IMOS Integrated Marine Observing System

Queensland's Integrated Marine Observing System (Q-IMOS)

Queensland's Integrated Marine Observing System (Q-IMOS) Node Science and Implementation Plan

2015-25

An Australian Government Initiative
National Collaborative Research Infrastructure Strategy

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

UTAS

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1 Executive Summary

In 2006, the Integrated Marine Observing System (IMOS), the Queensland Government, and the Collaborating Partners committed over $14M to the creation of a Great Barrier Reef Ocean Observing System (GBROOS) as the Queensland Node of IMOS. In 2007, the first data streams from moored instruments were placed in the national archive, now known as the Australian Ocean Data Network (AODN), and the entire allocated infrastructure was in place by 2009.

In 2009, the IMOS Board enhanced GBROOS with several new capabilities (ocean gliders, acoustic receivers, pCO2/pH sensors) and funded a National Reference Station (NRS) in South East Queensland (Figure 1). Following this expansion beyond the Great Barrier Reef Marine Park, the Node was rebranded as Queensland's Integrated Marine Observing System (Q-IMOS).

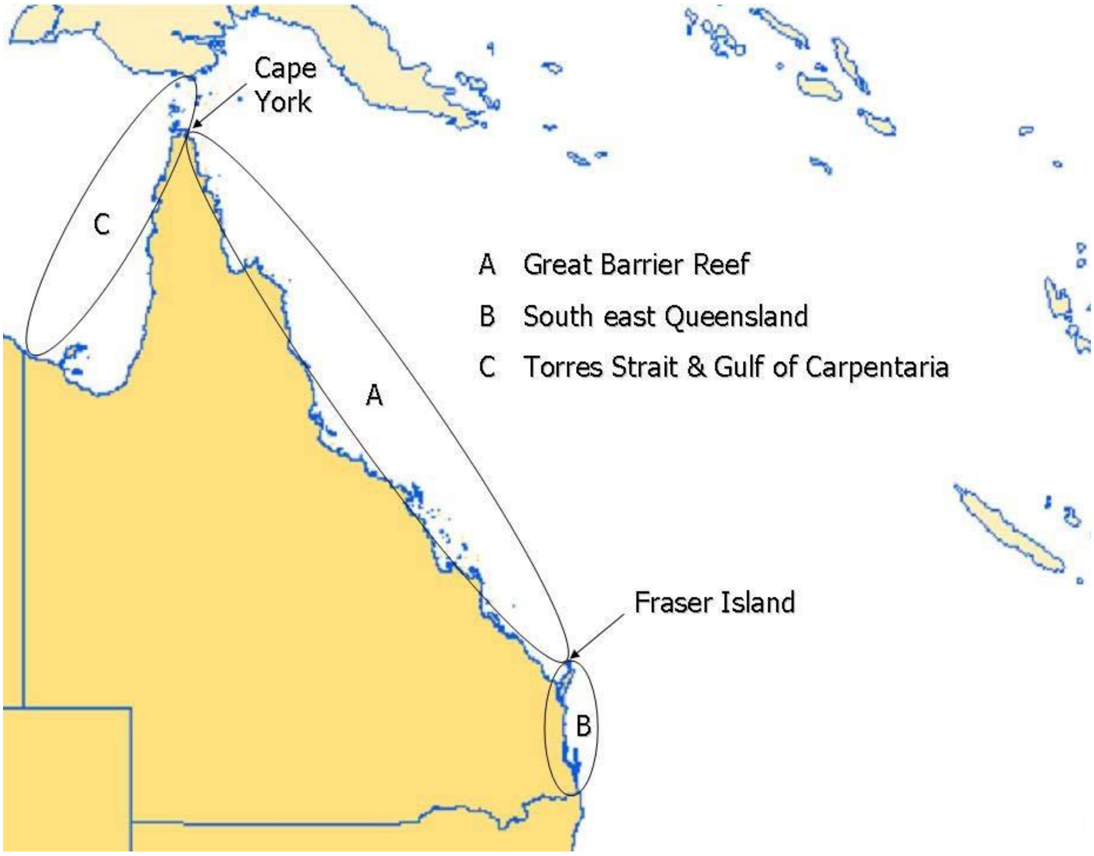

Figure 1. Map of Queensland showing three geographic regions referenced in this Plan. The transitions are Cape York (north) and Fraser Island (south).

The Q-IMOS Node Science and implementation Plan (NSIP) is based on understanding the impacts of ocean variability in the Coral Sea upon the condition and productivity of shelf ecosystems along the east coast of Queensland, with a current focus on the section of the continental shelf influenced by the southerly-flowing East Australian Current (EAC). This region includes the southern half of the iconic Great Barrier Reef (GBR), the majority of Queensland's commercial fisheries production, and the great majority of the State's coastal population. It is also contiguous with the NSW-IMOS observing region providing a synoptic view of Australia’s most important coastal boundary current (the EAC).

Currently, Q-IMOS activities are constrained to these priorities but this leaves more than half of the Queensland coast without any *in-situ* marine observations. This gap includes the northern GBR (influenced by the northerly-flowing Gulf of Papua Current), the Torres Strait, and the Gulf of Carpentaria (Figure 1). Thus a major challenge for the Node in the life of this Plan (2015-2025) is finding the resources to plug these critical knowledge gaps.

January 2014

2 Socio-economic context

Many of Australia's most precious natural assets are located in Queensland. These include a wide range of commodity resources as well as the iconic GBR, which is one of the world's most important biodiversity assets. Major economic activities such as mining, agriculture, shipping, fishing, urban development, tourism and recreation converge at the Queensland coast and their cumulative impacts are major drivers of ecosystem status and trend. The legacy of past development and population growth is coastal and marine areas with degraded water quality, and losses of habitat and biodiversity. The rapid pace of projected development will produce ever greater cumulative risks over the next decade, requiring nimble adaptive management and evidence-based decisions.

2.1 Great Barrier Reef

The GBR is the World's largest reef archipelago stretching >2,000 km from Cape York to Lady Elliot Island, which lies just 80 km north of the northern tip of Fraser Island. Today, the GBR is a multiple-use marine park generating more than $5 billion of annual economic activity and supporting around 70,000 jobs (GBR Outlook Report 2009). The Great Barrier Reef Marine Park (GBRMP) is also a World Heritage Area recognized internationally for its Outstanding Universal Value, which is today being threatened by the cumulative impacts of multiple human uses and ongoing climate change.

In 2003, the Australian and Queensland Governments recognised that broad-scale agriculture in the coastal catchments was having a deleterious impact on marine receiving waters in some sections of the Park due to the export of unnaturally high loads of sediments, nutrients, and pesticides in river run-off. In response, both governments committed to halt and reverse the decline of water quality entering the GBR Lagoon through a decadal program (Reef Plan) that is based on changing land management practices. Following a mid-term review and a Scientific Consensus raising concern about the level of threat, the two governments committed $375 million to support Reef Plan actions (2009-13). In 2013, after an update of the Scientific Consensus (Brodie et al. 2013b) and review of the Program showing some load reductions, Reef Plan was extended for a further five years (2013-18) with a similar level of investment and an aspirational target that "water quality should have no detrimental impact on GBR ecosystems by 2020".

Other pressures within the GBRMP (e.g. marine tourism, commercial and recreational fishing) are managed by a variety of regulatory apparatus including the GBR Zoning Plan that determines appropriate use. In 2004, a significant rezoning of the Park resulted in a third of 70 recognised bioregions being reserved in 'no take 'zones. As part of the re-zoning, the Great Barrier Reef Marine Park Authority (GBRMPA) is required to inform the Australian Parliament on the status of the GBR every five years. The first GBR Outlook Report (2009) concluded that the GBR ecosystem is at a cross-road with the extent and persistence of the damage to the ecosystem depending to a large degree on the amount of change in the world's climate.

In 2012, UNESCO sent a reactive mission to Australia to enquire into a proposition that the GBR be placed on a register of endangered World Heritage properties following international concern about the scale and pace of coastal development; particularly the expansion of infrastructure at bulk commodity ports to cope with a mining and energy boom. In 2013, the Queensland Government released a Queensland Ports Strategy that proposes to restrict any significant port development adjoining the Great Barrier Reef World Heritage Area to within existing port limits until 2022. In addition, the Australian and Queensland Governments prepared comprehensive Strategic Assessments for the marine and coastal environments (GBRMPA 2013a, QDSDIP 2013) as well as complementary Program Reports (GBRMPA 2013b) describing remedial actions to be taken in the next decade. Both Program Reports commit to a future reef-wide integrated monitoring and reporting program to underpin an adaptive management approach for this very large ecosystem. An effective integrated monitoring framework must include a layer of ocean observations.

2.2 South East Queensland

South East Queensland (SEQ) is an area of outstanding natural values with its own legacy of environmental issues; largely driven by very rapid expansion to accommodate the majority of the State's population in this region. The Gold Coast is Australia's most highly concentrated tourist destination and contributes more than $4B annually to the economy. Commercial fisheries in the region are worth more than $50M annually, and the recreational fishing sector in the greater Brisbane area generates many times more value.

Marine environments of the region include the Gold and Sunshine Coasts, Moreton Bay and Great Sandy Marine Parks. The iconic sand islands (Fraser, Moreton, and Stradbroke) are precious natural assets. Beach erosion is a significant threat to infrastructure because so much of the coast is sandy and this is in most parts an open coast facing an energetic ocean. The outstanding biodiversity values of SEQ include globally significant populations of sea turtles and dugongs, and annual shorebird migrations that have led to Moreton Bay being listed as an international RAMSAR site.

South East Queensland has one of the fastest growing populations in Australia. The population, which was 2.73 million in 2006, is predicted to exceed four million within 20 years. Such rapid growth will make strong demands on natural resources such as Moreton Bay and the rivers and streams feeding into it. The social costs of a decline in natural resource condition due to both local and global (e.g. climate change) are very substantial. It is estimated that the social costs in SEQ alone could be as high as $5.2 billion between now and 2031[1]. Initiatives such as the SEQ Healthy Waterways Partnership and the Gladstone Healthy Harbours Program have been established to help mitigate and manage such risks. Such initiatives cannot succeed without systematic environmental monitoring and reporting programs to measure the performance of management actions and for essential communication of status and trend reporting to the stakeholder network.

2.3 Torres Strait and Gulf of Carpentaria

The Torres Strait is a narrow waterway between Australia and Papua New Guinea that separates the Coral Sea in the east from the Arafura Sea in the west via the Gulf of Carpentaria. This shallow strait contains almost 300 islands, of which 17 have permanent settlements supporting around 7,000 people. These islands have been occupied for several thousand years by indigenous peoples who have a deep attachment to place and strong cultural and economic dependency upon local marine

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[1] Binney J. 2010 Managing what matters: The cost of environmental decline in South East Queensland Marsden Jacob Associates, 2010

resources. In addition, there is an even larger diaspora of Torres Strait people living in the coastal cities of north Queensland, who maintain active connections with their ancestral home lands.

While the environmental values of the Torres Strait compare favourably with more developed areas of the Australian coastal, they will not remain so without active management of potential risks and inevitably some adaptation. The Torres Strait now contains the largest population of dugongs in the World and is the final global refuge for these charismatic herbivores as their populations have declined elsewhere. In Queensland, the incidental catches of dugongs by the shark-netting program record a 95% decline in abundance along the developed coast since the inception of the program (Marsh et al. 2005) that is coincident with deep decline in their major food: seagrass. The Torres Strait contains the largest contiguous seagrass meadow in tropical Australia, which would be at risk from changes in water quality. These changes are less likely to be generated by local activities than by future industrialisation, deforestation, and human development occurring in Papua New Guinea and Irian Jaya. These risks of coastal pollution will interact with anthropogenic climate change. Torres Strait populations on low-lying islands have critical vested interest in sea-level rise because they already experience episodic tidal inundation of their lands and are at great risk from storm surge.

The Gulf of Carpentaria (GOC) is a large shallow sea west of the Torres Strait that is bounded by land on three sides and the Arafura Sea to the west. It covers 300,000 km^2 with a maximum depth of 70m. The region contains <1% of Queensland's population, but is a popular destination for recreational fishers and 'Grey Nomads' in the Dry Season, as well as supporting profitable commercial fisheries (prawns, crabs, fish) with a gross value exceeding $90M in 2011. Most of this production depends on coastal and estuarine ecosystems, with trophic linkages to mangroves and seagrasses. The GOC also has five commodity ports of which two are on the Queensland coast (the border with the Northern Territory starts slightly west of a line of longitude running through the middle of the gulf). In the south of the Gulf, the Port of Kurumba exports zinc and lead concentrates from a large open-cut mine. On the north west of Cape York Peninsular, bauxite is mined and exported near Weipa from a port that is capable of servicing post-Panamax vessels (up to 83,000 tonnes capacity). Currently most of the ore from this port is shipped either across the GOC to a refinery near Nhulunbuy on the Gove Peninsular or through the Torres Strait and down the shipping channel inside the GBR to the Port of Gladstone. Cyclones are a significant issue for shipping operations and all coastal communities scattered around the Gulf because it is an area of active cyclogenesis and because cyclone tracks in the GOC are among the most unpredictable due to sparse *in situ* observing infrastructure.

2.4 The value of a marine observing system in Queensland

The first Great Barrier Reef Outlook Report (2009) identified poor water quality from terrestrial run-off as a present threat to the health and resilience of this very large marine ecosystem, and indicated that the future risks are likely to be compounded by climate change. Long-term records of rainfall from climate proxies contained in coral skeletons show that the historical pattern is towards greater variability, which predicts more extreme droughts and floods in the future (Figure 2). This alternation between extreme conditions provides the perfect storm as major drought-breaking rains erode soils from bare terrestrial catchments and distributes the terrestrial materials widely through the marine receiving waters via greater flood plumes.

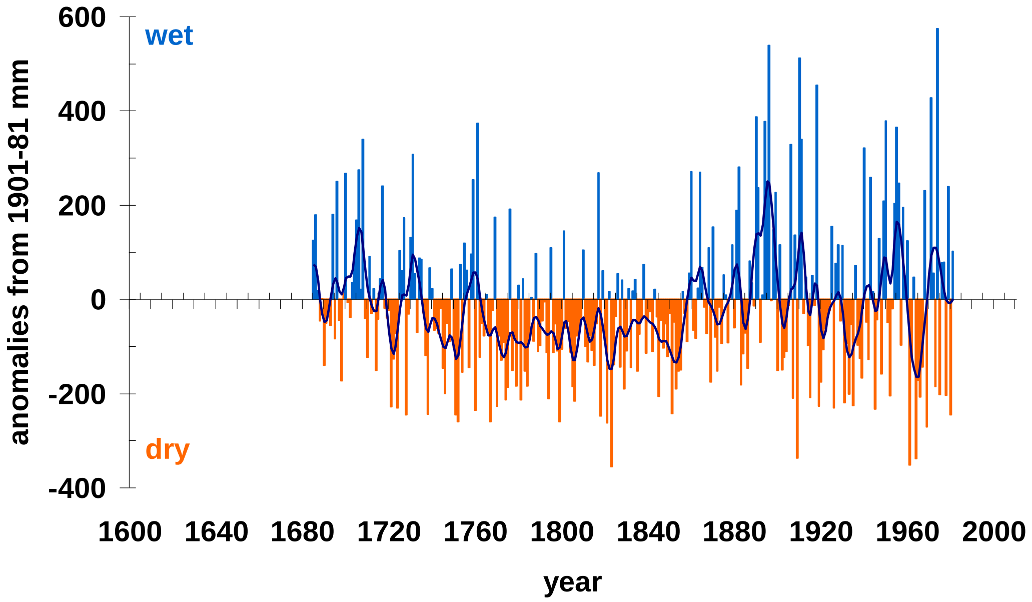

Figure 2. Rainfall anomalies (relative to the average between 1901-1981) in North Queensland over 300 years reconstructed from coral luminescence showing an extended natural drought 1760-1860 followed by 100 years of alternation between wet and dry periods each lasting 2-10 years (source: Lough 2011).

The scale and complexity of this problem is very challenging and beyond simple empirical monitoring because the largest flood plumes can extend many hundreds of kilometres along the coast, mixing along the way with plumes from other catchments. Hence the risk profile at any location is the historical accumulation of multiple impacts from water quality and other stresses.

A marine science partnership is meeting this challenge by creating an integrated modelling suite known as eReefs (Schiller et al. 2013). This is designed to become a real-time forecasting system operated by the Australian Bureau of Meteorology in an extension of its role as the nation’s weather forecasting agency. Both systems share many similarities including the need for essential observations.

In the marine space, eReefs is a 3-D hydrodynamic model that includes all of the essential forcing functions (winds, tides, atmospheric coupling, bathymetry, etc). It is resolved at 1km grid resolution on the continental shelf and nested within 4km and 10km models at progressively larger scales to obtain accurate oceanic forcing from global models (Figure 3). The domain of the 4km grid extends from Papua New Guinea to the NSW border (encompassing the east coast of Queensland) and encompasses all of the shallow bathymetry on the Coral Sea (Queensland and Marion Plateaux).

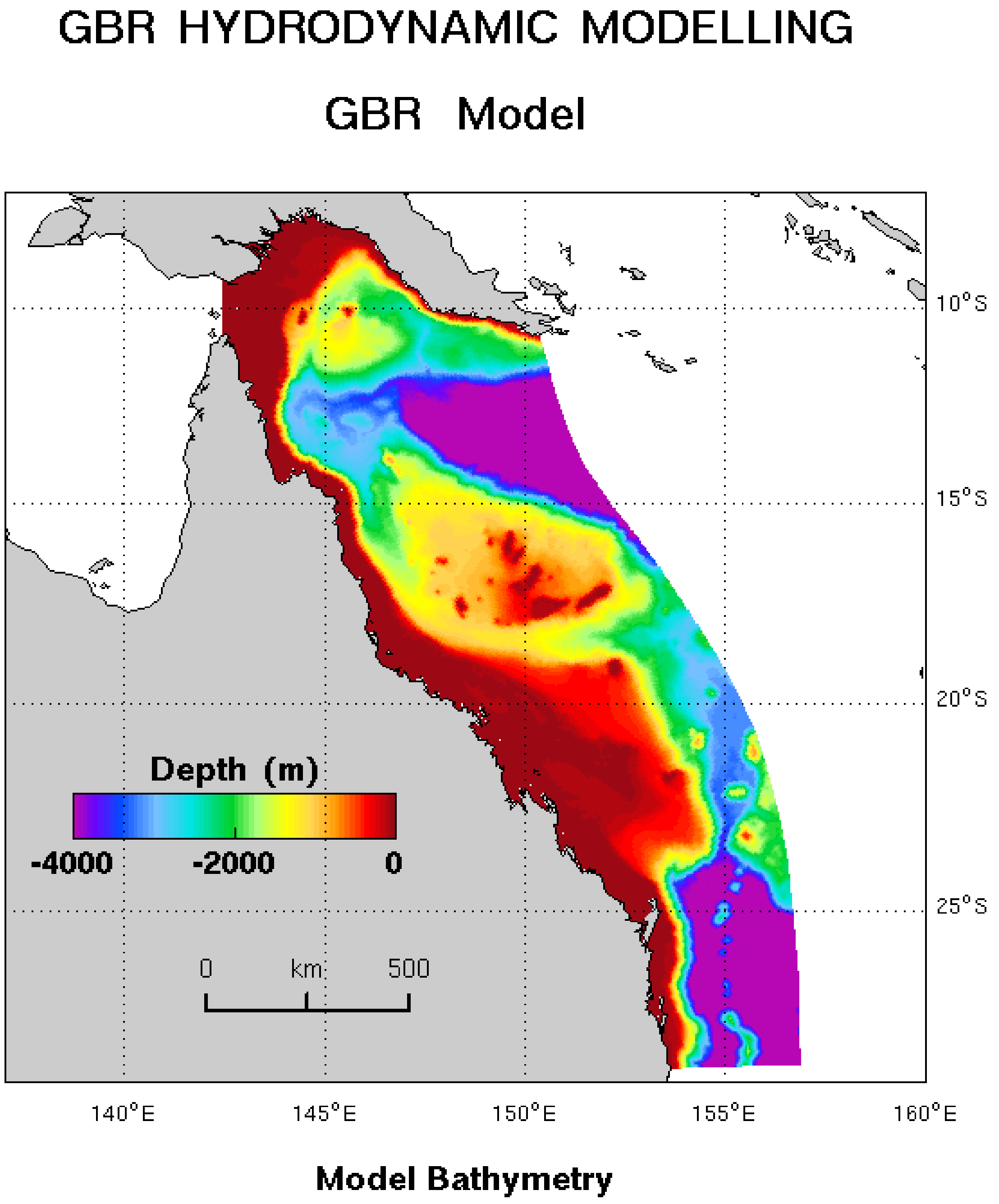

Figure 3. Spatial domain for eReefs model resolved at 4 km. Most of the domain where bathymetry is less than 1000 m (yellow-red) is covered by a nested grid resolved at 1 km (Source Richard Brinkman, AIMS).

The eReefs model of ocean physics is validated using data from the QIMOS node, tide gauges and Waverider buoys operated by the Queensland Government and Argo floats. . The QIMOS array of delayed mode moorings provides spatial coverage from Lizard Island to the Capricorn Bunker Group, and delivers time series of water column current profiles, and temperature and salinity at a number of fixed depths on each mooring. The model has been shown to capture key properties of the water column including temperature, salinity, and velocity (Figure 4), and these capabilities allow the model to forecast thermal and salinity stress, track the movements of flood plumes, and estimate shear at the seabed.

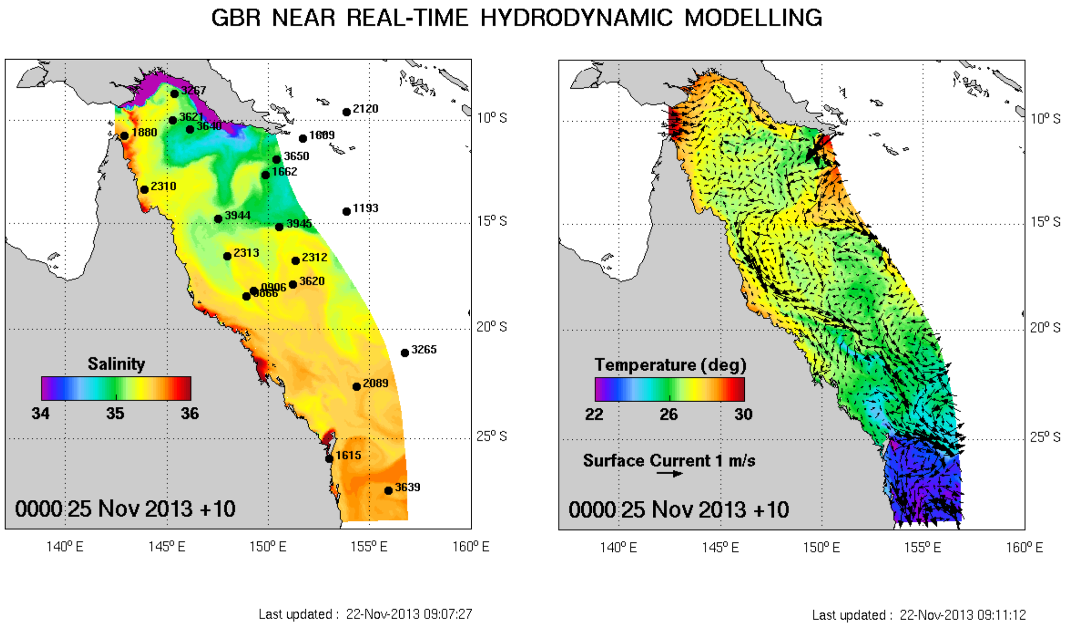

Figure 4. eReefs predicts temperature, salinity, and velocity at 47 depth layers resolved on either a 4km or 1 km grid (Source Richard Brinkman, AIMS).

The hydrodynamic model will be coupled at the same resolution to models for sediment transport and biogeochemistry (Figures 5,6).The coupled models under development will allow the integrated suite to predict sediment transport on the seabed, wave resuspension, turbidity, water clarity, benthic light levels and key attributes of the pelagic primary producers (standing stock, primary production, size spectrum of phytoplankton).

eReefs is planned to be an essential part of an integrated monitoring framework for the GBR (committed to in the GBR Strategic Assessments of the Australian and Queensland Governments) but it will also have equal application to south east Queensland.

SEQ is Australia's fastest growing region, with the population predicted to grow from 2.8 to 4.4 million people in the next 20 years. This rapid growth will need careful management to ensure that local receiving waters are not degraded with impacts on seafood supply, livelihoods, and /or recreational opportunities. The SEQ Healthy Waterways Partnership has developed its own model of water quality for the internal waters of Moreton Bay and the Gold Coast waterways. The open boundary of this regional model will be forced by eReefs to transmit observed oceanic variability of the EAC, which reaches its most forceful state at this latitude.

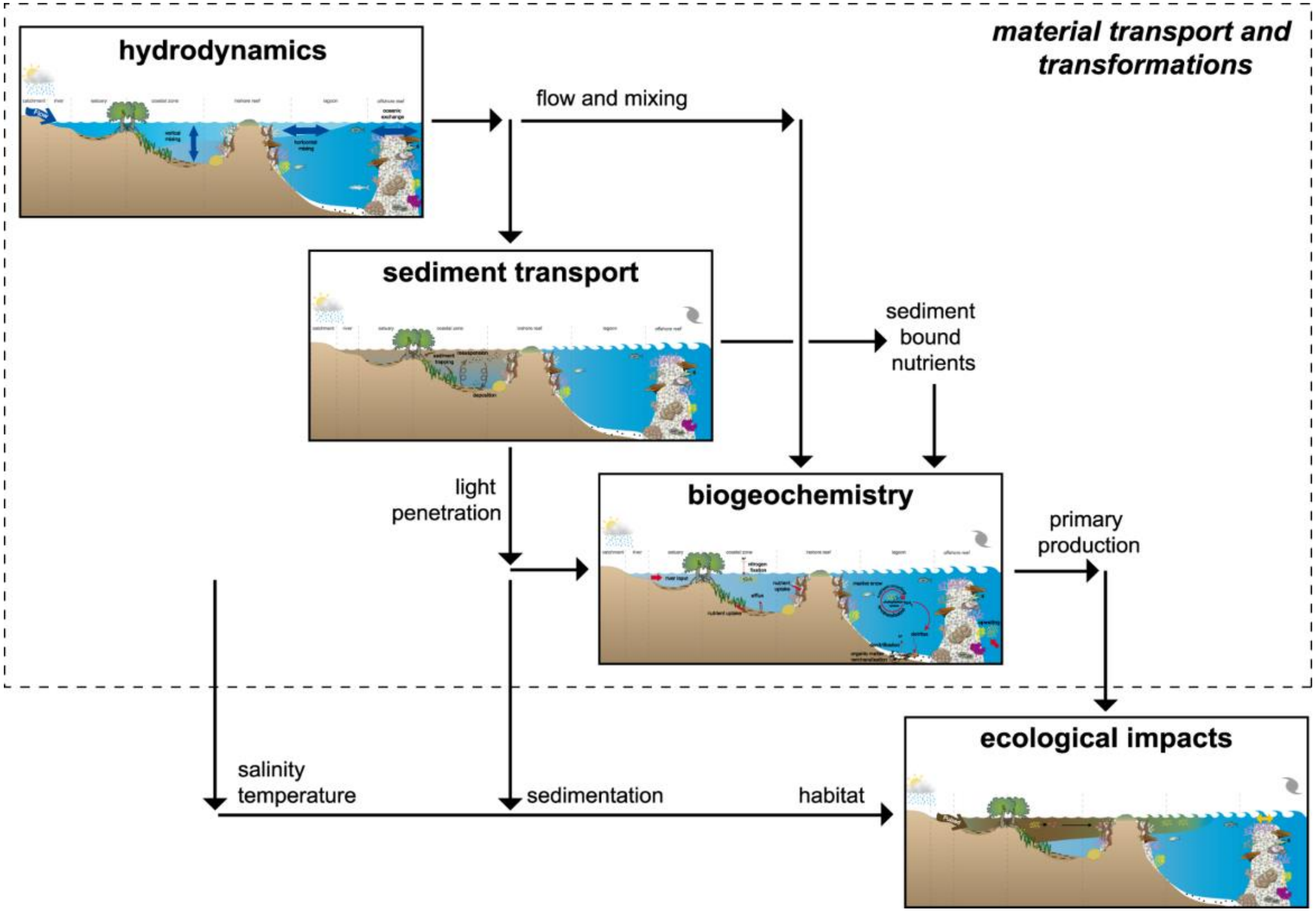

Figure 5. The eReefs modelling suite when operational in 2015 will consist of coupled models producing predictions at the scale of the grid for biogeochemical variables, sediment transport (dotted line). The ultimate goal is to predict ecological state (Source Richard Brinkman, AIMS).

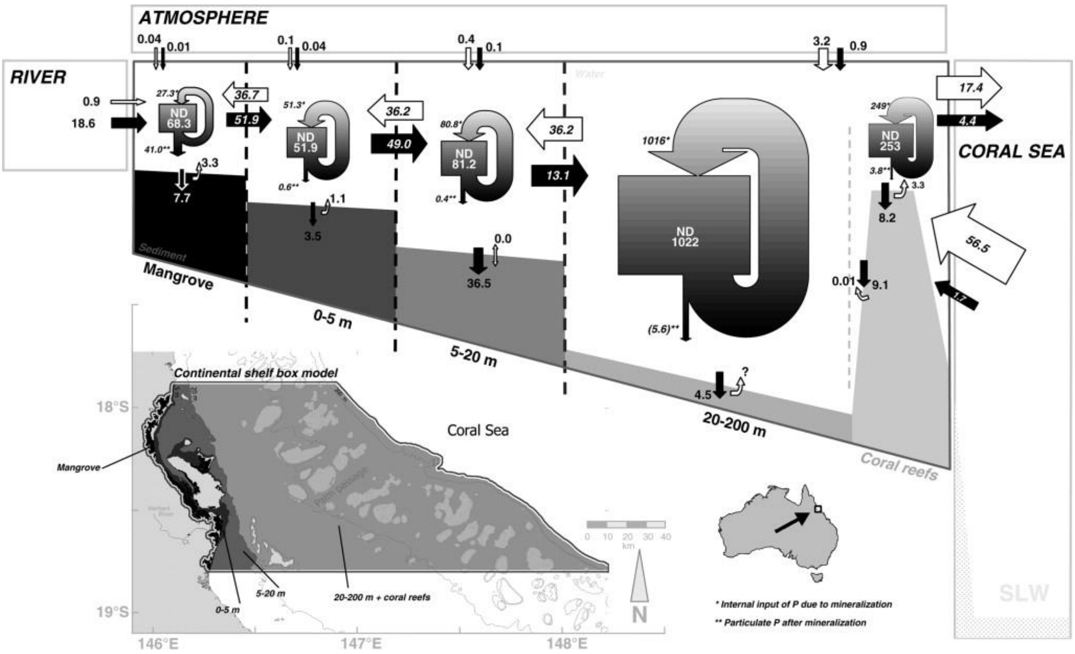

Figure 6. Traditional box model of phosphorus dynamics showing exchanges and transformations in functional spatial compartments (Source Monbet et al. 2007). Ultimately eReefs will resolve these processes to the nested grid sizes (4km, 1km, 0.1km).

