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Queensland's biodiversity under climate change:

coastal and marine ecosystems

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PREAMBLE

This report is one of seven background documents prepared by the CSIRO Climate Adaptation Flagship for the Queensland Government. Content from this report contributed to the synthesis report titled “Queensland's biodiversity under climate change: impacts and adaptation” by Williams *et al.* (2012a).

The seven background reports are:

A. Overview of climate change in Queensland (Williams & Crimp 2012)

B. Ecological scaling of terrestrial environmental change (Ferrier *et al.* 2012)

C. Terrestrial ecosystems (Murphy *et al.* 2012)

D. Freshwater aquatic ecosystems (Kroon *et al.* 2012)

E. Coastal and marine ecosystems (Bustamante *et al.* 2012)

F. Ecosystem services (Williams *et al.* 2012b)

G. Adaptation principles and options (Dunlop *et al.* 2012)

Gorgonian corals captured in the artificial light of CSIRO's remote operated research vehicle on the seabed off far northern Queensland. An area 50 km offshore between the coast and the Great Barrier Reef, known as the lagoon, hosts diverse gardens of marine life: soft corals, sponges, sea-whips and fish. A study by CSIRO Marine Research and the Queensland Department of Primary Industries found that prawn trawling in the region had a cumulative effect on this marine life, depending on trawling intensity and the capacity of individual species to recover between trawls (credit: CSIRO Marine and Atmospheric Research, science image AS0937).

EXECUTIVE SUMMARY

We have reviewed, assessed and synthesized the readily available scientific evidence for various responses of biodiversity to projected climate change in Queensland's coastal and marine ecological realms. Nationally and for Queensland, the generic and known ecological impacts expected from climate and ocean changes will include at least: (a) changes and variations on phenology of marine biota; (b) changes in the distribution and abundance of species; (c) changes in the extent and variation of ecological habitats; (d) effects on physiology, life history events and environmental tolerances; (e) changes in community structure and function; and (f) changes in ecosystem processes and functions.

Primary producers that form the basis of the food chain will be particularly affected, resulting in changes in seasonal abundances and peak production. Differential knock-on effects (ecological cascades) are expected to impact consumers (e.g., through a match-mismatch between food supply (prey) and predators). These changes are likely to be non-linear with possible ecological thresholds of change. Marine species that have rapid regeneration times may be able to adapt through natural selection and genetic drift (evolution) but in most cases species' capacity to adapt genetically will be challenged by the present and projected rate of climate change. Local extinctions have been proposed for corals, fishes and macroalgae, especially those close to their high temperate thresholds and for species that have their northern range limits along the southern Queensland coast.

Queensland's marine domain includes shallow coastal tropical and subtropical waters and one of the largest coral reef domains in the world: the World Heritage listed Great Barrier Reef (Section 2.1). The marine domain also includes a large shallow gulf, the Gulf of Carpentaria, with extensive seagrass beds and sunken reefs. Several large embayments are found along the Queensland coast (e.g., Moreton, Hervey, Shoalwater, Princess Charlotte and Albatross). These are important nursery grounds for marine fauna and home to several iconic and endangered species, including dugongs and turtles. Although the waters beyond the three nautical miles of the coast are mostly Commonwealth jurisdiction, there are a number of shared management responsibilities between state and federal government agencies. Notwithstanding these complex management arrangements, this report recognises the continuum in biodiversity and ecological processes from the land to the sea and considers all marine waters that directly support Queensland's social and economic well-being. The off shore marine waters contain unique and relatively unexplored habitats that range from abyssal plains to emergent corals reefs. Seamounts and extensive ocean plateaux provide habitats for a multitude of benthic fauna and flora, much of it undescribed. The pelagic environment supports large populations of marine mammals, tuna and billfishes.

Sea levels are rapidly rising, ocean storms have increased in intensity and cyclonic activity may be moving south.

Increasing atmospheric concentrations of greenhouse gasses are changing the climates of Queensland (see Williams & Crimp 2012). The flow-on of climate change and ocean change effects to the marine environment include changes in water temperature and current patterns, ocean stratification and nutrient supply, sea level, water acidity and the frequency and severity of ocean disturbances due to storms and cyclones (Section 2).

Human land and resource use pressures will interact with climate change to exacerbate the impacts on marine systems due to: poor water quality (e.g., terrestrial runoff) increases coral bleaching risk; coastal development may limit landward migration of estuarine habitats as sea levels rise; fishing pressures may limit the capacity of species to repopulate habitats following disturbance events.

Coastal habitats are situated at the interface between terrestrial, freshwater aquatic and marine environments. The likely effect of climate change on terrestrial and freshwater aquatic ecosystems is discussed in Murphy *et al.* (2012) and Kroon *et al.* (2012), respectively. Climate related changes in patterns of rainfall (seasonality, frequency and intensity) on terrestrial catchments generate changes in runoff and river flow regimes. Climate related changes in terrestrial freshwater inputs will influence the coastal-marine domain. Declining and more variable and intense rainfall events are expected for Queensland, with a net increase in extreme rainfall for coastal catchments and high unpredictability for northern Queensland (Williams & Crimp 2012). The interacting effects of resulting flooding events, intense cyclones and storm surges will likely drive large, episodic changes in coastal-marine ecosystems through changed disturbance regimes and coastal erosion processes, particularly on wetlands, estuaries and low-lying areas of the coastal zone.

A key driver of change in the marine domain is through change in the flow of currents. The South Equatorial Current presently meets the Queensland coast north of Townsville (~18°S) where it bifurcates into the south-flowing East Australia Current and the north-flowing Hiri Current. The East Australia and Hiri Currents are likely to strengthen in future, extending tropical influences into southeast Queensland. This tropicalisation of the subtropical southern Queensland coast, will lead to changes in biodiversity, population connectivity, ocean productivity and the distribution of pelagic species, in particular.

Warming sea surface temperatures are influencing marine resource distribution.

Sea surface temperatures in Queensland waters have already warmed some 1°C over the past 100 years. In future, the East Australia Current will transport greater volumes of ocean water southward, modifying the tropical and subtropical extents of coastal environments and marine habitats. Model projections indicate that sea surface temperatures in this region will warm by approximately 2°C by 2063–2065 relative to the historical period (1870–2004). The level of confidence of the likelihood of these changes is medium-to-high. This change will influence the growth and survival of marine biota, with a complex interplay between increased metabolism and heat stress. Temperature has a strong influence on the vertical and longitudinal distribution of marine biota, so these changes will result in a generally southward extension in distribution of species, where suitable habitat is available. The extraordinary response of zooxanthellate corals to increasing temperatures and the resulting phenomena of bleaching and coral mortality, has potentially large implications for the vast coral reefs of Queensland's marine domain. Given the prevailing ocean circulation, the warmer waters of the Coral Sea may provide recruits to the warming Great Barrier Reef ecosystem. Upwelling of cool waters on the central Great Barrier Reef may help maintain some coral reefs habitats within their present thermal tolerances (climate change refuges) but ocean acidification will alter the chemical environment of all habitats.

Overall, global sea levels have risen by about 20cm since pre-industrial times (~1850) and 6cm since 1960. The rate of increase is currently around 2.5cm per decade globally and appears to be accelerating due to more rapid ice melt and thermal expansion of the upper ocean (Church *et al.* 2009). Queensland's coasts, situated adjacent to warm ocean currents, can expect higher sea level rises than the global average which, particularly when coupled with high tides and storm surges, will lead to higher risks of inundation and coastal erosion. These physical impacts will vary locally and regionally and are initially likely to affect low-lying coastal zone and near-shore intertidal habitats, such as beaches, seagrass beds and rocky shores, followed by tidal wetlands, such as mangroves and salt marshes.

Ocean acidification is affecting the viability of some calcifying biota in the Great Barrier Reef system.

Ocean acidification has been increasing over the past 60 years (lower pH) and this trend is expected to continue for the long-term as rising atmospheric concentrations of CO_2 continue to dissolve in ocean waters. This change in pH has consequences for calcifying animals and plants, causing reduced calcification rates and higher metabolic costs to biochemically precipitating calcium carbonate from solution. The corals of the Great Barrier Reef may be already responding to lower pH with declining calcification rates reported in some massive coral species. As a consequence of this trend and including coral bleaching, the Great Barrier Reef is likely to transform into a more algal-dominated ecosystem by mid-to-late this century. Coral reefs may also lose their structural habitat functions (the reef architecture used as a shelter by other organisms) and be reduced to ecologically-depauperate carbonate platforms by 2100. The reef ecosystem as a whole will cease to function. The shallow and emergent parts of coral reefs will be smaller in size and provide less of a buffer to ocean swells impacting adjacent lagoons, islands and coasts.

The Great Barrier Reef ecosystem shows a pattern of higher resilience around offshore reefs compared to inshore reefs and greater pressures (lower resilience) in the southern region than far northern regions. Improvements in land use and management practices that reduce sediment volumes, nutrient concentrations and other pollutants in terrestrial run-off and in waters discharged from rivers, combined with sustainable fishery management in the remainder of the Great Barrier Reef, will ameliorate this impact to some extent by improving marine ecosystem health and resilience.

Salt marsh and mangrove ecosystems may invade low lying areas that currently contain freshwater ecosystems. Mangrove forests and other intertidal saline wetlands have the capacity to adapt or expand their range landwards in response to rising sea levels, if the rate of vertical sediment accretion of the wetland land surface equals or exceeds the rate of sea level rise and suitable landward habitat exists. Currently, the elevation by sediment accretion of mangrove and salt marsh ecosystems in southeast Queensland, for example, is keeping up with local rates of sea level rise (~2.4 mm/yr).

Seagrasses may decrease in productivity as temperatures increase. Local losses of seagrass beds are likely to occur with increased storm disturbance events and higher levels of mortality as light levels are decreased by turbidity. Changes in the distribution, abundance and productivity of seagrass beds will have important implications for marine fauna, including recreation/commercial fishery and high conservation value species that rely for whole or part of their life cycles on seagrasses for nurseries, food and/or shelter. The carbon sequestration potential of seagrass beds may also be reduced.

A translocated tropical biota is mixing with the local subtropical and temperate biota, with the greatest changes expected to be in the southeast coasts and further south.

In the marine waters off the Queensland coast, an expansion of sub-tropical planktonic species—the basis of the marine food web—is expected into south-eastern waters driven by warming and a strengthened East Australian Current. This will increase also episodes of harmful algal blooms in south-eastern waters in response to extreme rainfall events and warming. Changes in zooplankton community structure will result from modified productivity regimes, as well as range extensions with warming, such as the potential for venomous jellyfish to extend southward. Southward coral migration is limited by the availability of suitable limestone substrates.

These changes and the synergies with land-based and human activities are imposing rapid and increasing (positive and negative) changes in Queensland's coastal-marine biodiversity.

There may also be an expected increase in occurrence of tropical pelagic fish species in southern waters, as well as replacement of small cool-temperate pelagic fish species in southern waters by sub-tropical and tropical species driven by warmer temperatures. Tropical fish species will likely expand their distribution range into southern Queensland due to warming sea temperatures and passage with the East Australia Current. A general absence of suitable habitat for coral dependent species in southern Queensland waters may hamper this movement. In north Queensland, the overall extractive catch of species by commercial and recreational fisheries (e.g., prawns, barramundi and mud crabs) may be adversely affected by declines in summer rainfall. However, episodically heavy rainfall and floods may lead to increased prawn catches in the north due to La Niña climate patterns –a coupled ocean-atmosphere phenomenon that is the counterpart of El Niño in the El Niño-Southern Oscillation that occurs across the tropical Pacific Ocean. Due to the relationship between rainfall and prawn catches in the Gulf of Carpentaria, changes in rainfall patterns will influence prawn catches over the longer-term.

The effect of climate change on seabird populations is uncertain but will likely alter breeding success and adult survival through changes in prey species phenology, distribution and abundance. Seabird distributions will likely move southward, depending on the availability of breeding/roosting habitat and the distribution of prey species.

Marine turtle hatchlings, the sex of which is determined by the temperature of incubation, have shown increased female dominance in warm years on Queensland beaches. This trend is expected to continue as temperatures continue to warm and may approach such levels of imbalance in future population demographics that population viability will become compromised. All marine reptiles (turtles, salt-water crocodiles and sea snakes) are likely to be affected by changes in temperature and rainfall, with southwards extensions in distribution being limited by available habitat and human settlement.

Queensland's marine biodiversity directly supplies ecosystem services such as: food, income and leisure activities through commercial and recreational fisheries; income and cultural services through marine tourism; and 'option use value' through future unknown and speculative benefits, such as novel pharmaceuticals (Section 5). Queensland State Fisheries are likely worth more than $200 million per year to Queensland, the majority of that derived through the healthy, functioning Great Barrier Reef system. The total (direct plus indirect) economic contribution to Queensland in 2005-06 of tourism, commercial fishing and cultural and recreational activity in the Great Barrier Reef and associated catchments was valued at $5.4 billion per annum, or 3.1% of gross State product, with employment of 56,000 persons. Taking long term costs and non-use values into account, coral bleaching on the Great Barrier Reef will be roughly equivalent to constant losses of $1.08 billion per annum over the course of a century.

Damage to coastal infrastructure by increased wave exposure as a result of decreased coral formation and possible reef dissolution is a risk for the Queensland coastline. There will be many severe local impacts particularly for subsistence communities of the Torres Strait Islands but where industries can adjust to changed conditions there will be new opportunities: places for unique and attractive diving experiences; and new fisheries may arise.

The Great Barrier Reef is the largest and probably one of the best managed and therefore resilient reef systems in the world (see Section 6). Much fishing effort has been removed through rezoning of the Great Barrier Reef and industry adjustment. Fisheries are accustomed to adapting to changing fishing practices such as switching target species, fishing location, or new technology. Adaptation management responses to build coastal and marine ecosystem resilience will to a large extent depend on land-based actions that control sediment and pollutant runoff in coastal catchments, leading to improved water quality. While translocation, or assisted migration, is receiving increased attention as an adaptation strategy, the risk of negative consequences may outweigh the potential gains at this point in time.

Tropical reef fish. Townsville Aquarium, Queensland, November 1989 (credit: Robert Kerton, CSIRO Publishing, science image EM0721).

1. SCOPE AND CONTEXT

1.1 Coastal and maritime zones

For the purpose of this assessment we have included all coastal and marine zones and environments directly and indirectly relevant to the Queensland State's marine biodiversity, ecosystem services and sectoral uses contained in territorial, commonwealth and, in some cases, international waters (Figure 1). To the extent possible we have included all marine and benthic domains within Australia's exclusive economic zone (Figure 1).

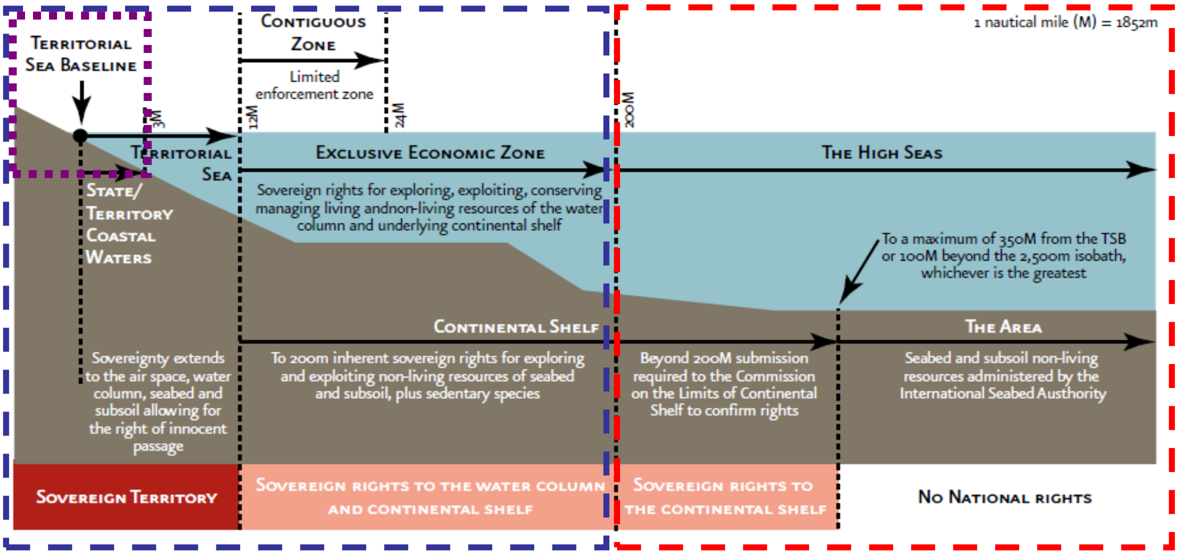

Figure 1: Australia's coastal and maritime zones with explanations of the State (purple dotted box), National (blue dotted box) and International (red dotted box) sovereignty and rights, including depiction of the high seas (modified from DEWHA 2008).

Queensland's coastal and marine ecological realms contain a wide range of ecosystems with unique and diverse juxtaposed and interdependent habitats, ecological communities and interacting species. The review and synthesis conducted here considered, to the extent possible, all coastal and marine domains specified in Queensland's Coastal Plan (Environment Planning 2011), State of the Environment (EPA 2008), Regional Planning (DIP 2011), Fisheries Strategy and its plans (DEEDI 2009), the Fish Habitats (Couchman & Beumer 2007; Derbyshire *et al.* 2008) as well Australia's marine North and East Bioregional Profiles (DEWHA 2008; DEWHA 2009, respectively). Technically, the jurisdiction of Queensland is the three nautical miles of State waters (the purple dotted box in Figure 1 delineates State/territory administrative boundaries in coastal waters). However, accounting for all coastal and marine domains that provide ecosystem services for Queensland's social and economic benefit, the area of interest extends well beyond the three nautical mile (nm) limit (Figure 1). Many of these ecosystems and their uses, services and biodiversity are highly inter-connected and interdependent at local, regional and marine basin scales. An example of these ecological connections is demonstrated through the commercial tuna and billfish fisheries in the Coral Sea (thus outside 3nm) that support fishing industries along much of Queensland's coast (Australian Government 2010). We therefore consider marine ecological realms well beyond

Queensland's State boundaries. At times in this report we consider the biophysical context of the exclusive economic zone and beyond (Figure 1).

1.2 Scope of natural environments considered

Queensland's coastal zone – the interface between the land and the sea – covers some 6,000km and contains an extensive array of habitats including sandy beaches, intertidal rocky and muddy shores, rocky headlands and reefs, sedimentary embayments and estuaries. These in turn are composed of mosaics of coral and rocky reefs, sand and sediments beds, seagrass beds, macro-algal and kelp beds, salt-marshes, wetlands, coastal lagoons and mangrove forests. This coastal zone is flanked by complex and fragile littoral forests (or heath), coastal vine thickets and beaches, coastal wetlands and dune vegetation types that have been mapped by the Queensland Herbarium (Neldner *et al.* 2005) and the Queensland Wetlands Program (DERM 2010c). The latter integrates the outputs of the Queensland Coastal Wetlands Mapping project (e.g., Bruinsma & Danaher 2000). These terrestrial and freshwater aquatic ecosystems are described in more detail elsewhere (Kroon *et al.* 2012; Murphy *et al.* 2012).

An illustration of the cross-section between the land, coastal and offshore marine domains and their close relationships and connectedness with the various habitats of eastern Queensland and the Great Barrier Reef is depicted in Figure 2. Here we illustrate the limited and fragmented coverage of coastal habitats and marine domains if we were only to consider the State jurisdictional waters (dotted purple lines in Figure 2). As outlined above (Section 1.1), for inclusiveness we have considered all relevant domains within and outside but biophysically connected to Queensland's jurisdiction.

Figure 2: Illustrative schematic cross-section of the Great Barrier Reef system depicting the varied coastal and marine habitat features (modified from the GBR Outlook report, GBRMPA 2009).

An alternative view is presented in Figure 3 which depicts the continuum and cross-linked land-sea ecosystems, as well as the jurisdiction and administrative complexities. This example shows the spatial segregation and overlapping jurisdictions (layers of governance) having an input into or being responsible for the conservation and management of the Great Barrier Reef. Here, we can see the complex and not always integrated layers of the various jurisdictions that are currently operating at State and National government levels to manage and develop adaptation strategies for dealing with the impacts of climate and ocean change on the Great Barrier Reef system.

Examples of biota that straddle these jurisdictions, coastal habitats and marine domains include Barramundi (*Lates calcarifer)*, Mud Crabs (*Scylla serrata and S. olivacea*) and Banana Prawns (*Penaeus merguiensis*). The life-history of these species includes creeks and rivers, estuaries, mudflats, coastal beaches and open sea, in some parts of their reproductive cycles (Figure 4). These and other examples support our consideration of change in waters beyond three nautical miles.

