CHARACTERISATION OF THE MARINE ENVIRONMENT OF THE NORTH MARINE REGION

Outcomes of an Expert Workshop

Darwin, Northern Territory
2-3 April 2007

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PREFACE

The Department of the Environment, Water, Heritage and the Arts is developing a Marine Bioregional Plan for the North Marine Region under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The aim of the Plan is to provide a comprehensive source of information and specific guidance for making decisions of relevance to the Region under the EPBC Act. The Department requires scientific input at the following key stages in the development of the Plan:

1. During development of the Marine Bioregional Profile, to ensure that descriptions of the ecological systems and characteristics of the Region are based on comprehensive and up-to-date scientific knowledge, integrated across the relevant disciplines. For the North Marine Region, this has been done through:
   a. the National Marine Bioregionalisation, which is based on a synthesis of biological, geological and oceanographic data;
   b. a comprehensive review of relevant data and literature, supplemented by a number of key reports including:
      - *The North Marine Region Marine Bioregional Plan: Information and Analysis for the Regional Profile* (Rochester *et al*., 2007),
      - *Seascapes of the Australian Margin and Adjacent Sea Floor: Methodology and Results* (Whiteway *et al*., 2007),
      - *Geomorphology and Sedimentology of the Northern Marine Planning Area of Australia* (Heap *et al*., 2004), and
      - *A Description of Key Species Groups in the Northern Planning Area* (National Oceans Office, 2004); and
   c. an expert workshop intended to provide a multidisciplinary ecological characterisation of the marine environment of the North Marine Region from a system perspective.
2. During strategic analysis of threats to the Region's conservation values, which will incorporate expert scientific understanding of the responses of the Region's ecological systems to current and future pressures.
3. During the identification of indicators and development of a framework for monitoring the state of the marine environment in the Region.

This report summarises the outcomes of an expert workshop held in Darwin, Northern Territory during 2–3 April 2007. The objective of the workshop was to characterise the marine environment of the North Marine Region in a way that would improve the Department's understanding of how the Region's natural systems work. The workshop outcomes will provide important information towards the development of a Bioregional Profile for the North Marine Region. More specifically, the workshop aimed to:

- characterise the ecosystems within the Region on the basis of their location, their biological and physical components, and how these may interact;

- provide an understanding of the broad scale drivers of ecosystem functioning across the Region, including identification of important links between ecosystems and the key processes that connect neighbouring systems; and
- identify the key areas of uncertainty surrounding the Region's ecological systems, as well as the areas for which empirical evidence is available.

The workshop focussed on the characterisation of the marine environment within the Commonwealth waters of the North Marine Region. However, the workshop also addressed aspects of the biophysical components, ecological processes and interactions occurring in adjacent State and Territory waters, particularly where coastal inputs and processes have an important influence on marine systems.

The workshop report was initially prepared in a draft form to seek further comments, clarifications and corrections from the workshop participants. This final report incorporates further information provided by workshop attendees in their comments on the first draft, or in subsequent correspondence.

WORKSHOP PARTICIPANTS

The workshop was attended by a broad range of marine and environmental scientists with expertise in the oceanography, coastal and offshore ecosystems, and marine species that occur in northern Australian waters. The attendees were:

Bruce Mapstone (Chair)	Cooperative Research Centre for Antarctic Climate and Ecosystems
Charlie (John) Veron	Australian Institute of Marine Science
Mark Meekan	Australian Institute of Marine Science
Bob Wasson	Charles Darwin University
Peter Rothlisberg	CSIRO Marine and Atmospheric Research
Rodrigo Bustamante	CSIRO Marine and Atmospheric Research
Dave Brewer	CSIRO Marine and Atmospheric Research
Wayne Rochester	CSIRO Marine and Atmospheric Research
Annemarie Watt	Department of the Environment, Water Heritage and the Arts
Suzanne Fyfe	Department of the Environment, Water Heritage and the Arts
Danielle Thomson	Department of the Environment, Water Heritage and the Arts
Ilse Kiessling	Department of the Environment, Water Heritage and the Arts
Pete Cotsell	Department of the Environment, Water Heritage and the Arts
Dave Foster	Department of the Environment, Water Heritage and the Arts
Tania Hoban	Department of the Environment, Water Heritage and the Arts
Louise Wicks	Department of the Environment, Water Heritage and the Arts
Nathan Harris	Department of the Environment, Water Heritage and the Arts
Robyn Hean	Department of the Environment, Water Heritage and the Arts
Peter Bayliss	Environmental Research Institute of the Supervising Scientist
Renee Bartolo	Environmental Research Institute of the Supervising Scientist
Andrew Heap	Geoscience Australia
Brendan Brooke	Geoscience Australia
Trevor Ward	Greenward Consulting/University of Western Australia
Chris Glasby	Museum and Art Gallery of the Northern Territory, Department of Natural Resources, Environment and the Arts
Helen Larson	Museum and Art Gallery of the Northern Territory, Department of Natural Resources, Environment and the Arts
Rod Kennett	North Australian Indigenous Land and Sea Management Alliance
Karen Edyvane	NT Department of Natural Resources, Environment and the Arts
David Williams	NT Department of Natural Resources, Environment and the Arts
Julie Martin	NT Department of Natural Resources, Environment and the Arts
Scott Whiting	NT Department of Natural Resources, Environment and the Arts
Neil Smit	NT Department of Natural Resources, Environment and the Arts
Kath Nash	NT Department of Natural Resources, Environment and the Arts
Andria Handley	NT Department of Primary Industry, Fisheries and Mines
Rik Buckworth	NT Department of Primary Industry, Fisheries and Mines
Col Limpus	Queensland Parks and Wildlife Service
Neil Gribble	Queensland Department of Primary Industries and Fisheries
Guido Parra	University of Queensland

THE NORTH MARINE REGION

The North Marine Region includes all Commonwealth waters from the western side of Cape York to the Northern Territory–Western Australian border. It covers around 715 000 km^2 of ocean in the Timor Sea, Arafura Sea and Gulf of Carpentaria, and also includes the airspace above the water and the seabed below.

While the Queensland and Northern Territory Governments have primary responsibility for State or Territory waters that lie (generally) within 3 nautical miles of their coasts, the Australian Government is responsible for the Commonwealth waters that lie between the State limit and the 200 nautical mile limit of the Australian Exclusive Economic Zone.

LARGE SCALE PROCESSES AND EXTERNAL DRIVERS OF THE NORTH MARINE REGION

Aspects of evolutionary history, geomorphology, climate, oceanography and biology distinguish the North Marine Region from the remainder of Australia's ocean Regions. Such bioregional differences in Australia's marine environment were recognised in the development of the *Integrated Marine and Coastal Regionalisation of Australia* (IMCRA)[1], an ecosystem-based classification of Australia's marine and coastal environments that provides the framework for Marine Bioregional Planning.

The North Marine Region is largely characterised by shallow, soft sediment, tropical marine environments that are unique within the Australian margin. The large-scale processes and drivers that are considered to be important in determining and maintaining the ecological character of the Region are discussed below.

Shallow depth

Ninety seven per cent of the area of the North Marine Region lies over the continental shelf at depths of less than 200 m (A. Heap, workshop presentation). Across most of the Region, including the Gulf of Carpentaria which is the largest tropical epicontinental sea in the world, the water depth does not exceed 70 m. Maximum depths occur at around 350 m in the canyons of the Timor Transition. Hence the North Marine Region comprises the shallowest ocean waters and most extensive area of continental shelf in Australia.

Geomorphology, geology and sedimentology

The Region is characterised by broad areas of gently seaward sloping shelf (to 350 km wide) which support two large and relatively deep mud basins (Bonaparte Basin and Gulf of Carpentaria basin), an extensive system of carbonate banks and a series of shallow canyons extending off shelf (A. Heap, workshop presentation). Submerged reefs are an important feature of the North Marine Region but have only recently been investigated. Many support living corals, hence, the coral reef province of the

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[1] IMCRA v4.0; available at http://www.environment.gov.au/coasts/mbp/imcra/index.html

Region has been found to be larger than previously recognised. The seafloor is dominated by soft sediments. Relict terrigenous muds and sands predominate and have combined with reworked terrigenous sands and modern carbonate deposits to produce a mixed siliclastic/carbonate margin. The Region supports the largest terrigenous province on the Australian shelf (>100 000 km^2) (A. Heap, workshop presentation).

Evolutionary history

As recently as 11 000 years ago, the entire continental shelf was exposed above sea level creating a land bridge between Australia and New Guinea. The seabed topography of the North Marine Region was largely formed during extended periods of lowstand sea levels, when the shelf was exposed to subaeral erosion and the Gulf of Carpentaria and Joseph Bonaparte Gulf supported brackish to freshwater lakes. Coral reef growth reached maximum extent between 8–10 000 years BP along the extant coastline, which included the present day shelf break and the rim of the Gulf of Carpentaria basin (by then a fully marine embayment due to sea level rise). These reefs were subsequently ‘left behind’ as sea level rise became too rapid to be matched by coral growth. There are living coral reefs now submerged some 20–30 m below present day sea level (A. Heap, workshop presentation).

Sea levels have been rising over the last 18 000 years since the last glacial maximum, yet the physical environment is still adapting and ecosystems are still changing in extent and distribution in response to the Holocene marine regime. In relatively short geological time, barriers to dispersal were removed and changes in circulation have resulted. The Indonesian Throughflow current, although it penetrates only weakly into the North Marine Region, is much older and likely to have had more influence on the dispersal of biota than the currents that move through the Torres Strait. Species composition is most like that of the Indo-West Pacific yet the biota also shows affinities with eastern Australian fauna.

Biogeographical disparities have arisen partly because of divergent geological and evolutionary histories, and partly as a result of differences in physical environmental factors that influence species dispersal, population dynamics and community structure. For example, there are clear taxonomic differences in the populations of fish and some groups of sessile invertebrate taxa (e.g. sponges and corals) east and west of the Wessel Islands chain. In contrast, species of polychaetes and molluscs are generally distributed throughout the North Marine Region but show pronounced zonation based on distance from the coast, probably in response to turbidity, sediment type and water depth (C. Glasby, pers. comm.).

