well as bio-acoustic measurements to examine latitudinal variations in zooplankton and phytoplankton species composition (Aim 4i);
- Undertaking sustained observations of benthic habitats, especially kelp distributions using an **autonomous underwater vehicle** (AUV) to measure changes in deep water reef biota in response to predicted changes in the EAC (2010 and 2012 repeat surveys in marine parks)(Aim 4ii);
- Sustained observing of fish and shark migration using **shore-normal arrays of acoustic receivers** off Sydney and Coffs Harbour and a network of other receivers, in collaboration with our industry partners (>30 million detections) (Aim 4iii);

**The expected outputs from NSW-IMOS with respect to national IMOS priorities (Fig. 1):**

Providing a national backbone for observing boundary currents

- Continued development of ocean circulation models particularly over the continental shelf region, ranging from hindcasting, nowcasting and forecasting and including model improvement;
- Enhanced models of biophysical coupling through increased measurement of mechanistic parameters driving biological variability (e.g. light) and via mapping of biological parameters onto the physical variability of the EAC;
- Increasing the accuracy of spatially broad, synoptic satellite remote sensing products such as ocean colour, phytoplankton productivity, and particle concentration;

Continuing to build institutional strengths into national capability

- Training of multi-disciplinary post graduate students in quantitative ecology, oceanography , meteorology and geomorphology;
- Building IT and instrumentation skills and ocean mooring capability within SIMS and the NSW community;
- Communicating IMOS outputs to the community, and especially informing K-12 students and educators about the EAC.

- Building stronger relationships with state and local government agencies and private institutions to foster data sharing and investment toward common goals with regional-national significance.
- Contributing to a national reanalysis data base for coastal and offshore waters around Australia.

Exploring the potential for whole-of-system approaches

- Understanding of latitudinal, seasonal and annual patterns in plankton diversity off the continental shelf;
- Understanding of cross-shelf flows, deep water intrusions and the impact they have on diversity and abundance of lower trophic levels;
- Linking up-stream (Q-IMOS) and down-stream (Tas-IMOS) EAC observations to better understand oceanographic and biological impacts of changes in the EAC;
- Collecting biogeochemical sampling at the mooring locations on a seasonal basis;
- Improved predictions of fish landings based on rainfall and oceanographic variation.

Driving down the cost per observation

- Validating contemporary Satellite Remote Sensing derived estimates of chlorophyll-a, primary productivity, and particle concentration against direct IMOS observations;
- Operating the glider in successive deployments per trip, reducing manpower and travel costs;

Creating and developing the information infrastructure

- Parameterization of future ecosystem models and the evaluation of forecasting abilities through the collection of biological and geochemical data streams;
- Improved data products for assimilation into and verification of ocean, wave, climate and weather prediction models; explore development of biogeochemical and ecological models for the EAC and shelf as risk assessment tools for improved ecosystem management.

**Highly desirable observations for coming decade not presently funded:**

- A pair of cross-shelf moorings within the separation zone, off the Stockton Bight and reestablishment of the moorings in southern NSW waters with velocity capability (Batemans Bay Marine Park - Narooma);
- Long-range HF radar (CODAR or WERA) observations off Sydney for the EAC separation zone and eddy formation;
- Real-time telemetry for the Coffs, Sydney and Narooma moorings to be incorporated into real-time and forecasting models and delivered on-line in a public-friendly and relevant format;
- Augmentation of the Coffs and Narooma moorings with bio-optical sensors;
- Complement the glider program with cross-shelf transects of T, S and bio-optics with a REMUS AUV;
- pCO2 sensors to monitor ocean acidification along the Sydney mooring array, including the Port Hacking Naional Reference Station;
- In-situ sensor monitoring of dissolved nutrient concentrations at the National Reference Station and on other moorings;
- Development of high resolution remote sensing capability in optically-complex coastal and estuarine waters with locally derived algorithms;

- Repeat transects across the continental shelf into deep water with seagliders and investigation of the viability of continuous glider operations providing long-term monitoring data as an alternative to moorings;
- Addition of a turbulence probe to the Slocum gliders to identify and quantify mixing below the surface mixed layer over the continental shelf;
- Communicate key research outcomes to the community via mechanisms such as a Coastal Observing application for smart phones and tablets;

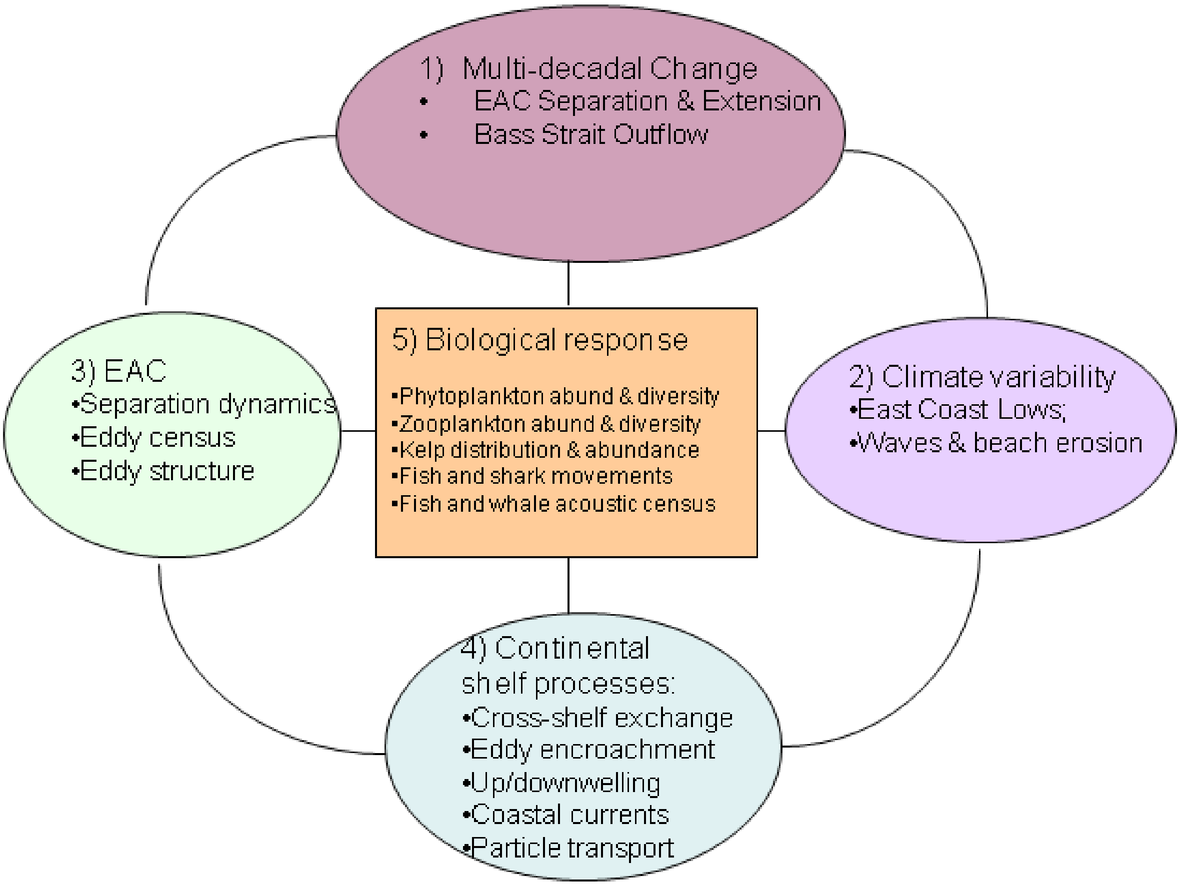

*Figure 1.1: Conceptual model of NSW-IMOS research themes in relation to national IMOS.*

*January 2014*

# 2 Socio-economic context

### Introduction

Most of Australia's urban population is located on the narrow eastern and southern seaboards (Fig. 2.1), making the associated coastal waters among the nation's most exploited and often stressed environments. More than 80% of Australians are located within 50 km of the coast and more than half the nation lives within the coastal fringe from Brisbane to Melbourne (Figure 2.1) (http://www.environment.gov.au/node/21641#coastalsettlement). The major problems for this coastline are urbanization, water quality, freshwater supply, severe storms and beach erosion.

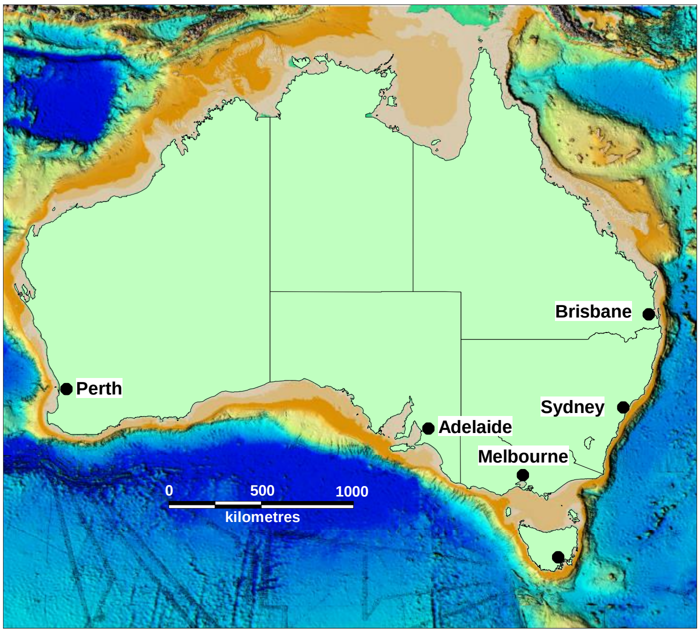

*Figure 2.1: Australia and its continental shelf in light brown (200 m isobath), illustrating the particularly narrow shelf and proximity of the EAC off New South Wales (Figure modified from GeoScience Australia).*

### Climate Change

Future climate change will have wide ranging effects on the coastal and marine environment of NSW. The East Australian Current (EAC) is predicted to both strengthen and warm significantly which will have many diverse effects from changing weather patterns to shifts in marine species distribution. Western boundary currents are among the most intense transport features in the ocean, delivering warm, nutrient-depleted water and tropical organisms to mid-latitude ecosystems. The intensification of such currents, including the EAC, under climate change suggests that productive continental shelves may be vulnerable to the risk of changed productivity and altered fisheries yields. An increase in storm frequency and intensity is also predicted and this will cause significant changes in rainfall patterns and the wave climate potentially resulting in greater beach erosion, storm surge and coastal inundation. Species range shifting as a response to these and other climate change effects will have impacts for biodiversity, invasive species and fisheries. The most dramatic changes are being observed on the Tasmanian coastline, with the demise of native kelp (*Macrocystis pyrifera*) due to the southern range extension by the sea urchin *Centrostephanus rogersii* (Ling *et al.* 2009). At present there are no published records of shifts in the distribution or abundance of the dominant kelp (*Ecklonia radiata*) in NSW due to climate change, although non-climate stresses (e.g. increased grazing, reduced water quality) are likely to already have had an effect on kelp abundance and will result in considerable interactions.

**Water**

The NSW coastal zone receives freshwater inputs from rivers and stormwater, as well as licensed municipal and industrial discharges. The coast receives <20 discharges from sewage outfalls directly with the largest discharges located offshore of Sydney. North Head, Bondi and Malabar deep-water outfalls discharge treated sewage with a combined volume of <1000 ML.d$^{-1}$ (Ingleton and Large 2004). An apparent increase in the frequency of phytoplankton blooms (red tides) were of intense concern especially in relation to Sydney's deep water sewage outfalls (Pritchard et al, 1996). The phenomenon was, however, linked to oceanographic events such as upwellings, that occur downstream of the EAC separation zone (Ajani *et al*. 2001; Dela-Cruz *et al.* 2003). Periods of declining rainfall have resulted in Sydney's storage being as low as 33% capacity (Sydney Catchment Authority Annual Report 2008-09 www.sca.nsw.gov.au). Other regional centres (e.g., Goulburn) have experienced even lower capacities resulting in closure of local business and temporary re-location of the state's Police Academy. In 2010, the desalination plant at Kurnell started operating to future-proof the water supply for Metropolitan Sydney delivering up to 250 ML d$^{-1}$ (www.smh.com.au/national/sydneys-desal-plant-switched-on-20100128-n13h.html).

**Storm events – East Coast Lows**

In recent years severe storm events generated by East Coast Lows (ECLs), have caused fatalities, severe flooding (e.g. Newcastle and northern NSW), erosion and hazards for shipping (e.g. the Pasha Bulker grounding in June 2007). The severe storms of 1973 and 1974 (Sygna storm) had extreme winds, causing large waves and significant coastal erosion (Speer and Leslie 2000). These storms led to the installation of 7 Waverider buoys along the coast of NSW. These buoys deliver real-time updates on wave heights and surface ocean temperature online for public access (www.mhl.nsw.gov.au). The storms of August 1986 were implicated in 6 deaths, and produced the worst flooding in Sydney for over a century (450 mm in 3 days), while the 5 ECL events in June 2007 caused nearly $1000 million in damage and were the cause of 10 deaths. ECLs also provide NSW with significant amounts of needed rainfall. Some 10-20% of coastal rainfall in NSW is attributed to ECLs and 66% of high inflow (days > 100 GL) for Sydney's catchments are attributed to ECLs. Most ECLs occur in winter and are associated with warm SST anomalies (Hopkins and Holland 1997). A range of research projects funded under the Eastern Seaboard Climate Change Initiative and Climate Change Adaptation Hub are examining threats of ECLs to coastal environments involving state government and research institutions.

### Waves and beaches

Prevailing sediment transport along the NSW coast is from south to north despite the prevailing EAC being in the opposite direction. Along-shore sediment transport occurs because of the dominant south-easterly incident direction of the wave climate. The role and rate of different transport paths, however, is virtually unknown. Changes in the wave climate such as an increase in wave height, change in the angle of incidence or increased frequency of high magnitude waves affect the energy at the beach zone and alter sediment transport. Given that the NSW coast has many substantial shoreline erosion hotspots, more monitoring data is essential to give insight into the role of offshore processes in nearshore beach form, sand volumes and configuration. The state government and SIMS are currently engaged in a collaboration monitoring storm event erosion on Sydney's northern beaches as part of the Climate Change Adaptation Hub program.

The state government (NSW OEH) recently completed the development of a nearshore wave model for use by local government to assess risks of their beaches to storm erosion. Developing an understanding of the nearshore wave climate is crucial but requires high resolution bathymetry across the entire coast. To date, a significant proportion of NSW's beaches and nearshore subtidal areas remain unmapped. A state-wide Bathymetry Strategy is currently under development by NSW OEH to provide not only hydrographic data but also hi-resolution information on seabed type across the marine estate. Remaining stocks of major sand deposits for construction are close to depletion around Sydney and the mining of offshore sand is again receiving consideration. In the absence of any comprehensive state-wide finescale sediment data, inner shelf seabed sediment monitoring, and with the significance of wave direction in determining nearshore bed formation, an improved understanding of the long-term dynamics across the shelf is critical.

### Marine Tourism

Our largest marine industry is marine tourism, the second largest of all states contributing 22% of the national marine industry ($27 billion in value added during 2002-03, The Allen Report 2004). The value of the marine industry (i.e. all recreational and light commercial vessels) in NSW has been valued at over $2 billion pa and employs over 11,000 – both figures are almost equivalent to all other states combined (mostly Victoria and Queensland, http://www.bia.org.au/data.html). Over a third of the national marine industry employment (36%) is in NSW – and mostly in marine tourism. Commercial tourism businesses operating in coastal NSW include beach equipment hire, boat hire, charter fishing, general charters, dive operators, marine mammal watching, ferry services, filming, photography, houseboat hire, jetski hire, kayaking, parasailing, surf schools. A large proportion of these activities occur in and around the state's marine parks. The state's bioregions support a wide range of sub-tropical to temperate species from corals to seals, turtles to fairy penguins, humpback and southern-right whales to great white sharks. Wildlife observation is a popular and growing activity along the NSW coast, with whale and dolphin watching representing a lucrative commercial activity. Nationally, whale and dolphin watching grew from 450,000 trips in 2010 to over 500,000 in 2013. In Port Stephens 250,000 passengers on dedicated dolphin watching trips generated $5 million in gross revenue in 2010 (Marine Parks Authority, 2010). There were over 11,500,000 trips to NSW beaches by Australian residents in 2013 with over 500,000 of these trips made to go surfing.