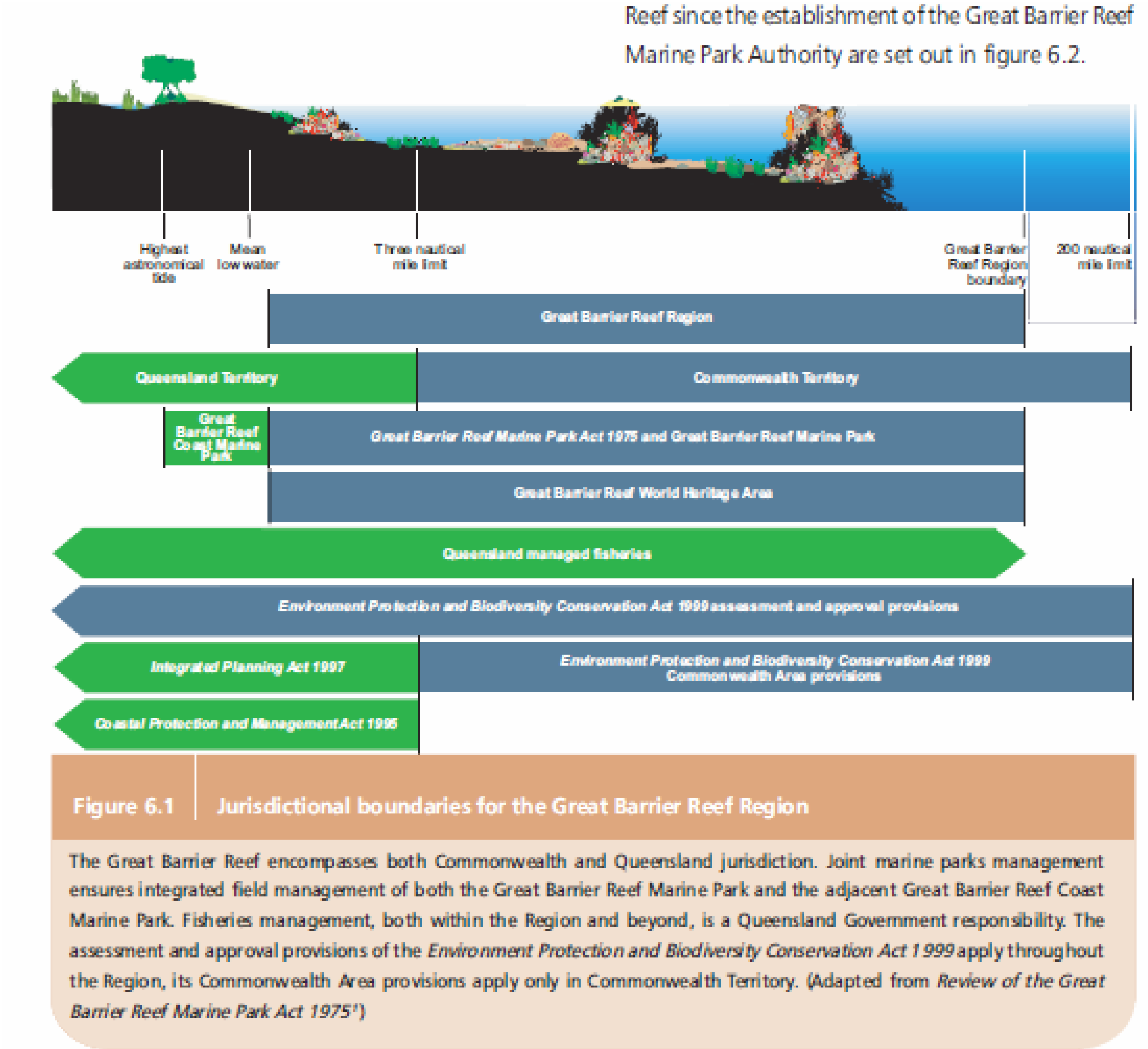

Figure 3: Illustrative schematic cross-section of the Great Barrier Reef system depicting the varied coastal and marine habitat features and the various and overlapping jurisdiction (GBRMPA 2009).

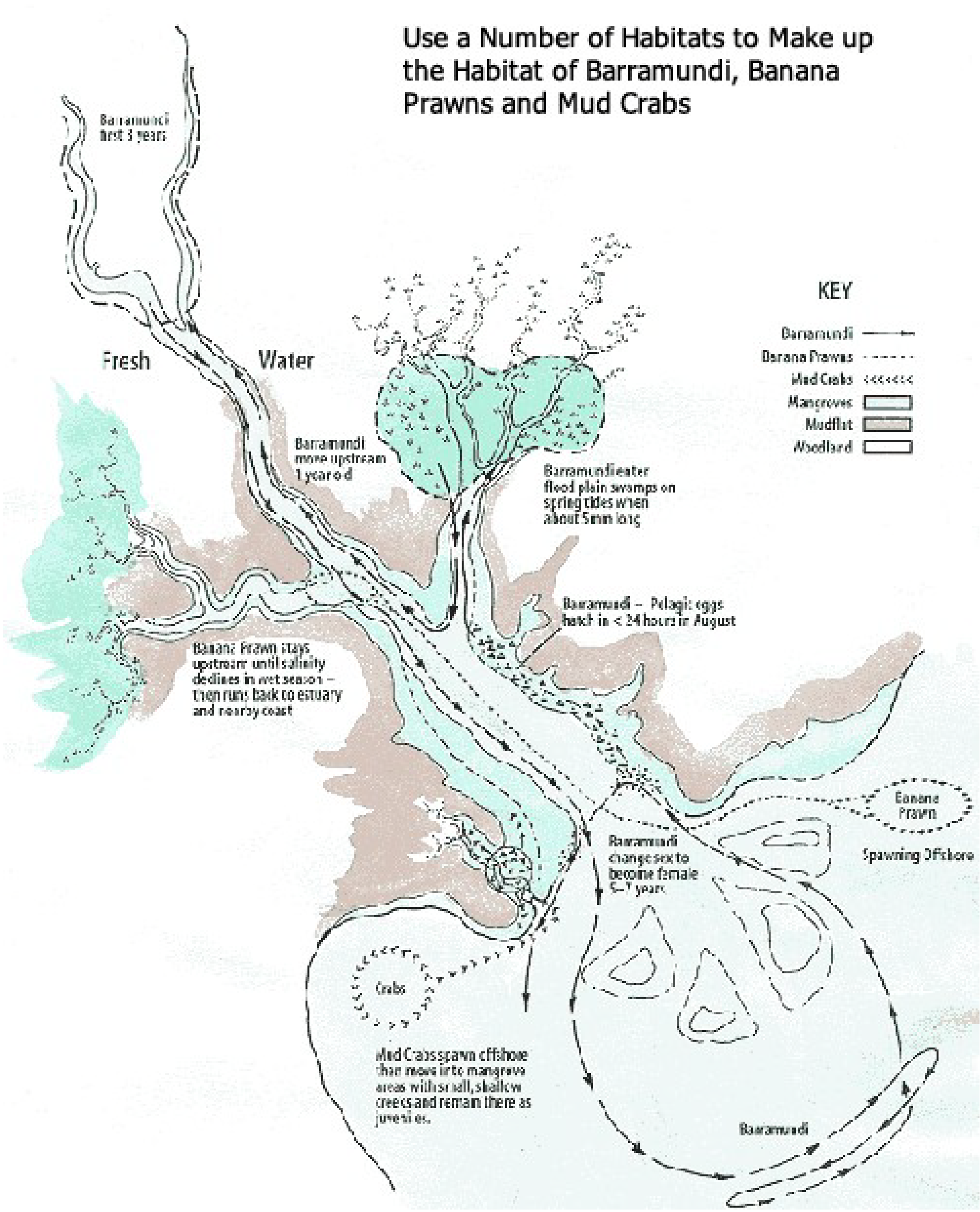

Figure 4: Many economically important fisheries resource species in Queensland use a range of interconnected land and sea habitats across their life-history (Environment Australia 2001).

1.3 Domains

Queensland’s nearshore marine domain is dominated by a coral reef barrier – the Great Barrier Reef, which extends to the edge of the continental shelf from Torres Strait to Rockhampton (Figure 5). South of the Great Barrier Reef is the south eastern region, dominated by large sand islands and their associated large embayments of Moreton Bay and Hervey Bay. The other large shelf domain is the Gulf of Carpentaria, a large shallow epicontinental sea, connected to the Arafura Sea and in the east connected to the Coral Sea through Torres Straits (Chivas *et al.* 2001) (Figure 5). The Gulf of Carpentaria also contains a newly reported coral reef province (Harris *et al.* 2008). These reefs are submerged relict reefs, formed when sea-levels were much lower and the climate cooler and growth rates were unable to keep up with contemporary rising sea-levels.

The offshore region of eastern Queensland contains deep-water pelagic tropical and sub-tropical parts of the Coral Sea, an area of 972,000km^2 with depths greater than 5,500m and containing numerous cays, atolls and islets of the underwater Queensland and Marion Plateau and the northern section of the Tasmantid seamount chain (Figure 5). This area also contains a major pelagic domain with pelagic cold-core and warm-core gyres and eddies associated with the East Australia Current (Figure 6) (DEWHA 2009). The massive and deep ocean of the Coral Sea (greater than 5,500m in places) contrasts with the shallow Gulf of Carpentaria (maximum depth of 80m), Torres Strait and the continental shelf (depths below 200m) that harbour the Great Barrier Reef system (Figure 5).

In Queensland's large-scale coastal and marine domains, the main oceanographic currents off the coast have strong biological and climatic influences on the land and coasts (Ridgway & Hill 2009; Suthers *et al*. 2011). These currents are: (i) the East Australia Current that flows south; (ii) Hiri Current that flows north; and (iii) the Gulf of Carpentaria Gyre that flows in a clockwise direction (Figure 6).

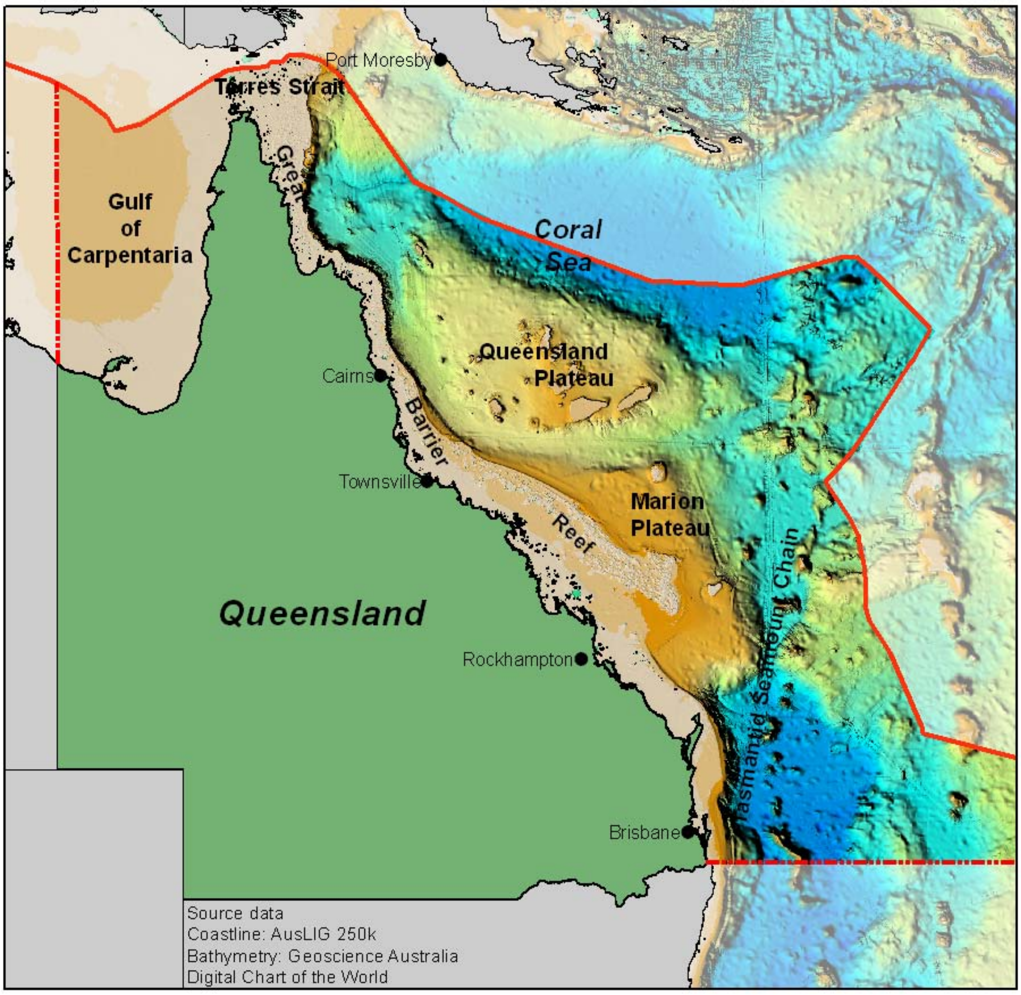

Figure 5: Marine domains of Queensland and Australia's eastern Exclusive Economic Zone.

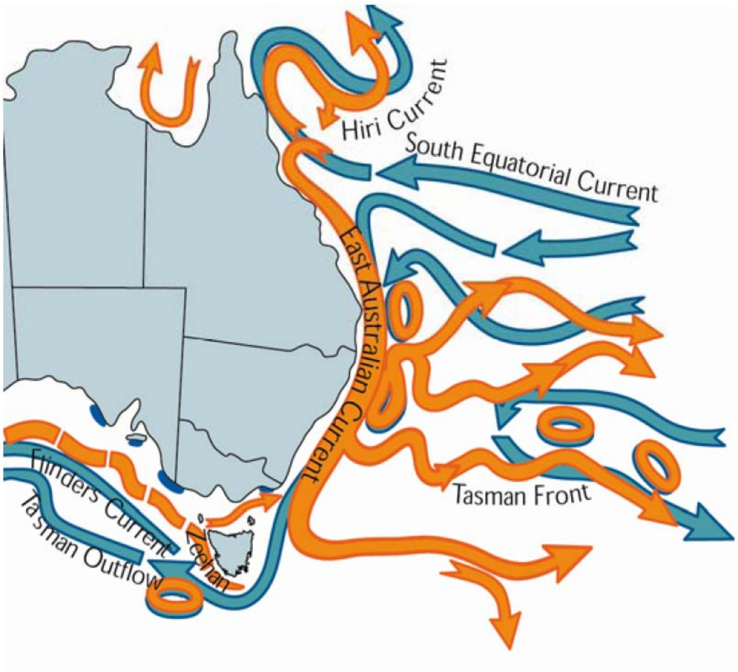

Figure 6: Major oceans current off Queensland[1] (DEWHA 2008).

1.4 Knowledge

Most of the biophysical knowledge of Queensland's coastal-marine domains is scattered and uneven. Comparatively, a great deal is known about the Great Barrier Reef system (GBRMPA 2009; Johnson & Marshall 2007) but little is known about the immediately adjacent deep seas of the Coral Sea. However, knowledge is accruing from current research which is focussed on management of the Eastern Tuna and Billfish fisheries and in relation to climate change (Griffiths *et al.* 2010; Hobday & Poloczanska 2010; Hobday *et al.* 2011; Young *et al.* 2011b). The coasts and the shallows of the continental shelf (<80m) are also regions for which there is a concentration of research effort and resource management, while the offshore and deep seas remain relatively unknown and unsurveyed (e.g., the Great Barrier Reef slope, Marion and Queensland Plateaux, Coral Sea islands and the open ocean) (Figure 5). This situation may soon change with the increasing value and shortage of oil and gas, as well as the economic viability of seabed mining, which has lead to increased exploration of offshore resources and the surrounding seabed (DEWHA 2008; DEWHA 2009; GA 2007; McKay 2006). It is expected that any commercial exploration and uses of the seabed and deep water resources would require environmental research to develop baselines, support ecologically sustainable development and to assess and manage any impacts of pollution and habitat disturbance (Bernecke 2010).

1.5 Marine regionalisation

Integrated, spatial coastal-marine conservation management and planning is not fully developed in Australia. The general lack of integration between some areas of National and State government policy and planning processes; due to different jurisdictional responsibilities; also limit the spatial integration of knowledge presented in this assessment. The spatial scale of analysis is a key

[1] Australasian ocean currents, http://www.csiro.au/resources/AustralasianOceanCurrents.html

consideration and is briefly outlined below to illustrate the reason behind the set of spatial units selected for analysis and synthesis in this report.

At the scale of the Queensland State, there is no single spatial planning process for the coasts and its adjacent ocean waters. There are a range of planning and management processes that have been developed either to meet a specific need and/or a partial focus (e.g., island, cays, reefs) on a continuous region that overlaps the jurisdiction. These include (see Figure 12 in Appendix 1): the Regional Plan Areas (DIP 2011) which extend into the coastal-marine zone to align with local government authority boundaries; the Queensland Coastal Plan regions (Environment Planning 2011) which considers coastal land and its resources within the coastal zone[2] based on local government boundaries; and the Natural Resource Management (NRM) Regions (DERM 2009; NRM Programs Data Manager 2011) which are based on catchments or bioregions for the purpose of administering and managing investments in (mainly terrestrial) biodiversity and environmental management. The Regional Plan Areas (DIP 2011) and the Coastal Plan regions (Environment Planning 2011) are based on regional groupings of Local Government Authorities negotiated by the Department of Local Government and Planning, with small differences in coastal zone extent aligned with the different planning processes (Figure 12a, b in Appendix 1). On the other hand, the Natural Resource Management Regions are based on natural features– clusters of bioregions, drainage basins or catchments (Figure 12c in Appendix 1). These different administration units focus on specific investment or statutory requirements of planning, which may or may not include a focus on sustainable management of natural areas. As a result of the different purposes, these different regions do not encompass the entire interconnected continuum of biodiversity and ecosystem processes, as well as the sectoral uses, that are represented across the coastal zone and marine waters of Queensland.

In other parts of Queensland, a finer scale of marine bioregional zone mapping has also been undertaken. The Great Barrier Reef for example has been subdivided into 30 reef and 32 non-reef bioregions (GBRMPA 2006; Kerrigan *et al.* 2010). This mapping was developed by consensus through a panel of experts who considered more than 40 layers of data. The panel's delineation of a bioregion aimed to represent 'an area where the known animal and plant assemblages and the physical features, are sufficiently distinct from the surroundings and the rest of the Great Barrier Reef World Heritage Area' (see GBRMPA 2011). This scale of mapping is too fine for the broader synthesis of ecological responses to climate change presented in the following sections.

The National Marine Bioregionalisation of Australia, which was developed to support National conservation management and planning processes, characterises broader patterns of spatial variation in the physical and biological zones of Australia's marine jurisdictions, including offshore island territories (Heap *et al.* 2005; Lyne *et al.* 2005). Similar to its terrestrial equivalent known as the interim bioregionalisation for Australia (IBRA v6.1, Environment Australia 2000), the spatial marine framework is known as the Integrated Marine and Coastal Regionalisation of Australia (IMCRA v4, Commonwealth of Australia 2006). Figure 13 (in Appendix 1) shows the provincial (a) and meso-scale (b) bioregion for the Queensland coasts and seas. IMCRA extends from the edge of Queensland State's waters (3nm from the coast) to the outer limits of Australia's Exclusive Economic Zone, some 200 nautical miles offshore (Figure 13a in Appendix 1). The 14 marine and coastal/shelf

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[2] The coastal zone includes Queensland's coastal waters, islands and land below 10m Australian Height Datum (or mid-tide level) or 5km from the coast (whichever is greater). This inland boundary is aligned with property boundaries. See, http://www.derm.qld.gov.au/environmental_management/coast_and_oceans/coastal_management/coastal_plan_maps.php

biogeographic regions identified for Queensland's marine biodiversity planning (DERM 2003) are drawn from the IMCRA 4.0 meso-scale bioregions (Figure 13b in Appendix 1).

None of the existing spatial mapping of marine bioregions and ecosystems discussed above satisfies the requirements of this assessment. Collectively, they do not comprehensively or consistently account for all coastal and marine habitat features and ecosystem processes that will necessarily respond to the expected change in the climatic and oceanic environment of Queensland. The provincial scale of bioregions in Australia's marine Exclusive Economic Zone (Commonwealth of Australia 2006), for example, were formulated from various ecological and physical characterisations and defined to reflect large-scale ocean biogeographic patterns based on the distribution of bottom-dwelling fish. As part of the process of compiling information for IMCRA v3.3, the finer meso-scale bioregions for continental shelf waters were identified by each State using regional biological and physical information and expert opinion. A consistent meso-scale marine bioregionalisation is currently not available for Queensland waters.

At a global scale other bioregionalisations have been generated and, most recently, the Marine Ecoregions of the World (MEOW) (Spalding *et al.* 2007). The MEOW ecoregions are the newest classification system covering the world's coastal areas and continental shelves. These ecoregions are based on an extensive review and synthesis of existing regional and national classification systems, as well as expert consultation and analyses. For Queensland, these marine bioregions (shown in Figure 7) were based largely on the Integrated Marine and Coastal Regionalisation of Australia (Commonwealth of Australia 2006). The ecoregion definition also considered the Great Barrier Reef bioregions (GBRMPA 2006; Kerrigan *et al.* 2010) and other relevant finer-scale species distribution, environments and habitat information. The MEOW ecoregion classification is intended to capture a regions' biophysical and biodiversity processes and services in significant, large, contiguous spatial units (Figure 7). These larger units contain a consistent level of spatial variation based on predictive information derived from climate and ocean circulation models.

The MEOW ecoregion boundaries also incorporate terrestrial processes by extending landwards to encompass catchments that are interconnected with the coastal zone; a feature that will be useful in subsequent assessment of potential adaptation responses that require land-sea coordination. The *Marine Ecoregions of the World* are also currently being used in a National assessment of marine biodiversity and climate change (e.g., as outlined in the Coastal and Estuarine National Adaptation Research Plan[3]). The MEOW classification is particularly relevant for this Queensland study of the possible coastal and marine ecological changes in response to climate change, enabling a synthesis of habitats, biodiversity, ecosystem processes and the human uses that depend on and affect these systems (Figure 7).

We modified the original MEOW ecoregions to be more inclusive and to represent a whole-of-system regionalisation for Queensland that recognises the interdependence between the coasts and the seas. In particular we subdivided the coastal Great Barrier Reef ecoregion into a northern and southern region and the Gulf of Carpentaria ecoregion into a northern and southern zone (see Table 1). We retain the landward portion of each MEOW ecoregion to encompass additional relevant environmental variation (e.g., rainfall, freshwater volume and sediment load, and catchment size). In modifying these ecoregion units, we constrained the coastal subdivision to coincide, to the extent possible, with the existing boundary limits of Queensland's state and regional coastal management plans (Environment Planning 2011). Each unit's name and number is shown in Table 1.

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[3] Coastal Ecosystems' Response to Climate Change Synthesis Project http://www.nccarf.edu.au/cerccs

For this synthesis, observed and expected environmental data, including data derived from global climate model projections, were compiled for each customised MEOW ecoregion unit (Section 2 below). Extraction of data within these units was possible using existing MATLAB® software[4] routines.