Tropical monsoon climate

The interaction between the tropical monsoon climate and extensive shallow shelf results in a dynamic marine environment that is unique in Australia. Wind strength, wind direction and rainfall vary dramatically between the wet and dry season, resulting in seasonal differences in water column mixing, turbidity, productivity, salinity, waves and wind-driven surface currents. Cyclones create large disturbances across shallower parts of the Region, with impacts ranging from localised damage to coral reefs, to widespread turbidity and the mobilisation of sediments. It is likely that climate change will have a significant impact on the Region, resulting in higher water temperatures, increased storm frequency or intensity, sea level change and acidification of the water column.

Terrestrial inputs and the coastal boundary layer

Monsoonal rainfall generates enormous quantities of freshwater, sediment and nutrients that enter coastal waters during the wet season. These terrestrial inputs are trapped within the coastal boundary layer, a body of turbid, eutrophic and highly productive inshore water that follows the coastline of the North Marine Region, extending out to a depth of approximately 30 m. The detritus and nutrients derived from mangroves, salt marshes and mudflats are fundamental to the functioning of coastal marine ecosystems in the Region. Very little mixing occurs between turbid coastal boundary layer waters and clear (oligotrophic) offshore waters, and hence there is little transfer of nutrients, freshwater or sediments into offshore waters. The junction of the two water bodies can be observed as a visibly distinct line during both the wet and dry season. During the dry season, there is little connection between river waters and the coastal sea, and the ‘inverse estuaries’ of northern Australia actually pump water and sediments landward (E. Wolanski, workshop presentation).

The large rivers of Papua New Guinea and Indonesia also deliver enormous quantities of sediment, freshwater and nutrients into the oceans to the north of the Region. These inputs are likely to affect the productivity of the offshore waters of the North Marine Region, although the extent of their influence is unknown. Productivity in offshore waters is predominantly associated with upwellings, eddies and currents, which bring nutrient-rich bottom water into the photic zone. Nutrients may be resuspended in the water column through disturbance by winds, tides, waves, currents and cyclones.

Strong tidal currents

While there are no major ocean currents in the North Marine Region, tidal currents are a significant force in the movement of water and biota, and mobilisation of bed sediments throughout the Region. Currents are particularly strong inshore around islands and reefs, and offshore in channels, canyons and valleys that drain off the shelf. Tidal currents are primarily responsible for the localised upwellings that occur around reefs, banks and islands (E. Wolanski, workshop presentation).

SYSTEMS OF THE NORTH MARINE REGION

Scientists recognised three large scale ecological systems in the North Marine Region: the Gulf of Carpentaria; the Arafura; and the Joseph Bonaparte Gulf. The latter is shared with the North-west Marine Region (figure 1). The Region was divided into systems on the basis of distinctive differences in the major physical drivers and processes that affect these functional areas in characteristic ways including the geomorphology, evolutionary history, oceanography and terrestrial inputs to the systems.

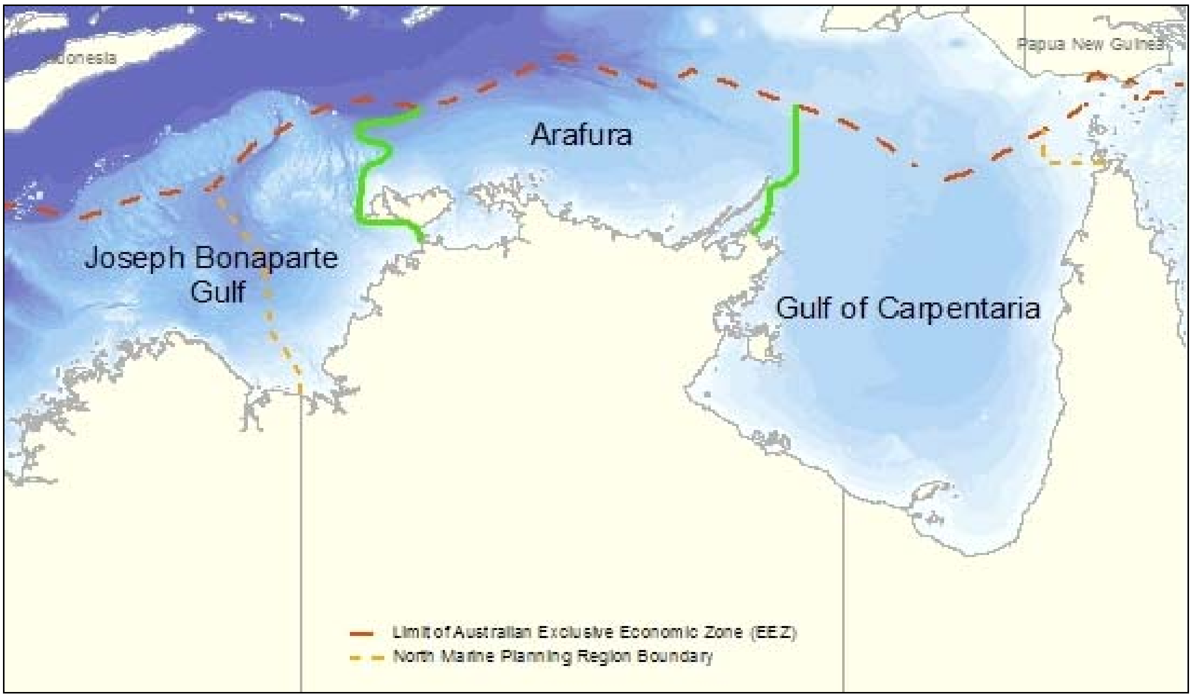


Figure 1 The three major ecological systems identified within the North Marine Region—Joseph Bonaparte Gulf, Arafura (refers to that part of the Arafura Sea that occurs within the Region) and Gulf of Carpentaria. Note that the (green) lines drawn between systems should be considered as ‘fuzzy’ rather than distinct boundaries.

Gulf of Carpentaria

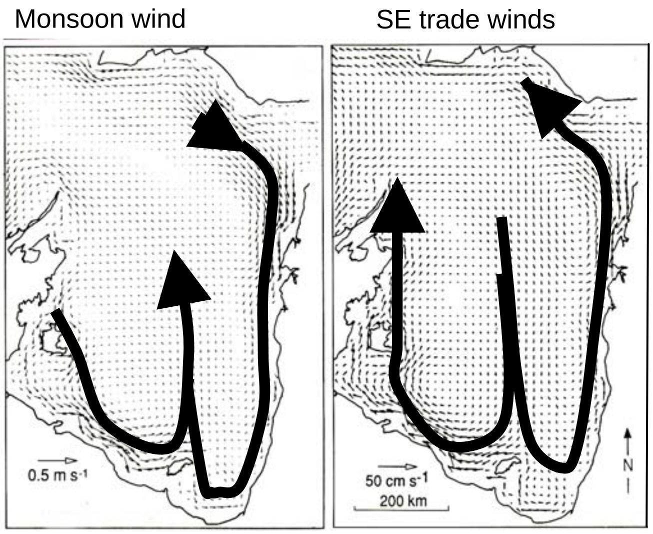
Major physical drivers of the system

The Gulf of Carpentaria is a large, tropical, shallow (< 70 m deep) epicontinental sea that extends from Cape Wessel to the Torres Strait. The geomorphology of the Gulf is dominated by a low-gradient, depositional basin that formed over the broad, seaward sloping shelf during sea level lowstands.

During the late Pleistocene-early Holocene (from 18–9000 years BP), the continental shelf including the entire extent of the present-day Gulf of Carpentaria system was exposed above contemporaneous sea level, forming a continuous land bridge between Australia and the island of New Guinea. The area occupied by the present day Gulf basin supported a brackish to fully freshwater lake varying in extent and connectivity with the ocean, which drained through inlet channels across the Arafura Sill. The transition to fully-open marine system occurred when sea levels rose above the level of the Arafura Sill from around 9000 years BP (A. Heap, workshop presentation).

Surface sediments in the Gulf provide evidence for a varied late Quaternary history of erosion and deposition under fluvial, lacustrine and marine environments. Large areas of relict terrigenous sands in the southern Gulf of Carpentaria have been reworked from shelf deposits during sea level rise, with relatively little input from modern rivers. Similarly, terrigenous mud deposits on the shelf in the north and central Gulf of Carpentaria are largely relict and of lacustrine origin. There are smaller areas in the north, east and west where carbonate banks have formed *in situ* under relatively recent marine conditions (A. Heap, workshop presentation).

Circulation is dominated by a clockwise net tidal residual current that revolves around a tidal amphidrome located to the north-west of the basin centre. Seasonal differences in the wind regime drive a more complex pattern of currents and eddies that have important implications for the differences observed in the biology of the eastern and western sides of the Gulf (E. Wolanski, workshop presentation) (figure 2).


Monsoon wind

SE trade winds

Figure 2 Seasonal differences in the internal currents of the Gulf of Carpentaria (E. Wolanski, workshop presentation, adapted from Wolanski, 1993).

Tidal ranges across the Gulf are mesotidal (2–4 m) and vary from mixed semi-diurnal in the north to mainly diurnal in the south. Tidal energy is generally lower than in the Arafura and Joseph Bonaparte Gulf systems, however tides are chiefly responsible for the mobilisation of bed sediments. Waves exert more influence on sediment transport and mixing in the shallower coastal waters, particularly in the south-eastern Gulf of Carpentaria. Tropical cyclones also contribute a dramatic but localised influence on mixing, sediment mobilisation and disturbance in the Gulf.

There is little net transport of water or nutrients into the Gulf from either the Torres Strait or the Arafura Sea. Strong tidal currents travel back and forth from east to west through the Torres Strait but the net throughflow from (in the dry season) and to (in the monsoon) the Coral Sea is small and transient (E. Wolanski, workshop presentation). Indonesian ghost nets that frequently wash up on the north-western shoreline of Cape York suggest possible penetration of a westerly current into the system. While this has been speculated to represent some penetration of the Indonesian Throughflow current into the system, it is more likely to result from surface currents generated by prevailing north-west monsoon winds. Fronts of productive water that probably originate as upwellings of colder (nutrient-rich) water at the Arafura Fan have been observed to move north-west to south-east across the top of the Gulf during the monsoon season. Trawl fisheries operate in this area, since skipjack tuna and other pelagic schooling fish probably follow these fronts of production. Hence, while some exchange of water and nutrients does occur between the Gulf of Carpentaria and the Arafura and Coral Seas, flushing of the basin is considered to be slow and limited.

