South East Australia Node Science and Implementation Plan

2015-25

IMOS is a national collaborative research infrastructure, supported by Australian Government. It is led by University of Tasmania in

partnership with the Australian marine & climate science community.

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Table of Contents

1 Executive Summary

The South East Australian Integrated Marine Observing System (SEA-IMOS) ten year science and observational plan has been designed to provide data streams across five major research themes that underpin key physical and biological processes important to the regions unique marine ecosystem. These data streams will help determine:

1. The spatial and temporal variation in physical oceanographic conditions off South East Australia, including shelf and slope currents, cycles of up-welling/down-welling, the influence of major boundary currents and climate variability, and how these influence biological processes, including benthic assemblages.
2. How variations in circulation influence connectivity and nutrient enrichment in south east Australia from the Bonney coast in western Victoria, Bass Strait, Tasmanian waters and Eastern Victoria.
3. How broader oceanographic phenomena such as the Bonney upwelling shared with the SAIMOS node and the extension of the EAC through the jurisdiction of the NSW-IMOS influence nutrient enrichment, and connectivity in south east Australia ecosystem dynamics, food web structure, and key biological patterns and processes from microbes and plankton to apex predators.
4. The key ecological features for the region (seafloor geomorphology) and the role this plays in establishing zones of influence for boundary layer currents, habitat distribution and ecosystem structure.

The SEA-IMOS node provides a new opportunity for IMOS to strategically invest and engage stakeholders to fill important knowledge gaps in the IMOS network through an expanded focus in South Eastern Australia.

Our future ambitions are to develop observations that link physical and biological processes, specifically by:

1. Deploying new bio-logging instrumentation on a diversity of apex predator species for additional physical and species behaviour in South East Australia with a particular focus on filling knowledge gaps in Bass Strait.
2. Establishing long term monitoring sites through the AUV facility in Bass Strait.
3. Deploying new acoustic receivers at sites in Bass Strait.
4. Initiating summer glider transects across Bass Strait to sample sub-surface physical and bio-optical properties.
5. Completing a regional algorithm for ocean colour to account for the high coloured dissolved organic matter of shelf waters of SE Australia.
6. Opportunistic instrument deployments (currents, CTD) in east, central and western Bass Strait using existing infrastructure leveraged through partnerships.
7. Enhancing focus on coastal waters through support to established observation systems.

The plan presented here will build on the previous efforts of TAS-IMOS in maintaining core observations. The core observations that are currently being conducted within the region include:

1. Cross shelf glider transects in Storm Bay to assess water mass changes off the East Coast.
2. Spatial and temporal patterns in cross shelf patterns of benthic assemblages by AUV
3. Ships of Opportunity- Bass Strait traverses.
4. Continuation of SRS Satellite Altimetry Cal/Val ground truthing station.
5. Maintaining acoustic arrays in Port Phillip Bay and off eastern Tasmania.
6. Maintaining and supporting mooring arrays in Port Phillip Bay and Storm Bay
7. Maintaining and supporting the Maria Island national reference station.

2 Introduction

The South East Australia Node for IMOS (SEA-IMOS) was created in late 2014. It is intended that it will reposition the Tasmanian IMOS Node (established in 2009) to take a more regional perspective. Australia's south east region encompasses industries such as aquaculture; biotechnology (including bioprospecting); commercial fishing; offshore mining; ocean waste disposal; oil and gas; ports and marinas; recreational fishing; shipping, ship/boat building; submarine cables and energy transmission lines; and tourism (Love, 2004). In addition to industry there is strong conservation support within the area with the network of Commonwealth Marine Reserves Network having been established in the south east to protect biodiversity and seafloor features. It includes 14 reserves covering an area of 388 464 km^2 over a depth range of 40 m - 4600 m which including features such as underwater canyons, sea mounts and ridges and the associated diverse marine life.

The SEA-IMOS Node will take the responsibility for articulating the science needs for the observing system design for IMOS investment within the region. The SEA-IMOS region overlaps part of the South East Marine region as defined in the South-east Commonwealth Marine Reserves Network management plan 2013-23 (Director of National Parks, 2013), and includes the far south coast of New South Wales, around Tasmania and as far west as the Bonnie Coast, Victoria and encompassing the shallow continental shelf that is Bass Strait.

This Science and Implementation Plan is organised as follows:

Section 3 summarises the socio-economic context for the South East Australia region.

Section 4 provides an overview of the scientific background for the five IMOS major research themes relevant to the SEA-IMOS Node: 1) multi-decadal ocean change; 2) climate variability and weather extremes; 3) major boundary currents; 4) continent shelf and coastal processes and 5) ecosystem responses. The discussion of each research theme concludes with a summary of the status, gaps, opportunities and priorities for future enhancement of the IMOS infrastructure relevant to each theme.

Section 6 discusses the use of IMOS data by the SEA-IMOS Node.

Section 7 provides an overview of major achievements and impacts of the science using IMOS data in the South East region.

Section 8 describes the governance, structure and support for the SEA-IMOS node.

3 Socio-economic context

The south east region supports approximately 60% of Australia's population (Gergis and Ashcroft, 2013), with the communities being socially and economically diverse, with environmental sustainability, biodiversity and the use of resources to secure future sustainable economic benefits highly valued by the community (National Oceans Office, 2004).

The two largest marine based industries in the SEA-IMOS region are marine based tourism and offshore oil and gas industries. These industries account for ~ 80% of the region's income generation, with the remaining 20% including activities such as aquaculture, commercial fishing, ports, ship building and shipping activities (Love, 2004).

The Gippsland Basin which is situated to the south east of Victoria is a major source of oil and gas, accounting for ~26% of Australia's crude oil, 10 per cent of its condensate, 43 per cent of its LPG (liquefied petroleum gas), and 19 per cent of its production of natural gas and naturally occurring ethane in 2002-03 (Love, 2004).

3.1 Managing a Variable and Uncertain Climate

The Australian continent is highly sensitive to ocean-influenced climate and weather, and regularly experiences drought, flood, tropical cyclones and other extreme events. Due to our reliance on commodity exports and our large agricultural sector, Australia's economy is highly sensitive to climate. The South East marine region has been identified as being extremely vulnerable to climate change. The effects of climate change to marine systems will not only affect biodiversity and ecosystem health, but also most of the marine industries and the security of coastal infrastructure. Southern Australia has experienced some of the fastest increases in ocean temperatures globally. The strengthening of the East Australian Current has seen the sea surface temperatures rise by ~2 °C since 1925 (Holbrook and Bindoff, 1997, Ridgway, 2007a). These warming temperatures are already impacting the marine ecosystems in the region, with the arrival of a number of species with warm water affinity documented off the coast of Tasmania and east coast Victoria. A potential increase in ocean acidification will also impact marine biodiversity in particular by calcifying species such as reef building corals, commercially important shellfish and a range of phytoplankton and zooplankton at risk from declining pH.

In addition, rising sea temperatures can also alter ocean currents, raise sea levels, and increase the occurrence and severity of storms. Changes in the frequency and magnitude of extreme sea level events, such as storm surges combined with higher mean sea level will increase the risk of coastal inundation. A more thorough and timely assessment of ongoing changes in our climate, oceans, and terrestrial ecosystems is imminently required. An improved projection of the state of climate, oceans and effect to ecosystems is needed to underpin adaptation and possible mitigation. Even with truly quantitative predictions, an adaptive approach to mitigation/adaptation policy is needed, guided by timely observations of how the system is responding to changes that are being forced up it. Monitoring is therefore required for:

- *The early detection of large or rapid shifts in the climate and marine ecosystems*
- *Information needed to develop climate change mitigation and adaptation policies*
- *Tracking the effectiveness of national and international actions to control climate change, including Australia's management of its carbon budget and as a contribution to the global carbon budget*

With ~ 85% of the nation's population living within 50 km of the ocean, understanding our oceans is a matter of national importance for current and future generations of all Australians.

3.2 Oil and gas

The economic backbone of the marine sector is the oil and gas industry, with more than 90% of Australia's liquid hydrocarbon and 74% of the nation's natural gas production extracted from seabeds without our EEZ. Oil and gas production in Australia is concentrated in the north-western and southern regions, with the Gippsland Basin established as the first major offshore area to be developed in the SW region showing a trend for many years as one of the largest zones for oil production. The region produces around 90 per cent of Victoria's electricity, 97 per cent of Victoria's natural gas, and 14 per cent of Australia's oil (Gippsland growth plan). It directly employs about 700 people in the south-east region and has generated more than $100 billion in revenue in the last 30 years (National Oceans Office, 2004). Production from this region is in decline however and offshore exploration for oil and gas is being undertaken in the Otway Basin of southeast South Australia, western Victoria and the Sorrell Basin off North West Tasmania (Love 2004) where offshore the resource is still considered under developed and likely to receive more attention in the near future.

The direct impacts of seabed structures such as wellheads, anchors and pipelines, shipping traffic and risks from accidents and spills are some of the issues associated with this industry. There is also the potential for impacts on the benthic fauna from high frequency seismic surveys. This also includes significant coastal impact from industrial sites where ports and processing equipment are located (Department of the Environment, 2011). As climate change is forecast to dramatically increase the exposure of oil and gas companies to climate change risks with flooding events, storm surges, sea level rise and increases in the wave climate there is an enhanced risk of assets being potentially damaged which will directly result in lost production and revenue and the need for newly designed platforms to cope in these changes (Smith, 2013).

3.3 Tourism

A major drawcard for tourism in Australia is its natural environment and Victoria and Tasmania have experienced an increase in international tourism in recent years. Marine based tourism activities undertaken in the region include diving, charter boating, recreational boating, whale and dolphin watching, cruise ship visits, yacht racing, surfing, coastal sightseeing, swimming, penguin watching and recreational fishing. Popular destinations in the region include: Phillip Island, the Great Ocean Road (Victoria); Robe, Beachport (South Australia); Merimbula, Bermagui (New South Wales); and Strahan and the Freycinet Peninsula (Tasmania). This industry generated over $2.6 billion in value added services in 2000–01 in the region and over 60 000 jobs (National Oceans Office, 2004).

With the economy of many coastal towns depending on marine industries, climate change represents a very large risk. The south east and south west of Australia are warming much faster than the rest of the world impacting the abundance (Simpson et al., 2011), distribution (Perry et al., 2005, Nye et al., 2009, Last et al., 2011), physiology (Somero, 2010, Neuheimer et al., 2011) and phenology (Dufour et al., 2010) of marine organisms. These changes will affect fisheries which could lead some communities to refocus in other industries such as marine tourism opening up opportunities in this particular marine industry (Van Putten et al., 2014).

3.4 Fisheries (commercial and recreational) and aquaculture

Waters in South East Australia are responsible for ~50% of Australia's wild fisheries and aquaculture production (Australian Bureau of Agricultural and Resource Economics, 2009), hosting high levels of endemism. Fisheries in this region are based on a wide range of species with resources utilised by commercial, recreational and indigenous sectors. There are five marine jurisdictions within the region (four states and the Commonwealth) with different environmental and fisheries management legislation and systems (Pecl et al., 2011). In 2011–12 Tasmania had the largest gross value of production ($690 million), accounting for 29 per cent of total fisheries production, followed by South Australia ($446 million, 19 per cent), with Victoria accounting for 3% ($71 million) (Fig. 3.1) (Australian Bureau of Agricultural and Resource Economics, 2013).

Climate related distributional shifts in recent decades have been observed in ~ 30 % of the inshore fish families occurring in south east Australia (Last et al., 2011), with at least one of the most important commercial species classified as high risk for each jurisdiction in the south-eastern region (Pecl et al., 2011). Fisheries species considered at highest risk include blacklip and greenlip abalone and southern rock lobster, the region's highest value fisheries, with temperature increase being the most common driver impacting both fisheries and aquaculture species.

In addition, rocky reef kelp forests are the primary habitat of commercial species such as rock lobster and abalone and warming of this region has seen the range extension of the spiny sea urchin *Centrostephanus rodgersii* move southwards. This species of sea urchin has been associated with the destruction of kelp and formation of urchin barrens along the east coast of Tasmania and Victoria (Ling et al., 2009). This habitat loss is also a major concern for both the lobster and abalone fisheries (Johnson et al., 2011, Pecl et al., 2011).

Figure 3.1 Shares in gross value of production by jurisdiction in 2011–12. Percentages were calculated based on the sum of gross jurisdictional production values. These values have not been adjusted for southern Bluefin tuna caught in the Commonwealth Southern Bluefin Tuna Fishery and introduced into farms in South Australia. p Preliminary estimate (Australian Bureau of Agricultural and Resource Economics, 2013).

The gross value of aquaculture production in Australia was estimated at $1.1 billion in 2011-12 with salmonids being the largest contributor (Australian Bureau of Agricultural and Resource Economics, 2013). However, prawns, tuna, edible oysters and pearl oysters being important contributors. Most of the salmonid production occurs in Tasmania while farmed tuna production (Bluefin tuna) occurs in South Australia, accounting for 14% of the total value in aquaculture production in Australia (Australian Bureau of Agricultural and Resource Economics, 2013). Pacific oyster and abalone are also economically important and are produced mostly in the south east region. Under climate change scenarios, rises in temperature can potentially impact immune suppression and increases in pest and diseases while ocean acidification could affect growth, development and survival of shellfish species (Pecl et al., 2011). On the other hand, increase in weather extremes could affect industry infrastructure, farming locations and operations (Pecl et al., 2011).

Figure 3.2. Real value of Australian aquaculture production from 2001–02 to 2011–12. p: preliminary (Australian Bureau of Agricultural and Resource Economics, 2013).

Recreational fishing is a popular activity that contributes economic and social benefits to the Australian economy, with some industries depending mostly or entirely on this sector. This sector is the responsibility of individual states and territories with most of them implementing output controls such as fish size, bag limits, season closures, area closures and gear restrictions. However, there is no requirement for the recreational fishing sector to report their catch, making it difficult to have data on this sector. The last Australia-wide survey was in 2000-01 and estimated an expenditure of 1.85 billion in services and items related to this activity (Australian Bureau of Agricultural and Resource Economics, 2013). Distributional shift of species of recreational value due mostly to a warming ocean will have economic and social challenges for the communities that gain or lose those species and it will be a major issue in South East Australia.