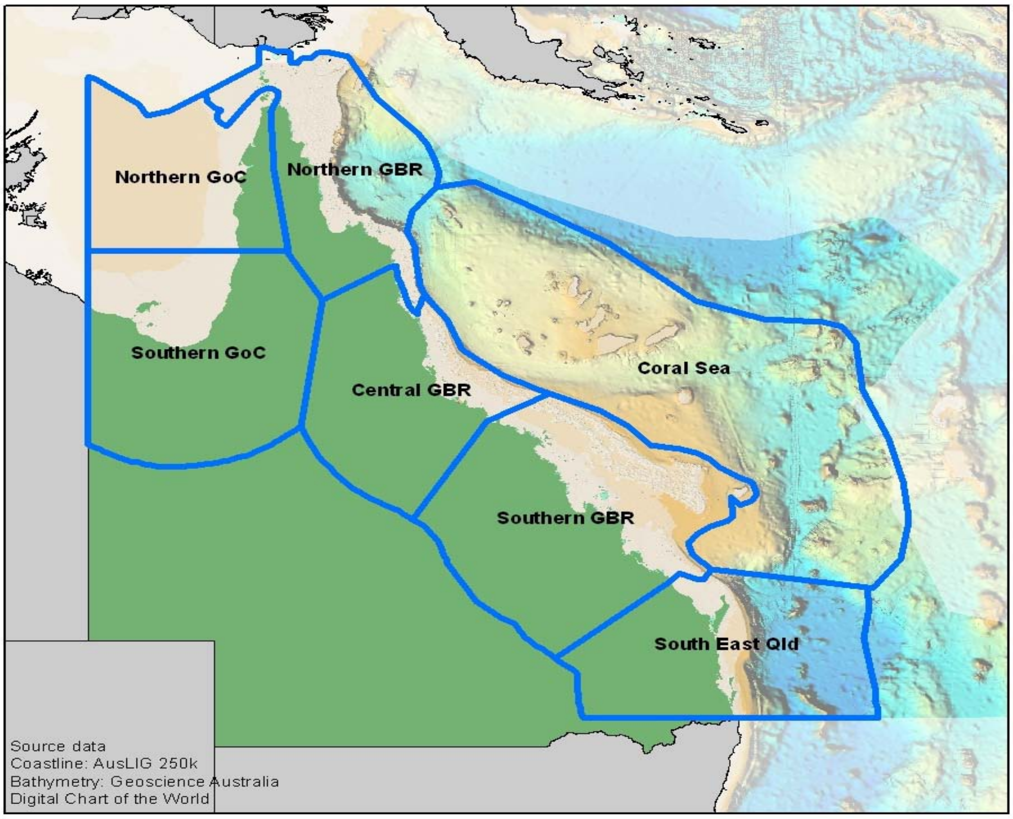

Figure 7: MEOW bioregions for waters adjacent to Queensland (modified from Spalding *et al.* 2007).

Table 1: Number, name and equivalence between the modified and original MEOW ecoregion and corresponding Queensland planning regions based on majority overlap.

Region Number (1)	Modified Region Name for this Synthesis	Original MEOW Ecoregion Name	Queensland Coastal Planning Region Names
0	Coral Sea	Coral Sea	Not considered
1	South East Qld	Tweed-Moreton	South East Qld and Wide Bay Burnett
2	Northern GBR	Torres Strait Northern Great Barrier Reef	Cape York - East(2)
3	Southern GBR	Central and Southern Great Barrier Reef	Central Queensland and Whitsunday Hinterland & MacKay
4	Southern Gulf of Carpentaria	Arnhem Coast to Gulf of Carpentaria	Gulf Region
5	Northern Gulf of Carpentaria	Arnhem Coast to Gulf of Carpentaria	Cape York - West
6	Central GBR	Central and Southern Great Barrier Reef	Townsville – Thuringowa and Far North Queensland

(1) Region numbers are cross-referenced in section 1.3 for the data extractions and analyses. (2) The single Cape York Coastal Planning region (Environment Planning 2011) was subdivided into west and east parts to correspond with the synthesis regions.

4 http://www.mathworks.com/products/matlab/

2. ENVIRONMENTAL CHANGE IN THE MARINE ECOREGIONS

2.1 Introduction

Warming of the oceans, rising sea-level, intensification of storm surges, changes in ocean chemistry and changes in ocean currents are anticipated to have widespread impacts on Australia's marine life, coastal and marine ecosystems and the social and economic systems they support (Hoegh-Guldberg & Bruno 2010; Poloczanska *et al.* 2007). The resulting positive and negative effects of these changes on inter-connected coastal and marine biological communities are only generally understood (Hobday *et al.* 2006a; Hobday *et al.* 2006b; Richardson *et al.* 2009a). However, sufficient knowledge has accrued along with scientific advances in the monitoring and measurement of changes in recent years, allowing a first general synthesis of the relatively dispersed and fragmented sources of information.

As the composition of greenhouse gasses in the atmosphere changes and global warming accelerates, the rate of change in the ocean is also increasing (Church 2010; Genda & Abe 2005; Goodwin *et al.* 2009; Hoegh-Guldberg & Bruno 2010; Holland *et al.* 1986; Sigman *et al.* 2010). Observations and modelled projections of change are in agreement and demonstrate that the rates of change are faster for most of the relevant environmental factors that shape the supporting habitats for biodiversity. For example, current observations of extreme ocean wind speeds and, to a lesser degree, extreme wave heights are increasing faster than the rate of increase in the mean ocean condition (Young *et al.* 2011a). Similarly, the more rapid than expected melting of the polar ice caps and ice sheets is tracking close to the worst-case scenario presented in the IPPC Fourth Assessment Report of 2007 (Bahr *et al.* 2009; Church *et al.* 2010; Radic & Hock 2011). Likewise, increased acidification (lower pH) of the oceans is occurring as the atmospheric carbon dioxide concentration rises. The rate of change in pH levels is orders of magnitude greater than even the fastest rates of oceanic environmental change seen during the ice age transitions of the last million years or more (Hoegh-Guldberg *et al.* 2007).

Globally, a strong increase in the number and proportion of the most intense tropical cyclones has occurred over the past 35 years (Hoyos *et al.* 2006; Webster *et al.* 2005). Increased cyclone activity in the Australian region has been associated with La Niña years, while below-normal activity has occurred during El Niño years (Kuleshov *et al.* 2008; Plummer *et al.* 1999). However, in the Australian region no significant trends in the total number of tropical cyclones or in the proportion of intense tropical cyclones has been found (Kuleshov *et al.* 2010). Severe tropical cyclones (TC) making land fall over eastern Australia has declined from 0.45 TCs per year in the early 1870s to about 0.17 TCs per year in recent times – a 62% decline (Callaghan & Power 2011). Fine resolution atmospheric models project a 30% decline in the number of tropical cyclones by the end of the 21st century for the Australian region (Lavender & Walsh 2011). Projections of tropical cyclones for the eastern Queensland coastline for 2055 and 2099 using 11 regional models and A2 emission scenario, also indicate a tendency for a reduction of tropical cyclone activity in the future and a 1° southwards shift in average latitude in activity (Fuentes & Abbs 2010).

These changes are already influencing the Queensland marine ecological realm in the following ways: (i) sea levels are rapidly rising, ocean storms have increased in intensity; (ii) ocean acidification is threatening the viability of calcifying biota in the Great Barrier Reef system; (iii) increasing sea surface temperatures are influencing marine resource distribution; and (iv) the East Australia Current is extending further south (further into NSW and Tasmania) and modifying the tropical and subtropical Queensland's southern extents of coastal environments and marine habitats and a translocated tropical biota is mixing with the local biota (Hobday *et al.* 2006a; Hobday *et al.* 2006b; Poloczanska *et al.* 2008; QCCCE 2011; Whitfield *et al.* 2010).

An overview of the scientific evidence and basis of climate change is given in Williams and Crimp (2012). That report includes background information on current observations of climate change globally and in Queensland, the process of developing emissions scenarios (Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000) and projections of climate change. More specific marine projections of climate change are presented in this background report.

2.2 Climate change variables of interest

A range of climate change variables of interest to Queensland's marine waters were summarised by the modified *Marine Ecoregions of the World* (MEOW – see Section 1.5) and, in cases where a finer scale of differentiation was significant, a finer scale of change within regions was also evaluated. A range of primary environmental drivers of ecological change were evaluated: sea surface temperature, which varies by location (latitudinal and longitudinal) by water depth and seasonally; ocean acidification which varies by location and water depth, tropical cyclone regimes in relation to return times, seasonal timing, frequency and intensity; oceanic environments including currents, sea level, wind speed and direction; and terrestrial runoff.

Several large scale oceanic and atmospheric processes are relevant to Queensland and may also be influenced by what seems to be longer-term climate cycles. These include: (i) El Niño Southern Oscillation, ENSO (e.g., Holbrook *et al.* 2009); (ii) the Pacific Decadal Oscillation, PDO (e.g., Power *et al.* 2006); (iii) the Interdecadal Pacific Oscillation, IPO (e.g., Heinrich *et al.* 2009); and (iv) the Indian Ocean Dipole IOD (e.g., Ummenhofer *et al.* 2009).

Some of the environmental changes that are projected to occur over the next century—such as sea-level changes and temperature rises—have also occurred repeatedly throughout the past two million years of the Quaternary geological period. Other environmental changes are new phenomena, such as the rapid rise in atmospheric CO_2 concentration and accompanying ocean acidification (Pandolfi & Greenstein 2007). The present period differs from the past in the rate of change and in the number of other anthropogenic stressors, such as coastal development and pollutants in terrestrial runoff that may limit the adaptive capacity and responses of natural systems.

For this report, projections of sea surface temperature and other climate change variables were derived from a range of Global Climate Models (GCM) using both the direct data outputs of GCM models and the smoothed, downscaled outputs provided through the OzClim tool (Ricketts & Page 2007). These were averaged to produce an ensemble mean value for each region and time period as described in Hobday (2010). The following emission scenarios of the IPCC's fourth assessment report were used (details are given in the IPCC Special Report on Emissions Scenarios, SRES: Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000; summarised in Williams and Crimp 2011): A1FI, which represented the highest emission scenario envisaged at the time but now represents the trajectory currently being tracked (Rahmstorf *et al.* 2007); A2, which is a moderately high emission scenario; and A1B which is a mid-range emission scenario. The timelines considered were an average of the years 1990–1999 (baseline period), 2030 (an average of the years 2025–2035), 2050 (an average of the years 2045–2055) and 2070 (an average of the years 2065–2075).

2.2.1 Sea surface temperature

The ocean has been warming at a similar rate to the global average around Australia but this warming is greatest in the ocean waters of eastern and southern Australia. Queensland's waters have an intermediate increase in sea surface temperature (Lough, 2009). The South Pacific gyre has increased in strength, driven by a southward intensification of extra-tropical wind. This has altered the complex current system of the southwest Pacific and changed the structure of water temperatures in the region (Bindoff *et al.* 2007; Lough 2009).

The surface waters of the upper tropical and west Pacific Ocean have warmed by 0.6°C to 1.0°C to a depth of 100 to 200m, depending on latitude, with cooling in some regions at greater depths. This has resulted in an increase in ocean stratification, which limits the vertical exchange of water and has major implications for the supply of nutrients into pelagic and benthic ecosystems and their biodiversity (Lough 2009).

Historical change in sea surface temperature for each of the modified MEOW ecoregions was analysed using the HadSSTv2 reconstructed dataset (Rayner *et al.* 2006). This dataset has a monthly temporal resolution and a spatial scale of one degree grids for the historical period from 1870 to 2004 (Figure 14 in Appendix 2). For all regions, sea surface warming has occurred consistently by decade since the 1950's, such that present ocean temperatures are approximately 0.5°C warmer than the historical average.

Future projections of ocean temperature based on the suite of global climate model outputs indicate ocean warming will continue into the next century, with absolute annual average temperatures reach 32°C in some regions under either projection (Figure 15 in Appendix 2). The projected change in each region shows significant increases towards the end of the present century (Figure 16 in Appendix 2). Warming is most intense under the A1FI scenario (Figure 15 and Figure 16 in Appendix 2).

Off Queensland's east coast, the East Australia Current will transport greater volumes of warm water southward. Model projections indicate that sea surface temperatures in this region will warm by approximately 2°C by 2063–2065, relative to the historical period (1870–2004). The level of confidence in the likelihood of these changes is medium-to-high (Ridgway & Hill 2009). This implies that the whole pelagic environment will shift southward, expanding with it the tropical components and species of northern Australia.

This massive shift not only has strong implications for biodiversity but has a direct effect on the current conservation management of these marine ecosystems. For example the fixed or planned conservation areas currently underway by the Commonwealth (Areas for Further Assessment in the East Marine Region[5]) are not being assessed as to whether these areas will be adequately representative given the likelihood of future changes (see Section 6). One approach that can inform future conservation planning is to consider the location of the present surface physical environment in an area, represented by sea surface temperature, by the years 2063–2065. This involves estimating the upper (5th percentile) and lower (95th percentile) sea surface temperature values from the present frequency distribution of sea surface temperatures found in the region and then mapping the distribution of temperatures within this range in the future (2063–2065).

[5] http://www.environment.gov.au/coasts/mbp/east/east-afas.html

Projected increases in sea surface temperatures are available from global climate models; however, the spatial resolution from these models is coarse (increases of 1 to 2°C). Dynamically downscaled projections using finer resolution climate models are now becoming available, albeit for a limited number of future scenarios and represent an opportunity to inform conservation planning at a regional scale. Hobday (2011) used daily sea surface temperature from the Bluelink[6] ocean model nested within the CSIRO Mk3.5 global climate model (Gordon *et al.* 2010), available for a single historical (1998–1999) and future period (2063–2065) at a spatial scale of 0.1 degree grids (approximately 12km^2). Only the medium A1B scenario has been used in the downscaled global climate model. This finer resolution data was previously used by Hartog *et al.* (2011) to project the future distribution of southern bluefin and yellowfin tuna and their pelagic habitats.

The location of the present sea surface temperature environment in the future years (2063–2065) is projected to be south for the Coral Sea region (Figure 8), however, some of the original environment is still retained in all seasons by the years 2063–2065.

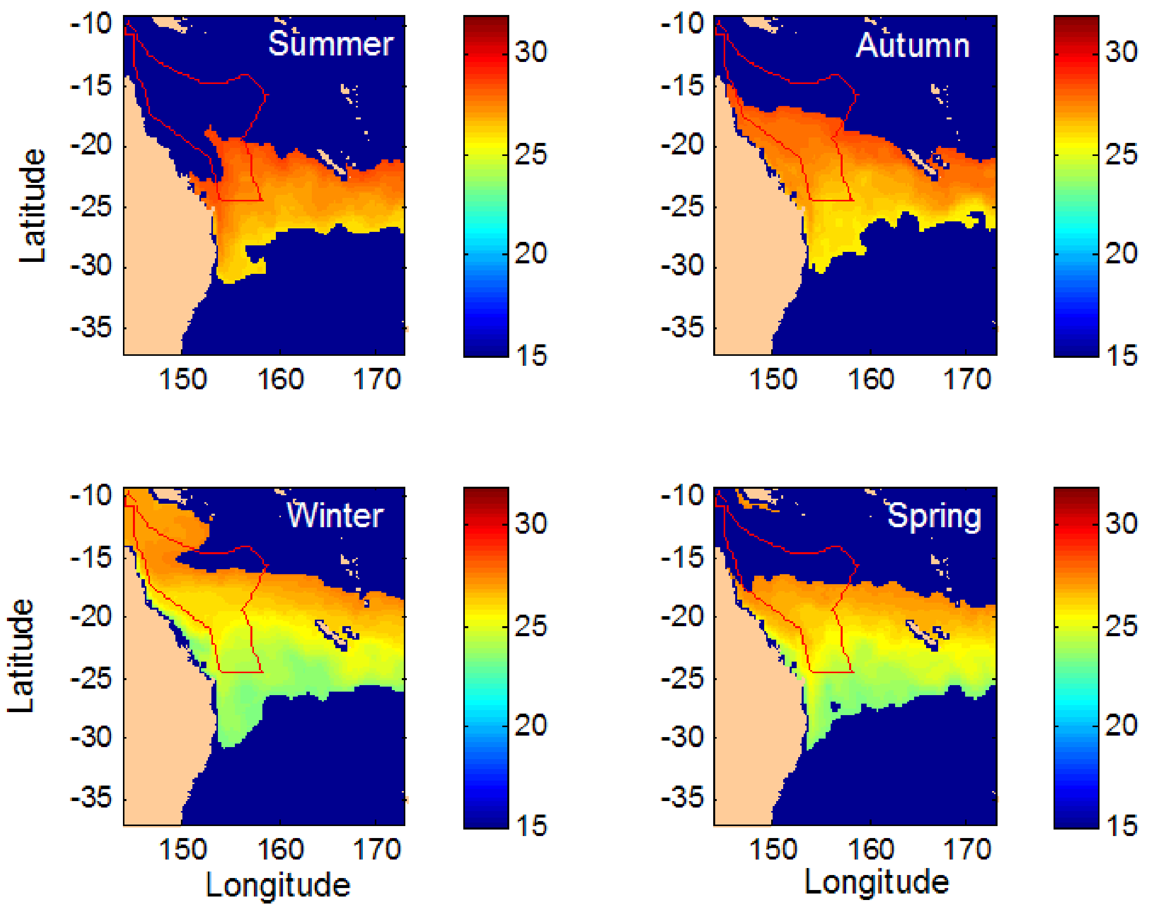

Figure 8: Projected future location of the present pelagic environment within the Coral Sea Conservation Zone (red line), a designated 'Area for Further Assessment'[7] as represented by sea surface temperature (colour bar), averaged for each season for the period 2063–2065 (Source: Hobday 2011).

[6] http://www.bom.gov.au/bluelink/

[7] Described in (Hobday 2011). Areas for Further Assessment (AFA) encompass representative examples of the range of biodiversity and ecosystems for developing marine protected area systems within a marine region.

2.2.2 Ocean Acidification

Ocean pH at a global scale has fallen 0.1 logarithmic units since the industrial revolution (~1850's). Global projections indicate that a further decline of 0.2-0.3 units can be expected by 2100 (e.g., Orr *et al.* 2005). This projection represents an environmental change in the concentration of dissolved hydronium ions of about 90-120% since the 1850s. Such pH levels in oceanic waters have not been encountered for millions of years and this rate of change is unprecedented (e.g., Luthi *et al.* 2008). Marine biota form three different calcium carbonate minerals: aragonite, calcite and magnesium calcite. Aragonite and calcite are naturally occurring polymorphs of calcium carbonate with differing crystal lattice structures and hence solubilities, aragonite being about 1.5 times more soluble than calcite at 25°C. Magnesium calcite is a variety of calcite with magnesium ions randomly substituted for the calcium ions in a disordered calcite lattice. At low mole fractions of magnesium (<4%) the solubility of this phase is lower than that of calcite, whereas at high mole fractions (>12%) the solubility is greater than that of aragonite. Red coralline algae (major 'cementing' taxa on tropical coral reefs), benthic foraminifera, bryozoans and echinoderms all lay down high magnesium calcite (Andersson *et al.* 2008). The aragonite saturation of warm tropical oceans is higher than that of polar oceans because carbon dioxide is more soluble in cold water (Hoegh-Guldberg *et al.* 2007). As a result, changes in ocean pH will initially occur in polar waters and progressively move with ocean mixing towards lower latitudes and the tropics (McNeil & Matear 2008).

In Queensland, the pH of surrounding oceans will decline, becoming more acidic with slight regional variation expected (Figure 17 and Figure 18 in Appendix 2). It is possible that spatial and temporal heterogeneity of the coast-ocean continuum may influence regional variation in pH. However, the complex role of factors such as benthic topography, the scale of spatial configuration in land, reef and island positions and temporal (daily and seasonal) variations in ocean currents is not clear and, therefore, regional prediction of ocean water pH variation is currently uncertain. Experiments at several field locations in the Great Barrier Reef region—for example, the Free Ocean Carbon Enrichment experiment on the reef crest at Heron Island (Marker *et al.* 2010)—aim to determine the principal drivers of this spatial variation.

Different biological taxa use different forms of calcium carbonate in their skeletal structures and so will have differing responses and vulnerabilities to the change in saturation state (Hoegh-Guldberg *et al.* 2007). Additionally, evidence of synergies among marine geochemical processes has been found. Seasonal carbon dynamics may potentially hasten ocean acidification and a 450-ppm atmospheric CO_2 has been proposed as a tipping point for calcifying biota in the southern ocean (McNeil & Matear 2008). These authors conclude that their results are not limited to the Southern Ocean and that '*natural seasonal amplification of anthropogenic oceanic acidification in all ocean basins and coral reef ecosystems will result in delaying or accelerating the onset of detrimental oceanic acidification conditions for a variety of calcifying marine organisms throughout the marine biosphere*' (McNeil & Matear 2008).

2.2.3 Sea level rise and derived coastal inundation

We conducted an appraisal of the likely impacts of future sea level rise on Queensland's coastal ecosystems. Our analysis is based on data generated by the Queensland government in support of the coastal plan (Environment Planning 2011). We used a recent estimate of coastal inundation risk, which was based on high resolution LiDAR data from the Coastal Hazards Mapping program[8]

[8] http://www.derm.qld.gov.au/environmental_management/coast_and_oceans/coastal_management/maps/index.html

(QCCCE 2011), to evaluate the expected coastal area potentially affected by 2100. Potential areas of inundation are based on a sea-level rise of 80 centimetres[9] (DERM 2011; QCCCE 2011). These areas represent the proportion of the coastal zone[10] that will be permanently influenced by the sea by 2100; that is, they are likely to become marine and/or intertidal ecosystems. The interim results of data from the ongoing work (QCCCE 2011) are presented as a simple illustration of the likely effects of sea level rise, without synergistic interaction with other factors and datasets, such as *Erosion Prone Areas* and *Storm Tide Inundation Areas*, which are further outputs of Queensland's Coastal Hazards Mapping program (Environment Planning 2011; QCCCE 2011).

The descriptive analysis presented here considers the entire Queensland coast with examples for that part of the coast where mapping was complete as at April 2011 (from Coolangatta in the southern border to Lucinda in the north, Figure 19 in Appendix 3). Detail maps are presented for two regions: Coolangatta to Double Island Point and Hervey Bay to Shoalwater Bay (Figure 20 in Appendix 3). The data and resulting maps for the coastal areas further north to Cairns and for remote coastal and island communities of Cape York Peninsula, the Gulf of Carpentaria and Torres Strait will be published later in 2011 (Queensland Climate Change Centre of Excellence - QCCCE, personal communication).