Pools of nutrients measured in the waters of the Gulf of Carpentaria Basin are much lower than could be expected given the extent of terrestrial run-off entering the Gulf from surrounding catchments during the monsoon season. Whilst large quantities of freshwater, sediments and nutrients flow into the Gulf during the wet season, the run-off is largely trapped within the coastal boundary and there is limited exchange between the coastal and basin water bodies. Hence, local processes of nutrient recycling predominantly control productivity within the Gulf of Carpentaria basin (figure 3).

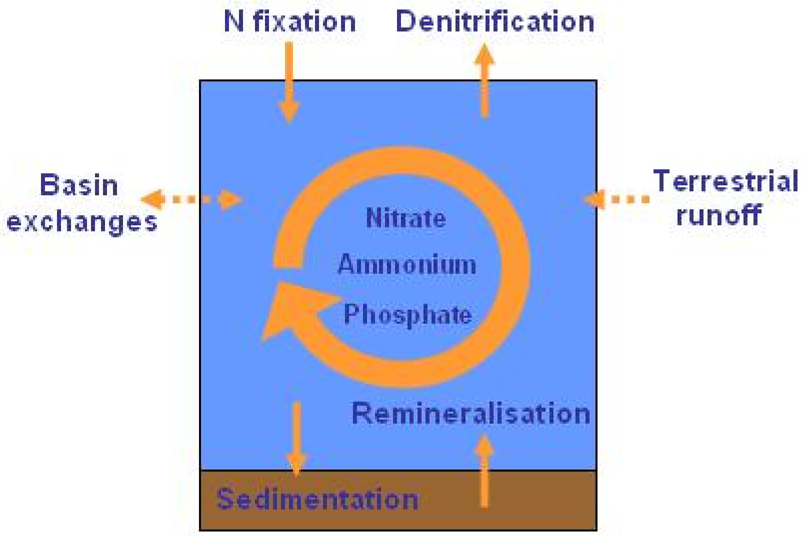


Figure 3 Conceptual model of the nitrogen cycle of the Gulf of Carpentaria (Burford and Rothlisberg (1999), redrawn at workshop by P. Rothlisberg).

Nitrogen and phosphate concentrations in the waters of the Gulf basin are relatively low and there is little if any export of terrestrial carbon into the central Gulf. The terrestrial carbon isotope ratios observed in juvenile prawns found in estuaries are not seen in adult prawns after they have inhabited the basin for a few months. It appears that there is little transfer of carbon, nitrogen and other nutrients from the coastal boundary layer into the basin. Within the basin, nutrients are cycled in and out of the water column via the settling of dead organic matter and subsequent resuspension of basin sediments. The size of the pool of nutrients held in the sediments and the rates of flux have been hypothesised but not yet quantified, although nitrogen has been observed to be a limiting factor to productivity in certain situations (CSIRO has recently commenced research into these factors). Research has shown substantial nitrogen fixation by blue-green algae (predominantly *Trichodesmia*) but denitrification rates are still under review. The range of productivities measured during the wet season in the offshore waters of the Gulf do, however, fall within the range of ‘high productivity’ measured in the coastal boundary layer and in other coastal (i.e. eutrophic) waters around the world.

While wet season (summer) monsoon winds can be dynamic, they blow intermittently. This allows for the waters of the Gulf basin to become stratified, with surface mixing of the water column restricted to a depth of around 30 m. Stratification results in development of a localised deep chlorophyll (productivity) maximum at around 40 m depth (figure 4). At this depth, light penetration coincides with higher concentrations of nutrients that are resuspended into the water column by energetic tidal currents. Research by Condie *et al.* (1999) has shown that ‘hotspots’ of productivity are often associated with regions of high tidal bottom stress. Since wet season productivity can be limited by light penetration through the more turbid water column (relative to dry season conditions, particularly in coastal waters), the areas of highest productivity in the Gulf of Carpentaria do not always coincide with those of highest nutrient concentrations, but rather where mixing is sufficient to bring nutrients into the euphotic zone.

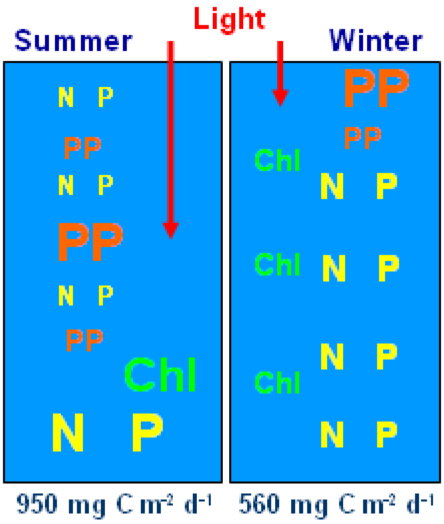


Figure 4 Schematic representation of nutrient, chlorophyll and productivity profiles in wet season (summer) and dry season (winter) (Burford and Rothlisberg (1999) redrawn at workshop by P. Rothlisberg).

In the dry season (winter), south-east trade winds are consistent and strong, and the waters of the Gulf of Carpentaria become well-mixed to the maximum depth of the basin (around 70 m). Nutrients generated from benthic microbial processes are resuspended and become well-mixed into the euphotic zone resulting in primary productivity throughout the water column (figure 4). Any nutrients that are released are rapidly taken up and utilised by phytoplankton so productivity is probably limited by benthic nutrient recycling rates.

The coastal boundary layer is turbid but well-mixed throughout the year due to the combined effects of coastal boundary currents, strong tides and wave action. Hence, primary production in these eutrophic waters is higher and less seasonal than that occurring in the central basin. Variations in production rates observed in the coastal zone are due to north-south differences in outflows of freshwater, nutrients and sediments from the rivers that empty into the Gulf (for further information see CSIRO’s work on catchment classification (http://www.ndsp.gov.au/catchclass/index.html). Anecdotal reports speculate that fish tend to congregate at the periphery of the coastal boundary layer, with inshore species (e.g. barramundi) on the coastal side and pelagic species on the basin side of the margin. Commercial fisheries take advantage of this by concentrating fishing effort in this vicinity (figure 5).

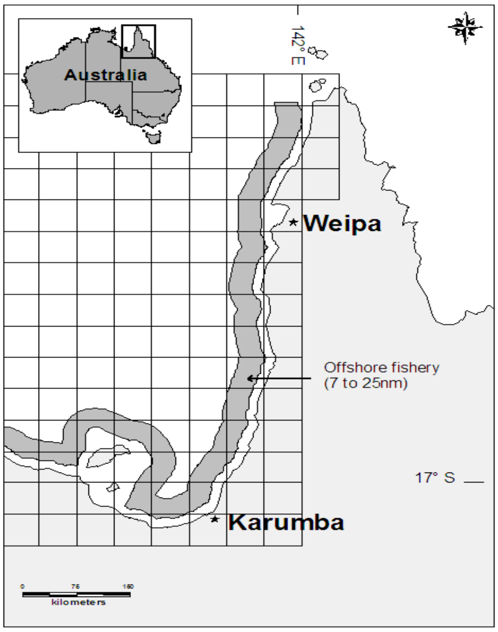


Figure 5 In Queensland, the Gulf of Carpentaria offshore fisheries are generally located between 7–25 nautical miles off the coast (displayed at workshop by N. Gribble)

Overall, the central basin of the Gulf of Carpentaria appears to be a predominantly closed system in terms of water circulation and nutrient cycling. On the other hand, migratory birds feed from Gulf waters and must transfer a large biomass of nutrients to breeding areas on the shore. Similarly, marine turtle breeding is not linked to nutrient availability at breeding sites. Approximately 100 000 t of juvenile marine turtles (with possibly 50 per cent survival rate) leave nesting areas and migrate across and out of the Gulf each year. Hence, in regard to migratory species, the Gulf should not be considered a closed system. In addition, it was speculated that the biomass of coral shrimp (*Metapennaeus* species) moving in and out of estuaries into the basin far exceeds that of commercially important species. The potential for nutrient transfer by these and many other small and abundant organisms is not known. Inverse relationships in the catch rates of inshore and offshore grunter and grey mackerel fisheries have demonstrated that environmental stresses affecting the land (e.g. drought) do have flow-on effects on fish populations in the Gulf basin (Qld Fisheries data presented at workshop by N. Gribble).

Subsystems of the Gulf of Carpentaria

The functional variation that occurs within the ecosystem of the Gulf of Carpentaria is predominantly gradational and relatively minor compared to the differences that discriminate this system from the other major systems of the North Marine Region. The Wessel Islands and Torres Strait were considered by experts to provide unquestioned spatial boundaries to the system, whereas the identification and spatial discrimination of subsystems within the Gulf engendered much discussion.

The division of the Gulf of Carpentaria system into two functional cells was relatively straightforward; there is a clear boundary between the turbid, well-mixed coastal boundary layer and the deeper, less turbid and seasonally stratified offshore waters. Further subdivision into the nine subsystems displayed in figure 6 were based on N-S and E-W differences interpreted in biophysical factors such as coastal catchment inputs and processes, seasonal wind and current regimes, surface sediments, changes in productivity and mixing that occur with depth from the coast, and changes in the biota. For example, genetic research has identified discrete populations in fish species (e.g. mackerel) from E-W across the Gulf. Northern Gulf fisheries target different species to the fisheries based in the southern Gulf of Carpentaria.