**Fishing**

Recreational fishing brings approximately $2.5 billion dollars to the Australian economy each year and engages some 3.4 million Australians (Skirtun *et al*. 2013). In NSW approximately 17% of the NSW population fish at least once a year. More recent statistics are to be published with an updated state-wide survey of recreational fishing due for completion in May 2014. Previous surveys indicate that recreational fishing effort has increased annually, sometimes up to 7.5% from the previous year (Gwynne 1994). This is especially important around Australia's largest and fastest-growing cities on the eastern seaboard, including NSW's capital, Sydney. In NSW the recreational catch has in the past constituted about 30% of the commercial catch, but for 6 major species the recreational catch is actually greater than the commercial. In NSW, funds from recreational fishing were used to buy out commercial fishing licenses in 25 estuaries in 2001 and these estuaries are now described as recreational fishing havens. Target species that are especially relevant to recreational fishing, tourism and IMOS are bream, flathead, mulloway, prawns, kingfish, dophinfish, Australian salmon, grey nurse shark, bullshark and white shark.

In 2011-12 gross commercial fisheries production for NSW reached $136 million per year (Fisheries Research and Development Corporation 2012). While school prawns made up the greatest proportion of the wild-fishery catch volumes, mullet, whiting, snapper, bream, kingfish and salmon also contributed significant commercial value. While production values were down 4%, value increased by 2% compared to the previous year (2010-11). Oysters (aquaculture), prawns and abalone are also key species in state aquaculture production.

Commercial fishing is not a large contributor to the economy across the Temperate East Marine Planning region (EMP Figure 2.2).Relative contributions of commercial fishing to the country's economy has remained relatively small (20-25% combined) for which NSW contributes only around 6% to the national value. The Australian Fisheries Management Authority (AFMA) manages a range of Commonwealth fisheries (http://www.afma.gov.au/fisheries/default.htm). Those of the greatest value include the East Coast Deepwater trawl fisheries, from NSW to Lord Howe Island (LHI; the Southern and Eastern Scalefish and Shark Fishery as Commonwealth Trawl as well as Gillnet, Hook and Trap Sectors; the Eastern Tuna and Billfish Fishery (ETBF) with over 100 permits, 72 vessels using pelagic long-line, minor line (handline, troll, rod and reel) (Skirtun *et al*. 2013). Temporal variation in phytoplankton due to upwelling, EAC strengthening and sea-surface warming (with an associated increase in ECL's), and their significance to fisheries have yet to be investigated. Changes in phytoplankton availability as a natural food source for in-situ aquaculture farming due to increasing sea-surface temperatures may also require investigation.

**Shark Attacks**

There have been 244 shark attacks in NSW waters since 1791, of which 68 were fatal, 121 had non-fatal injuries, and 55 instances where people were uninjured. In November-December 2013, two shark attacks occurred in NSW waters, one off Coffs Harbour (resulting in a fatality) and another off Port Macquarie. In February-March 2009, 3 separate shark attacks occurred in Sydney waters. These attacks in 2009 were the first attacks for nearly 50 years, despite observations of sharks in summers over this time. The presence of sharks in Sydney Harbour surprised the public and resulted in a decline in beach attendance. This period was distinguished by strong, wind-induced upwelling which reduced local water temperatures at the warmest time of the year from 25ºC to as low as 15ºC). Recent observations of juvenile white shark (*Carcharodon carcharias*) homing to surf beaches near Port Stephens (Barry Bruce pers. comm.), have renewed interest in shark movements in relation to the EAC.

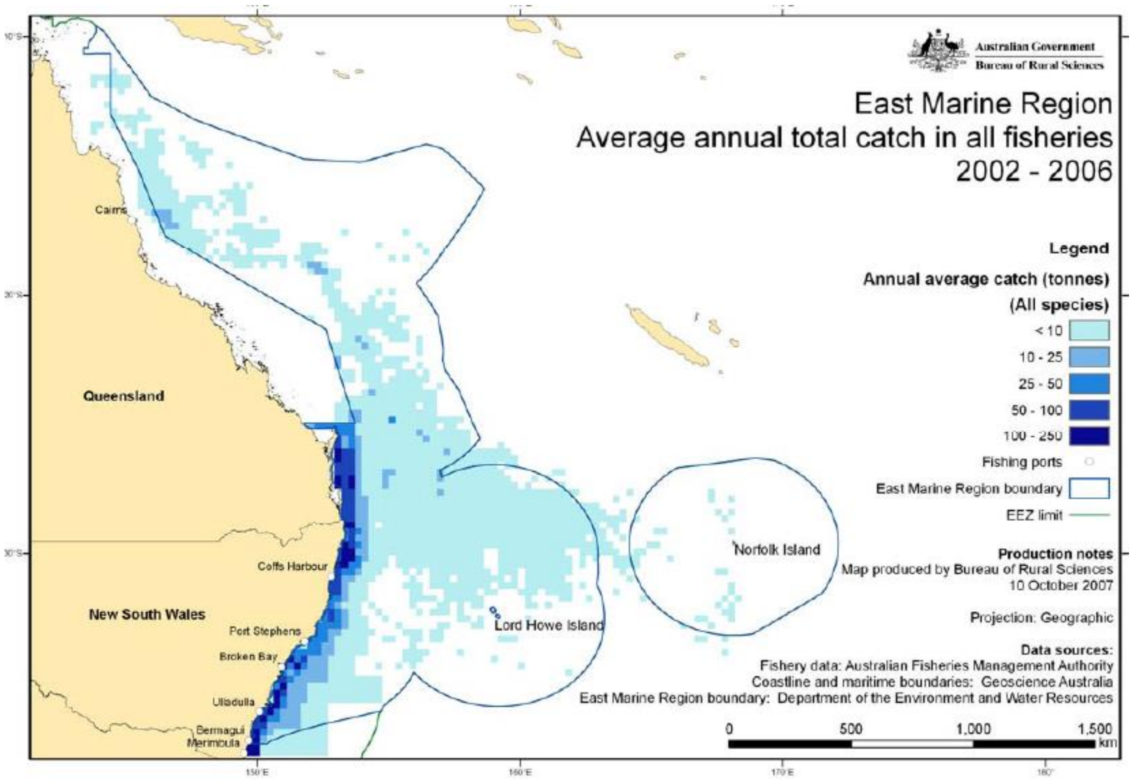

*Figure 2.2. The East Marine Planning region (excluding the GBR but including the Coral Sea and much of the Tasman Sea between the NSW coast to Lord Howe Island). The colours represent annual average tonnage 2002-2006 recorded by AFMA (i.e. Commonwealth fisheries beyond 3 nm). Note the distribution is largely restricted to the very narrow, continental shelf (after Moore et al. 2007).*

## Marine Estate

Marine protected areas for NSW are located at Cape Byron, Solitary Islands, Lord Howe Island, Jervis Bay, Port Stephens-Great Lakes and Bateman's Bay regions and cover a total area of ~3,500 km$^2$ of state waters (to 3 nm). The NSW Marine Parks Authority (MPA), now the Marine Estate Management Authority (MEMA) established and managed this system of multiple-use marine estates to conserve marine biodiversity, maintain ecological processes and provide for ecologically-sustainable use, public appreciation and education of the marine environment. An important factor requiring consideration during marine park zoning is the extent of connectivity among populations of key species, although it is recognised that this is a feature of marine populations about which we know relatively little. There are still considerable gaps in our understanding of how the key habitats along the NSW coast are connected by larval dispersal, whether existing marine park sanctuary zones act as larval sources, sinks or neither, and how these locations vary seasonally and inter-annually. It is clear, however, that the EAC is a major driver of the spatial and temporal patterns of connectivity (e.g. Ruello 1975; Roughan *et al*. 2011b; Coleman *et al.* 2011). Information on post-settlement connectivity is also essential to ensure that the location, size and configuration of sanctuary (‘no-take’) zones provide adequate protection to mobile species during different life-history stages (Curley *et al*. 2013; Ferguson *et al*. 2013). A state funded program using swath acoustic sonar and towed video to map generalised habitat distributions within the parks has covered some ~1200 km$^2$ of the seafloor within state waters since 2005 (Jordan *et al*., 2010). These data are providing essential baseline information on the extent, distribution and structure of seabed habitats required for effective marine resource management in NSW.

The establishment of the NSW Marine Estate Management Authority in early 2013 has changed the governance arrangements of marine parks, now marine estates, and new legislation and management arrangements are expected to be in place during 2014. At present, marine estates in NSW undergo an extensive review of zoning arrangements, approximately every five years, to provide a mechanism to incorporate information on population connectivity and recent scientific knowledge into the zoning review. To assist with adaptive management of these estates and their zoning a more thorough understanding of connectivity amongst areas is required. Knowledge of how economic and ecologically important benthic habitats (e.g. kelp forests) are influenced by the EAC and climate will aid in determining marine estate success in achieving its goal of conserving biodiversity. For example, evaluating the hypothesis that the decline of kelp may be less in MPAs due to an increase in the overall resilience of the ecosystems requires an effective understanding of the oceanography and benthic habitats, and the interactions between the physical and biotic drivers.

### Shipping

For 2005-2006, ports of the East Marine Planning region (mostly Newcastle, Sydney, Brisbane, Port Kembla) accounted for 42% of the nation’s exports and 51% of national imports by tonnage (Anon. 2007). These ports accounted for 18% of freight loaded and 67% unloaded by all Australian ports. The busiest sea lanes are through the Coral Sea.

### Marine Biotechnology

Bioprospecting – the use of naturally derived compounds for the development of drugs or other products – has a rich history (> 30% of current drugs come from natural sources), and has obvious socio-economic benefits. The complex oceanography in the NSW region associated with mixing of the EAC with coastal water and in the generation of eddies suggests a relatively diverse source of potential microbiological targets for use in medicine and other industries.

### Mining

There are currently no mining activities off NSW, but there is potential for sand mining, manganese nodule harvesting, or base/precious metals on the Lord Howe Rise. Sand mining has the greatest potential for NSW in light of beach erosion and construction needs. An Environmental Impact Statement (EIS) for sand mining off Sydney was conducted during 1990s.

**Defence**

One of the two major Royal Australian Navy (RAN) centres is based in Sydney-Garden Island, with additional bases at Jervis Bay (HMAS Creswell; HMAS Albatross). The RAN's primary need from IMOS is supporting data to improve operational ocean forecasts (BLUElink), especially wave and sonar impact forecasts.

**Summary**

In summary, the common socio-economic issues of relevance to NSW and IMOS are: the warming and strengthening of the EAC and implications for ocean productivity, severe storm (wind, wave and rainfall) events which lead to storm surge and beach erosion, marine park and marine estate planning, kelp distribution, threatened, endangered, or invasive species, shark attacks, marine tourism and fisheries.

# 3 Scientific Background, by Major Research Theme

## 3.1 Multi-decadal ocean change

Southeast Australian waters have experienced a multi-decadal warming over recent decades at a rate of between three and four times the global average (Holbrook and Bindoff 1997; Ridgway 2007) – the global average warming rate being about 0.5-0.6°C century$^{-1}$. The southeast Australian region is a global hot-spot for ocean temperature change. At the coastal station off Port Hacking, ocean water temperature has risen at a rate of 0.75°C century$^{-1}$ compared to 2.02°C century$^{-1}$ at Maria Island (Thompson *et al*. 2011). Holbrook and Bindoff (1997) calculated a depth-averaged warming to 100-m depth of 1.5°C century$^{-1}$ off Tasmania based on objectively mapped historical vertical temperature profiles over 34 years (1955-1988). More recently, using the Maria Island long term quasi-monthly monitoring station (1944-2002, almost 60-yr), Ridgway (2007) reports a SST warming rate of 2.3 ºC century$^{-1}$ and increasing salinity of 0.34 century$^{-1}$. Ridgway (2007) and others have noted the remarkable impact of the EAC's southward penetration off Tasmania. Recent work has shown that over the past 30 years the poleward transport of water within EAC eddies has increased significantly (especially from 2005 onwards, Cetina Heredia *et al* 2014). In addition while the EAC separation point has only moved ~60km poleward, the EAC is separating at the southern extent of its separation range more often (Cetina Heredia *et al* 2014).

The Tasman Sea region, and particularly the poleward extension of the EAC, is predicted to be strongly impacted by climate change (Matear *et al*. 2013; Cai *et al*. 2005). The EAC is predicted to increase in flow by 12% and the flow in the EAC extension to increase by 40% (Matear *et al*. 2013). The strengthening of the EAC is predicted to further warm Australian waters by 1-2 ºC by 2030 and 2-3 ºC by 2070s, particularly off Tasmania (Poloczanska *et al.* 2008). These changes are predicted to increase primary productivity by 10% (Matear *et al*. 2013). In a review, Murphy and Timbal (2007) investigated the relationship between rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) of continental southeastern Australia (SEA) and three SST indices (NINO4 – an equatorial Pacific index, Indian Ocean Index, IOI, representative of the eastern arm of the Indian Ocean Dipole, and an index of the Tasman Sea, TSI – mean of 150-160E, 30-40S). TSI was more strongly correlated with rainfall, Tmax and Tmin of SEA in autumn than either NINO4 or IOI, and was the best overall predictor of temperature throughout the year. It is clear that temperature dependent crops (i.e. frost sensitive) and those crops that depend on autumn rainfall are sensitive to the variability and potential changes in the Tasman Sea.

### 3.1.1 Science Questions

Within IMOS, estimates of multi-decadal ocean change are drawn from broad-scale, global, surface and subsurface observations of key parameters (temperature, salinity, and carbon), as well as monitoring fluxes of heat, mass, and salt for the East Australian Current and Tasman Outflow.

The following high-level science questions will guide the New South Wales Node observing strategy in this area:

***Ocean Heat Content:***

- How is the heat transport of the EAC changing, including the offshore recirculation and eddy transport south?
- How do the offshore heat transport changes of the EAC affect transport by the coastal currents?
- Can a distinct EAC undercurrent be detected? If so, what is its contribution to the heat transport and how does it vary?

***Global Ocean Circulation:***

- What are the mass and heat transports contributions of the Tasman Outflow?

***Global hydrological cycle:***

- How are NSW river outflows changing?What are the effects of these changes on salinity patterns?

***Global carbon budget:***

- What is the carbon inventory for the coastal waters off NSW and how is it changing on decadal timescales?
    - What are the key biological and physical processes involved in air-sea $CO_2$ exchange in the coastal waters off NSW and how sensitive are they to climate change?
    - How are $CO_2$ fluxes over the continental shelf off NSW evolving and how are the fluxes on the shelf related to the Tasman Sea and the EAC?

Many variables are needed to track the multi-decadal changes occurring in the currents, carbon budget, and energy balance off NSW and to monitor the rate of global change. Surface and subsurface temperatures, salinity, and velocity are required to monitor trends and variability in the EAC transport and associated heat fluxes. In addition, quantification of the eddy field requires sea surface height, and precipitation rates are needed for the hydrological cycle.