With sea level rise over the course of this century, most if not all coastal habitats (and human-dominated ecosystems) of Queensland will be affected to some extent. Despite the incomplete geographic coverage of detailed coastal mapping for Queensland, the current indicative sea level rise map shows widespread and highly variable coastal inundations (Figure 19 in Appendix 3). These disparate inundations are likely to be a reflection of local complexity, topography and geomorphic conditions that influence the local outcome of sea level rise (Figure 19 in Appendix 3). The coastal processes influencing these outcomes associated climate change interactions are described in detail by QCCCE (2011). Coastal lowlands and lagoons, salt marshes, wetlands and estuarine habitats will be most affected in the first instance. Prominent examples are those areas adjacent to population centres of the Gold Coast south of Brisbane (arrow 1, Figure 19 in Appendix 3) and Gladstone (arrow 2, Figure 19 in Appendix 3). In these highly heterogeneous regions, characterised by a diverse land-sea-river continuum, coastal inundation is expected to be more widespread and with significant inland penetration (Figure 20a, b in Appendix 3). Coastal urban areas and natural habitats will be locally affected, experiencing significant change in local conditions. The consequences of and variation in local inundation effects represents significant challenges for existing and planned future coastal adaptation and erosion mitigation strategies (Environment Planning 2011; QCCCE 2011; Queensland Government 2007). The likely outcome of the interplay between sea level rise inundation and changes in freshwater inputs and flows is uncertain, because scientific uncertainty about projected change in rainfall patterns is currently low. The significant consequences of these interactions demand scrutiny and detailed study, in particular for those areas close to urban centres and coastal conservation areas. These urgent issues are being addressed by government research and planning programs DERM (e.g., Improved Coastal Mapping Project[11], Coastal Hazards[12]).

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[9] http://www.derm.qld.gov.au/factsheets/pdf/environment/en28.pdf

[10] The coastal zone is where the policies of the Queensland Coastal Plan apply. It includes Queensland's coastal waters, islands and land below 10m Australian Height Datum (or mid-tide level) or 5km from the coast (whichever is greater). This inland boundary is aligned with property boundaries. The inundation maps are based on a high resolution coastal digital elevation model derived from remote sensing LiDAR (Light Detection And Ranging) technology (QCCCE 2011).

[11] http://www.longpaddock.qld.gov.au/coastalimpacts/improvedcoastalmapping.html

[12] http://www.derm.qld.gov.au/coastalplan/coastalhazards.html

2.2.4 Regional impacts of sea level rise

Although there is currently no detailed data available for the far north of Queensland[13] (Torres Strait, the offshore Islands and north of Lucinda), sea level rise impacts by 2100 are expected to be relatively large in the Gulf of Carpentaria because this region has the largest coastal zone (ca. 20,000km^2, Table 2) and includes a large and diverse network of estuaries and flood plain ecosystems. Similarly, low-lying islands off Queensland are expected to experience increasingly regular marine inundation and, in cases, complete submergence due to their vertical profile and extent. Increases in sea level attributed to climate change are expected to pose the greatest threat to several low-lying islands in central and northern Torres Strait (Green *et al.* 2009). There have already been significant flooding events of low-lying coastal areas in Torres Strait associated with king tides, though there is no evidence of significant biodiversity impacts at this stage (Green *et al.* 2010).

Preliminary estimates of potential inundation of the coastal zone for Coastal Planning Regions indicate that between 10 to 25% of the coastal zone could be inundated by an 0.8m sea level rise by 2100 (Table 2). Of the mapped regions, South East Queensland exhibits the largest expected coastal zone inundated, with 24.3% (Table 2). This analysis, albeit preliminary, illustrates the types of issues and data resolutions required to effectively anticipate the inundation consequences of sea level rise on Queensland's coastal ecosystems. A detailed analysis of the likely change in coastal zone ecosystems is warranted. This could be done by combining coastal zone data with existing vegetation and coastal wetland mapping, coastal substrate mapping and an understanding of the biophysical processes likely to influence ecosystem states and transformations.

As Queensland's coastal hazards data is completed, tested and used, refined analyses will be needed to assess local-scale impacts; separately for urban, protected areas and ecosystems; and design likely adaptation and mitigation strategies and policies. Note that the use and analysis of this information is new and will require some ground-truthing, calibration and validation. However, for our purposes, it provides a reasonable indication of likely sea level rise inundation areas and can, in combination with the other coastal hazard synergies, constitute the basis for spatially-explicit risk and vulnerability assessments for the coastal ecosystem of Queensland under climate and ocean change.

Table 2: Preliminary calculation of the total area of land surface inundation (in km^2) for Queensland's Coastal Plan Areas within the currently designated coastal zone (land only), the expected sea level rise inundation hazard area (land only) and the extent and percentage (%) of the expected Inundations in the Coastal zone. Not available (n.a.) indicates where sea level rise inundation hazard maps are in progress at the time of this report[13].

Coastal region name	Total region	Coastal zone	Expected Inundation	Inundation %
Gulf Region	178,558	19,923	n.a.	n.a.
Cape York	127,074	15,613	n.a.	n.a.
Far North Queensland	73,915	3,768	n.a.	n.a.
Townsville - Thuringowa	80,453	3,791	686	18.1
Mackay & Whitsunday	91,187	5,314	927	17.5
Central Queensland	119,540	9,034	1,425	15.8
South East Queensland	23,700	3,298	800	24.3
Wide Bay-Burnett	49,893	5,744	590	10.3

[13] The data and resulting maps for the coastal areas further north to Cairns and for remote coastal and island communities of Cape York Peninsula, the Gulf of Carpentaria and Torres Strait will be published later in 2011 (QCCE, personal communication).

2.2.5 Storms and derived coastal inundation

In addition to the direct physical damage to coastal and reef ecosystems caused by storms, severe tropical lows and cyclones with landward incursions and intense rain also result in extended periods of terrestrial run-off and sediment re-suspension that temporarily change the turbidity and salinity environment of coastal waters affecting local marine ecosystems (Furnas 2003). For example, watershed discharges have been documented to reach reefs of the Great Barrier Reef over 100km from shore, affecting the key environmental parameters of water and substratum quality and hence, biological parameters of coral reproduction and recruitment (Richmond *et al.* 2007; Wolanski *et al.* 2004). Retrospective analysis of freshwater flood events from massive coral skeletons on the nearshore Great Barrier Reef provides insight into north east Queensland rainfall variability (Lough 2011). An extended drier period reconstructed from ~1760s to 1850s is associated with lower interannual rainfall variability. Since the late 19th century average rainfall and its variability have significantly increased with wet and dry extremes becoming more frequent than in earlier centuries. This suggests that a warming global climate maybe associated with more variable tropical Queensland rainfall. Warmer seas are likely to result in more intense storms (Emanuel 2005; IPCC 2007), with the prospect that some coral reefs may receive increasing episodes of damage from destructive storms that arrive more frequently (Hoegh-Guldberg 2011).

Coastal development at Surfers Paradise: storm surge on with high-rise development in the background and narrow coastal ecosystem buffers in the foreground (credit: Bruce Miller, CSIRO Marine and Atmospheric Research, science image AS1149).

3. ECOLOGICAL CHANGE

3.1 Introduction

In this section we consider the impacts of climate-driven environmental stressors on individual plants and animals. We then extrapolate these to changes in species distributions, ecological community structure and composition and ecosystem function.

Climate change driven environmental stressors—temperature, ocean acidification, sea level rise and storm intensity—will affect marine species in different ways. The future environmental envelopes of individual species, reflected in their geographic distribution ranges, may fall outside their current and historical extents of the past several millions of years, principally due to changes in ocean chemistry caused by ocean absorption of CO_2. Nationally and for Queensland, the generic and known ecological changes, observed or anticipated as a result of climate and ocean changes, will include at minimum: (a) changes and variations on phenology of marine biota; (b) changes in the distribution and abundance of species; (c) changes in the extent and variation of ecological habitats; (d) varying effects on the physiology, life history events and environmental tolerances of individual species; (e) changes in species interactions leading to different community composition, structure and function; and (f) changes in whole-of-ecosystem processes and functions.

As with terrestrial biota, one of the most conspicuous signs of climate change is the change in seasonal timing of biological events (phenology). So far for Queensland coastal-marine biota we have found that phenological changes are expected for mangroves, macroalgae, plankton and pelagic fishes (Hobday *et al.* 2009; Lovelock *et al.* 2009; Wernberg *et al.* 2009). More importantly, phenological changes have magnifying effects when the changes are altering the temporal mismatch between key trophic interactions (phenological asynchrony), that is, where the consumer's growth is not in synchrony with the producer's production (Edwards & Richardson 2004). This has been shown to be a broad scale signal (terrestrial, aquatic, marine) and that changes in the bottom of the food web are already cascading upwards, particularly with a slow response from the secondary consumers (Thackeray *et al.* 2010).

Another important feature of marine ecosystems is the connectedness of species and populations through the trophic food web, however, little is known about the change in connectedness of marine systems under climate change: a topic of current research (Griffiths *et al.* 2010). The fundamental role of phytoplankton in marine system productivity, especially offshore, is also deserving of further attention. Inshore, marine plants, such as seagrass and algae, also play an important role in productivity and habitat formation roles.

On the whole, there is scant scientific information on the responses of species and particularly habitats and ecosystems to climate change. Existing knowledge is also usually focused on one aspect rather than the synergistic effects of multiple stresses. Some of the most developed science is in the context of reef-building scleractinian (stony) corals, driven partly by the stark reality of coral bleaching and the apparent links with climate change (e.g., Hoegh-Guldberg *et al.* 2007).

3.2 Changes in individual biology

Individual marine species will react differently to climate change stressors through changes in their surroundings and environmental conditions. Climate change therefore influences: photosynthetic rates in phytoplankton and marine plants; growth rates, metabolic rates and natural mortality in plants and animals; phenology; and behaviour, morphology and physiology (Brown & Cossins 2011; Donelson *et al.* 2011; Hoegh-Guldberg & Bruno 2010).

3.2.1 Water temperature

Projected changes in water temperature will affect marine species in several ways. Generally, there is a positive relationship between growth and temperature—the warmer the water the faster the growth—up to a point when growth decreases as temperature increases and become more and more detrimental; this is known as the pejus effect (e.g., Neuheimer *et al.* 2011). Higher water temperatures often lead to lower dissolved oxygen levels which is an additional stressor for a wide range of species (Cheung *et al.* 2009; Pörtner 2008; Pörtner & Knust 2007) .

Species will generally have a preferred temperature envelope or range in which they operate best (e.g., Pörtner & Knust 2007). However, operating temperature is one environmental parameter for which considerable adaptive potential can be expected, at both at the phenotypic level (acclimatisation and developed resistance) and at the genotypic level (evolutionary modification through natural selection). When optimum living temperatures are exceeded, the performance of individuals may be compromised in various ways, for example through changes in growth, survival and/or reproductive success. Other temperature-related changes may have an even greater impact on marine populations by affecting life history dynamics, as exemplified in the relationship between the sex of marine reptiles (e.g., crocodile and marine turtle hatchlings) and egg incubation temperature (Fuentes *et al.* 2009).

Primary producer organisms in the marine environment, such as phytoplankton, seagrass and benthic algae, all generally increase their growth rates in response to increasing water temperature but shallow-water intertidal seagrass and algae may be damaged by higher temperatures (Hallegraeff *et al.* 2009; Waycott *et al.* 2007). The temperature thresholds for most marine flora are poorly understood and declines in productivity at higher temperatures can be expected.

Most marine animals are ectotherms (dependent on environmental heat) and temperature changes of a few degrees Celsius can influence their physiological condition, developmental rate, growth rate, reproductive performance and behaviour. Consequently, the projected 1-2°C increase in sea surface temperatures by 2030 and 2-4°C increase by 2100 are expected to have significant consequences for marine fishes and reptiles, particularly in the far north of Queensland and for those species that have restricted dispersal capabilities (Munday *et al.* 2009a).

Marine mammals, such as dugongs, dolphins and whales, are air-breathing endotherms (generate heat to maintain body temperature) that are generally long-lived and slow breeding (Lawler *et al.* 2007). The consequences of climate change for marine mammals is very uncertain due to a lack of knowledge of their behaviour and biology, however, there is little evidence that dugongs or whales would be limited by warm water (Lawler *et al.* 2007). The effect on whales may be greatest in their Antarctic feeding grounds where changes in prey abundance are postulated (e.g., Tynan & Russell

2008), whereas they do not usually feed while in Queensland waters. Warmer waters associated with climate change may enhance calf survival.

Rising sea-surface temperature has been shown to alter the timing of seabird breeding. In addition food web changes impact on adult condition and breeding success because life histories of tropical species are strongly linked to food availability. Any long-term negative change in food supply can affect breeding success and may see local populations decline, collapse or migrate southward if suitable habitat exists. All these expected ecological changes have a low-to-medium level of confidence (Chambers *et al.* 2009).

Corals have an iconic and almost unique response to rising sea water temperatures, due to changes in the function and chemistry of the corals' symbiotic algae (zooxanthellae) and the strong reaction to those changes by their host coral. At higher than normal sea water temperatures, the zooxanthellae become toxic to the coral by producing free radical oxygen species—highly chemically-reactive molecules that contain oxygen—and thereafter the zooxanthellae are rapidly expelled by the corals. While the reactive oxygen does do some direct harm to the corals through a variety of chemical pathways (Lesser 2011), the major problem is that once the corals expel their zooxanthellae they also lose access to the photosynthetic products of zooxanthellae (mostly organic sugars and organic acids) and the corals begin to starve. Corals can repopulate with zooxanthellae if water temperatures decline to safe levels. However, if this does not occur within several weeks, the corals die.

Some corals bleach more readily than others. Branching and plate type corals are the most susceptible and massive corals the least likely to bleach (Marshall & Baird 2000). Variation in response occurs within species (Ulstrup *et al.* 2006) and spatially, due to temperature acclimatisation and genetic variation among both the zooxanthellae and host coral (Brown & Cossins 2011). Other factors that affect the levels of bleaching include variation in physiology of different species of coral, depth of coral occurrence and the incidence of ultraviolet light.

Reef ecosystems of the Great Barrier Reef have been affected by heat-related coral bleaching six times over the past 25 years (GBRMPA 2009). The most severe episode to date was in 2002 when 60% of the reefs within the Great Barrier Reef Marine Park were affected resulting in 5-10% of corals dying (Berkelmans *et al.* 2004; Garnaut 2008; Oxford Economics 2009). Fortunately, the Great Barrier Reef has not yet suffered the extensive level of bleaching that has been observed in other coral reef domains, such as the reefs of the Indian Ocean (Ahamada *et al.* 2008). This may be due to a number of factors, including the intrusion of the cooler South Equatorial Current which upwells onto the coral reef habitats, ameliorating the worst effects of higher surface water temperatures (e.g., Pratchett *et al.* 2008; Pratchett *et al.* 2009).

The currently accepted threshold for bleaching is when sea surface temperatures are more than 1°C higher than normal summer maximum temperatures. The corresponding Degree-Heating Weeks (DHW)— which is the sum number of degrees weekly water temperatures are above the bleaching threshold for a particular location—has been a good indicator of bleaching risk globally with global alerts provided through the NOAA Coral Reef Watch[14] (CRW 2008). Bleaching-related coral mortality generally occurs at about 8 DHW (Hoegh-Guldberg 2011). Sea surface temperature projections have shown that DHW values of 8 or more will occur on an annual basis within the next 30–50 years under 'business as usual' climate projections, as ocean temperatures in tropical and

[14] http://coralreefwatch-satops.noaa.gov/SBA.html

temperate regions rise by 2°C or more above preindustrial levels (Done *et al.* 2003; Donner *et al.* 2005; Hoegh-Guldberg 2011).

3.2.2 Ocean acidification

Ocean acidification will affect all calcifying algae and animals. The deposition of calcium carbonate ($CaCO_3$) by calcifying biota, such as corals, molluscs, crustaceans, foraminifera and calcareous algae, is essentially a biochemical process and this process requires more energy exerted by biota as ocean water pH is lowered. The ocean alters the proportions of dissolved carbon dioxide from carbonate and bicarbonate ions of which carbonate is a crucial element for shell-making organisms (Howard *et al.* 2009). Physiological processes are sensitive to pH itself but the cascade of consequences arising from these ocean water chemistry changes are not well understood. Observations have already detected changes in calcification in Southern Ocean zooplankton (Moy *et al.* 2009) and in Great Barrier Reef corals (Cooper *et al.* 2008; De'ath *et al.* 2009), indicating that acidification has already having a detectable effect on biological processes (Howard *et al.* 2009).

Acidification will affect calcification rates of calcareous zooplankton (foraminifera) (Richardson *et al.* 2009b). Shell weight of Southern Ocean forams has already declined by 30-35% since pre-industrial times (Moy *et al.* 2009) and continuing dramatic declines may survival and therefore population viability. Coralline algae (Anthony *et al.* 2008), bryozoans (Smith 2009) and other benthic calcifiers (McClintock *et al.* 2009) will similarly exhibit reduced calcification and/or increased dissolution of existing skeletal structures (Wernberg *et al.* 2009).

Acidification will also affect particular life history stages of other fauna and flora. Reduced fertilisation success has been documented in some marine invertebrates, such as the Sydney rock oyster (Parker *et al.* 2009), and impaired olfactory-based navigation has been observed among reef fishes (Munday *et al.* 2008; Munday *et al.* 2009b). Furthermore, squid, annelid worms and bivalve molluscs have been reported to show metabolic depression as pH of surrounding waters decreases (Pörtner 2008). Many of these impacts are little understood or unknown (Howard *et al.* 2009).

There is presently no information with which to assess the sensitivity of marine mammals to the expected pH decrease, however, there is unlikely to be a direct effect of ocean acidification (Lawler *et al.* 2007). Habitat and trophic impacts, such as the loss of seagrass beds for dugong and krill for whales, are likely to occur but outcomes are difficult to predict with certainty.

Ocean acidification will impact on corals, making it more difficult for them to build skeletons. A number of studies have shown that a doubling of pre-industrial atmospheric carbon dioxide concentrations will result in decreases of up to 40% in the calcification and growth of corals and other reef calcifiers (Erez *et al.* 2011; Hoegh-Guldberg 2011). Under an A2 emissions scenario, aragonite (the more soluble of the two natural forms of crystalline calcium carbonate) saturation levels in the tropical west Pacific Ocean are expected to fall below 3.25 by 2035–2040. This change will jeopardise the growth of species such as reef-building corals and some calcifying plankton (Erez *et al.* 2011; Hoegh-Guldberg 2011; Veron 2008; Veron 2011). Severe consequences for coral reefs are likely if the aragonite saturation level decreases to 2.4 as it is expected to do in 2100 under A2 (Hofmann *et al.* 2010; Howard *et al.* 2009). Corals are already exhibiting decreased calcification and growth rates that correspond with reductions in seawater pH (Richmond & Wolanski 2011), with coral growth on the Great Barrier Reef already showing reduced calcification rates over the past decade (De'ath *et al.* 2009). There is some evidence that corals will survive low, or even no calcification, reducing extinction risk, however their function as a reef building organism will be severely diminished (Hoegh-Guldberg *et al.* 2007).

Aragonite saturation state declines with water depth, meaning that benthic calcifiers, such as deep-water corals, coralline algae and other benthic calcifiers, will also show reduced calcification as ocean acidification causes the aragonite saturation horizon to become more shallow (Howard *et al.* 2009). The aragonite saturation state is also correlated with ocean temperature, meaning that southern calcifiers will suffer greater degrees of decalcification than tropical species (Hoegh-Guldberg *et al.* 2007). A simplified summary of the experimental response of various marine calcifiers in relation to the expected changes in average ocean surface pH through time was developed by Turley *et al.* (2010) for four emission scenarios (Figure 9). Most responses to increased pH are negative to the biological fitness of the taxa (Figure 9). The deep water calcifiers will start being impacted by around 2025, exhibiting reduced calcification, while the brittlestars will start showing endoskeletal muscle wastage at the higher pH and emissions by 2100 (Schiermeier 2011).

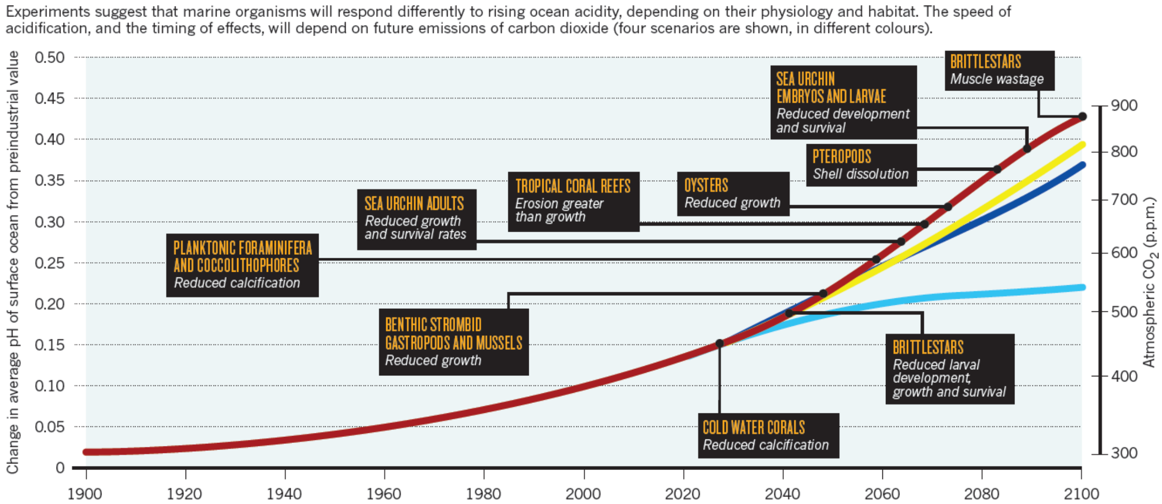

Figure 9: A simplified summary of the experimental response of various marine calcifiers taxa in relation to the expected changes in average ocean surface pH through time from for four emission scenarios (colour lines).

"Future Shocks" figure as presented in Schiermeier (2011) and as redrawn and reinterpreted from Turley *et al.* (2010). Projections for atmospheric CO_2 and surface global mean pH(SWS) difference from pre-industrial to 2100 for IPCC 2007 Emission scenarios A1F1 (red line), A2 (yellow line), ISP92a (dark blue line) and B1 (light blue line) (Nakicenovic & Swart 2000). The points on the pH-CO_2 curves are the years at which the first localized seasonal occurrence of aragonite undersaturation have been projected to occur (Schiermeier 2011; Turley *et al.* 2010).