In addition to forecasting water quality, eReefs will provide context for understanding and forecasting the movement of migratory animals along the Queensland Shelf, variations in the replenishment of major fisheries and the occurrence of toxic algal blooms and fish kills. It will also assist maritime operations including search and rescue, contaminant spill response, and forecast risk of tidal surge and beach erosion in coastal communities. The potential audience for this information includes government, industry, and community. The uptake of the information and usefulness of the forecasts will depend on their reliability and accuracy. As with conventional weather forecasting models, this will be ensured to the fullest extent possible by data assimilation and forcing the models with real-time observations.

This is how an ocean observing system in Queensland could deliver the greatest value to society.

Summary: Q-IMOS will make sustained observations so that oceanic variability can be included in better evidence-based management decisions for a broad range of issues. For example, data on the EAC will provide valuable information to meteorologists and planners because warm-core gyres can affect the strength of destructive east coast lows, which in turn impact water supplies, coastal erosion, and the integrity of infrastructure. In north Queensland, the equivalent knowledge is better prediction of tropical cyclone tracks and intensities. In SEQ, more knowledge is required about how the EAC influences coastal currents crucial to marine sediment transport. Coastal currents also impact marine biodiversity with implications for ecotourism as well as Fisheries Management and

Marine Park planning. Oceanographic processes affect the productivity of marine ecosystems as well as the movements and migrations of animals in coastal waters.

Data collected by Q-IMOS will contribute to better outcomes for fisheries management and conservation planning through incorporating knowledge about oceanic forcing into decision support systems. The principal tool for predicting risk and impact will be the eReefs modelling suite, which will be calibrated and validated by the sparse network of *in situ* observations collected by the IMOS infrastructure.

3 Scientific Background, by Major Research Theme

The IMOS National Science and Implementation Plan is built on five ocean science themes and each of them has at least partial relevance to Queensland. Hence the Q-IMOS Node Plan starts with defining the areas of interest under the following topics:

- Multi-decadal ocean change: monitoring broad-scale changes in the surface layers of the Coral Sea as potential long-term drivers of coastal and marine ecosystems in Queensland
- Modes of climate variability and extreme weather events impacting Queensland's coastal and marine ecosystems
- Boundary currents and interbasin flows on Queensland's continental margin
- Continental shelf processes impacting Queensland's coastal and marine ecosystems
- Biological responses to ocean variability in Queensland's coastal and marine ecosystems

3.1 Multi-decadal ocean change

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

Accurate and sustained observations of global surface temperatures began in the 19th century. Subsequent monitoring has shown that the planet has warmed over the last 1600 years (Figure 7) and continues to do so. This is consistent with the scientific consensus that anthropogenic impacts have been responsible for a large portion of the global warming observed since the mid-20th century (IPCC-ARS in press). On average, surface sea temperatures around Australia have increased by about 0.6-0.74°C over the past century (Lough and Hobday 2011; Lough et al. 2012). If the rate of warming observed over the last 30 years were to continue throughout the 21st Century, average temperatures on the GBR will be warmer by more than 1°C compared with the average for the last century (Figure 8). However, there is evidence that the rate of warming is accelerating and many climate models predict warming of up to 3°C on our current global trajectory of increasing greenhouse gas emissions.

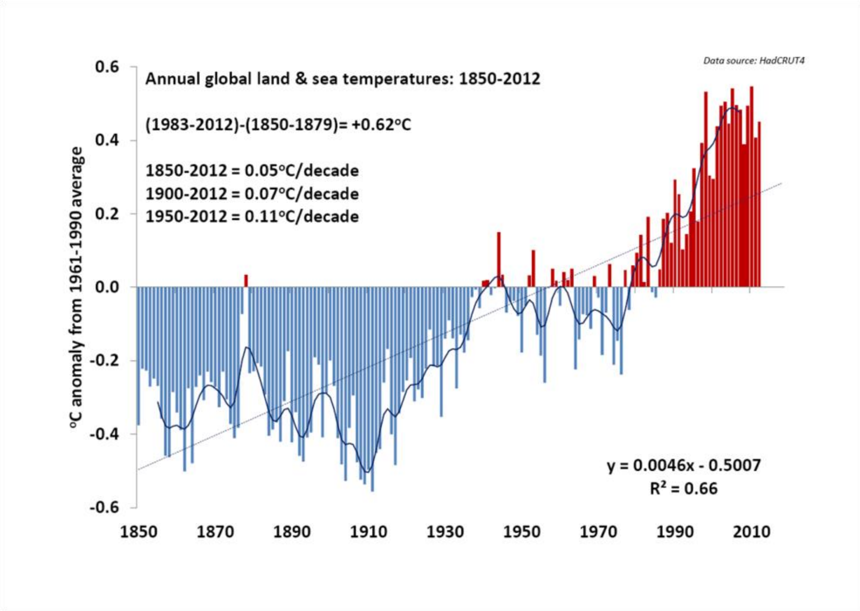

Figure 7. Global temperature anomalies relative to a 1961-1990 baseline (source www.cru.uea.ac.uk)

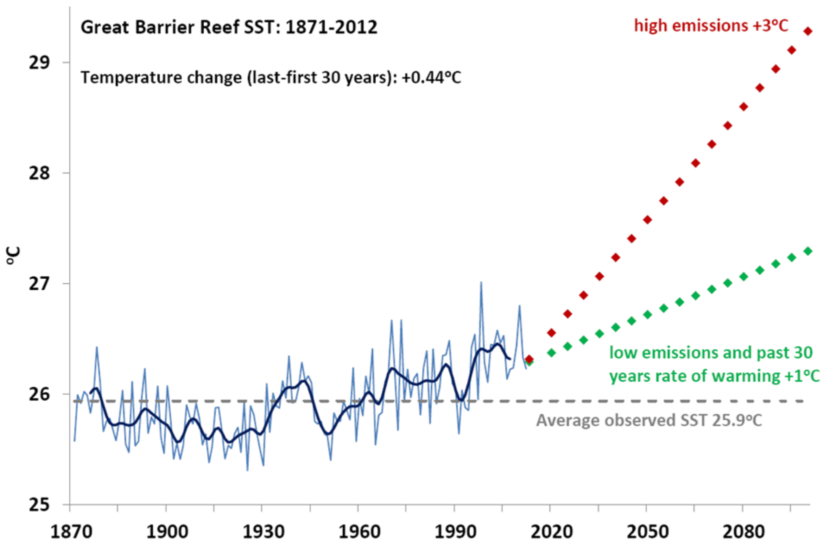

Figure 8. Sea temperatures from the GBR 1871-2005 with model forecasts (source Janice Lough, AIMS)

Long-term changes in temperature associated with global warming are considered the greatest threat to the survival of coral reefs in the next 100 years (Hoegh-Guldberg 1999, 2009). Efficient reef-building is dependent on an intimate symbiosis between an animal host (the coral polyp) and internal unicellular dinoflagellates (the symbionts) known as zooxanthellae. The symbionts capture energy via photosynthesis and provide the animal host with nutrition. This energetic contribution from the plant-like zooanthellae accounts for the ability of scleractinian corals to build coral reefs.

Natural selection has resulted in symbioses that operate most efficiently near the upper thermal tolerance of the local combination of coral and zooxanthellae genotypes. As a result of this fine balance, the coral-algal symbioses can be destabilised by several external stresses including thermal stress (Berkelmans et al. 2004, 2010), excess light (Lesser and Farrell 2004), low salinity waters (Kerswell and Jones 2003, Fabricius 2005, Berkelmans et al. 2012) and excess nutrients (Wooldridge 2009). When placed under stress, the animal host ejects its endosymbionts and the loss of their pigments results in colonies of bleached appearance. If the corals remain in a bleached state for more than a few days, the coral animal starves and dies.

Since the local thermal environment is a primary driver of coral bleaching and mortality, sea temperature is one of the most important variables to be monitored in the Great Barrier Reef.

As the upper layers of the global oceans have warmed, thermal expansion has also forced a slow rise in sea levels. Since 1870, the global average sea level has risen by ~250 mm. Sea levels rose at an average of 1.7 mm.yr^{-1} during the 20th century but by about 3.1 mm.yr^{-1} from 1993 when sea level began to be tracked by high accuracy satellite altimeters (Figure 9).

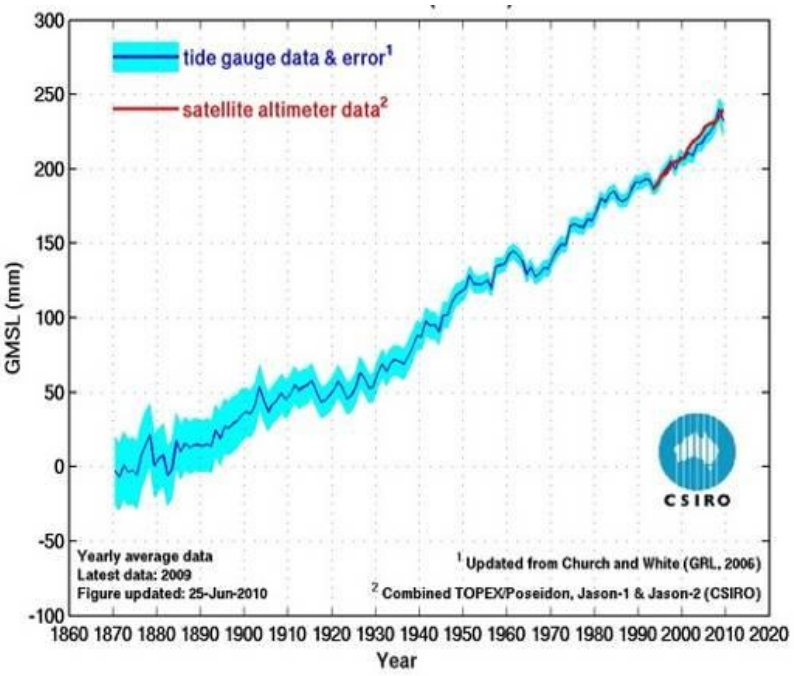

Figure 9. Changes in Global Mean Sea Level between 1870 and 2009 (source www.cmar.csiro.au/sealevel/).

Sea level rise has not been uniform, and in Australia, since 1993, sea levels have risen 7-10 mm to the north and west of the continent but only 1.5-3 mm in Queensland (Figure 10). Nonetheless, sea level rise has importance to low-lying communities, for example in the Torres Strait (Green et al. 2010), and for species that use the littoral zone for critical life stages (Fuentes et al. 2010. It is recognition that the National Tidal Facility (Bureau of Meteorology) is monitoring coastal sea levels at a number of established reference sites in Queensland, and Q-IMOS NSIP does not include any commitment to monitor sea-level rise..

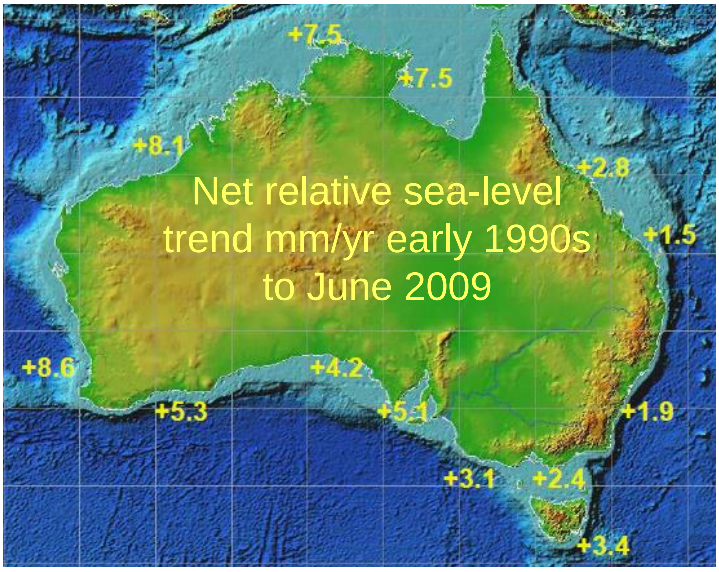

Figure 10. Sea level anomalies observed around the Australian coast (source: www.bom.gov.au/ntc/IDO60202/IDO60202.2009.pdf).

3.1.2 The global ocean circulation

Evidence is growing to suggest that the South Equatorial Current (SEC) flowing into the Coral Sea will experience long-term change (Roemmich et al. 2007) reflecting a strengthened South Pacific Gyre caused by stronger southeast trade winds. Climate modelling by Cai et al. (2005) has found that the poleward EAC (see 2.3.1) will strengthen in the Tasman Sea due to the Southern Annular Mode causing lighter mid-latitude winds and stronger southern ocean westerlies. Further climate scenario modelling presented in Ganachaud et al. (2009) has shown an overall decrease in the SEC in equatorial regions but an increase in its strength across a narrow band at 12°S and a broadening of the SEC in the southern approaches to the Coral Sea (Figure 11). The cause of this in the models is a decrease in equatorial winds, and an increase in strength and rotation to a more easterly component of the SE trade winds in the subtropical Pacific. The increase in the southern branch of the SEC is at the expense of the seasonal South Equatorial Counter Current (SECC) and will reinforce the flow of the EAC into the Tasman Sea; an area that is already experiencing some of the fastest rates of ocean warming in the world's oceans (Ridgway 2007).

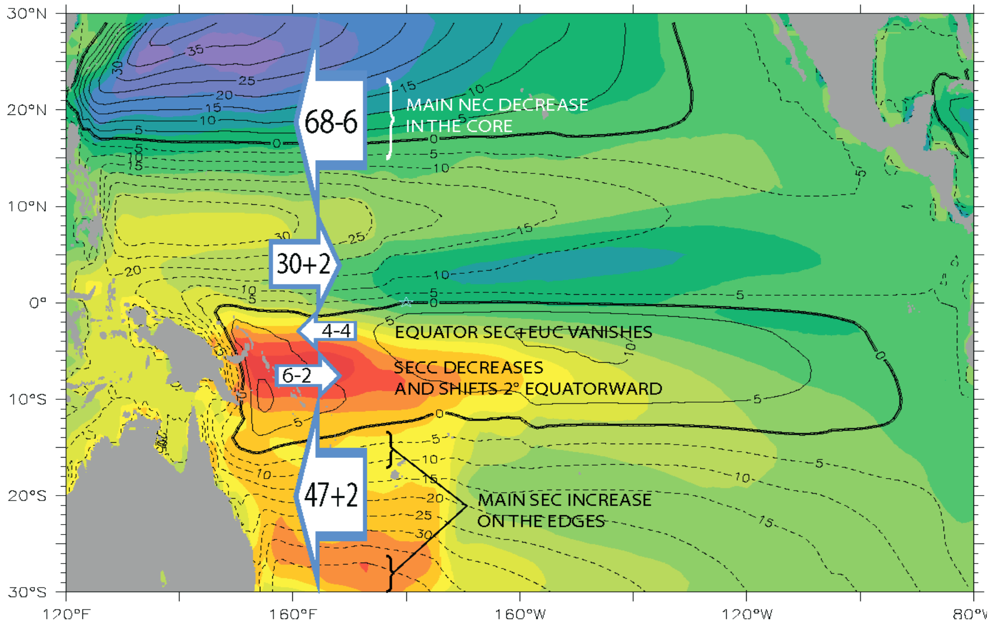

Figure 11. Projected changes to flow (in Sverdrups) for the major Pacific current systems. The data are from the mean of 11 IPCC class coupled climate models under IPCC scenario A2 projected to 2090 relative to 1990 (averaged 1980-1999) transports (Source: Ganachaud, 2009).

Changes in the major circulation patterns of the atmosphere and the oceans raise questions about the future strength and frequency of oceanic eddy production which is a major contributor to net flow, and the extent of upwelling regions that will affect biological productivity. Ganachaud et al. (2009) predict reduced productivity in tropical marine ecosystems due to shallowing of the surface mixed layer caused by increased stratification (stronger warming, weaker winds) and a resulting decrease in upwelling activity (3.4.2).

3.1.3 The global hydrological cycle (salinity)

Global climate models predict an amplification of the global hydrological cycle in the future, which means dry areas getting drier and wet areas getting wetter (Durack et al., 2012; Biasutti 2013). There is still inconsistency among multi-model climate projections for the Wet Tropics of the northern coast of Queensland as to whether the summer monsoon will show an overall increase or decrease in average rainfall. It is, however, clear that there is likely to be an increase in rainfall variability, i.e. wet years will be wetter and dry years drier than present. A major driver of this rainfall and river flow variability are El Niño-Southern Oscillation (ENSO) events, with El Niño years characterised by drier than usual conditions and La Niña years by wetter than normal conditions (Risbey et al., 2009; Ward et al. 2010). There is still, however, a lack of consistency between global climate models as to how the frequency and/or intensity of ENSO events may change in a warmer world (Collins et al., 2010; Guilyardi et al., 2012). We must assume, therefore, that ENSO events will be a continued source of rainfall and river flow variability in the region but superimposed on warmer sea surface temperatures (unusually warm SSTs around northern Australia contributed to the extensive flooding associated with the 2010-2011 and 2011-2012 La Niña events[2]) and their considerable impacts both on land and at sea (e.g. Holbrook et al., 2012). Northeast Australian rainfall and river flow variability and linkages with ENSO activity are also modulated on inter-decadal timescales through the Pacific Decadal Oscillation (PDO)/Interdecadal Pacific Oscillation (IPO) (Power et al. 1999). During PDO cool phases, the teleconnections between ENSO and eastern Australian rainfall tend to be stronger with more coherent rainfall anomalies and higher rainfall variability than during PDO warm phases (e.g. Verdon et al., 2004). Again, it is unclear from the current generation of global climate models how PDO may change in a warming world. As riverine export is the major driver of coastal water quality, a regional marine observing system must have comprehensive data on rainfall and river discharges. Suitable monitoring networks are in place and being maintained by the Bureau of Meteorology and Queensland agencies (e.g. Environment and Heritage Protection).

3.1.4 The global carbon cycle (Inventory, air sea fluxes, physical controls)

Atmospheric carbon dioxide was just 280 ppm when James Watt patented his improved steam engine in 1770. Since the Industrial Revolution in the 18th century, the burning of fossil fuels as a cheap source of energy has injected massive quantities of carbon dioxide (CO_2) to the global atmosphere (Figure 12). Since CO_2 is the main greenhouse gas, this increased atmospheric concentration has trapped more heat in the atmosphere resulting in observed global warming. Anthropogenic forcing is considered to be the major driver of global warming since the mid-20th century (IPCC-AR5, in press).

About a third of the carbon dioxide released into the atmosphere from burning fossil fuels has been absorbed into the global oceans (Raven et al. 2005). The rising partial pressure of CO_2 dissolved in seawater is making the oceans less basic and slightly more acidic (Doney et al. 2009). This trend towards increasing pCO_2 and reducing pH has been monitored at a number of ocean reference sites including Station ALOHA: a deep ocean research site 100 km north of Oahu, Hawaii. Monthly observations from that site have confirmed that surface pH has dropped by slightly less than 0.1 units since the industrial revolution (Figure 13a), and current estimates are that it could drop by a further 0.3 to 0.5 units by 2100 as the oceans absorb more anthropogenic carbon.

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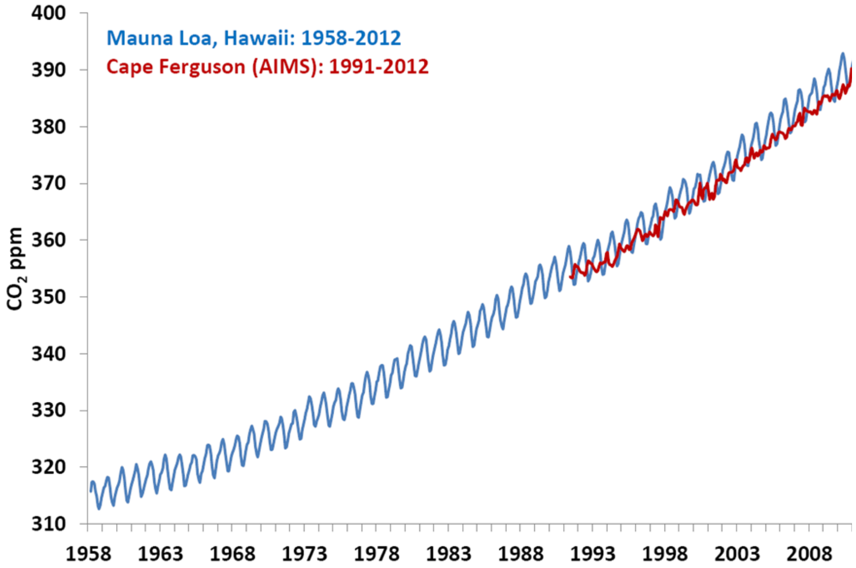
[2] http://www.bom.gov.au/climate/enso/history/La-Nina-2010-12.pdf



Data Sources: World Data Centre for Greenhouse gases & CSIRO Gaslab

Figure 12. Monthly sampling of CO_2 levels in the atmosphere from sites in Hawaii and north Queensland (source: World Data Centre for Greenhouse Gases http://ds.data.jma.go.jp/gmd/wdcgg/).

These small changes in ocean chemistry could have a profound consequence for all marine organisms building calcareous body structures (shells, skeletons, fish otoliths). Such structures are vulnerable to dissolution unless the surrounding seawater contains saturating concentrations of carbonate ions. Recent changes are reducing the saturation states of aragonite and calcite (Figure 13b,c), the two most important crystal forms of $CaCO_3$. Impacts of these changes are still poorly known (Hendriks et al. 2010), but theoretically they are great enough to pose a significant challenge to all marine biological calcification because ocean pH is falling at rates not experienced for many millions of years and associated with episodes of mass extinction of marine life (Hoegh-Guldberg et al. 2007, Veron et al. 2009).

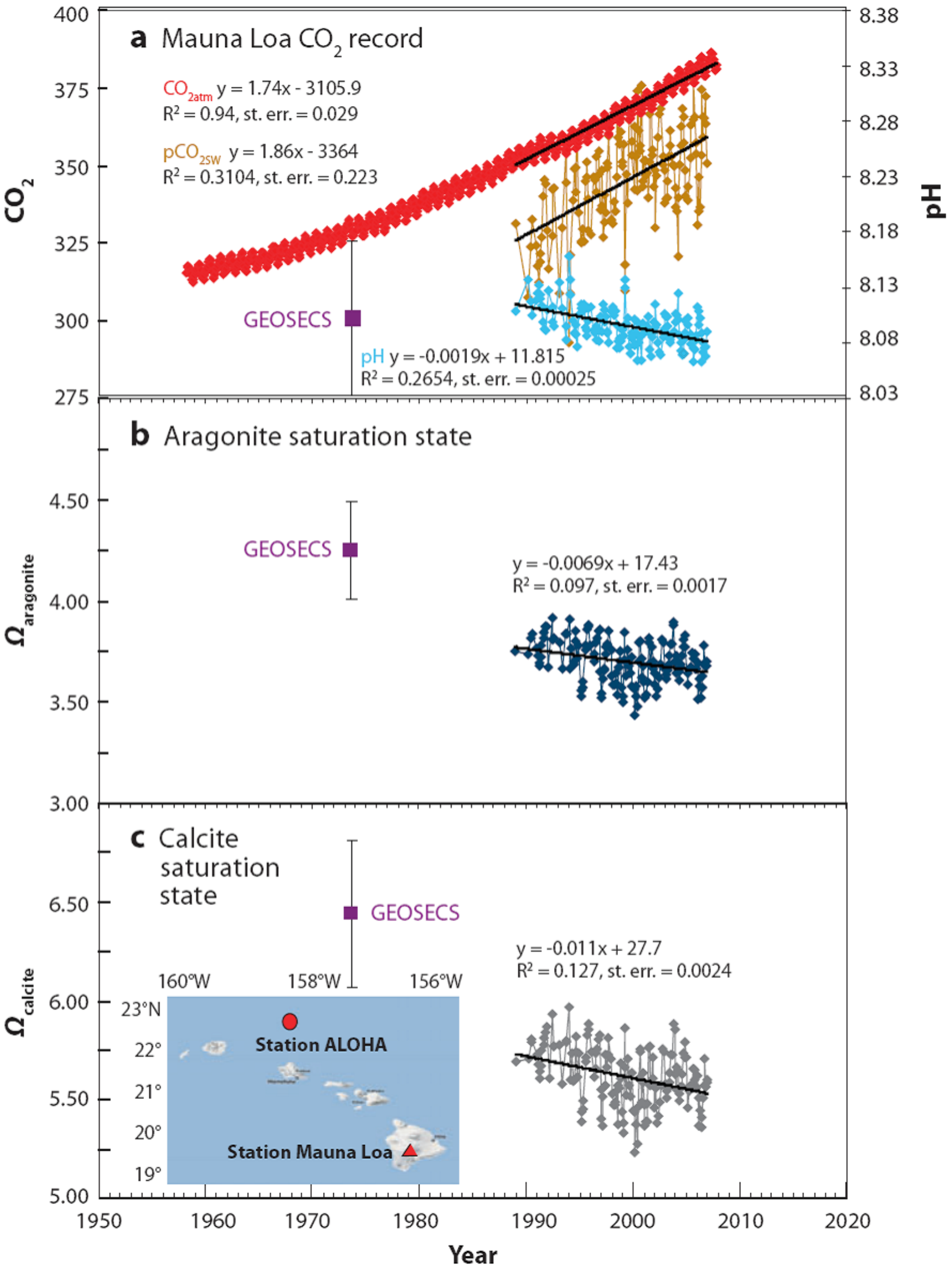


Figure 13. Time series of atmospheric CO_2 and responding ocean variables from a deep ocean reference site off Hawaii based on monthly sampling (source Doney et al. 2009). GEOSECS data were collected in 1973 from a station near ALOHA.

3.1.5 Science Questions

As a coastal observing Node, Q-IMOS does not collect many observations off the continental shelf and obtains the necessary reference data from the Bluewater and Climate Node. Q-IMOS will be a user of data on multi-decadal change rather than a generator of mechanistic hypotheses or source of predictions. The Q-IMOS data streams will capture regional dynamics and therefore provide observations useful for calibrating some of the models of these larger processes.

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

Ocean Heat Content:

- *Are changes in ocean temperatures in the Coral Sea similar at all depths?*
- *Do changes in ocean temperatures in the Coral Sea change the depth of the mixed layer?*
- *Do Coral Sea temperature variations drive changes in temperature on the continental shelf?*

Global carbon budget:

- *Do changes in pCO_2/pH on the GBR shelf mirror trends observed at deep ocean reference sites?*

Q-IMOS seeks to know whether changes in the heat content of the Coral Sea drive changes in temperature on the continental shelf and requires information on the pCO2/pH of oceanic water as a reference state for changes observed in shelf waters and ecosystems. It will also collect data on shelf salinity that be linked with multi-decadal changes in rainfall and river discharge.

3.1.6 Notable gaps and future priorities

Notable gaps:
While there are a number of ARGO floats that sample oxygen, there is the need for increased data density in the Coral Sea and along the margins of the QLD shelf.

Future priorities:
Sea Gliders to observe bio-physical properties of the upper global ocean adjacent to the QLD shelf
Slocum Gliders for repeat cross-shelf transects bio-physical properties.

3.2 Climate variability and weather extremes

3.2.1 Interannual Climate Variability

3.2.1.1 El Niño –Southern Oscillation (ENSO)

Interannual climate variability over the Pacific is dominated by the El Niño–Southern Oscillation (ENSO) cycle, which is a quasi-periodic climate pattern of ocean and atmospheric anomalies across the tropical Pacific Ocean (McPhaden et al. 2006). In the atmosphere, this corresponds with the east-west migration of the Walker overturning circulation (Figure 14), which can be tracked (and predicted) by the difference in atmospheric pressure across the Pacific Ocean. The Southern Oscillation Index (SOI) is a measure of the difference between air pressure in Darwin and Tahiti, although multivariate proxies involving more stations are becoming the norm in models seeking better prediction of response variables like rainfall. The SOI varies between extreme states at intervals of three to seven years.