### 3.1.2 Notable gaps and future priorities

The NSW-IMOS node identified the following gaps and future priorities for Multi-decadal ocean change:

**Notable gaps:**

Due to ship availability there is a gap in the data from the deep water moorings monitoring the EAC. We strongly advise preventing any further gaps in this data set in the future. This is a key data set for the EAC transport and fluxes along with several other features, such as the EAC Undercurrent and internal waves. A sustained record of the EAC flow is critical for both multi-decadal change and for determining the variability of these currents and their transports. We also encourage deployment of Seagliders across the continental shelf out to the deep basin along the EAC mooring line to investigate the potential for their use in a sustained manner as an alternative to the line of moorings. Additionally, the cessation of the moorings off Bateman's Bay Marine Park (Narooma, 36$^{o}$S) will impact our understanding of the along-coast flow and processes, as well as biological linkages with the AATAMS array. Glider endurance lines may also prove useful in this region, well downstream from the EAC eddy field. Data delivery from passive acoustic moorings has been problematic and an information gap remains with respect to the higher trophic levels. Glider deployments were planned to occur seasonally with 3-4 Slocum glider deployments off the NSW coast per year. Although there have been 3-4 Slocum glider deployments per year, they have not been evenly distributed through the seasons on any given year and often within a year, the deployments have been bunched together within several months.  This situation needs to be addressed to achieve better short and long-term temporal understanding of the NSW shelf processes.

**Future priorities:**

To assess multi-decadal change, one needs data spanning multiple decades. Thus, the priority is to maintain the present data set and if resources allow, addressing the gaps above.

## 3.2 Climate variability and weather extremes

### 3.2.1 Interannual Climate Variability

#### *3.2.1.1 El Niño –Southern Oscillation (ENSO)*

The EAC transport varies with the El Niño-La Niña oscillations (Holbrook *et al*. 2011). However, the link between EAC transport and ENSO is much weaker for the waters off eastern Australia than for western Australia. The changes in EAC transport affect the temperature, salinity, nutrient concentrations, and the distribution of biological species.

#### *3.2.1.2 Southern Annular Mode (SAM)*

The increases in the transport of the EAC and EAC extension are believed to be due to changes in the wind forcing. This wind forcing is also linked to SAM. Consequently, changes in SAM will coincide with changes in the EAC; however, it has not yet been determined if SAM is one of the primary driving factors for EAC transport.

### 3.2.2 Intra-seasonal variability and severe weather

#### *3.2.2.1 East Coast Lows (ECL's)*

East Coast Lows (ECL's) are extreme low-pressure cells, which occur off the southeastern coast of Australia. They are believed to originate under various conditions, including in a low pressure trough under certain upper atmospheric conditions, in the wake of a cold front moving into the Tasman Sea, or the decay of a summer cyclone. The ECL's develop quickly, sometimes overnight, and are associated with gales and heavy rains. They occur throughout the year, but are more common in autumn and winter, particularly June (http://www.bom.gov.au/nsw/sevwx/facts/ecl.shtml) .

### 3.2.3 Modes of variability in a changing climate

The waters off Eastern Australia are one of the most rapidly changing regions of the global ocean, primarily as a result of the increasing transport in the EAC and the EAC extension (Holbrook *et al.* 2011). On top of this trend are the influences of the climate variability factors mentioned earlier in this section.

### 3.2.4 Science Questions

Three major, coupled ocean-atmospheric climate modes address most of the seasonal variability of Australia's climate: El Niño/Southern Oscillation (ENSO), Southern Annular Mode (SAM), and the Indian Ocean Dipole (IOD). These weather conditions strongly influence Australia's weather, including the East Coast Lows, with the first two having significant impact on NSW.

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

***Interannual:***

- How do ENSO and SAM affect the EAC and the coastal waters off NSW and how will the predicted changes in the frequency and strength of ENSO events and SAM impact NSW?

***Intraseasonal:***

- How are the development of East Coast Lows and severe winter storms on the eastern seaboard of Australia relate to ocean variability (such as SST patterns - including eddies)?
- How do East Coast Lows and severe winter storm events effect nearshore, intertidal and beach topography, wave dynamics, storm surge and coastal inundation? How do wind and wave field data (radar) combine with wave models to better resolve small spatial scale variability for coastal hazard risk assessment?

To characterize the climate variability and the weather extremes, a suite of variables are needed, including temperature, salinity, velocities, sea surface height, air-sea fluxes, and gases (dissolved oxygen and $pCO_2$.

### 3.2.5 Notable gaps and future priorities

The NSW-IMOS node identified the following gaps and future priorities for climate variability and weather extremes:

**Notable gaps:**
The gaps here are the same as noted in the multi-decadal ocean change section.

**Future priorities:**
The priorities here are the same as noted in the multi-decadal ocean change section. We also suggest enhancing existing systems to increase spatial and temporal coverage, if it can be done efficiently and economically.

For example, an increase in spatial coverage could be attained though “back-to-back” glider deployments along the NSW coast. Stage one of deployment could start in Yamba, with the glider being retrieved off Forster or Port Macquarie, where the batteries could be replaced, or better yet, with the purchase of rechargeable batteries, all that would be required is a quick re-charge (alleviating ballasting issues that arise from opening the housing). Stage two of deployment could involve redeployment at Forster/Port Macquarie with pick up of the glider north off Newcastle or Sydney.  This would double the amount of data collected with little extra cost.

## 3.3 Major boundary currents and inter-basin flows

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

The East Australian Current (EAC) is the major western boundary current of the South Pacific Gyre, flowing from the southern Coral Sea and along the northern NSW coast (Ridgway and Dunn 2003). The EAC is Australia's largest current and is typically 30 km wide, 200 m deep and travelling up to 4 knots (2 $ms^{-1}$), with a variable annual transport estimated as 20-30 Sv (Mata *et al.* 2000; Ridgway and Dunn 2003) (1 Sverdrup (Sv), = $10^6$ $m^3$ $s^{-1}$). For comparison, the EAC has ~5 fold greater volume transport than the seasonally flowing Leeuwin Current on the west coast. The core of the EAC is centred over the continental slope, although its coastal presence is felt through eddy encroachment over the shelf.

Source water for the EAC originates in the south Coral Sea. Derived from the South Equatorial Current, the source water has spent 1-2 years flowing across the Pacific (15ºS), resulting in a tropical and nutrient poor water mass. The sea level elevation in this warm pool may be up to a metre higher than the surrounding sea (the steric height). Ridgway and Dunn (2003) describe 4 stages to the EAC flowing along Australia's east coast; 1) the formation in the south Coral Sea (15-24ºS); 2) the intensification of the current off northern NSW (22-35ºS); 3) the separation stage from the coast (31-32ºS); and then 4) evolving into eddies and coastal fingers off southern NSW, eastern Victoria and to Tasmania (38ºS). The portion that continues south past the separation is referred to as the EAC Extension. Recent work has shown that over the past 30 years the poleward transport of water within EAC eddies has increased significantly (especially from 2005 onwards, Cetina Heredia *et al* 2014). In addition while the EAC separation point has only moved ~60km poleward, the EAC is separating at the southern extent of its separation range more often. The EAC also transports tropical reef fish well outside their normal range, almost 6º of latitude further south (Booth *et al.* 2007; Figueira and Booth 2010). EAC flow is also disturbed by seamounts, headlands and islands and has great potential to structure plankton and influence larval transport.

During intensification the current deepens and accelerates, especially off Smoky Cape (31ºS) where the shelf is its narrowest (~15 km). Thereafter, most of the current separates from the coast, forming the Tasman Front, which trends eastward towards Lord Howe Island and NZ, leaving behind a coastal southward flow and a series of large warm core and cold core eddies. The Tasman Front is the middle of 3 eastward branches of the EAC, bounded by the weak North Tasman Current and the sub-tropical convergence (Wilkin and Zhang 2007). The meanders of the Tasman Front typically occur in specific locations and seem related to the bottom topography (references in Ridgway and Dunn 2003). The EAC goes on to form the East Auckland Current. The separated EAC and Tasman Front are source regions for southwest Pacific subtropical mode water (Holbrook and Maharaj 2008).

It is useful to have a proxy for the strength of the major currents. For example, the strength of the Leeuwin Current has been found to be related to the sea level in Freemantle. Unfortunately, there is no such proxy for the poleward flow of the EAC, although results reported by Holbrook (2010) and Holbrook *et al*. (2011) suggest that the Fort Denison sea level record may be useful in this regard. The Maria Island record clearly shows the southward penetration of isotherms is occurring. BLUElink (Australia's ocean forecasting system) and the data supporting it, is our primary tool. Although

BLUElink is still limited at 10 $km^2$ resolution, and has limited accuracy limited over the narrow continental shelf where most of the sailing and fisheries occur. Efforts are underway to improve these predictions, particularly in the coastal regions. Reanalysis (BRAN) provides useful input at the boundary of higher resolution models that are designed for continental shelves. Ocean forecasts may under-represent cyclonic cold core eddies, and the Tasman Sea shows persistent deviation between observations and forecasts. Studies have been made of large anticyclonic eddies (>100 km diameter), but we have no understanding or index of smaller scale features (<50 km diameter). Our knowledge of processes at the shelf break (200 m isobath) is very limited; we have no knowledge of the EAC Undercurrent noted by George Cresswell. This is a serious shortcoming, since the Leeuwin Undercurrent is important in forming counter-rotating eddies and the EAC Undercurrent may also be forming eddies, but presently we have no knowledge about this. By comparison to the knowledge of the behaviour and variability of other western boundary currents such as the Gulf Stream and Kuroshio there has been remarkable lack of investigation into the EAC and its eddy field, for a current renowned for its mesoscale variability.

### 3.3.2 Eddy Processes in boundary currents.

Off NSW, the mesoscale (100's km) variability is so large that very often a single continuous current is indistinguishable. This large variability distinguishes it from other western boundary currents (Godfrey *et al.* 1980b; Wilkin and Zhang 2007) and is a result of the separation from the coast and the formation of eddies. The separation has been ascribed to various sources: wind stress, coastal geometry (i.e. the westward retraction of the coast), bottom topography, or the interruption of the basin circulation by NZ (Ridgway and Dunn 2003). The current is generally known to separate anywhere between 29 and 32$^o$S, however recent work (Heredia *et al.* 2014) studying a 30 year ocean reanalysis product shows a bi-modal separation pattern with a distinct preference for separation either at 29$^o$S or 31-32$^o$S. After separation the EAC retroflects northward and can feed back into itself, as an anticyclonic eddy. Further separations and retroflections are evident along the NSW coast around 34 and 37ºS (Ridgway and Dunn 2003), although far less common. While the EAC exhibits a seasonal cycle upstream of the separation point, downstream of the separation point the velocities are dominated by the eddy shedding period. The eddies are formed at 90 to 180 d intervals and are driven in part by intrinsic instabilities (Marchesiello and Middleton 2000; Bowen *et al.* 2005). The anticyclonic eddies transport considerable amounts of heat into the Tasman Sea, or may turn northeast and coalesce back into the main current. Additionally, at the continental shelf break off Sydney, up to 50% of the current variability is driven by coastally trapped waves that propagate from the Great Australian Bight (Woodham *et al*., 2013; Middleton and Bye, 2007), while the seasonal and eddy signal account for less than 10% of the variability (Wood 2014).

### 3.3.3 Science questions

The primary inter-basin flow for this region is the Tasman Outflow, where the EAC penetrates into the Southern Ocean (van Sebille *et al.* 2012).

The following high-level science questions will guide the New South Wales Node observing strategy in this area:

***Fluxes:***

- How do the mass, heat, and salt transports of the EAC and the coastal currents off NSW vary on seasonal, interannual, and multi-decadal timescale?
- How does the EAC feed back into the climate system?
- What are the temporal variations in the advective and air-sea components of the EAC heat flux contributions?
- Can an index for the strengthening of the EAC be developed for use in correlating different parameters?
- How do air-sea interactions with EAC warm core eddies influence the strength and path of East Coast Lows?

***Drivers:***

- What is the cause of variations in current strength?
- What forcing mechanisms drive the seasonal cycles of the EAC?
- What is the relationship between boundary currents off NSW and modes of climate variability and change?

***Dynamics:***

- What processes govern the EAC?
- What processes govern the formation and propagation of eddies by the EAC? How do these processes vary temporally, and how are they related to the mean EAC flow?
- What processes govern the separation of the EAC?

Monitoring the fluxes, drivers, and dynamics of the EAC and the Tasman Outflow requires the standard suite of physical variables: surface and subsurface temperature, salinity, velocity, sea surface height and wind velocity. As before, internal waves and tides will be characterized using the subsurface temperatures and/or velocities.

**NSW-IMOS observations aim to:**

1) **To contribute to national observations of decadal changes and climate variability of the EAC using common platforms and metrics**.
    i) To determine the variability in EAC strength from its source in the Coral Sea, the seasonal and spatial variability in the separation of the EAC from central NSW, and the EAC's southward extension;
    ii) Contribute to the national backbone through the National Reference Station network and the supplementation of Satellite Remote Sensing products with local data.
    iii) To identify and quantify the elusive EAC undercurrent and its contributions to heat and salt fluxes

2) **To investigate the EAC, its separation from the coast, and the resultant eddy field along the coast of SE Australia**.
    i) To determine the frequency, form and function (horizontal and vertical) of EAC eddies;
    ii) To understand air sea interactions, particularly to determine the development of East Coast Lows and severe winter storms in relation to warm core eddies;

iii) Quantify the impact of key physical processes such as onshore encroachment of the EAC, slope water intrusions, upwelling, downwelling, internal waves, and interaction of the current with topography.

### 3.3.4 Notable gaps and future priorities

The NSW-IMOS node identified the following gaps and future priorities for major boundary currents and inter-basin flows:

**Notable gaps:**

The gaps here are essentially the same as noted in the multi-decadal ocean change section, with the exception of ocean gliders. Due to difficulties with the Seaglider communications, Seaglider operations have been sporadic. Furthermore, persistent large eddies off southern NSW have made Seaglider retrievals difficult.

**Future priorities:**

The priorities here are the same as noted in the multi-decadal ocean change section except for Seagliders that would allow resolution of vertical (subsurface) processes in locations inappropriate for Argo floats (e.g., continental slope). It would be useful to again have Seaglider operations off NSW. It is proposed to use seagliders across the EAC transport array where the current is most coherent. Another alternative is to use seagliders in the southern portion of the domain where there are presently no observations. This region is significant as warming is occurring at a rapid rate.

## 3.4 Continental Shelf and Coastal Processes

In the last decade, there have been a number of studies undertaken on the dynamics of coastal ocean processes off the coast of south-eastern Australia. Much work has focused on measurement and modelling of regional and coastal circulation together with the hydrological structure. Objectives have included understanding of the forcing effects (by the EAC and wind) on the response of the continental shelf waters at the surface, mid-water column, and bottom boundary layer regions. Presently, there are two primary simulation efforts for the region, both using the Regional Ocean Modelling System (ROMS). One of these efforts (SEAROMS) focuses on simulating the EAC, it's eddy field and upwelling processes (e.g., Macdonald *et al*. 2013a, 2014, Everett et al 2014). The simulations are complemented by extensive observational studies focused on slope water intrusion dynamics on the continental shelf. The current and hydrographic structures are complex and knowledge of these upwelling processes is essential for understanding the regional physical oceanography, future physical model developments and as supporting knowledge for other marine disciplines and atmospheric studies. This modelling effort has recently been funded to assimilate observations into the simulations. The other modelling effort investigates tides, internal tides, and internal waves and their effects on currents, hydrography, cross-shelf transports, and mixing in the region using the *ROMS modelling suite. It showed good agreement to the existing IMOS moorings when compared to observations (Hartlipp and Robertson 2014) and includes geostrophic currents, such as the EAC along with the eddies they spawn.

### 3.4.1 Boundary current eddy –shelf interactions

Cyclonic (clockwise, cold-core) coastal eddies and the smaller billows are often generated as the EAC meanders and separates from the coast anywhere from 29-33$^{o}$S. These eddies occasionally entrain coastal water from the enriched separation area in the vicinity of Port Stephens and the Stockton Bight (e.g Everett et al 2014, Macdonald et al 2014). Such eddies and billows are reported to hold the key to survival and recruitment of fish larvae in the Kuroshio system (Kasai *et al.* 2002). It is therefore thought that entrainment of coastal separation zone water into cold-core eddies and billows off NSW could provide an oceanographic index of fisheries yield. Despite their potential impacts, there is little data on the physical characteristics, frequency and other basic information regarding the EAC's cyclonic cold-core eddies. By comparison, the EAC's large anticyclonic warm core eddies are essentially a marine desert (Griffiths and Wadley 1986). Warm core eddies can induce upwelling at the perimeter (Tranter *et al*. 1986) as they interact with the continental shelf downstream of the separation zone (Schaeffer *et al*. 2013,2014) and entrain and advect waters poleward (Baird and Ridgway 2012). How these processes affect coastal processes, drive primary productivity and other ecological processes over the shelf are of major socio-economic significance for stakeholder communities along the eastern seaboard.