The impacts of ocean acidification will severely affect carbonate-based biota, in particular coral reefs, being expected to be fully affected by mid century and a recent review states that these could be reduced to ecologically collapsed carbonate platforms by 2100 (Veron 2011). Thus, biodiversity losses for the Queensland reefs and the Great Barrier Reef are likely to be greater since acidification will interact with other impacts, such as reduced water quality, fishing and coral bleaching (Anthony & Marshall 2009), and as a consequence will lose its structural habitat function with resulting lower diversity and widespread metazoan extinctions (Veron 2011). All these predictions are considered to be of medium-to-high confidence (Howard *et al.* 2009).

Despite the bleak outlook, in particular for corals, there is increasing emerging evidence for variability in the coral calcification response to acidification, Pandolfi *et al.* (2011) propose an alternative view proposing that "…*geographical variation in bleaching susceptibility and recovery, responses to past* *climate change, and potential rates of adaptation to rapid warming, supports an alternative scenario in which reef degradation occurs with greater temporal and spatial heterogeneity than current projections suggest*". They conclude that to achieve a better level of confidence in projections of likely ecological responses an understanding is needed of past responses of corals to interacting factors such as acidification, temperature and nutrients. Insights into the biological and evolutionary costs and constraints of coral acclimation and adaptation to climate and ocean changes are also needed (Pandolfi *et al.* 2011).

3.2.3 Storms

Stronger and more frequent storms will affect shallow marine species through direct physical damage and alteration or destruction of their benthic habitats. Larger and extended periods of terrestrial run-off and sediment re-suspension in catchment discharges will also affect species through increased turbidity and decreased salinity of coastal waters (Furnas 2003). These water quality changes and alterations to substratum quality adversely affect coral reproduction and recruitment (Richmond *et al.* 2007; Wolanski *et al.* 2004). Recently, category 5 tropical cyclone Hamish (7 March 2009) severely affected a large proportion of the Great Barrier Reef and coral reef communities, including serious impacts on reef fish that dominate the catch of the local finfish fishery (e.g., Haapkylä *et al.* 2010).

Marine mammals may be vulnerable to severe tropical storms, floods and cyclones through direct mortality caused by physical injury including drowning or from the effects of these widespread disturbances on their normal food sources (Lawler *et al.* 2007).

3.2.4 Sea level rise

Much of the detrimental effects of sea level rise will occur in coastal ecosystems, such as tidal and intertidal wetlands and seagrass beds. Sea level rise will contribute to coastal erosion and inundation of low-lying coastal regions (Church *et al.* 2009). For those coastal ecosystems affected by sea level rise (up to 25% of the coastal zone), there will be a complete transformation; that is, intertidal habitats will become fully subtidal with colonisation by biota from adjacent shallow waters. The more elevated but juxtaposed terrestrial and tidal wetland habitats (e.g., beaches and dune systems, salt flats, salt marshes and mangroves) will be reshaped and effectively migrate inland, where coastal processes are unimpeded (Lovelock *et al.* 2009).

Mangrove forests and other intertidal wetlands on the coast may adapt to rising sea level and remain stable if the rate of vertical accretion of the soil surface of the wetland equals or exceeds the rate of sea level rise. Current elevation of mangroves and salt marshes, in southeast Queensland in particular, are keeping up with local rates of sea level rise. Accretion rates are variable but can be as high as 3.4 mm/yr at Cape Ferguson (BOM 2010). In Moreton Bay, sandy areas in the eastern part of the bay have the highest surface elevation gains in both mangrove and salt marsh (5.9 mm/yr and 1.9 mm/yr) while in the muddier western parts of the bay accretion rates are lower (1.4 mm/yr and -0.3 mm/yr in mangrove and salt marsh respectively) (Lovelock *et al.* 2010; Lovelock *et al.* 2009). With sea level rise, salt marsh and mangroves may invade freshwater ecosystems. Built structures on the landward edge of salt marshes will increase the impact of sea level rise on salt marshes because such structures will prevent landward movement of salt marshes and result in them being "squeezed" between mangroves and the built environment. Salt marshes may retain their current land coverage where losses of seaward mangroves are low and if barriers to landward migration (topographic or built structures) are minimal (QCCCE 2011). On the other hand, expansion in mangrove communities will be associated with retraction of coastal sedge, grassland and woodland communities. There may be conservation gains for mangrove-dependent species, like the false water rat, but these gains will be tempered by other threats (diseases, pollution, and feral predation) and urban development (QCCCE 2011).

Mangroves and coastal wetlands have an important role in protecting coasts from storm and tsunami damage, storm and cyclone-related tidal surges. Rates of erosion of mangrove fringes, due to the impacts of storms and waves, are not known for southeast Queensland but rates in other settings are known to be 2-3m per year. For tidal wetland ecosystems projected rates of change are expected with a medium level of confidence (Lovelock *et al.* 2010; Lovelock *et al.* 2009). The adaptive capacity of mangrove wetlands may be increased by high rainfall because it increases sediment inputs and enhances plant growth rates. If rainfall declines, the productivity, diversity and area of mangrove wetlands will decline. This could possibly result in increases in samphire and salt flats (Lovelock *et al.* 2010; Lovelock *et al.* 2009).

Sea-level rise on its own is unlikely to affect offshore benthic organisms in deeper waters, which exist in relatively stable situations (IPCC 2007; Rahmstorf *et al.* 2007). However, likely changes in the hydrodynamics of shallow reef complexes will have flow-on effects for biophysical processes and the spatial distribution of associated habitat niches that are defined by water depth and flows.

Mangrove canopy and exposed roots at Oyster Point, Hinchinbrook, Far North Queensland, Australia (credit: Alex Thomas, CSIRO science image AT1511).

3.2.5 Upwelling

Upwelling onto the continental shelf and in pelagic systems is an important driver of shelf and pelagic ecological communities, particularly on the central Great Barrier Reef (Berkelmans *et al.* 2010). The effects of climate-related environmental changes include changes in meso-scale currents (the East Australia Current is predicted to strengthen) and changes in local wind regimes (Ridgway & Hill 2009). Most climate models are presently too coarse to resolve these hydrodynamic processes, so projections are not considered useful at this time.

3.2.6 Interactions between stressors

The combination of climate change driven environmental stressors on plants and animals will have cumulative and synergistic effects. For example, the combined negative effect of rising water temperature and ocean acidification on corals (Hoegh-Guldberg *et al.* 2007), in which acidification predisposes some species of corals to bleaching (Anthony *et al.* 2008). In other cases multiple stressors will have moderating effects in which the outcome depends on the strength of opposing influences in, often, complex ways. For example, the positive influence of temperature, CO_2 concentration and acidification on seagrasses productivity will be countered by sea level rise and increased storm activity. There is expected to be a compositional shift in seagrass species favouring heat-tolerant taxa and range expansion upshore and southward. Despite the potential creation of extensive new areas of suitable habitat for seagrass beds, these ecosystems may decline due to the interacting effects of increasing water depth, competition from algae and sedimentation in terrestrial runoff discharged through estuaries as a result of unsustainable land use practices. The prediction for seagrass, considering all these factors, is a general decline (Connolly 2009; Lovelock *et al.* 2009).

Complex ecosystem, habitat and trophic impacts will determine the indirect effects of climate change on marine biodiversity. For example, the direct effects of climate change on dugong may be low (Lawler *et al.* 2007) but changes in the composition of preferred seagrass species will have a large impact on dugong populations. This effect could vary from enhanced meadow formation through temperature rise and sea level increase (Waycott *et al.* 2007) to seagrass loss due to coastal flooding.

3.3 Changes in abundances

The types of changes that will occur to marine species will drive a cascade of changes in the abundance and distribution of populations. Generally, there will be an increase in the abundance of thermally tolerant species and an general poleward shift in species distributions (Poloczanska *et al.* 2007). Global analyses of the velocity of recent climate change (warming over 50 years from 1960 to 2009) indicates that the shift in marine species' distribution is likely to occur at similar rates to terrestrial systems despite slower ocean warming (Burrows *et al.* 2011). Burrows *et al.* (2011) also observed that local shifts in climatic environments often deviate from the expected trend of poleward expansion and earlier spring events (see figures for Australia derived from that global analysis presented in Williams & Crimp 2012). Species that can move will move to areas with suitable conditions similar to their original habitat, although in the marine environment it is likely that novel habitats will be pervasive when all environmental changes are taken into consideration (i.e., sea surface temperature, acidity – pH, salinity and energetics). For example, ocean pH will be at levels not seen for at least several million years (Pearson & Palmer 2000).

In general, however, marine species will follow the thermal environmental envelope of preference for optimal growth, lowest mortality and highest reproductive potential. Pelagic species, which are naturally migratory, will have an advantage over benthic species which cannot move great distances except in larval stages. Benthic habitats may become unsuitable for some species that rely on a particular environmental envelope or a set of conditions that are likely to change with global warming and ocean acidification. For example, as water temperatures increase, corals may be able to settle and grow in more southerly regions that reflect their preferred temperature envelopes; however, the limestone substrate they require for settlement is not widely available south of the Great Barrier Reef (e.g., Heyward & Negri 2010; Veron 2008).

Some populations will have the capacity to shift. At least 90 species of fishes from the northern half of the Great Barrier Reef do not currently occur, or are relatively uncommon, in the southern regions of the Great Barrier Reef, while at least 30 species of fish are restricted to the southern part of the reef system (Munday *et al.* 2007). Northern species may be able to move south but, for these southern species, compression into smaller ranges and increased competition from vagrants may increase the risk of declining population abundance and increase the potential of local extinction. Monitoring of population abundances of species likely to be geographically limited at the southern part of their range will provide an early warning of postulated trends toward extinction.

Warmer ocean temperatures will cause distributional shifts in some tropical fishes, increasing the geographic ranges of some species and decreasing the ranges of others, including some commercially important species (Munday *et al.* 2009a). Wilson *et al.* (2006) explored the data from 17 independent studies from the previous decade finding that 62% of fish species on coral-dominated reefs declined in abundance within three years of disturbances that resulted in >10% decline in coral cover. Inspection of the types of fish that disappeared as corals decreased in abundance revealed species that either eat coral directly or require live coral as a settlement queue are among the first to be lost from the system (Hoegh-Guldberg 2011).

There is still some uncertainty about the impacts of climate change on ecological community composition. While there are indications that fish diversity may fall by up to 50% on climate affected coral reefs (Hoegh-Guldberg & Hoegh-Guldberg 2004), other studies find little change in diversity or abundance in the short term (Bellwood *et al.* 2006). Some of these studies also indicate that there may be replacement of some species types by others (e.g., herbivorous fish) (Bellwood *et al.* 2006; Johnson & Marshall 2007), suggesting that functional redundancy is supporting a resilient system. However, most analyses that have examined how coral populations are likely to respond to climate change suggest that the abundance of corals on reefs will decrease sharply as mortality increases and growth slows (Hoegh-Guldberg 2011).

It is clear that tropical algal distributions will expand poleward, resulting in shifts in community composition at any single location due to differential responses by algal species to the individual and interacting drivers of environmental change associated with climate change (Fong & Paul 2011).

Changes in the mean geographic position of the East Australian Current will be a key driver for range extension among small pelagic fishes in the Coral Sea (Hobday *et al.* 2009). The observed outcomes of climate change are restricted to changes in local abundance and distribution and particularly southward range extensions (Hobday 2010).

While there are indications that fish diversity may fall by up to 50% (Hoegh-Guldberg & Hoegh-Guldberg 2004), other studies find little change in diversity or abundance in the short term (Bellwood *et al.* 2006). Some of these studies also indicate that there may be replacement of some species types by others (e.g., herbivorous fish) which then raises the question of whether such replacements (if any) would be marketable to consumers (Bellwood *et al.* 2006; Johnson & Marshall 2007).

3.4 Extinction risk

Marine species most vulnerable to extinction in the Queensland region will include species that: have a narrow spatial or habitat range; have pronounced or abrupt ontogenetic changes closely tied to environmental cues; have low dispersal capabilities; are slow growing or have low regeneration capabilities; or have a specific sensitivity to a climate change parameter (e.g., coral bleaching and sea surface temperature thresholds). However, at this time, the implications of climate change for the vast majority of coral reef organisms is poorly understood (Przeslawski *et al.* 2008).

Known extinctions of marine fish are a small fraction of the extant species (Field *et al.* 2009) due to the relatively limited anthropogenic impacts on the marine environment (compared to terrestrial environments) and because knowledge of marine fauna and flora is limited (relative to terrestrial). Species that have been identified as vulnerable to extinction from climate change (often exacerbated by synergistic impacts, such as fishing pressure or coastal sediment and pollution runoff) include large coastal chondricthians (sharks, rays and chimaeras) and especially those species with restricted ranges and/or specific habitat requirements (Field *et al.* 2009).

As discussed in Section 3.2, there is some evidence that corals will survive at low, or even no, calcification rates and this will reduce the extinction risk for corals from this specific threat (Fine & Tchernov 2007). However, their engineering function as a reef-building organism will be severely diminished (Hoegh-Guldberg *et al.* 2007).

As discussed in Section 3.3, at least 30 species of fish are restricted to the southern Great Barrier Reef ecosystem (Munday *et al.* 2007). For these fishes, their narrow geographic ranges represent an increased risk of extinction when combined with changes in species interactions, such as competition with range-expanding species and changes in the foods web structures of their normal habitat.

3.5 Changes in biotic interactions

Changes in individual species distribution and abundance will have a flow-on of effects to other species through habitat or trophic linkages. Primary producers have a fundamental influence on ecosystem productivity.

Hard corals perform important reef functions, varying from their physically rugose surface as substrate for other fauna, to the laying down of accreted reef structures. They also assist with rock cementing and calcium carbonate (limestone) deposition. Live corals provide food for fish directly and are a source of primary productivity, through their zooxanthellae symbionts and of secondary productivity, through ingestion of plankton and detritus (Anthony & Marshall 2009; Hoegh-Guldberg 2011).

As the environmental effects of climate change continue as projected, coral reef ecosystems will likely change in character from coral-dominated to algal-dominated ecosystems due to multiple interacting stressors. These shifts are likely to accelerate as average temperatures rise by more than 1ºC over the next 30 years and the algal state may become stabilized as a cumulative outcome of climate change. Thus, algal-dominated tropical reefs may represent alternative stable states that resist transition back to coral domination due to the strength and persistence of ecological processes that stabilize the algal state (Fong & Paul 2011).

3.6 Interactions with other stressors

Integrated modelling of land use change, crown of thorns starfish population cycles and climate change indicates that the reefs of the Great Barrier Reef will see a significant reduction in hard corals, especially among inshore areas, by 2050 (Wolanski & De'ath 2005). This modelling also predicts that the demise of hard corals may be ameliorated at some inshore reefs if land use practices are changed to halve the total outflow of sediment and nutrients from the land.

In general, poor water quality (e.g., due to terrestrial runoff at the coast) will increase bleaching risk. For example, during the 1998 and 2002 bleaching events on the Great Barrier Reef, a far greater proportion of inshore reefs were bleached compared to mid- and outer-shelf reefs due to the added stress of poor water quality (GBRMPA 2009). This observation correlates with modelled projections by Wolanski and De'ath (2005).

The effects of sea level rise on our coasts will be most severe during extreme storm surges and storm wave events corresponding with high tides and king tides. Along the developed parts of the coastline, extending over much of south-eastern Australia and parts of south-western Australia, the ability of coastal habitats to naturally adapt to sea-level rise and migrate landwards is reduced; a process known as “coastal squeeze” (Church *et al.* 2009). The process of landward movement by coastal ecosystems interacting with sea level rise and their present distributions was discussed in Section 3.2.

The effects of a king tide on Queensland's Gold Coast. King tides are natural events that happen twice a year. By 2060 to 2070 we could be experiencing tides of at least this magnitude every month, rather than just twice a year due to climate-change induced sea level rise (credit: Bruce Millar, CSIRO Marine and Atmospheric Research, science image AS11582).

3.7 Adaptive capacity of species and ecosystems

The science on acclimation, acclimatisation and adaptation of marine species is very scant. Animals with a rapid regeneration time may be able to adapt genetically (evolution through natural selection), however, natural adaptation through genetic drift will be challenged by the present and projected rate of climate change.

The capacity for corals and specifically, their zooxanthellae symbionts, to adapt to increasing water temperature is somewhat uncertain and controversial. There is some limited evidence that some corals have increased their temperature tolerances and reduced their bleaching susceptibility (Anthony & Marshall 2009; Brown & Cossins 2011), partly due to their choice of alternative zooxanthellae clade as symbiont with appropriate thermal tolerances (Brown & Cossins 2011). However, there are no broad-scale observations to date of corals adjusting their thermal threshold in response to rising sea surface temperature. With more rapid increases in sea surface temperatures likely in the future, the prospect that zooxanthellae could adapt, or that corals could change their zooxanthellae to more tolerant forms within the timeframe of climate impact over the next 50 years or so, is still considered unlikely (Hoegh-Guldberg 2011).

There is some likelihood of regional differences in coral bleaching and adaptive physiological responses. For example, in the Gulf of Carpentaria, corals are already occupying a warm region with average temperatures regularly reaching 31ºC down to 20-30m depth during the early summer months, a degree higher than the Great Barrier Reef (Harris *et al.* 2004). The waters of the Gulf of Carpentaria flow seasonally in both directions (east-west), providing some degree of marine continuity with the Great Barrier Reef. The Gulf of Carpentaria may act as a climate change refuge, providing a source of propagules for species dispersing eastward and southward to fill niches potentially vacated by coral species less tolerant of warmer temperatures.

3.8 Refugia from climate change

Areas that are resilient to climate change and maintain suitable environmental conditions within the normal operating range of resident species will have potential as climate change refugia. For example, cool upwelling areas that regularly occur on the central Great Barrier Reef (Berkelmans *et al.* 2010) may help maintain coral reefs within normal thermal tolerances and maintain reef habitats. As mentioned above, however, in the marine environment, the combination of climate change stressors means there will be very few locations that have the full suite of original conditions; for example, ocean pH will be at levels not seen for at least several million years (Pearson & Palmer 2000).

The likelihood of a shift in species distributions southward, which as has already been observed in south-east Australia for pelagic species and temperate fishes (Last *et al.* 2011) and sea urchins (Ling *et al.* 2009), depends on the availability of suitable substrate and habitats for colonisation, especially for benthic species. It is unlikely, for example, that suitable limestone substrate exists south of the Great Barrier Reef for coral colonisation. Moreton Bay, for example, which has limestone habitats, is unlikely to act as a stepping stone for corals moving south, due to the current hydrology and coastal inputs into the bay which are mostly associated with human activity (Lybolt *et al.* 2011) and have smothered the suitable substrate with sediment.

3.9 Change in ecosystem structure

Ecological theory predicts many possible patterns of change for species populations and ecological communities. More recently, attention has focused on the possibility of dramatic nonlinear shifts in ecological composition, given the extreme nonlinearities that have occurred in response to both natural and anthropogenic changes in environmental forcing functions. As discussed in Section 3.5, for example in Queensland, shifts from coral-dominated to algal-dominated communities have been observed among tropical reefs (Diaz-Pulido *et al.* 2009; Hughes *et al.* 2007a; Hughes *et al.* 2007b). There are many examples of rapid, catastrophic collapse of reef ecosystems with shifts in species composition from coral to algal dominance and evidence is accumulating that these algal states may be stable or resistant to reversal (Fong & Paul 2011). Ecosystem shifts have proved difficult to predict because they can occur with little warning and many ecosystems exhibit natural dynamic states in response to environmental perturbation or cycles. A concerning trend is the symptom of incremental coral loss, which, beyond a certain point, may be difficult to reverse because ecological feedbacks inhibit recovery to the alternative state (Mumby & Steneck 2011).

Given current projections of rising atmospheric CO_2, ensuing ocean acidification rates and estimates of coral response, most coral reef ecosystems throughout the world may find themselves in waters where dissolution of carbonate structures (coral skeletons) occurs within a few decades. In the most dramatic cases, the entire coral ecosystem may collapse and eventually be reduced to piles of disaggregated rubble (Erez *et al.* 2011; Silverman *et al.* 2009; Veron 2011). Ocean acidification, combined with coral mortality due to thermal bleaching, may cause most coral reefs to start dissolving when atmospheric CO_2 levels reach values as low as 450 ppm (Hoegh-Guldberg *et al.* 2007; McNeil & Matear 2008). This level of atmospheric CO_2 may be reached between 2030 and 2050 (IPCC 2007). While decadal predictions may be debatable, the effects of pH on aragonite saturation levels are incontrovertible (Richmond & Wolanski 2011). The reef architectural shelter used by so many fish and other organisms will disappear and the reef ecosystem as a whole will cease to function (Erez *et al.* 2011). With the loss of coral will go an enormous number of species that are directly dependent on living reef-building corals and the carbonate structures that they create (Hoegh-Guldberg 2011).

Overall, the topology of change in Queensland waters will be seen as a macro-scale distribution shift in species occurrence and dynamic ecological compositions in general disequilibrium. In some locations there will be a reduction in coral cover, with a probability of extinction for dependent species. New species may move from more northern waters (i.e., New Guinea) to replace the departing species; however the tropics is at the end of the range with respect to warm waters for many species and they will soon find themselves experiencing novel thermal conditions.

Our understanding of the ecological implications of global warming and ocean acidification is limited. However, given the enormous range of processes that are likely to be impacted by the physical and chemical changes exerted on tropical/subtropical oceans by global warming and ocean acidification, it is highly likely that coral reefs will continue to be influenced in complex and often surprising ways (Hoegh-Guldberg 2011).

In the short-term (up to 2030), the impact of climate change on Australia’s tropical coastal and demersal fishes is largely tied to the fate of critical benthic habitats, such as reefs, shoals and estuaries. In the longer-term (after 2030), sea level rise and altered rainfall patterns will also significantly alter coastal wetlands that are important nursery areas for estuarine and nearshore species (Munday *et al.* 2009a). Depending on the presence of coastal impendence structures, coastal erosion processes and human land use, some estuarine-marine habitats may expand landward, increase in extent or change structure and function.

4. REGIONAL VARIATION

An over view of regional variation in environmental drivers of ecological change in the marine system is given in Section 2 (see maps in Appendix 2). There is likely to be some variation in the impact of climate change over the entire region of the Great Barrier Reef due mostly to regional variation in oceanographic processes or variation in thermal bleaching susceptibility between coral populations and/or species (Anthony & Marshall 2009). Modelling has indicated that some amelioration of reef damage may occur if land-use practices are changed to reduce sediment and pollutant runoff, particularly when this leads to improved water quality in the nearshore reef systems (Wolanski & De'ath 2005).