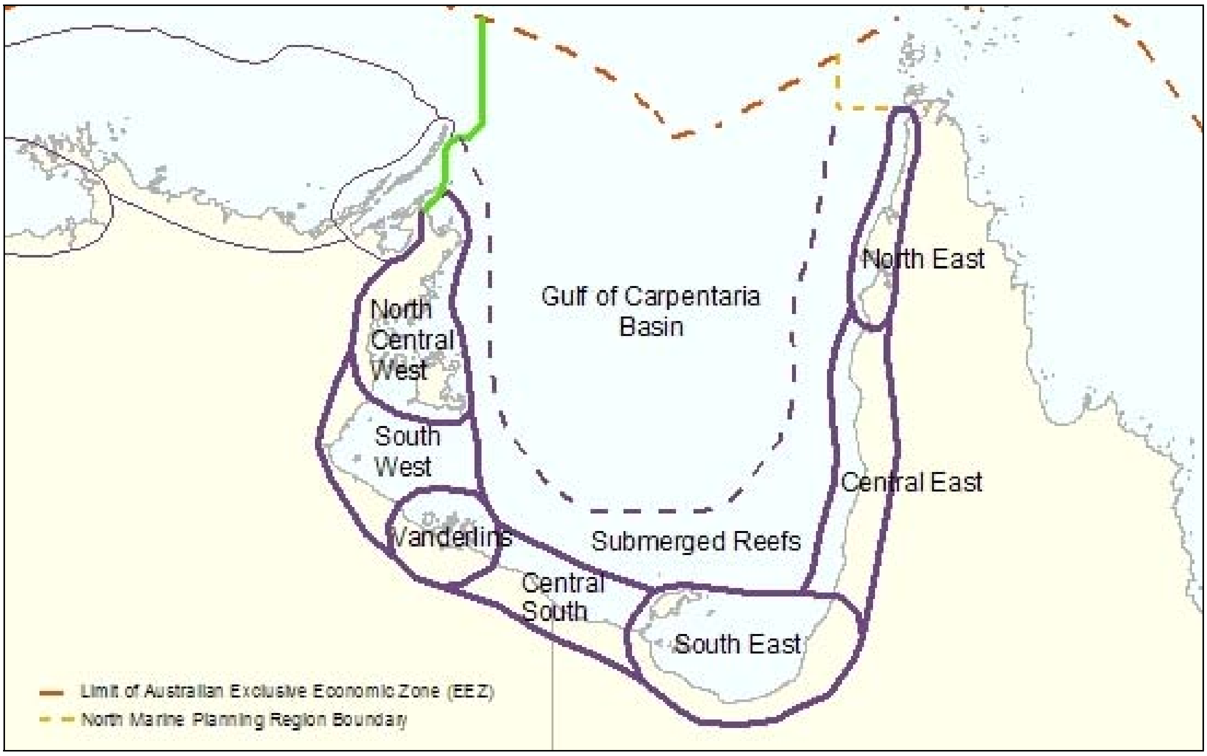


Figure 6 Subsystems identified for the Gulf of Carpentaria system (N.B. 'Vanderlins' refers to the Sir Edward Pellew Group and surrounds). Boundaries are indicative only.

The lines drawn between subsystems should be considered as 'fuzzy' boundaries since functional dissimilarities between the coastal subsystems are predominantly gradational rather than discrete, and because different taxonomic groups may separate spatially in a different way to those reported in the following subsystem descriptions.

GULF OF CARPENTARIA BASIN

The centre of the Gulf of Carpentaria is characterised by a low gradient, relatively featureless, soft sediment basin varying in depth from around 45–80 m. Surface sediments vary from sandy muds on the western side of the basin to muddy sands on the eastern side (A. Heap, workshop presentation). Productivity is driven by the resuspension of fine, nutrient-rich seabed sediments into the euphotic zone of the water column. Benthic microrganisms and deposit feeders play a major role in the recycling of nutrients within this relatively closed system. In the dry season, productivity may be limited by the rate of benthic decomposition and nutrient release into the water column while in the wet season, stratification of the water column restricts the mixing of nutrients into the euphotic zone.

The Gulf of Carpentaria basin supports a rich assemblage of pelagic fish species including planktivorous and schooling fish, with an abundance of top predators such as sharks, tunas and mackerels. There is a clear distinction between the demersal fish assemblages of the basin and those of the adjacent coastal subsystems. Anecdotal evidence from commercial fisheries suggests that there may be some increase in productivity and biodiversity in the vicinity of the Arafura Sill, possibly due to localised upwelling. The Gulf basin encompasses important migratory routes for seabirds and shorebirds and for the pelagic dispersal of marine turtles. The area provides foraging grounds for seabirds and for flatback and olive ridley turtles, which predominantly feed on small pelagic fish and invertebrates. The macrobenthic fauna of the Gulf of Carpentaria basin has been relatively well studied in comparison with other parts of the North Marine Region. The soft sediments of the basin are characterised by benthic scavengers and deposit feeders, including moderately abundant and diverse communities of infauna and mobile epifauna dominated by polychaetes, crustaceans, molluscs and echinoderms, notably brittle stars and heart urchins.

SUBMERGED REEFS

Shallow water fringing reefs and isolated coral colonies are known to occur along the northern coastlines of the Gulf of Carpentaria (see work of Veron, 2004), however, living submerged patch reefs were only recently mapped and described in the southern Gulf of Carpentaria (A. Heap, workshop presentation; for further information refer to the research of Harris *et al*., 2008). Fishermen have known about and charted the existence of such patches of hard substrata termed ‘untrawlable grounds’ for many years.

Submerged patch, platform and/or barrier reefs form a broken margin around the perimeter of the Gulf basin, rising from seafloor depths of 30–50 m. The reefs vary in distance from the coastline depending on the slope of the seabed to this depth. Hence, they are in closest proximity to the coast along the western rim of the Gulf near Groote Eylandt and furthest offshore in the southeast Gulf of Carpentaria. The reefs exhibit flat-topped patch reef morphology, with reef platforms in depths of around 25–30 m and reef tops or crests that rise to around 20m depth. Reefs that have been surveyed are oval-shaped and demonstrate steep, spur-and-groove fore-reef slopes and talus accumulations on their leeward margins. In the southern Gulf, isolated living patch reefs are situated over two broad, flat-topped plateaus that extend north-west from Mornington Island. These plateaus represent much older, eroded karst surfaces (A. Heap, workshop presentation).

Most reef growth occurred during a prolonged sea level stillstand between 8–10 500 years BP, when sea levels were around 30 m lower than present and environmental conditions were more suitable for carbonate deposition. Since then, while live corals continue to inhabit the reefs, bioherm building activity has not ‘kept up’ with modern sea level rise. This is consistent with a ‘give up’ reef growth history (P. Harris, pers. comm.).

Although the reef structures are predominantly relict, they support a thin and patchy cover of live corals including large plate corals (*Turbinaria* species), abundant hard corals (*Leptoseris* species) and a large proportion of soft corals. The reefs are inhabited by typical northern Australian coral reef fauna including octocorals, sponges, ascidians, gorgonians and reef fish. Anemones predominate on the sandy talus slope while the steeper reef margin is dominated by sponges, bryozoans, crinoids and ascidians. Macroalgae are sparse but primary productivity may be enhanced through localised micro-upwellings induced by tidal currents that stimulate phytoplankton blooms around the reefs. Mobile faunal assemblages of relatively low diversity dominate the shelf area surrounding the reefs. Prawns and sea urchins are most abundant in these soft sediment shelf habitats.

The submerged reefs provide breeding and aggregation areas for many fish species including mackerel (*Scomberomorus* species) and large commercially important snappers (*Lutjanid* species), and offer refugia for seasnakes and predators including sharks. The coral trout that inhabit the Gulf reefs are somewhat smaller than those found on the Great Barrier Reef and may prove to be an endemic subspecies.

The submerged reefs of this subsystem are considered highly vulnerable. Surface water temperatures are high compared to surrounding water (28–30°C year round) and therefore, under present climatic conditions are close to sea surface temperatures known to induce coral bleaching. The deep and relatively turbid water conditions may protect the corals from bleaching, but are less than ideal for coral reef growth; corals demonstrate patchy cover and very slow growth rates (1 m per 1000 years) on these submerged reefs. The relatively closed circulation in the Gulf of Carpentaria may restrict the ability of reef species to recolonise from the Indo-Pacific and may already limit dispersal into the south of the Gulf.

NORTH-CENTRAL WEST

The North-Central West subsystem extends from east of the Wessel Island chain, largely taking in the coastal waters on the north-western side of Gulf of Carpentaria to the south of Groote Eylandt. The coastal geomorphology of this subsystem is complex and very different to elsewhere in the Gulf. In the north, rocky headlands and reefs are interspersed with sandy embayments. Inshore relict sands grade rapidly with depth into muddy, offshore shelf sediments (A. Heap, workshop presentation). Further south, numerous islands with sandy margins and fringing coral reefs sit on a wide, shallow sandy terrace. Tidal heights are notably lower in this subsystem than elsewhere in the Gulf (< 2 m), but there are localised areas of high tidal energy. Inshore of the islands, coastal sediments contain higher concentrations of mud (A. Heap, workshop presentation). The hinterland of the North-Central West subsystem is swampy and characterised by a low density of rivers and streams with small catchments. The only substantial fluvial deposition occurs in Blue Mud Bay. Consequently, the waterways contribute the smallest terrigenous inputs of freshwater, sediment and nutrients to the coast of any of the Gulf subsystems and hence the coastal boundary layer is narrower here than elsewhere in the Gulf.

The subsystem offers a diverse range of habitats for marine organisms. Although hard substrate faunal assemblages have not been studied extensively in this region, the microtidal range would allow for the development of more abundant and diverse invertebrate and macroalgal assemblages on the rocky intertidal and shallow subtidal areas. Corallimorpharians and corals are plentiful although hard corals do not build reefs in this area (see Veron, 2004). Hawksbill and green turtles forage on the submerged rocky reefs. The sandy beaches and offshore islands provide important nesting sites for crested, bridled, roseate and black-naped terns, and green, olive ridley, hawksbill and flatback turtles.

The water column is particularly turbid in the region, restricting the depth to which seagrasses can grow. However, extensive meadows occur in intertidal and shallow subtidal areas of Blue Mud Bay and in sheltered bays around Groote Eylandt and its offshore islands. Dugongs and mud crabs depend on the seagrass meadows for feeding and breeding. Blue Mud Bay is a particularly important dugong calving area and it supports some of the richest mud crab and barramundi fishing grounds in northern Australia. Juvenile prawn communities are closely associated with the seagrasses but move offshore as they mature. The subsystem supports the largest tiger prawn (*Penaeus esculentus* and *P. semisulcatus*) fishery in the Gulf of Carpentaria. Top predators including sharks and mackerels are also considered important in this subsystem.