The Royal Australian Navy (RAN), which has designated exercise areas in the Tasman Sea, has a requirement to understand these mesoscale features, in order to assess the acoustic properties of the ocean for Anti-Submarine Warfare (ASW) applications (Jacobs *et al.*, 2009). Knowledge of currents is also used by the Navy for planning the most efficient vessel passages, and would be used in the event of Search and Rescue (SAR) activities. For this reason, the RAN is a participant in the BLUElink project, which uses IMOS data streams for data assimilation, and is engaged in NSW-IMOS through its research and development arm, the Defence Science and Technology Organisation (DSTO).

### 3.4.2 Upwelling and downwelling

Two primary mechanisms for upwelling occur off the NSW coast, wind-driven and current-driven, with a secondary mechanism associated with canyons. Off NSW, the current-driven upwelling by the EAC dominates the classic wind-driven upwelling with 70% of the upwelling current-driven (Oke and Middleton 2000; Schaffer *et al*. 2013; Matear *et al*., 2013). Rossi (2014) found that while the winds are generally downwelling favourable along this coast, up to 10 upwelling favourable days per month can occur in the spring-summer period. The EAC accelerates off northern NSW where the continental shelf off Smoky Cape (~31ºS) narrows in less than 0.5º latitude to just 16 km wide. This acceleration sporadically generates upwelling of cooler water, rich in nitrate and phosphate, particularly during the summer. These signatures can be identified in changes of Sea Surface Temperature (SST) and chlorophyll *a*, typically between 30-33ºS (Oke and Middleton 2000, 2001; Roughan and Middleton 2002, 2004; Roughan *et al.* 2003). Further upwelling is facilitated by the interaction of the EAC with the shelf edge upstream of the separation point, where Schaeffer et al 2013 found a direct relationship between the strength of the EAC and the cross shelf bottom temperature gradient. Other upwelling mechanisms include traditional wind driven upwelling (Rossi *et al*. 2013, Schaeffer et al 2013) and the interactions of eddies with the shelf (Schaeffer et al 2014), and the separation of the jet from the coast (Roughan and Middleton 2002, Schaeffer and Roughan submitted 2014), all of which can stimulate phytoplankton blooms and red tides.

The majority of visible blooms are of non-toxic species and act as nothing more than a nuisance or irritant to swimmers. Some marine and estuarine blooms, however, are of species that produce toxins and can be harmful to consumers of shellfish. The presence of toxins prompts an all-of-government response through Regional Algal Coordinating Committee's that issue public (press release) and industry warnings that enact a monitoring response until the threat has passed. Armbrecht *et al*. (2014a,b) showed that off Coffs Harbour, phytoplankton assemblages responded differently to different oceanographic drivers. The nutrient load delivered by these upwelling events outweighs that delivered by river discharge or sewage discharge (Pritchard *et al.* 2003) by an order of magnitude. Nevertheless, it is worth noting that both wind and current driven upwelling is sporadic (Rossi et al 2014), while sewage discharge is continuous and rich in the more biologically available forms of nitrogen (such as ammonium). Furthermore, the sewage plumes can be large, with estuarine plumes off Sydney (from the Hawkesbury River) sometimes extending up to half way across the continental shelf (15 km, Kingsford and Suthers 1994). Using stable isotope methods, more than 50% of N in a planktivorous fish was derived from a coastal outfall in Jervis Bay (Gaston *et al.* 2004).

Canyons have potential as conduits of nutrients from the deep ocean to the continental shelf. Canyons have been found to have much higher concentrations of benthic biomass than the surrounding continental slope and correspondingly higher abundance of fish stocks feeding on this biomass [De Leo *et al*. 2010]. These local circulations could serve as nurseries and have significant importance for genetic structuring of benthic invertebrates and other marine organisms (Banks *et al*. 2007).

Cresswell (1983) noted the presence of weak clockwise eddies in the embayments of northern NSW (e.g. between Smoky Cape and Korogoro Pt, Hat Head and Crescent Head; Crescent Head and Pt Plomer), which could isolate local fish communities or serve as a seed population for entrainment into frontal eddies.

### 3.4.3 Wave climate, including internal and coastally trapped waves.

Internal waves and tides are a significant source of mixing in the ocean and contribute to productivity (Wilson 2011; Stevens *et al*. 2012). Although internal tides and waves off NSW are smaller than those off the North West shelf of Australia, measureable internal tides and waves do occur in the coastal waters off eastern Australia. There is evidence of them both in global and regional tidal models (Hartlipp and Robertson, 2014; Egbert and Ray 2001; Holloway and Merrifield 1999) and IMOS observations from various sources, including moorings, ocean gliders, and SOOP XBT data (Bell 2013; Robertson and Bell 2014; Boettger and Robertson 2014). Internal tides interact non-linearly with currents, with both generating mixing (Robertson 2006, 2009) and impeding the current flow (Robertson 2005), and inducing cross-shelf transports of cold water (Robertson and Hartlipp, 2014a). Like upwelling, this will impact nutrient availability. Although the nutrient replenishment may be small in comparison to upwelling events, tidal pumping is a regular, event. In oligotrophic waters, such as that coming from the Coral Sea, internal waves have been found to contribute to the nutrient replenishment and primary productivity, particularly near topographic features (Stevens *et al*. 2012). Furthermore, both the chain of seamounts and the continental slope will experience diurnal critical latitude effects in this region. At the critical latitude, where the inertial frequency equals the tidal frequency, resonant effects become prominent, internal tidal effects are amplified, and even relatively flat slopes can generate internal tides (Baines 1986; Middleton and Denniss 1993; Robertson 2001). Wilson (2011) found that a nearly permanent bloom occurred in the North Pacific due to internal tides generated near Hawaii propagating north and experiencing critical latitude effects. A study of latitude effects on internal tides for conditions off the NSW coast using the Regional Ocean Model System (ROMS) indicated high mixing and significant energy transfers to higher frequency waves in the vicinity of the diurnal critical latitudes (28$^o$ and 30$^o$S) and 4$^o$ further south (Robertson and Kobashi 2014). The seamounts and canyons off NSW provide an excellent opportunity to investigate critical latitude effects on internal tides and mixing. Furthermore, internal waves generated off the southern portion of New Zealand impact the Australian coast off southern NSW and/or Tasmania (personal communication L. Rainville 2012). Internal tide and wave observations are necessary for model verification, evaluation, and initialization. An internal tide and wave climatology is being developed for the Royal Australian Navy (RAN) based on these simulations (Robertson and Hartlipp, 2014b). This information will be available to the RAN and Royal Australian Air Force (RAAF) to evaluate the effects of internal tides on sonar operations, which internal tides are well-known to impact. Furthermore, the mixing results are being used to improve the parameterization of vertical mixing in ROMS and other models.

Along with internal waves, coastally trapped waves (CTWs) propagate along the NSW coast (Hamon 1962, 1966; Freeland 1986; Maiwa *et al*. 2010; Woodham *et al*. 2013). It was thought that the CTWs originated off South Australia or in Bass Straight, but recently it was learned that they are often generated as far away as the North West Shelf by events such as tropical cyclones and they propagate around Australia following the coast and with the variance of the sea surface height amplitude correlated with the local continental shelf width (Woodham *et al*. 2013). These CTWs modulate the cross-shelf position of the EAC and interact with internal tides.

### 3.4.4 Science questions

The IMOS observing strategy for the continental shelf and coastal regions off NSW is to provide a background observing system with intensive observations in the vicinity of ports and harbours, such as Sydney. The key processes to be observed include boundary currents, their long-term (decadal) trends and variability, and the biological response.

The following high-level science questions will guide the New South Wales Node observing strategy in this area:

***Boundary Current/Shelf Interactions:***

- What are the influences of the boundary currents and the associated meso-scale and sub-meso-scale eddies and billows off NSW on the waters over the continental shelf and how do they impact cross shelf exchange and water properties?
- How does the EAC interact with the continental shelf/slope break and topographic features (such as canyons) generating wakes, Taylor columns, upwelling, internal waves, and mixing?

***Upwelling and Downwelling:***

- What are the frequency, magnitude, and drivers of upwelling/downwelling processes and slope water intrusions in the coastal waters off NSW and how do they influence cross shelf exchange of properties?
- How does the EAC moderate the strength, extent, and variability of upwelling?
- What is the role of canyons in upwelling by the EAC?
- What are the distribution, variability and drivers of dense shelf outflows?

***Shelf Currents:***

- What is the magnitude and variability (interannual, seasonal, and higher frequency) of shelf currents off NSW?
- What are they dynamical drivers of shelf currents off NSW and how do they interact with the EAC and assumed EAC undercurrent?

***Wave Processes:***

- What are the roles of internal and coastally trapped waves, including tides in continental shelf processes?
- What is the tidal regime and how does it influence shelf processes?
- What is the influence of coastally trapped waves on shelf circulations?
- What is the contribution of the various wave processes to mixing over the shelf and at the shelf edge?
- What is the contribution of internal tides and waves to on-shelf transport of nutrients and off-shelf transport of pollutants?
- What are the range and concentrations of pollutants entering our coastal zone from catchment sources and how do they pose a threat to shelf biodiversity?
- Quantify changes to beach topography and wave fields across different beach types before and after significant East Coast Low events?

To understand continental shelf and coastal processes, observations are needed for temperature, salinity, velocity at regional scales (metres to hundreds of m) and timescales from minutes to years.

**NSW-IMOS aims to:**

**To quantify oceanographic processes on the continental shelf and slope of SE Australia:**

i) Examine the coastal wind and wave climate in driving nearshore currents and the northward sediment transport;
ii) Understand the time and spatial scale response of phytoplankton to upwelling processes;
iii) Determine the transport and dispersal of passive particles (e.g. larvae, eggs, spores) and the degree of along coast connectivity and trophic linkages

### 3.4.5 Notable gaps and future priorities

The NSW-IMOS node identified the following gaps and future priorities for continental shelf and coastal processes:

**Notable gaps:**
As noted in the previous sections, one of the biggest gaps is the distribution of observations along the continental shelf. The cessation of the moorings off Bateman's Bay will impact our understanding of continental shelf processes in the southern part of our domain. Some of the spatial gaps are filled in by Slocum gliders, but they have been operated nearly exclusively off northern NSW, North of Forster. Furthermore, many NSW stakeholders (e.g., Office for Environment and Heritage and Department of Primary Industries) have a high priority in understanding near-shore processes (within 3 NM of the coast), and thus along and across shelf observations are of high value. Outreach in the form of development of data products relevant to the general public and industry are required to realise the value to tax payers. Furthermore, we have no turbulence measurements. Turbulence and mixing are associated with nutrient replenishment and many of the processes being studied.

Wind stress forcing is a critical driver of oceanographic processes. In the absence of over-ocean wind measurements, re-analysis products and over-land measurements are often used. Wood et al 2012 undertook an assessment of the various wind products available for off the coast of Sydney (at varied resolution) and showed that correlations were varied, with a minimum of 0.28. Off the coast of NSW the sole over ocean wind observation station came from the Sydney Water Ocean Reference Station which ceased real time operation in 2008 (Wood *et al* 2012). This is in stark contrast to the extensive network of more than 100 buoys around the US coastline with datasets extending over 30 years (Wood *et al* 2012), many of which feed into their wave and met forecasting systems. Presently there is little understanding of what resolution meteorological product is needed to accurately represent coastal (wind-driven processes). Particularly in the near shore (0-5km) range which has the greatest significance for coastal communities. Wood *et al* 2012 went on to show that re-analysis products were unable to resolve variability with periods shorter than 2 days, indicating that they are presently inappropriate proxies for coastal oceanic winds. Presently there are very few over ocean wind monitoring stations along the coast of eastern Australia. This means that our ability to monitor, model and forecast coastal winds is highly hampered (Wood et al 2012). Having real-time data transfer of coastal meteorological information would significantly improve our understanding of coastal wind fields and the variability, and could potentially aid in the better forecasting of severe weather events. Incorporating meteorological into any real time system as one of the key data streams is a method that would contribute significantly to the uptake of the data. This would also show the utility of the system that could potentially be rolled out into an operational system in the future.

Real time monitoring of environmental parameters such as water quality (fluorescence and turbidity) in addition to temperature and salinity is presently ongoing in a number of major estuaries in conjunction with local councils and catchment management authorities. The data are of interest to a range of organisations and stake holders, as varied as 'Sydney Ports Authority' and the Oyster Farmers of the Hawkesbury River, and yet there is no near-real time modelling system or operational forecast that ingests this data, partly due to the lack of offshore data. The aquaculture industry (oysters) uses the data to monitor for environmental parameters (e.g salinity/ temperature thresholds) that might trigger a disease outbreak. Similar examples were recently funded in the USA (NANOOS) in conjunction with the oyster aquaculture industry in Oregon.

Around the coast of the USA, a university based program at Scripps (UCSD) operates the coastal data information program (CDIP, cdip.ucsd.edu) which provides real time buoy observations of wave height, and period, sea surface temperature in addition to now-cast and forecast wave models and regional swell models. All this is packaged up in an easy to use app. The data is used by coastal engineers, planners and managers as well as scientists and mariners.

**Future priorities:**

As noted earlier, we would like to prevent further gaps in mooring data, and increase the number of glider operations. To fill in spatial gaps, we suggest operating Slocum gliders in successive deployments to get the most data for the least travel costs. Additionally we would like to operate Slocum gliders south of Sydney and Seagliders in a cross-shelf mode (away from the separation zone and not in eddies) to provide more information on the EAC in this region. The node would seek to increase the spatial coverage of acoustic curtains for detecting fish tags to better assess fish movements in and out of estuaries, as well as fish movements across the continental shelf. This would greatly improve our understanding of fish behaviours over smaller spatial scales especially key recreational and commercial species.

Transitioning some of the coastal moorings (particularly off Sydney) to real-time data acquisition mode would provide the capability for direct assimilation into forecasting models invaluable to government and industry. The real time aspect of the data would be taken up by the recreational and commercial fishing industries, aquaculture, shipping, and for emergency response. Real-time data delivery from Sydney moorings could combine with other IMOS data streams to derive early warning algal bloom models for Sydney Harbour or oyster growing areas, provide ocean beach temperature information to bathers, deliver current speed/direction and wave information to the state's Port Authority for managing ship navigation at entrances to Port Jackson and Port Botany. Information on the sub-surface temperature structure could provide insight into the potential presence/absence of target fish species for recreational fishers considering a day out at South Head's artificial reef.

Setting up new near shore moorings and/or coastal radar stations would address data needs in key areas of EAC influence over the shelf; i.e. Stockton Bight (radar at this location could also benefit Newcastle Ports and PSGL Marine Park). An expansion of sensor capability to include turbulence probes on Slocum gliders would help to determine estimates of mixing as they travel along the coast.

Seasonal/opportunistic biogeochemical sampling at other locations (i.e. Coffs, Narooma and Newcastle mooring array sites) would provide opportunities to validate satellite/remotely sensed products such as Chl-a and provide data for biogeochemical and ecological models. Such models would provide a means by which perceived threats to the coastal shelf environment can be risk assessed.

Further engagement with stakeholders in an effort to leverage additional funding and encourage co-investment is required for an expanded network of state-based observations that contribute to a nationally significant EAC story.