From the SEA-IMOS Node perspective, the IMOS infrastructure is a valuable component of the observations required to build the predictive tools and understand the nature of this risk to our fisheries. With waters in the south east Australia region experiencing multi-decadal warming over recent decades at a rate of between three and four times the global average (Holbrook and Bindoff, 1997, Ridgway, 2007a), this region provides our best, and *earliest*, opportunity to understand the responses of our natural resources to climate change. IMOS will be a key player in providing the observations that can underpin the ecosystem based management of our fisheries resources and thus deliver to our national food security.

3.5 South east marine reserves

The South-east Commonwealth Marine Reserves Network has been established to protect examples of the biodiversity and seafloor features of the Commonwealth waters of the South-east Region. The network stretches from the far south coast of New South Wales, around Tasmania and Victoria and west to Kangaroo Island off South Australia, covering an area of 388 464 km2.

The South-east Commonwealth Marine Reserves Network was established in 2007, comprising 14 Commonwealth marine reserves (Figure 3.3), of which 13 were proclaimed under section 344 of the Environment Protection and Biodiversity Conservation (EPBC) Act, and one, Macquarie Island Commonwealth Marine Reserve, proclaimed under the National Parks and Wildlife Conservation Act 1975 (Director of National Parks, 2013).

Figure 3.3. South-east Commonwealth Marine Reserves Network. Department of the Environment

Between Tasmania and Victoria there are also a number of state managed marine protected areas (MPAs) which also contribute to the protection of marine biodiversity, species representation and uniqueness. These state reserves complement the national network of Commonwealth MPAs by being representative of the inshore habitats (inside 3 nm) of the states coastal waters. In Victoria thirty MPAs represent a highly significant landscape and ecological value with over 5% of Victorian state waters being no-take areas designed to maintain examples of Victoria's biodiversity and associated ecological processes.

The South-east Marine Region contains 11 provincial bioregions that can be either provinces or transition regions and includes a broad range of temperate and sub-Antarctic environments. Depths in the region range from 40 metres on the continental shelf to > 4000 metres on the abyssal plain and include sea-floor features such as seamounts, canyons, escarpments, soft sediments and rocky reefs, all of which support high levels of biodiversity and species endemism (Director of National Parks, 2013). These reserves, if protected from human activity pressures, have the potential to buffer climate-related biological variability by building community resilience through a number of mechanisms to promote species and functional stability, and resist the initial stages of tropicalization (Bates et al., 2013).

Given the high endemism of marine species in south east Australia, it is important that Australia has long-term baselines to know how our marine biodiversity is being affected by climate change (e.g. Pittock, 2003, Poloczanska et al., 2007). Therefore it is important that we not only observe the physical and chemical changes in the marine environment, but also the biological changes that will have ecological and socio-economic consequences as these in their own right will influence the pace and extent of climate change itself.

4 Scientific Background by Major Research Theme

South-east Australia has been shaped geologically by the catchment of Australia's major river systems from Victoria, Tasmania and the Murray-Darling Basin. These river systems provide inputs into coastal ecosystems and have influenced the development of underwater features such as the canyon structures east of Bass Strait and the Murray Canyons. The water depth in the region varies from the shallow expanse of Bass Strait, averaging 60 metres deep, to the Hjort Trench, near Macquarie Island, where the sea floor lies at ~ 6700 m depth (National Oceans Office, 2004). Some sections of the continental shelf in the south east region encompass a mosaic of rocky reefs and soft sediments (including Bass Strait), which support a diverse range of species including the highest biomass and diversity of seabirds and marine mammals in the nation (Hobday et al 2014). In the south and east of Tasmania seamounts rise from the abyssal plain to a height of ~2000–4000 metres and may act as obstacles to deep ocean currents by restricting and intensifying their flow (Director of National Parks, 2013).

The oceanography of south east Australia demonstrates strong influence from the Southern Ocean and the Antarctic Circumpolar Current (ACC). The ACC flows along a number of narrow fronts where water mass properties change sharply (Orsi et al., 1995, Sokolov and Rintoul, 2007). Among them, the subtropical convergence zone (STC) is the frontal zone which separates the subantarctic waters of the West Wind Drift from the subtropical waters in the north. These two water masses differ in their biological, chemical and physical properties, and its position varies seasonally (Butler et al., 1992, Hosack and Dambacher, 2012). In summer, the EAC strengthens and extends poleward and the STC zone shifts south, while in winter the EAC flow lessens and retreats northward and the STC zone moves north into the region. The western portion of the region is influenced by the Leeuwin Current, which flows through the Great Australian Bight and feeds the Zeehan Current off the western and southern coasts of Tasmania (Hosack and Dambacher, 2012). The two dominant features of the ocean along the southern Australian margin are a warm mixed-surface layer that is underlain by cooler Antarctic Intermediate Water (AAIW) (Newell 1961, Wyrtki 1971, Bye 1972, Callahan 1972, Newell 1974, Rochford 1977, Lewis 1981, Bye 1983, Godfrey et al. 1986, Hahn 1986, Schahinger 1987, Cresswell and Peterson 1993, Hufford et al. 1997). The mixed surface layer flows in a generally east-southeast direction and is known as the Leeuwin Current off west Australia, the Coastal Current off South Australia and Victoria, and the Zeehan Current off west Tasmania. During the summer this surface current is sometimes arrested by the north westerly flow of the wind forced Flinders current which at depth is fed by the Tasman outflow and equatorward transport of AAIW from more southerly latitudes.. Throughout the year the underlying current of AAIW and Tasman outflow water moves in a generally northwestward direction at a depth of about 400-600 m extending to approximately 1200 m (Wood and Terray 2005). This flow extends to Western Australia where it was named the Leeuwin Undercurrent (LUC) (Cresswell and Peterson 1993).

The circulation in Bass Strait is characterised by an eastward flow in summer and low net flow in winter. A warming of the western Tasman Sea waters relative to Bass Strait, as seen in Fig. 4.1, is likely to increase the density difference between the two regions, driving an increased winter cascade of Bass Strait Water into the Tasman Sea.

Figure 4.1. Mean circulation in Bass Strait in the summer (top) and winter (bottom) of 2014 from a 4 km resolution 3D hydrodynamic model forced.

4.1 Multi-decadal ocean change

The oceans are the main source of thermal inertia in the global climate system and contain the largest pool of active carbon in the planetary system. Therefore they are an important factor influencing the rate at which anthropogenic gases are removed from the atmosphere and how fast the surface of the planet warms.

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

Sea surface temperatures around Australia have increased by about 0.6-0.74°C over the past century (Lough and Hobday, 2011, Lough et al., 2012). However, south eastern Australian waters experienced warming three to four times the global average, becoming a global hot spot for ocean temperature change. Holbrook and Bindoff (1997) calculated a depth-averaged (0 to 100 m) warming of 1.5 ^{o}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), Ridgway (2007a) reported a sea surface temperature (SST) warming rate of 2.3 °C century-1 and increasing salinity of 0.34 century-1, consistent with the southward penetration of the EAC over the past 60 years (Fig. 4.2).

Figure 4.2 Climatological sea surface temperature anomaly (1992–2006) around Tasmania (^{o}C) in February with Maria Island station (black dot) (Ridgway, 2007a).

Changes in temperature and salinity are highly correlated at timescales greater than seasonal indicating significant coherence on intermediate (<10y) time scales. The summertime trends in temperature and salinity are greater than in winter – there is an additional pulse of warm, high salinity subtropical water associated with the EAC in summer. The strengthening of the EAC is caused by strengthened winds over the South Pacific, and hence a stronger South Pacific gyre (Hill et al., 2008). Although the enhanced warming in the region shows variation at shorter time scales, it shows a consistent upwards trend over a ~ 60 years' time scale (Fig. 4.3).

Figure 4.3. The (a) surface temperature and (b) salinity time series from the Maria Island station, and c) the decadal patterns of T and S at Maria Island (blue, cyan), satellite composite (red) and the trend of the temperature (black) (Ridgway, 2007a)

The intensification of the EAC flow past Tasmania is also seen in recent model studies describing both a spin-up and southward shift of the southern hemisphere subtropical ocean circulation. The oceanic changes are forced by an intensification of the wind stress curl arising from a pole-ward shift in the circumpolar westerly winds due to the trend in the Southern Annular Mode (SAM).

Modelling of extreme SST off the south east Australia region predicted an increase of ~2 C on the entire domain, except the extreme south, and an increase of ~2-4 C in the central and western Tasman Sea (Oliver et al., 2014).

In contrast to the strong sea surface warming, evidence of long term change in the region was recorded from deep water octocorals collected at 1000 m depth that showed long-term cooling of the deep waters that commenced ~ 200 years ago and could be related to the increase in surface temperatures (Thresher et al., 2004).

4.1.2 The global ocean circulation

The change in ocean circulation and future impact in its ability to sequester and transport heat and carbon is an important question. Evidence suggests that both surface and deep circulation patterns are changing, with recent studies showing that the South Pacific subtropical gyre is projected to spin up by about 25% in response to surface heat and freshwater fluxes and surface wind stress changes, with a poleward shift of Southern Hemisphere westerly winds (Cai et al., 2005, Roemmich et al., 2007, Zhang et al., 2013). This results in the intensification of the heat transport from the tropics to the poles via the western boundary currents such as the EAC. The intensification of the EAC results in large warming rates in the Tasman Sea and eastern Bass Strait that will have significant implications for sea level rise and broader impact on the southern mid latitude marine ecosystems (Cai et al., 2005).

With respect to the ACC, it has been suggested that there has been only a small change in transport in decadal time scales (Böning et al., 2008). Although a shift south has been observed (Böning et al., 2008, Gille, 2008, Sokolov and Rintoul, 2009), the link to changes in winds associated with the Sothern Annular Mode (SAM) is not conclusive. Indeed, a topic of active debate has been on whether or not the ACC is spinning up in response to increased winds.

4.1.3 The global hydrological cycle (salinity)

Estimates of surface salinity changes to date based on comparing Argo data with historical archives suggest large and coherent changes already underway (Hosoda et al., 2009, Durack and Wijffels, 2010). These changes are consistent with an amplification of the global hydrological cycle over past decades (i.e. wet areas are getting wetter and dry areas are getting dryer).

In south east Australia, there has been a decline in overall rainfall in the region with very low winter/spring rainfall linked to rising temperatures and associated changes in the large-scale atmospheric circulation. Modelling studies showed that the observed changes in large-scale circulation affecting south east Australia are associated with global warming, among other factors, and projections indicate an increasing risk of below average rainfall for the region (Commonwealth Scientific and Industrial Research Organisation, 2010).

El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and SAM are some of the ocean atmospheric modes that influence the climate of south east Australia with links to these large-scale drivers varying through time (Wright, 1988). The region is usually drier than average during El Niño and wetter than average during a La Niña (Mcbride and Nicholls, 1983, Hope et al., 2010). However, SAM plays a stronger role than ENSO on rainfall variability in winter, while in spring ENSO plays a more significant role (Mcbride and Nicholls, 1983, Meneghini et al., 2007, Hope et al., 2010).

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

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

Changes in ocean stratification, warming, winds and the buffering capacity of the ocean all have the capacity to change the ocean uptake of carbon. The same processes could also influence the biological export of carbon and carbonate production providing positive or negative biological feedback to the air-sea exchange of CO_2 (e.g. Gruber et al., 2004).

There is evidence of inter-annual variation in CO_2 air-sea fluxes modulated by variations of wind speed that affects the gas transfer velocity and the intensity of the air-sea CO_2 flux south of Tasmania (Borges et al., 2008). In addition, seasonality in mixed layer carbon has been found to exist in the Southern Ocean, with biological processes playing the main role while mixing and sea-air exchange playing a smaller role (Mcneil and Tilbrook, 2009). Seasonal variation in the mixed layer depth of the Subtropical Front (STF), in the Southern Hemisphere, contains the Southern

Hemisphere's largest accumulation of anthropogenic CO_2 (Fig. 4.4) (Sabine et al., 2004). However, variation in the carbon content of for this region is complex given that the STF supports a global scale bloom of coccolithophorids, which raise *p*CO2 while simultaneously reducing DIC and transport a significant fraction of the organic and inorganic carbon to deeper waters.

Figure 4.4: The column inventory of anthropogenic CO_2 for the oceans (Sabine et al., 2004).

In the south east Australia region, the atmospheric observing station at Cape Grim (NE Tasmania) has demonstrated compelling evidence for the rise in atmospheric CO_2 (Fig. 4.5). The shelf and offshore waters near Tasmania show significant seasonality in CO_2 (Mcneil and Tilbrook, 2009), with evidence of inter-annual change in the physical/solubility uptake (Borges et al., 2008). Since 2010 the Maria Island NRS station has included a continuous measurement of seawater dissolved oxygen and CO_2 concentrations. These observations show strong seasonality in the concentrations of these dissolved gases. These data sets provide one of the two data sets that can be used to validate a mechanistic model of inorganic carbon cycling in temperate Australia.

The capacity of the terrestrial biosphere to remove C from the atmosphere through bio-sequestration has now been well-studied (e.g. forest C farming initiatives), but it is now emerging that the greatest opportunities for C offsetting may be in the coastal ocean. Specifically, within the coastal ocean exist three vegetated habitats – seagrass, saltmarsh and mangrove – that have a disproportionally large influence on the global C cycle. These habitats, commonly known as 'blue C habitats', occupy <1% of the seafloor, yet contribute half of all C burial in the oceans.