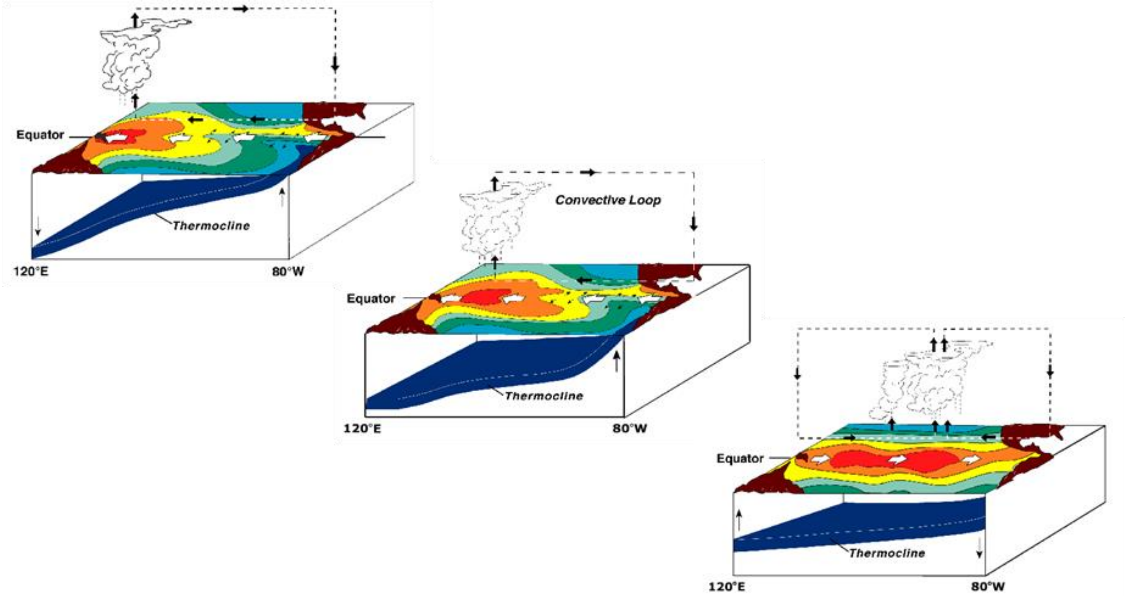


Figure 14: ENSO cycle showing La Niña (left), neutral (centre), and El Niño (right) states (source www.pmel.noaa.gov/tao/elnino/nino-home.html).

Warm tropical waters are a major evaporative source of rain-bearing clouds. Although the ocean-atmosphere forcing is still a subject of study, it is clear that the east-west position of the warm pool in the ocean along the equator is correlated with similar change in the longitude of the atmospheric changes; hence the name ENSO. The extreme states of this coupled atmosphere-ocean system are when the warm pool in the ocean and the major uplifting convection cell in the atmosphere are in the western Pacific (known as the La Niña phase) and the opposite condition when both have moved to their extreme position in the central Pacific (known as El Niño phase).

El Niño episodes have long been recognised in the eastern Pacific (Wyrtki 1984) as the arrival of warmer surface waters that depress the thermocline shutting off the coastal upwelling that normally supports productive scale fisheries in the Americas. In the neutral state, trade winds drive hot equatorial surface water to the western Pacific, where it forms the West Pacific Warm Pool (WPWP) and upwelling occurs in the eastern Pacific to replace these surface waters (McPhaden et al. 2006)

La Niña episodes represent the extreme opposite state when strong surface winds have pushed the WPWP to its western limit (noting that topography sets a limit on this displacement). In this alternate state, the thermocline in the western Pacific is depressed at the same time as it rises to the surface in the eastern Pacific to compensate for the volume of surface water being driven westwards.

These quasi-cyclic reverberations have strong and opposite influences on a range of variables (temperature, rainfall, wind, storminess, and upwelling) on both sides of the oceanic basin so that ENSO is a major source of climate variation impacting on ecosystems and sovereign economies. Figure 15 shows an example of the impact of ENSO upon coastal currents with practical implications for port operations (e.g. dredge spoil disposal).

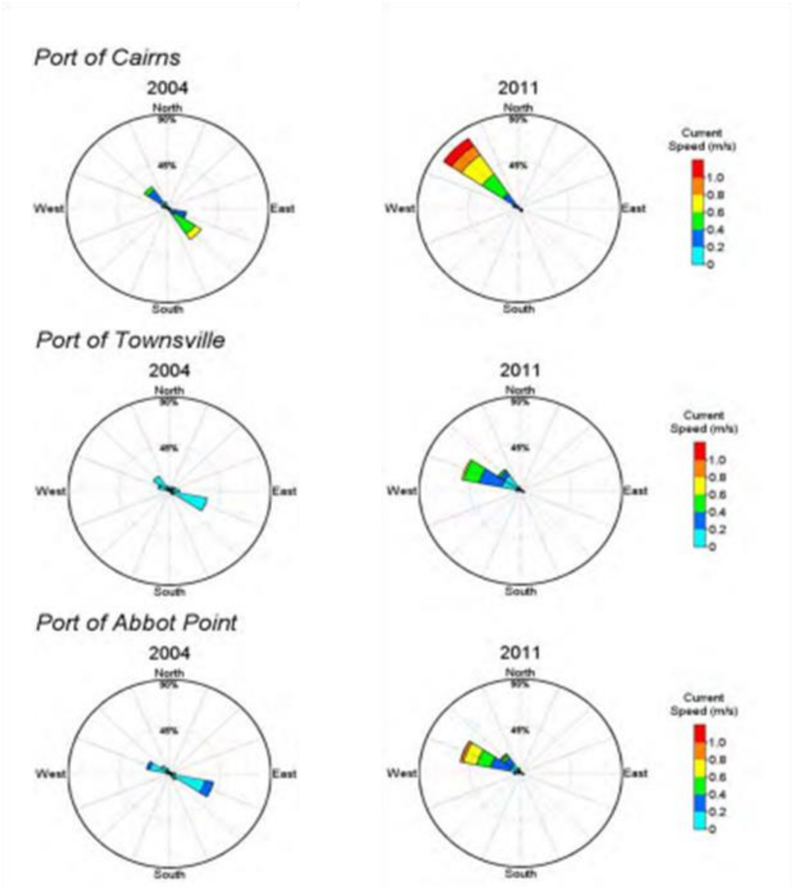


Figure 15. Surface large-scale currents for El Niño (2004), and La Niña (2011) phases at three major ports in north Queensland (source: GBRMPA 2013a).

In   eisberg 1984) and 1997/98.
Si   s across the Pacific (SEC in
th   sea levels in the Western
P   d coastline.

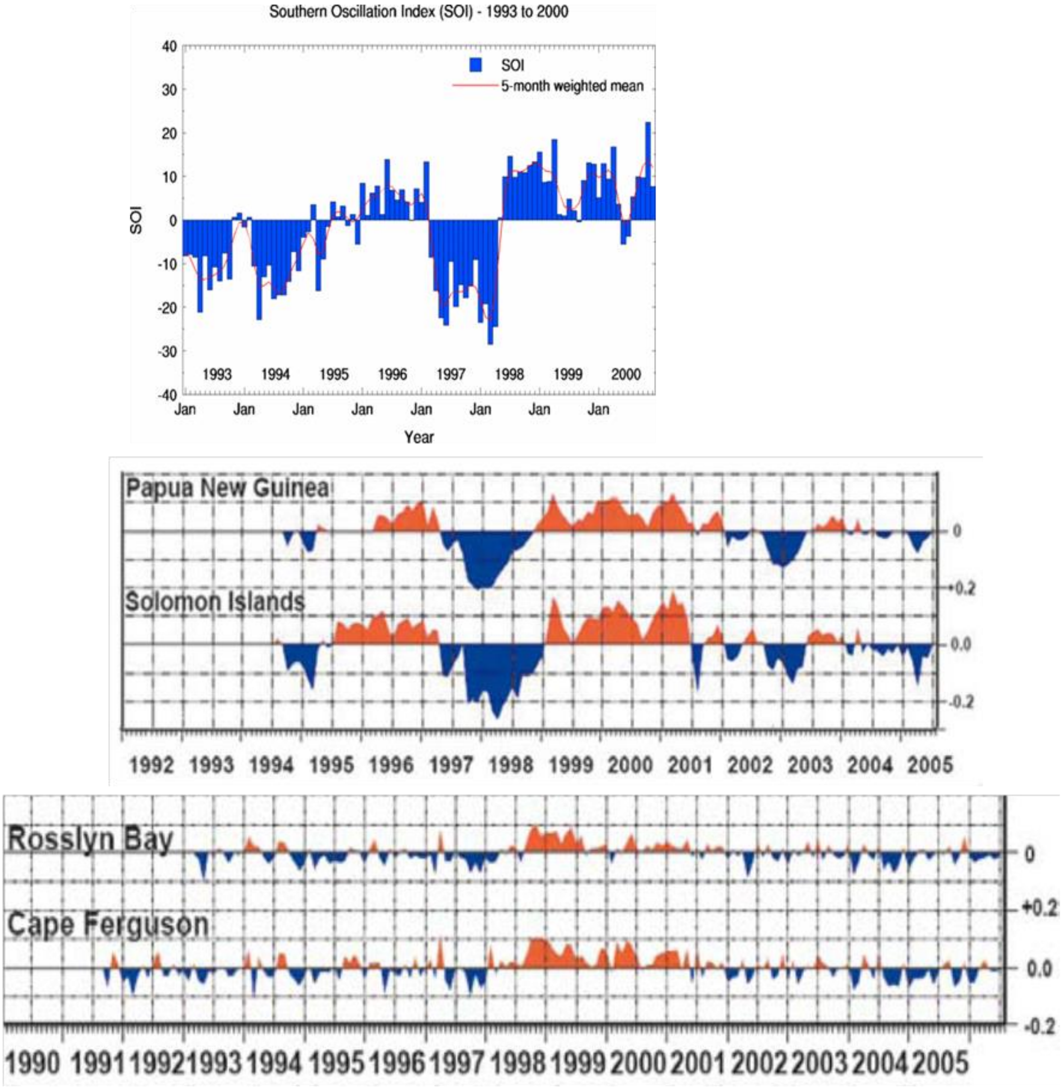


Figure 16. (Top) SOI index, (Middle) Sea levels from tide gauges in PNG, Solomon Islands (Lower) Sea levels from NE Australia (sources below).

http://reg.bom.gov.au/climate/current/soi-1993-2000.shtml
http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml
http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml

Ridgway et al. (1993) examined an ENSO event from 1986-87 that was of similar magnitude and the same sign as the 1997-98 event shown above. Although not as severe as the very strong El Niño of 1982/83, mean sea level at Honiara (Solomon Islands) dropped by 25 cm in early 1987. Their modelling of data from tide gauges and XBT casts showed a large region of depressed sea level centred on Honiara within a zonal band between the equator and 15°S (Figure 17).

This depression was steeply contoured between 150-165°E especially in the Solomon Sea, implying strong westward geostrophic flow in the south and the opposite in the north. The crowding of the contour lines in the Solomon Sea shows very strong NW flow along the PNG coastline and the authors estimated a flow anomaly of 15 Sv through the Vitiaz Strait, and a similar enhancement of flow through the nearby Solomon Straits. They also commented on the lack of response along the Australian coast between 10-30°S and from the tide gauge at Port Moresby interior to the Gulf of Papua. This suggests that much of the extra flow in the northern part of the SEC during El Niño episodes is channelled directly into the Solomon Sea.

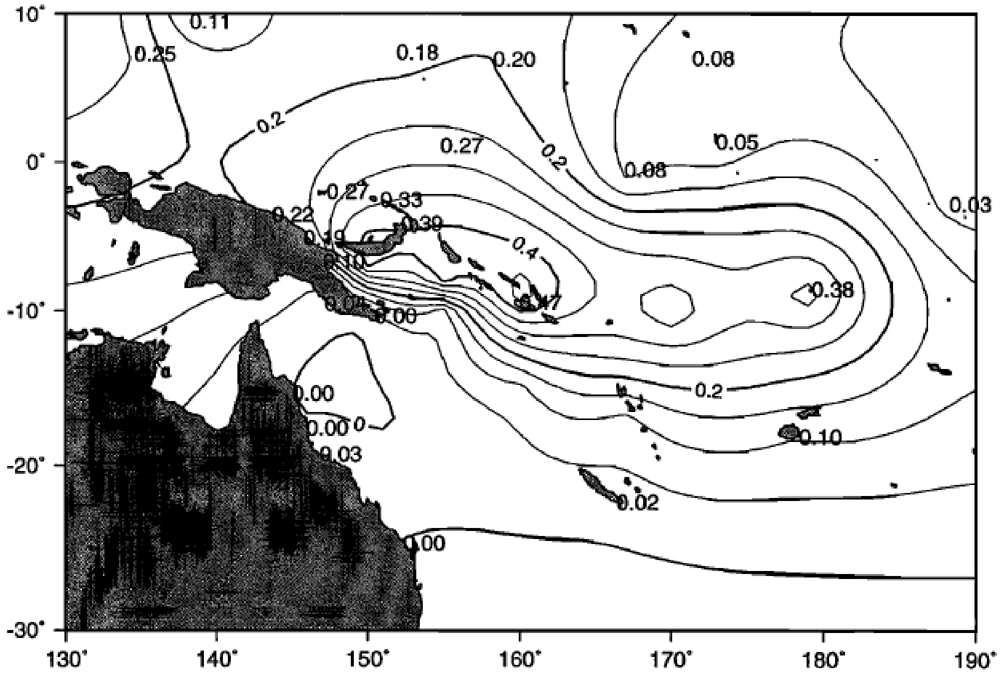


Figure 17. Contours of sea level anomalies (source Ridgway et al. 1993).

Notwithstanding this observation, the southern arm of the SEC and hence the EAC (see next section) should also strengthen during El Niño episodes due to the southern displacement of the SEC by WPWP water flowing east along the equator (Wrytki 1984, Meyers and Donguy 1984, Johnston and Merrifield 2000). Burrage et al. (1994) observed a strengthening of the EAC adjacent to the central GBR but Ridgway (2007) found only a very weak ENSO signal with a nine month lag in observations from the Maria Island site in Tasmania. He also suggested that this signal was delivered to south-east Australia from the Indonesian Through-flow in north Western Australia after propagation along the coastal wave guide. The most distant expression of this connectivity is the coupled dynamics of the poleward Zeehan Current flowing down the west coast of Tasmania.

In 3.1, the multi-decadal **trend** in ocean temperatures is described. A major a**nomaly** in that trend occurred between 1945 and 1977 (Figure 7). The overall temperature increase of the Southern Hemisphere for the period 1946–1975 was only 0.06°C compared with 0.14°C for the period 1976–1998 (Salinger et al. 2001). These multi-decadal cycles have been correlated with a basin-scale pattern of sea surface temperature and pressure anomalies expressed away from the equator in both hemispheres known as the Inter-decadal Pacific Oscillation (IPO) or Pacific Decadal Oscillation (Mantua et al. 1997).

The IPO/PDO (Figure 18) is a low frequency signal in sea surface height and sea surface temperatures reflecting slow internal processes in ocean mixing and circulation in the Pacific Ocean that can obscure global trends in the climate. This oscillation specifically separates alternating periods, each lasting 2-3 decades, of different warming patterns with effects on temperature, rainfall, and winds.

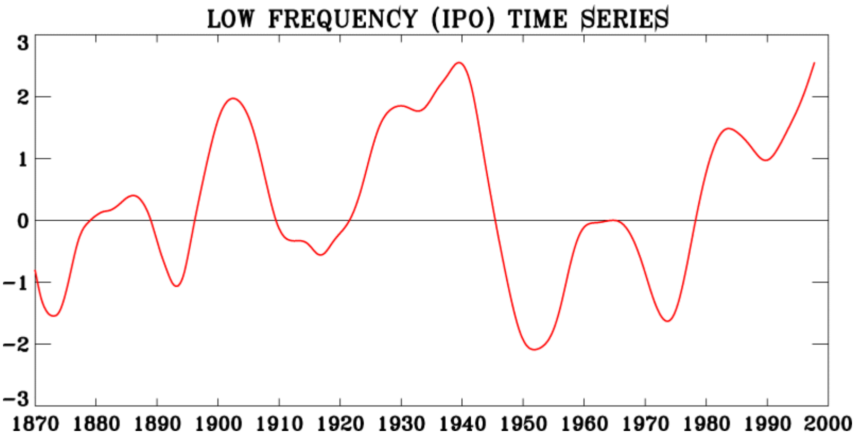


Figure 18. Index showing phases of the IPO (source www.bom.gov.au/climate/cli2000/jimSal.html)

The IPO signal as defined from Meteorological Office HadISST data shows positive phases in 1922–1944 and 1978–1998, and a negative phase between 1946 and 1977 (Salinger et al. 2001). These periods correspond with sustained heating and cooling episodes in global temperatures (Figure 7). When the IPO is in a positive phase, SST anomalies over the North Pacific and near New Zealand are negative, whereas SST anomalies over the tropical Pacific are positive. In the negative phase, these patterns are reversed.

The pattern and timescale of IPO variability has been attributed to atmospheric teleconnections from the Tropics (i.e. ENSO variability) to the extra tropics (known as the Pacific-South American Mode), followed by extra tropical oceanic teleconnections propagating westwards in the form of baroclinic Rossby waves. As the latter take over a decade to cross an ocean at subtropical latitudes, they are thought to dictate the temporal scale of basin-scale decadal variability and hence the broader spatial pattern of decadal ENSO (Power et al. 2006; Sasaki et al. 2008). Since Rossby waves act as ‘integrators’ of wind forcing as they propagate across the Pacific, the response of the extratropical ocean has been thought of as a low pass filter of high frequency atmospheric variability (Sasaki et al. 2008).

Power et al. (1999) showed that the two phases of the IPO strongly modulate the relationship between ENSO and rainfall variability over Australia. Specifically there is no clear relationship between interannual variations in the Australian climate and ENSO during warm phases of the IPO but robust relationships during cold phases of the IPO between ENSO and variability in rainfall and surface temperature. The strong ENSO event in 1997/98 is thought to have been reinforced by an in-phase IPO (Burgman et al., 2008).

3.2.2 Intra-seasonal variability and severe weather

Most of the physical phenomena to be captured by an Integrated Marine Observing System have annual cycles, which in many cases are driven ultimately by the seasonal patterns of global surface heating due to the earth's orbit. For example, the bifurcation of the westerly flows in the Coral Sea (Figure 19) at the surface moves south during the season of SE trade winds (April-November). During the summer monsoon, southerly flows contributing to the EAC start near 15°S. In the winter, the coastal bifurcation is found nearer to 18°S. Figure 19 suggests that this is due to a different fate for surface flow steered to the north of the Queensland Plateau. Given the implied influence of the wind fields, this displacement is likely to vary among years.

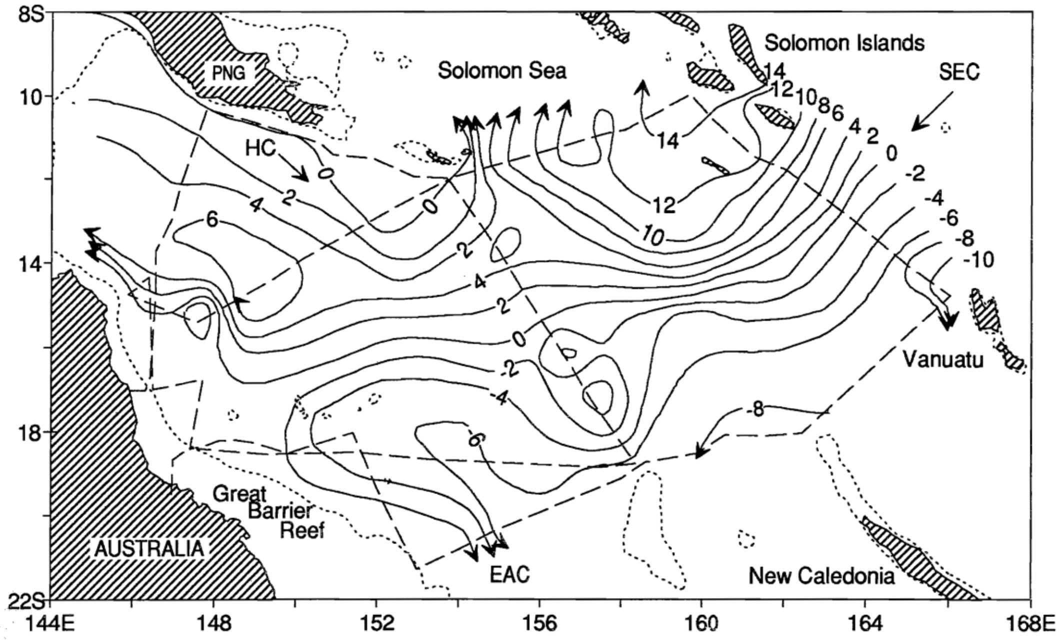


Figure 19. Coral Sea circulation inferred for the upper 1000m in October 1985; SEC – South Equatorial Current; EAC – East Australian Current; HC – Hiri Current (source Burrage 1993)

Ridgway and Godfrey (1997) detected a strong seasonal cycle in the open ocean zonal geostrophic transport north of 25°S and a similar strong seasonal cycle in the EAC down the Australian coastline between 25-45°S, with the strongest southward flow observed during the austral summer. They also showed that the amplitude of this seasonal cycle in the EAC strength diminished with southward progression especially below Sydney (34°S).

While average sea temperature across the GBR has increased by about 0.4°C since the 19th century (Figure 8, Lough 2007), interannual variations within a decade at fixed sites have larger amplitude and is a key factor affecting the risk of coral bleaching. Figure 20 shows three historical bleaching episodes on the GBR coincident with summer maximum water temperatures about 1°C above the flanking years. All three events occurred during years with strongly negative SO indices indicative of El Niño episodes. However the index was equally strong with the same sign in 1993 and 1997 (Figure 20), which remained cooler and without bleaching. The 1996/7 summer experienced five tropical cyclones between January and March, which collectively drew a lot of heat from the Coral Sea and may have reduced heat stress along the GBR.

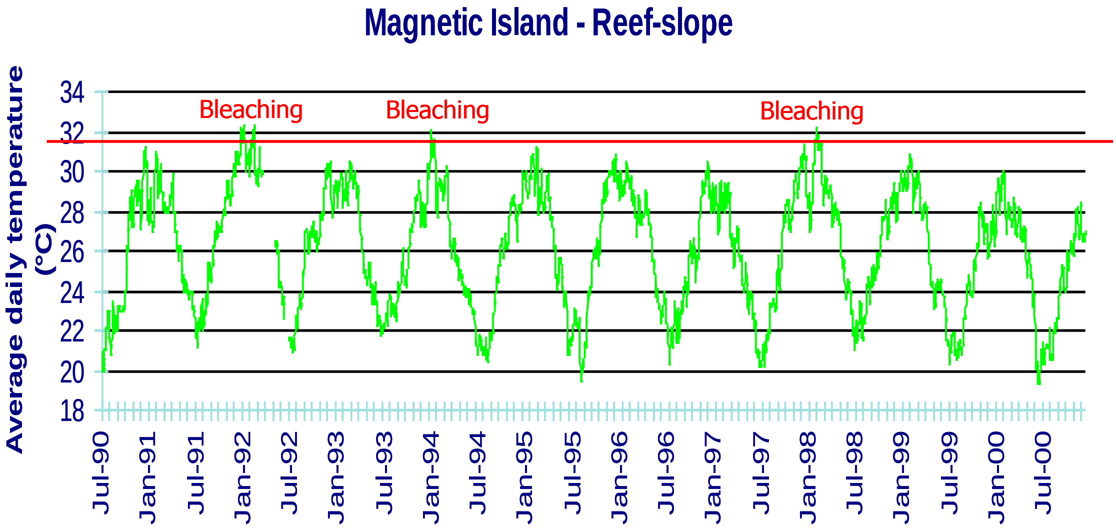


Figure 20. Interannual variations in temperature on the reef slope at Magnetic Island (source Madeleine van Oppen, AIMS).

Schiller et al. (2009) reanalysed the conditions prevailing during three episodes when the Coral Sea showed significant SST anomalies (including that caused by TC Justin in 1997). They found that the dynamics of all three events were different due to a unique mix of local and remote influences, which points to the difficulty of interpreting interannual variation without observational data.

3.2.2.1 The Madden-Julian Oscillation (MJO)

The northern Australian summer monsoon is also modulated on 30-50 day timescales by the MJO (Risbey et al. 2009). This is a large-scale eastward moving atmospheric wave-like disturbance along the equator mainly operating between the Indian and Pacific Oceans. As it passes through a given region, it can enhance or suppress convective activity and thus can lead to bursts and breaks in the northern Australian summer monsoon (Wheeler et al., 2009).

The MJO is classified into eight phases based on the pattern of convection and zonal winds in near equatorial latitudes and its phase is tracked in near-real time by the Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/). Passage of the MJO, by enhancing/suppressing monsoonal activity not only affects rainfall but also can lead to surface water cooling or warming at critical times for thermal stress events; thus influencing the risk of coral bleaching.

The MJO interacts with ENSO. In northern Australia, MJO-forced dry spells are drier in El-Niño years than in La Niña years (Risbey et al. 2009). During winter, the rainfall response along the Queensland coast co-varies with the MJO phase due to modulation of the SE trade winds. While the spatial domain influenced by the MJO is not as great as for ENSO or IPO, the time domain is much shorter with variation in wind and rainfall expressed at scales of days to weeks rather than seasons and years.

3.2.2.2 Tropical Cyclones

Differences in the strength of the summer monsoon circulation over northern Australia associated with ENSO events also result in marked differences in the occurrence of tropical cyclones along the GBR, with reduced activity during El Niño years when the tropical warm pool has receded into the east and enhanced activity during La Niña years (Lough 1994). Although there are several environmental conditions required for tropical cylone formation, these highly energetic atmospheric disturbances require SST above 26°C (Emanuel 2003). The recent record suggests slightly enhanced activity during La Niña episodes in the western Pacific but the record of their tracks over the same period shows that they have varied origins and diverse trajectories (Figure 21), which are only predictable from knowledge of ocean temperatures and atmospheric conditions applying near and following their formation.

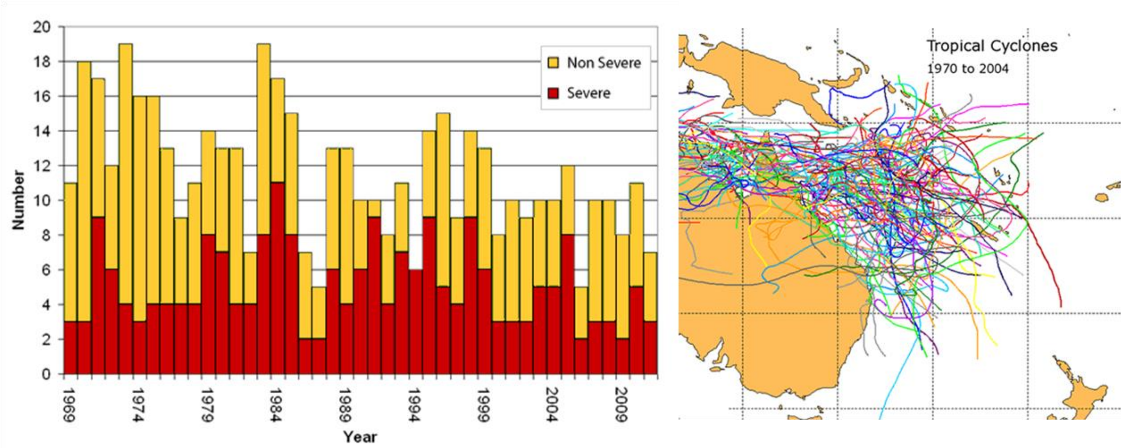


Figure 21. (Left) Interannual variation in the number of tropical cyclones affecting northern Australia (source: http://www.bom.gov.au/cyclone/climatology/trends.shtml). (Right) Cyclone tracks in the Western Pacific (http://www.bom.gov.au/cyclone/about/eastern.shtml#history).

Due to their sporadic occurrence and tracks, there is, as yet, no clear evidence as to whether the frequency and/or intensity of tropical cyclones in the southwestern Pacific has changed (Australian Bureau of Meteorology and CSIRO 2011). Some come from the far field (distant western or eastern origins) but severe tropical cyclones (Categories 4,5) impacting the Queensland coast inevitably require a period of intensification over the adjacent Coral Sea.

Even though the long-term trend is unclear, the GBR has been impacted substantially by severe (Category 4,5) tropical cyclones since 2005 (Figure 22). The cumulative exposure to cyclones since 1985 has been responsible for approximately half of an observed decline in coral cover (De'ath et al. 2012) across the whole GBR but the impacts have been much more severe in the southern GBR (Figure 23).

The potential for these severe atmospheric disturbances to create extreme and anomalous weather conditions is revealed by comparing the extent of fresh water flooding of the GBR observed in 2010-11 with the average result from two decades of observation (Figure 22). In 2010-11, separate events (TC Yasi and TC Oswald) resulted in exceptional rainfall in the Burdekin and Fitzroy catchments, respectively, which resulted in flood plumes influencing reef habitats much further offshore from the coast than seen in the previous 20 years.