## 3.5 Ecosystem Responses

The Tasman Sea encompasses two basic water masses: the warm, northern Coral Sea waters which are biologically unproductive and the cooler, more productive, southern Tasman Sea waters (Baird *et al.* 2008) (Figure 3.1). Under this simplified view, warm-core eddies represent regions of pinched-off meanders of Coral Sea (EAC) water surrounded by Tasman Sea water. Any shift in Coral Sea waters southward, or in the characteristics of eddies produced by the EAC may impact biological productivity and alter the species of fish caught. This has implications for the state's economy in the value derived from southeast Australian fisheries (Hobday and Hartman 2006). Increases in water temperatures in the Tasman Sea have been shown to spur the growth rates of juvenile commercial fish such as redfish and jackass morwong. These species generally reside in the upper 250 m of the water column (Thresher *et al.* 2007). Conversely, juvenile growth rates of deeper water fish (orange roughy and oreos, >1000 m) actually decreased, which has been attributed to cooler temperatures.

Understanding connectivity patterns is crucial to unlocking the long-standing "black box" of dispersal in marine organisms**.** Connectivity has particular relevance to marine resource management because areas protected from fishing (e.g., marine protected areas) can be a source of larvae to replenish habitats over broad geographic scales. Furthermore, some species (e.g. king prawns) rely on the EAC for connectivity between spawning grounds in northern NSW and estuarine juvenile nursery habitats in southern NSW and Victoria. The benefits of marine parks to surrounding non-reserve areas are more difficult to measure and depend strongly on the proximity to other areas under protection (Gladstone 2007). Marine park design requires strategic choice of appropriate and sufficient habitat types and an understanding of biological connectivity with other nearby communities. The spacing of protected areas for optimal metapopulation performance (maximum benefits to population persistence across its whole geographic range) will depend on factors including the life histories of protected and exploited species and the dynamics of local oceanography (Botsford *et al.* 2003; Palumbi 2003; Lipcius *et al.* 2005; Roughan *et al.* 2005; Curley *et al*. 2013).

The east coast of Australia supports a broad range of species-rich and diverse habitats that transition from subtropical to temperate climatic zones. Understanding marine connectivity in this region is a challenge for managers. Knowledge of how habitats along the NSW coast are connected by larval dispersal, whether through existing marine park sanctuary zones acting as larval sources, sinks or neither, and how these locations vary seasonally and inter-annually (Roughan *et al*. 2011b) is unresolved. Some issues to be addressed include variation in reproductive timing, organism life histories, planktonic durations and larval behaviour (Curley *et al*. 2013).

SE Australia is a global hot-spot for ocean temperature anomalies (Hill *et al.* 2008; Thompson *et al.* 2009) and its marine ecosystems are expected to be strongly affected by global climate change. Predictions indicate a further strengthening (Cai *et al.* 2005) and southward migration (Ridgway 2007) of the EAC throughout the century. The net effect of these changes on the biological connectivity of coastal populations is a critical concern for coastal management. Circulation modelling from the Solitary Islands and the NSW coast will directly feed into the assessment and review of marine estate zoning (Roughan *et al.* 2005; Mace and Morgan 2006).

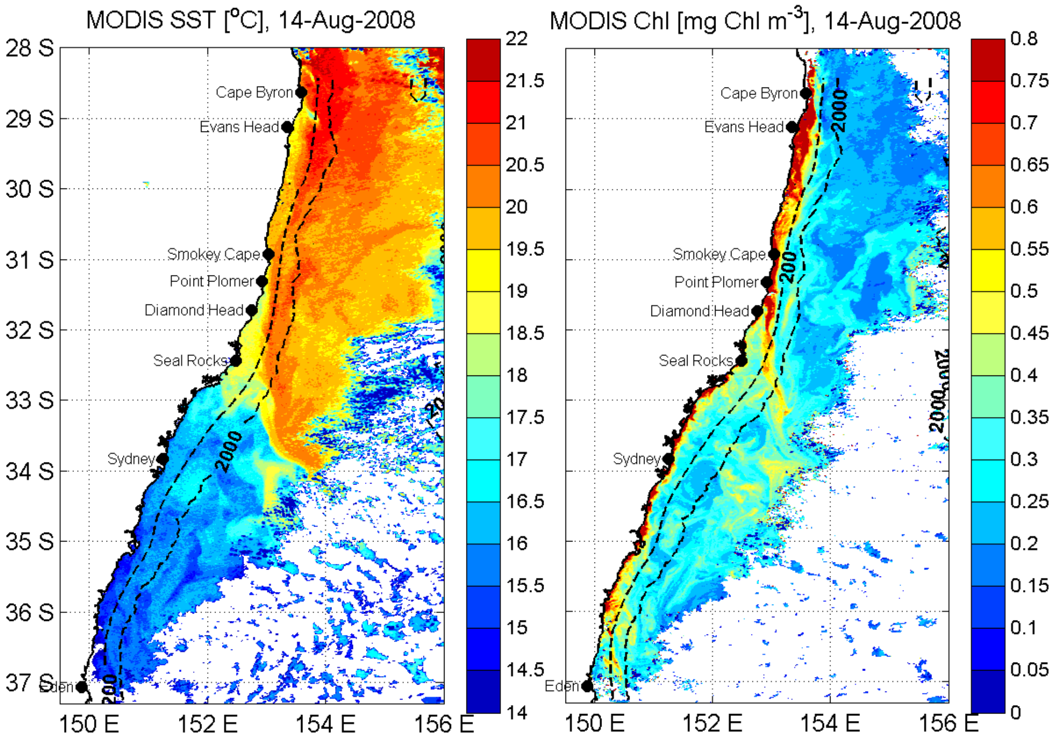

*Figure 3.2 Satellite image of sea surface temperature (left) and ocean colour (right) along the east coast of Australia. The separation of the EAC from the coast is shown clearly, as is the biological response represented by the ocean colour (Courtesy M. Baird).*

Interactions between climate and marine ecosystem processes are also created through dust deposition. Aeolian dust is enriched in iron which is often a key limiting nutrient in High Nutrient Low Chlorophyll (HNLC) waters. Dust transport may significantly reduce solar radiation to the ocean's surface, increase nitrogen and iron inputs, potentially leading to an increase in phytoplankton growth and $CO_2$ draw-down. Dust export from continent to ocean is expected to increase as the Australian continent becomes drier and more prone to bush fires (McGowan *et al.* 2000; Murphy and Timbal 2007). Dust from central Australia typically exits the continent over Victoria and across the Tasman, sometimes being deposited on NZ shores. A major dust storm covering large section of Australia's east coast was experienced on 22 September, 2009.

### 3.5.1 Ocean Chemistry – Nutrients

There are two broad nutrient limitation regimes in the contemporary ocean: iron limitation across ~30% of the ocean's surface area with high macronutrient concentrations, and nitrogen limitation across most of the oligotrophic low-latitude systems (Moore *et al*. 2013). Nutrient inventories around the Australian continent show generally low nitrate concentrations, particularly along the western and eastern coastlines (Figure3.2) which are both strongly influenced by poleward-flowing boundary currents, the Leeuwin Current and EAC, respectively. Western boundary currents such as the EAC advect warm, oligotrophic waters into temperate latitudes, displacing productive waters but also influencing phytoplankton growth through current-induced upwelling, mesoscale eddy intrusion and seasonal changes in strength (Everett *et al*. 2013). These physical processes affect the stocks of dissolved nutrients which provide some indication of the potential for primary production. As a result, macronutrient concentrations are included in the suite of IMOS biogeochemical measurements at the National Reference Stations (Lynch et al 2014), and have led to the detection of changing macronutrient ratios (increase in the N:Si due to declining Si concentration) at two locations on the east coast (Thompson *et al*. 2009).

### 3.5.2 Ocean Chemistry – Carbon and acidification

Since the beginning of the industrial revolution, human activities such as the burning of fossil fuels, industrialization, deforestation and intensive agricultural activities have raised atmospheric $CO_2$ concentrations (Gattuso and Lavigne 2009). As a consequence, surface seawater temperature has increased by 0.6°C over the last century (Houghton 2009). Moreover, an increase in atmospheric $CO_2$ concentration, from pre-industrial levels of 280 ppm to approximately 395 ppm 2013 (co2now.org), has led to ocean acidification by elevating the dissolved $CO_2$ concentration in the surface ocean, which lowers pH.

An increase in sea temperature and atmospheric $CO_2$ will influence the health and survivorship of marine organisms, especially calcifying species, such as molluscs, crustaceans, echinoderms (Dupont and Thorndyke 2009), corals (Reynaud *et al*. 2003; Jokiel *et al*. 2008), calcareous algae (Smith and Roth 1979; Jokiel *et al*. 2008), foraminifera (Hallock 2000) and some phytoplankton (Rost and Riebesell 2004; Raven *et al*. 2005; Iglesias-Rodriguez *et al*. 2008). As a result, accurate measurements of Dissolved Inorganic Carbon (DIC), pH and $pCO_2$ in key locations are necessary to understand potential impacts of changes in ocean chemistry.

### 3.5.3 Plankton

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has collected data at two stations offshore from Port Hacking (50 m and 100 m station) since the 1940's, one of Australia's longest ocean time-series data records. Studies at these stations have included variations in plankton pigments (Humphrey 1960, 1963; Hallegraeff, 1981), water quality parameters (Newell 1966) and their relationship with phytoplankton abundance (Grant and Kerr 1970; Grant 1971), and the seasonal succession of phytoplankton in relation to the hydrological environment (Jeffrey and Carpenter, 1974; Hallegraeff and Reid 1986, Pritchard *et al.* 2003; Ajani *et al*. 2001). The long-term variability of the oceanographic data at the Port Hacking stations has been summarised by Sydney Water (Water Board, 1988) and was discussed by Hahn *et al*. (1977), Hallegraeff (1993) and more recently by Thompson *et al*. (2009).

Hallegraeff (1993) suggested that nitrate and phosphate concentrations had increased at these stations between 1960 and 1990. Similarly, he noted that there has been an apparent increase in the frequency, strength and extent of visible algal blooms between 1984 and 1993, with only a handful reported prior to this time. Hallegraeff and Reid (1986) investigated phytoplankton species successions at the 100m station in relation to physicochemical factors and confirmed the species sequence found by previous investigations.

Ajani *et al.* (2001) continued investigations into Port Hacking 100m phytoplankton assemblages and their physicochemical environment during 1997-98. Phytoplankton blooms of similar frequency and magnitude seen in this study had been previously recorded. However, in contrast to earlier work, where a variety of taxa dominated throughout the year, the small diatom *Thalassiosira partheneia* generally dominated blooms throughout the 1997-98 sampling year. In addition, presence/absence data for the heterotrophic dinoflagellate, *Noctiluca scintillans*, indicated a higher frequency of occurrence for this species than previously documented.

Since 1998, CSIRO/DECCW have continued to monitor physicochemical parameters (temperature, salinity, dissolved nutrients, dissolved oxygen, and chl-*a*) and archive monthly phytoplankton net samples from the 100m station. There have been no studies in terms of phytoplankton composition and seasonal patterns since Ajani *et al.* (2001).However, research is currently underway to complete a decadal time-series (from 1998) record of phytoplankton occurrence at Port Hacking (P. Ajani, PhD Macquarie University) and assess impacts of climate variability on NSW microalgal coastal blooms over the last 20 years (Ajani *et al*. 2011). Thompson *et al.* (2009) showed from the data accumulated to date that the strengthening of the EAC and the variation between El Niño/La Niña events has impacted on the physical, chemical and biological properties of the Australian temperate water systems down to Maria Island, Tasmania. Increased strength and impact of the EAC, and declining silicate concentration levels have the potential to influence the relative abundance of diatoms to flagellates in the autumn bloom period.

Armbrecht *et al*. (2014a,b) have shown differences in phytoplankton assemblages under contrasting oceanographic conditions in the Solitary Islands Marine Park (Coffs Harbour) using IMOS time series data.

### 3.5.4 Mid Tropic Levels (Nekton)

The relationship between the EAC activity and fish movements and distribution is not well characterised for NSW. The EAC transports larval fish from the Great Barrier Reef to southern NSW (Booth *et al*. 2007). The strengthening EAC has shifted the Temperature-Salinity properties 350 km south (Figure 3.2), and therefore enhanced over-wintering survival of warm water fish (Figueira and Booth 2010). A recent report indicates a shift of 30 new, warm water species into Tasmanian coastal waters and a corresponding decline in 19 cold water species (Last *et al.* 2011). One ecosystem outcome for such shifts in Tasmania is evident in the demise of bull kelp and the rise in abundance of sea urchins from NSW (Ling *et al*. 2009). The ecological effects of warming NSW waters are unknown. Offshore, the Tasman Sea long-line fishery is now managed in real time by SST (Hobday and Hartmann 2006), which in turn is correlated with other water type characteristics (pelagic habitats), with long-term fluctuations in habitat area (Hobday *et al*. 2010; Hartog *et al.* 2011).

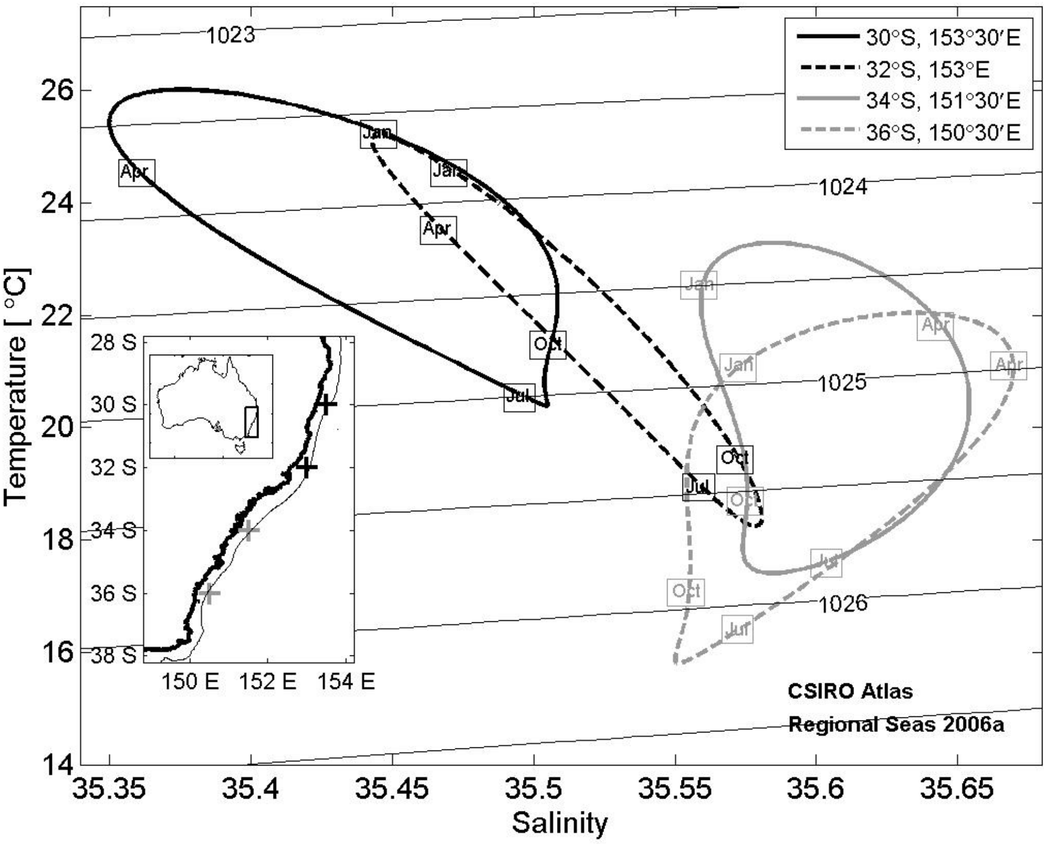

*Figure 3.2. Climatological temperature-salinity properties of the southeast Australian continental shelf, showing the annual cycle of surface T-S properties in the CSIRO Atlas of Regional Seas version 2006a for the points closest to the 200 m isobath at 30ºS, 32ºS, 34ºS, and 36ºS. Month labels are centred on the 15th of each month. The insert shows the location of the CARS sites along the southeast Australian seaboard with the 200 m isobath drawn as a thin line. Note the shift in seasonal cycle in T-S from above and below the separation zone (figure modified from Suthers et al. 2011).*

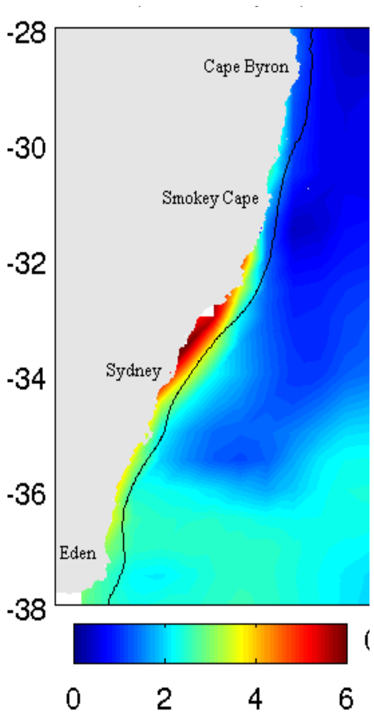

*Figure 3.3. The nitrate climatology for the region, for <200 m from the surface, derived from CARS (Suthers et al.2011). Scale bar in µM.*

### 3.5.5 Top Predators

Just as the relationship between the EAC activity and fish movements is not well characterised, the link between EAC and the distribution and behaviour of apex predators is even less well understood. Passive acoustic moorings deployed by IMOS have revealed the presence of a blue whale population that migrates along the eastern Australian coast, but significantly more data needs to be collected to investigate whale movements in relation to EAC variability. Juvenile great white shark are also known to aggregate in the surf zone in a nursery area that extends from Stockton Beach to Seal Rocks (W. Gladstone, pers. comm.), and aggregations of the Port Jackson Shark in the Jervis Bay Marine Park are also known to occur. The drivers of this behaviour are not well understood, but there is strong demand for information by the community who perceive increased risk of shark-human interactions.