SOUTH WEST

The South West subsystem comprises the large, shallow bay (< 30 m in depth) known as the Limmen Bight which is situated between the southern end of Groote Eylandt and the north-western side of the Sir Edward Pellew Group. A large (approximately 1 km wide), tide-dominated delta marks the convergence of the Roper River with the head of the Bight. This extensive estuarine system seasonally delivers huge terrigenous inputs of sands and freshwater from the largest catchment in western Gulf of Carpentaria into the coastal boundary layer, which may extend 75–100 km offshore in this subsystem. The sandy nearshore sediments are stirred by waves and tides.

The coastal waterways are characterised by expansive supratidal salt marshes and saltpans, tidal mudflats and narrow fringes of mangroves. These highly productive wetland areas are significant for populations of waterbirds and shorebirds that feed on the mudflats and salt marshes, although numbers are not as abundant as found in the south-eastern Gulf where freshwater inflows are greater.

The South West subsystem is known to be particularly important for mud crabs, barramundi and dugongs, which inhabit the seagrasses that form expansive meadows along the intertidal areas and in shallow waters to the north and south of the Roper River delta. Seagrass habitat has been protected through fisheries closures in significant seagrass beds (e.g. in the Northern Territory Barramundi Fishery and the Northern Prawn Fishery). Grey mackerel (*Scomberomorus semifasciatus*) and sharks are fished in the area. Large numbers of crocodiles are present in the estuaries but only a small amount of marine turtle nesting takes place within the subsystem.

VANDERLINS (SIR EDWARD PELLEW GROUP)

The Vanderlins subsystem incorporates the Sir Edward Pellew Group and surrounding waters. This varied ecosystem provides heterogeneous habitat for a wide range of marine biota, and is also very important, culturally, to the people of the Gulf of Carpentaria. The extensive estuarine system of the McArthur and Robinson Rivers empty into a large delta with outflows entrained into a shallow bay by the offshore island chain. Significant seagrass meadows occupy the muddy sands trapped inshore of the Sir Edward Pellew Group, supporting a major population of dugongs. The coast is characterised by large sand dunes, tidal channels fringed by mangroves, wide supratidal mudflats and extensive salt marshes and saltpans. In contrast, the intertidal margin of the offshore islands is bare and rocky, with some development of intertidal and subtidal coral communities. Many coral reef species were documented from the Sir Edward Pellew Group in 1927, but the marine environment in this region has not been studied for corals since, so it is not known whether such diverse coral communities still exist. Subtidal and intertidal coral reefs around the Sir Edward Pellew Group are known to have been damaged by cyclones in recent years; the extent to which they have recovered is unknown.

Coastal salt flats are flushed of nutrients and saline water during the wet season, stimulating productivity in the coastal boundary layer. The area provides important nursery grounds for juvenile crabs and prawns, and sustains rich mud crab and banana (*Penaeus merguiensis*) and tiger prawn fisheries. The islands and inshore waters are also popular for recreational fishing. The Sir Edward Pellew Group provides nesting and/or foraging grounds for flatback, hawksbill and olive ridley turtles. Small seabirds and shorebirds are abundant in this subsystem, occurring in high numbers but with lower biomass than the bird populations of the south-eastern Gulf of Carpentaria.

CENTRAL SOUTH

There is little to define the remote coastal region lying between the Sir Edward Pellew Group and the Wellesley Islands and, in general, the area has been poorly sampled. The coastline supports sandy beaches backed by low dunes and freshwater lakes and swamps. Small river catchments deliver little in the way of terrigenous inputs to the coastal boundary layer and the sandy seabed is characterised by reworked relict shelf sands. No significant primary production occurs in the water column and the shoreline supports only a narrow strip of seagrass, with few mangroves fringing the mouths of creeks. The Central South is an important area for freshwater birds but only small numbers of seabirds inhabit the subsystem. Similarly, few marine turtles and crocodiles inhabit the area.

SOUTH EAST

The South East subsystem, which extends from Mornington Island to the Staatan River, incorporates an expansive area of gently sloping, shallow shelf overlain mainly by reworked terrigenous sands (A. Heap, workshop presentation). Several large catchments drain into the south-eastern Gulf of Carpentaria, including those of the Nicholson, Flinders, Leichhardt, Norman, Gilbert and Staaten Rivers. These rivers deliver large amounts of sediment, nutrients and freshwater into the Gulf, which become trapped in the coastal boundary layer. Consequently, the coastal boundary layer reaches its widest extent (100–150 km) and the waters of the South East are highly productive within this subsystem.

The estuarine system supports extensive and continuous wetlands (the Southern Gulf Aggregation), which include mangrove communities, salt marshes and supratidal clay pans that release pulses of nutrients and saline water after extreme high tides. This subsystem experiences the highest tidal range (3–4 m) in the Gulf of Carpentaria; hence there are broad areas of intertidal mudflat supporting high concentrations of benthic microalgae (BMA) but only small meadows of seagrass. Tidal velocities are relatively low but coastal waters remain turbid as a result of consistent mixing by wave action across the shallow shelf.

Due to high levels of coastal productivity, the South East subsystem represents a ‘hotspot’ for the banana prawn fishery (April–May) with lesser populations of tiger prawns fished in the vicinity of the Wellesley Islands. Productive waters also generate a high biomass of pelagic fish and the area supports a small mackerel fishery but is better known for recreational fishing of species such as grunter (*Pomadasys kaakan* and *P. argenteus*). There are important seabird rookeries on offshore islands of the Wellesley Islands Group, however, it is the large populations of migratory wading birds for which this area is renowned. Aerial surveys have revealed just how significant the South East subsystem is to migratory shorebirds and breeding populations of waterbirds that exploit the rich food resources of the intertidal mudflats and marshes. The coastal estuaries and wetlands also support significant numbers of crocodiles.

Areas of rocky intertidal and shallow reef around the Wellesley Islands probably support small amounts of macroalgae, invertebrate assemblages characteristic of hard substrates, and some reef fish. East of Mornington Island, there are widespread hard grounds characterised by eroded tidal channels and a largely relict bryomol (i.e. bryozoan and mollusc) platform reef with its upper surface in 30 m water depth. Both sessile and mobile fauna inhabit the benthos, with bryozoans and crinoids dominant in valleys, and brittlestars, hydrozoans and bryozoans most abundant on the bryomol reef (see Post, 2006). In general, the sandy muds of the shelf are dominated by mobile epifauna including prawns and sea urchins.

The Wellesley Islands are culturally very important to indigenous communities who hunt marine turtles and dugongs in the coastal waters. Offshore islands are particularly significant for green turtle breeding. Dugongs do not reside in large numbers in this subsystem but appear to move through the waters regularly.

CENTRAL EAST

The Central East subsystem describes the coastal waters in the eastern Gulf of Carpentaria between Aurukun and the Staaten River. Seabed sediments are coarser (dominated by sands and gravels) and display higher carbonate content than elsewhere in the Gulf of Carpentaria (A. Heap, workshop presentation).

The catchments of the eastern Gulf are smaller than those of the southern Gulf, however, the largest river of Cape York (Mitchell River) empties into this subsystem. Terrestrial inputs to the coastal boundary layer are moderate but productivity is lower than in the south. Sandy beaches interspersed with small estuaries are typical of the shoreline and there are no significant seagrass meadows in this area. Mangrove communities display relatively low diversity and are confined to river mouths. Salt marshes and saltpans border the mangroves but are not as extensive as those found in the southern Gulf.

The subsystem supports a viable banana prawn fishery and river-based gillnet fisheries and is a popular area for recreational fishing. Mud crabs are commercially harvested and are particularly abundant in the Mitchell River. The blue swimmer crabs that occur in the Central East subsystem are of different genetic stock to those found elsewhere in the Gulf and are not commercially fished due to their smaller size. Other commercial species of interest include a subpopulation of barramundi that appears to be endemic to the west coast of Cape York (see genetic studies by Shaklee and Salini, 1985). Crocodiles and flatback and hawksbill turtles breed in significant numbers within the subsystem.

NORTH EAST

The North East subsystem of the Gulf of Carpentaria encompasses the coastal waters of Cape York from Aurukun north to the Torres Strait. The coastal boundary layer receives relatively little in the way of terrestrial inputs and consequently, is narrower in this subsystem compared with the southern and central Gulf. River catchments are small and rainfall is lower in the northern part of Cape York, hence sediment, nutrient and freshwater inflow are limited. Albatross Bay, Port Musgrave and the estuarine systems that drain into these sheltered embayments, support seagrass meadows and mangrove forests. The coastline displays features of a wave-exposed environment and is typically dominated by sandy beaches and large, erosion-prone dunes. Wave energy is higher here than elsewhere in the Gulf, particularly during the monsoon season when north-west winds drive a long fetch across the top of the Gulf. High tidal velocities in this region contribute to a dynamic nearshore environment, hence the sandy seabed is highly mobile and frequently disturbed. In the north, the subsystem begins to share many characteristics in common with the Torres Strait, including extensive tidal sandbanks and offshore reefs. The coral reefs of the Submerged Reef subsystem occur closer to the coast at this location than elsewhere in the Gulf.

The Love and Kirk Rivers contain notable populations of sawfishes. Estuaries and rivers are inhabited by brackish water sharks including juvenile bull sharks that move offshore as they mature, the critically endangered speartooth shark (*Glyphis glyphis*) and a previously unrecognised *Glyphis* displaying different colouring on its fins that may prove to be a new species (H. Larson, pers. comm.). Reef fishes (e.g. coral trout, red emperor, sweet lip) are relatively common in the North East subsystem. In the past, the Albatross Bay area supported a large banana prawn fishery. Offshore fisheries target mackerel, which feed on juvenile prawns coming out of the estuaries at the end of the wet season (the ‘mackerel highway’).

Several marine taxa demonstrate a change in genetics in this subsystem. For example, distinct genetic stocks of barramundi and mud crabs occupy the estuaries of the North East subsystem. There was speculation that the fauna of north-eastern Gulf of Carpentaria have stronger biogeographical connections with eastern Australian marine taxa than anywhere else in the North Marine Region. This is not true for all groups, however. For example, there is a dramatic turnover in species composition and richness of sponges at the boundary between Cape York and the eastern Gulf of Carpentaria (see Hooper and Ekins, 2004).

The North East subsystem supports the world's largest breeding colony of flatback turtles (Crab Island) and moderate levels of olive ridley turtle nesting. The estuaries and rivers of north-western Cape York, especially Port Musgrave, are known to provide the most significant crocodile breeding habitat in Queensland. Dugongs are relatively scarce in the area, and are mainly confined to Albatross Bay and Port Musgrave. No major seabird breeding occurs in the area.