Figure 4.5. Long term trend in atmospheric CO_2 concentration measured at Cape Grim in NE Tasmania. http://cdiac.ornl.gov/trends/co2/csiro/csiro-cgrim.html

4.1.5 Science Questions and variables needed to address them

The following high-level science questions will guide the South East Australia Node observing strategy:

Ocean Heat Content:

- *How are the global energy balance and the broadscale ocean temperature patterns changing and its impact on sea level rise in the South East Australia region?*
- *How are open ocean temperature changes related to temperature changes on the South East Australia shelf?*

Ocean Circulation:

- *How and why are the East Australian Current, Leeuwin and Antarctic Circumpolar Current changing?*
- *How is the shelf – open exchange changing as a result of, among other processes, Bass Strait winter discharge into the Tasman Sea.*

Global hydrological cycle:

- *How is ocean salinity in the SEA region changing and what do these changes in salinity tell us about the response of the regional hydrological cycle to climate change?*

Global carbon budget:

- *What is the seasonal through interannual variability in air-sea CO_2 fluxes for SEA shelves and regional seas?*
- *What are the key biological and physical processes driving air-sea CO_2 exchange in the Southern Ocean and South East Australian region and how sensitive are they to climate change?*
- What is the **role of microbes in stabilising 'blue C' stocks via production of recalcitrant C. in coastal oceans?**

Observations needed:

Local observations to address issues of the South East Australia region are needed particularly data to resolve questions such as sea level rise, and oceanographic conditions including temperature, salinity, pH and CO_2 content among others. The most significant gap for interpreting decadal signals in ocean heat content and shelf – open ocean exchange is the quantification of the physical state (temperature and salinity) of the water below the mixed layer in Bass Strait during the stratified summer period (see below).

4.1.6 Status, gaps and future priorities

Status:

IMOS uses a number of platforms to collect the observations needed to track multi-decadal change in Australia's oceans. IMOS facilities are providing broad-scale observations of temperature, salinity, velocity (and increasingly oxygen and chlorophyll) from Argo floats (Argo facility) and sensors deployed on marine mammals (AATAMS); physical and biogeochemical sampling of the upper ocean along ship of opportunity lines (SOOP); and deepwater moorings deployed in key boundary currents and inter-basin exchanges relevant to South East Australia, such as the East Australian Current mooring array. The time series of atmospheric, physical oceanographic and biogeochemical variables provided by the Southern Ocean Flux Station (SOFS) and Southern Ocean Time Series (SOTS) stations are uniquely valuable (DEEP WATER MOORINGS) because they provide the only high-quality, continuous observations of these properties in the Southern Ocean.

SEA-IMOS primary goal is to observe the temporal dynamics of the oceanographic conditions and predict their impacts on our local and regional marine ecosystems as well as impacts on our social, economic and environmental values.

Figure 4.6. Historical salinity observations (as of 10 April 2015) from the CSIRO data centre, Argo program and World Ocean Atlas (2009), excluding the SOOP transect from Melbourne to Devonport.

Figure 4.7. High resolution salinity observations on the SOOP transect from Melbourne to Devonport.

Gaps:

Physical observations in Bass Strait. The waters of Bass Strait are chronically under-sampled (Figure 4.6) . This is a result of the Argo floats not sampling in shallow waters, and a lack of regional studies. This is somewhat overcome by the SOOP transect (Figure 4.7). However the transect only provides near-surface observations. As of 10 April 2015, only one tagged animal (a male Australian fur seal) with a CTD went through the Strait.

Multi-decadal change in Bass Strait. The is a need to better understand the annual intrusion of Antarctic Intermediate Water (AAIW) in the regions west , which is often masked by a warm surface layer in satellite images and is a likely driver of fishery production for the region. -

Inter-annual variability of EAC. The EAC has varied in intensity over decadal time scales, as well as showing a warming trend. Continued monitoring of the EAC is required to better understanding this current and its impact on shelf waters in this region (i.e., *both* in eastern Tasmania on the shelf and in eastern Bass Strait).

Inter-annual variability of the driver of summer upwelling of the Bonney Coast and its impact on winter events in the Bass Canyon.

Understanding the effects of internal tide energy dissipation on the eastern shelf region.

Future priorities:

A top priority is to maintain the present observation data streams, in particular:

Maria Island NRS. The Maria Island NRS is one of the longest time series of ocean temperature, and is placed in a hotspot for warming. Its record must continue.

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

SOOP Bass Strait transect. The four year record of surface temperature, salinity and fluorescence is showing both seasonal and inter-annual trends.

Bass Strait and Storm Bay SRS calibration / validation stations. Continuation of these records is especially important in the transition between satellites.

Storm Bay glider transects. At their offshore limit these transects are recording the location of the front between boundary currents. Reduction of the 6 yearly transects to quarterly could be considered to allow for the below prioritised Bass Strait transect.

Greater presence in Bass Strait: develop partnership opportunities for sustained moored bio physical data in Bass Strait with existing infrastructure associated with oil and gas (ESSO- eastern Bass Strait, Origin Energy- western Bass Strait) and the Wonthaggi desalination plant (Central Bass Strait).

Enhance coastal focus: through support to existing infrastructure. Support and augment existing coastal observation systems in Port Phillip Bay (existing 14 year mooring record at Central Bay; and new observing system being developed at Popes Eye (Port Phillip Bay entrance) by the Nature Conservancy, Parks Victoria, Environmental Protection Authority (EPA) Victoria.

Further, additional observations should be prioritised:

Summer trans-Bass Strait Slocum glider deployments to observe sub-surface waters of Bass Strait. Late summer provides the best meteorological conditions. At 30 km d^{-1}, a Slocum glider could transit from near the mouth of the Tamar to Wilson's Promontory, with a return at the limit of the range of the batteries.

There are also extensive ongoing animal tracking studies across Bass strait (i.e. seals, penguins, gannets) that may provide useful alternatives for data collection in appropriately instrumented through IMOS facilities (i.e CTDs and other sensors through AATAMS) and also an ecological context to the observations observed (i.e. animal movement, foraging ground, prey capture success, health). Instrumentation of existing gas and oil rig platforms (in particular Bass strait) should be considered as options for continuous data collection (ADCPs and CTDS) as well as the deployment of cost effective temperature moorings to better understand processes associated with upwelling.

4.2 Climate variability and weather extremes

There are three major well described coupled ocean atmospheric modes which account for a significant portion of Australian seasonal climate variability – El Niño/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM), with centres of action in the equatorial Pacific, equatorial Indian, and Southern Oceans, respectively (Risbey et al., 2009). ENSO is the strongest mode both globally and in terms of impact on Australia, while SAM impacts the oceanic circulation in the South Pacific and Indian Oceans and large scale circulation and eddy properties of the Southern Ocean (Cai et al., 2005, Farnetti and Delworth, 2010). All three ocean atmospheric modes have impact on the South East Australia region.

4.2.1 Interannual Climate Variability

ENSO, SAM and IOD coupled ocean atmospheric modes influence rainfall variability on the Australian continent, with some modes influencing different regions at different seasons. However, ENSO is perhaps the dominant driver of rainfall variability in Australia. The south east Australia region is influenced by the multiple drivers with all three; ENSO, IOD and SAM affecting rainfalls in autumn, winter and spring, although their influence varies on decadal scales (Risbey et al., 2009).

4.2.1.1 El Niño –Southern Oscillation (ENSO)

In the south east Australian oceans, evidence shows ENSO affecting the Tasman Seas where there are significant signals in the subtropical gyre and south Tasman Sea and with subtropical mode water formation enhanced in the region during El Niño (Sprintall et al., 1995, Holbrook and Bindoff, 1997, Holbrook and Maharaj, 2008). Decadal ENSO variations also affect the EAC transport variability and coastal sea levels through the influence of Rossby waves connected to changes in wind stresses at the Tasman Sea and South Pacific (east of New Zealand) and decadal ENSO variations (Holbrook et al., 2005a, b, Holbrook et al., 2009). However, ENSO variability along Australia's south east coast appears to be weaker than along Australia's west coast.

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

ENSO's natural variability in frequency and amplitude is large and projected changes are small for this century according the IPCC AR5. There is high confidence from the models that rainfall variability induced by ENSO will likely intensify but confidence is low in changes in climate impacts on the Australian region (I.P.C.C., 2013).

4.2.1.2 Indian Ocean Dipole (IOD)

Inter-annual variability in the tropical Indian Ocean has been recognised as a factor in global and Australian seasonal climate variability (Schott et al., 2009). Shoaling of the thermocline, anomalous easterly winds and low rainfall in the eastern Indian Ocean are associated to positive IOD, and reversed signs of all the anomalies in the same region in a negative IOD, with IOD related events reaching a peak in autumn (Schott et al., 2009).

The origin of IOD events are not clear, with the seasonal timing of El Niño onset sometimes essential for IOD development, but with IOD events also influencing the life cycle of ENSO (Schott et al., 2009). However, IOD development can also happen in the absence of ENSO (Saji and Yamagata, 2003). Recently, research on the influence of IOD and ENSO on the southeast Australian rainfall showed that the influence of ENSO is restricted to the subtropics during winter and spring, and that a positive IOD plays a major role in the droughts in the south eastern Australia, with El Niño playing a lesser role (Pepler et al., 2014 and refs. within). However, the interaction between ENSO and the IOD is complex, with strongest rainfall anomalies observed in years where both drivers co-occur (Ummenhofer et al., 2009, Pepler et al., 2014). In addition, the pattern of IOD influence in rainfall variability across southern Australia is significantly correlated to all drivers (i.e. IOD, ENSO and SAM) in most seasons, with high variance explained by IOD and ENSO in southeaster Australia in spring and SAM in western Tasmania in the same season (Fig. 4.8) (Risbey et al., 2009).

Figure 4.8. Maps showing the climate drivers with the highest correlation to monthly rainfall across Australia for each season. Abbreviations are: DJF; December, January and February. MAM; March, April and May. JJA; June July and August. SON; September, October and November. BLK; blocking. SAM; Southern Annular Mode. ENSO; El Niño Southern Oscillation. IOD; Indian Ocean Dipole. (Risbey et al., 2009).

IOD predictability appears to be much less than ENSO's and remains an active area of international research, with challenges in the observation, description, understanding and prediction.

4.2.1.3 Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) describes the north–south movement of the westerly wind belt that circles Antarctica. It dominates the middle to higher latitudes of the southern hemisphere and it is the leading mode of climate variability in the southern mid to high latitudes. The changing position of the westerly wind belt influences the strength and position of cold fronts and mid-latitude storm systems, and is an important driver of rainfall variability in southern Australia. Variations occur on timescales of 10 days or longer and exert a dynamic influence over ocean circulation, water-mass formation and the distribution of heat and energy around the entire planet (Fig. 4.9) (Sen Gupta and England, 2006). In its positive mode, the belt of strong westerly winds contracts towards Antarctica, resulting in lighter westerly winds and higher pressures over southern Australian latitudes. Conversely, a negative SAM shows an expansion of the belt of strong westerly winds towards the equator, resulting in more or stronger storms and low pressure systems over southern Australia.

From an Australian perspective the positive phase of SAM shifts low pressure systems southwards reducing rainfall over southwest Western Australia (WA), Tasmania, Victoria and South Australia (Hendon et al., 2007). In addition, SAM positive phase is associated with increase in daily rainfall on the southeast coast as a result of an increase occurrence of moist upslope flow from the Tasman Sea, explaining 10-15% of weekly rainfall variability during spring and summer in the southwest and southeast coasts (Hendon et al., 2007). There is also strong evidence that the SAM positive trend has driven a spin up and southward shift of the south Pacific subtropical gyre (Cai, 2006, Roemmich et al., 2007, Hill et al., 2008). Observations indicate that regional responses to these gyre changes include a southward extension of the EAC and intensification of its flow past Tasmania (Ridgway, 2007a) and a large scale warming of the thermocline in the mid-latitude region of the Indian Ocean (Alory et al., 2007). This has resulted in a shift in the distribution of certain marine species (e.g. an expansion of a mainland sea urchin species, *Centrostephanus rodgersii* to southeast Australian waters (Ling et al., 2009). In the Southern Ocean (SO), early models showed that the higher index state of SAM is associated with the strengthening of the circumpolar wind stress, which results in an increase of the Antarctic Circumpolar Current (ACC) transport, a change in its position and the intensification of the SO eddy field with a lag of 2-3 years (Meredith and Hogg, 2006). However, in recent eddy-resolving models, a doubling of the wind stress increase the overturning circulation by 70% but the ACC transport remained nearly unaltered (Meredith et al., 2012, Morrison and Hogg, 2013).

Figure 4.9. Regression of sea level pressure (colour bar) and wind vectors (1m/s shown) from a climate model onto the SAM index (Sen Gupta et al., 2006)

Of particular importance to Australia is how the modes of variability will change in a warming world. ESMs suggest an intensification of the SAM is being driven by both reduced ozone levels and greenhouse forcing (Cai et al., 2005, Cai, 2006), driving a poleward shift in the circumpolar westerly winds (Gillet and Thompson, 2003).

4.2.2 Intra-seasonal variability and severe weather

South eastern Australia weather experiences what has been termed Mediterranean climate, with hot, dry summers and mild, wet winters due to their geographical position relative to rain bearing weather system in the westerlies. On a short day to day time scale the region is affected by the rain bearing fronts that travel with the mid-latitude westerly circulation (Wright, 1988, Hope et al., 2006, Pook et al., 2006), while on a longer time scale it is influenced by SAM, ENSO and IOD (Hendon et al., 2007, Meneghini et al., 2007). Rainfall in southern Australia has seen a reduction in the recent decades, experiencing a prolonged drought since 1996 (Hope et al., 2010). A predictor used for localised rainfall is the mean sea-level pressure (MSLP), which is closely linked to rainfall (Timbal and Murphy, 2007, Timbal and Jones, 2008). The reduced rainfall and increased temperature during the drought established hypersaline conditions in the large embayment's on the Victorian coast altering their flushing regimes and containing productivity (Lee et al, 2012).

Variation of rainfall patterns and temperature regimes are important in a region prone to wildfires, such as the southern Australia region (Fig. 4.10a). This is because the winter and spring rains allow fuel growth, and the dry summers allow fire danger to build. The risk of wildfires is aggravated by droughts that occur as a part of interannual climate variability (Lucas et al., 2007). Typically, dangerous fire situations in the region occurs when a strong cold front approaches a slow moving high pressure system in the Tasman Sea, causing very hot and dry north-westerly winds (Fig. 4.10b) (Lucas et al., 2007).

a) b)

Figure 4.10. a) Fire seasons in Australia (http://www.bom.gov.au/weather-services/bushfire/about-bushfire-weather.shtml). b) MSLP contours (hPa) on the 16 February 1983. Heavy arrows depict general wind direction and fire symbols denote approximate locations of bushfires observed on the day (Lucas et al 2007).