### 3.5.6 Benthos

The EAC is a major factor influencing the distributions of benthic organisms. This warm water current is known to vary substantially among years in its strength and southward extension and is forecast to change further given climate change. This is of major concern for the long-term persistence of important ecosystem engineers such as corals, sponges and kelps, which are key habitat forming species, critical in supporting a much greater array of pelagic, epiphytic and benthic organisms. While corals are significant ecosystem engineers in areas such as Lord Howe Island and at offshore islands in the northern part of the state, they occupy relatively small percentage of the state's reefs. Cooler water coral species also occupy reefs further south. Sponges play a key role in deeper water, consisting of a large group of species and morphotypes. Much of the taxonomy of these organisms remains unknown. Kelps are by far the most abundant habitat type for the state. Kelps are characteristically a cool water species and any increase in water temperature (and associated decrease in nutrients) via strengthening of the EAC is likely to have a significant impact on distribution and abundance. Further, because kelps on our temperate reefs support extremely bio-diverse communities (e.g. Edgar 1983, 1984; Coleman *et al.* 2007, Ling 2008) and represent a key part of marine food chains, any changes in kelp abundance and distribution will have cascading effects on these ecosystems for NSW.

Recent observations from the east coast of Australia suggest that our most abundant and conspicuous habitat-forming kelp, *Ecklonia radiata* may already be shifting its distribution southwards in response to changes in SST and the more southerly intrusion of the EAC (Marzinelli *et. al.* in review). Further, there may also be changes in depth distribution with *Ecklonia radiata* restricted to depths greater than 20m in SE Queensland and greater depths at Norfolk Island where it was once abundant in shallower waters (Marzinelli *et. al.* in review). Observations indicate that kelp are afforded refugia at depth because stratification and cooler, nutrient rich water (upwelled from the shelf break) are able to sustain populations. Similar observations have been documented for the kelp, *Eisenia galapagenis* and their associated communities in the Galapagos (Graham *et al.* 2007). Despite the prediction of poleward contraction of kelp forests by most climate models, recent surveys in northern NSW afford no evidence of lower abundances of *Ecklonia* near its northern limit (Cardno Ecology Lab 2010).

Marine Protected areas may play an important role in the long-term persistence of kelp forests in NSW. Firstly, areas exposed to limited anthropogenic impacts are set aside (i.e. sanctuary zones) in an effort to limit synergistic stressor effects, . In these areas theeffects of climate change on kelp are expected to be  less severe. Second, marine protected areas may enhance the abundance of kelp forests as a result of the return of larger, predatory fishes to santuary areas,  through a decrease in the abundance & distribution of herbivorous sea urchins (e.g. NZ; Babcock *et al.* 1999, Shears and Babcock 2002). Given the importance of kelp forests for biodiversity and ecological processes on subtidal reefs, understanding how the EAC might be driving changes in kelp distribution will be of major significance for east coast states with implications for their fisheries, tourism and their economies.

There is also a broader national benefit focused on quantifying the effects of changes in the major boundary currents in the east (EAC) versus the west (Leeuwin Current) coasts. Such questions include;  whether the strength of biophysical coupling and rate of environmental change, (*E. radiata* and associated biota), is similar on reefs in the west and east; whether boundaries between  kelp and coral are changing; and if deep water refugia (as observed in other low latitude areas (Graham *et al.* 2007)) is similarly evident in the east and west.

### 3.5.7 Science questions

Australia's large ocean territory encompasses a diverse range of marine ecosystems.  IMOS is seeking to take an integrated approach, whereby measurements ranging from biogeochemistry through lower to higher trophic levels are undertaken across particular systems.

Ecosystem responses to variability and change also need to be considered at all levels of the food web (trophic levels), from primary producers to apex predators.  An integrated approach seeks to undertake biogeochemical measurements and combine them with biological data, across the base of the foodweb through to higher trophic levels, to provide information about ocean productivity, organism abundance at a number of spatial and temporal scales. Spatially these may encompass broad/basin-wide and bioregional scales, along shelf scales and regional-across shelf scale.

Marine primary production (PP) is a fundamental measure of the ocean's capacity to convert carbon dioxide to particulate organic carbon needed to fuel the marine foodweb, and sets the upper limit for ocean productivity. As such, PP is an essential property used in ecosystem and biogeochemical models to assess trophic dynamics and carbon cycling. Traditionally measured through tracer techniques (e.g., incorporation of 14C; Steeman-Nielsen 1952), measurements of carbon fixation are being superceded by use of active fluorometers which quantify photosynthetic rates, specifically the rate of electron transport through photosystem II (PSII), $ETR_{PSII}$ (Kolber et al. 1998; Oxborough et al. 2012). In principle, $ETR_{PSII}$ measurements can then be used to derive gross $O_2$ evolution or $CO_2$ uptake rates by applying a conversion factor that accounts for the various physiological pathways that can de-couple the ETR and $O_2$ evolution/$CO_2$ fixation from unity (Suggett *et al*. 2009; Lawrenz *et al.* 2013); these non-linear processes include alternate electron sinks such as nitrate reduction (see Suggett *et al*. 2011). While PP is not currently being measured within IMOS, it is anticipated that current and future research will yield improved satellite products of PP developed for the Australian region, and lead to a greater understanding of the principal drivers of PP in Australian waters. These drivers include parameters currently being measured by IMOS (e.g., dissolved nutrients, photosynthetically active radiation) that could be used to estimate PP.

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

***Productivity:***

- What are the key productive regions along the NSW coast and what are the drivers of this productivity? (latitudinal zones, EAC separation zone, frontal zones, shelf zones, mixed layer)
- How does the ocean pH and carbonate chemistry vary in key ecosystems, and how is it changing over the continental shelf off NSW?
- How do climate variability and change affect trophic levels and trophic connectivity?
- What are the effects of climate change on the structure and functioning (i.e., energy, nutrient cycling) of ecosystems and on the processes and phases of life cycles?
- Can we determine indices for assessing ecosystem health?
- What are the most vulnerable ecosystems and species (either particularly sensitive or unable to adapt, such as kelp, Sargassum, etc) to changing environmental factors?

***Distribution and Abundance:***

- What is the distribution and abundance of organisms by species/trophic/functional group level, and how does this vary in space and time?
- How do distributions and abundance of organisms relate to physical oceanography (temperature, circulation), nutrient availability, and population connectivity?

NSW-IMOS aims to:

**To integrate the ecosystem response with oceanographic processes:**

i) Quantify the daily to decadal variation of planktonic communities in relation to oceanographic and climate-driven changes in physical and chemical ocean properties;
ii) Quantify rocky reef biota variables (kelp distribution and abundance) associated with climate variability, at deep reefs along the NSW to Tasmanian coast;
iii) Relationship of the EAC, its eddies and oceanographic conditions on fisheries, and movements by fish.

### 3.5.8 Notable gaps and future priorities

The NSW-IMOS node identified the following gaps and future priorities for ecosystem responses:

**Notable gaps:**

Currently, there is a gap in AUV observations for reefs between Solitary Islands and Stradbroke Island (Qld) and south from Batemans Bay to Tasmania. While AATAMS has achieved significant spatial coverage across the EAC separation zone, continued collaboration and investment with State partners is required to improve our understanding of benthic components of marine ecosystems. Soft sediment habitats are not routinely monitored within the program. Due to operational issues a gap in sustained observing for the higher trophic levels still remains.

Decommissioning of the Batemans Bay moorings will cease downstream EAC observations and limit integration between environmental variables and reef communities. This will limit interpretation of animal tagging data gathered from the Narooma line.

While primary productivity is not currently being measured within IMOS, it is anticipated that current and future research will yield improved satellite products of PP developed for the Australian region, and lead to a greater understanding of the principal drivers of PP in Australian waters. These drivers include parameters currently being measured by IMOS (e.g., dissolved nutrients, photosynthetically active radiation) that could be used to estimate PP.

**Future priorities:**
It would be beneficial to expand capability with AUV to visit more sites and at more frequent time intervals to increase our understanding of the spatial and temporal variability within benthic communities influenced by the EAC. Although 1-2 EAC sites monitored long-term are likely to be afforded for a national perspective (i.e. NERP Biodiversity Hub program), exploration of smaller spatial and temporal scale processes are more locally focused and potentially funded through state agencies or other opportunistic sources. The data are critical as a measure of biodiversity outcomes across the south-east bioregion and for demonstrating the relative effectiveness of marine conservation planning efforts.

The node seeks to maintain AATAMS success and collaboration/co-investment with DPI. Presently, the deepwater receiver stations on the Coffs Harbour and Bondi curtains are being transitioned to lower-cost more effective curtains. We want to continue this effort, plus we support the deployment of short, supplementary curtains adjacent to existing curtains, to give directionality of movement along the coastal migration corridor. The node seeks to also reduce costs of deployment by seeking opportunities for co-deployment/retrieval where possible and appropriate. To reduce cost per observation and increase spatial and temporal coverage of biological observations, we advocate the co-collection of bio-optical and/or biogeochemical data where possible. These data would then be used to validate existing satellite products, as well as the development of improved products. Satellite products such as improved coastal algorithms for chl-a are essential for a range of stakeholders. State agencies require them for monitoring seasonal and inter-annual trends in algal blooms and ocean water quality while others could use them to examine primary productivity relative to fisheries production.

A BGC and ecological model for the EAC would be the ultimate aim. Ideally, a funded program similar to the GAB (SA) or eReefs (Qld) programs would be required to adequately address modelling the EAC system as a whole. There is a need to identify and fill the gaps for what data are required to drive these models.

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

IMOS data is being utilized by numerous groups in the NSW node for a wide range of research from physical, chemical, and biological oceanography, ecology, environmental science, and coastal engineering (Figure 5.1). The primary types of uses are fundamental oceanographic research, including comparison to or assimilation into ocean models, and investigating trends and variability of physical and ecological systems. Research focus is expected to change as databases expand and become useful in assessing long-term change and variability. New initiatives are currently expanding data usage to include model validation and verification as well as improving performance, forecasting and parameterization.

Present uses of IMOS data generally include research on climate change, climate variability, coastal management, defence maritime activities, environmental information, emergency response, biodiversity measures, fisheries and aquaculture. The research outputs include peer-reviewed publications, conference presentations, improvements in numerical models, and developing products such as climatologies and operational forecasts. The data is being used by research and government scientists, academics, post-doctoral fellows, post-graduate and undergraduate students and international collaborators.

Coastal mooring, HF radar and glider data are being used to investigate upwelling processes, eddies, and community connectivity. In current work pursued by post-docs and post-graduate students, data are being assimilated into ROMS to improve model performance for forecasting in the coastal environment. Model results could inform future sampling plans and determine radii of influence, which is important for connectivity studies. The research is critical for understanding ocean-shelf interactions as BLUElink forecasts underperform in the coastal zone (Woodham 2013). SOOP XBT, deepwater moorings, shelf mooring, and ocean gliders are currently utilized to investigate turbulence and the internal tide and wave fields off eastern Australia. Others are comparing observations to models of tides, internal tides, internal waves, and mixing. A broader goal is to determine climatologies of internal tides and waves for use by the RAN and RAAF in antisubmarine warfare. State and local governments are using the data to report on coastal ecosystem health, natural resource management and day-to-day operational decisions as well as providing advice to the general public, media and ministers across a broad-spectrum of marine and coastal issues.

Imagery and physical data from the AUV are being used to examine the distribution of benthic assemblages within areas of varying management controls (e.g. no-take sanctuary zones and general use zones), to examine changes associated with the marine estate zoning. The science and data are critical to underpin the decision making process and inform the highly emotive debate that ensues around marine conservation planning. The data is also providing essential information on the scales of spatial variability within rocky reef habitats which is required to test optimum survey design for on-going monitoring programs. It is also being used to relate benthic cover with fish assemblages in order to separate habitat effects from zone effects. These data is being used by post-doctoral fellowships, post-graduate and undergraduate students.

IMOS data is also being used in the education of future marine scientists with the direct application in a number of ACT and NSW university courses including *Ocean Waves and Modelling*; *Australian*

*Waters and Their Dynamics* (UNSW Canberra) and *Topics in Australian Marine Science* (SIMS, through UNSW, UTS, Macquarie and U SYD). Many of the results have been presented at conferences by students. This has included special sessions at the Australian Meteorological and Oceanographic Society (AMOS) conferences (2013, 2014) and the Australian Marine Science Association (AMSA) conferences (2011, 2012, 2013), such as “Insights from IMOS”.

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

| | Bluewater and Climate | WA | QLD | NSW | SA | TAS |
|---|---|---|---|---|---|---|
| Argo | P | s | s | P | s | s |
| SOOP | P | P | P | P | s | s |
| Deepwater moorings | P | s | s | P | | s |
| Ocean gliders | s | P | P | P | P | P |
| AUV | | P | P | P | | P |
| Shelf Moorings | P | P | P | P | P | P |
| Ocean Radar | | P | P | P | P | |
| Animal Tagging | P | P | P | P | P | P |
| Sensor networks | | | P | | | |
| SRS | P | P | P | P | P | P |
| eMII/AODN | P | P | P | P | P | P |

NSW-IMOS has over 140 members who are full time scientists, from more than 10 state and federal institutions. Between them, these members have more than 30 students from honours to post-graduate level who are using IMOS data.

**Impact and delivery through improving model output**

Results obtained from research questions examining: 1) decadal scale change and climate variability in the EAC (Research Question 1) and 2) the EAC separation zone and resulting eddy field off SE

Australia (Research Question 2) will support ocean, meteorological and climate numerical model simulations including hindcasts and forecasts from models such as BLUElink, SEAROMS, and the *ROMS internal tide/wave simulations. We have made it a node priority to provide as many of the data streams as possible in near real time such that these data can readily be ingested into forecasting models of the ocean and atmosphere. This is particularly necessary for the glider, moorings and HF radar data. The Tasman Sea region has typically been difficult to model due to the large variability in the mesoscale eddy field. RMS error in the BLUElink model is greatest off southeastern Australia where NSW-IMOS has deployed significant infrastructure (Woodham 2013). Furthermore large scale models do not perform well on the continental shelf region hence coastal observations (particularly from gliders, animal tagging, and HF radar) are essential. Furthermore, other data types including SOOP XBT data, satellite altimetry data, both deepwater and coastal mooring data, and glider data are being used to verify the primary transport/flow of the EAC and internal tide/wave simulations. The vertical profiles of bio-optical data available from glider deployments provide a newly available resource for assessment of ecosystem models that has not previously been available. This is an emerging and powerful method of ecosystem model assessment (Fujii *et al.* 2007). The meteorological measurements at the air-sea interface will contribute to numerical weather prediction models, which will have the benefit of improved early warning systems particularly during storm events and of benefit for all stakeholders. Data can also feed into a range of other model types to support operational functions of government and industry and of benefit to the general public.