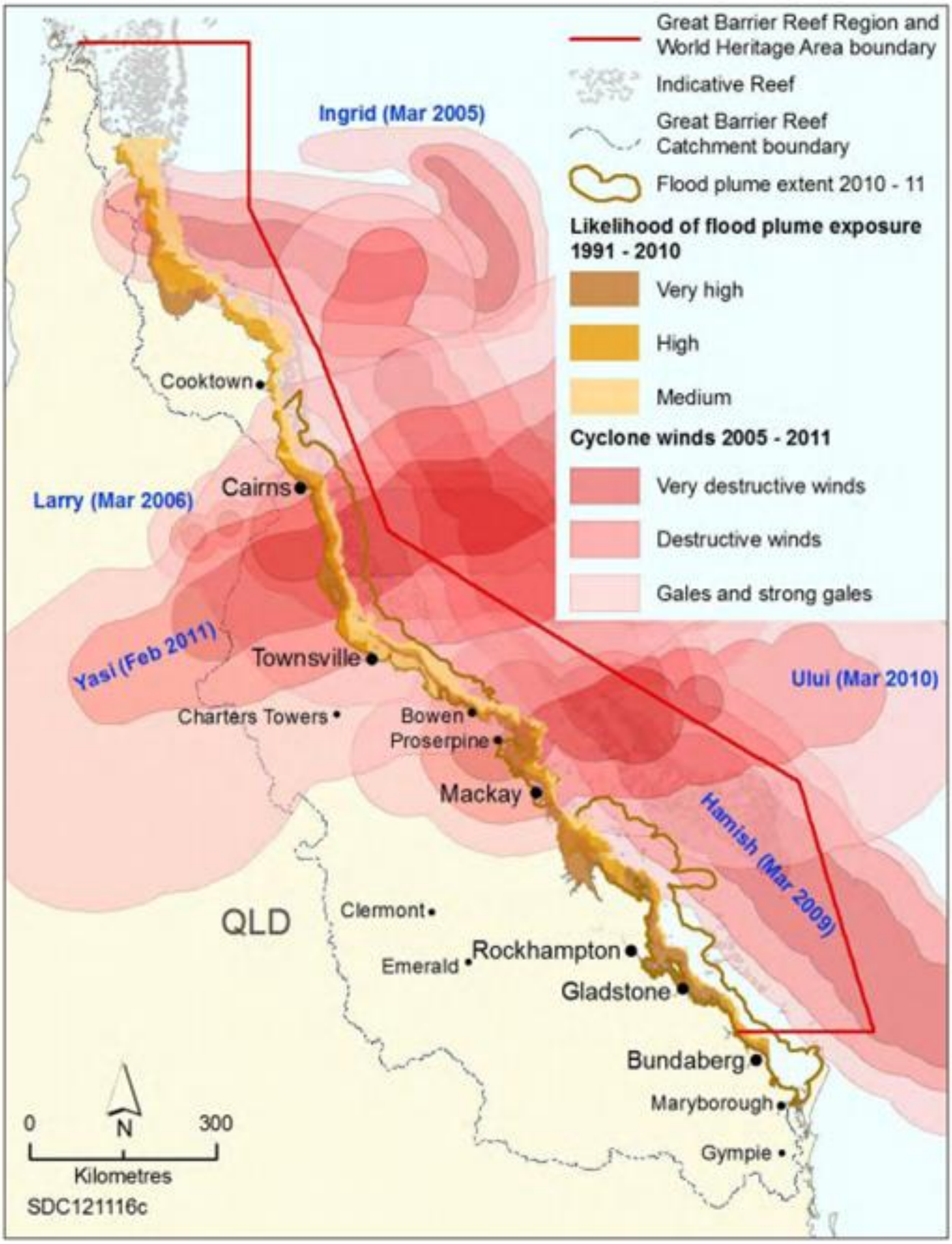


Figure22. Cumulative exposure of GBR ecosystems to cyclonic winds arising from five severe events (2005–2011). Historical exposure to flood plumes (1991–2011) compared with an extreme season in 2012-11 (Source: GBR Strategic Assessment 2013)

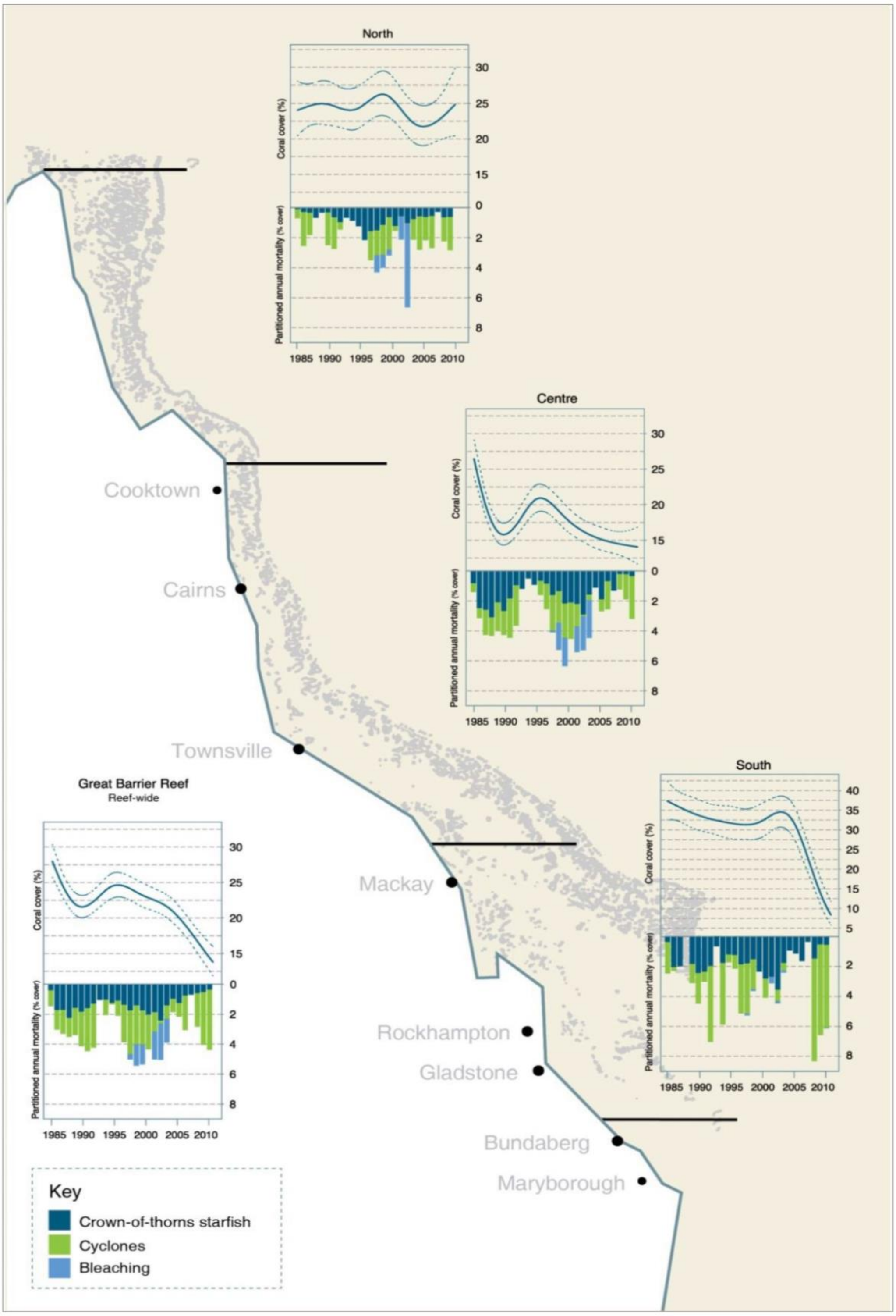


Figure 23. Recent cyclones in the southern GBR have been the major driver of a catastrophic decline in coral cover due to physical damage (Source: GBRMPA 2013a)

Figure 24. Flood plumes in the GBR Lagoon after heavy rainfall (source Craig Steinberg, AIMS).

TC Oswald did not produce destructive winds but the resulting rain depression created exceptional flooding in central Queensland and significant river plumes on the GBR (Figure 22). This event resulted in a major regional town, Rockhampton, being isolated for several weeks and the cost of repairing the regional roads exceeded $6 billion dollars (also includes the flood damage from TC Yasi).

The remnants of this system also produced substantial flooding of parts of south east Queensland (with significant loss of life) and large impacts in the capital city, Brisbane, when water engineers were forced to open the flood gates on the Wivenhoe Dam in order to protect it from catastrophic collapse. Low lying areas along the Brisbane River were flooded although not as extensively as in 1974, which preceded the creation of the Wivenhoe Dam as a flood mitigation measure.

In 1974, which remains Queensland’s wettest year on record, the ultimate cause of the record flooding was Tropical Cyclone Wanda which formed in the Coral Sea during a strong La Niña in 1973/74. These were the worst floods in the Brisbane area since 1893. The heavy rainfall arose from a quasi-stationary monsoonal trough displaced further south than usual over Queensland; demonstrating the importance of interactions between weather and extreme events.

In north Queensland, rainfall from cyclones is a major source of river flow into the coastal seas (Lavender and Abbs 2013). Figure 24 shows strong sediment plumes coming from the Burdekin and Herbert Rivers plus discoloured waters marking flood plumes carrying CDOM (Coloured Dissolved Organic Matter) that can be tracked hundreds of kilometres along the coast from their sources before dissipating even in year less exceptional than 2010-11.

Unlike the next topic (East Coast Lows), tropical cyclones are relatively long-lived systems; typically lasting a week with some large slow moving systems lasting longer. Tropical Cyclone Justin was an extreme example that was tracked by the Bureau of Meteorology between 6-24 March 1997. This large system was formed by the merging of two lows in a very active monsoon trough in the Coral Sea. After reaching maximum intensity on 9 March, the system remained stationary and began to weaken as it sucked heat out of the upper ocean. After being downgraded to a tropical low, it drifted northeast over warmer water where it re-intensified to a Category 3 system before travelling southwest across the Coral Sea to make landfall.

Observations of Sea Surface Height (SSH) gained by satellite altimetry have shown that slow moving tropical cyclones can impart substantial momentum to the upper water column. Figure 25a shows the track of TC Ului, which was tracked from Vanuatu to Queensland between 8-21 March 2010. After reaching Category 5 intensity, the system paused in the eastern Coral Sea between 15-17 March before moving rapidly to the coast.

Figure 25b shows a significant SSH anomaly and associated geostrophic flow over an area of 2 degrees of latitude on 17 March that was clearly created during this slow moving phase of the cyclone. Four days later, TC Ului had crossed the Queensland coast and degenerated into a rain depression. In strong contrast, the SSH anomaly generated in the eastern Coral Sea was persistent and slowly drifted westwards; approaching the continental margin almost three months after it had been spun up (Figure 25c).

Although the geostrophic flow is an estimate based on SSH gradients, it suggests the potential for at least some cyclones to have a lasting influence on mixing processes in the upper ocean well beyond the life of the atmospheric disturbance. To date this hypothesis remains unvalidated although satellite observations could clearly guide a field campaign to collect the required *in situ* measurements after a future event.

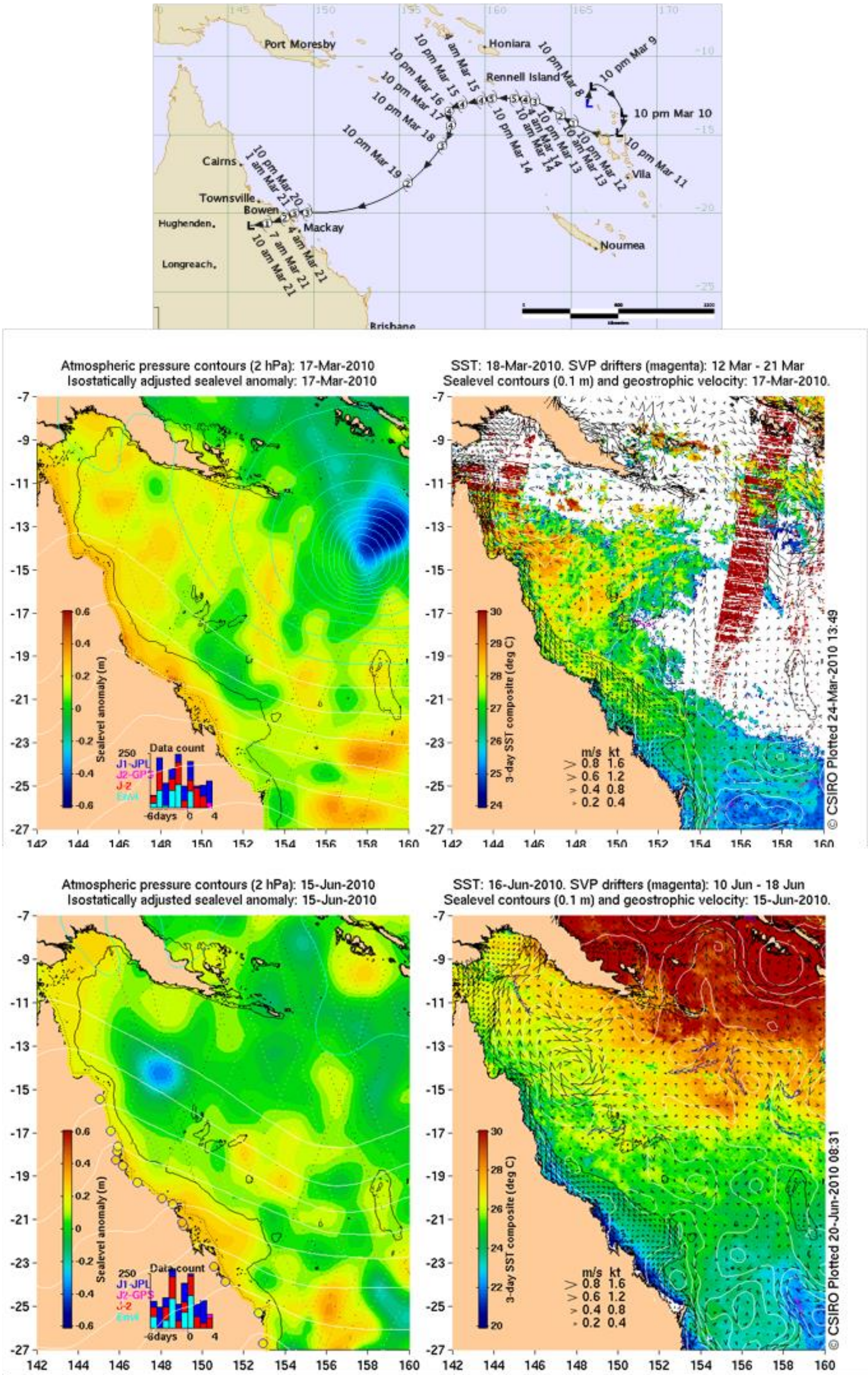


Figure 25. (a, Upper Panel) Track of TC Ului (source BoM website), (b, c, Middle and Lower panels) Observed sea level anomalies and estimated geostrophic velocities on 17 March and 15 June 2010 (Source: David Griffin, CSIRO).

3.2.2.3 East Coast Lows (ECL's)

Unlike tropical cyclones, East Coast Lows (ECLs) are relatively short-lived but highly energetic meteorological systems that form close to the coast and last only a few days. Although most common on the coastline of New South Wales adjacent to the offshore eddy field produced by the separation of the EAC from the coast, ECLs manifest every few years in southern Queensland. In 1998, an ECL denuded reef slopes of coral cover in the southern GBR (Figure 26) and several events off Brisbane have been associated with significant flooding and/or major episodes of coastal beach erosion (Figure 27).

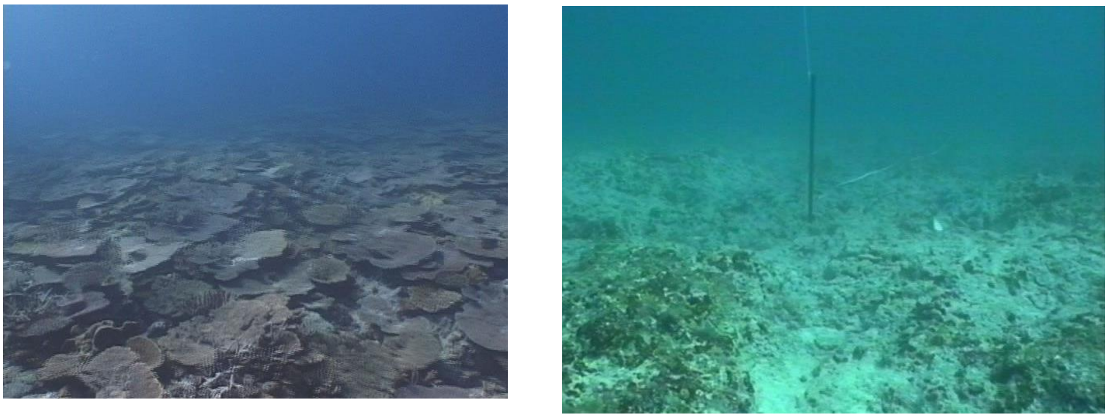


Figure 26. Coral cover on One Tree Reef at 10m before and after an intense storm (source: AIMS).

Figure 27. Examples of beach erosion in SEQ (source: www.ozcoasts.org.au/indicators/beach_erosion.jsp)

The seasonality of ECLs is also opposite to that of cyclones being most common in winter. Again unlike cyclones, ECL are driven by temperature gradients in the upper atmosphere colliding near the coast. The SST gradient between the coast and the EAC offshore also appears to be critical in the evolution of coastal low pressure and trough systems (Holland et al. 1987).

The significance of ECLs is their rapid intensification (most often overnight) that can produce highly energetic systems (of local to meso-scale size) capable of producing gale force winds and large waves on the adjacent coast. While less severe than Category 5 cyclones, ECLs can have maximum wind speeds above 30 $m.s^{-1}$.

3.2.3 Science Questions

Variation in environmental forcing within this spatial and temporal domain matches a variety of information needs ranging from adaptive management of multi-year plans (e.g. natural resource management, marine conservation) to tactical responses after extreme weather events (e.g. disaster recovery). Q-IMOS seeks to understand the changes to the physical and chemical environment driven by short (extreme weather events) and meso-scale (ENSO phases) variability in the climate.

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

Interannual:

- Can we improve understanding and prediction of ENSO dynamics in the Coral Sea?
- Is there a predictable pattern of cyclone clustering, spatially or temporally?
- What is the spatial cyclone risk distribution now and in the future?

Intraseasonal:

- How is the genesis of cyclones and east Coast Lows related to variability in the Coral Sea?
- Do we need to incorporate MJO intra-seasonal variability into predictive models?
- What are the dynamics of riverine flood plumes in the marine receiving waters?
- What are the physical stresses from the passage of cyclones across the continental shelf?
- What is the influence of extreme weather events upon sediment transport?

Q-IMOS provides ocean observations from a tropical and subtropical coastline where the marine systems have strong seasonality (within years), modified by quasi-cyclic meso-scale ocean variability (e.g. ENSO phase shifts, IPO), and unpredictable perturbations by extreme events (i.e. Tropical cyclones, floods, and East coast Lows). Consequently platforms need to provide sustained high-frequency data streams from robust systems that will be used primarily to calibrate and validate the eReefs marine prediction model for the continental shelf of the east coast of Queensland.

3.2.4 Notable gaps and future priorities

Notable gaps: Oxygen is only measured in oceanic water via the Sea Glider. This needs to be matched by data streams from the shelf, delivered via Slocum Gliders, because benthic oxygen could be limiting after extreme floods.

Future priorities: Slocum gliders deployed on repeat cross-shelf transect, but also taskable to specific impacted regions during and after extreme events.

3.3 Major boundary currents and inter-basin flows

3.3.1 South Equatorial Current

Both boundary currents in Queensland (EAC, Gulf of Papua Current) are forced by the same broad inflow of the South Equatorial Current (SEC) from the western Pacific Ocean (Figure 19). The complex bathymetry of the Coral Sea Basin filaments the SEC into a series of strong jets (Figure 28). Discrete filaments have been labelled as the North, South Vanuatu Jets (NVJ, SVJ), and the North, South Caledonia Jets (NCJ, SCJ).

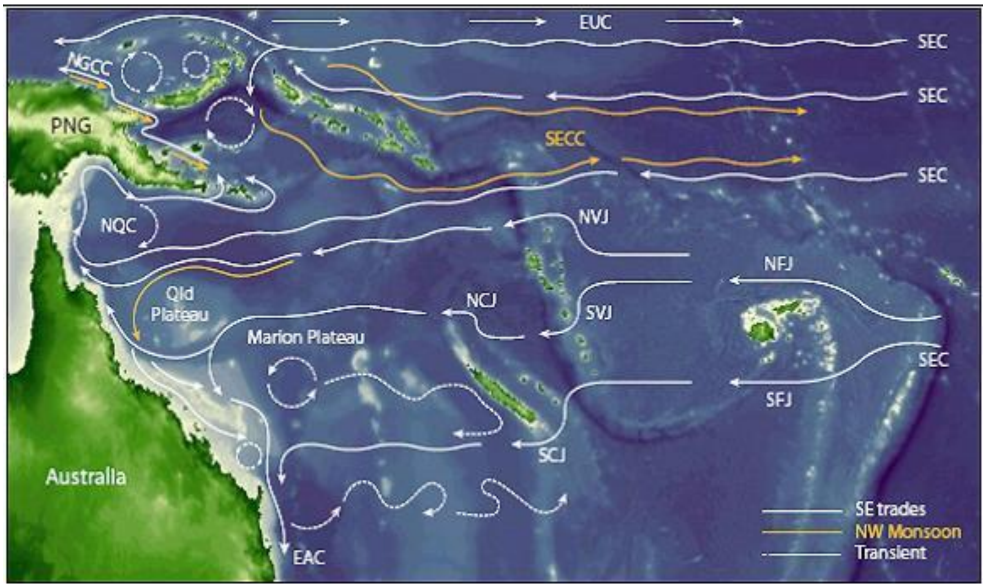


Figure 28. Flow streams in the western Pacific (source Steinberg 2007).

The SEC flows westwards into the eastern Coral Sea at depths to at least 1000 m (Church 1987, Andrews and Clegg 1989) but with evidence of vertical shear near the coast. At the surface, the bifurcation in the SEC is found near 16°S whereas, at 1000 m, it is found near 22°S (Figure 29). This deepening of the bifurcation with latitude means that there is a deep undercurrent (known as the GBR Undercurrent, GBRU) flowing northwest through the Queensland Trough (Church and Boland 1983) underneath the southward flowing surface expression of the EAC offshore of the central and southern GBR. The GBRU is presumed to become continuous with the NQC north of 14°S (Figure 28).

South of the GBR, the subsurface flows from the SEC become continuous with the surface expression of the EAC and both tightly track the Continental Slope south of Fraser Island.

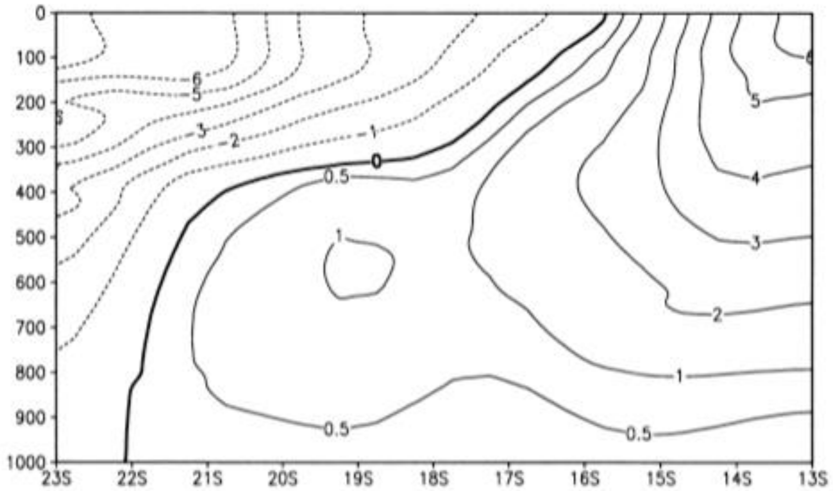


Figure 29. Alongshore velocity (cm.s^{-1}) averaged within 2^{o} longitude of the coast. Positive values are northwestward and the zero contour shows the bifurcation of the SEC (Source: Qu & Lindstrom 2002).

3.3.2 East Australian Current (EAC) system

The East Australian Current (EAC) is both the western boundary of the South Pacific Gyre and the linking element between the Pacific and Indian Ocean gyres (Speich et al. 2002). It forms between 15° and 22°S in the Coral Sea depending on depth (Figure 29). It reaches to Tasmania (Figure 30).

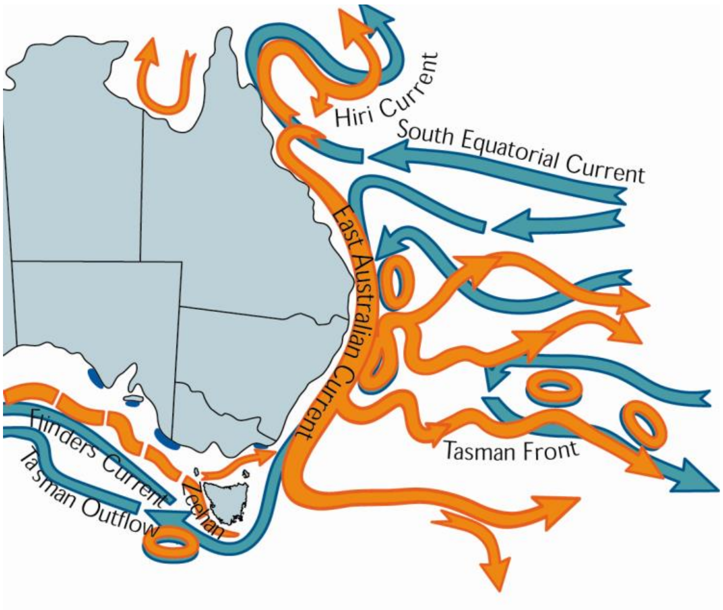


Figure 30. Schematic of major surface (orange) and subsurface (cyan) flows off eastern Australia (Source: www.oceanclimatechange.org.au).

The EAC is a western boundary current of modest energy but considerable complexity (Ridgway and Godfrey 1994). It is strongest and most coherent south of the GBR where it tracks the continental margin closely (Figure 31).

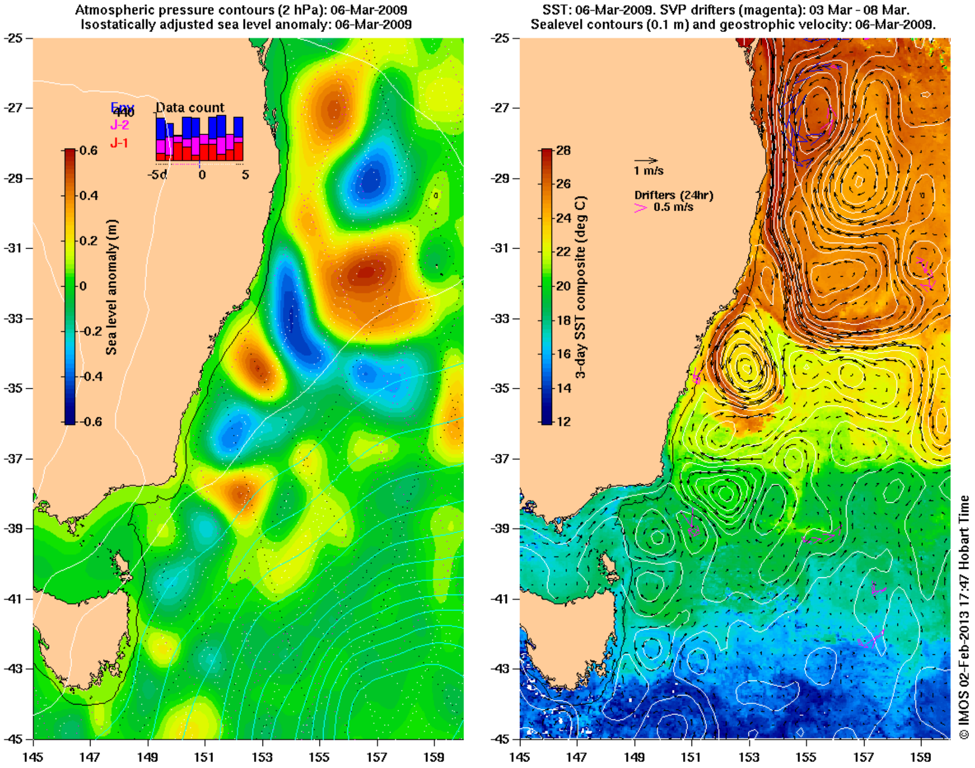


Figure 31. Satellite derived SSH anomaly (left) and SST and surface current (right) showing an intense and coherent EAC off Brisbane (Source IMOS Oceancurrent)

The EAC plays a critical role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Roemmich et al. 2005). This heat transfer is a dominant environmental influence on regional climate and fisheries production along the eastern seaboard (Poloczanska et al. 2007).

Variability in offshore sea surface height (SSH) leads to uncertainties in storm surge prediction along the coast. For South East Queensland, the difference between the predicted mean 100 year and 1000 year storm surge is about 0.3 m, similar to the short-term variation observed in SSH at this latitude. Thus, variability in the EAC complicates accurate risk assessment of coastal inundation levels, which is critical for the long-term strategic planning of coastal infrastructure.

South of Brisbane, at around 31°S, the surface flow separates into north-eastward (Subtropical Counter Current), eastward (Tasman Front) and residual southward (EAC Extension) components (Godfrey et al. 1980, 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 (Figure 32). The residue of the EAC transport continues southward along the Australian coast as far as Tasmania, with mesoscale eddies dominating the flow (Boland and Hamon 1970; Boland and Church 1981; Bowen et al. 2005; Mata et al. 2007).

The largest of the EAC eddies are 200-300 km in diameter and 2-3 of these warm-core eddies are generated annually with lifetimes often exceeding a year (Nilsson and Cresswell 1981; Bowen et al. 2005). They follow variable southward trajectories, but are generally constrained within the deep basin just offshore from the EAC extension. Cold-core eddies are also embedded in this flow.

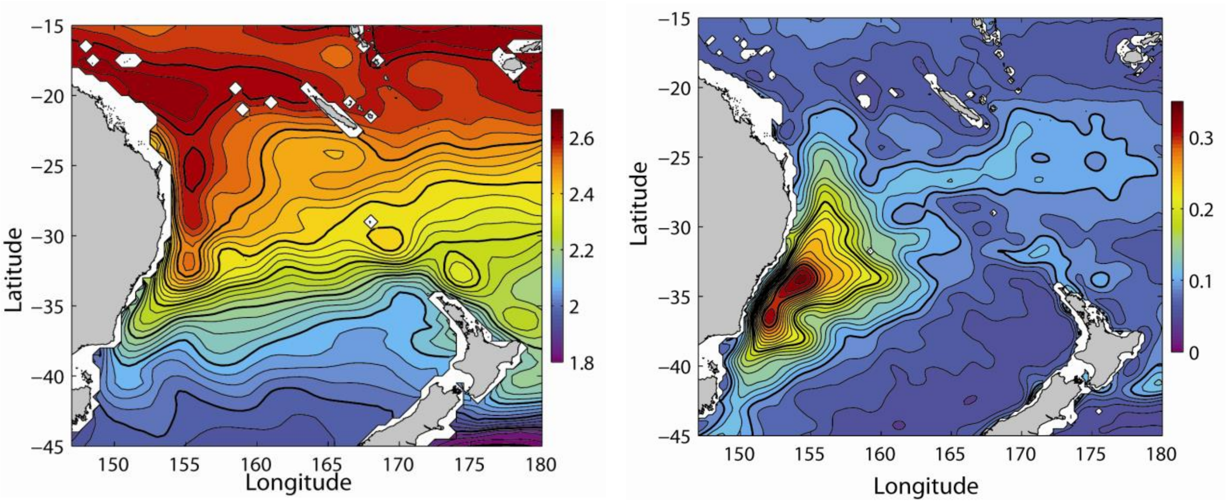


Figure 32. The mean surface height field (left) and its variability (right) in the south-west Pacific between 1992-2006 (contour interval is 0.05 m). The southward flowing EAC is the dominant feature off eastern Australia. The highly variable region is caused by mesoscale eddies below the separation point (Source: www.oceanclimatechange.org.au).