The increase in dryness for southern and eastern Australia resulting from a decrease in extra tropical storm activity in the region due to the reduction in intense wind events across south east Australia is predicted to continue (Alexander et al., 2011, I.P.C.C., 2013).

4.2.3 Science Questions

Interannual:

- How do ENSO, IOD and SAM affect circulation in south east Australia? What role do they play in upwelling/downwelling events in shelf currents?
- How do long-term changes in these modes of variability affect the boundary currents important to the region?

Intraseasonal:

How do severe winter storm events effect nearshore, intertidal and beach topography, wave dynamics, storm surge and coastal inundation.

4.2.4 Status, gaps and future priorities

Status:

While climate variability operates on inter-annual timescales, and weather extremes operate on shorter space and time scales, the observations needed to understand them are similar. Observations are needed of upper ocean temperature and salinity, air-sea exchange of heat and momentum (wind stress), and sea level. Direct measurements of air-sea fluxes are of particular importance to this theme, as well as satellite measurements of wind stress, sea level, and sea surface temperature.

Several IMOS facilities are delivering data streams relevant to climate variability. Argo is providing broad-scale measurements of temperature and salinity in the upper ocean. Measurements of atmospheric and oceanographic variables from ships of opportunity (SOOP) contribute to this theme. Satellite remote sensing of wind stress, sea surface temperature, and sea surface height are also important to investigate climate variability and weather extremes. Air-sea fluxes measured at the SOFS site south of Tasmania are helping to improve understanding of air-sea interaction south of Australia.

Gaps:

The gaps in observations identified in the multi-decadal ocean change theme also limit the monitoring of interannual variability and extreme events.

Future Priorities:

In addition to priorities set in the multi-decadal ocean change theme, the impact of weather extremes needs to be tackled by dedicated studies using the above-listed observations.

4.3 Major boundary currents and inter-basin flows

The waters around Australia form a complex intersection of the Pacific and Indian Oceans. The three major boundary currents (Fig. 4.11) are the East Australia Current (EAC), which forms the western boundary current of the South Pacific gyre, and the Leeuwin Current (LC), a unique eastern boundary current of the Indian Ocean, and the third ‘boundary current’ flowing along Australia’s longest coastline is the westward drift component of the Antarctic Circumpolar Current (ACC) found at the Subtropical Front (STF). The south east Australia region is influenced by all 3 major currents (Fig. 4.11).

Figure 4.11: Boundary Currents in the Australian region (image provided by CSIRO).

The influence of the different currents in the region varies seasonally, with summer and winter patterns of the surface circulation influenced by the EAC and the Zeehan Current (ZC) respectively. The Zeehan current is a current that runs southeastward along the continental shelf edge of western Bass Strait and western Tasmania (Fig. 4.9). On the east coast in summer (Jan-Mar) there is a polewards flow of warm, saline water forced by an episodic coastal boundary flow. The cross-shelf pressure gradient driving this flow is formed from the difference between the seasonal changes in coastal sea level and the offshore eddies. There is a seasonal reversal of this flow in winter with cool, fresh, modified subantarctic surface waters drawn up from the south. Off the west coast the ZC operates 180^o out of phase with the EAC. The strongest pole-ward flow is in winter when it projects warm, relatively saline waters down the western Tasmania coast and around the southern tip of Tasmania. There is a sharp division between the EAC and ZC influence adjacent to the Tasman Peninsula off southeast Tasmania.

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

The East Australian Current (EAC) is a complex and highly energetic western boundary current in the south-western Pacific off eastern Australia J.R. (Ridgway and Dunn, 2003). Although its mean flow is relatively weak (Ridgway and Godfrey, 1997) it is known to be a highly variable system with large mesoscale eddies dominating the flow (Bowen et al., 2005, Mata et al., 2007). The EAC has an important role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Roemmich et al., 2005). It has a major influence in the Tasman Basin, which is an ocean region of importance to Australia, being adjacent to large population centres, encompassing major shipping lanes, and including regions of environmental significance. The EAC is also the dominant environmental influence on offshore pelagic fisheries in the region (Hobday and Hartmann, 2006).

The EAC flow bifurcates into northern and southern components near the coast (Church, 1987). This bifurcation location moves southward with increasing depth (from 15°S at the surface to 19°S at 500-m depth) such that over the first 300-km the there is an undercurrent which only extends to the surface at ~ 15°S (Church and Boland, 1983, Ridgway and Dunn, 2003). The southern component of the current is accelerated poleward along the coastal boundary, to form the main EAC transport. It then separates into northeastward (Subtropical Counter Current), eastward (Tasman Front) and residual southward (EAC Extension) components at around 31°S (Figure 3.8) (Ridgway and Dunn, 2003). A portion of the Tasman Front re-attaches to the northern coast of New Zealand, forming the East Auckland Current and a sequence of semi-permanent eddies. The EAC Extension is the residue of the EAC transport which continues southward along the Australian coast as far as Tasmania, propagating towards Tasmania largely as an eddy field (Fig. 4.12).

The EAC flow varies seasonally strengthening in summer, with a minimum observed southward flow of 27.4 Sv in winter, and a maximum of 36.3 Sv in summer (Ridgway and Godfrey, 1997). The EAC Extension turns westward into the eastern Indian Ocean (Tasman Outflow) with an important impact on the global ocean circulation (Speich et al., 2002). The Tasman Outflow occurs mainly at intermediate depths between 500 and 1200 m. As well as connecting the gyre systems in the Pacific and Indian Oceans (Figure 4.12) (Ridgway and Dunn, 2007) this current forms a third element of the global thermohaline circulation (Speich et al., 2002). The Tasman Outflow subsequently feeds the Flinders Current (Ridgway and Dunn, 2007). This westward subsurface boundary flow is also partially forced by Southern Ocean Sverdrup dynamics (Middleton and Cirano, 2005). It is an upwelling favourable flow with enhanced onshore nutrient exchange (Middleton and Bye, 2007). The FC intensifies as it moves westward and provides source waters for the Leeuwin Undercurrent once rounding Cape Leeuwin.

Figure 4.12: Ocean currents of South East Australia region during summer (Hosack and Dambacher, 2012)

The impact of ENSO on the EAC remains an active area of research. Ridgway and Dunn (2007) suggests that ENSO has little impact on the EAC, as the ENSO signal predominantly follows the waveguide through the Indonesian archipelago and continues down the west coast of Australia. However, on decadal timescales, the strength of the EAC extension and the Tasman Front are anticorrelated, representing two states of the South Pacific gyre. This has been related to decadal ENSO variability projecting onto the westerly winds of the South Pacific basin (Hill et al., 2011).

A variety of observational evidence suggests the EAC and South Pacific gyres have strengthened in recent decades in response to changes in wind stress (Cai et al., 2005, Clivar, 2006, Roemmich et al., 2007, Hill et al., 2008). The EAC Extension seems to be extending further south along the east coast of Tasmania, impacting Tasmanian ecosystems by carrying warm water and new species further south (Johnson et al., 2011). Models suggest that the EAC and EAC Extension are likely to strengthen further in response to greenhouse warming (Cai et al., 2005). The EAC extension is known to interact with the Subtropical Front (STF), and possibly with the Zeehan Current, to determine the productivity of the Tasman Sea. Therefore quantifying the impacts of the EAC extension on the ecology of the Tasman Sea is likely to be fundamentally important to prepare for and mitigate the socioeconomic impacts of climate change in this region.

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

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

The LC is highly unstable with mesoscale eddies regularly generated along its path and the eddy energy associated with it is higher than any other eastern boundary current system (Feng et al., 2005). It has a strong seasonal cycle, being strongest during winter when opposing equatorward winds weaken (Smith et al., 1991, Feng et al., 2003). In late autumn/early winter, the LC accelerates and rounds Cape Leeuwin off the southwest coast of WA to enter waters south of Australia, and continues as an eastward shelf current (the South Australian Current) along that coast (Ridgway and Condie, 2004, Middleton and Bye, 2007). During the summer season, sporadic wind-driven northward inshore currents and coastal upwelling events occur in limited shelf regions off the west coast, while wind-driven upwelling is more persistent off the southern coast of Australia.

On interannual timescales, variation in the depth of the thermocline associated with ENSO propagates through the Indonesian archipelago in the equatorial waveguide, and then poleward in the coastal waveguide, affecting the entire WA coast and into the Great Australian Bight (GAB). Higher sea level anomalies, warmer sea surface temperatures, and deeper thermocline, and a dose stronger Leeuwin Current are expected along the coast during La Niña years and vice versa during El

Niño. Observations suggest that the LC has been getting gradually weaker over the last 60 years, but recent research suggests that this trend reversed in the early 1990's (Feng et al., 2010).

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

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

4.3.3 Antarctic Circumpolar Current and Subtropical Front

The Antarctic Circumpolar Current (ACC) is the largest current in the world, carrying 150 Sv eastward around the Southern Ocean (SO), and has a major influence on Earth's climate and ocean circulation. It is closely coupled to the SO overturning circulation and therefore critical for this region (Marshall and Radko, 2003). The ACC thermally isolates Antarctica, with much of the flow occurring along narrow jets or fronts. Water properties across fronts change dramatically while between the fronts they are relatively uniform (Orsi et al., 1995, Sokolov and Rintoul, 2007). From north to south, the fronts and zones of the SO are: the Subtropical Front, the Subantarctic Zone, the Subantarctic Front, the Polar Frontal Zone, the Polar Front, and the Antarctic Zone.

The STF represents the northern limit of the Antarctic Circumpolar Current (ACC) that carries a large volume eastward around the entire globe and passes through the Southern Ocean between Antarctica and the Australian mainland (Orsi et al., 1995). The path of the ACC is constrained by land through the Drake Passage where flow has been estimated to vary between 28-290 Sv (Peterson, 1988, Bryden et al., 2005). Climatological estimates by Orsi et al. (1995) based on hydrographic data show that the ACC transport, relative to 3000 m, is about 100 Sv at all longitudes.

The northernmost extent of the ACC, the Subtropical Front (STF), is of interest to the South East Australia Node because of its role in determining the productivity of its waters (Harris et al. 1988). The Subtropical Front (STF) sits north of Tasmania in the Great Australian Bight, deviates around Tasmania and becomes very poorly constrained across the Tasman Sea. The STF is characterised by positive meridional temperature and salinity gradients. The effect of the temperature change on density is usually larger than the effect of the salinity change. The location of this front was carefully mapped by (Orsi et al., 1995) including the intrusion of this feature into the southern Tasman Sea.

However, the STF defined by Orsi et al. (1995) is a surface water mass boundary and water mass derived climatologies on the eastern side of basins suggest the STF coincides with a separate region of enhanced temperature gradients termed the Subtropical Frontal Zone (STFZ) where there is little transport (Graham and De Boer, 2013). The strong currents associated with the STF do not align with the STF water mass boundary, and it is apparent that the areas of enhanced SST gradients at the STF water mass boundary on the west and east of each basin correspond to two distinct features; the Dynamical Subtropical Front (DSTF) and the STFZ, respectively. The DSTF differentiates from the STFZ in that it is characterised by strong SST and SSH gradients, has no seasonal cycle and is a deep water mass boundary, as opposed to the STFZ which has weak SSH gradient and strong seasonal cycle (Fig. 4.13) (Graham and De Boer, 2013). The extent and location of the STFZ has been associated with productivity of the Tasman Sea (Harris et al., 1987) and the water properties south of Tasmania, show strong contrast between east and west sectors with the EAC and the Tasman Outflow driving the variability in the eastern side of Tasmania, a region with weak flow and enhanced input of subtropical water (Herraiz-Borreguero and Rintoul, 2011).

Figure 4.13: Annual SST gradient annual for the period 1999–2009; Climatology for the STF and SAF (orange—Orsi et al. 1995); DSTF (pink/white); and STFZ (pink circles) (Image from Figure 5 in Graham and De Boer, 2013).

4.3.4 Eddy Processes in boundary currents.

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

In South Eastern Australia, the region of the EAC from 34°S to below Tasmania is often described as an ‘eddy field’, with eddies generated off eastern Australia. The EAC eddies are 200-300 km in diameter and 2-3 eddies are generated annually and have lifetimes often exceeding a year (Nilsson and Cresswell, 1981, Bowen et al., 2005). They are likely to derive from a mixed barotropic/baroclinic instability of the mean flow (Mata et al., 2007). They follow complex southward trajectories, but are generally constrained within the deep basin. These eddies exhibit a westward vertical tilt with increasing depth indicating that they are actively fluxing heat poleward (Oke and

Griffin, 2011). Approximately one EAC eddy per year travel southward far enough to then move westward around the deep channels south of Tasmania. Less than half of these eddies continue their journey all the way into the Indian Ocean (Fig. 4.14). These EAC eddies are important in terms of the biological effects they can create during movement which can increase primary production in the region (Matear et al., 2013). Matear et al.'s (2013) improved, eddy resolving, model suggests that changes in the location of the STF and the movement of more nutrients into the euphotic zone due to eddy pumping can increase productivity in the Tasman Sea.

Figure 4.14: Eddy tracks obtained from altimeter maps for the period 1993-1999 show that some EAC eddies transit below Tasmania and into the GAB (Knuckey et al., 2010).

4.3.5 Science questions

Fluxes:

- *How do the mass, heat, and salt transports of the EAC, LC and ACC and the coastal currents in South Eastern Australia vary on seasonal, interannual, and multi-decadal timescale?*
- *How do boundary current transports respond to and influence regional climate?*
- *What are the relative contributions of air-sea fluxes, the mean flow, and eddies to the regional heat and freshwater budget?*

Drivers:

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

Dynamics:

- *What is the dynamical connection between boundary currents, interbasin flows and gyres in the South East Australian region?*
- *What controls variations in the strength of the eddy field associated with the major Australian current systems that affect the South East Australian region?*

4.3.6 Status, gaps, and future priorities

Status:

IMOS has deployed arrays of current meter moorings to measure the transport of the EAC. These measurements of this major deep-reaching current is complemented by glider and coastal mooring measurements made on the continental shelf by several regional nodes. SOOP XBT lines have been used to derive accurate transport estimates for the EAC, ACC and south Tasman Sea. Transport estimates from major current systems like those provided by IMOS are some of the most valuable and widely used metrics available for testing of ocean and earth system models.