**Ensuring the data are used**

The significant number of funded projects and publications combined with the large number of active node members (~140) demonstrates the value of IMOS data and how it is being used. In recent years, members of NSW-IMOS have been successful at receiving competitive ARC (n=27) or other grants that are built around IMOS data streams (Table 5.2). It is inherent in each of these proposals that IMOS data are taken up and used. The majority of the proposals have been funded for research commencing after 2012, highlighting the fact that the volume of research and associated output is expanding.

Shown below is a table summarising Australian Research Council discovery grants leveraged from IMOS infrastructure.

Projects with IMOS link

| Year | Institution | # of years | Total Project ('000) | Total Year ('000) |
|---|---|---|---|---|
| 2014 | UTS | 3 | 588 | |
| 2014 | WA | 3 | 185 | |
| 2014 | UNSW | 3 | 180 | 953 |
| 2013 | | | | 0 |
| 2012 | UNSW | 3 | 260 | |
| 2012 | UNSW | 3 | 170 | 430 |
| 2011 | Deakin | 3 | 190 | 190 |
| 2010 | UNSW | 4 | 500 | |
| 2010 | Syd | 5 | 798 | |
| 2010 | UWA | 3 | 430 | |

| | | | | |
|---|---|---|---|---|
| 2010 | UWA | 3 | 603 | |
| 2010 | Tas | 3 | 275 | 2606 |
| 2009 | UNSW | 5 | 695 | |
| 2009 | UNSW | 3 | 240 | |
| 2009 | Flind | 5 | 675 | |
| 2009 | WA | 3 | 460 | |
| 2009 | ANU | 4 | 670 | 2740 |
| 2008 | UNSW | 3 | 415 | |
| 2008 | UNSW | 5 | 617 | |
| 2008 | Syd | 3 | 270 | |
| 2008 | Syd | 3 | 134 | |
| 2008 | | 3 | 393 | |
| 2008 | Melb | 3 | 584 | |
| 2008 | Melb | 3 | 270 | |
| 2008 | QLD | 3 | 197 | |
| 2008 | QLD | 3 | 474 | |
| 2008 | Tas | 3 | 318 | |
| 2008 | | 3 | 313 | 3985 |
| | | TOTAL | | 10,904 |

Related Projects

| Year | Inst | # of years | Total Value ('000) | Total per year |
|---|---|---|---|---|
| 2014 | UNSW | 3 | 458 | |
| | UTS | 3 | 375 | |
| | WA | 3 | 467 | |
| | WA | 3 | 360 | |
| | Tas | 3 | 223 | 1883 |
| 2013 | Swin | 3 | 330 | |
| | Tas | 3 | 480 | |
| | Tas | 3 | 325 | |
| | ANU | 3 | 420 | 1555 |
| 2012 | UNSW | 3 | 360 | |
| | UTS | 3 | 320 | |
| | Grif | 3 | 300 | |
| | WA | 3 | 520 | |
| | ANU | 3 | 390 | 1890 |
| 2011 | AM | 3 | 285 | |
| | Syd | 3 | 378 | |
| | Syd | 3 | 255 | |
| | UTS | 3 | 400 | |
| | JCU | 3 | 225 | |
| | Flind | 3 | 225 | |
| | Tas | 2 | 140 | |
| | CSIRO | 5 | 560 | |
| | ANU | 3 | 250 | |
| | ANU | 3 | 280 | 2998 |
| 2010 | UNSW | 4 | 265 | |
| | UNSW | 5 | 580 | |
| | UTS | 3 | 290 | |

| | | | | |
|---|---|---|---|---|
| | Swin | 3 | 310 | |
| | Swin | 3 | 315 | |
| | Melb | 3 | 350 | |
| | Tas | 3 | 280 | |
| | ANU | 3 | 435 | 2825 |
| 2009 | UNSW | 3 | 380 | |
| | QLD | 3 | 420 | |
| | WA | 5 | 522 | |
| | ANU | 3 | 370 | 1692 |
| 2008 | UNSW | 3 | 250 | |
| | Melb | 3 | 235 | |
| | Grif | 3 | 268 | 753 |
| | | TOTAL | | 13,596 |

IMOS data streams are also of major significance to the operation of the state of NSW and its stakeholders. The NSW state government has committed $600K to salaries for NSW-IMOS (2013-2015) demonstrating significant state co-investment. IMOS data streams contribute to many aspects of state business from longer-term fisheries management, marine conservation planning, coastal primary productivity and ocean water quality monitoring as well as day-to-day operational support and decision making as well as providing expert advice to agencies, ministers and the general public. This value is not captured within a research output context.

*Table 5.2. Currently funded projects using NSW-IMOS data streams.*

| **Principle Investigators and Timeframe** | **Project Title** | **Funding Type** |
|---|---|---|
| Doblin, Murray, Matear and Hutchins (2014-2016) | Incorporating new knowledge of phytoplankton diversity and nutrient utilisation into an ocean-climate model to improve forecasts of ocean function | ARC Discovery |
| Roughan, Oke, and Powell (2014-2016) | Advancing dynamical understanding in the East Australian Current: Optimising the ocean observation and prediction effort | ARC Discovery |
| Roughan and Coleman (2010-2012) | Connectivity and Climate Change | Environmental Trust Grant |
| Robertson (2014) | Finding the shadows using the eyes of gliders | Defence Related Research Scheme UNSW |

| | | |
|---|---|---|
| Suthers (2012-2015) | Do coastal currents feed the harvest from purpose-built, offshore artificial reefs? | ARC Linkage; DPI |
| Hallegraeff (2012-2015) | Phytoplankton atlas of Australia | Univ. Tasmania |
| Suthers, Hunt, Pakmov, Taylor (2012-2014) | The krill pump off eastern Australia | ARC Discovery |
| Richardson (2012-2013) | The IMOS plankton ecosystem assessment report | CSIRO |
| Vezzulli (2012-2013) | Long-term changes in *Vibrio* bacteria | CSIRO |
| Swadling (2012) | Zooplankton atlas of Australia | Univ. Tasmania |
| Johnson, Holbrook, Barrett, Steinberg (2011-2014) | Effects of climate change on temperate benthic assemblages | ARC Super Science Fellowship |
| Babcock, Dunbabin, Barrett (2011-2014) | Image-based automated macrobenthic species | SIEF Fellowship |
| Henschke, Everett, Doblin, Pitt, Richardson, Suthers (2011-2014) | Demography and interannual variability of salp swarms | Commonwealth Government |
| Suthers, Lowry, Taylor, Roughan, Johnston, Gray | An offshore artificial reef | ARC Linkage |
| Harcourt (2011-2012) | Assessing the efficacy of small marine protected areas for conservation of eastern blue gropers | Seaworld Research and Rescue Foundation |
| Robertson (2011) | What's up with Nemo? Interaction of the EAC with tides and topography | UNSW Special Research Grant |
| Edgar, Stuart-Smith, Booth, Jordan, Ayre, Waters, O'Hara, Poore (2010-2015) | Biotic connectivity within the temperate Australian marine protected area network at three levels of biodiversity, communities, populations and genes. | ARC Linkage |
| Pizarro, Williams, Jakuba, Eustice, Whitcomb (2010-2014) | Cost effective autonomous systems for large scale monitoring of marine protected areas. | ARC Discovery |
| Taylor, Suthers (2010-2013) | Feeding and breeding: | UNSW |

| | | |
|---|---|---|
| Gray, Taylor (2010-2013) | Profiling the biology and fishery of rock blackfish | DPI |
| Williams, Pizarro, Jakuba (2010-2013) | Autonomous repeatable surveys for long term monitoring of marine habitats | ARC Linkage |
| Williams, Bryne, Figueria, Barnett (2010-2013) | Machine assisted, multi-scale spatial and temporal observation | ARC Linkage |
| Turner *et al.* (2010 – 2013) | Australian coastal observation network: monitoring and forecasting coastal erosion in a changing climate. | ARC Linkage |
| Taylor, Suthers, Booth, Gray (2010-2012) | Feeding and breeding: Rainfall effects on connectivity and fidelity of iconic coastal fishes. | ARC Linkage |
| Waite, Roughan, Pattiaratchi, Kotta, Orav-Kotta (2010-2012) | Ocean reef interactions as drivers of continental shelf productivity in a changing climate. | ARC Discovery |
| Hassler and Doblin *et al.* (2010-2012) | Novel technologies to resolve the role of organic matter on Fe chemistry and bioavailability in the South Pacific Ocean. | ARC Discovery |
| Steinberg *et al.* (2010-2012) | Stress, virulence and bacterial disease in temperate seaweeds: the rise of the microbes. | ARC Discovery |
| Bruce, Bradford (2010-2011) | Near-shore habitat use by juvenile white sharks | Tag for Life |
| Knott, Taylor (2010-2011) | Movements and habitat use of luderick within Jervis Bay | NSW Marine Parks |
| Suthers, Richardson, Swadling, Ralph, Taylor, Doblin, Virtue (2010) | A Laser Optical Plankton Counter for laboratory and in-situ size distributions of zooplankton, to assess the basis and outcomes of changing ecosystems | ARC LIEF |
| Ajani (2010) | Phytoplankton diversity in coastal waters of New South Wales, Australia. | Australian Biological Resources Study Capacity-Building Grant. |

| | | |
|---|---|---|
| Ajani (2010) | Phytoplankton patterns in the coastal waters of New South Wales, Australia for the period 2010-2013. | NSW Food Authority. |
| Williams, Byrne, Figueira  Barrett (2010) | Machine assisted- Multi-scale Spatial and Temporal Observation and Modeling of Marine Benthic Habitats. | Super Science Fellowship U.Syd, UTas |
| Gales, Nicol, Hindell, Harcourt (2010) | Pelagic ecosystem linkages in a changing Southern Ocean | Super Science Fellowship |
| Johnson, Barrett, Steinberg, Babcock (2010) | East Coast Kelp Habitat Mapping | Super Science Fellowship 2010 |
| Johnson, Holbrook, Barrett, Steinberg (2010) | Effects of climate change on temperate benthic assemblages on the continental shelf in eastern Australia | Super Science Fellowship UTas, UNSW |
| Schaeffer (2011-15) | Cross-shelf processes in the EAC regime | UNSW |
| Heron, Banner, Wyatt (2009-2012) | Wave climate in the Southern Great Barrier Reef. | ARC Linkage |
| Stewart (2009-2012) | Assessment of barotruma on offshore species in NSW | II-NSW |
| Suthers and Oke (2009-2011) | Coastal cold core eddies of the East Australian Current and their fisheries potential. | ARC Discovery |
| MacDonald, Huveneers, Harcourt (2009-2011) | Assessing the adequacy and effectiveness of eastern blue groper | Caring for Coasts DECCW |
| Gray (2008-2013) | Movements and ecological interactions of key fish species | II-NSW |
| Suthers and Baird (2008-2010) | Quantifying the role of salps in marine food webs and organic carbon export. | ARC Discovery |
| Williams (2008-2010) | Autonomous Exploration and Characterization of Benthic Habitats Linked to Oceanographic Processes | ARC-Discovery |
| Smoothy and Peddemors (2007-2012) | Movements and biology of coastal sharks in NSW | II-NSW |

|  |  |  |
|---|---|---|
| Otway (2007) | Great white shark tagging project | II-NSW |
|  |  |  |
| Rowland and Butler (2006-2011) | Fishtrack | II-NSW |
| Otway (2006-2008) | Grey nurse shark monitoring system (SWACAMS) | II-NSW |
| Broadhurst (2003-2012) | Estimating and maximizing the survival of key species | II-NSW |
| Everett | Eddies and upwelling: using satellites | Univ. Tech. Sydney |
| Tilbrook, Lenton | Ocean carbon and acidification | Australian Climate Change Science Program (CSIRO) |
| Suthers, Booth, Harcourt | Dual frequency identification SONAR | ARC LIEF |
| Suthers, Richarson, Doblin | A laser optical plankton counter | ARC LIEF |
| Marzinelli | Virulence and bacterial disease in temperature seaweeds | ARC Future Fellowship |
| Douillard | Multi-scale recognition: generating meaning from multi-resolution data | ARC APD Fellowship |
| Suthers | The krill pump | ARC Discovery |
| Ferrari | Model benthic habitat and assemblage distribution | NSW State Government |
| Williams | Marine video | Australian National Data Service |
| Williams | Delivering information suitable for studying spatial and temporal variability in benthic habitats | ARC Future Fellowship |
| Doblin, Seymor, Ralph, Vigneswaran Whitechurch | A transportable containerised laboratory for rapid cell sorting and high-resolution bioimaging of living aquatic microbes | ARC LIEF |
| Williams, Pizarro, Kendrick, Barrett, | Autonomous benthic observing | ARC LIEF |

| | | |
|---|---|---|
| Babcock, Heyward, Jordan | system | |

Two SIMS partners were successful with 2 Super Science Initiative fellowships. In 2009 NSW-IMOS initiated a special issue on the East Australian Current in the journal Deep-Sea Research (edited by Suthers, Roughan, Young, Baird and Ridgway). A summary of outputs generated from NSW-IMOS (up to May 2014) is shown below.

| | AUV | ANMN | AATAMS | Total |
|---|---|---|---|---|
| Research Projects | 15 | 7 | 15 | 37 |
| Postgraduate projects | 12 | 12 | 14 | 38 |
| Book chapters | 4 | 2 | 0 | 6 |
| Community White papers | 0 | 0 | 1 | 1 |
| Conference proceedings | 37 | 5 | 0 | 42 |
| In press | 0 | 1 | 3 | 4 |
| Journals | 16 | 10 | 2 | 28 |
| Thesis | 6 | 2 | 3 | 11 |
| Public seminars | 6 | 10 | 24 | 40 |
| Conference Presentations | 42 | 54 | 42 | 138 |

**Partnering for sustained ocean observing**

SIMS is a collaboration of the four main universities in Sydney, The University of New South Wales (UNSW), including UNSW Canberra, University of Technology Sydney, University of Sydney and Macquarie University. Hence by its nature, SIMS is a collaborative institute. Over the past few years SIMS has grown from strength to strength, and this is reflected in the list of associate members who have joined SIMS including University of Wollongong, University of Western Sydney, Defence Science and Technology Organisation (DSTO), NSW Office of Environment and Heritage, NSW Department of Primary Industries and The Australian Museum.

Many of the infrastructure proposals submitted in this current round of funding carry significant support from our industry partners including Sydney Water Corporation, Defence Maritime Services, thus giving at least a dollar for dollar return on investment. Partnering with the NSW state departments will continue to grow as we make the science (observations) and data products relevant to state agencies. As a priority, IMOS data needs to be used to show the linkages between blue water and shelf oceanography to near-shore state concerns in the form of a National Coastal Observing System.

# 5 Regional, national and global impacts of IMOS observations

Western boundary currents (WBCs) form on the western side of all the major ocean basins and are amongst the largest and fastest currents in the global ocean (Tomczak and Godfrey 2001). The poleward flows of the Gulf Stream, Agulhas, Brazil, Kuroshio and East Australian currents are responsible for redistributing heat, nutrients and organisms in the global ocean, often forming steep abiotic and biotic gradients in coastal shelf habitats.