Long-term observations from an ocean reference site in Tasmania (Maria Island) have shown warming trends much greater that the average global ocean trend: 2.3°C vs 0.6°C respectively over the past 100 years (Ridgway 2007). Most of this increase has occurred since the mid-20th Century. The T-S signal of this warm water arriving in Tasmania identifies the EAC as its source and the long-term record indicates a poleward advance of this boundary current by ~350 km since 1994. This intensification of the EAC near its southern limits has been attributed to mid-latitude changes in ocean circulation driven by changes in wind stress and curl.

In the 1970s, a pattern of atmospheric disturbance known as the Southern Annular Mode was identified in the Southern Hemisphere (Marshall 2003). The Southern Annular Mode is an oscillation of pressure anomalies of opposite sign between Antarctica and the mid-latitudes. In its positive phase, the index is associated with lighter winds in the mid-latitudes and stronger westerly winds and increased storminess over the Southern Ocean. In its negative phase, these patterns reverse. While these phases reverse stochastically at weekly time-scales, there has been a steady trend towards more frequent periods of positive phase since the oscillation has been monitored. Thompson and Solomon (2002) have attributed this to recent trends in the lower stratospheric polar vortex caused by the Ozone Hole over Antarctica. Cai et al. (2005) have linked this atmospheric behaviour with a multi-decadal trend to increasing mean sea level pressures in the mid-latitudes; a spin up and poleward shift of the Southern Ocean super-gyre circulation; and intensification of the EAC in the Tasman Sea. Their model also predicts a weakening of the EAC in the north and there is some observational evidence to support this (Ridgway and Godfrey 1996, Figure 33).

As a result of the long-term intensification of the EAC in the Tasman Sea, north eastern Tasmania has experienced significant long term change in some sub-littoral communities (e.g. Last et al. 2010). Among other invasive species from mainland populations, a voracious sea urchin is converting areas that were once lush kelp forests into urchin dominated barren grounds with profound implications for many other species. There is no evidence that these recent changes are part of a cycle.

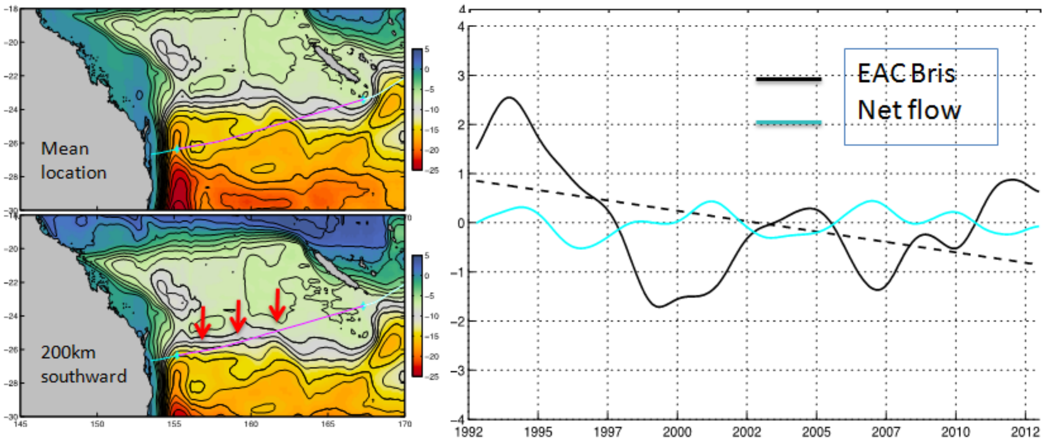


Fig. 33. Data from PX30 XBT line in relation to net eastward EAC flow (Brisbane to New Caledonia). Southward shifting of the western end of the South Pacific gyre appears to have resulted in a displacement of the more intense and cohesive regions of the EAC to areas further south (Source: Ken Ridgway)

Ultimately, the EAC Extension extends to Tasmania before shearing vertically (Figure 30). Surface waters turn eastward and enter the Tasman Sea towards New Zealand. Deeper flows turns westward around southern Tasmania (Tasman Outflow) and can be traced to the eastern Indian Ocean with an important impact on the global ocean circulation (Figure 30). As well as connecting the gyre systems in the Pacific and Indian Oceans (Ridgway and Dunn 2007), the Tasman Outflow forms a third element of the global thermohaline circulation (Speich et al. 2002).

3.3.3 Gulf of Papua Current

On encountering the continental margin of Australia, the northern part of the South Equatorial Current (SEC) forms an equatorward western boundary current system. The surface expression of this northerly flow is found between 15°S and 18°S depending on seasonal and interannual variations. At depth, northerly flow starts as far south as 22°S (Figure 30) resulting in a subsurface Great Barrier Reef Under Current (GBRUC); which merges with the surface flow north of about 15°S to form the North Queensland Current (NQC), which flows up to Cape York and beyond (Figure 34).

Almost none of this water can pass through the Torres Strait (Wolanski et al. 1988b) because of its extremely shallow depth (average 20 m). Consequently the NQC must be continuous with an easterly flow detected south of the Louisiade Archipelago that has been labelled the Hiri Current (Qu and Lindstrom 2002). Ganachaud (2012) argues that all three regional current identities are simply parts of a single system that should be referred to by geographical tradition as the Gulf of Papua Current. At the eastern tip of Papua New Guinea, the GPC turns north and enters the Solomon Sea.

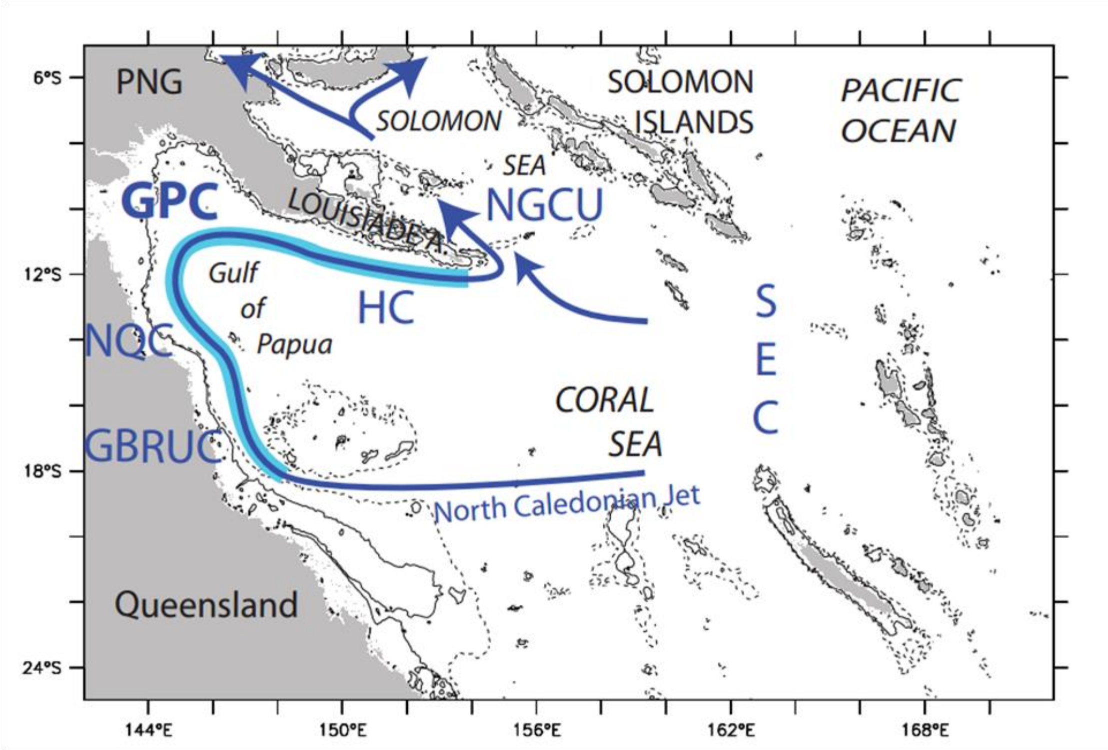


Figure 34. The component currents (GBRUC, NQC, HC) forming the Gulf of Papua Current (Source Ganachaud 2012).

Temperature-salinity signatures identify the GPC as the source of water in the New Guinea Coastal Undercurrent (NGCU, Lindstrom et al. 1987) which is thought to be a major source for the Equatorial Undercurrent (EU). Ganachaud et al. (2012) argue that the NGCU in the Solomon Sea is more than an extension of the GPC because it is fed both by the boundary current from the Coral Sea and by inflow of SEC waters of lower latitudes. Schiller et al. (2008) modelled a mean return of 8.2 Sv from the SEC to the Western Pacific and the EU is considered to be major modulator of ocean variability on shorter time scales (see 3.2.1).

The clockwise flow of the GPC creates a quasi-stable recirculation feature internal to the Gulf of Papua (Wolanski et al. 1995) and potentially another outside the mouth to the Gulf. The gyre in the Gulf of Papua has the potential to define a Large Marine Ecosystem (LME) *sensu* Sherman and Duda (1999). It is critical to the early life history of the Tropical Rock Lobster (*Panulirus ornatus*), which is the most valuable fishery in North Queensland and the Torres Strait (Pitcher et al. 2005).

3.3.4 Science questions

Queensland is unique in having two boundary currents (GPC, EAC) moving in opposite directions along its coast. The EAC transports heat from the tropics to southern latitudes and impacts the entire eastern seaboard of Australia. The Gulf of Papua Current creates a unique pelagic ecosystem in the inner northern Coral Sea. Both boundary currents have a major influence on shelf processes (next section); hence it is critical to monitor all significant changes in their dynamics. In the national context, both boundary currents need to be monitored for changes in vertical structure and volume transport as the South Equatorial Current exhausts through both exits (GPC-north, EAC-south) from the Coral Sea.

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

Dynamics:

- Will the EAC strengthen with climate change as predicted?
- Will the GPC weaken with climate change as predicted?
- Will the bifurcation point and/or dynamics alter in a warmer ocean?

Q-IMOS will rely on the BW&C Node to provide detailed information about the properties of these currents and their dynamics (because of their strong influence on shelf processes), critical information to the eReefs model that will propagate the changes to shelf systems.

Within the scope of this plan (2015-25), the BW&C is expected to be able to monitor the full-depth transport of the EAC near 27^{o}S. However, the GPC will remain largely unobserved except by satellites. Consequently, reliable repeat transects across the GPC to 1000 m by Seagliders, starting from near 14^{o}S, will have disproportionate value as a source of critical cal/val data for eReefs.

3.3.5 Notable gaps and future priorities

Notable gaps:
In addition to the lack of in situ observations north of 14°S (other by SOOP), the only fixed infrastructure in South East Queensland (south of the Great Barrier Reef) is the National Reference Station at North Stradbroke Island.

Future priorities:

1. The Northern Great Barrier Reef, Torres Strait, Gulf of Carpentaria have inadequate coverage through in-situ observations. Necessary observations include temperature (surface and subsurface), salinity, sea surface height and velocity delivered through moorings, slocum gliders, ocean radar and enhanced SOOP. Given the size and remoteness of the northern regions of interest to the Q-IMOS Node, the Node and facilities will look to leveraging existing infrastructure (e.g. AMSA tide gauges and moorings, fishing vessels etc) to increase our access to and footprint in this area. Further, the Australian Government's emerging Northern Australia Strategy will be monitored as a potential opportunity to define science questions relevant to the region and as a catalyst to bring together the scientific community, industry and government as potential supporters of observing infrastructure in this region.

2. Understanding the transport and variability of boundary currents relevant to the region (e.g EAC, NQC and HC) remains a critical science need for the Node cimmunity. The Node will work with mooring and glider facilities, and other relevant Nodes (e.g. BW&C), to develop and evaluate a strategy for boundary current monitoring using sea gliders.

3.4 Continental Shelf and Coastal Processes

3.4.1 Boundary current eddy –shelf interactions

The classic view of Coral Sea circulation reveals a broad South Equatorial Current bifurcating as it meets the Queensland continental shelf, however the SEC is filamented by the topography arriving as jets that eventually join up on the western boundary to form the poleward EAC or equatorward GPC (Figure 29). Embedded within these jets are large eddies that can be cyclonic or anti-cyclonic.

On occasion a large anti-cyclonic eddy can reverse the clockwise circulation of the GPC. Due to geostrophy, the GPC raises sea level and depresses the thermocline along the outer GBR. When it reverses, however, the thermocline lifts and brings deeper waters closer to the continental shelf. Tidal and geostrophic pumping (Thompson and Golding 1981; Nof and Middleton1989) can then channel those waters through the ribbon reefs onto the shelf itself.

As eddies move toward the shelf, their momentum also squeezes waters from depth up onto the shelf. This can produce a cross shelf flow that results in warm surface coral sea waters impinging on the shelf but also drives cooler water from depth along the seafloor toward the shelf. The shelf break and outer reef topography can also produce instabilities in the flow forming smaller scale eddies between the main boundary current flows and the reef. Enhanced mixing and cross shelf components of flow are the result. Shear instabilities also occur along the shelf break where there are significant density changes between outer shelf waters and the Coral Sea.

3.4.2 Upwelling and downwelling

Surveys of seabed communities throughout the GBR Marine Park have revealed several regions on the shelf where marine plants are unusually abundant (Figure 35 shows two such expressions near offshore from Townsville and on the outer reef well east of Mackay). These regions are likely to have persistent upwelling of nutrients from deeper layers in the Coral Sea. Several physical mechanisms appear responsible.

3.4.2.1 Wind driven upwelling

The dominant south-east trade winds act to suppress upwelling along Queensland's east coast by producing Ekman transports that depress the thermocline. Consequently the evidence for regional upwelling suggests that it is produced by processes other than classic wind-driven uplift of isotherms.

While the dominant SE trades act to deepen the mixed layer, any weakening of the wind stress reduces the retarding force on the EAC and allows an acceleration of the poleward flow. The thermocline will then lift toward the surface near the shelf margin. There are also periods of NW monsoonal winds from November to March that reinforce the poleward flow of the EAC and promote upwelling forced by the boundary current (Andrews and Gentien 1982, Andrews and Furnas, 1986).

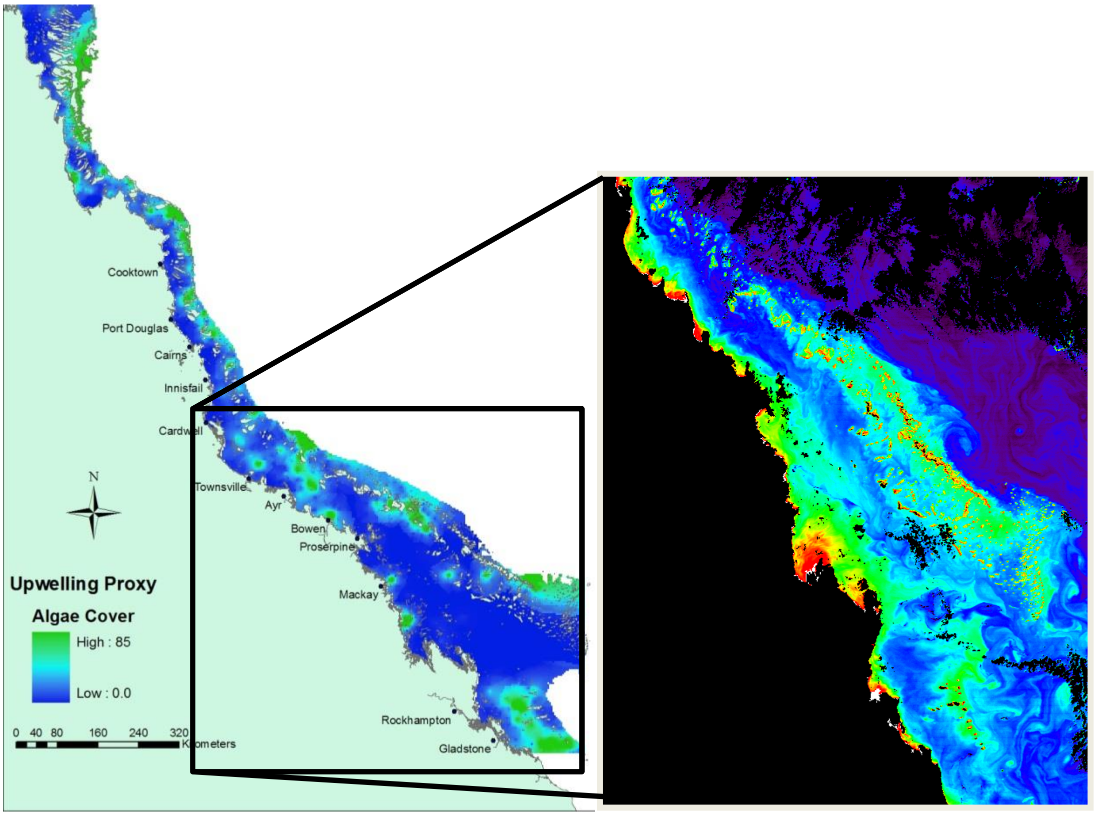


Figure 35. Algal cover of seabed communities in the central GBR (right) juxtaposed with satellite imagery of chlorophyll a revealing the intrusion of oceanic waters upon the continental shelf (sources Scott Wooldridge, AIMS;).

3.4.2.2 Boundary current upwelling

A strongly southerly boundary current along the lower GBR should produce upwelling favourable conditions, lifting isotherms along the slope through Ekman transport, although topographic steering and tidal pumping may be more significant at the local scale in drawing deeper waters onto the shelf (see next section). Between 17-19°S, however, where the reef matrix is more open, there is evidence of oceanic water being forced into the GBR Lagoon (Figure 35); possibly by eddy encroachment of the EAC onto the shelf as seen elsewhere (Roughan and Middleton 2002). Cold bottom water layers have been detected in this region across the full width of the shelf (Andrews and Gentien 1982; Andrews and Furnas 1986; Berkelmans et al. 2010) and are coincident with strong expressions of macroalgae (outer shelf) and seagrasses (mid-shelf).

South of 22°S, an abrupt contraction of the shelf width and steepening of the slope bathymetry produces quasi-stable recirculation features in the lee of the Marion Plateau (Griffin et al. 1987; Middleton et al. 1994; Burrage et al. 1996). Satellite drifters drogued in the surface layers (Figure 36) support evidence from the MODIS imagery (Figure 35) that the offshore circulation includes small cyclonic eddies, which can have elevated isotherms under their core (Steinberg 2007). Figure 36 shows one example (green track) of an eddy impinging on the shelf margin and this may be one mechanism by which cold water is advected onto the shelf.

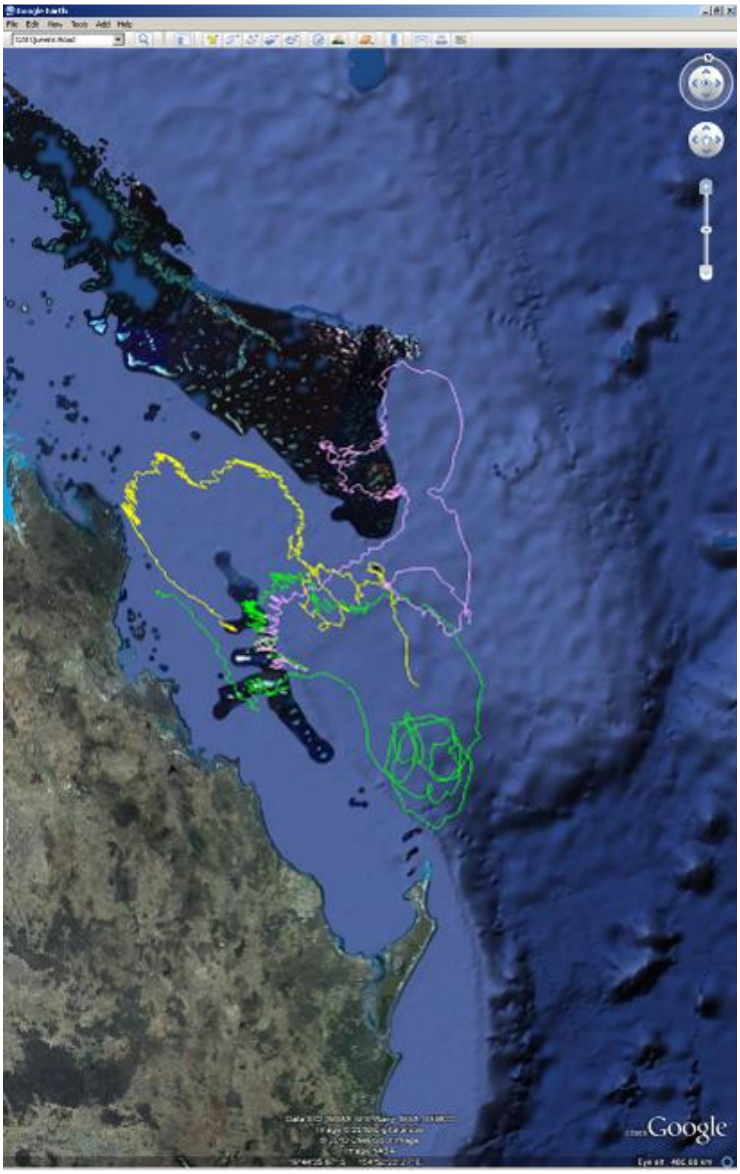


Figure 36. Drifter tracks from drogues released near Heron Island (Source: Craig Steinberg, AIMS).

Griffin et al. (1987) also found evidence for uplift of deeper waters onto the shelf in this region by tidal pumping and quasi-periodic pumping by coastal trapped waves. Moorings deployed on the shelf have verified vertical stratification of the water column caused by episodic intrusions of cold bottom water operating at tidal and lower frequencies (Weeks et al. 2010). The enhanced biomass of plants found on the shelf inside the Capricorn-Bunker archipelago (Figure 35) provides indirect evidence that these cold nutrient-rich intrusions are regular and substantial.

South of the Great Barrier Reef, satellite imagery often shows a band of cool SST on the shelf in the lee of Fraser Island that is also coincident with a band of high primary production (Figure 37). The coupled biophysical signatures are clear indicators of local upwelling, although there have been few studies in this area since Middleton et al. (1994). The physical mechanism causing the SST anomalies is unknown but multiple causes are possible by analogy with better known areas along the NSW coast (Roughan and Middleton 2002). These include encroachment of the EAC onto the shelf, topographic effects on flow (Oke and Middleton 2000), and flow separations from the shelf break (Roughan and Middleton 2002).

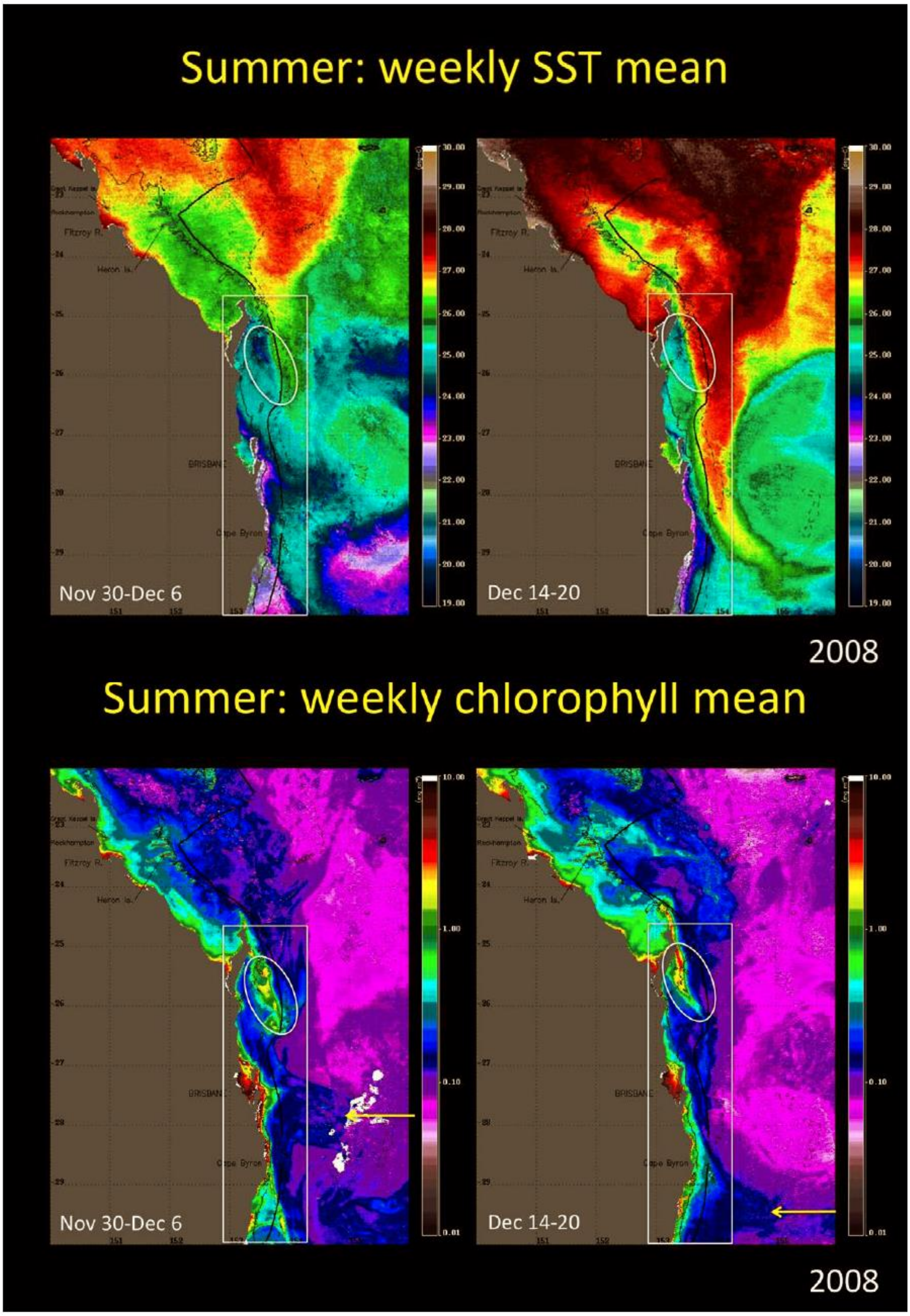


Figure 37. Satellite images of SST (a, upper panels) and chlorophyll (b, lower panels) showing surface enrichment in the circled area south of Fraser Island (Source: Scarla Weeks, UQ).

Figure 37b shows that the whole coast between 25-29°S (encompassing south east Queensland and northern NSW) has potential to have localised upwelling zones where the shelf edge topography is suitable (Oke and Middleton 2000) although the Fraser Island eddy field is the most prominent response seen in the water column.

Divers in SEQ frequently report cold bottom water layers from areas where kelp habitat is present providing anecdotal evidence of upwelling on parts of the shelf near Brisbane. IMOS mooring data from the North Stradbroke Island National Reference Station confirm that such upwelllings occur on the shelf south of Fraser Island but that they may not normally reach the surface, being restricted to depths greater than 20m (Marin 2013).

Middleton et al. (1994) investigated circulation and water mass characters between 21-26°S including transects immediately upstream (Sandy Cape) and downstream (Double Island Point) of Fraser Island. The EAC joins the shelf break at Double Island Point after being deflected around the Marion Plateau in the southern GBR. Measurements around Fraser Island revealed a strong poleward EAC with steeply sloping isotherms to the west and clear evidence of a strong bottom Ekman flux lifting water from below 200 m to above 100 m and onto the shelf. In addition, this study found an anomalous parcel of water on the shelf with temperature and salinity profile consistent with the properties of water at 200-300 m depth offshore and suggested that it had been lifted onto the shelf by the vigorous Ekman pumping.

3.4.2.3 Canyon/topographic upwelling

In the northern GBR, the equatorward flow of the Gulf of Papua Current above 14°S should favour downwelling and suppress Ekman upwelling. The Great Barrier Reef seabed surveys, however, located another area of enhanced plant biomass on the shelf near 12°S indicating persistent upwelling through the Pandora Passage near Raine Island. Thomson and Wolanski (1984) showed strong tidally-induced upwelling in this Passage with vertical displacements of 35-75 m and horizontal advection of a dense bottom layer on the shelf. Other possible mechanisms for local upwelling in this area include trapped internal waves rotating around the adjacent detached reefs (e.g. Raine Island), which are steep pinnacles rising out of deep water (Wolanski 1994), or flow instabilities in the GPC interacting with the shelf topography (Oke and Middleton 2000).

Further south (near 14°S), Wolanski et al. (1988a) showed that tidally-induced upwelling through gaps in the Ribbon Reefs explains the growth of large bioherms of the calcareous algae, *Halimeda.*

The same mechanism (tidal pumping) may apply between 19-22°S, where the reef matrix is dense but penetrated by numerous deep channels with very swift tidal currents. At the shelf-break, a strong poleward EAC creates conditions favourable to upwelling. Strong cross-shelf tidal mixing would be highly complementary and may be the major driving mechanism over the last mile (Thompson and Golding 1981). Regular upwelling is consistent with the persistently high water column productivity seen throughout the Pompey and Swain Reefs (Figure 35).

3.4.2.4 Dense shelf outflows

Another feature of the complex flows and water masses detected near Fraser Island by Middleton et al. (1994) was the presence of bottom water on the shelf with unusually low oxygen values not previously measured in water from the Coral Sea shallower than 200 m. Similar water was also detected in the Sandy Cape transect just north of Fraser Island. Middleton et al. (1994) attributed this water to outwelling from mangrove forests in the Great Sandy Strait separating Fraser Island from the mainland. Relative to the surrounding shelf water, these water masses were characterised by lower temperature, lower dissolved oxygen, and higher dissolved nutrients.

A similar parcel of water characterised by anomalously high nutrient values was located at the outer end of the transect; off the shelf at 100 m depth. Middleton et al. (1994) suggested that it was the result of a density current originating on the shelf (see 3.4.2.4).