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

The Maria Island National Reference Station has been key in observing the role of the Subtropical Front in stabilising the winter temperatures and nutrient conditions.

The offshore limit of the Storm Bay glider transects captures the clash of the Leeuwin Current and East Australian Current. As this interface is 3D dimensional in nature, the depth-resolved sampling of the glider is valuable in understanding the boundary current interaction.

Gaps:

- There are significant gaps in understanding the interaction of water masses of Bass Strait, in particular in upwelling/ downwelling zones (i.e. Bonney coast, Bass Canyon)
- Bass Strait discharge in winter links the Indian and Pacific Oceans, as well as shelf water to open oceans, but its transport is not measured.

Future Priorities:

In addition to priorities listed above, a mooring that captures the flow through Bass Strait would be of great value. Existing infrastructure and opportunities exist with oil and gas and Wonthaggi Desalination plant to strategically locate ocean instrumentation in the west, central and east of the strait. Given the cost of sustaining stand-alone moorings, use of this existing infrastructure to deploy instrumentation, would greatly reduce costs. Should this not be fundable, transport could be estimated through knowledge of ocean state (T, S) from the SOOPs trans Bass Strait transect using a data assimilating ocean model.

4.4 Continental Shelf and Coastal Processes

The boundary current systems transfer heat, salt and nutrients onto the continental shelf and into the coastal region. It is at the interface between the currents and the shelf that the large scale climate patterns such as ENSO, PDO, and the SAM undergo regional modulation through the interaction of the currents, eddies, and local coastal flows. Furthermore, the exchanges between the deepwater systems and the shelf are a two-way process, with outflows of freshwater and nutrients also spreading from the shelf to the deep ocean. Identifying local manifestations of these global phenomena is crucial to understanding the drivers of variability on the continental shelf and their influence on regional marine ecosystems.

4.4.1 Boundary current eddy –shelf interactions

Along the temperate east and west coasts, eddies formed in the boundary currents transport heat, nutrients and other properties between the open ocean and the shelf. Large-scale climate modes such as ENSO and SAM can influence the nature of the boundary currents and hence the exchange of properties across the shelf break. Eddies are particularly important off the narrow shelf regions on the temperate east and west coast of Australia. EAC eddies frequently move onto the continental shelf and close inshore and influence the local circulation patterns. At prominent coastal features the EAC moves away from the coast, driving upwelling that draws nutrient-rich water from a depth of 200-m or more. However, while the EAC may drive nutrient-rich water onto the shelf, upwelling-favourable winds (northerly) bring the water to the surface (Rochford, 1984, Cresswell, 1994). In the south east of Australia, the surface flow of the EAC and Zeehan Current (ZC) come into direct contact off south eastern Tasmania. The differences in forcing mechanisms, water masses, and seasonal expression directly influence shelf/slope exchanges around Tasmania (Ridgway, 2007b). Off south east Australia, mesoscale eddies are formed as part of the EAC traveling parallel to the coast with approximately one eddy per year traveling westward around the deep channels of southern Tasmania (Knuckey et al., 2010). These eddies can be re-absorbed by the EAC, can merge with other eddies making their path quite complex (Baird et al., 2011). These eddies entrain coastal waters influencing the biology of the region. There is a strong seasonal flow around Tasmania, where the EAC advects warm saline water poleward during summer followed by a seasonal reversal where cool fresh subantarctic surface water is drawn up by the now northward flowing current (Ridgway, 2007b).

The western side of the SEA-IMOS region, an eastward downwelling slope current is generated during winter along the southern shelf, when the Leeuwin Current (LC) is strongest. This creates a continuous boundary current that flows from North West Cape to southern Tasmania and forms the ZC when it enters waters west of Tasmania. The ZC influences this region in winter with its flow deflecting away from the coast in southern Tasmania following a meandering poleward trajectory and looping to the east. The southward current flow associated with the ZC is evident over both the continental shelf and slope (Fig. 4.15) and it peaks during winter. The ZC operates 180^0 out of phase to the EAC with the influence of both currents showing a strong division around the Tasman Peninsula (Ridgway, 2007b).

Figure 4.15: Monthly anomaly of SST from a composite SST product (1993-2003) (Ridgway, 2007b)

4.4.2 Upwelling and downwelling

Upwelling

Within the south east Australia region, a prominent surface cool-water upwelling plume extending from Cape Nelson, Victoria toward Kangaroo Island, South Australia, often referred to as the Bonney Upwelling, is the most predictable and intense upwelling off southern Australia, which occurs during the summer months (Fig. 4.16) (Butler et al., 2002, Nieblas et al., 2009). During that time, summertime mean winds blow towards the northwest along the coast, supporting the typical wind-driven upwelling, with the source of upwelling water in the region identified as Subantarctic Surface Water (SASW) (Kämpf et al., 2004). This coastal upwelling occurs at three centres simultaneously, namely off southern Eyre Peninsula, off southwestern Kangaroo Island and along the Bonney Coast, with the latter relevant to the SEA-IMOS Node. On a yearly basis there are approximately 2 to 3 major upwelling events, each ~one week duration. However, it is apparent that upwelling in the region does not always occur when winds are upwelling favourable, and studies have shown that where there is offshore Ekman transport occurring due to a divergence in alongshore currents, significant reductions in wind forced Ekman upwelling can happen (Middleton and Platov, 2003, Middleton and Leth, 2004). The role of this mechanism needs to be examined in the context off the Bonney Coast upwelling.

Figure 4.16: The summertime SST (February 2014) around the Bonney Coast region. Arrows denote estimated surface velocities from radar(blue and red arrows) and altimetry (black arrows) (OceanCurrent map from ***http://oceancurrent.imos.org.au/index.htm****).*

There is a linkage in water temperature linkage between the Bonney Upwelling and the waters of the western Victorian region, however, the cool pool of water evident in the Bonney Coast is masked by a warm mixed surface layer in western Victoria due to the wider shelf in that region (Levings and Gill, 2010). It is possible that there is a subsurface extension of this upwelling reaching into western Bass Strait as well (Butler et al., 2002).

These southern Australia upwelling centres are important in supporting Australia’s most valuable pelagic ecosystem, where a rich and diverse ecosystem is evident by the large numbers of sharks, whales and pinniped colonies (Kämpf et al., 2004).

To the south of Tasmania, interaction of the EAC with the slope can sometimes result in upwelling around D’Entrecasteaux Channel during March and April. This small scale uplift of nutrient rich waters is hypothesized to be the result of onshore flow in the bottom boundary layer to the passage of the EAC south of Tasmania (Volkman et al., 2009).

Downwelling

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

4.4.3 Shelf Currents

The coastal shelf in the South East Australia region is relatively narrow (10-25km wide) except for Bass Strait, which is has an average depth of 50-70 metres and connects Tasmania with mainland Australia and the Great Australian Bight to the Tasman Sea. This region supports a diversity of marine ecosystems that includes submerged temperate rocky reefs and canyons on each side of the strait that supports high biological diversity and endemism (Sandery and Kämpf, 2005). In addition, a diversity of marine industry activities such as fishing, shipping and oil drilling and processing take place in this particular region. Tides and wind action mix the waters in Bass Strait, however, the central the central region becomes stratified during the summer months. Wind driven flow dominates tidal flows at a seasonal scale, with wind-driven depth-averaged currents topographically controlled and geostrophic in nature (Sandery and Kämpf, 2005). The central area of the strait is a stagnation-area of weak currents and long flushing times (~160 days). Tidal currents in the strait are the cause of the strong vertical mixing at the edges, while wind-driven currents determine the overall seasonal-scale circulation and flushing in Bass Strait. Mean westerly winds during winter and spring bring a net eastward flow in the strait and flushing from the west, with water mass transported from the west having a greater influence than that from the east.

Elsewhere in the South East Australia region there are no well-defined shelf currents due to the narrow shelves. However, the interaction between the ZC, EAC, and Subtropical Front makes for a dynamic shelf environment at the confluence of 3 different systems. Along the southern shelf the circulation is predominantly the result of wind forcing, with an eastward current over the continental shelf flowing from Cape Leeuwin to the southern tip of Tasmania (Godfrey et al., 1986, Cresswell and Peterson, 1993, Cirano and Middleton, 2004).

4.4.4 Wave climate, including internal and coastally trapped waves.

Along the south east Australian coast, waves are generated by a range of meteorological systems such as tropical cyclones, east coast cyclones, zonal anticyclonic highs from the east, intensified extratropical cyclones from south Tasman Sea, and local summer sea breezes (Short and Trenaman, 1992). Under climate change scenario, it is important to understand the wave climate of the region since wind driven waves can contribute to higher than normal sea levels during storm events as well as short and long-term coastline recession from ephemeral and chronic coastal erosion (O'grady and Mcinnes, 2010). In south eastern Australia, wave heights in eastern Bass Strait are 40% lower than at sites around Tasmania's west coast and southern Australia but are 10% higher than those around Eden in the east coast and wave periods in Bass Strait are lower than in the west and east (O'grady and Mcinnes, 2010). The southern Australian coast faces the highest energy surface waves in the world that come from the Southern Ocean (Short, 1988). Orientation of the coastline as well as reefs and headlands serve to decrease some of the wave energy near the coast (Short, 1988) and thus this part of the coast can have high and low wave-energy environments.

Coastally trapped waves (CTWs) are generated by the alongshore component of the wind stress, and are the primary mechanism by which the ENSO signal is transmitted around the coast of Australia and at a global scale climate change has a significant effect on surface wave climate (Young et al., 2011). Waves generated along the southern shelves drive CTWs within Bass Strait and on the NSW shelf (Middleton and Black, 1994), dominating the variability of the SSH in the South East Australia region on timescales between one day to several months (Woodham et al., 2013 and references within). Along the southern shelf CTWs of large amplitude (~0.5 m) are observed regularly (Provis and Radok, 1979, Church and Freeland, 1987). The wind stress along shelf component drives CTWs in the GAB which can either propagate to the south around Tasmania and then north along the east Australian coast or propagate east through the western entrance of Bass Strait (Church and Freeland, 1987, Woodham et al., 2013). Model and observation data showed that CTWs propagate as continues features between south-west and north-east Australia unaffected by the sharply changing coastline orientation, shallow bathymetry (Bass Strait) or wind forcing regions. Although CTWs travel faster and have greater wavelengths where the continental shelf is wider and their amplitude is modulated by the local bathymetry (Woodham et al., 2013).

4.4.5 Science questions

Boundary Current/Shelf Interactions:

- What are the influences of the boundary currents and the associated meso-scale and sub-meso-scale eddies off south east Australian waters over the continental shelf and how do they impact cross shelf exchange and water properties?
- How does the EAC and ZC interact with the continental shelf/slope break and topographic features (such as canyons) generating upwelling, internal waves, and mixing?
- What effect does the dissipation of internal tides from the Tasman Sea, which break on the eastern shelf, have on the productivity in this region- and is this likely to change with a changing climate?

Upwelling and Downwelling:

- What are the frequency, magnitude, and drivers of upwelling/downwelling processes and slope water intrusions in the coastal waters off South East Australia and how do they influence cross shelf exchange of properties?
- Does tide or wind driven upwelling increase the productivity of Bass Strait?
- What are the mechanisms for upwelling and the magnitude and spatial extent in the Bonney Coast.
- What role do canyons play in variations in upwelling/downwelling cycles in southern Australian waters?
- What is the spatial and temporal extent of the downwelling in eastern Bass Strait?
- Is the southern extension of the EAC providing any likelihood for summer upwelling fluxes in Bass Canyon?

- Are there changes noted in the fisheries, that can be mapped to changing dynamics in the Bass Strait upwelling/downwelling system?

Shelf Currents:

- What is the magnitude and variability (interannual, seasonal, and higher frequency) of currents off south east Australia?
- What are they dynamical drivers of currents off south east Australia and how do the EAC, ZC and ACC interact?

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?
- Are internal waves important? Internal waves may also be important in vertical mixing as found on the northwest shelf slope.
- Is there likely to be a change in the CTW propagation through Bass Strait given the likely shifts in geostrophic currents and seasonal wave patterns?
- Offshore pipeline stability design is of vital importance in the offshore industry. Stability of an offshore or subsea pipeline is greatly influenced by the external environmental conditions. This is especially true around near shore crossings where current and wave interactions can induce sediment transfer and scour around pipelines. As the need for natural resources, such as oil and gas grow within Australian waters, so too does the infrastructure needed to facilitate this industry.

4.4.6 Status, gaps and future priorities

Status:

The IMOS observing strategy for continental shelf and coastal processes is to provide an extensive national backbone around the continental shelf, and more intensive observations in regions of socio-economic and ecological significance e.g. coral reefs, biodiversity hotspots, population centres, and regional development hubs. These observations include National Reference Stations such as the Maria Island reference station and other shelf moorings. Argo, boundary current arrays, ship of opportunity measurements (particularly in Bass Strait), and satellite remote sensing also contribute to observations in the region. Slocum glider deployments in Storm Bay are also contributing to observations in the coastal area of the SEA-IMOS region. In many cases, IMOS measurements on the continental shelf and in the deep ocean have been coordinated to exploit the synergy between them (e.g. extension of the EAC and ITF mooring arrays over the continental shelf).

Figure 4.17. Combined correlation maps for interannual SST. The location of each NRS is marked with a green bullet. Yellow depicts regions where observations from all NRS stations.