Over the last century, there has been a rapid temperature rise within the paths of WBCs in all ocean basins, enhancing regional warming of surface waters by 2-3 times the global average (Wu *et al*. 2012). In addition, this accelerated warming is associated with a synchronous poleward shift and/or intensification in current strength (Wu *et al*. 2012). Given that changes in the strength and direction of oceanographic currents can have profound impacts on the supply of nutrients and oxygen, transport and retention of organic matter, as well as the delivery of plankton and larvae that sustain fisheries in coastal regions (Barth *et al.* 2007, Chan *et al*. 2008), there is a clear imperative to understand the biogeochemical and biological consequences of WBCs on adjacent continental shelf ecosystems. **For this reason, the research outcomes of activities in the NSW node are likely to receive significant international attention.**

Our greatest impacts will be on the physical and ecological interactions of the East Australian Current with coastal waters, in determining the synergistic impacts of urbanization and climate change. We expect the greatest impact in the next 10 years from NSW-IMOS will be in the areas of:

- Understanding of cross-shelf flows, deep water intrusions and plankton and microbial diversity and their relationship to past observations and predicted changes.
- Continued development of ocean circulation models particularly over the continental shelf region, ranging from hindcasting, nowcasting and forecasting and including improvements of parameterizations such as mixing.
- Assimilation of subsurface information, such as glider and ARGO data, into models such as BLUElink and the coastal implementations of ROMS to improve forecasting.
- Improved data products for assimilation into and verification of ocean, wave, climate and weather prediction models.
- Further improvements in the understanding of tidal mixing, particularly in the coastal regions and near the continental shelf, including improvements of the treatment of vertical mixing in ocean models such as ROMS and BLUElink.
- Enhanced models of biophysical coupling through enhanced measurement of mechanistic parameters driving biological variability (e.g. light) and via mapping of biological parameters onto the physical variability of the EAC.
- Prediction of climate change impacts on sediment transport, storm surge, coastal erosion and inundation.
- Increased understanding of the extent and complexity of fish and apex predator movements on and off the NSW coast.
- Estimates of larval connectivity along the coast of southeastern Australia, amongst ports, harbours as well as among marine parks; planning for marine parks.

- Greater understanding of biophysical changes in benthic reef communities in relation to long-term environmental change;
- Improved predictions of fish landings based on rainfall and oceanographic variation.
- Validating contemporary ocean colour derived estimates of chlorophyll, CDOM and TSS against direct IMOS observations.
- Developing NSW specific optical inversion algorithms for near shore, optically complex coastal waters.
- Parameterization of future linked ecosystem models and the evaluation of forecasting abilities through the collection of biological and geochemical data streams.
- Improvements in the modelling of surface waves, both amplitude and directionality to supply local agencies and shipping interests with sufficient wave information
- Our understanding of the links between winds and other forcing processes will also improve, enabling us to identify and quantify the roles and strengths of various processes with the forcing factors and the impacts on the environmental factors and ecosystems.

Over the longer term, NSW IMOS observations will enable us to better quantify natural variability versus long-term climate change and its associated impacts on coastal communities and marine industries in NSW.

As the data record becomes longer, identifying the multi-decadal trends and variability will contribute to our long term goal of evaluating climate-induced change versus natural variability (Henson *et al*. 2010, 2013).

***Identify the strategic issues and problems that IMOS will address if sustained in the longer term.***

**With sustained observing, IMOS will address the following strategic research priorities facing Australia:**

1. **Living in a changing environment**
   Through its physical, chemical and biological observations, IMOS will help identify the seasonal, inter-annual and decadal variability in continental shelf and EAC waters, link the variability and trends with the primary climate modes, and characterise linked ecological responses. Understanding the amplitude and frequency of events across more than 10 years will also allow identification of anomalies which will provide an opportunity to manage extreme events, increasing the opportunities for protecting public and private assets, and improving social, economic and environmental outcomes.

   With respect to biological monitoring, the combination of phytoplankton sampling at the historic time series National Reference Station at Port Hacking, zooplankton tows, fish tagging, benthic high-resolution imagery, and marine mammal observations through the passive acoustic mooring provides relatively good coverage of trophic groups. Expanded acquistition would enable more definitive and higher resolution answers to these questions.

   IMOS will also support the integration of multi-disciplinary observations into circulation, biogeochemical and ecosystem models that will be used to represent the complex natural ecosystem. Such models will be used to help interpret and predict the behaviour of the pelagic and benthic compartments of the NSW marine ecosystem to future change.

Greater effort is required in making statistical and dynamical projections of both the surface and internal wave climates under future climate scenarios. Knowledge of the surface wave climate and its trends and variability are critical in predicting coastal erosion, inundation, and beach and shorefront loss. Knowledge of the internal wave climate impacts mixing, cross-shelf transports, nutrient replenishment, and pollutant dispersal. Both the surface and internal wave fields will be altered by changes in wind and the ocean characteristics, respectively. The present observational records for both are inadequate for characterizing the fields, much less resolving changes in wave climates. The future priority is to acquire coastal bathymetry and both surface and internal wave data on a seasonal basis for the next decade in order to monitor shoreline and sediment changes.

2. **Managing food and water resources**
   Increased understanding of the marine ecosystem will give insight into the distribution and abundance of commercially significant finfish and crustacea and how this varies over time and in response to extreme events. Improved understanding of the spatial and temporal variability in primary production on the continental shelf and its link with near shore waters will also assist in the management of coastal aquaculture facilities. This includes the physical oceanographic processes involved in nutrient replenishment and distribution of nutrients and larvae.

   Understanding transport and dispersal of marine organism life stages using circulation models underpinned by observations will also provide a better understanding of population connectivity and the efficacy of marine parks and reserves in facilitating biodiversity.

3. **Promoting population health and wellbeing and lifting productivity and economic growth**
   With sustained observing to 2025, IMOS will benefit Australians because it will advance knowledge about human impacts on coastal marine ecosystems, information that is essential to help pinpoint vulnerabilities in the face of a growing population as well as changing climate. For example, the contribution of rivers (pollutants) as threats to coastal marine ecosystem health has been identified as an important threat to marine biodiversity that requires detailed studies in NSW. Without this knowledge, government, industry and the wider Australian community will suffer economic impacts including stranded public and private investments, a decline in coastal amenity and increased health risks for many Australians.

# 6 Governance, structure and funding

The Sydney Institute of Marine Science (SIMS) hosts the NSW node of IMOS (NSW-IMOS). As the host organisation and the operator of 3 facilities (see below), SIMS is investing substantially in IMOS, (~$1.25 M cash) including $15,000 cash per year for running the node. The NSW government has also co-invested in NSW-IMOS with $600,000 to fund 3 personnel to mid-2013 and has committed $260,000 to support three positions out to September 2014. SIMS is the designated operator of two IMOS facilities and one sub-facility, these being:

- The autonomous underwater vehicle facility (AUV, led by Dr Stefan Williams),

- The Australian Acoustic Tracking and Monitoring System (AATAMS, led by Prof Rob Harcourt) and
- The NSW sub-facility of the Australian National Mooring Network (ANMN led by Dr Moninya Roughan).

**Membership**

The membership of NSW-IMOS is open to anyone with a professional interest in ocean observations along the coast of NSW. It will have no restriction other than a willingness to be enrolled on a membership database. Presently NSW-IMOS has over 140 members who are full time scientists, from over 10 state and federal institutions. Node priorities are set through consultation with the NSW-IMOS community via public meetings (twice per annum) and distributing all significant documents by email to the membership list. Members can then provide input to science priorities. The node has a scientific reference group led by Dr. Martina Doblin (node leader) and Drs. Tim Ingleton and Robin Robertson (co-deputy node leaders). The Governance structure for NSW-IMOS is shown in Fig. 6.1.

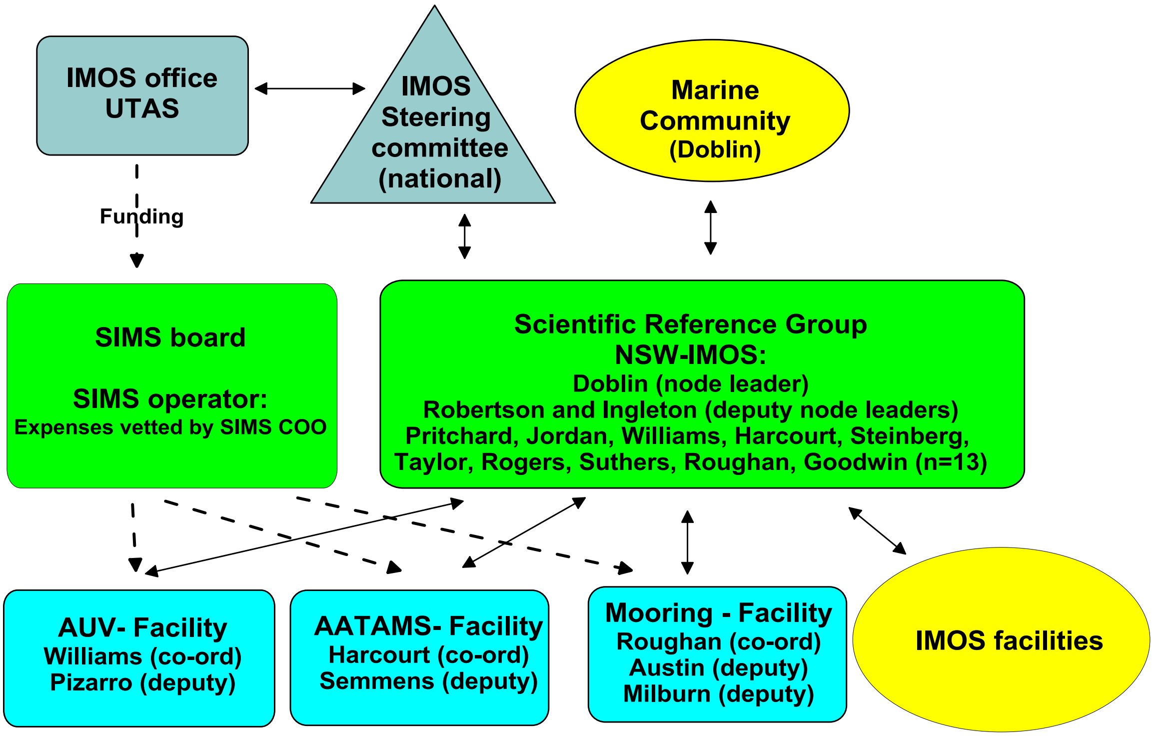

*Figure 6.1. Diagram showing governance of NSW-IMOS from Sept 2013. NB Suthers was node leader prior to September 2010 and Roughan followed him until Sept 2013.*

**How the stakeholders will be engaged including indicative levels of co-investment**

We have held annual node meetings at SIMS since Feb. 2007, attracting 40-50% of members:

| Meeting # | Date | Agenda |
|---|---|---|

| | | |
|---|---|---|
| 1 | Feb. 2007 | Formation and governance of NSW-IMOS |
| 2 | 24 Sept. 2007 | 1) To summarise the activities and plans of the 3 facilities based at SIMS (AUV, AATAMS, Moorings)<br>2) To plan our applications for the IMOS mobile elements - the AUV, the High Frequency coastal radar (ACORN) and the ocean glider. Due on 17 Nov 2007. |
| 3 | 5 Aug 2008 | NSW IMOS update - Key note address: Andreas Schiller (CMAR) "BLUELink and NSW IMOS" |
| 4 | 10 Nov 2008 | NSW IMOS update - Key note address: George Cresswell on the EAC and preparation for a special issue in DSR-II |
| 5 | 30 April 2009 | "LOOKING FORWARD – an integrated coastal observing system 2011-16"<br>To outline a 2 page scoping paper for the IMOS office on the science needs and infrastructure for NSW for beyond 2011 |
| 6 | 29 September, 2009 | Review the revised Node Science and Implementation Plan for the new EIF funding |
| 7 | 19 May 2010 | Update and outcomes of EIF decision process |
| 8 | 22 September 2010 | Key note address Tom Malone - Coastal ocean observing systems |
| 9 | 12 June 2011 | IMOS Annual node meeting - UTS |
| 10 | 30 May 2012 | IMOS Annual node meeting |
| 11 | 19 July 2013 | IMOS Annual node meeting |
| 12 | 19 November 2013 | Visit of Zdenka Willis from US-IOOS |
| 13 | 7-8 August 2014 | Port Hacking time series workshop, Sydney Institute of Marine Science |

The following industry partners are engaged in NSW-IMOS through the node community meetings, shared grants and joint publications. They also provide financial and logistical support to NSW-IMOS. Their indicative levels of co-investment are listed in each of their letters of support supplied to the facilities.

NSW Office of Environment and Heritage (OEH)
Contact: Mr Tim Pritchard
Port Hacking NRS transect biochemical sampling
In-kind support (boats, time)

Department of Primary Industries (Fisheries)
Contact: Dr Matt Taylor and Dr Alan Jordan
SEACAMS (70 VR2W receiver network)
AATAMS receivers

Manly Hydraulics Laboratory (DSTA)
Contact: Dr Ed Couriel
In–kind support

Sydney Water Corporation
Contact: Dr Peter Tate
Ocean Reference Station data

Oceanographic Field Services
Contact: Mr Clive Holden
In-kind support

NSW-Office for Medical and Scientific Research
Contact: Mr Chris Armstrong
In-kind support

Defence Science and Technology Organisation (DSTO)
Contact: Dr Doug Cato
In-kind support

Defence Maritime Services
Contact Mr Mark Todd
In-kind support – boats

NSW IMOS receives the following cash co-investments:

Cash co-investment totalling $1,019,105 in 2012/2013 under EIF and $4,028,600 expected 2013/2014 under CRIS/NCRIS2

| | | |
|---|---|---|
| GBROOS | AATAMS | GBR Tags, GBR ship time and personnel and equip |
| NIWA | AATAMS | Campbell Island deployment vessel, people and sundries |
| CNRS | AATAMS | Expedition to Kerguelen 3 pax 3 pax |
| SA Dept EnvandHeritage | AATAMS | Mooring Support |
| CSIRO | AATAMS | NRETA Ship time, Mooring consumables |
| NSW Government | ANMN | Salary |
| NSW Government | AUV | Salary |
| University of Sydney | AUV | Salary and Insurance |

In-Kind co-investment totalling $3,283,148 in 2012/2013 under EIF and $4,616,500 expected 2013/2014 under CRIS/NCRIS2

| | | |
|---|---|---|
| Macquarie Uni | AATAMS | Salary support Rob Harcourt |

|  |  |  |
|---|---|---|
| SARDI | AATAMS | Glenelg line boat and divers |
| Macquarie Uni | AATAMS | Field Support |
| AIMS | AATAMS | NRETA Ship time |
| AIMS | AATAMS | Salary support |
| NIWA | AATAMS | logistics- field personnel etc biologger deployment |
| CNRS | AATAMS | logistics- ships personnel etc biologger deployment |
| CSIRO | AATAMS | NRETA Personnel |
| Flinders | AATAMS | mooring deployment/servicing/tags |
| UTAS | AATAMS | mooring deployment/servicing/tag/salary |
| Marine Park Auth | AATAMS | mooring deployment |
| Qld Dept EnvandRM | AATAMS | mooring deployment |
| SARDI | AATAMS | mooring and biolgger deployment/servicing |
| SARDI | AATAMS | Salary support |
| SIMS | AATAMS | Ship time - DMS |
| SIMS | AATAMS | Lab/Workshop, Vessel |
| Murdoch University | AATAMS | Salary support |
| WA Fisheries | AATAMS | Ship Time and personnel WA |
| JCU | AATAMS | Salary support |
| NSW DECCW | ANMN | Data |
| Syd Water | ANMN | Data |
| AIMS | AUV | Ship time |
| NSW DPI/NERP | AUV | Ship time |
| CSIRO/DEEDI | AUV | Ship time |
| Uni of Sydney | AUV | Salaries and Logistic |
| TAFI/Utas | AUV | Ship time and salary |
| CSIRO/UWA/Fisheries WA | AUV | Ship time |

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