A risk assessment of the factors that are likely to cause stress and contribute to reef resilience showed a pattern of greater pressures in the southern region than far northern regions and a higher resilience around offshore reefs compared to inshore reefs (Fabricius *et al.* 2007). This assessment suggests that on a regional scale, the far northern region and in particular its offshore reefs may have the most favourable spatial, biological and physical conditions within the Great Barrier Reef. In contrast, inshore reefs of the southern and central regions of the Great Barrier Reef appear to have the least favourable environmental conditions, exposing them to the greatest probability of long-term damage from climate change (Johnson & Marshall 2007). Ocean warming is also projected to be proportionally the greatest in the southern waters off Queensland's east coast, since this region will be affected by the deeper and prolonged tropical influences of the East Australia Current (Figure 16 in Appendix 2).

Impacts on the more distant Coral Sea reefs (in less regulated International waters) are even less well understood than is the case for the Great Barrier Reef. These areas are considered potential stepping-stone sources for immigration and dispersal of coral and other south equatorial biota into Queensland waters. Effective Coral Sea stewardship and a good understanding of ecosystem dynamics, and its likely consequences, is also in Queensland's interests. However, observed environmental and coral bleaching events in the Coral Sea have followed the same spatial patterns observed in the Great Barrier Reef. That is, significant coral bleaching has occurred in the spring/summer period in the central and southern regions and not in the most northern, more tropical regions (Schiller *et al.* 2009; Weller *et al.* 2008). The effects on reef-dependent biota are expected to be similar; however, the local flow dynamics and topography may lead to local differences in coral survival during warmer water events. Connectivity between the Coral Sea and the Great Barrier Reef is also unknown, although, given the prevailing ocean circulation, the Coral Sea may provide recruits to the Great Barrier Reef. Maintaining a healthy 'upstream' reef ecosystem in the Coral Sea and adjacent Torres Straits and Gulf of Carpentaria are desirable adaptation options for the Great Barrier Reef (see Section 6).

Other major changes with regional variation are expected from sea level rise and its interplay with storm surges and coastal erosion (QCCCE 2011). A simple example drawn from data generated to support Queensland's Coastal Plan (Environment Planning 2011) shows the potential impact of a 0.8m sea level rise[15] on the coastal zone (see Appendix 3) (see Appendix 3 in Bustamante *et al.* 2012)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see Appendix 3 in Bustamante *et al.* 2011)(see

[15] http://www.derm.qld.gov.au/coastalplan/coastalhazards.html

Appendix 3 in Bustamante *et al.* 2011). Low-lying tidal wetlands and estuarine systems of southern Queensland will be most affected (see Traill *et al.* 2011). Considerable change is also expected to occur in the southern Gulf of Carpentaria region due to its low vertical profile, the wide extent of its coastal zone and the interplay between flash floods, rivers and tidal wetlands.

5. ECOSYSTEM SERVICES

5.1 Introduction

Queensland's marine biodiversity directly supplies ecosystem services such as food, income and leisure activities through commercial and recreational fisheries and income and cultural services through marine tourism. It also supplies an 'option use value' through future unknown and speculative benefits, such as novel pharmaceuticals. Indirectly, it contributes to several other regulating and support services such as coastal protection by reefs and mangroves and nutrient cycling (Atkins *et al.* 2011). A general overview of ecosystem services in Queensland is given in Williams *et al.* (2012b).Queensland State Fisheries are likely worth more than $200 million per year to Queensland, the majority of that derived through the healthy, functioning Great Barrier Reef system (Access Economics 2007). Offshore (Commonwealth managed) fisheries in the Gulf of Carpentaria, Torres Strait and the Coral Sea are worth an additional $35 million to Queensland, (Wilson *et al.* 2010 – 2008/09 catch value and assuming half the ETBF catch landed in Queensland). Apart from fisheries, marine biodiversity valuation is an area of research that is developing (Richmond & Wolanski 2011). Cultural values of iconic species, such as dugong, turtles and grey nurse sharks, are difficult to quantify because these species are typically also under threat from existing pressures.

5.2 Great Barrier Reef

Ecosystem services provided by marine biodiversity of the Great Barrier Reef region make a significant contribution to the economy of Queensland. The Great Barrier Reef region provides direct and indirect income from tourism; income, food and recreation from fisheries; income and health benefits from novel pharmaceuticals; coastal protection from storms and cyclones; and social wellbeing through its awe-inspiring beauty and recognition as a World Heritage Area (GBRMPA 2009).

The total (direct plus indirect) economic contribution to Queensland in 2005-06 of tourism, commercial fishing, and cultural and recreational activity in the Great Barrier Reef and associated catchments, was valued at $5.4 billion per annum, or 3.1% of gross State product, with employment of 56,000 persons (Access Economics 2007). The tourism industry's share was 84%-87% of the economic value and 81%-84% of employment. Interstate and International visitors contributed about one quarter each of the overall economic value. Commercial fishing contributed about $220M per year from 04/05 and 05/06 (though this had declined to $114M in 2006/07 – Access Economics 2007).

Oxford Economics took a different approach to valuing the Great Barrier Reef. They used a 100 year timeframe and a social discount rate of 2.65%, included all direct and indirect use values and estimated the present value of the Great Barrier Reef as a whole (excluding indigenous values) to be $51.4 billion, in 2009 Australian dollars (Oxford Economics 2009). The largest component of this was tourism and recreation related activities which accounted for 45% of the value, national non-use values (that value assigned by the Australian public) accounted for 30% and indirect use value – the assessed value of the Great Barrier Reef as a physical coastal protection barrier was 19%. Commercial fishing was valued at $1.4 billion or 2.7%. The cost of the total and permanent bleaching of the Great Barrier Reef in 2009 was then estimated to 'cost' $37.7 billion. The largest component of the cost of bleaching was assigned to Tourism at 44%, followed by National non use value (that value assigned by the Australian community) at 40%. This estimated cost was based on a 50% drop in the million or so visitors to the Great Barrier Reef and a 30% loss of value of fisheries production. Put another way, the cost of coral bleaching on the Great Barrier Reef is roughly equivalent to a constant $1.08 billion per annum over the course of a century (Oxford Economics 2009). In just these terms, the continuing cost of climate change represents a major loss of income across many industries and overall for the Queensland economy.

This may appear a pessimistic point of view given the potential for smaller scale enhancement to some parts of the reef in order to maintain tourist numbers (especially at the ‘day-tripper’ level) and the likelihood for a more gradual decline and the ameliorating effects of ‘shifting baselines’ on tourist attitudes as visitors to the Great Barrier Reef. Also, some tourism values are reflected by the continental drop off, cays and natural physical wonders of the Great Barrier Reef, vistas that will continue to inspire even if their biota’s may not. The Great Barrier Reef system has some advantages that could still see prosperity: 1) other reef domains are in worse shape or have more pessimistic outlooks; 2) the reef experience can be seen as part of a package of attractions that include land-based tourism; 3) the reef is large and diverse, in which there are a range of habitats (inner and outer reefs) and locations (Cooktown to Bundaberg) that spread the risk of providing only an attractive reef experience; 4) the region provides a stable and safe socio-political setting among an increasingly unsettled global society; and 5) there is potential for modified environments for tourism/science (e.g., coral ‘theme parks’ or wild zoos using shade, electrical grids, enrichment) (Rinkevich 2005).

Predicting the economic loss to fisheries from the ensuing impacts of climate change is very difficult (Sands 2011). While numerous studies of fish populations after bleaching events have been conducted, by definition these have not been long term making it difficult to project change in fish populations over time. A decline in overall abundance and a change in reef fish community structure are likely outcomes (Hoegh-Guldberg & Hoegh-Guldberg 2004; Munday *et al.* 2009a). Some of these studies also indicate that there may be replacement of some species types by others (e.g., herbivorous fish by carnivorous fish) which then raises the question of whether such replacements (if any) would be marketable to consumers (Bellwood *et al.* 2006; Johnson & Marshall 2007)

Damage to coastal infrastructure by increased wave exposure as a result of decreased coral formation and even reef dissolution is a risk for the Queensland coastline. The relatively rapid disintegration of fringing reefs in the Seychelles following the 1998 bleaching event resulted in higher wave energy reaching the shore, leading to increased rates of coastal erosion (Sheppard *et al.* 2005). However, the extensive nature of the reefs along the Queensland coast and the substantial nature of the underlying structure in many of those reefs (GBRMPA 2009) means it will to continue to act as a wave barrier in many areas, even in the event of bleaching.

5.3 Communities affected

The reduction in tourism and fisheries income and reduction in coastal protection will overwhelmingly be felt at the local level, with smaller effects at state and national level. Impacts to social services (wellbeing and contentment) will be more evenly shared nationally and even internationally. On the Great Barrier Reef, tourism operators and fishing communities will be directly impacted by ecosystem collapse, followed by supporting industries. That said, negative impacts on tourism may be overstated. Smaller areas with high biodiversity or other interesting fauna (such as spawning grounds and other aggregation sites) or geomorphology (such as drop offs) may still provide a unique and attractive diving experience. There is some utilisation of food resources by indigenous communities as well, and reductions in supply will disproportionately affect those communities.

In Torres Strait, there is an extremely high reliance of local indigenous communities on the marine environment for food, income, protection from extreme weather events and cultural identity. The Torres Strait Islands are a specific and geographically bounded example of a 'highly vulnerable' society. Over 7,000 people live in 18 communities on these islands, several of which are only a few metres above local mean sea level (Green *et al.* 2010). There is a high level of concern among Torres Strait Islanders, in particular, that climate change could impact the marine environment to such a degree that it may no longer support subsistence fisheries. A cascade of impacts is anticipated through impacts on extensive seagrass beds that support dugong and turtle populations and on coral bleaching which supports a diverse array of subsistence and artisanal fisheries. These impacts would flow-on to local subsistence and commercial economies alike and erode the insurance value of marine biodiversity across Torres Strait (Green *et al.* 2010).

A scientist preparing to set crab pots as part of an investigation into the distribution, abundance and size structure of the population of mud and sand crabs in Moreton Bay (credit: Richard Pillans, CSIRO Marine and Atmospheric Research, science image AS11599).

6. ADAPTATION OPTIONS

6.1 Current management of coastal-marine natural resources

This section provides a general description of the current management of the coastal-marine ecosystems and its services that are or will be part of the state's responses to managing adaptively for the effects of climate and ocean changes. Queensland's natural resources and biodiversity are legislated by complex jurisdictional instruments (e.g., see Figure 3 for the Great Barrier Reef) that include specific federal and state Acts and Directions Australia's commitments to international conventions and agreements (e.g., RAMSAR[16], UNCLOS[17], CITES,[18] or CBD[19], as examples).

6.1.1 Coastal Biodiversity and Ecosystems

The coastal development and management of the Queensland coastal zone (Figure 19) is regulated by the *Coastal Protection and Management Act 1995* (Coastal Act) and *Sustainable Planning Act 2009*. The main actions and activities are currently managed under the Coastal Management Plan[20] (Environment Planning 2011) which focuses on two major policy components: (1) coastal management to maintain, rehabilitate and protecting coastal land; and (2) managing activities on public coastal land and coastal protection – outlining criteria for land-use planning and development assessment for the coastal zone. Queensland's Coastal Management Plan comprehensively provides general and specific guidance for achieving policy outcomes. These include 13 high-level policy outcomes, each of which provide a wide range of expected specific management responses. In turn, the plan lists up to 66 performance outcomes aggregated into six classes: coastal hazards, nature conservation, scenic amenity, public access, coastal dependent development and canals and artificial waterways (Environment Planning 2011).

6.1.2 Marine Biodiversity

The Queensland's *Nature Conservation Act 1992* provides the legal definitions for managing and conserving terrestrial, aquatic and marine biodiversity. A central policy of the Queensland government is the building of a resilient nature for dealing with human uses and future climate change. Here, the guiding document is the Draft Biodiversity Strategy for Queensland (DERM 2010a), that sets two main goals for 2020: (i) reverse the decline in biodiversity; and (ii) increase the resilience of species, ecosystems and ecological processes. The draft strategy is designed to deal with the principle processes threatening the persistence of coastal-marine biodiversity: terrestrial land run-off into waterways and degrading the inshore reefs and coastal-marine habitats; dredging and spoil disposal; and commercial and recreational fishing impacts in highly populated (e.g., urbanised) areas. Adaptive management of the impacts of climate change are central to the biodiversity strategy.

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[16] http://www.ramsar.org
[17] http://www.un.org/Depts/los/index.htm
[18] http://www.cites.org/
[19] http://www.cbd.int/
[20] http://www.derm.qld.gov.au/coastalplan/index.html

6.1.3 The Great Barrier Reef

The *Great Barrier Reef Marine Park Act 1975* is the primary Act in respect of the Great Barrier Reef Marine Park. This Act sets the main conservation objectives and definitions and other Commonwealth and Queensland Acts are also in force. Because the Great Barrier Reef has World Heritage status it, like the mainland of Queensland, is also under a number of international conventions (e.g., CBD[19], CITES[18], RAMSAR[16], UNCLOS[17]). The uses and conservation management within the Great Barrier Reef are largely established through its regulations (e.g., aquaculture discharges), the 25-Year Strategic Plan for the Great Barrier Reef World Heritage Area (GBRMPA 1994), its four regional Plans of Management, four site-specific Management arrangements and its 2003 Zoning and Revision Plan (GBRMPA 2004). The Great Barrier Reef Marine Park Authority (GBRMPA) reports its management performance under three major objectives: (i) environmental sustainability, (ii) marine park management and (iii) communication and policy coordination. The first Great Barrier Reef Outlook Report (GBRMPA 2009) established the formal process for assessing performance of conservation management in terms of environmental, social and economic values. This report also examined the pressures and current responses and the likely future outlook for the reef ecosystem.

6.1.4 Fisheries and Aquaculture

Queensland state fisheries and aquaculture management falls under the Department of Employment, Economic Development and Innovation (DEEDI)[21] jurisdiction whose aims are to protect and conserve fisheries resources, maintaining commercial viability and recreational fishing sectors. The aquaculture practices are also required to be sustainable and minimise risks of exotic species and diseases, improve their environmental footprint, production and biosecurity[22]. These sectors are largely legislated by the Queensland Fisheries Act (1994), a range of fisheries-specific management plans and various access and resource allocation policies and legislations[23]. The current and near-future management is largely guided by the Queensland Fisheries Strategy 2009–14 (DEEDI 2009). The aim of this strategy is to maximise the value of fisheries resources for all Queenslanders by: (i) managing fisheries resources in an ecologically sustainable way; (ii) sharing resources equitably; (iii) facilitating the growth of the aquaculture sector; (iv) supporting profitable commercial fisheries; (v) maximising the recreational fishing experience; (vi) respecting traditional and customary fishing; and (vii) protecting fish habitats. This strategy focuses on Queensland actions as well as the shared responsibility between state and federal government agencies, including the important roles of the community, the aquaculture, recreational, commercial industries and Indigenous fishing sectors. This strategy promotes sustainable, strong and diverse fisheries and aquaculture futures.

6.2 Management objectives

A synthesis of all of Queensland's coastal-marine management objectives is a complex and large task. There are a number of agencies with a myriad of different foci on strategies, policies and plans that sometimes overlap or are aimed at specific outcomes. A comprehensive synthesis of management objectives pertinent to coastal-marine ecosystems of Queensland was considered to be outside the scope of this report. We have however defined a few criteria to focus on objectives directly aimed at biodiversity and its most important services. For simplicity we focus here on high-level criteria that

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[21] http://www.dpi.qld.gov.au/28_13164.htm
[22] http://www.dpi.qld.gov.au/28_14276.htm
[23] http://www.dpi.qld.gov.au/28_143.htm

will most likely enable contributions to Queensland's policy integration, development and planning in the face of climate and ocean change. The list provided below represents a mix of objectives, targets and policy outcomes are aimed at coastal-marine biodiversity and conservation management.

6.2.1 Coastal

The objectives of coastal management (policy outcomes) listed below are simplified and modified as stated in the Queensland Coastal Plan (Environment Planning 2011). The Plan seeks to implement a wide range of detailed policies following policy outcomes with regard to coastal management and coastal protection.

Coastal Management

1. Protects, conserves and enhances coastal resources (the natural and cultural resources of the coastal zone).

2. Maintains natural physical coastal processes through appropriate design of works and structures or by setting them back from vulnerable areas.

3. Ensures infrastructure and services facilitate managed public use of the coast without having significant adverse impacts on ecological values or physical coastal processes.

4. Ensures that management actions on State or local government coastal land are consistent with the policy outcomes of the Queensland Coastal Plan.

5. Encourages public participation in the management of public coastal land, collaborative actions, knowledge sharing, community awareness and the monitoring, review and reporting of the effectiveness of management.

The coastal management plan also identifies a number of priority locations where specific management actions are required and that are geographically related to the above policy outcomes.

Coastal Protection

The State Planning Policy for Coastal Protection aims to protect the coastal resources uses and development in or within the coastal zone[2,10] and coastal waters. It seeks the following high-level policy outcomes:

1. Development in the coastal zone is planned, located, designed, constructed and operated to:

    - avoid the social, financial and environmental costs arising from the impacts of coastal hazards, taking into account the projected effects of climate change;

    - manage the coast to protect, conserve and rehabilitate coastal resources and biological diversity; and

    - preferentially allocate land on the coast for coastal-dependent development.

2. . The policy outcome will be achieved when development to which the policy applies is consistent with each of the principles, policies and applicable specific outcomes, for the following topic areas::

   - Land-use planning
   - Coastal hazards
   - Nature conservation
   - Scenic amenity
   - Public access
   - Coastal-dependent development
   - Canals and artificial waterways

The State Planning Policy for Coastal Protection also applies an assessment code to achieve the outcomes of the plan and set a number of specific performance outcomes for the above topic areas, including also storm-tide inundation areas (Environment Planning 2011).

6.2.2 Marine Biodiversity

The State's draft Queensland Biodiversity Strategy (DERM 2010a) states that its main goals by 2020 are (i) to reverse the decline in biodiversity and (ii) to increase the resilience of species, ecosystems and ecological processes. To achieve those goals, it states three primary and three supporting management objectives, as listed in the background report for the terrestrial ecological realm (Murphy *et al.* 2012). These objectives are highly generic and only two are explicit for Queensland's marine biodiversity:

(1) Primary objective: Building Protected Areas – *Marine biodiversity is better understood and better protected and valued.*

(2) Supporting objective: Building knowledge – *The role of freshwater and marine ecosystems in the broader landscape is better understood and valued*.

Although it could be interpreted that there is a bias, we interpret that almost all primary and supporting objectives aimed to species, threats, habitats, stressor, risks, people and sectors are equally applicable to coast and seas' biodiversity. In the draft Queensland Biodiversity Strategy, however, there are more explicit key outcomes and priority actions that focus on marine biodiversity. Here the most important and relevant target is that for 2020, where it is expected that an expanded network of border to border marine parks will be established (DERM 2010a); although the current science plan for expanding protected areas is focussed on terrestrial outcomes (DERM 2010b).

6.2.3 Great Barrier Reef

Management of the Great Barrier Reef has been evolving constantly over recent past decades and this region is now has one of the most comprehensive and complex ecosystem and resource management in the world. The 25-Year Strategic Plan (GBRMPA 1994) established the main vision and direction for implementation, as required by the *Great Barrier Reef Marine Park Act 1975*. The most recent process has been the Great Barrier Reef Outlook Report (GBRMPA 2009) which is structured around the eight assessments required under Section 54 of the *Great Barrier Reef Marine Park Act 1975*

(Figure 10). We note, however, that this is proposition that may change in future given the multitude of explicit Management Plans, Plans of Management and a series of Management Uses objectives. There are no simple high level objectives that we know of to date.

Figure 10: Depiction of the process by which the various values and questions for the eight assessed components that generate the Great Barrier Reef status and further outlook (GBRMPA 2009).

6.2.4 Fisheries and Aquaculture

The Queensland Fisheries Strategy (DEEDI 2009) identifies three management elements: (i) habitat protection, (ii) harvest strategies and (iii) maximizing values of resources (Figure 11). For protecting fish habitats, the strategy focuses on managing key threats and also on sustaining and enhancing freshwater and marine resources. Key to this strategy is the implementation of explicit harvest strategies that ensure that individuals, businesses and local communities fish in an ecologically sustainable way. This is largely done through the management of the stocks and fishing effort. To maximise the value of fisheries, the strategy aims to foster investment in fishing and related industries, enhance the recreational fishing experience and assist commercial fishing and aquaculture to meet growing consumer demands for their high-quality, nutritious product.

These three high-level elements are in turn broken down into a series of specific strategic objectives that in turn have specific goals and strategies. These include:

A. **Sustainable resources** aimed at investing in habitat protection and conservation, maximising the area and quality and minimising conflicts with users (+12 strategies).

B. **Responsible fishing** aimed at investment in harvest allocation, management, compliance and markets (+13 policies).

C. **Profitable industries** aimed at enhancing values, profitability, growth of new industries and enhancing the recreational experience and develop inland opportunities (+6 strategies).