Arafura

Major physical drivers of the system

The Arafura system includes the portion of the Arafura Sea that lies within the North Marine Region. The system is bordered on the western side by the carbonate banks of the Van Diemen Rise, and on the eastern side by the Wessel Islands, which separate this system from the Gulf of Carpentaria. The northern boundary is defined by the limit of the Exclusive Economic Zone (figure 1).

The Arafura system comprises a broad, shallow continental shelf that was drowned during sea level rise less than 18 000 years BP. The present seabed morphology is largely the result of subaeral erosional processes. Characteristic features include a broad expanse of relatively featureless shelf topped by limited areas of banks, shoals, submerged reefs and terraces. Further offshore the shelf slope and a system of canyons drop into the deeper water of the Arafura Depression. Surface sediments across the shelf contain a relatively high proportion of carbonate grains (A. Heap, workshop presentation). Sediments become progressively coarser in texture and higher in carbonate concentration with distance offshore away from terrigenous sources on the coast. On the outer shelf and upper shelf slope, the carbonate sediments mix with terrigenous clays from Indonesian rivers (see Heap *et al*., 2004).

Few oceanographic data are available for the Arafura Sea region. The Indonesian Throughflow brings tropical waters from the Western Pacific Ocean through the Indonesian Seas into the Timor and Arafura Seas but the influence is probably restricted to the outer shelf (E. Wolanski, workshop presentation). This current does have some influence on pelagic dispersal and therefore the composition of the Arafura fauna, which, with the exception of a few taxonomic groups, largely shares affinities with the taxa of the western Indo-Pacific. Surface currents move towards the west between April and November under the influence of the prevailing trade winds and possibly under the influence of the South Equatorial Current. During the monsoon period (December to March), surface currents are weak and have no distinct direction (see Harris *et al*., 1991).

Tidal ranges vary along the coast but are predominantly mesotidal (2–4 m). Tidal currents, however, move with higher velocity throughout the Arafura system than through the Gulf of Carpentaria and tidal energy dominates the mobilisation of bed sediments across the shelf. Where the bathymetry is rugged (e.g. around canyons, shoals, reefs or islands) these strong tidal currents generate internal waves, eddies and jets that probably result in upwellings and localised hotspots of productivity (E. Wolanski, workshop presentation).

The Arafura system is distinct in that (with the exception of the Van Diemen Gulf subsystem) it does not receive high volumes of terrigenous input compared with the Gulf of Carpentaria or Joseph Bonaparte Gulf. While trophic relationships inshore within the coastal boundary layer are influenced by terrestrially derived sediments, freshwater and nutrients, productivity offshore is derived from nutrient rich upwellings of cooler water, eddies and currents.

Subsystems of the Arafura

Scientists recognised four distinct subsystems within the Arafura system (figure 7), which were labelled as the Arafura Fan, Arafura Shelf, Van Diemen Gulf and Wessel Islands subsystems. The subdivision of the system was largely based on depth, geomorphology and characteristics of the biogeography of the area. There was discussion as to whether the semi-enclosed, macrotidal Van Diemen Gulf represented a separate system in itself, since the physical environment and ecosystem function of the Gulf is so different to that of the Arafura Shelf. Similarly, the deeper waters of the Arafura Fan were considered different enough to represent a potentially separate system. In retrospect, it was considered that the Arafura Shelf subsystem could have been further divided into an offshore shelf subsystem and a narrow coastal zone subsystem, in line with the ecosystems identified for the Gulf of Carpentaria and Joseph Bonaparte Gulf. Such a coastal/offshore division is supported by polychaete and mollusc data (C. Glasby, pers. comm.). Experts also suggested that the Wessel Islands subsystem might be considered as a transition system since the area represents an important biogeographical disjunction for some taxonomic groups (e.g. sponges) although not for others (e.g. polychaetes and molluscs which show more pronounced regionalisation based on distance from the coast in response to physical environmental factors).

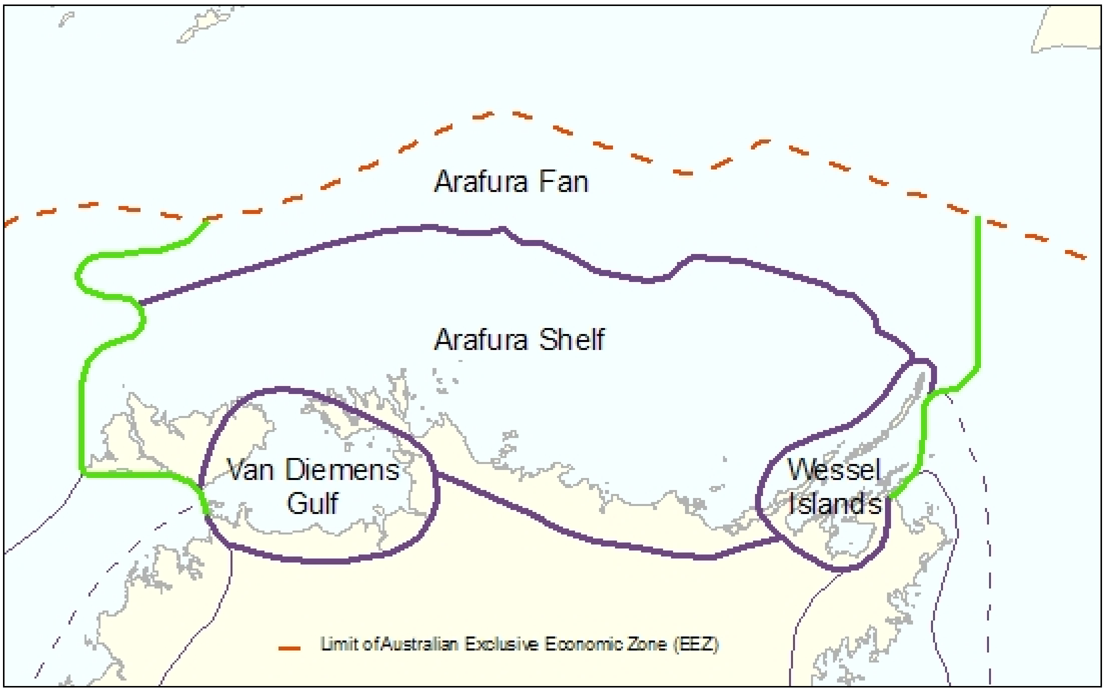


Figure 7 Subsystems identified for the Arafura system. Boundaries are indicative only.

VAN DIEMEN GULF

Nick-named 'the bathtub' by workshop participants, the Van Diemen Gulf subsystem occupies waters of Northern Territory jurisdiction between Melville Island, the Cobourg Peninsula and the mainland coast. It is a semi-enclosed embayment, poorly flushed but with a large tidal range (3–4 m) and scoured by strong tidal currents. Large catchments, including those of the East and South Alligator, Adelaide and Mary Rivers, contribute significant inflows of sediment, freshwater and nutrients into this subsystem during the monsoon season. The coastline is pro-grading (advancing toward the sea) because of the significant deposition at river mouths, which is reworked by tides. A sand barrier created by tidal deposition in the centre of the basin enhances the trapping of freshwater inflows during the wet season, leading to low salinities within the Van Diemen Gulf. Waters are continuously turbid with many of the nutrients from onshore attached to suspended sediment particles. In spite of the turbidity, coral reef outcrops are present off the coast of the South Alligator River, and the Vernon Islands contain a surprisingly well-developed coral reef system with large reef flats.

Hawksbill and green turtles inhabit the reef flats near the Vernon Islands and Alligator Rivers. The rivers and estuaries of the Van Diemen Gulf are nursery areas for juvenile dolphin and *Glyphis* species. The coastal estuaries, mudflats and wetlands are extremely important for migratory shorebirds and colonially breeding waterbirds (Chatto, 2000, 2001, 2003, 2006)

ARAFURA FAN

The Arafura Fan subsystem comprises the northern portion of the Arafura Shelf and areas of shelf terrace and slope that extend into deeper waters (200–300 m deep) in the Arafura Depression. The gently sloping platform of the shelf is dissected into a series of canyons around 80–100 m deep and 20 km wide, the largest of which extends some 400 km from Cape Wessel into the Arafura Depression. The canyons represent a drowned fluvial system that existed during Pleistocene (and possibly older) sea level lowstands. The Arafura Fan itself is the result of continuous Late Quaternary marine and probably terrigenous deposition at the outflow of the canyons (see Heap *et al*., 2004).

The subsystem is primarily influenced by oceanographic processes, possibly associated with the Indonesian Throughflow and surface, wind-driven circulation resulting from the north-west monsoons. The location of canyons at the head of the Timor Trough directs upwellings of deep water onto the shelf and sill to the north of the Wessel Islands. Productivity within this subsystem is likely to be driven by these deep water upwellings of nutrient-rich water since primary production by phytoplankton forms the basis for offshore food webs such as this (compared to coastal food webs where benthic production and outflows of organic matter are also important factors driving the food web).

Pelagic species dominate the open ocean environment of the region and many of the fish species that inhabit the area also have pelagic larval stages. Seasnakes, including the pelamis seasnake (or yellow-bellied seasnake, *Pelamis platurus*) are found associated with slicks and drift lines in water depths of 50–60 m or more. There is a distinctive biota associated with the location of upwellings along the shelf-edge and shelf slope, which includes whale sharks and a distinct offshore suite of threadfin species (Polynemidae). Migratory species (e.g. dugongs and marine turtles) may utilise the area as a connecting point across the deeper Timor Trench to the Indonesian Sea. Research on red snapper (*Lutjanus erythropterus*) shows a distinct genetic stock associated with the canyons and channels of the subsystem (see research work by Blaber *et al.*, 2005), and there was a suggestion that unique fish assemblages had been uncovered on the Lynedoch Bank during a Southern Surveyor voyage. Geoscience Australia surveys in the canyons have located deep sea sponges, barnacles and stalked crinoids known previously only from southern deep waters around Australia (CSIRO, 2005), and there is also anecdotal evidence of high densities of sawfishes in these deep channels. This generally indicates how little is known about the biology of the area, particularly the benthic and demersal communities that inhabit canyons.