Ribbe (2006) was the first to conduct sustained research into the circulation of Hervey Bay, which is the large embayment north of Fraser Island. He showed that the combination of low freshwater input and high evaporation results in an inverse laterally inhomogeneous estuary that produces a cold subsurface salinity maximum in the shallow southwest of the Bay. The formation of this hypersaline zone through evaporation results in a baroclinic gradient producing a slow cyclonic circulation within the Bay, which weakens during the summer (Grawe et al. 2010). While this is counter-intuitive in terms of the increased heating and evaporation expected at that time of year, it is the result of an interaction with a weak anticyclonic circulation of similar strength in the Bay that is driven by the EAC, which strengthens during summer.

Grawe et al. (2010) show that the frequency of hypersaline and inverse conditions has increased over the last 18 years due to prolonged drought that has reduced river discharge by 23% compared to a 60-year (1941-2000) climatology. Consequently the evaporation induced residual circulation has increased and the salinity flux out of the Bay has increased. This high salinity “Hervey Bay Water” enters the open ocean to the north (and possibly south) of Fraser Island and is undoubtedly the source of the subsurface salinity maximum within the EAC east of Fraser Island detected by Middleton et al. (1994).

More recently, Andutta et al. (2011) have reported that the coastal waters along the GBR are frequently hypersaline in the dry season as a result of evaporation exceeding rainfall within numerous bays that prevent rapid flushing. These hypersaline waters are not transported across the shelf as deep baroclinic currents because the trade winds resist stratification of the water column. Instead they accumulate to form a coastal boundary layer of hypersaline waters that are slowly mixed across shelf by turbulent diffusion but with a net southward transport to the southern GBR.

In the Capricorn Channel, a Slocum Glider deployed by DSTO found the first evidence of a dense water cascade across the shelf in the vicinity of Cape Clinton, which appears to originate from hypersaline water escaping the Broad Sound despite the strong tidal mixing experienced in this region (Figure 38).

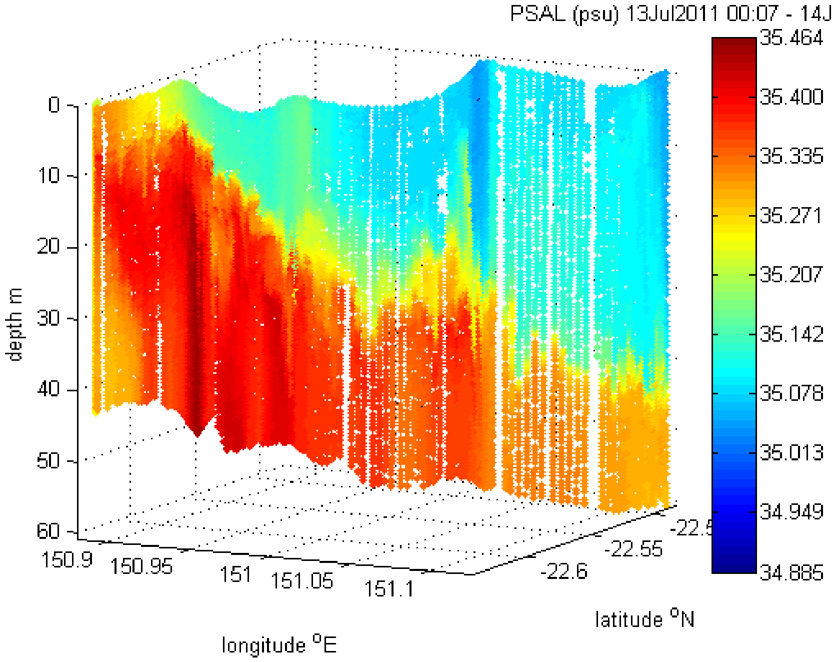


Figure 38. Density front detected in Capricorn Channel near Cape Clinton (source: DSTO unpubl. data)

This subsurface feature aligns well with a tendency of surface drifters to traverse offshore at this latitude despite winds from the south east (C. Steinberg, unpubl. data). Figure 36 contains one example of such a track (depicted by the yellow trace). This region has since been labelled the Cape Clinton Front and requires further definition.

3.4.3 Shelf Currents

The bathymetry of the Coral Sea (Figure 39) results in much topographic steering of ocean currents both upstream (zonal jets forced around New Caledonia, Vanuatu, Bellona Platform) and adjacent (Queensland and Marion Plateaus) to the continental margin (Figure 28). Eventually, all westerly flows are forced to follow the slope bathymetry as northern (GPC) and southern (EAC) boundary currents, albeit with a seasonal variation in the bifurcation point (see 3.3).

Between 11-23°S, the GBR occupies 210,000 km^2 on a continental shelf that varies in width from just 50 km in the far northern section to 250 km at 22°S. The majority of the 3000 discrete reefs and shoals forming the GBR grow on the outer half of the shelf (Figure 24), indicating an association with water of oceanic quality (Maxwell 1968). The density of this outer reef matrix varies along the 2000 km perimeter of the GBR, with relatively low density in the central section (near 18°S) and much denser formations both north and south. Wolanski and Spagnol (2000) coined the term “sticky waters” to illustrate the faster rate of flow around, rather than through, some of the densest formations. Middleton et al. (1984) showed the blocking action of the dense offshore reef matrix in the Pompey-Swains section of the GBR results in anomalous tides that are 5-6 times greater than elsewhere along the east coast.

Along most of its length, the offshore reef matrix is separated from the coast by a shallow lagoon of variable width and depth that deepens with latitude below 18°S.

Although there are many applications requiring knowledge of shelf currents, the complexity of the continental shelf bathymetry and inflows means that synoptic views can only be realised in hydrodynamic models. The main role of empirical observations on velocity is calibration and validation of these models, which must incorporate realistic forcing from the oceanic open boundary to produce accurate results.

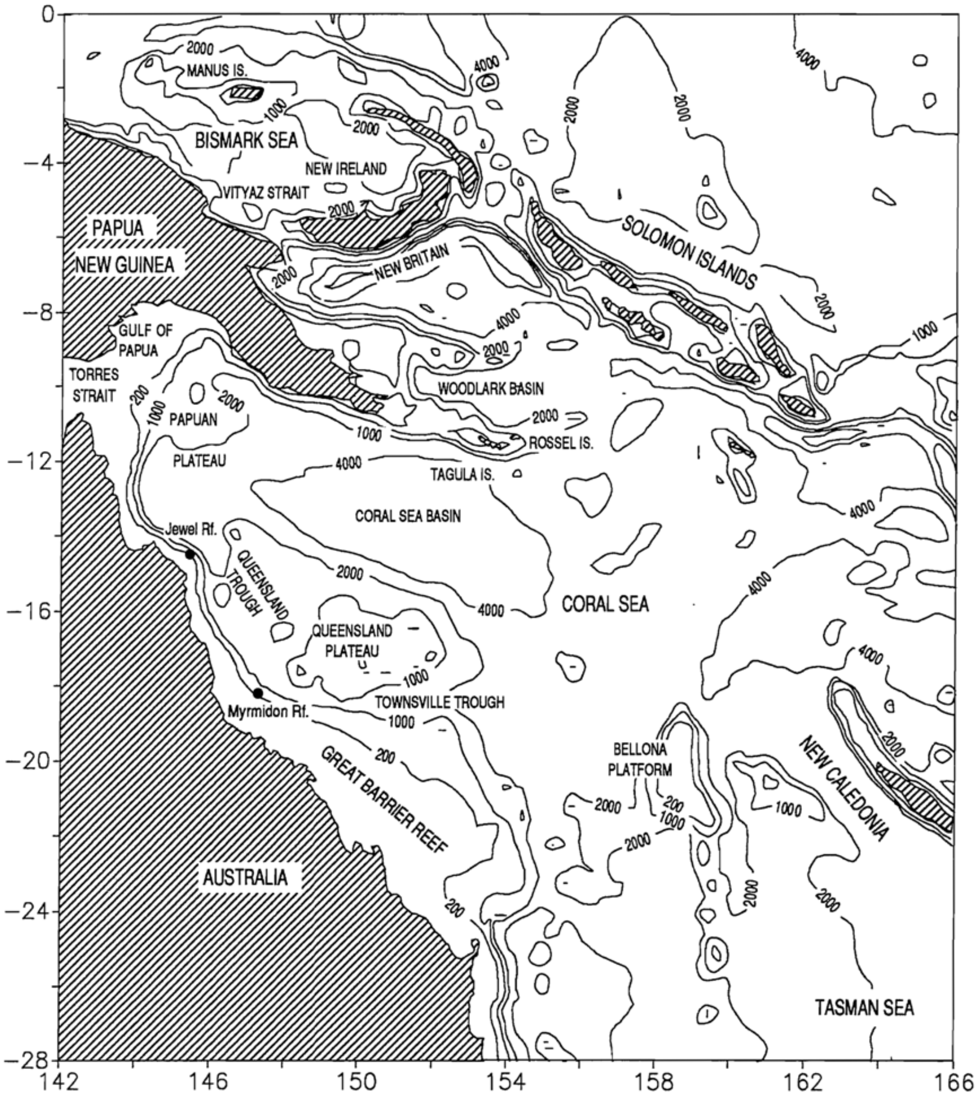


Figure 39. Coral Sea bathymetry and depth contours (source Burrage 1993).

Burrage et al. (1991, 1995) developed Linear Systems Models to predict alongshore flow at a fixed point in the central GBR Lagoon (Figure 40) based on sea level differences across the Coral Sea (measured at the Ports of Townsville and Noumea). They concluded that sea slope proxy captured the lower frequency variability in the EAC adequately but was a poor predictor of the weather band variability measured in the slope water offshore. Although inadequate and not synoptic, their model showed frequent reversals in the alongshore currents in the central GBR Lagoon revealing the opposition of the SE trade winds and the poleward boundary current (EAC).

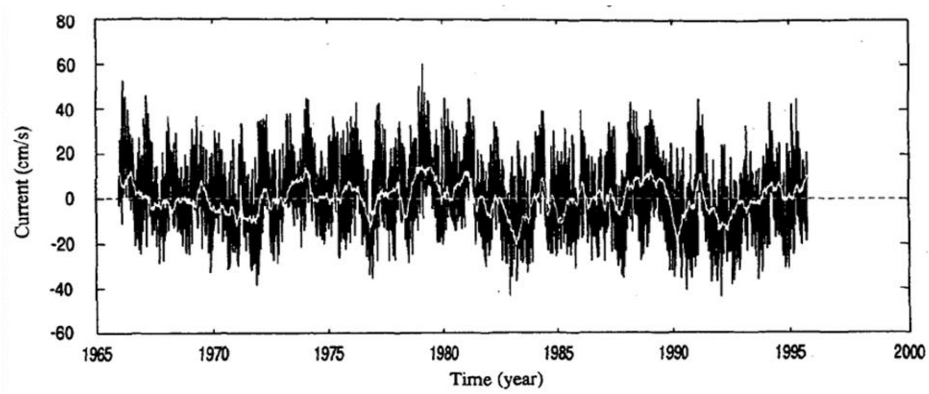


Figure 40. Predicted Eulerian currents at a site in the GBR Lagoon (Source: Burrage et al. 1991).

The subsequent development and elaboration of synoptic solutions through 2-D and 3-D numerical hydrodynamic models has added to the early evidence (Wolanski and Pickard 1985) that the EAC influences shelf currents in the central and southern half of the GBR. The cross-shelf extent of this influence is confirmed to be a balance between sea level pressure at the shelf break in the central section and the strength of the wind field (Figure 41). The latter is the major force on transport on shallower water near the coast, producing current shear in the Lagoon wherever the reef matrix is open enough to admit significant intrusion of oceanic water on the outer shelf.

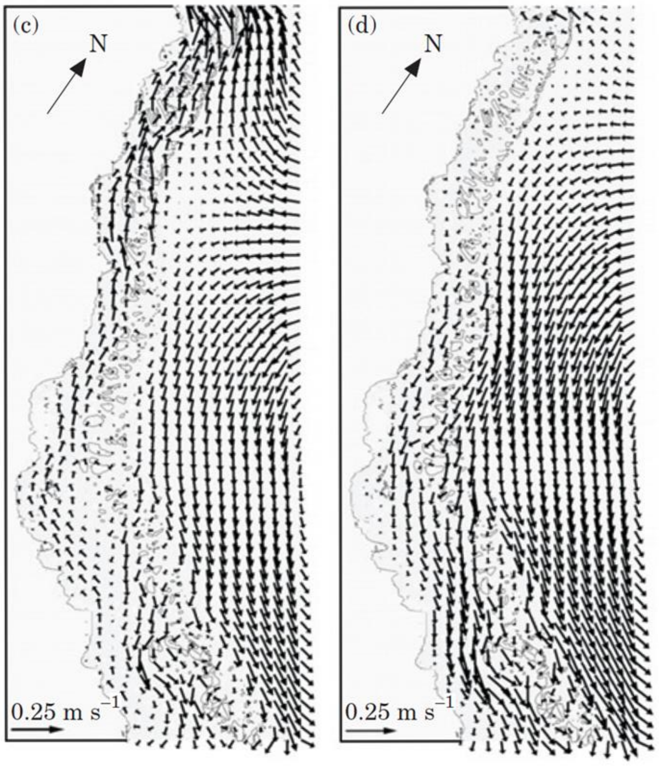


Figure 41. Modelled currents in the GBR Lagoon during periods of (right) calm and (left) strong SE winds (Source: Brinkman et al. 2001).

For computational reasons, most past models of the GBR have truncated the model domain at 14°S and only limited direct observations have been made on shelf currents above this latitude. Given the shallow depths of the northern shelf, it is likely that the SE trade winds will be the dominant forcing factor. Any boost from the offshore boundary current (the GPC) will be in the same direction.

GBR currents have been the subject of more hydrodynamic model solutions than any other marine area in Australia and knowledge of the shelf currents in this topographically complex domain continues to evolve as new solutions are implemented.

The latest and most sophisticated hydrodynamic model of the GBR region is an integrated modelling suite known as eReefs (Schiller et al. 2013) that is designed to become a real-time forecasting system operated by the Australian Bureau of Meteorology.

In the marine space, eReefs is a 3-D baroclinic model that includes all of the essential forcing functions (winds, tides, atmospheric coupling, bathymetry, etc). It is resolved at 1km grid resolution on the continental shelf and nested within 4km and 10km models at larger scales to obtain accurate oceanic forcing from global models (Figure 3). The domain of the 4km grid extends from Papua New Guinea to the NSW border (encompassing the east coast of Queensland) and encompasses all of the shallow bathymetry on the Coral Sea (Queensland and Marion Plateaux). In the vertical, the eReefs model tracks 47 layers and is being trained against IMOS observations in four dimensions.

The eReefs model confirms that the EAC makes its closest approach to the coast south of 25°S where the shelf is narrower and largely free of obstructions (Figure 39). Haradasa et al. (1991) detected EAC signatures in coastal waters as close as 1 km off Moreton Island, which set up circulation cells within the Gold Coast embayment. Ultimately the model will be required to reproduce similar fine scale features in the coastal circulation and this is being accommodated through a relocatable window (ROAM) that is a nested model resolved at fine scales (10’s – 100’s m) over local areas of interest.

3.4.4 Wave climate, including internal and coastally trapped waves.

Surface wave climate is a strong determinant of coral reef health. It controls community structure, reef zonation, and reef morphology (Dollar, 1982; Done and Massel 1993; Bannister et al. 2007). It determines suspended sediment concentration (SSC) and consequently sub-surface light, which limits the growth and health of inshore coral reefs (De’ath and Fabricius 2010; Orpin and Ridd 2012). The spatial and temporal scales of impact are diverse and range from seasonal variability in broad-scale SSC within the GBR lagoon(Logan et al. 2013), short-duration but large scale tropical cyclone effects on coral reef communities (Fabricius et al. 2008), through to enhancing mass transfer at the scale of a single coral colony (Monismith 2007). At a global scale, Young et al. (2011) have shown that global climate change has a significant effect on surface wave climate. At times scales of the order of 7-14 days, coastally trapped waves propagate northwards from south of Fraser Island and are associated with significant vertical motion of the thermocline which appears to modulate both upwelling at the shelf break, and the magnitude of shelf currents in the southern GBR (Griffin and Middleton, 1986). Below the surface, internal waves are a ubiquitous feature of the world‘s oceans; typically generated by oscillating tidal flow of stratified water over steep topography. Such waves have large wavelengths (10‘s of kms) and amplitudes equivalent to a significant proportion of the total water depth. Observational data suggest very large (+100 m peak to trough) semidiurnal internal waves along the outer GBR (Wolanski, 1986), where they would modify variability in thermocline depth, but their impact is limited to the outer margin of the GBR shelf.

There is presently very limited sustained observation of wave climate within the GBR. The Queensland Department of Environment and Heritage Protection operate 10 waverider buoys between Brisbane and Cairns, and existing IMOS infrastructure at Yongala, Palm Passage provide wave data from moored ADCPs. The IMOS Capricorn coastal radar is capable of providing directional wave spectrum, wave height, period, peak direction, but generation of these parameters requires further validation and quality control. Together these observation programs are being employed to validate a surface wave model for the QLD shelf currently under development as part of the eReefs project. The validation of this and other wave models is hindered by the sparse availability of wave measurements.

Wave models applied through eReefs include Wavewatch III (v4.11) implemented using source term physics (Ardhuin et al. 2010) and applied on the GBR4 hydrodynamic model grid. The wave spectra are discretised with 29 logarithmically spaced frequency bins from 0.035 Hz to 0.5047 Hz and 24 directional bins (15 degree resolution). Open boundary forcing for each of the hindcast runs is derived from a 1 degree resolution global implementation of WaveWatch III (v4.08), forced with surface winds derived from the NCEP Climate Forecast System Reanalysis (Saha et al. 2010). Correct parameterisation of the step reef topography in wave models is still an area of immature research. The primary aim of the eReefs wave modelling is to simulate information on wave data (significant wave height and period, orbital bottom velocity) which then can be used to run the sediment transport and biogeochemistry sub-models.

3.4.5 Science questions

As a coastal observing system, Q-IMOS will monitor and understand the impacts of variations in boundary currents upon shelf and coastal processes such as currents, stratification, and transports.

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

Boundary Current/shelf interactions

- What is the influence of the EAC on eddy dynamics in the lee of the Swain Reefs?
- What is the influence of the EAC on formation of the Fraser Island Gyre?
- What is the influence of the EAC on longshore flow on the shelf south of Fraser Island?

Upwelling and Downwelling

- What are the determinants of persistent upwelling regions in Queensland?
- What are the dynamics (seasonal, interannual) of regional upwelling areas?
- Are different upwelling regions in phase or independent?
- Do upwelling dynamics in any region correlate with the sign of the SOI?

Shelf Currents

- What is the influence of the EAC on longshore flow in the GBR Lagoon?
- What is the influence of the EAC on cross-shelf transport in the GBR Lagoon?
- What is the influence of the EAC on longshore and cross-shelf flow on the SEQ shelf

Wave Processes

- What is the tidal regime and how does it influence shelf processes?
- What is the importance of coastally trapped waves in driving shelf circulation?
- How will changes in global wind fields alter wave climate, and associated sediment mobilisation?

Q-IMOS needs to monitor a suite of physical-chemical drivers of ecosystem processes in order to understand how ocean variability from the boundary currents and the Coral Sea are propagated onto and throughout the shelf, as well as measuring inputs and transports from the coastal catchments.

3.4.6 Notable gaps and future priorities

Notable gaps:

Negligible data streams (e.g. water column temperature, salinity and current structure) that could be used for calibration and validation of the eReefs model on the shelf north of 14o30’S or south of 23o30’S.

Future priorities:

1. Increased number and frequency of Slocum glider missions along repeat transect in all sectors of the GBR (Far North, North, Central and southern) during wet and dry season conditions.
2. When the BW&C Node reinstates the Deep Water mooring array to measure the full depth transport of the EAC near 27°S, there will be a compelling need for additional velocity, temperature and salinity profile data, delivered via moorings and gliders on the southern GBR and SEQ to better describe shelf mixing processes.
3. The design of a shelf observing system can benefit from Observation System Simulation Experiments (OSSE), which utilise numerical simulations to evaluate the value of particular observations (locations and parameters) and arrive at an optimal observing system design. Q-IMOS is in ongoing discussions with a range of GBR stakeholders, with the intention to utilise models developed through the eReefs project to evaluate the existing GBR observing system and identify improvements and enhancements that may form part of a GBR Integrated Monitoring Framework.

3.5 Ecosystem Responses

The physical and chemical environment strongly influences the biology of coastal and oceanic systems. Historically, however, there has been relatively little integrative work on the linkages between physics, chemistry and biology in Queensland's marine ecosystems. Much of the focus has been on short-term studies of biology and ecology in the coastal zone without the 'big picture' context provided by integrated physical, chemical and biological knowledge, and without a comparative approach between ecosystems.

In the sections above, we have identified various modes of climate variability affecting temperature, upwelling, and shelf currents, plus long-term trends in ocean pH. The latter will potentially be very important in the future to organisms reliant upon calcification whereas temperature changes are critically important now for all poikilothermic organisms. As example, Hoegh-Guldberg (1999) argued that thermal stress will eliminate zooanthellate corals on a much shorter time scale that the ultimate threat from ocean acidification. Thus the marine community needs to collect data on the spatial and temporal variability of pCO_2 and alkalinity of water on a complex carbonate shelf like the GBR to better define the future risks from ocean acidification (Doney et al. 2009; Hendricks et al. 2009) but it should prioritise other variables that display significant variability over shorter time scales.

Changes in temperature, upwelling, and shelf currents will be critical drivers of Queensland's marine ecosystems over the next decade. There are many research questions appealing to different investigators and it is not possible to capture all of them here, so we illustrate the utility of ocean observations to understanding and predicting ecosystem responses through selected examples.

3.5.1 Temperature

In the tropics, scleractinian corals create habitat for other species on scales ranging from a single colony to whole landscapes. In sub-tropical Queensland, kelp forests create habitat mosaics in a similar way as well as being an important source of carbon for herbivores. When these habitat-forming dominants disappear (see Figure 26 for a reef example), there is a huge collateral loss of other biodiversity, catastrophic decline in the local transfer of energy and materials, and potential downstream impacts on fisheries.

Long-term changes in temperature associated with global warming are considered the greatest threat to the survival of coral reefs in the next 100 years (Hoegh-Guldberg 1999) because the animal-plant symbiosis responsible for reef building is destabilised by temperature anomalies as little as 1°C. Corals have not yet shown any great ability to adapt to thermal stress, and current rates of global warming are considered much too fast to anticipate an evolutionary response. While these may be doomsday scenarios, the risk of catastrophic change to an iconic system like the Great Barrier Reef justifies the need for detailed information about the thermal environments around coral reefs.

Coral bleaching is the end state for colonies subject to excessive cumulative heat stress. The mechanism is so deterministic that bleaching risk can be forecast by tracking anomalies in the ambient heat load. Web-based warning systems are now operational for the GBR (ReefTemp[3]) and

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[3] http://www.cmar.csiro.au/remotesensing/reeftemp/web/ReefTemp.htm

global reef systems (Coral Reef Watch[4]). Both products are based on satellite remote sensing and both have required *in situ* observations of bulk temperature to calibrate and validate algorithms for tropical atmospheric conditions.

While the satellite products capture the risk of large-scale coral bleaching, they have also revealed spatial anomalies in the level of risk. Places with poor water quality (i.e. high loads of dissolved nitrogen) are more prone to bleaching than elsewhere (Wooldridge 2009). Places with strong turbulent diffusion (e.g. tidal mixing) are more resistant to bleaching than surrounding locations (Steinberg pers. comm.). Such detailed contextual knowledge is critical to inform studies into the molecular and genetic basis of coral bleaching risk, and the potential for adaptation to future climate.

In the subtropics, canopy forming kelps reach their northern limit along the east coast and can be expected to retreat to higher latitudes as the oceans continue to warm, while tropical species will extend their ranges southwards (Figueira and Booth 2010) with potentially large impacts (Ling et al. 2009).. The loss of kelp forests from the rocky reefs of southern Queensland would represent the loss of major primary producers, with impacts on food webs and habitat dependent associates. It is unlikely that ecological assemblages will retain their integrity during displacement, since different elements are likely to migrate at different rates; thus local extinctions are possible. Changes could be even more dramatic if the system was to collapse under acute rather than chronic stress.

In both regions, there are important stocks of large pelagic and demersal fishes that are likely to adjust their distributions along the shelf to remain with optimum temperature windows. Major readjustments could have significant economic and social costs to the commercial and/or recreational sectors of the fishing industry.

In deeper waters, SST may be a poor predictor of bottom temperatures, so resource managers need the capacity to predict temperature changes throughout the water column. This will only be possible through 3-D modelling validated by *in situ* ocean observations (e.g. Marin 2013). Such capacity could greatly enhance the ability to explain and forecast changes in future fish catches.

3.5.2 Ocean Chemistry – Nutrients

Ecosystems on the continental shelf are largely supplied with nutrients from two external sources: terrestrial run-off from coastal catchments, and marine upwelling from the adjacent ocean. Other sources include rainwater and nitrogen fixation by cyanobacteria.

On the GBR, coastal water quality is compromised along much of the coast between 16°S and 22°S, with the main concern being unnaturally high loads of dissolved nitrogen and phosphorus being leached from many forms of broad-scale agriculture (Brodie et al. 2013a). These excess nutrients increase the risk of coral bleaching and disease, produce phytoplankton blooms, promote the growth of benthic macroalgae that compete with corals, and promote epifaunal fouling of seagrass foliage. The enhancement of water column chlorophyll can have several impact pathways: (1) reducing water clarity with direct negative consequences for benthic primary producers, (2) fuelling pelagic food webs to produce “sticky marine snow” that smothers sessile benthic life forms, and (3)

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[4] http://coralreefwatch.noaa.gov/satellite/index.php

triggering outbreaks of the crown-of-thorns starfish with decadal consequences for coral cover over very large areas.

In some locations along the shelf, upwelling adds additional loads of dissolved nutrients from subsurface waters. These loads and their dynamics are very poorly quantified (by comparison with the terrestrial loads) but their contribution appears to be substantial given the inability to balance shelf-scale nutrient budgets with current known inputs (Furnas et al. 2011).

Marine plants, especially sea grasses, are basal to many food chains supporting invertebrates, fish, turtles and dugongs. Local upwelling has been identified in a number of places along the Queensland shelf margin especially south of 15°S; the section adjacent to the poleward EAC. In the GBR, two locations (Townsville 18°S, Gladstone 23°S) provide opportunities to observe upwelling dynamics and to match this with the abundance and condition of deep seagrass meadows in the GBR Lagoon.

The southern section of the GBR yields some of the most valuable commercial fisheries (prawns, slipper lobsters, scallops, and reef fish) extracted from tropical Queensland. This is likely to be a consequence of the generally high production in the water column visible in satellite imagery (Figure 35). It is not unreasonable therefore to anticipate that interannual variability in ocean conditions will influence the replenishment and/or condition of valuable stocks. Low frequency variability like that caused by the IPO (3.1.3) could have sustained impacts on harvest size and profitability. In the future, it is likely that marine harvest industries will use information about ocean variability in the same way that farmers have incorporated ENSO phases into their business decisions.

Upwelling signatures (cold SST, high Chl-a) have been identified in satellite imagery of waters near and south of Fraser Island (Figure 37). This section of the Queensland shelf also supports productive fisheries (Figure 42) including the bulk of the catch of the Eastern King Prawn (*Melicertus plebejus*), which is the most valuable species in the East Coast Otter Trawl fishery. The Queensland Department of Forestry and Fisheries (QDAFF) is currently using IMOS data streams to correlate fisheries catch statistics to environmental variability.

Shelf break upwelling is likely to be important in maintaining the cool bottom temperatures and elevated nutrient levels that allow significant areas of kelp forest habitat to exist in southeast Queensland. These habitats exist at depths below 20 m and do not have surface expression. They are also patchy, with their distribution suggesting that there may be fine-scale variations in upwelling processes that we do not yet understand, but which may be important for predicting how kelps will respond to climate change. In an equivalent exercise, Graham et al. (2007) used models containing information about local scale variation in mixed layer depth to predict the existence of deepwater kelp populations in the tropical Pacific that await discovery. More recently a combination IMOS data from moorings, AUV observations and receiving water quality models have been used to construct predictive species distribution models for kelp in the SEQ region (Marin 2013).

In the future, the EAC is predicted to weaken in the north with climate change (Cai et al. 2005) potentially resulting in reduced upwelling. This trend would be reinforced if rising sea temperatures increase stratification of the upper water column resulting in a shallower mixed layer.