Gaps:

- The continental shelves off western and southern Tasmania have no current continuous observations, and no time-series have been taken. Nationally this is one of the largest gaps in continental shelf observations (Fig. 4.17). Fig. 4.17 quantifies this gap by temperature, a proxy for water mass. Therefore the gap in physical observations is likely to be true of biogeochemical properties, as sampled by the NRS network.
- There is a gap in the understanding of the ‘through put’ of energy in Bass Strait due to a lacl of continuous deployed instruments and data collection. In addition there is limited understanding of the flux through canyons at each end of Bass Strait were it is likely that climate change will impact on the existing “known” function of this system (~ Church et al 1980’s).
- Furthermore state government stakeholders have a high priority to understand nearshore processes (i.e. less than 3 nautical miles d from the coast). For example better understanding of linkages (chemical/physical/biological connectivity) between shelf and inshore/coastal/bay-estuary systems/ecosystems.
- Data to calibrate high resolution inshore current and dispersal models

Future priorities:

The priorities listed in above themes will also aid in the answering the science questions of this theme.

- Although unlikely to be funded in the near future, the above mentioned analysis demonstrates that western and southern Tasmania are among the regions least represented by the national reference stations, and should be considered first if a new NRS site was to be funded.
- Leverage opportunities in Bass Strait with existing infrastructure in the east (ESSO, central Wonthaggi Desaliniation Plant) and west (Origin platforms; Deakin temperature moorings dataset).

4.5 Ecosystem Responses

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

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

Another key area for the south east Australia region is the Southern Ocean. Changes in Southern Ocean circulation can be thought of as sensitive early indicators of global climate changes (Houghton et al., 2001), which also affect the Southern Ocean ecosystem. Despite the fact that the Southern Ocean plays a central role in the global climate system (Busalacchi, 2004) and increasingly supports human activities such as commercial fishing, the nature of the interactions between physical and biological processes is poorly understood.

Another important physical driver of pelagic ecosystems and their responses to climate change are mixed layer dynamics, including the south east Australia region, with strong seasonal cycle in mixed layer depth. These dynamics are widely expected to be impacted by global warming as the surface layer of the ocean warms and the normal seasonal dynamics of the mixed layer are affected. The major impact is expected to be on seasonal nutrient recharging of the surface mixed layer and the consequences this might have on primary production as nutrient availability is a major factor influencing phytoplankton abundance (Yoder et al., 1993). The supply of nutrients to the euphotic zone is primarily dependent upon the depth, rate and temporal dynamics of vertical mixing. Vertical mixing can also be a major determinant of phytoplankton irradiance, thus it is of fundamental importance to phytoplankton ecology. Off the east coast of Tasmania in winter the mixed layer depth (MLD) can exceed 80 m and this deeper winter mixing must slow phytoplankton growth (Sverdrup, 1953) and create a different ecological niche (e.g.Margalef, 1978).

The spring bloom of phytoplankton in the SE region of Australia is very dependent upon the transition from a deep mixed layer in winter to a shallower mixed layer in summer. In addition there is clearly an important shift in MLD at the location of the subtropical Front where the annual amplitude is as large as the North Atlantic (Fig. 15). Small changes in MLD in this region are likely to dramatically shift the productivity of this front.

4.5.1 Ocean Chemistry – Nutrients

Primary production in the ocean is limited by regional patterns of light and nutrients. Background nutrient levels are controlled by the large-scale ocean circulation. The response of nutrients to changes in ocean circulation is key to understanding how the productivity in Australian waters will change. However, observations in Australian regional seas are patchy for macronutrients N, P and Si, but especially for micronutrients such as iron.

Primary production in the oceans is limited by the availability of light and nutrients. For the purpose of this discussion it is considered that dissolved inorganic nutrients are the primary nutrients of interest while noting there are some prominent exceptions. The major reason for considering dissolved inorganic nutrients is that phytoplankton are mostly autotrophic (syn. lithotrophic), i.e. they acquire most of the elements they require as inorganic salts. The inorganic nutrients known to be required by most algal cells includes a long list of major and minor elements with most elements present in abundance and bioavailable. The elements that most often limit phytoplankton growth or biomass in the ocean are: C, N, P, Si and Fe. Thus these elements and their biogeochemistry are most important to the functioning of our ecosystems.

The naturally occurring concentrations of nitrate, silicate and phosphate can be obtained from the CSIRO Atlas of Regional Seas (CARS, http://www.marine.csiro.au/~dunn/cars2009/) and comprises gridded fields of mean ocean properties over the period of modern ocean measurement, and average seasonal cycles for that period. The CARS analysis by Condie and Dunn (2006) shows low concentrations for nitrate around the whole continent (Fig. 4.17). The east coast and the SE region all the way to the GAB are very low in silicate.

Figure 4.17: Regional nutrients: Analysis of all CSIRO surface (0m) data for silicate (top panel), nitrate (middle panel) and phosphate (bottom panel). Concentrations (µM) are given on the major contours

On the continental shelf, ecosystems are largely supplied with nutrients from two external sources: terrestrial run-off from coastal catchments and marine upwelling from the adjacent ocean. Other nutrient sources include rainwater and nitrogen fixation by cyanobacteria. Nutrient inventories around the Australian continent show generally low nitrate concentrations, particularly along the western and eastern coastlines which are both strongly influenced by poleward flowing boundary currents. Upwelling adds additional loads of dissolved nutrients to subsurface waters and signatures of upwelling (cold SST, high Chl-a) have been identified around the south east coast of Australia. Other processes that seemed to be involved in nutrient supply around Tasmania are associated with wind patterns and water mass variation, or cross-shelf exchanges at the shelf break. Relative to dissolved inorganic N and Si, the phosphate concentrations are high and do not suggest an ecosystem where P is limiting. Si concentrations off the east coast of south east Australia, including Tasmania have shown a decline in the past 30 years, perhaps in response to variation in the SOI and the strengthening of the EAC (Thompson et al., 2009). In the case of Fe, phytoplankton growth in large areas of the world's oceans has been shown to be limited by this nutrient. In the Australian and Tasmanian regions the main source of Fe is aeolian dust (Mackie et al., 2008), with delivery that depends on the distribution of drought (Fig. 4.18). Whether the availability of Fe limits the primary production in Australian coastal waters is an area of active investigation.

Figure 4.18: Major dust transporting winds and ensuing dust pathways over continental Australia (from McGowan et al. 2000, redrawn from Sprigg 1982).

4.5.2 Ocean Chemistry – Carbon and acidification

Current CO_2 emission trajectories indicate the upper ocean will undergo a shift in carbonate chemistry in this century that is profound. The upper ocean pH has declined by about 0.1 since preindustrial times and will decline by 0.4 if atmospheric CO_2 concentrations reach 800ppm by the end of this century (Caldeira and Wickett, 2005). All regions of the ocean will show a decline in calcium carbonate saturation states. The Southern Ocean is predicted to cross a threshold where aragonite, a form of carbonate produced by many important marine calcifiers, will be undersaturated by about the middle of this century (Fig. 4.19) (Orr et al., 2005).

Figure 4.19: Changes in the saturation state of aragonite for surface waters from the preindustrial era, represented by the year 1765, until year 2100. Values below one are undersaturated. The saturation states were modelled using the CSIRO carbon cycle model. Changes after the year 2000 based on the IS92a emission scenario have now been exceeded (Canadell et al., 2007), indicating a more rapid approach to undersaturation. Note the lowered saturation near Antarctic and the declines in saturation state further north. (Figure generated from CSIRO BGC model using the model simulations of Orr et al., 2005.)

The ecosystem response to acidification is not well understood and is an area of intense international research. Incubations of corals and other marine calcifying species grown at elevated CO_2 do show reduced rates of calcification (Riebesell et al., 2000, Langdon and Atkinson, 2005, Gazeau et al., 2007), although the response varies among species (Iglesias-Rodriguez et al., 2008). Multiple stressors like warming can also affect the acidification response (Byrne et al., 2013). Non-calcifying species may be impacted in ways that could alter ecosystem dynamics and nutrient availability (e.g. Boyd and Doney, 2003, Hutchins et al., 2007). The potential for impact on fish populations and larval survival is undetermined. Lack of data on the change in carbonate chemistry in these environments makes a definite link difficult to establish. In the coastal zone most taxa are well adapted to quite a wide range in pH and alkalinity. There are, however, a range of calcifying species including reef building corals, commercially important shellfish and a range of phytoplankton and zooplankton at some risk from the falling pH. One of the world's largest blooms of calcifying phytoplankton occurs along the SubTropical Front and intersects with Tasmania. The changes in and drivers of carbonate chemistry need to be measured to determine the exposure of ecosystems to acidification and to evaluate the likely ecosystem response to the change.

4.5.3 Pelagic: Plankton

Phytoplankton

Phytoplankton contributes half of the primary production on earth, and while the “standing biomass” of phytoplankton is small compared to the terrestrial ecosystems, the rate of primary production is about equivalent due to their rapid lifecycles. Predicting the response of phytoplankton productivity and community structure to climate change is complex, with some modelling studies (Bopp et al., 2001, Boyd and Doney, 2002, Le Quéré et al., 2003, Bopp et al., 2005) suggesting a global decline in phytoplankton biomass in a warmer world.

In Australia the two poleward warm boundary currents are nutrient poor leading to low productivity marine systems. However, high rates of primary productivity are found in the south coast of Australia, around the Bonney Coast, due to the influence of upwelled water mass, and are comparable to levels reported for the highly productive upwelling systems of the Benguela Current off southern Africa, and the Humboldt Current off the coast of Chile (Van Ruth et al., 2010a, b). Highest phytoplankton abundances in the region associated with the upwelled water mass is composed by >5 µm phytoplankton dominated by diatoms and dinoflagellates, with small flagellates present but much less abundant (Van Ruth, 2009a). There are no continuous local time series of phytoplankton suitable to investigate long term changes. SeaWiFS data showed long term trends in the annual spring bloom near Maria Island, which has declined for 10 years. Consistent with this has been the reduction in phytoplankton biomass in spring (October).

In the east of Australia, there is evidence of phytoplankton species communities changing with diverse consequences to the local ecosystems. Warm water species are moving southward along the east coast, perhaps associated to the strengthening of the EAC paving the way for the apparent range extension of warm-water organism into Tasmanian waters. There is concern that some of these species could be toxic or harmful with potential blooms causing a shutdown of fisheries and aquaculture operations in the region. Blooms of a toxic dinoflagellate species, *Gymnodinium catenatum*, have regularly shut down aquaculture operations in Tasmania. This species shows significant interannual variability in Tasmania but the underlying mechanism remains unclear. In 2012 and again in 2013 a bloom of *Alexandrium tamarense* resulted in the closure of a wide range of fisheries along most of the east coast of Tasmania. This taxon has been found in Tasmania before but never bloomed. Investigations are underway to understand more about this dangerous pest but it is reasonable to speculate that its new levels of abundance are related to the long term changes in our marine ecosystems associated with climate variability.

Ocean colour satellites are the best way to observe large scale changes in phytoplankton abundance and distribution. The marine and climate science community has highlighted the need for a consistent, well calibrated time series of ocean colour products to assess primary productivity and phytoplankton biomass for the Australia’s regional seas and the Southern Ocean.

Zooplankton

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

In south east Australia, there is evidence that warm-water “signature” species are moving into the region (Johnson et al., 2011). Some of these changes in the zooplankton communities are associated with changes in nutrient conditions forced by wind-driven circulation (Harris et al., 1991, Harris et al., 1992), incursion of the EAC, increased water column stability and reduced biological production (Johnson et al., 2011). The phenomenon of “tropicalization” of temperate plankton communities has potentially important ecosystem consequences. The reduced nutrient availability in warm years has led to reduced production and a shift to smaller phytoplankton species, resulting in a drastic reduction of large zooplankton biomass, particularly krill (*Nyctiphanes australis*) which has seen a reduction of its population since the 1980s (Johnson et al., 2011). *N. australis* is a major component of the zooplankton community in coastal waters of south-eastern Tasmania (Ritz and Hosie, 1982) and it is also the main prey of many coastal bird and fish species in this region (O’brien, 1988). The abundance of *N. australis* is related to the balance between subtropical and subantarctic waters and the stability of the water column, with stratification and high temperatures at Maria Island associated with low abundances (Young et al., 1993). Another indication of this “tropicalization” is the expansion of the calanoid copepod *Parvocalanus crassirostris* which is primarily a tropical and subtropical species. This shift will have flow on effect over the entire food-web and will ultimately impact fisheries production. In addition to the temperature effects driving redistribution, coastal eutrophication has also been shown to change the size spectrum of zooplankton assemblages (Uye, 1994). The arrival of *Noctiluca scintillans* (Thompson et al., 2008) in southern Tasmania has been a major impact of climate change on zooplankton within Australia. The appearance of *Noctiluca scintillans* and the apparent decline in *N. australis* indicate profound trophodynamic shifts, possibly a mismatch between successive trophic levels and a change in the synchrony between primary, secondary, and tertiary production. Efficient transfer of marine primary and secondary production to higher trophic levels, such as those occupied by commercial fish species, mammals and birds, depends largely on the temporal synchrony between successive production peaks, especially in temperate marine systems (Cushing, 1990). In addition**, t**here has been heated debate about whether jellyfish populations are increasing globally as a result of climate change and overfishing (e.g. Richardson et al. 2009). One of the longest standing time-series for jellyfish in the World comes from Port Phillip Bay (Condon et al. 2013) and has proved a key resource for assessing climate change impacts on this group. Yet the time-series has been discontinued due to funding cuts. Monitoring jellyfish changes of abundance remains important.

Peak meso-zooplankton abundances and biomass in the eastern Great Australian Bight have been shown to occur in highly productive upwelled waters, in areas with greatest phytoplankton abundances, with the community dominated by copepods (Van Ruth, 2009b, Van Ruth and Ward, 2009). Similarly, the spatial and temporal abundance of macro-zooplankton and small pelagic fish at a site off western Victoria are closely associated with the proportion of upwelled water on the shelf, and alongshore wind stress (Morrice, 2014). It is likely the neritic fauna and thus sediments off the Bonney Coast are also closely linked to meteorological and ocean processes affecting primary production and sediment formation (James and Bone, 2011).