ARAFURA SHELF

The Arafura Shelf subsystem encompasses a large expanse of gently sloping shelf, adjacent inshore waters and the coastline of Arnhem Land in the Northern Territory. The nearshore environment is characterised by rocky reefs and sandy bays. Rivers and catchments are generally small so there is less terrigenous input to this subsystem. Consequently, the turbid coastal boundary layer is narrower than that found in Van Diemen Gulf. There are extensive shallow areas of muddy sediments susceptible to disturbance and mixing by strong tidal currents. Resuspension of nutrient rich sediments into the photic zone may be an important driver for productivity in offshore areas of the subsystem. Tidal eddies around islands also induce localised upwellings and hot spots of productivity, which correspond with aggregations of marine life. Sediments become progressively coarser and contain a higher carbonate concentration with distance from the coast.

The coral communities of Arnhem Land are diverse and some species form unusually large colonies, but they do not form reefs (see Veron, 2004). The exceptions within the Arafura Shelf subsystem are the coral reefs of the Cobourg Peninsula. The Indonesian Throughflow may transport some coral species from Indonesia and Western Australia into this region, but taxonomic affinities are clearly with the coral biota of Torres Strait (Veron, 2004). A coral bleaching event recorded between November 2002 and January 2003 caused significant destruction to corals and surrounding habitats in Coral Bay on the Cobourg Peninsula. For example, 75–96 per cent of *Acropora* species were lost and had not recovered some three years after the event, although non-acroporid corals were showing some recovery (see Gomelyuk, 2007).

The Cobourg Peninsula is known to be a hot spot for sponge diversity (see Hooper and Ekins, 2004). Marine turtles are present in this subsystem with olive ridley, leatherback and flatback turtles nesting on Cobourg Island and around Cape Arnhem. Higher order predators including killer whales (orcas), small toothed whales, offshore and inshore dolphins, and shark species (e.g. black tip and bull hunters) are common in the Arafura Shelf subsystem. More information on the biota of this subsystem may become available on completion of the North Australia Marine Biodiversity Survey of inshore waters of the South Eastern Van Diemen Gulf and North Western Arnhem Land between the Goulburn Islands and Castlereagh Bay, Northern Territory, which commenced in 2004[2].

WESSEL ISLANDS

The Wessel Islands subsystem is situated around the Wessel Islands group and includes the English Company Islands. There was uncertainty about where the eastern boundary of this subsystem should be located because the area was thought to represent a biogeographic transition rather than a distinct ecosystem. No distinctive features of geomorphology were noted for the subsystem and the physical environment was considered to be similar to that of the Arafura Shelf subsystem. The area receives little terrigenous input and has a narrow coastal boundary layer. Strong tidal currents move between and around islands, resulting in localised eddies, upwellings and the resuspension of sediments and nutrients. Hence, the Wessel Islands is a highly productive area and an important upwelling zone.

The Wessel Islands are one of the most diverse and species-rich areas in the North Marine Region. Tidal streams influence the coral reef ecology of the region and the Wessel Islands are known to contain 70 per cent of the coral reef biodiversity of the Great Barrier Reef. Corals play an important role in the food chain of this subsystem. The subsystem supports a wide range of coral, fish (especially damsel fish) and sponge species. The Wessel Islands subsystem also displays higher levels of endemism than elsewhere in the North Marine Region. Taxonomic studies have shown that a distinct biogeographical boundary between sponge taxa occurs in this area; it is a major species turnover point for sponge species of the Gulf of Carpentaria and Western Australia (see Hooper and Ekins, 2004). Fish biodiversity is high due to the wide range of available habitats including coral reefs, enclosed waters and open ocean, however, mollusc, polychaete and prawn fauna are typical of the Arafura region in general. Freshwater springs that run off the islands (mapped by David Williams) create a freshwater lens over the saltwater. As a result, a number of freshwater fish inhabit these areas including dartfish, gobies and some ‘aquarium’ fish.

The subsystem supports an important Northern Territory mackerel fishery and is significant for aggregations of migratory shorebirds, breeding colonies of waterbirds and nesting sites for seabirds and flatback, green and olive ridley turtles. There may also be an important area for adult *Glyphis* species (speartooth and Northern river shark) offshore from the Wessel Islands, however, it is not known how and when they travel from their nursery areas in coastal rivers into the area. River (inshore) dolphin species (spotted bottlenose, Australian snubfin and Indo-Pacific humpback dolphin) feed on fish in this subsystem.

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[2] See http://www.nt.gov.au/nreta/wildlife/marine/research.html#north

Joseph Bonaparte Gulf

Major physical drivers of the system

The Joseph Bonaparte Gulf system lies over the Sahul Shelf in the Timor Sea from west of Bathurst Island to the western boundary of the North Marine Region (figure 1). The system is characterised by complex geomorphology, including coastal, shelf and basin features in the Joseph Bonaparte Gulf, dissected banks, shoals, valleys and terraces on the Van Diemen Rise, and deeper areas on the shelf slope to the north of the Rise.

The Bonaparte Basin, which dominates the western portion of the Joseph Bonaparte Gulf system, was formed 15–13 000 years BP after rapid sea level rise inundated most of the Sahul Shelf creating fully open marine conditions within the area known as the Bonaparte Depression. During the Late Quaternary, the environment of the Bonaparte Depression varied with fluctuating sea levels and climatic conditions, from an estuarine embayment to a shallow, freshwater lake. Extensive palaeo-river channels, some up to 150 km long, 5 km wide and 240 m deep, connect the present day basin to the old shoreline at the edge of the shelf (see Pinceratto, 1997).

A series of submerged carbonate banks supporting unique ecosystems are located on top of the bedrock terrace of the Van Diemen Rise, and along the outer edge of the Sahul Shelf. Channels between the banks allow ocean currents, tidal flows and upwellings of cold oceanic water to penetrate onto the Van Diemen Rise and through to the Bonaparte Basin. The outer shelf banks are thought to represent drowned carbonate formations that formed a string of islands seaward of the palaeo-coastline. Many are relict coral reefs that were unable to keep pace with rapidly rising sea levels over the past 20 000 years (see Pinceratto, 1997). Some carbonate banks were formed by the natural seepage of thermogenic hydrocarbons onto the seafloor (see, for example, Rollet *et al.*, 2006; A. Heap, pers. comm.).

The Indonesian Throughflow brings warm water of low salinity into the region from the Tropical Western Pacific Ocean and may drive upwellings of cold water onto the shelf from the deep Timor Trough to the north. Localised upwellings may also appear at the head of valleys and channels in the seabed as a result of deep tidal currents. Offshore waters are very clear and the euphotic zone can extend to 100 m across the shelf. Hence, primary productivity in offshore waters is probably limited by nutrient availability and the ability of winds, waves and tides to resuspend benthic deposits into the water column. Within the Bonaparte Basin, monsoonal winds have an important influence on productivity and the depth at which phytoplankton are concentrated because of seasonal stratification of the water column. Basin and shelf productivity may therefore be dependent on internal nutrient cycling and the upwelling of productive oceanic waters. Hence, in many respects the oceanography of this basin is similar to that of the Gulf of Carpentaria.

The Joseph Bonaparte Gulf is subject to the highest tidal range in northern Australia (> 4 m). High energy tidal currents along much of the region’s coastline stimulate mixing and sediment movement throughout the year, contributing to the highly turbid and relatively productive inshore environment. Terrestrial inputs of freshwater, sediments and detritus are generally compartmentalised within a fairly distinct coastal boundary layer, which is particularly well-developed within the Joseph Bonaparte Gulf. There is no evidence to suggest that terrestrial inputs influence offshore productivity as there is little transfer of nutrients from coastal waters to oceanic waters. Turbidity in the inshore zone limits light penetration for benthic production (e.g. by seagrasses and macroalgae). Microbial communities associated with the high concentrations of ‘marine snow’ are presumed to dominate the nutrient dynamics of the inshore zone.

Biogeographically, the Joseph Bonaparte Gulf system appears to be a transitional zone between the east and the west of Australia, yet affinities lie predominantly with the Indian Ocean. This may in part be due to the Region’s Quaternary history. Marine flora and fauna assemblages are clearly more similar to western Australian biota than eastern biota. For example, fisheries data indicate that Indian banana prawns are predominantly caught in the Joseph Bonaparte Gulf while Pacific banana prawns occur in the Gulf of Carpentaria. There are also notable differences in the species composition of fisheries by-catch associated with the prawn fisheries of these two regions. It was suggested that there may be a higher level of endemism in the species of by-catch caught in the Joseph Bonaparte Gulf.

Subsystems of the Joseph Bonaparte Gulf:

Three subsystems were recognised within the Joseph Bonaparte Gulf system: the Coastal Zone; the Joseph Bonaparte Gulf Basin; and the Van Diemen Rise (figure 8). The subsystems were discriminated on the basis of distinct differences in their physical environment, ecosystem function and biology.

The inshore limit chosen for the Joseph Bonaparte Gulf Basin subsystem is relatively distinct, coinciding with the extent of mud basin geomorphology at around the 50 m depth contour. In contrast, the extent of the coastal boundary layer of Joseph Bonaparte Gulf is not well described and although it may only extend out to around the 20 or 30 m depth contour, some 30–40 nautical miles (approximately 55–75 km) from the shoreline, it may extend considerably further offshore during the wet season. There was some discussion over whether the area of less turbid shelf waters lying at depths of 20–50 m between the coastal zone and basin of the Joseph Bonaparte Gulf could be a separate subsystem in itself, since this area differs from the coastal boundary layer in primary productivity, species distribution and sediment composition. As a result, these less turbid, offshore shelf waters were considered to represent a subdivision of the Coastal Zone subsystem. The subdivision has been identified in figure 8 as the ‘Joseph Bonaparte Gulf (JBG) Shelf’ with a broken line drawn to distinguish it from the inshore Coastal Zone.