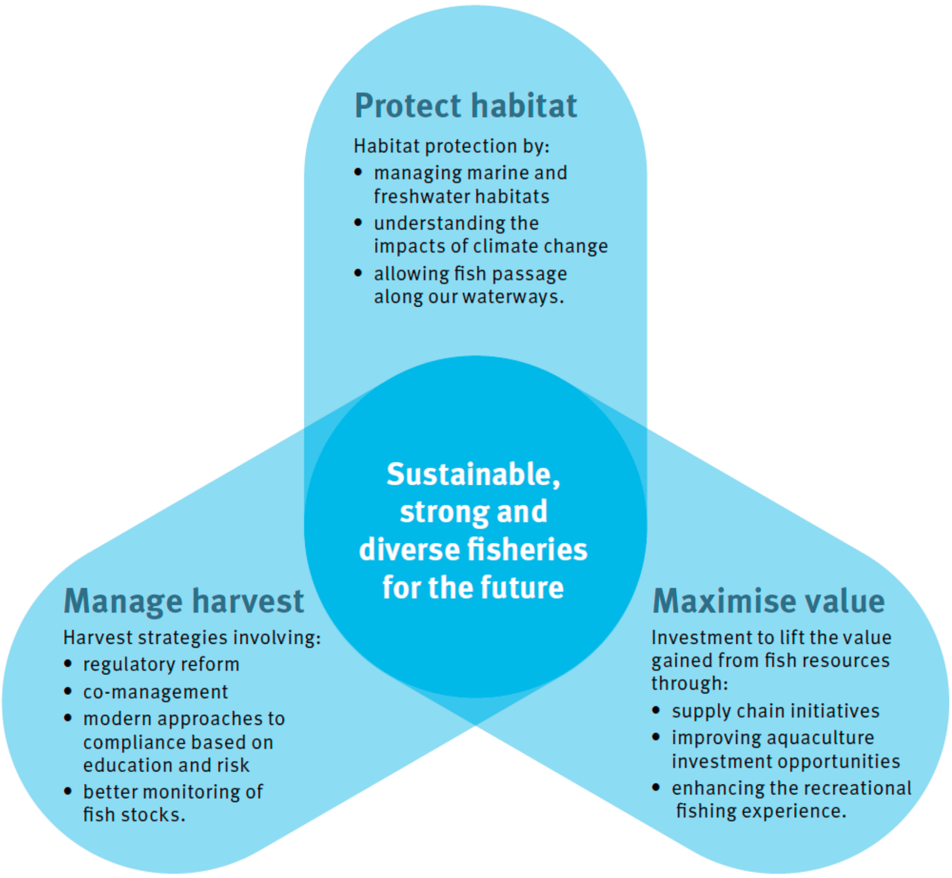


Figure 11: Key elements and management goals Queensland Fisheries Strategy 2009 – 2014 (taken from DEEDI 2009).

6.3 Managing biodiversity and ecosystems under climate change

The Great Barrier Reef is not only the largest reef system in the world, it is also one of the best managed (Pandolfi *et al.* 2003). This has resulted in a resilience that has contributed in some (largely unknown) extent to the current relatively good condition of that reef. Only two fishery species are considered overexploited in the Great Barrier Reef region – both have been closed to fishing for more than 10 years. A great deal of fishing effort has been removed from the system as part of the recent rezoning of the Great Barrier Reef and the Regional Adjustment Program.

In the short term, strategies for adaptation are to minimize regional and local-scale impacts of climate change by maximizing reef resilience (i.e., the potential for restoring reef function following disturbances). These include restoring and maintaining high water quality and healthy populations of herbivores through sustainable fishing strategies to minimize the future risk of community phase shifts from coral to algal dominance (Anthony & Marshall 2009). Coastal terrestrial runoff is still a significant issue that impacts the reef negatively, affects its health status and resilience. Managing terrestrial catchments to minimise runoff is one pathway to adaptation that could be improved without delay to ensure reef resilience increases and withstands both short-term (e.g., bleaching) and long term (climate change) environmental perturbations. Reef restoration is one adaptation option. This includes interventions to build and maintain coral gardens using electric fields (Goreau *et al.* 2004), shading, transplantation, substrate stabilisation or other substrate intervention (Rinkevich 2005). Other than laboratory and experimental transplantations, in Queensland there are no large-scale reef translocations or transplants of corals. There are however experimental projects performing assisted migration and colonisation under the Great Barrier Reef Foundation's ZooX™ Fund[24] as a form of adaptive management for coral reefs. Early results have shown that translocated corals from warmer (northern) to the cooler (southern) regions of the GBR can interbreed but with low reproductive success and the fitness of the hybrid corals appears less robust than that of purebred corals (GBRF 2010). Because translocation can result in negative outcomes, a rigorous decision framework for assessing the need for translocation is required for this to be considered a useful response for managing climate change impacts (e.g., Hoegh-Guldberg *et al.* 2008).

Translocation, or assisted migration, however, is receiving increased attention as an adaptation strategy to enhance species and/or ecosystem resilience to climate change (Hoegh-Guldberg *et al.* 2008; Loss *et al.* 2011). This approach involves human-assisted movement of animals to enable range expansion, or enhance depleted populations. Historically, assisted migration has been used to replenish extinct or endangered populations, create arks for species under threat and more recently, to help ameliorate loss of habitat due to climate change. Assisted migration generally involves translocating species beyond their existing or former range, particularly where barriers to dispersal would prevent natural range change. Theoretical frameworks and advocacy calls for translocation as a response to climate change have appeared in recent years (e.g., Hoegh-Guldberg *et al.* 2008; McDonald-Madden *et al.* 2011), together with responses and counterpoints that suggest such an approach is foolhardy (Ricciardi & Simberloff 2009). Terrestrial researchers might be reluctant to embrace such approaches given the ecological surprises that have resulted from past introductions (Webber *et al.* 2011). Despite this, translocation has in fact been used in management of endangered freshwater and terrestrial species for many years. It has been one of the most commonly used tools for biodiversity restoration worldwide. It seems this old strategy in some spheres (e.g., freshwater systems) may be given new life in others (e.g., marine), with little crossover in lessons learnt. While

[24] http://www.barrierreef.org/OurProjects/ZooXFund.aspx

this debate continues, a number of primary research projects around Australia are testing these principles and exploring the practicality of translocation as an adaptation response to climate change. Translocation can also be for particular life stages. For example, turtle eggs may be moved to cooler beaches, where the sex ratio is less affected by warming sands.

Fisheries (or fishers) can adapt by changing fishing practices such as switching target species, fishing location, or modifying technology. In the past, fishers have adapted to changes in policy and management (Sands 2011). Flexible and adaptive management frameworks that account for climate change will be essential to ameliorate the worst of the economic and social impacts of climate change on fishers and fisheries (Plaganyi *et al.* 2011). More specific information about adaptation to climate change for the management of Queensland's biodiversity and ecosystems is given in Dunlop *et al.* (2012).

Gorgonian corals and a large sponge on the seabed off far northern Queensland. An area 50 km offshore between the coast and the Great Barrier Reef, known as the lagoon, hosts diverse gardens of marine life: soft corals, sponges, sea-whips and fish. A study by CSIRO Marine Research and the Queensland Department of Primary Industries found that prawn trawling in the region had a cumulative effect on this marine life, depending on trawling intensity and the capacity of individual species to recover between trawls (credit: CSIRO Marine and Atmospheric Research, science image AS0939).

7. CONCLUSIONS

The marine environment of Queensland has already changed compared to pre-industrial conditions as a result of climate change and a number of other environmental stressors. These physical changes are also expected to flow on to impact the biology of marine organisms. For example, changes in water temperature will likely result in a general southward shift in species as they follow their niche conditions south, as has already been observed in the faster-warming southern regions of Australia (e.g., Last *et al.* 2011). Tropical species in the northern Great Barrier Reef have suitable habitat in the southern portion of Queensland waters, as long as temperatures don't rise too rapidly. Southern reef-dependent species may be more challenged by climate change, because there are few suitable habitats places further south where they could settle. There are few obstacles to the southward movement of habitat generalists and pelagic species. The effects of ocean acidification will most significantly affect calcifying biota - carbonate-using plants and animals, which when combined with ocean warming and more frequent extreme storms, will be problematic for corals in the next few decades.

For species that do not follow the climate envelope, climate change will result in local reductions in species abundance, density, growth and reproductive success. This will result in a higher extinction risk. The number of species that will be lost is uncertain, however, extinction risk will increase with the degree of environmental change.

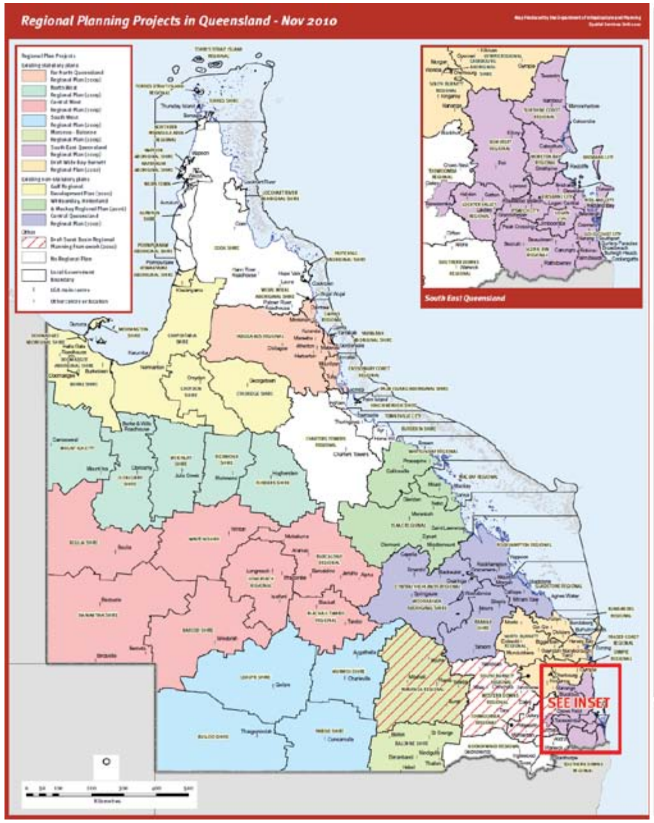
With regard to habitats, climate change is now recognised as the greatest long-term threat to the Great Barrier Reef. The Great Barrier Reef region will most likely be transformed as an ecosystem by mid to late this century due to changes in coral reef ecology. Increased occurrence of coral bleaching and the insidious effects of ocean acidification will mean that hard and soft coral and calcareous algae will be in low density and/or slow growing and reefs will be dominated by fleshy macro algae and herbivorous fishes. Corals as a species will survive but they will probably be smaller and occur deeper due to dissolution through acidification and sea level rise and provide less of a barrier to ocean swells in both island lagoons and the mainland coastline. The greatest changes will be in the inshore and central and southern parts of the Great Barrier Reef system. There is potential for improvements in land use practices that reduce sediment and nutrient in terrestrial runoff, and sustainable fishery management in the remainder of the Great Barrier Reef, to ameliorate this impact to some extent. Other pressures, such as coastal pollution and fisheries harvest, will act synergistically to exacerbate the impacts of climate change and should be managed to increase resilience of Queensland marine ecosystems and its biodiversity.

The Great Barrier Reef is already one of the best managed and most intact large reef domains in the world. Coordination of management is occurring through cooperative agreements between state and federal authorities, such as the eREEF[25] and the Reef Plan (Reef Water Quality Protection Plan Secretariat 2010). While this is not an integrated authority, the coordinated effort is achieving integration in management. This approach could be extended throughout other coastal-marine waters of Queensland, so that the impacts of climate change are limited to the unavoidable; allowing the continued valuable ecological, economic and social use of these remarkable waters.

[25] http://www.barrierreef.org/Home/SiteMap/eReefsPilotFundingAnnounced.aspx

APPENDIX 1. MARINE REGIONALISATION

(A)



(B)

(C)

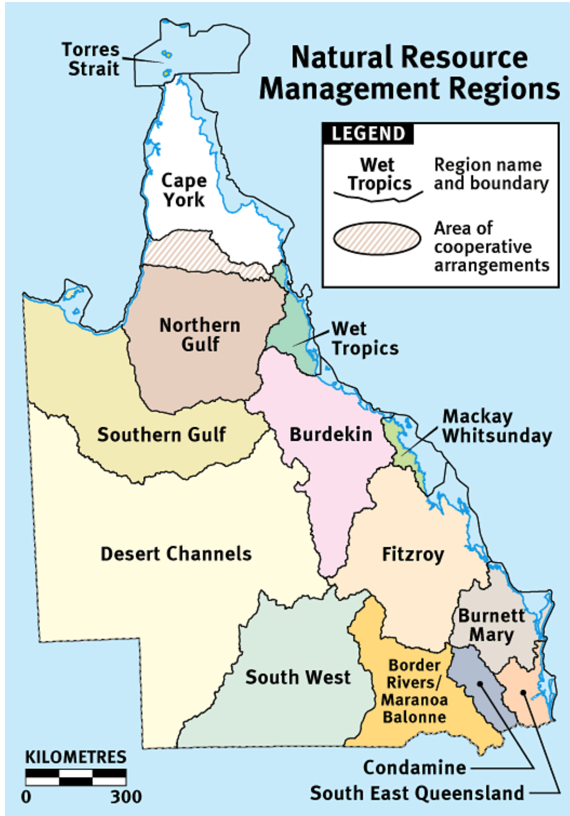


Figure 12: Various Queensland spatial administration units and regions that contain coastal-marine domains currently used for planning and management: (A[26]) Regional Plan regions (DIP 2011); (B[27]) Coastal Plan regions (Environment Planning 2011); and (C[28]) Natural Resource Management regions (DERM 2009).

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[26] Regional Planning Projects in Queensland http://www.dlgp.qld.gov.au/resources/map/map-regional-planning-projects.pdf

[26] Queensland Coastal Plan http://www.derm.qld.gov.au/coastalplan/index.html

(A) (B)

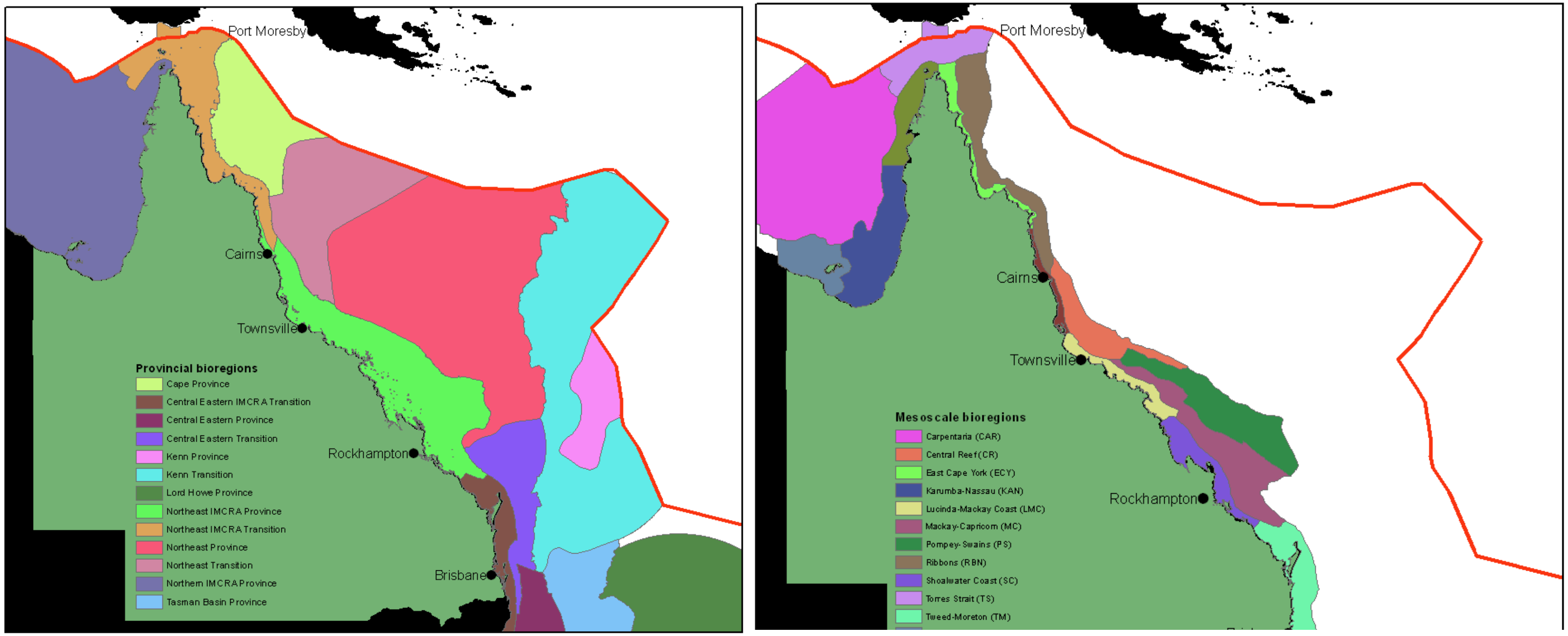

Figure 13: IMCRA 4.0 Provincial (left panel) and meso-scale (right panel) bioregions for coastal and open ocean waters adjacent to Queensland (Commonwealth of Australia 2006).

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[26] CoastInfo Resources for Regional Natural Resource Management (NRM) Regions http://www.derm.qld.gov.au/coastinfo/nrm-regions/index.html

APPENDIX 2. CLIMATE CHANGE VARIABLES BY MODIFIED MARINE ECOREGIONS

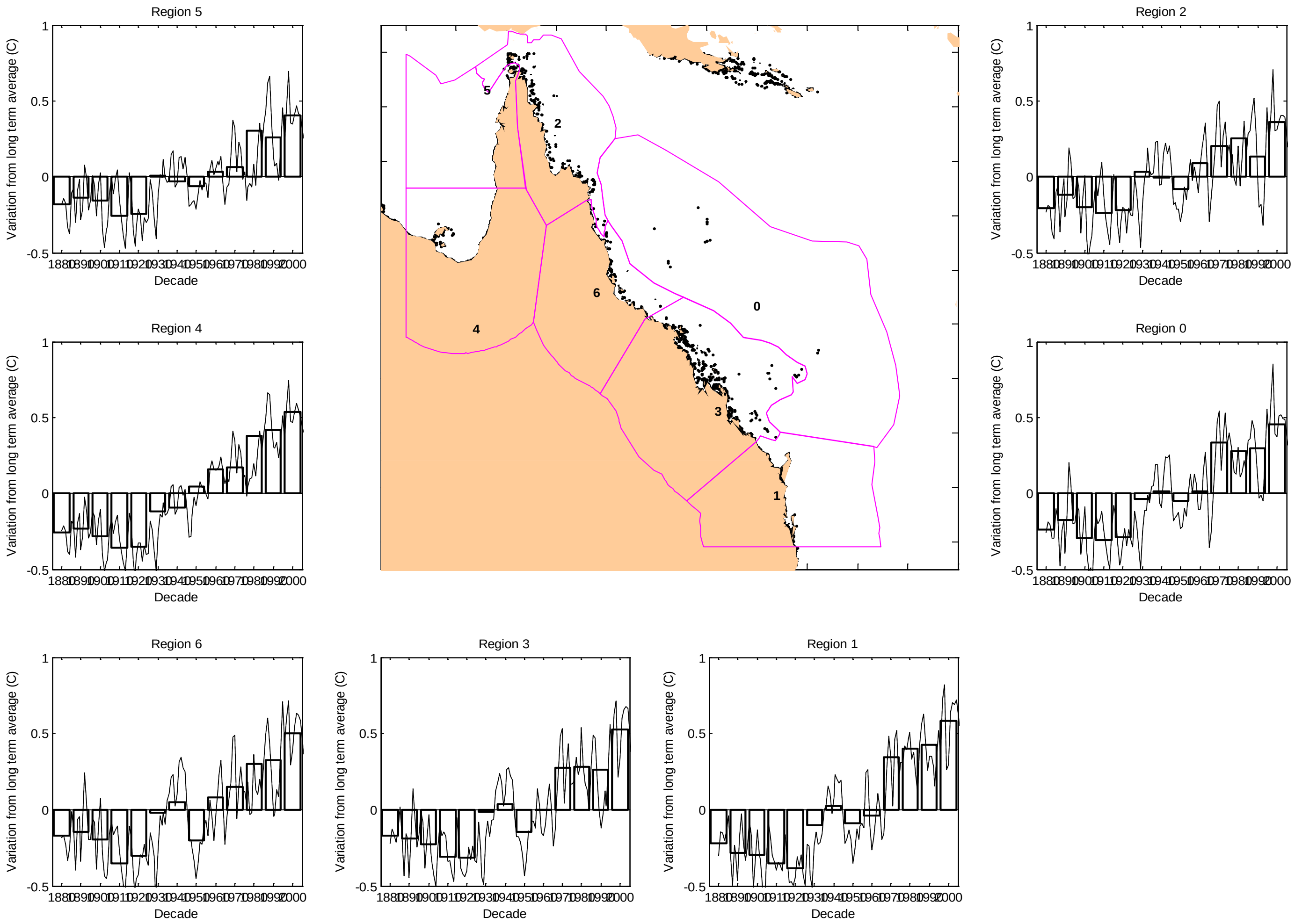

Figure 14: Historical sea surface temperature change by MEOW ecoregions modified for Queensland (numbers are referenced in Table 1) based on the HadSSTv2 dataset (Rayner *et al.* 2006).

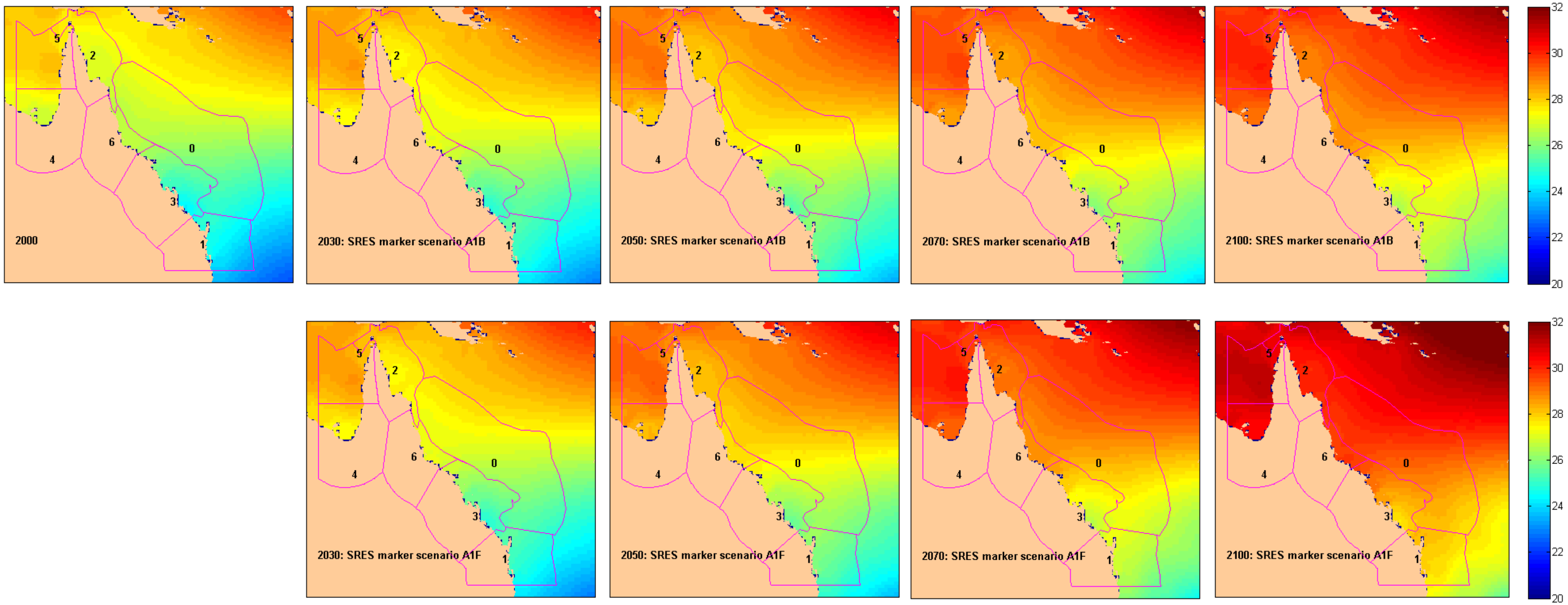

Figure 15: Annual average sea surface temperature map for MEOW ecoregions modified for Queensland (numbers are referenced in Table 1) for current climate and projections: 2030 (far left), 2050, 2070 and 2100 (far right) and SRES scenarios (Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000) A1B (top) and A1FI (bottom). Data from OzClim, 2011 (CSIRO 2007; Ricketts & Page 2007).