4.5.4 Pelagic: Nekton

Micronekton

Micro-nekton plays a pivotal role in the ecosystem, connecting plankton at the base of the food web to the higher trophic levels. The group comprises the larger zooplankton and smaller nekton (2-20 cm) which includes adult krill, small fish, crustaceans, squids and gelatinous species. They may account for a significant fraction of the ocean's biota, however, accurate estimates are difficult to obtain as their distributions are patchy in time and space and thus are a poorly studied faunal group. Many are carnivorous and some are herbivores and are important prey for seabirds, larger fishes and marine mammals. Krill are especially important as prey for many marine species and are a major source of food for whales, penguins and some pinnipeds in the SO. Recent coupled ocean-biogeochemical-population models have identified a gap in knowledge on the distribution, biomass and energetics of mid-trophic level organisms such as this one (Fulton et al., 2005, Lehodey et al., 2010). Micro-nekton biomass at an ocean basin scale has been estimated at 29 g m^{-2} off eastern Australia using a combination of net samples and multifrequency acoustic methods (Kloser et al., 2009). In the nearshore, other important components of micro-nekton that dominate the biomass in Australia are small pelagic fish species such as anchovies, sardines (Ward et al., 2006) and red bait. Around the shelf and shelf break off the east coast of Tasmania upwelled cool, nutrient-rich water which enhances productivity showing greater biomass of zooplankton and micronekton than on the shelf than off the shelf waters and serves as prey for small pelagics in this region (Young et al., 1996). Expected impacts of climate change will modify the distribution and abundance of some of these species, with the range of many warm water species potentially expanding south and replacing species with cold water affinities, while an increase in upwelling favourable conditions could see populations of species living near upwelling regions, such as sardines, benefit (Hobday et al., 2006). South east Australia is one of the fastest warming regions in the southern hemisphere where there is evidence of climate-related distributional change for a range of marine taxa, including: phytoplankton (Hallegraeff, 2010), zooplankton (Johnson et al., 2011), invertebrates (Ling et al., 2009), and coastal fishes (Last et al., 2011). Off eastern Tasmania, the shift in the abundance of small pelagic fish species has been linked to environmental changes, where the replacement of jack mackerel with redbait was consistent with altered zooplankton communities and long-term climate change (Mcleod et al., 2012).

However, the sparse observations that come from a variety of sampling devices are of limited spatial and temporal extent, making it difficult to compare biomass estimates or to establish trends. Developing a synoptic dataset through time on these mid-trophic groups would fill an essential gap between the abundant observations available at the physical scale from satellites and modelled data, and the higher trophic levels via fisheries data and electronic tagging of top predators.

Large fishes

High trophic level fishes such as tuna, billfish and some species of sharks often act as integrators of the oceanic ecosystem. They are sensitive to changes in the distribution and abundance of their prey, which in turn respond to changes in lower trophic levels and the physical environment. In general, most of the information on distribution and abundance of pelagic species comes from fishery dependent records where the species are exploited (Worm et al., 2003, Zainuddin et al., 2006). Fishery-independent data on the distribution of the larger pelagic species has been gathered by electronic tags that record the location of the fish and some environmental information such as temperature and depth (Arnold and Dewar, 2001, Gunn and Block, 2001, Block et al., 2003, Schaefer and Fuller, 2003). These records have shown that many of these species are constantly on the move at ocean basin scales possibly in search of food or migrating to common spawning areas.

The effect that climate change may have on large pelagic species will be on their distribution. For example, change in ocean temperature can impact the distribution of Southern Bluefin tuna, which are restricted to the cooler waters south of the EAC and expand further north when the current contracts up the NSW coast (Majkowski et al., 1981). Therefore, their population could be restricted further south if Tasman Sea warming continues. Preliminary analyses indicate that changes may have already occurred, with fewer fish moving to the east coast in the Austral winter (Polacheck et al., 2006). On the other hand, the increased southward penetration of the EAC may increase the suitable habitat for species such as yellowfin and bigeye tuna. Some groups, such as eels that live as adults in the rivers of southern Australia but breed in the Coral Sea, are likely to be heavily impacted by changes in the EAC. Yet the at-sea movements of this group remain unknown even though systems now exist for tracking them for extended periods.

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

Last et al. (2011) study shows that ~45 fish species have exhibited major distributional shifts in the region around Tasmania that is thought to be climate related, with about a fifth of the coastal fish fauna undergoing compositional shifts. Of these, at least 5 species have showing sharp declines and some species such as the greynurse shark and mulloway locally extinct perhaps due to fishing pressure. Citizen science schemes such as REDMAP are allowing the monitoring of species range shift to be monitored in a cost effective way enhancing monitoring efforts of science organisations.

In the Bonney Coast, upwelling introduces deeper cool nutrient-rich water to the nearshore increasing chlorophyll concentrations that suggest enhanced primary production (Nieblas et al., 2009). This in turn leads to high densities of krill *N. australis* which attracts schooling jack mackerel and their predators such as migrating southern bluefin tuna (Young et al., 1993, Young et al., 1996) as well as blue whales (Gill, 2002).

Other important productive regions where aggregation of large fishes and other predators occur are around Victoria in Bass Strait and east of Eden, both regions related to the related to the Bass Cascade.

Marine mammals

Marine mammals are found in all of the world's oceans with Australia recognised as a hotspot of marine mammal species richness (Pompa et al., 2011). They can be found at different trophic levels, these include herbivores such as dugongs, mid-trophic levels such as baleen whales and high trophic levels such as pinnipeds and most species of cetaceans (Pauly et al., 1998). The majority of research on Australian marine mammals has been focused on accessible species such as seals, coastal dolphin species or whales which appear in seasonally predictable near-shore regions.

There is currently a low level of confidence in the predicted effects that climate change may exert on Australian marine mammals due to a lack of information on most species, particularly of the distributions, population sizes or ecologies of many species. Therefore, the adaptive capacity of marine mammals to climate change in Australia is poorly known (Schumann et al., 2012). However, non-climatic stressors such as fishing activities, harvesting, boat strikes, coastal development and degradation and acoustic pollution, among others, are thought to exacerbate the vulnerability of marine mammals by acting in synergy with climatic impacts (Schumann et al., 2012). The paucity of data on Australian marine mammals and consequently, the long- term cumulative impacts of human activities and climate change on marine mammals are not well understood. It is evident that the primary climatic influence on many marine mammals appears to be food availability and distribution, which is linked to ocean temperature (Neuman, 2001, Leaper et al., 2006). Therefore, sea surface temperature (SST) is commonly used as a proxy for biological productivity (Bradshaw et al., 2004), with many marine mammals selecting particular SST in which to forage.

The Bonney Coast is one of the 12 feeding sites recognised worldwide for Blue Whales (*Balaenoptera musculus*) (Gill et al 2011), where they aggregate in relatively high numbers, they have also been spotted feeding off Eden and between King Island and Tasmania in Bass Strait. The region harbours in total 26 listed threatened species of which 2 are whales (Butler et al., 2002).

In the east of Tasmania, the Subtropical Convergence Zone is an area of high productivity where seasonal pelagic production that favours large diatoms and zooplankton supports fisheries of Jack mackerel and tuna and also aggregation of whales (Dambacher et al., 2012).

Sea turtles

Recent work has highlighted that the southern coasts of Australia are a globally important feeding ground for the giant leatherback turtle (Dermochelys coriacea) (Benson et al. 2011).Australia has national and international obligations to protect endangered species that migrate widely, being a signatory to the Convention of Migratory Species (http://www.cms.int). The EPBC Act also lists leatherbacks as an endangered species and actions to reduce threats are included in the Australian Government's Marine Turtle Recovery Plan (currently under revision). Although bycatch mitigation and mandatory catch reporting occurs in some Australian fisheries, there is no concerted work to identify how turtle deaths might be reduced. This knowledge gap is alarming. While the occurrence of leatherback turtles in Australian waters has now been highlighted, they could very quickly be gone tomorrow if high levels of bycatch continue, with individuals being incidentally caught in various types of fishing gear. Hence monitoring of sea turtle patterns of occurrence, foraging hotspots, long-term trends and bycatch mitigation strategies are needed.

Seabirds

Seabirds are highly visible, charismatic animals in marine ecosystems that feed exclusively at sea, in either nearshore, offshore or pelagic waters. They are efficient integrators of ecosystem health, as many feed on small pelagic fish and zooplankton and thus are sensitive to changes at lower trophic levels. In Australia, a diverse seabird fauna breeds on mainland and island coastlines. Almost a quarter of all albatross species have nesting sites on islands around Tasmania and Macquarie Island, and some species also benefit local economies through ecotourism, such as with the colonies of little penguins on Phillip Island and Tasmania.

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

4.5.5 Benthos

Benthic ecosystem vulnerability to climate change is still undergoing research as variability and local effects become the subject of evidence based time series observations. Climate change may modify population dynamics over time and space, phenology, and the geographical distribution of communities (and species; Dulvy et al., 2008). These modifications could result in habitat loss and species extinctions over time, with repercussions for biogeochemical fluxes, ecosystem functioning, and biodiversity. The need to assess and monitor benthic changes in relation to a wide range of stressors, including climate change, has prompted researchers to collect information over a long time ‐ scale. The South East Australia region has a high diversity of benthic ecosystems that include kelp forest, cold water corals, canyons and seamounts, all of which supports a high diversity of endemic marine organisms.

Current requirements under international legislation (Water Framework Directive (WFD), Habitats and Bird Directives, EU Marine Strategy Framework Directive(MSFD), US Clean Water Act (CWA), US Oceans Act, etc.) focus on the quality and status of the marine environment (see Borja et al., 2008, 2010, for an overview). However, under the new MSFD, climate change is included. Possible effects are, at present, an unquantified pressure on species and ecosystems. Little is known about the robustness and sensitivity of the proposed “Good Environmental Status” (GES) descriptors that will be used to support future assessments (see also additional information provided in Borja et al., In press). Benthic systems have been studied by employing a suite of indices as tools to characterize community status (e.g. Borja et al., 2000; Rosenberg et al., 2004; Muxika et al., 2007). Although there is merit in these approaches, there is still a need to fully understand the function and mechanisms that are altering these processes; such studies will lead to a better knowledge of benthic responses and a more targeted tool for the environmental management of marine systems (Birchenough et al.). Throughout the life of IMOS to date, the IMOS AUV facility has been adopted by the Australian ecological community in a coordinated nation-wide program to describe and monitor spatial and temporal patterns in marine benthos associated with temperate and tropical reef systems across the continental shelf. In this time, surveys have described meso-photic reef systems in the GBR, the influence of coral bleaching at Scott Reef, the impact of marine heatwaves at the Abrohlos Islands, the spatial and depth distribution of *Centrostephanus barens*, marine canyon fauna in NE Tasmania, and the benthic fauna of a range on new CMRs (Smale et al. 2012; Williams et al. 2010; Bridge et al. 2012; Perkins et al. 2014; Marzinelli et al. 2015)..

Kelp forest

Kelp species are distributed throughout the southern half of Australia wherever there is persistent hard substrata with enough light and they exhibit unusually high endemism and diversity (Womersley, 1990, Phillips, 2001). Southern Australia contains by far the highest diversity of brown algae (140 species per 100 km section) of all the rich kelp areas of the world, with the distributions of some individual kelp species limited to areas such as the South Eastern and South Western Large Marine Domains.

Kelp forest ecosystems are vulnerable to potential climate changes because they are sensitive to increase in temperatures and turbidity, decrease in nutrients and light penetration, and outbreaks of herbivores due to depletion of predators. The ramifications that changes in the density, distribution, or production of canopy-forming algae will have to the structure and functioning of these important seaweed-based communities are likely to be widespread (Dayton and Tegner, 1984, Reed and Foster, 1984, Johnson and Mann, 1988, Schiel, 1988). Kelp dominated habitats are highly biodiverse (Edgar, 1983, 1984, Ling, 2008), and in Tasmanian waters these forests support economically important abalone, rock lobster and scale fish fisheries. *Ecklonia radiata* forests are being impacted on two fronts: an increase in temperature shifting south its northern limit and the arrival of warm water species such as the spiny sea urchin *Centrostephanus rodgersii*, which is associated with the destruction of kelp and the formation of urchin barrens along the east coast of Tasmania and Victoria. It is thought that the southward movement of *C. rodgersii* is related to a strengthened EAC transporting their larvae, which in combination with rising east coast temperatures provide a suitable environment for them. The expansion of extensive areas of ‘urchin barrens’ habitat in the north east, and ‘incipient’ barrens over many other areas of the east coast, represent an important threat to the integrity and biodiversity of nearshore reefs and associated valuable fisheries in the region (Johnson et al., 2005, Ling, 2008). The IMOS AUV facility has contributed to a wide range of studies documenting kelp forest cover throughout temperate Australia, ranging around the temperate coastline from deep-water Ecklonia forests off Brisbane to the coral/kelp interface at the Abrohlos Islands in WA. These studies have allowed documentation of the impact of marine heatwaves in WA, the impact and extent of Centrostephanus barrens on kelp cover in Tasmania and NSW, and nation-wide patterns in kelp distribution and condition.

Deep water reefs

Deep sea cold-water corals are distributed globally but in Australian waters they are only found around south and southeastern Australia. Similar to tropical coral reefs, deep sea cold-water coral reefs are essential fish habitat and are considered “hotspots” for biodiversity. However, unlike their tropical shallow water counterparts, deep sea corals lack the symbiotic algae and are found down to depths of over 1000 meters below sea level. These ecosystems can have large aggregations of fish, such as the commercially important orange roughy (*Hoplostethus atlanticus*) found on some seamounts, providing shelter, feeding grounds, spawning grounds and nursery areas (Bull et al., 2001, Dower and Perry, 2001, Reed, 2002). However, knowledge of the ecology, population dynamics, distribution and ecosystem functioning of deep-sea corals is sparse. In addition, these reefs are long-lived, slow-growing and susceptible to physical disturbance, making them extremely slow to recover from damage (Morgan, 2005). The three major threats to cold water corals are bottom trawl fishing, ocean acidification and seabed mining. They are highly vulnerable to rapidly declining aragonite saturation associated with rising CO_2 and declining pH consequently making seamount habitats off South Australia inhospitable for cold water corals below a few hundred metres. Since these deep sea corals are a foundation species, their disappearance will have dramatic consequences for the entire ecosystem sustained by them.