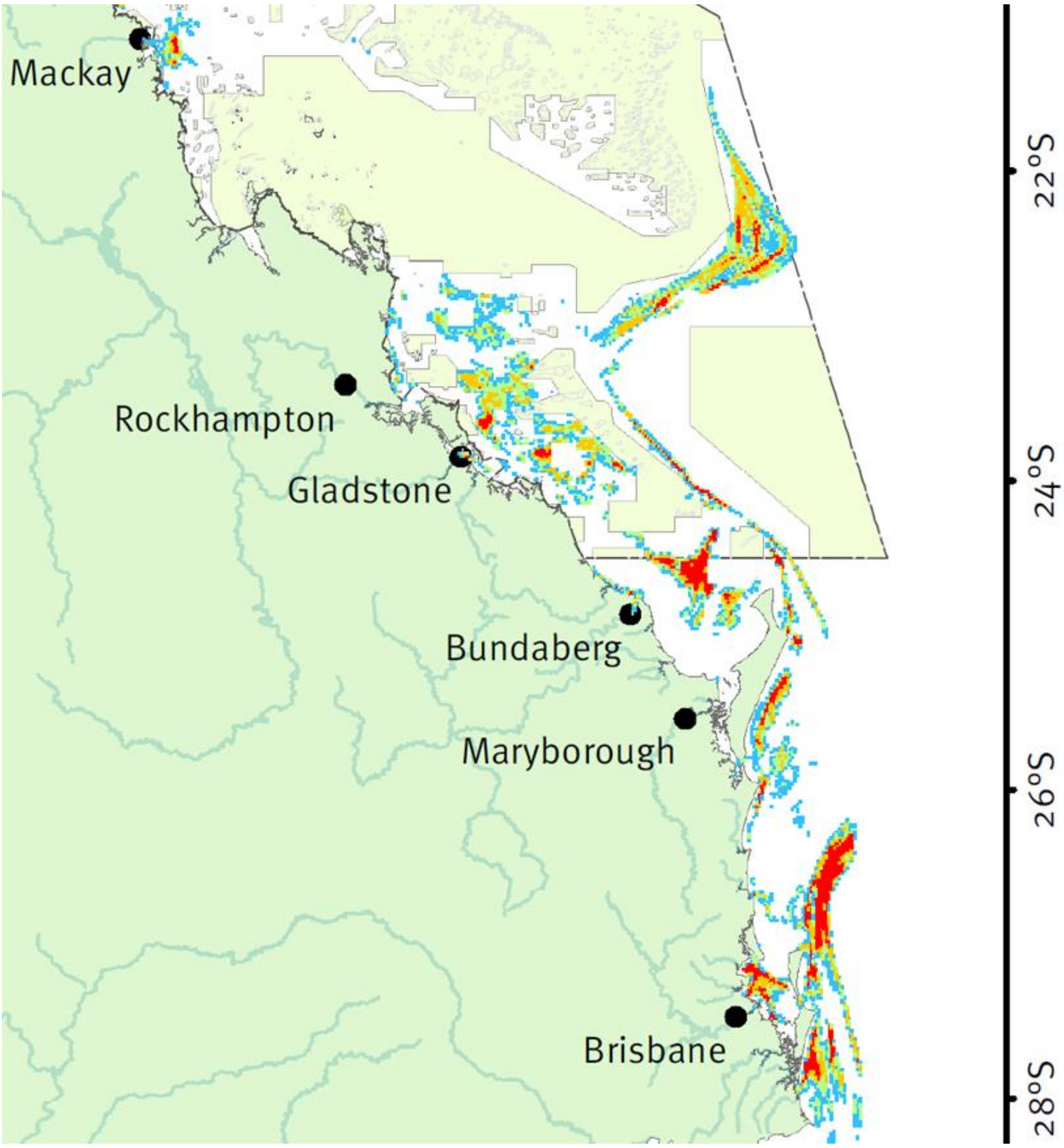


Figure 42. Relative trawl effort (red: high, blue: low) in southern Queensland indicates highly productive ecosystems sustained by regional upwelling (source DEEDI)

3.5.3 Ocean Chemistry – Carbon and acidification

Ocean acidification is the chemical consequence of the increasing carbon dioxide concentration in the atmosphere (Caldeira and Wickett 2003; Sabine et al. 2004), and is a growing threat to marine calcifiers globally (Raven et al. 2011). Calcification rates of coral reef builders are predicted to decline significantly during this century (Kleypas et al. 1999; Langdon and Atkinson 2005; Hoegh-Guldberg et al. 2007), shifting reefs from being net accreting to net dissolving communities (Andersson et al. 2009; Silverman et al. 2009). Ecologically, ocean acidification will steadily erode reef resilience, in part by increasing vulnerability to bioerosion and cyclone damage (Anthony et al. 2011b) but also by reducing capacity for recovery through impaired recruitment and growth.

Projections for ocean acidification are based mainly on the exchange of carbon between atmosphere and oceanic surface waters (Caldeira and Wickett 2003; Gledhill et al. 2008) and therefore do not take into account the exchange of carbon between seawater and benthic communities (Duarte et al. 2013). In the relatively shallow waters of Australia's coastal and shelf systems, benthic carbon fluxes are superimposed on the anthropogenic carbon signal, and may in some situations mask variations in the carbon chemistry of the open ocean source water (Anthony et al. 2011a; Santos et al. 2011). Recent work has demonstrated that small changes in benthic composition can alter seawater carbon chemistry patterns at the local scale and modify the risk coming from the Coral Sea in both directions (Anthony et al. 2011a; Anthony et al. 2013). Communities dominated by corals and crustose coralline algae (CCAs) amplify acidification risk, while communities dominated by algae and sand can partly ameliorate ocean acidification at the local scale. The net result of these additive effects depends most critically on water depth, residence time, and the mix of primary producers and calcifiers (Figure 43).

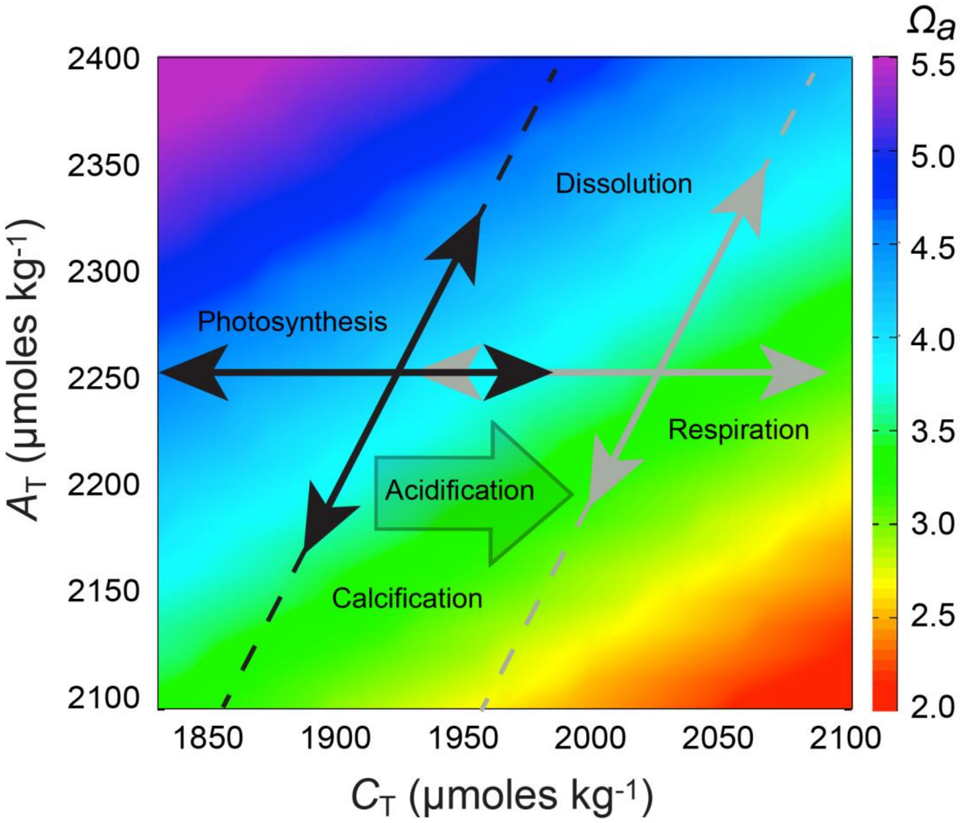


Figure 43.Biogeochemical drivers of reef water carbon chemistry and effects of ocean acidification on aragonite saturation state (Ωa). Vectors indicate the shift of the benthic biological/biogeochemical processes from a present-day (solid) to an acidified (dashed) scenario at 27OC and 35PPT. Absolute vector lengths are hypothetical, but will vary with water depth, residence time, and the mix of primary producers and calcifiers (Source: Ken Anthony, AIMS).

To understand the full risk of ocean acidification to Australia's marine ecosystems requires deeper insight into the (a) biological processes driving carbon chemistry variation in coastal and shelf waters, (b) the oceanographic processes linking open ocean to coastal systems, and (c) interactions with ocean warming and changes in several attributes of water quality (salinity, nutrients, turbidity). Currently we lack time series information on carbon water chemistry at any scale for continental shelf habitats. The pair of IMOS acidification moorings on the GBR and a SOOP transit through the

GBR shipping channel (RTM Wakmatha, funded by industry) is a start to generate the long-term observations that will be required to validate spatial risk models as they are developed from small-scale experimental results. Ideally, monitoring should include measurements of alkalinity (currently available only through water sampling) in addition to automated measurements of pCO_2 (or DIC) to fully constrain the carbonate system and enable calculations of aragonite saturation state. In the central GBR, this is being achieved by co-locating one of the acidification moorings with the Yongala National Reference Station.

3.5.4 Plankton

James Cook and Joseph Banks made the first recorded observations of phytoplankton (*Trichodesmium*) in the GBR (Beaglehole, 1955). Organized phytoplankton research in the Great Barrier Reef started with the Royal Society Expedition to Low Isles in 1928 and subsequent studies have produced a good general understanding of assemblage composition (Marshall, 1933; Revelante and Gilmartin 1982; Relevante et al. 1982; Furnas and Mitchell, 1986, 1987; Furnas 1991; Ayukai 1992).

Phytoplankton biomass in GBR waters is usually dominated by picoplankton (< 2 µm; Furnas and Mitchell 1986) accounting for up to 65% of the chlorophyll standing stock and up to 69% of the water column primary production in the GBR Lagoon (Furnas 1990). Small cyanobacterial cells such as *Synechococcus* and *Prochlorococcus* are the dominant taxa (Crosbie and Furnas 2001a). Larger taxa become relatively more important in some parts of the southern GBR where the size spectrum shifts towards larger nano- and microphytoplankton (Furnas and Mitchell 1986; Crosbie and Furnas 2001a) possibly indicative of higher nutrient availability (see below).

Phytoplankton community composition typically shows an inshore-offshore gradient, with relatively more microplankton (e.g. diatoms) inshore and more pico- and nanoplankton (e.g., *Synechococcus* and especially, *Prochlorococcus*) offshore (Crosbie and Furnas, 2001a; Furnas and Mitchell 1986). Dinoflagellates are commonly found and widely distributed (e.g. Marshall, 1933; Revelante and Gilmartin, 1982), but less important numerically in the plankton. The general picture from much of the tropical shelf is that of an oligotrophic environment characterised by rapid carbon cycling with uptake dominated by small cells and nutrients returned through a pelagic microbial loop (Furnas et al., 2011).

Despite their larger cell sizes, the diatoms commonly found in the GBR have higher intrinsic growth rates than the dominant smaller cyanobacteria (e.g. Furnas, 1991; Crosbie and Furnas, 2001b). As a result, bloom events following nutrient inputs are more likely to be initially dominated by diatoms. Recent studies of flood plumes show that assemblages growing in plumes can be different where there are high external inputs of nutrients (Brodie et al. 2013). The appearance of diatoms at plume fronts confirm that fast-growing microplankton can compete for spikes of high nutrients through their fast growth rates (Furnas 1991) producing ephemeral blooms that persist until their zooplankton predators are able to adjust their population sizes (McKinnon and Thorrold 1993). This upwards shift in the size spectrum of the phytoplankton community may advantage some meroplankton that does not feed efficiently on the small cells normally dominant in shelf waters and this change is thought to be the trigger for the explosive expansion of coral-eating starfish (e.g. Fabricius et al., 2010; Furnas et al., 2013).

Marine zooplankton are useful indicators of climate-driven changes in marine ecosystems, and calanoid copepods in particular have proven useful in demonstrating changes in distribution primarily attributable to effects of warming (Hays et al. 2005). In Australia, there is evidence that warm-water “signature” species are moving southward into Tasmania (Johnson et al. 2011). This conclusion was based on a group of temperate species that declined in abundance during warm years. One dominant calanoid species, *Parvocalanus crassirostris,* contributing to this discrimination is primarily a tropical and subtropical species and there are indications that its range is extending.

The phenomenon of “tropicalization” of temperate plankton communities has potentially important ecosystem consequences. Since warm water copepods have less food value than cold water species, food chains may be impacted, resulting among other things in reduced 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).

Planktonic animals fall into distinctive categories according to their use of the water column. The biggest distinction is between the ‘holoplankton’, where all life history stages are pelagic, and the ‘meroplankton’, which is composed predominantly from only the early life history stages of benthic species

In the northern GBR, tropical rock lobsters from the east coast stock migrate to the shelf break to release their offspring into the northerly flowing GPC. These early life stages complete a long pelagic development of at least 4-5 months within the gyre system enclosed by the GPC (Figure 34). The clockwise circulation of the GPC eventually returns the potential colonists to the vicinity of the continental shelf, where they metamorphose to the puerulus stage and complete the last part of the journey to coastal nurseries by swimming across the shelf. Gravid female mud crabs (*Scylla serrata*) throughout Queensland undertake similar offshore movements to release their larvae although the release sites and subsequent dispersal pathways are unknown.

Below the GBR, a number of temperate species migrate to spawning grounds in South East Queensland including the Eastern King Prawn (*Melicertus plebejus*), which has major spawning grounds on the continental margin near 23°S and 27°S revealed by the spatial distribution of trawl effort (Figure 42). From these grounds, the EAC distributes their spawn down the eastern seaboard where the postlarvae colonise coastal estuaries. Some years later, mature prawns return to the continental shelf and swim north in schools to reach the same spawning grounds. Prawns tagged in NSW have been tracked over 1000 km during this migration (Montgomery 1990).

Among the fishes, tailor (*Pomatomus saltrix*) make a similar annual migration to spawning grounds east of Fraser Island (25°S). The adult spawning run is very important to recreational and commercial fishers, who exploit the schools of ripe fish as they transit along the beaches. For the target, the choice of spawning location not only places their early life stages in an area of high productivity (Figure 37), and potentially in optimal temperature zones, but also near the EAC which will transport the developing larvae south past many suitable juvenile nurseries.

3.5.5 Mid Trophic Levels (Nekton)

Nekton is defined by animals that swim against the flow. While prawns and tailor do this to release planktonic larvae, some larger animals migrate to exploit seasonal variations in resources or environment.

Project Manta at the University of Queensland is tracking the seasonal migrations of Manta Rays (*Manta birostris*) between the southern GBR and Stradbroke Island (separated by 4° of latitude). Although large, these pelagic rays feed on zooplankton. They can be recognised as individuals by colour patterns. Normally they visit SEQ only during summer months but in 2010, divers reported early arrivals in late winter that may well reflect interannual variation in water temperature. The project aims to understand whether these animals are moving between alternative sources of food that are seasonally available or simply relocating along the shelf to stay within an optimum temperature envelope.

Seabirds are mid-level consumers that seek small pelagic fishes at the surface. Their prey is often concentrated at hotspots of production driven by oceanographic processes including upwelling. Congdon et al. (2007) have used small satellite tags to track individual seabirds on foraging journeys from island rookeries in the southern GBR. Wedge-tailed shearwaters regularly fly as far as 2000 km (round trip) into the Coral Sea to feed at upwelling fronts in the SEC associated with seamounts and emergent reefs on the Queensland and Marion Plateaus (Figure 44). Some birds from the same colony fly south to feed along oceanographic features in the EAC separation zone and the associated eddy field.

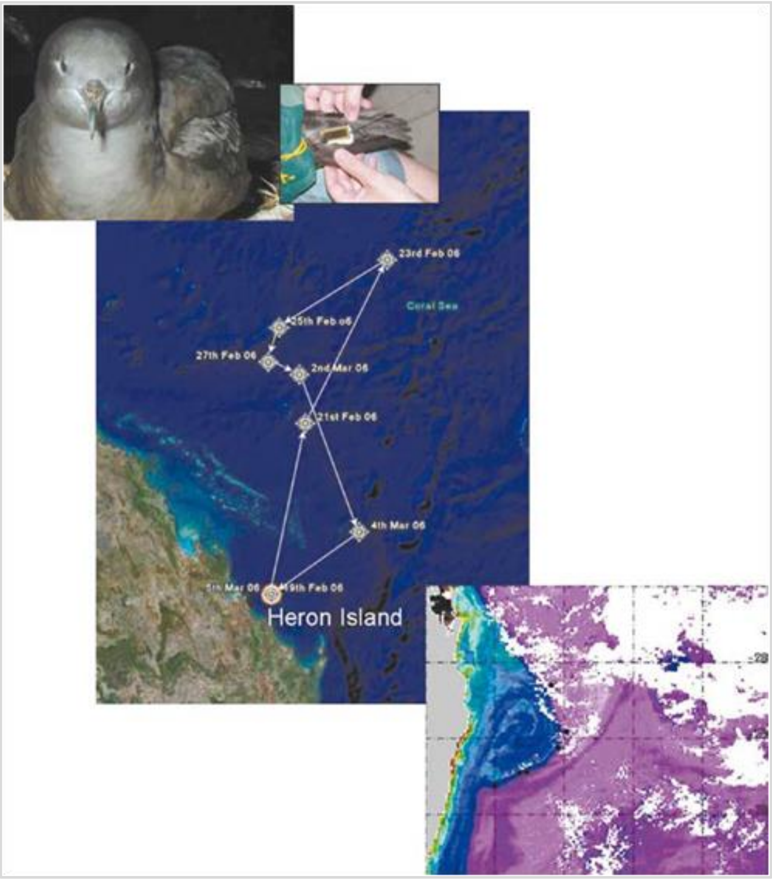


Figure 44. Tagged shearwaters regularly make long journeys (>1000km) to distant foraging sites (Source: Brad Congdon, JCU)

While unable to move as fast as birds, satellite tags have also revealed long distance movements by turtles and dugongs in the GBR and Torres Strait during normal foraging (Hamann unpubl. data). Leatherback turtles from a nesting beach in the western Strait (Waral Kawa) have been tracked to extensive feeding grounds on the North West Shelf or lost after entering Indonesian waters. Flatback Turtles that breed on beaches in the southern GBR make long reproductive migrations restricted to the continental shelf. Flatbacks tagged at rookeries in southern Queensland have been recaptured more than 1300 km from their nesting beach (Limpus et al. 1983).

As AATAMS receiver arrays are installed in more places around the Australian coast (Figure 45), the list of mobile fish species keeps increasing. For example, a number of classic species sought by the recreational fishing sector in north Queensland (Mangrove Jack, large- and small-mouth Nannygai's, and Red Emperor) have been shown to make one-way ontogenetic migrations from coastal nurseries to offshore habitats, while some reef resident species are showing mobility among reefs that compromises the protective power of spatial closures (unpubl. data, Michelle Heupel, AIMS).

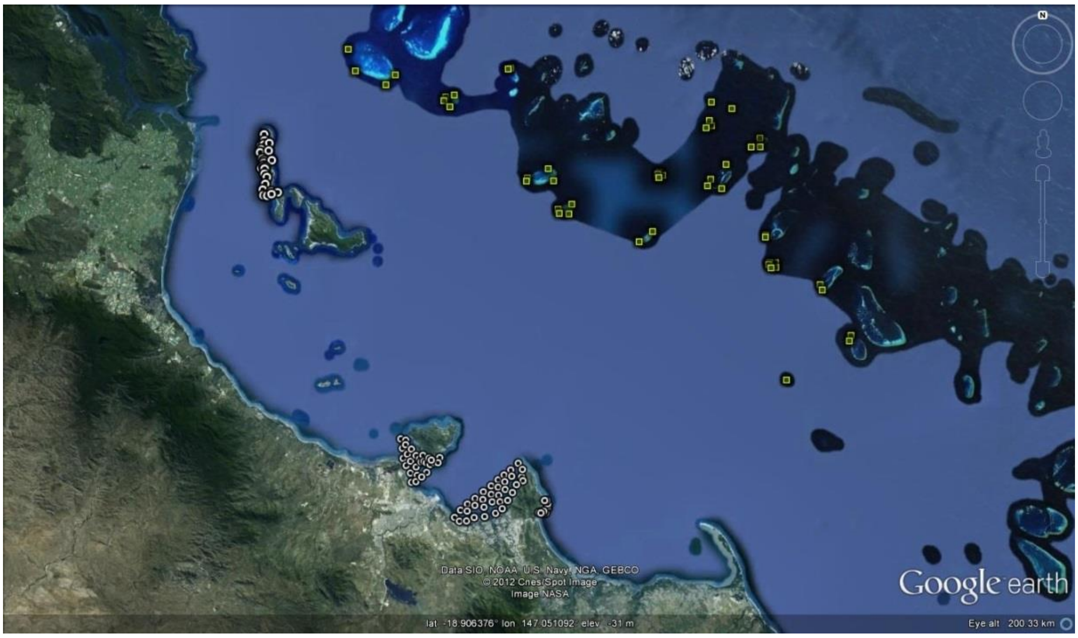


Figure 45. Acoustics receivers in the Townsville region are tracking the movement of tagged animals across the continent shelf and among habitats in the offshore reef matrix (Source: Michelle Heupel, AIMS).

The ultimate journeys along the Queensland coast by nekton with mid-trophic level status are made by the 10,000 plus Humpback Whales that migrate annually between summer feeding grounds in Antarctica and winter calving grounds in the GBR that offer thermal advantages to the newborns. Long-term studies have shown that 90% of the migrating whales pass within 10 km of Stradbroke Island on their way north (Paterson and Paterson 1989), which likely represents a selected response to the strong southerly flow of the EAC further offshore at this latitude (Figure 37).

3.5.6 Top Predators

Figure 46 tracks the movements of a large shark tagged in South Australia that reached Fraser Island before returning south. As a top predator, this animal may have been attracted to the seasonal spawning run of tailor or it may simply have been foraging more opportunistically along the shelf until it encountered the warmer waters flowing south from the GBR.

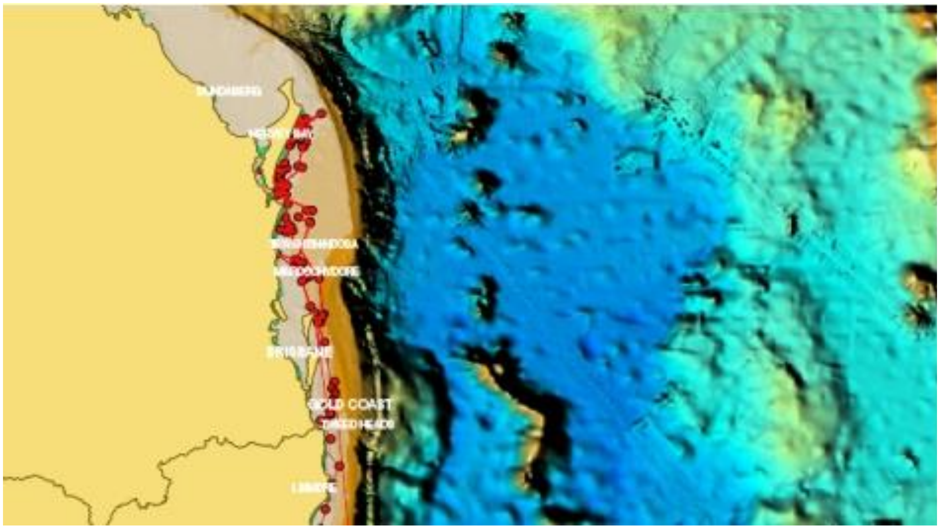


Figure 46. Path of a great white shark tagged in South Australia which travelled north to Fraser Island before returning to the south (Source: Barry Bruce, CSIRO).

Other sharks are also known to make long distance movements along the coast. Bull sharks tagged in Sydney Harbour have been detected in the Townsville acoustic receiver array (Figure 45) and subsequently reappeared in Sydney Harbour. The Townsville array has tracked smaller shark species from coastal nurseries to the reef matrix offshore (distances of 100 km), as well as movements of sharks among reefs within the reef matrix.

On one occasion, when a Tropical cyclone was approaching the coast, many large tagged animals showed a synchronous evacuation of Cleveland Bay a few days before the event (C. Simpfendorfer, unpubl. data) and returned after absences varying between days and weeks. Presumably they spent the interim period in deeper waters of the GBR Lagoon to avoid the extreme turbulence experienced in shallower waters.

Demersal fish predators have shown a similar response after two severe cyclones (TC Justin, TC Hamish). Commercial fishers experienced radical reductions in catch rates for coral trout on reefs affected by both cyclones and were forced to relocate their operations. After TC Justin, the catch rates returned to normal after a lengthy delay of 18 months. Since the rebound was too fast to be explained by recruitment, migration to deeper waters remains the most likely explanation with recovery delayed perhaps by physical damage to the habitat impacting on prey populations. The impact, although poorly understood, was sufficient for the industry to seek disaster relief funds.

Oceanic fish predators (billfishes, tuna, and sharks) are constantly on the move and tag returns have shown movements at ocean basin scales either seeking food or migrating to common spawning areas.

3.5.7 Benthos

Sessile benthos (plants and animals) and small animals with sedentary lifestyles, which includes the bulk of invertebrates and small demersal fishes, depend upon currents to disperse their propagules in order to colonise new habitats. In a clear demonstration of long distance dispersal, Booth et al. (2007) have documented the seasonal arrival of tropical fish recruits in sub-tropical Sydney Harbour, which are clearly expatriated from sources in SEQ or northern NSW by the fast-flowing EAC.

Periodic population explosions of the crown-of-thorns starfish stand out from the background and provide a rare opportunity to trace larval dispersal because primary outbreaks originate from a small section of the northern shelf near 14-15°S and secondary outbreaks are the result of transport by shelf currents of larvae with weak swimming ability (Reichelt et al. 1990). The spatial and temporal pattern of outbreaks suggests dispersal steps of 1-300 km in a larval period lasting 14-30 days.

The recovery of reefs from the catastrophic coral loss caused by starfish outbreaks is also linked with connectivity. Fastest recovery has been observed on mid-shelf reefs surrounded by intact coral populations whereas inshore reefs that lack such local sources of replenishment have shown almost no recovery in the same period. This implies smaller dispersal steps. Jones et al. (1999) showed that as much as 60% of the replenishment of local fish populations originates from the same population (i.e. self-recruitment). In the case of brooding corals or species with very short larval duration, the fraction of locally produced offspring is likely to be even higher.

The same issues apply when coral cover is reduced through physical damage (e.g. Tropical cyclones), or death after bleaching caused either by excessive heating or flood impacts.

The physical disturbance and increased rainfall episodes associated with extreme weather events such as cyclones and tropical lows also cause severe impacts on other benthic habitats. Following the 2010-2011 wet season, the Great Barrier Reef Marine Park Authority began to record a marked increase in the numbers of dead dugongs and turtles washing ashore in the region with empty guts and diminished fat reserves. This was attributed to the loss of seagrass beds caused by the extensive flooding. A mission to survey deep water seagrass beds in mid 2011 using the IMOS AUV equipped for high resolution benthic photography found no seagrasses in areas that had previously supported extensive seagrass beds when surveyed in 2005-06 as part of the GBR Seabed Biodiversity Project.

3.5.8 Science questions

Q-IMOS seeks to understand and predict the impacts of oceanic variability upon the health and performance of shelf ecosystems including individual components (e.g. key biodiversity elements, valuable living resources). The Queensland Node observing strategy will contribute to the following high-level science questions from the National Plan:

Productivity:

- What is the risk of climate change to reef building corals?
- How does carbonate chemistry vary in coral reef ecosystems?
- What is the risk of ocean acidification to coastal and reef ecosystems?
- Does the risk of ocean acidification vary between tropical and temperate zones?

- How does the spatial variability in physical processes (currents, waves energy, mixing) influence and modulate the spatial variability of risk to benthic and pelagic communities associated with climate change (e.g. temperature induced bleaching, acidification)
- What drives productivity hotspots on the continental shelf of Queensland?
- How do external sources of nutrients change pelagic and benthic communities? (e.g. stinging jellyfish, Crown-of-thorns starfish)
- Do deep seagrass meadows on the GBR shelf reflect upwelling history?

Distribution and Abundance:

- What drives the northern limits of kelp forests in SEQ?
- What are the environmental drivers of animal migrations?
- What are the oceanographic correlates of nesting success of seabird colonies in the GBR?
- How can we predict connectivity of populations in shelf ecosystems? (e.g. Crown-of-thorns outbreaks)
- What is the impact of extreme weather on benthic communities along depth gradients?
- How do environmental perturbations affect animal migrations?

Q-IMOS needs to take observations on the physical and chemical environment on the continental shelf in order to provide the context and to explain changes in trophodynamics, population dynamics, community composition, recovery and resilience, and animal migrations.

3.5.9 Notable gaps and future priorities

Notable gaps:

The same spatial gaps in coverage as noted for the physical drivers.

Primary production measurements as opposed to net community production. Primary production is not currently measured by IMOS observational programs (e.g. through the NRS sub-facility), as the most widely applied methods (e.g. 14C incorporation) involve incubations. However, the triple oxygen isotope method is an incubation-independent approach now being widely deployed that could potentially be applied within the IMOS framework

Future priorities:

1. Increased number and frequency of Slocum glider missions along repeat transect in all sectors of the GBR (Far North, North, Central and southern) during wet and dry season conditions.
2. Given the importance of the bulk chlorophyll signal to shelf processes and ecosystem performance, the Ocean Colour product from satellite remote sensing needs comprehensive ground truthing in shelf waters. The most efficient and value-adding way to collect such data will be additional Slocum gliders with multi-sensor packages.

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

The data streams from Queensland come from a sparse infrastructure network that leaves the majority of the east coast without *in situ* observations. Their value, however, is amplified enormously when used to calibrate and validate products providing synoptic coverage.

Among the observing technologies, satellite remote sensing offers a number of synoptic products than can be used to monitor spatial and temporal variability in SST, ocean colour, and altimetry. The latter already provides useful estimates of geostrophic flow in the upper ocean, validated by surface drifters, but is unlikely to be useful for shallow areas such as the continental shelf.

SST is the best example of a mature product from satellites applied to ocean observation. The reliability and accuracy of satellite estimates is well established by cross-calibration with many different *in situ* measurement streams collected in a wide variety of ocean settings. As a result, a number of agencies and commercial companies now deliver operational map products for SST.

Ocean colour products are reasonably mature and stable for oceanic conditions (Case 1 water) but require further development to be truly useful in the coastal zone (Case 2 water) where there is huge unmet demand for monitoring of turbidity, chlorophyll, CDOM and benthic light exposure. While SOOP vessels can provide some essential cal/val data from the surface, the Node Plan identifies the lack of subsurface equivalents as a significant gap that could be most effectively delivered by Slocum gliders.