The lower resolution sea surface temperature data is overlain by a detailed coastline – the fringing black pixels represent land.

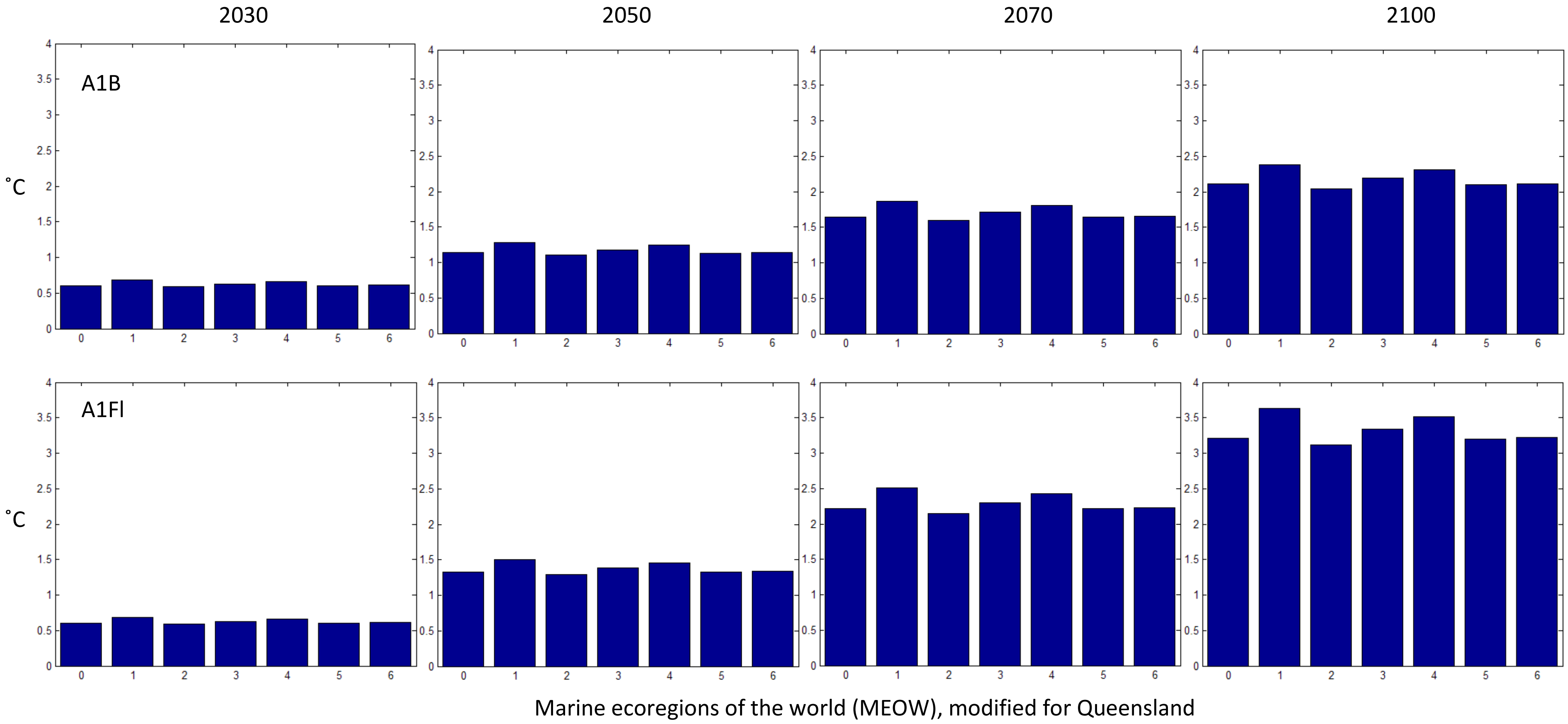

Figure 16: Sea surface temperature change (°C) for MEOW ecoregions modified for Queensland (numbers are referenced in Table 1) for climate projections: 2030 (far left), 2050, 2070 and 2100 (far right) and SRES scenarios (Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000) A1B (top) and A1Fl (bottom). Data from OzClim, 2011 (CSIRO 2007; Ricketts & Page 2007).

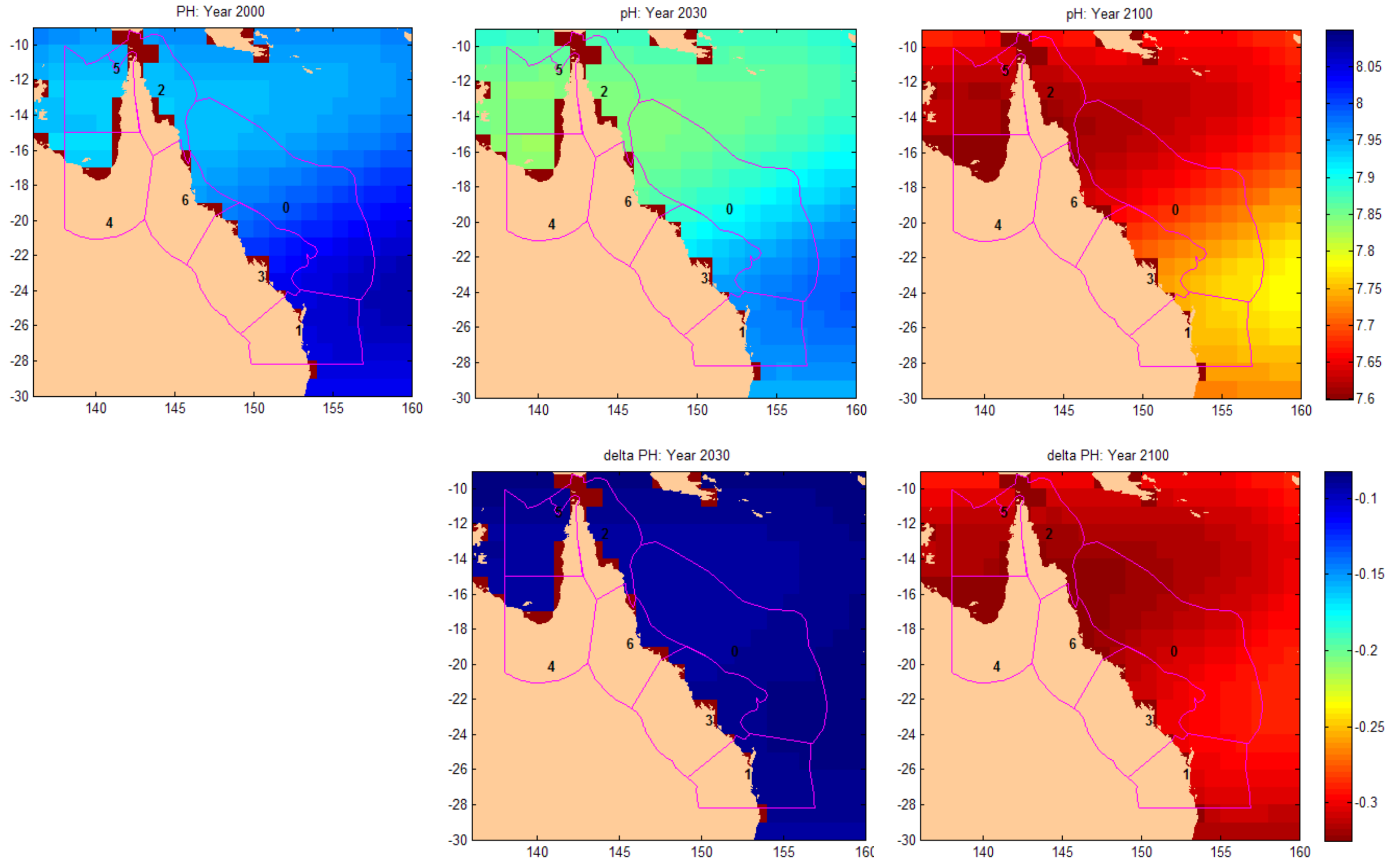

Figure 17: pH for the years 2000, 2030, 2100; and change in pH for the years 2030 and 2100, based on the A2 SRES scenarios (IPCC 2000) with MEOW ecoregions superimposed (modified for Queensland: numbers referenced in Table 1). Data courtesy Richard Matear, CSIRO Marine and Atmospheric Research.

The lower resolution sea surface temperature data is overlain by a detailed coastline – the fringing deep maroon pixels represent land.

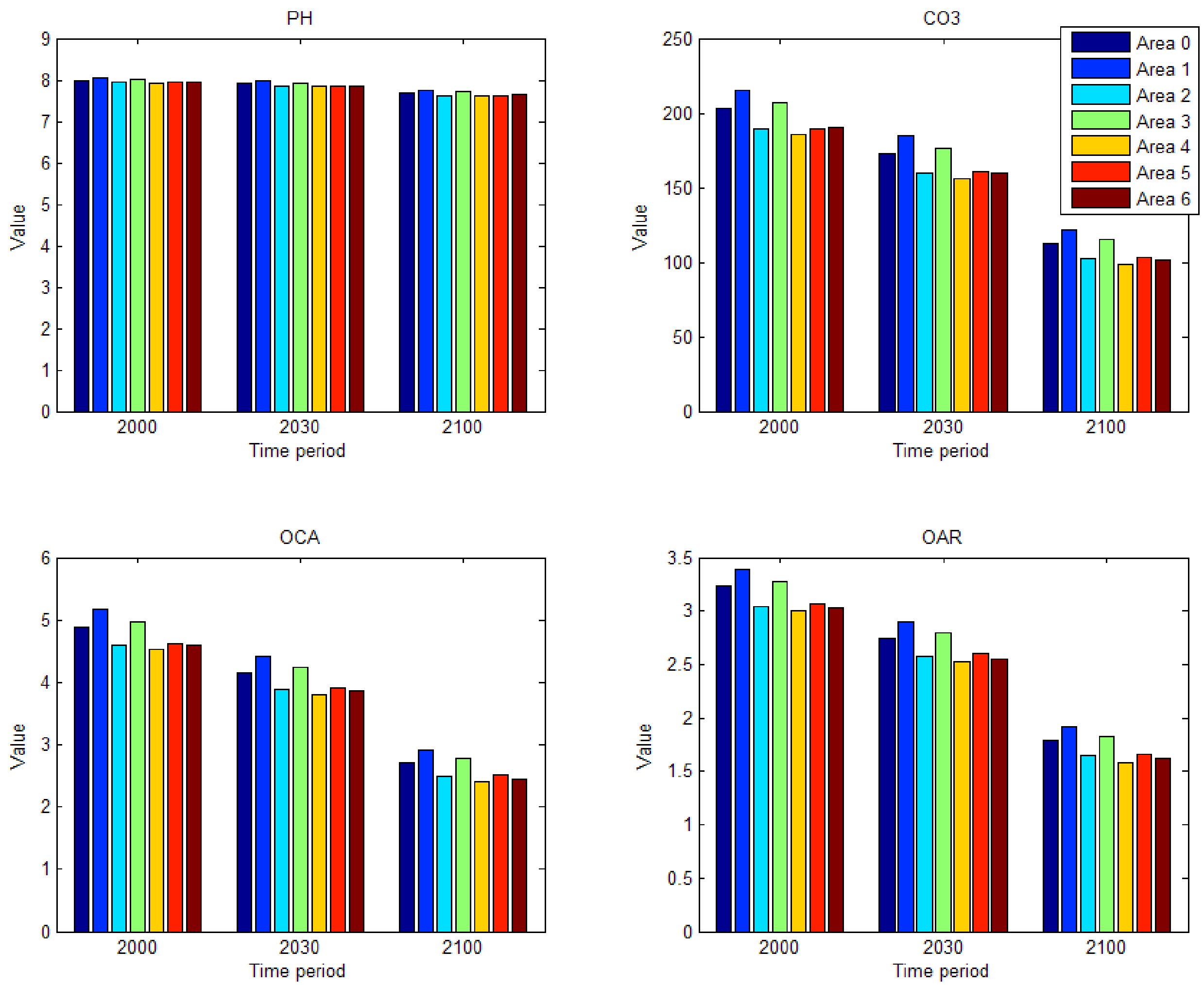

Figure 18: Plots of current and predicted (for 2030 and 2100) pH, CO_3 ion concentration (µmol.l^{-1}) and the calcite and aragonite saturation coefficients (Ω), for each of the Queensland MEOW ecoregions superimposed (modified for Queensland: area numbers referenced in Table 1). Data courtesy Richard Matear, CSIRO Marine and Atmospheric Research.

APPENDIX 3. SEA LEVEL RISE AND COASTAL INUNDATION MAPPING

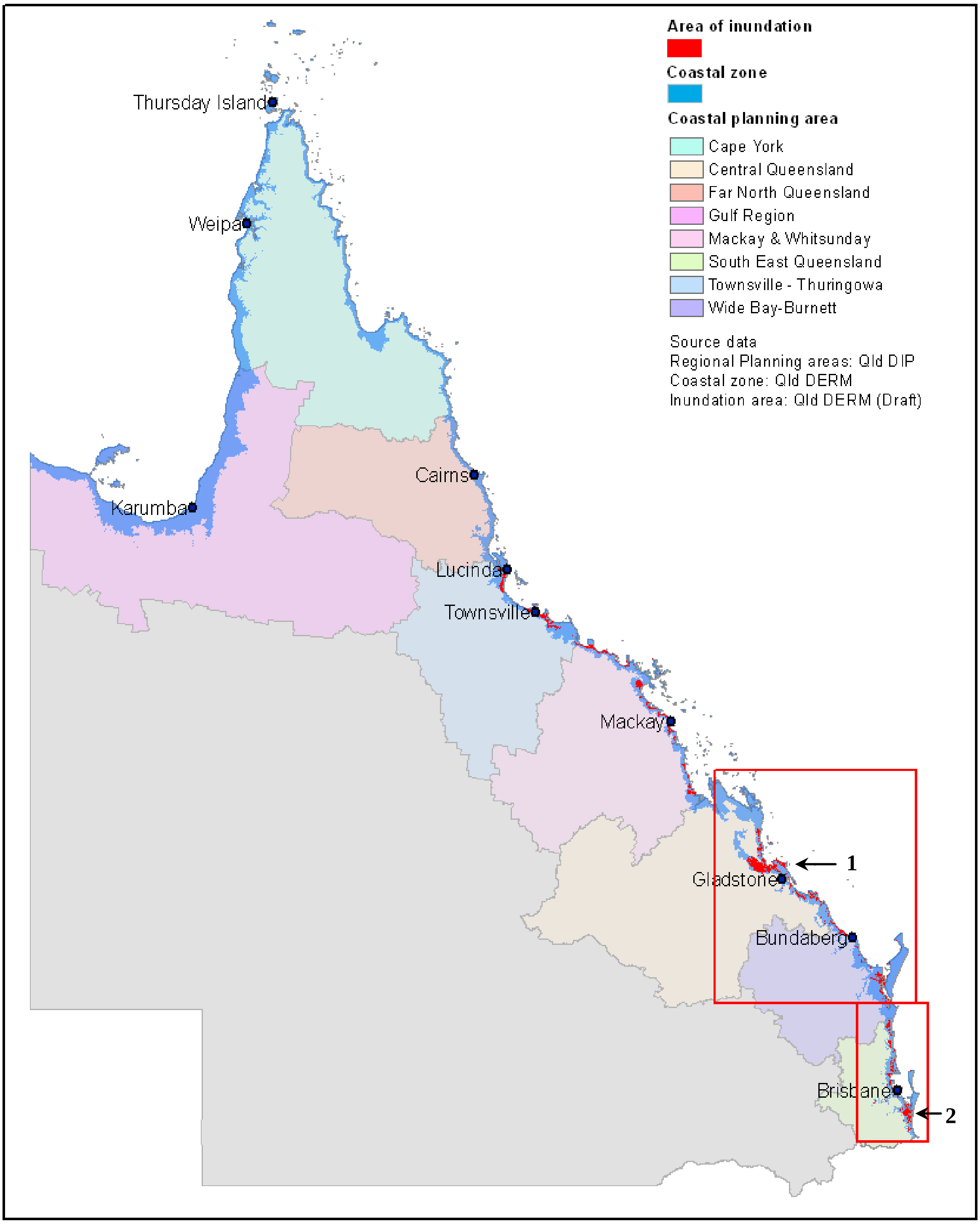

Figure 19: Map of Queensland's Coastal Plan regions. The Coastal zone (blue shade) and expected sea level rise inundation area (red shade) for 0.8m sea level rise. Coastal areas are mapped with LiDAR (Light Detection and Ranging) technology, currently available from Coolangatta in the south to Lucinda in the north. Arrows show two areas with prominent expected inundations – south of Brisbane and north of Gladstone. Insert maps within the red boxes are shown in (Figure 20). Data used with permission, Queensland Department of Environment and Resource Management.

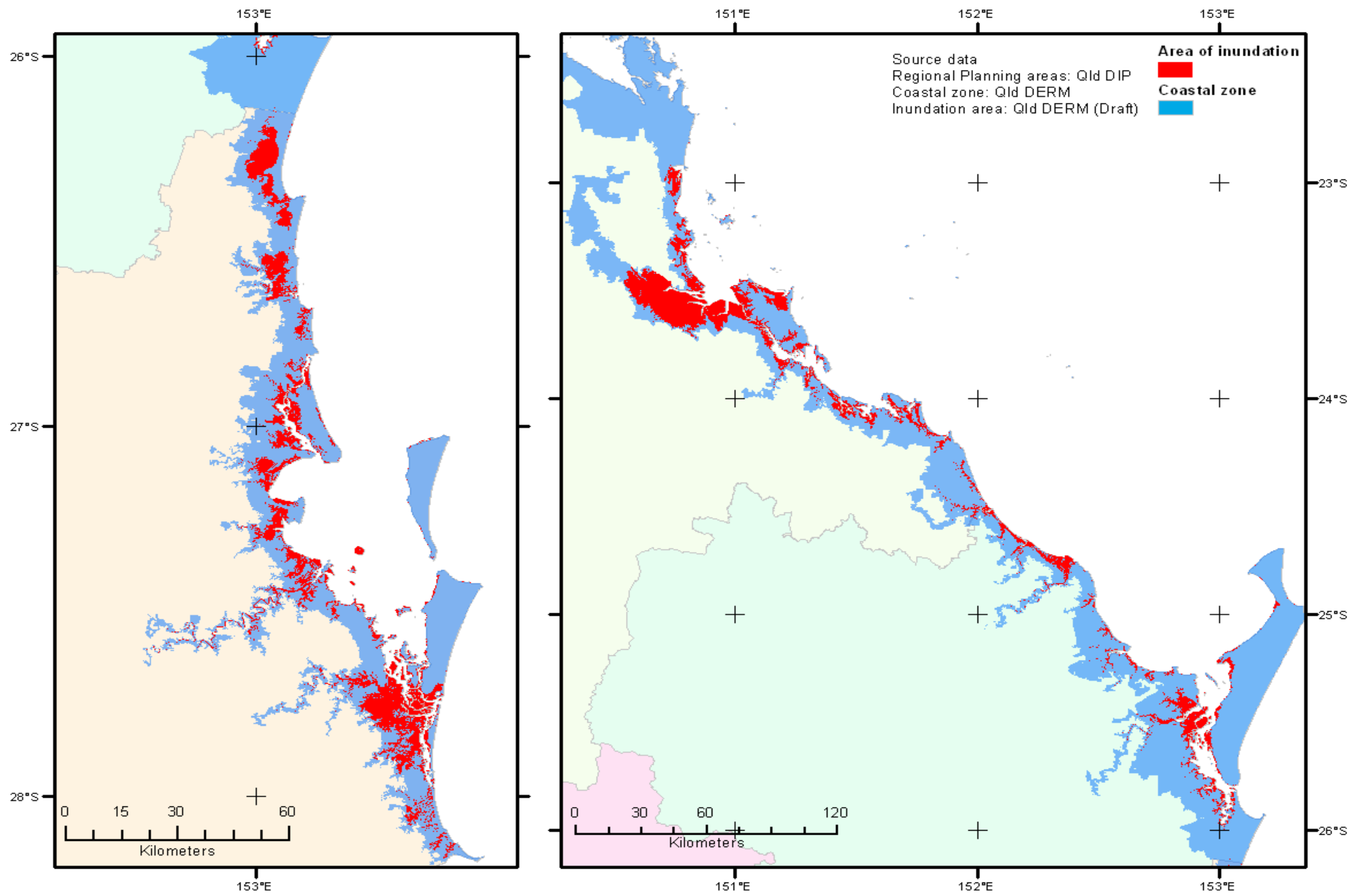

Figure 20: Coastal Plan regions for southern Queensland showing coastal zones that could be inundated by a sea level rise of 0.8m by 2100. Coastal areas are mapped with LiDAR (Light Detection and Ranging) technology - Coolangatta to Lucinda (QCCCE 2011). Map LHS: Coolangatta to Double Island Point. Map RHS: Hervey Bay to Shoalwater Bay. Data used with permission, Queensland Department of Environment and Resource Management.

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