Submarine canyons

Over 100 submarine canyons cut into the continental margin around south east Australia (Hill et al. 2005) with some extending from the continental shelf edge (150 to 200 m depth) to the abyss (> 3000 m depth) (Schlacher et al., 2007). Seamounts, which are regarded as benthic hotspots in the deep sea display high levels of benthic biomass, diversity and endemism (Rogers, 1994, Richer De Forges et al., 2000) and show comparatively high levels of species richness. For some species such as sponges the diversity found in canyons in south east Australia can even rival those found in the Coral Sea (Schlacher et al., 2007).

Seamounts and submarine canyon are recognised as ‘special’ types of geomorphic surrogates for biodiversity hot spots (Harris, 2007) and knowledge of Australia’s deep sea ecosystems that includes seamounts, and submarine canyons has increased dramatically over the last 2 decades (Kendrick et al., 2014). However, many important aspects of deep-sea functioning remain a mystery such as the unexplained extraordinarily high biomass of benthic megafauna on a rocky seabed in 2300 m depth off south eastern Tasmania (Thresher et al., 2011).

Benthic macro invertebrates and demersal fish

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

4.5.6 Science questions

Productivity:

- *What is the role of the EAC and eddies on primary production in the south east region?*
- *Does tide or wind driven upwelling increase the productivity of the south east region?*
- *Are there spatial patterns in the distribution of productivity that can be related to upwelling at a local scale, such as at canyon-heads, and where such features incise the shelf?*
- *What mechanism determines the location of the SubTropical Front and how does this impact on South East Australia ecology.*
- *What controls the temporal variation in biogeochemical fluxes and how they respond to climate variability?*
- *How will the biotic changes impact on carbon uptake and sequestration?*
- *How will components of the ecosystems respond to variation physical processes including global change?*
    - *Microbial/Phytoplankton*
    - *Zooplankton*
    - *Nekton*
    - *Benthic communities*
    - *Commercial fish stocks*

Biodiversity:

- *What is the relationship between biodiversity, structure, function, and stability of marine ecosystems?*
- *What is the distribution and condition of marine habitats within Bass Strait?*
- *What are the characteristics of canyon heads and do they support greater biodiversity?*
- *Do Bass Strait and other sites around Tasmania have 'hotspots' of biodiversity? The region to the south and east of King Island also appears to be an area of interest in August and September for dwarf minke whales and likely other predators and fish species, similarly in the region of SW Cape and off Southern Bruny- Why?*
- *Are "Pelagic biodiversity hotspots" and "seafloor biodiversity hotspots" co-located with key ecological features [KEFS]?*

Distribution and abundance:

- *What are the long term impacts of climate variability on benthic ecology?*
    - *What determines the spatial and temporal variation in C. rodgersii and of M. pyrifera?*
    - *Beyond the photic zone, what are the drivers of productivity on benthic systems and how might they be influenced by warming conditions?*
- *How interconnected are our populations of mobile species?*
- *There is increasing interest in spatial management for both fisheries and conservation management yet we do not have a clear picture of the movement dynamics of most species and hence the efficacy of such management. In particular the management of endangered species requires more information on spatial dynamics.*

4.5.7 Status, gaps, opportunities and priorities for future enhancements

Status:

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

The SEA-IMOS Node has interests in biodiversity, productivity and resource management. IMOS observations of biodiversity, productivity or living marine resources are being collected at the basin scale around the Tasman Sea, the Southern Ocean and there are a few measurements in the Indian ocean for: zooplankton (CPR), some phytoplankton (CPR and satellite) and nekton (bio-acoustics). Through the National Environmental Research Program (NERP- 2013- 2015) and National Environmental Science Program (NESP 2015-2020) Marine Biodiversity Hubs, biodiversity observations have also being collected on the continental shelf and coastal regions (including submarine canyons in the Flinders and Freycinet Commonwealth Marine Protected Areas).

Due to the strengthening of the EAC flow the waters along the east coast of Tasmania are warming faster than any other region of Australia. There is considerable effort being invested by IMOS and other research providers on observing the ecological responses in this region. The greatest IMOS effort on ecosystem responses involves observations of benthic responses using the IMOS supported AUV. This AUV observation program is national in scope and co-ordinated across states to ensure compatibility of surveys to identify patterns and processes at local, regional, and national scales , and, as part of that, has been utilised in a range of Tasmanian shelf scale observations that are bioregionally based and guided by regional oceanography. These observations will be maintained with SEA-IMOS planning from 2015.

Gaps:

Clear gaps exist in Bass Strait for a number of observations collected from platforms such as ocean gliders, AUV, the national Mooring Network, animal tagging and satellite derived ocean colour. Because of the lack of this information we have no capacity for contributing to time series analysis to measure change or assess the condition of benthic ecosystems within Bass Strait. This information is required if our goal is to improve on the understanding of the relationships between scale and connectivity in marine environments, long term resilience of ecological communities, and the function these communities provide in terms of ecosystem services and food production in the region between Tasmania and Victoria.

South eastern Australia, in particular Bass Strait, has the highest biomass of seabird and apex predators in Australia (Hobday et al 2014). As a starting point to establishing a data network for Bass Strait, we can begin by examining the existing long term dataset for Port Phillip Bay. Benthic and fish diversity data has been collected between 1990-2011 using standardised benthic trawl techniques. This would provide an ideal data set to continue to detect future change in assemblages (see Hewitt et al 2004). An existing single acoustic array is available within Port Phillip Bay but there is currently no funding for future maintenance and for deployments of more animal tags. The Nature Conservancy, supported by Parks and EPA Victoria are deploying an observation system (cameras and sensors) at Popes Eye (Port Phillip Heads). SEA-IMOS could support this program by linking to the datastream and hosting the data to enhance data profile.

The shelf waters of southeast Australia, particular around Tasmania, contain optically-significant concentrations of coloured dissolved organic matter, which invalidate global ocean colour algorithms such as OC3, and associated atmospheric corrections. An in situ data set required to develop such algorithm is published (Cherukuru et al., 2014and is available through the IMOS Bio-optics database. However the final stage of algorithm development to produce regional ocean colour products has not been completed.

Future priorities:

A future additional priority that the SEAIMOS node is considering is a Bass Strait regional focus for the collection of data from ocean gliders, AUV, the national Mooring Network, and animal tagging for the region. This information will allow us to combine the resources of Victoria and Tasmania within a shared highly productive and unique region. This information will form the foundation of the establishment of long term monitoring sites for benthic and pelagic communities and provide the necessary data with which to develop protocols for monitoring impacts of environmental variation on indicator species and develop a suite of spatial and temporal metrics for climate change impacts.

5 How is IMOS data being used?

The Node's primary IMOS focus is in gliders and the National Reference Station at Maria for hydrodynamic observations, acoustic curtains to record movements of mobile taxa, and AUV observations to record changes in the benthos. IMOS data are currently being used to improve the management of the region. There are large projects represented by the aquaculture industry, pulp and paper production, mineral production, waste water disposal, government planning that use IMOS data streams to improve their hydrodynamic and biogeochemical models, and understanding of biodiversity and ecosystem values.

A number of smaller projects based at CSIRO and the University of Tasmania have used a range of IMOS data streams to investigate biological responses to climate variability including the following:

- Comparative analysis of chlorophyll measurement techniques from Maria Island NRS
- Change in size and production of *Nyctiphanes australis* over 30 years
- Environmental drivers of *Thaliacean* blooms and their ecology in Storm Bay, Tasmania
- Hydrodynamic control of plankton in Recherche Bay
- Influence of the EAC on plankton in eastern Australia
- Predict the future ocean climate in the SE region over the next 60 years
- Future changes in reef associated biota in response to regional climate prediction

The previous Tasmania IMOS Node (up until December 2014) led an assessment of the national reference stations as appropriate means to measure the biotic responses of Australia's EEZ to climate variability. This has included the assessment of changes in nutrients, phytoplankton and the spatial footprint of all NRS.

IMOS observations are applied to a range of projects supporting regional development and the sustainable use of our marine resources. The goal of the Node is to assist society to manage our aquatic resources and too achieve this goal it is necessary to do more than observe the physical effects of climate change. It is expected that the new SEA-IMOS Node will interact with the following sectors: climate change, coastal management, marine industry, environmental information, marine environment, fisheries and aquaculture, tertiary education and science and research.

Table 18: How IMOS Facilities deliver to the Nodes. P = primary relationship and S = secondary relationship

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

5.1 Recent highlights of research using IMOS data streams

- EPA Victoria have instrumented *The Spirit of Tasmania* vessel with autonomous water quality sensors since 2008. This dataset has contributed to the Ships of Opportunity facility within IMOS. The information has provided a high resolution window into the dynamics of Bass Strait and the adjoining Port Phillip Bay and Mersey Estuary. The data has been used to inform environmental managers and port authorities, aid fisheries research, integrate with numerical models, and investigate climate change studies. The data has highlighted Port Phillip Bay as a significantly climate modified marine system and the data has picked up seasonal and weather-band intrusions from Bass Strait that into Port Phillip Bay.
- The University of Melbourne has used this temperature data to calibrate and verify the plankton mathematical model developed for Port Phillip Bay.
- Fisheries Victoria, James Cook University and UTAS are using the acoustic arrays in Port Phillip Bay to study seven gill sharks.
- Deakin University- Animal tracking of Australian fur seals and Influence of SST and wind (Gibbens and Arnould 2009) to determine link with body condition
- The Node is in a strong position to demonstrate the benefits of IMOS observations through improved model outputs. Researchers active within the Node and based in Hobart are responsible for the development of key national and international hydrodynamic, biogeochemical and ecosystem models. These researchers are currently implementing nested models for the Node’s region, spanning ocean basin, shelf/slope and inshore/estuarine scales. The Tasmanian region is being used as a demonstration / proof-of-concept location for models and approaches which have been transferred to other regions (e.g. SEQ, GBR). CSIRO is prepared to make the model output available on the IMOS web page allowing all marine researchers access to the model results.
- Comparison of phytoplankton and zooplankton community composition at Port Hacking and Maria Island showed that community composition co-varied with water mass, illustrating the impact of intrusions of EAC water into eastern Tasmanian shelf (accepted manuscript – Paige Kelly).
- EPA Victoria, have recently commissioned CSIRO with the development and sustained operation of realtime 3D models, known as VIC-MOM, downscaled from ACCESS and Ocean MAPs products. Existing observational infrastructure such as tide gauges, temperature sensors and Spirit of Tas 1 ship tracks are used to validate the operational model products. The EPA have been using these models to track risk of illegal ballast discharges, monitor algal blooms, support oil spill response investigations, assess risk of marine pest incursions and support decision making on proposed developments

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

- **Next five years:**

In the next 5 years, continuation and establishment of new SEAIMOS data streams will enable many of the key science questions detailed in the Node Plan to be addressed and answered. In particular, data over the next decade will enable relationships between patterns and process in marine systems. In particular:

- Provide a continuing record of strength, and southward extension, and ecosystem impacts of the East Australian Current, as influenced by global change and decadal variability.
- Through continued use of SOOP Bass Strait transect, opportunistic moorings in Bass Strait and summer glider missions, a better estimation of Bass Strait flow, and shelf – open ocean exchange will be possible.
- Through new observations using biologging and AUVs make new ecological discoveries in the biological hotspots of the coastal regions of the SEIMOS node.

Further, IMOS is looking to improve the integration of observations and modelling. In SEA waters, numerical modelling within the scope of future priorities to allow us to improve the way that data are used and interpreted, through, for example, connectivity studies or observation system design. Example projects include those characterised by spatial data observed over time. The observation period could be constant through time, or have linear or accelerating variations. The observed changes could be in the form of shifting levels or evolving patterns and may be linked to their societal impact and the adaptive response of policy and community. Further projects include those characterised by an inductive or probabilistic approach which provides insight into unobservable regions or quantities. The breakthrough component comes from the transforming effect of using datasets to infer patterns. These may be a result in their own right, or could be used to constrain more conventional deterministic modelling to make significant refinements to current understanding.

Example projects include those that make links between currently disparate datasets (e.g. physical and social) and those where frontier knowledge is currently inaccessible through low-dimensional data analysis made accessible through data fusion, i.e. pattern identification across multiple, high-dimensions of layers or using a probabilistic approach. In some examples, the power of combined inductive and deductive approaches could be illustrated with existing IMOS data. Example projects for future investigation- 1.Coastal change and its physical and societal impacts; 2.Deep ocean fish stocks and management of change and uncertainty

- **Long-term:**

The SEA region is has experienced some of the strongest warming trends in the world's temperate ocean, and this is likely to continue. Thus the most important observations will be those that capture long term trends. The Maria Island NRS station is well placed to capture this trend. Future priorities in the above themes highlight that changes in Bass Strait and along the Victorian coast are not as well instrumented for long term observations.

7 Governance, structure and funding

Governance is provided by the South East Australia Node's Steering Committee. The Steering Committee is drawn from CSIRO's Ocean and Atmosphere Flagship (OnA), the University of Tasmania's Institute for Marine and Antarctic Studies (IMAS), University of Tasmania's Australian Maritime College, Deakin University, University of Melbourne and Victoria EPA.

It consists of:

1) Mark Baird (Node leader, CSIRO)
2) Vanessa Lucieer (Node deputy leader, Institute for Marine and Antarctic Studies, UTAS)
3) Daniel Ierodiacanou (Node deputy leader, Deakin University)
4) Stephen Swearer (Melbourne University)
5) Randall Lee (Victoria, EPA)
6) Peter Thompson (CSIRO, Principal Research Scientist)
7) Kerrie Swadling (IMAS, Senior Lecturer).
8) Dr Steffan Howe (Parks Victoria)

The SEA-IMOS Node is a recent change that integrates the previous Tasmanian Node and Victoria, therefore there has been no meetings held for this node or any stakeholder engagement meetings at this stage.

Node Meetings

TBA

Node Membership

The membership of SEA-IMOS is open to anyone with a professional interest in ocean observations along the south east Australia region. It will have no restriction other than a willingness to be enrolled on a membership database.

Stakeholder engagement

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