In addition to supporting the satellite products, Q-IMOS will use a number of data streams (SOOP, gliders, moorings, radar, wireless sensor networks) for calibration and validation of the eReefs modelling suite (2.4). To date, the hydrodynamic component model has been tested satisfactorily against the available data streams for temperature, salinity, and surface height. It is assumed that some of the predictions about vertically-profiled transient signals in salinity (Figure 47) or temperature (Figure 48) arising from extreme events (e.g. flood plumes, cyclones) could only be reproduced if the velocities and transports were robust. While this process of cross-validation will be a continuing and growing task, the physics have reached a stage where the baroclinic model has been used for useful prediction.

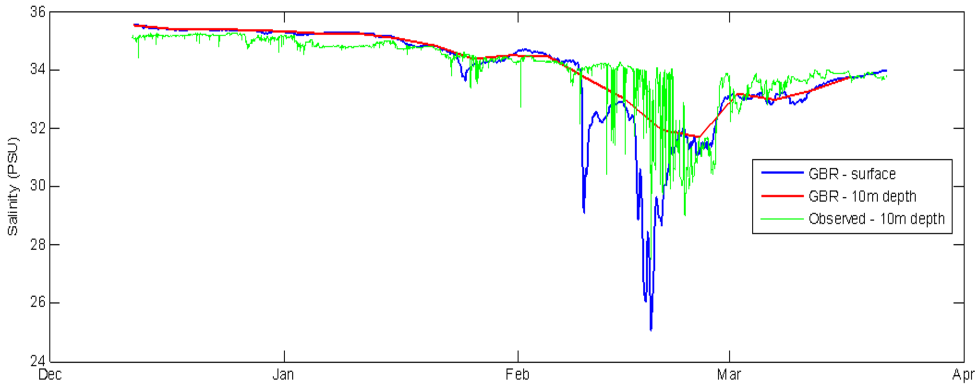


Figure 47. Comparison of modelled and predicted data for salinity at 10m at the Yongala NRS following a rainfall event (Source: Richard Brinkman, AIMS).

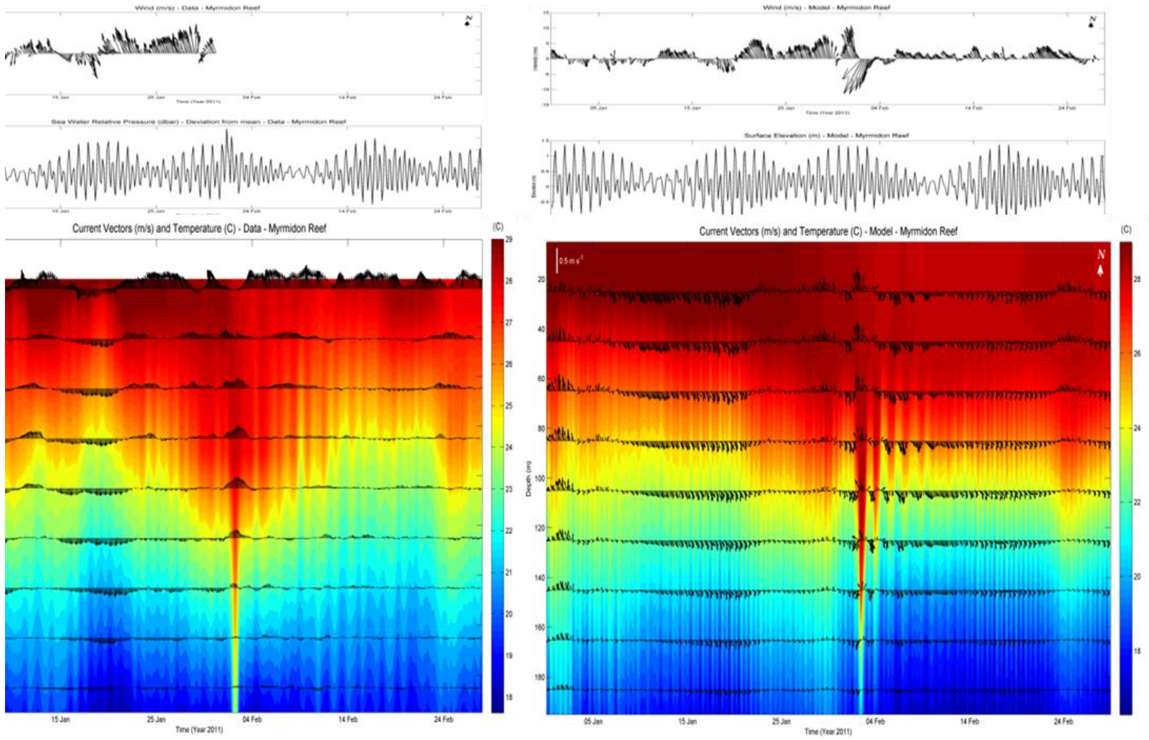


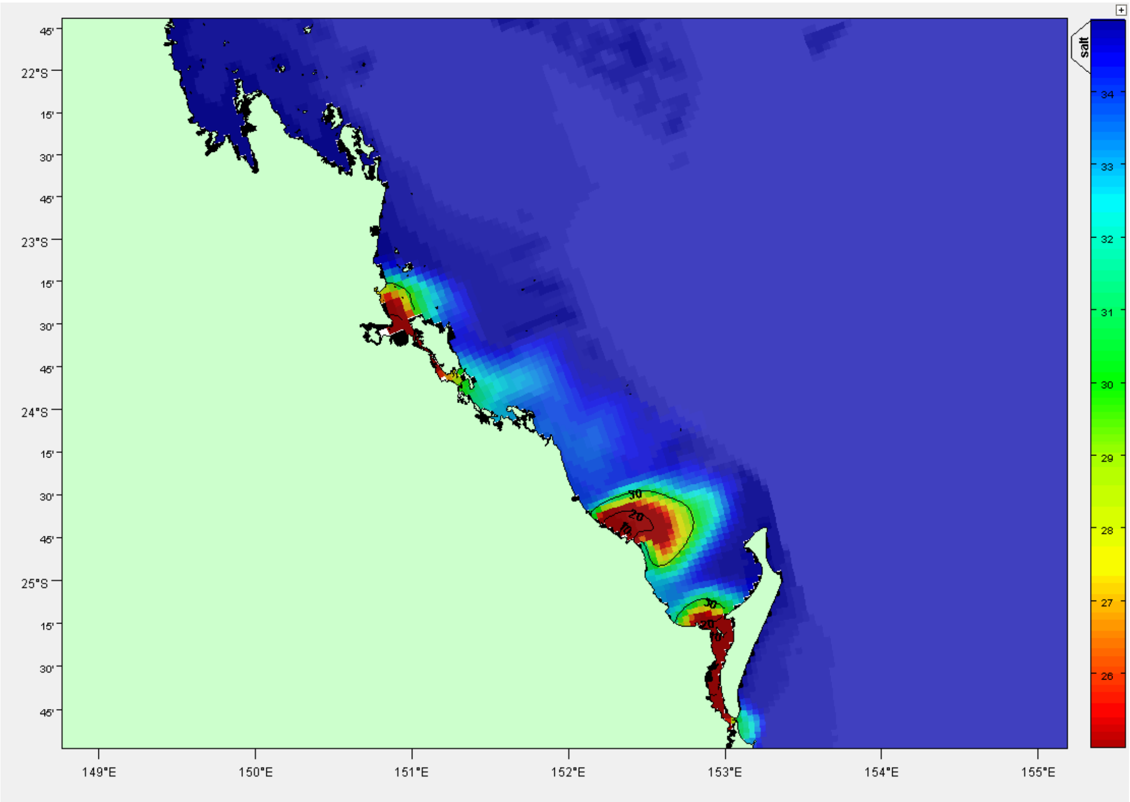
Figure 48. Comparison of actual (left) and modelled (right) time series for wind, sea level, and temperature in the upper 200m at Myrmidon Reef between November 2012 and April 2011 including

The major example of application and uptake of the eReefs model to date has been the modelling of discharge plumes (Figure 49) from all the major rivers in north Queensland in order to determine the relative contribution of different catchments to the nitrogen pool of the northern shelf between 14-17^{o}S. These inputs are assumed to be responsible for recurrent outbreaks of the crown-of-thorns starfish originating from this area, which pose a high risk to coral cover in the central GBR (De'ath et al. 2012). The results of this modelling were accepted and highlighted by the 2013 Scientific Consensus Statement on GBR water quality (Brodie et al. 2013b), which identified priority catchments for remedial action. Ultimately, this risk-based assessment will influence investment decisions within the Reef Plan overseen by a Ministerial Forum representing the Australian and Queensland Governments.

Since eReefs is still in a developmental space, the predictions for nitrogen load assumed some conservative dynamics that reflected dilution rather than biogeochemical transformation. To become more useful, the coupled models need to be capable of predicting sediment transport (including turbidity) and the water column chlorophyll signal. Again, cal/val measurements from SOOP, suitably equipped shelf gliders, and instruments on fixed moorings will be required and assimilated.

In the next 5-10 years, realistic prescriptions for eReefs will fall short of the aspirations held by many stakeholders for a system capable of tracking and predicting ecosystem health. In this period, research is needed to identify cost –effective indicators that could be added to future monitoring.

Figure 53. Predicted salinity isohalines on 29 Jan 2013 after TC Oswald (Source: Richard Brinkman, AIMS)



The wireless sensor networks at GBR island research stations provide a huge opportunity for the research community to innovate with methods for smart environmental monitoring. Acoustic receivers are already capable of transmitting real-time data streams. Integration with the local wireless network will open new frames for discovery on the drivers of large animal movements (active listening mode) or broaden the accessibility of the research community to the acoustic environment (passive listening mode). Similar opportunities exist for linking imaging systems (cameras, videos, infra-red for nocturnal observing) to local or remote investigators. Community metabolism and carbon chemistry can be monitored in the appropriate context when new sensors are connected with the real-time network. While the GBR island research stations represent hubs of observing activity with comprehensive and complementary data sets and significant observational infrastructure, there has been limited uptake of IMOS data from within the region by the University community. The exception is data generated by the animal tagging facility, which is heavily used for research training and university research projects. Q-IMOS will actively promote increased uptake of IMOS data to the marine science community during the life of this Plan, through targeted ‘Data workshops’ at Queensland universities – showcasing the data streams delivered through IMOS and made available through the IMOS Ocean Data portal.The Node will attempt to emulate the example of NSW-IMOS and collaborate with universities to embed the use of (including access to, and analysis of) IMOS data in teaching of under and post graduate students. This will provide opportunities for student training and research (Figure 50).

The residual investments in data streams (AUV, CPR, NRS biogeochemical sampling) all represent the contribution of regional observations to a national program of monitoring long-term, broad-scale changes around the Continent in key components of the coastal water, plankton, and benthos. These national observing programs are all linked with explaining changes in the distribution and abundance of species. The change perspective gained by comparing the multi-decadal records from the original NRS at Port Hacking and Maria Island illustrate the value of ocean observing at this scale.

Other examples of uptake from Queensland include:

- Weather data reported daily on public radio from sensor networks in the Torres Strait
- Groundwater levels on Raine Island reported through a wireless sensor network to monitor and understand the threat to egg survival in Green Turtles nests of at the largest rookery
- Ocean currents near Gladstone available in real time from ACORN radar for use by shipping and port operations (e.g. real-time monitoring of sediment plumes from dredging)
- AATAMS receiver arrays in Cleveland Bay supporting the Queensland Government’s Large Shark Tracking Program; reef arrays in the Capricorn-Bunker Group supporting NERP research on local fishes and capturing the movement of large animals to the southern GBR from Moreton Bay and across the shelf from the coastal zone (including the Port of Gladstone)
- Maps of currents and ocean temperature http://oceancurrent.imos.org.au/ downloaded on a daily basis by marine managers and researchers

Figure 50 illustrates the IMOS strategy, which is to collect ocean observations through a network of facility operators and deliver them to different user groups that variously translate these data streams into diverse outcomes ranging from discovery, training and innovation to operational and decision-support systems. The graphic shows that the Operators deliver substantially to the Node and that the Node contributes substantially to the national vision.

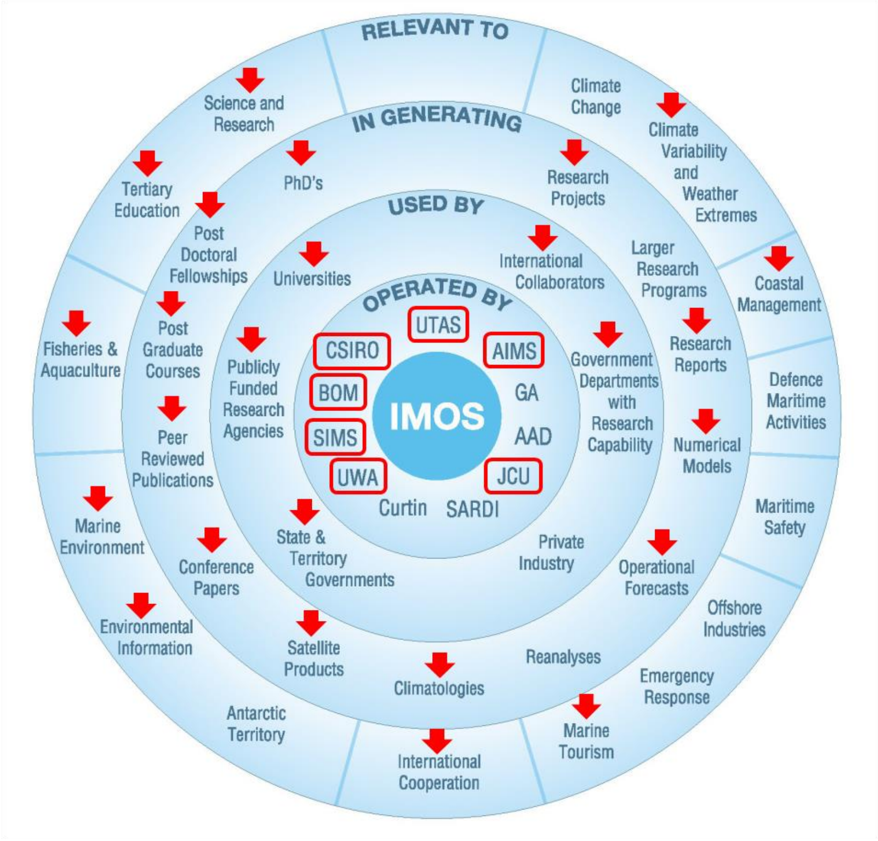


Figure 50. Points of common intersection between Q-IMOS and IMOS. Rectangles identify Operators of IMOS Facilities that supply marine observations relevant to Queensland. Arrows identify user groups, outputs, and outcomes arising from the collection and use of these data in the State.

4.1 Existing requirements by Node partners

Q-IMOS data streams will support informed marine management in the State of Queensland.

Currently, the Great Brisbane Region is home to over two million people living within a 200km coastal strip adjacent to marine environmental assets such as the Gold Coast Waterway and Moreton Bay Marine Park. The SEQ Healthy Waterways Partnership (HWP) monitors coastal water quality and habitat condition through evidence based and adaptive management approaches designed to improve the health of aquatic ecosystems throughout this region. As part of this, it manages extensive and intensive monitoring programs to measure progress in managing coastal nutrient and sediment inputs. The HWP has already determined that it requires highly resolved and nested hydrodynamic and biogeochemical models of the SEQ shelf between Fraser Island and the NSW border to apply correct forcing to the bays and estuaries. IMOS infrastructure near Brisbane (Stradbroke NRS) have provided valuable data to calibrate and validate the model (Figure 51).

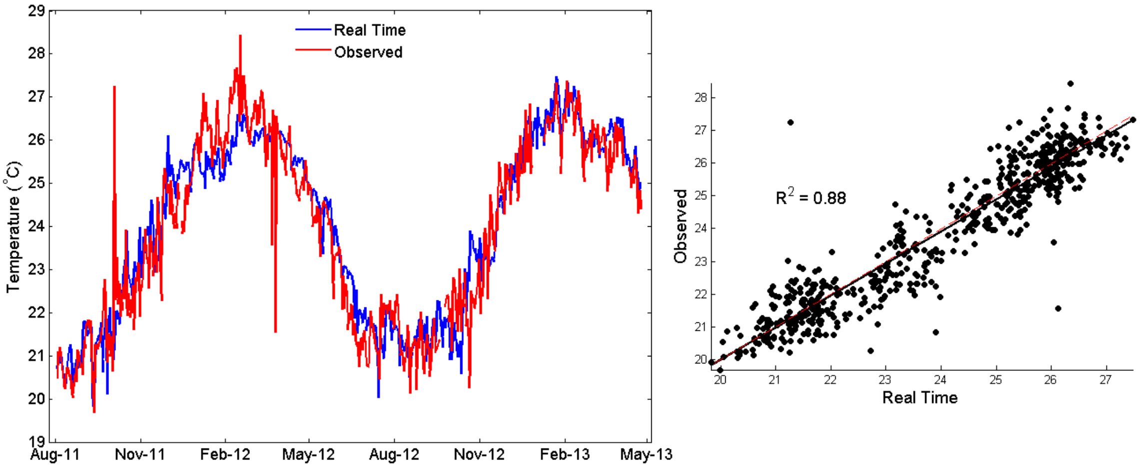


Figure 51. (a, Left) Daily surface temperature time series estimated by the Receiving Water Quality Model of Moreton Bay (blue) and observed data (red) from the North Stradbroke Island National Reference Station. (b, Right) Scatter plot of the modelled and observed data. The red dotted line represents the y = x line (Marin 2013).

eReefs is a translation of the SEQ vision applied to the whole east coast. As a model that has had great expectations thrust upon it by users urgently needing its capabilities, eReefs needs essential ocean observations for calibration and validation. Even though the external expectations have been capped at predicting sediment transport and pelagic primary production at shelf scales, these tasks will be challenge enough. As a dynamic model recalibrated daily over a very large spatial domain, eReefs needs near-real-time (NRT) data streams from many and widely distributed sources. Ultimately the need of eReefs for *in situ* observations from all parts of its domain to keep the model predictions as close as possible to realism is no less than that of the comparable modelling system used by the Bureau of Meteorology for routine forecasts of the surface weather and relied upon by all parts of society.

4.2 Partnership opportunities

The Great Barrier Reef Marine Park is managed by GBRMPA, which since the 2004 rezoning has been obligated to furnish five-yearly Outlook Reports on the status and future of this complex ecosystem.

Well before the first GBR Outlook Report (2009), GBRMPA strategy for managing ecosystems and biodiversity was predicated on reducing local threats to ecosystem resilience. Apart from the direct benefits, such actions were believed to be the best and perhaps the only way to prepare GBR ecosystems for additional and potentially unmanageable pressures from extreme weather and a rapidly changing climate. The joint government action to halt and reverse the decline in water quality entering the GBR Lagoon will continue to at least 2018 supported by half a billion dollars.

In 2013, the Australian and Queensland Governments produced complementary Strategic Assessments for the GBR and the adjacent coastal zone. In 2014, the two governments are due to develop a Long-term Sustainability Plan for the GBR. A key feature of the Plan is expected to be an Integrated Monitoring Program designed to inform adaptive management as this was a key action identified in both Program Reports. The IMP must include an underpinning layer of observations on weather and ocean variability if it is to be informative and effective.

The ongoing health of the GBR is more dependent than ever on accurate and timely environmental observation and modelling. A case in point is the development of large industrial ports in the GBR World Heritage Area. Such developments require the dredging and disposal of huge quantities of sediment, activities which could threaten the ongoing health of the reef if not properly managed. IMOS presents an ideal opportunity for partnership with industry in this regard since IMOS data streams as well as third-party modelling potentially provide the basis for managing dredging and disposal activities in ways that minimise risk. Shipping traffic through the reef could also benefit from real-time data streams from moorings and coastal radars to forecast local conditions (e.g. currents) reducing the risk of shipping accidents. While some discussions have taken place with industry (e.g. with the Port of Brisbane in relation to co-investment in coastal radar with IMOS) such partnerships are still to be fully realised.

Major developments in the coastal zone require environmental impact assessments that need information on diverse subjects ranging from ecohydrology to megafauna. Almost all of this work is conducted by consultants on behalf of development proponents. These organisations could make extensive use of IMOS data directly and indirectly. For example the firm WBM BMT was contracted to operate the Moreton Bay receiving water quality model in southeast Queensland on behalf of Healthy Waterways. The ongoing operation of this model will depend on validation and assimilation of data from IMOS moorings and other data streams as well as being nested within larger models (e.g. eReefs) that are similarly reliant on IMOS data.

4.3 Enhanced research training

Beyond all else, the data and observing systems will provide new opportunities for research by students and mentors. These opportunities range from using observations to address core questions of the Node (e.g. the impact of the EAC on shelf currents, upwelling processes, or primary production, etc.) to improvements in sensor technology, communications protocols, and data management for smart environmental monitoring. This is appropriate for infrastructure that was funded to support research. The newly established Marine Science foundation course at University of Queensland uses IMOS data streams as key parts of assignments and field exercises. There is no doubt that Q-IMOS observations will become increasingly important in teaching courses and framing dissertations in the future.

5 Regional, national and global impacts of IMOS observations

5.1 Regional impacts

IMOS is about infrastructure for sustained ocean observations to support research and new learning. Consequently, the first impact will be upon the expanded opportunities for the marine researchers of Queensland. While there are large groups in Townsville and Brisbane who obviously stand to benefit, the recent work on the inverse estuarine circulation in Hervey Bay (Ribbe 2006, 2010) is an example of work being done by a research group operating from a regional centre. Similarly, coastal engineers at the Gold Coast campus of Griffith University led by Professor Charles Lemckert have clear views about how they will use IMOS data on the dynamics of the EAC into their models of coastal processes (circulation, erosion, sediment transport, water quality) and have built this assumption into an ARC Linkage proposal.

The Upwelling Alert System being deployed off Townsville will awaken the local research community to cross-shelf processes that have been happening unobserved on their door step for a very long time and with demonstrable consequences for local marine ecosystems. Information in near real-time from temperature sensors on the sea floor, velocities from cross-shelf moorings, and other data sources (e.g. meteorological data, sea slope, etc) should allow the development of probabilistic but useful indicators of upwelling activity. Access to such predictions would encourage process studies into the downstream consequences of EAC intrusions upon pelagic and benthic systems.

The FAIMMS wireless sensor networks around coral reefs provide unparalleled opportunity for close monitoring of microclimate from four contrasting latitudinal locations providing Australian academics and their students with relatively inexpensive opportunities to either (a) use the basic observations, (b) enhance the density of observations at their choice, (c) shift experiments from the laboratory to the field, or (d) develop new sensors. Since the IMOS infrastructure is really just an early rollout of the National Broadband Network to regional Australia (i.e. each local system is an open access wireless network over a coral reef adjacent to an island research station), there are many opportunities for value-adding uses and/or developments.

The observations collected from the acoustic receiver networks will allow researchers to document and understand the links between ocean variability and the movements of tagged marine animals. The receiver curtains across the shelf in SEQ will monitor seasonal migrations of valuable fish species and species of conservation concern (including turtles, whales, manta rays, and large sharks including the endangered Grey Nurse and Great White sharks). The receiver arrays in the GBR will provide essential proof (or otherwise) of the effectiveness of current spatial management arrangements in the GBR Marine Park.

In SEQ, IMOS will be able to take advantage of the co-location of agencies in the new Eco-Sciences Precinct. This development, across the river from the University of Queensland, houses more than 1,000 researchers from Commonwealth and State Government agencies including those directly involved or interested in IMOS data (Marine and Atmospheric Research, Land and Water, and Mathematical and Information Sciences), and State Government science agencies. Opportunities provided by this nexus include larger collaborative marine science projects in SEQ, as well as more student research projects, both of which will want to use IMOS data. Q-IMOS will seek to enhance its profile with Industry. IMOS members at UQ have close links with many consulting companies (e.g. WBM, SKM, and Worley Parsons) with recent UQ PhD students and graduates becoming key players in SEQ coastal modelling.

Key areas where IMOS will have regional impact over the next 5 to 10 years.

- Provide data and context to assess effectiveness of management and conservation strategies for coastal and marine regions, including :
    - Water quality improvements established to reverse the decline of water quality on the GBR,
    - The long-term sustainability plan for the GBR World Heritage Area, including Federal and state plans for the management of coastal developments.
    - Management plans for valuable fish species and species of conservation concern (including turtles, whales, manta rays, and large sharks including the endangered Grey Nurse and Great White sharks)in SEQ.
    - Spatial management arrangements (e.g. Marine park zoning plans) in the GBR Marine Park.
- Integration of IMOS data into regional scale models of hydrodynamics, sediment transport, turbidity, water clarity, benthic light levels and key attributes of the pelagic primary producers will leverage data from a sparse observing system into regional predictions (of SEQ and the GBR), to inform management and conservation strategies (as described above)
- Sustained ocean observations of ocean and weather variability provided through IMOS infrastructure will form a foundation component of a GBR-wide integrated monitoring and reporting program to provide comprehensive and systematic monitoring and reporting of key values, processes and impacts on the GBR.
- Improved understanding of climate variability and extreme weather events impacting Queensland's coastal and marine ecosystems will lead to an enhanced predictive capacity, which in turn will support the preparation for, and response to extreme weather events

5.2 National impacts

Q-IMOS will contribute in several ways to the national ethos of IMOS to promote integrated studies of Australia's marine climate and environment. These include:

(a) Observations on the properties of the East Australian Current near 28°S to monitor the full-depth transport of the EAC.

(b) Observations from the Yongala and Stradbroke National Reference Stations to the national network monitoring the physical and biological responses of Australia's coastal environments to climate change.
(c) Observations from deep Seagliders on the properties of the upper 1,000 m of the western Coral Sea near 14^{o}S.
(d) Observations to ground truth national remote sensing data for SST and Ocean Colour products.
(e) Observations from cross-shelf curtains and networks of acoustic receivers from SEQ to the GBR that extend the limits of detection of tagged animals moving along the east coast of Australia as far as the tropics.
(f) Observations from the Autonomous Underwater Vehicle of changes in local benthic communities that can be related to nested phenomena of change (e.g. regional variations in primary producers caused by interannual variations in upwelling plus long term changes in both that can be attributed to changes in boundary currents or ocean conditions).
(g) Observations from plankton recorders towed behind ships of opportunity heading both north and south of Brisbane to monitor long-term changes in the plankton communities along the east coast of Australia that can be related to observations on the EAC and changes in ocean chemistry.

Key areas where IMOS will have national impact over the next 5 to 10 years.

Most observations collected by Q-IMOS will have the potential to strengthen existing marine programs elsewhere in Australia. For example,

- all observations collected by the mooring array and the Sea gliders in the Coral Sea will be assimilated, or used for validation, by the CSIRO/BoM/RAN Bluelink program (Oke et al. 2008), which is building a national capability for forecasting oceanic and coastal circulation.
- The upgrade of the satellite receiving station in Townsville will benefit the national ocean surveillance program led by the Bureau of Meteorology for improved climate prediction.
- The upgraded weather stations and the MetOcean buoys in the Q-IMOS network will provide comprehensive calibration/validation measurements to the national (CMAR-BoM joint venture) and international (e.g. NOAA-NESDIS) remote sensing communities researching heat and light fluxes from tropical waters.

5.3 International impacts

As the last example shows, national and international boundaries are increasingly transparent in 2014. Key data sets collected by IMOS on ocean properties off Queensland will quickly find their way to international collaborators (such as NOAA-NESDIS) that return the favour by posting frequent and regular forecasts of ocean condition including risks.

IMOS observations delivered through Q-IMOS will allow Australia to maintain a leadership position in coral reef science. The coral reef science community is truly awake to the threats arising from global changes. Coral symbiosis, which is the engine of reef building, is very sensitive to thermal variations and water pollution. There is now a global science focus on the limits of these systems to adapt to further warming of the oceans (Hoegh-Guldberg 1999, 2009). Beyond this is the additional challenge presented by slow acidification of the ocean (Doney et al. 2009), which impacts primarily on organisms attempting to build calcareous skeletons (Hendriks et al. 2010). Q-IMOS will help Australian and foreign researchers (using the Island Research Stations of the Tropical Marine Network) to provide answers to complex but urgent questions of risk and adaptation relating to the future of the World's coral reefs (Hoegh-Guldberg 1999).

The potential impacts of climate change on coral reefs is a matter of global concern. Members of Q-IMOS are engaged already with international programs such as the ILTER (International Long Term Ecological Research sites) strongly supported by the US National Science Foundation and the CREON (Coral Reef Ecological Observatory Network), which is a collaboration among countries (USA, Taiwan, Australia) attempting to monitor coral reef environments with new technology solutions such as wireless sensor networks.

6 Governance, structure and funding

In the IMOS matrix, Nodes propose outputs and Facilities deliver capability. The IMOS Office purchases selected outputs by allocating capabilities to Nodes and investing appropriately in Facilities. As a result, Nodes manage no funds directly but play a key role in articulating the regional needs for ocean observations in their domain.

Since IMOS is investing in infrastructure to support research, the research community should be the key constituency heard by the Node. Other stakeholders can have an equal voice through their influence upon the priorities recognised by the local scientific community. With that caveat, the membership of Q-IMOS is open to anyone with a professional interest in ocean observations in Queensland.

Node business will be done by consulting the Q-IMOS membership through public meetings (at least once per annum) and distributing all significant documents by email to the membership list. Significant documents include the Annual Work Plans and Annual Reports required by IMOS.

To raise awareness of the Node operations, Q-IMOS has an Advisory Group consisting of the following appointments:

Q-IMOS Node Leader (Richard Brinkman, AIMS)	
Brisbane	**Townsville**
CSIRO (Russ Babcock) _ Deputy Node Leader	AIMS (Scott Bainbridge)
UQ (Anthony Richardson)	JCU (Mike Kingsford)
Griffith University (Charles Lemckert)	GBRMPA (Laurence McCook)
QDAFF (Warwick Nash)	
DSITIA (Julia Playford)	
EPA (Liz King)	
GBRF (Eva Abal)	
DPC (Chris Chinn)	

The key responsibilities of the Q-IMOS Advisory Group are

- to monitor implementation of the Node Science Plan
- to advise the Node leadership
- to respond to matters from the IMOS office
- to disseminate information about Q-IMOS to their organisations
- to identify opportunities to enhance the marine observing network

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