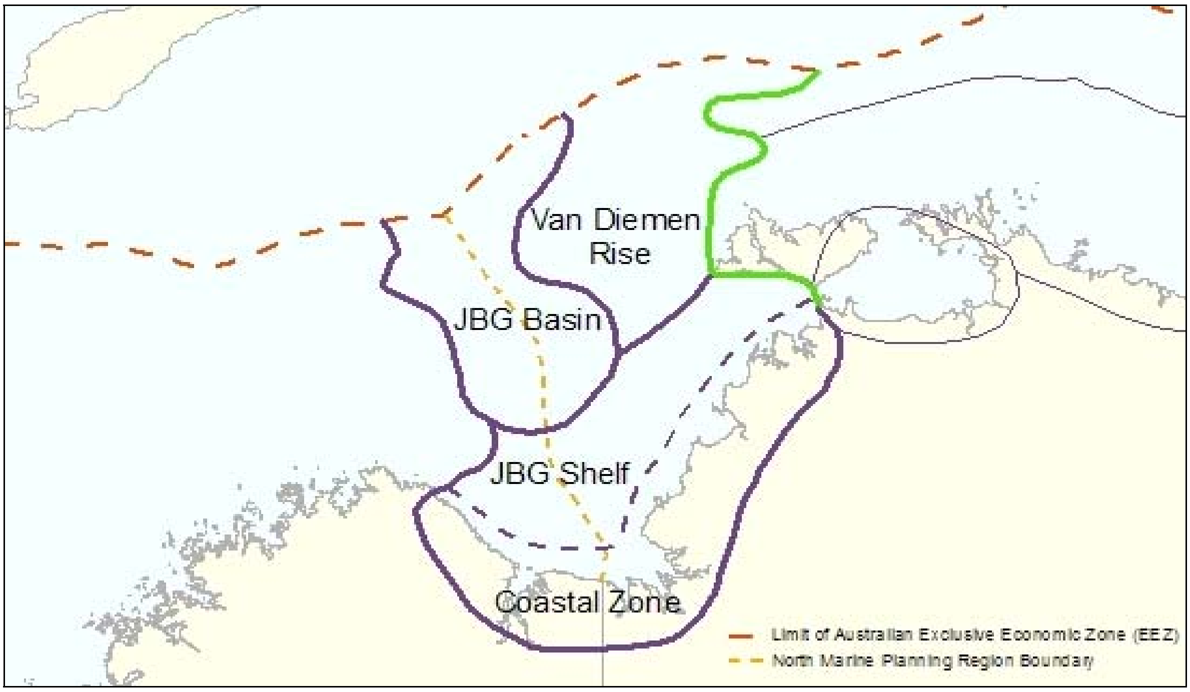

Figure 8 Subsystems identified for the Joseph Bonaparte Gulf system. Boundaries are indicative only.

COASTAL ZONE (including Joseph Bonaparte Gulf Shelf)

Two major estuarine systems discharge large quantities of freshwater into the head of the Joseph Bonaparte Gulf during the wet season (see Clark *et al*., 2001); the Ord, Pentecost and Durack Rivers supply inputs from the Western Australian side of the Gulf while the Keep, Victoria and Fitzmaurice Rivers converge into a large delta on the Northern Territory side. Large estuaries including the Daly River along the eastern coast, south of Darwin, also deliver significant terrigenous inputs into the Coastal Zone. Hence the muddy surface sediments of the coastal boundary layer are predominantly of modern origin and contain a high proportion of gravels. Conversely, in deeper offshore areas of the shelf the surface sediments are carbonate sands presumably derived from *in situ* production and reworked detritus from the carbonate bank deposits of Londonderry and Van Diemen Rises.

The large tidal range and broad intertidal zones along the coastline of the Joseph Bonaparte Gulf system contribute to a physically dynamic and turbid coastal margin, particularly within the first 10 km of the shoreline. Strong monsoonal winds, cyclones and wind-generated waves combine with tidal energy to maintain the highly turbid coastal boundary layer which is continually mixed to a depth of 20–30 m.

Terrestrial inputs of freshwater, sediments and nutrients contribute to primary production in the coastal subsystem but their influence does not extend much beyond the limit of the coastal boundary layer. During the dry season, the outflow of nutrients and freshwater is restricted by mud bars that build up at the mouth of estuaries, ponding the system. Salt and nutrients that accumulate on salt marshes and saltpans are received in ‘pulses’ during wet season flushing of estuaries. This affects the salinity of the inshore zone, affecting nutrient recycling and the health of the mangrove communities fringing the shoreline of the subsystem.

Benthic algae and seagrass communities are confined to the intertidal zone because of the turbidity of inshore waters. Although phytoplankton production may be relatively high at the top of the water column (as indicated by high surface water chlorophyll concentrations), primary productivity is limited by light at depth. Due to high concentrations of ‘marine snow’ observed in the Coastal Zone subsystem, it can be presumed that nutrient cycling is dominated by bacterial primary production as microbial communities breakdown the flocculant, gelatinous material produced by zooplankton. The abundance and biomass of primary consumers in this subsystem is very high compared with the rest of the North Marine Region, e.g. blooms of ‘corn flake crabs’ found in shelf waters can occur at times. Figure 9 provides some indication of the trophic relationships characteristic of the Coastal Zone subsystem.

Intertidal 1° production → zooplankton → marine snow → crustaceans

Phytoplankton and some benthic production → zooplankton →1° consumers (planktivorous fish) → 2° consumers (carnivorous/piscivorous fish)

Figure 9 Conceptual diagram of trophic relationships in the Coastal Zone subsystem of the Joseph Bonaparte Gulf

The Joseph Bonaparte Gulf supports a very productive banana prawn fishery, which operates in clearer shelf waters outside the coastal boundary layer. Healthy offshore populations of crustaceans, including prawns, are indicators of inshore productivity but the direct linkages between these systems are poorly understood. The by-catch of coastal fisheries, particularly the prawn fishery, indicates different species composition to the trawl by-catch from the Gulf of Carpentaria. By-catch from the prawn fishery contains a high relative abundance of a few species, which is a unique characteristic of the region and has a distinctly different species composition to the other demersal communities found in the Northern Prawn Fishery (see Tonks *et al.*, 2008). Sharks are commercially fished in this subsystem whilst sawfishes are caught as by-catch.

Two dolphin species that may be endemic to Australia, the Australian snubfin dolphin and Indo-Pacific humpback dolphin, occur in the nearshore area and river mouths of the subsystem. The coastline may prove to support the highest concentration of flatback turtle nesting in the world.

JOSEPH BONAPARTE GULF BASIN

The Bonaparte Depression, bounded by the Londonderry, Sahul and Van Diemen Rises, forms a muddy basin with maximum depth of around 70 m. Sediments within the basin are mostly relict compared to the coastal zone, and the predominantly carbonate composition indicates formation of sediments from settlement of detritus out of the water column, rather than export from the coastal zone and/or previous terrigenous origin. The Joseph Bonaparte Gulf is predominantly a depositional basin that accumulates organic detritus and mud settling out of the water column. Tides appear to have little impact on the movement of sediment or the distribution of benthic fauna. Apart from some advection of marine snow from the waters of the Coastal Zone, catchment inputs and coastal processes have limited influence on the basin subsystem. Monsoon winds during the wet season and consistent trade winds in the dry season mix the waters of the Joseph Bonaparte Gulf sufficiently so that it remains turbid throughout the year. Phytoplankton primary productivity is indicated by surface water chlorophyll concentrations.

Deep palaeo-river channels branch out from the basin to the east and west, with the largest, the Malita Shelf Valley, which is the Late Quaternary entrance to the estuary during low sea levels, extending north into the Timor Sea. This channel reaches a depth of 155 m and may be important in the transfer of water between the Sahul Shelf and Timor Sea. Hard substrates are common on the seabed. The depth of channels limits disturbance to the seabed by waves but accelerated tidal movements scour and redistribute finer-grained silts and muds, depositing them in the Gulf basin. There is some potential for increased levels of productivity in (or at the heads of) these channels associated with upwellings of colder, nutrient-rich water from the Timor Sea. It was also suggested that high levels of endemism are likely to be found in the channel fauna, given that the water in the channel has a long residence time during which either nutrients and productivity can be generated or given the deep, undisturbed and nutrient-rich environment. Geography may, however, be a barrier to marine organisms, including deep diving migratory cetaceans, because the channels do not extend continuously into the deep ocean.

Numerous limestone pinnacles up to 10s of km in length and width, some of which rise into the euphotic zone 50 m above the seafloor, which is 10–15 m below the sea surface, occur throughout the basin. These pinnacles are thought to be the eroded remnants of the underlying strata.

Almost nothing is known about the biology of the Joseph Bonaparte Gulf Basin subsystem. Figure 10 provides some possible indication of the trophic relationships characteristic of the subsystem. Benthic faunal assemblages are presumably influenced by depth and the grain-size of the surface sediments. Some bacterial production may occur but deposit feeders are likely to dominate in this environment. Sponges, soft corals and other sessile suspension feeders may be abundant on the hard substrata lining the deep channels. There may also be a more diverse fish fauna associated with the channels. The carbonate pinnacles offer a very different environment to the remainder of the Basin. They are known to offer refugia for fish and presumably support phototrophic organisms where they extend into euphotic surface waters.

Deep Channel:
Strong currents in deep channel → hard substrate → epibenthic community (e.g. sponges) → 1° consumers → 2° consumers

Basin:
Phytoplanktonic and some benthic 1° production (on pinnacles) → Zooplankton → 1° consumers → 2° consumers

Figure 10 Conceptual diagram of trophic relationships in the Joseph Bonaparte Gulf Basin subsystem

VAN DIEMEN RISE

This subsystem comprises areas of shelf and slope but is broadly characterised by the series of shallow carbonate banks and shoals separated by narrow valleys that occur over the limestone terrace portion of the Sahul Shelf known as the Van Diemen Rise. The carbonate banks are flat topped and extend to near-surface waters (~ 20–30 m depth) from a relatively shallow base compared to the surrounding areas of the Bonaparte Depression (~ 100 m) and Arafura and Timor Seas (> 1000 m). In general, the banks are relict features but modern growth is probably due to a combination of hydrocarbon seepage, and the accumulation of calcium carbonate deposited by corals and coralline algae, including *Halimeda* species. Similar banks in north-western Australia are largely colonised with *Halimeda* species accompanied by typical coral reef fauna. Hydrocarbon flux from sedimentary deposits has been described in similar banks in north-western Australia (see Heyward *et al*., 1997).

The Van Diemen Rise subsystem is distinctly different in morphology and character to other parts of the North Marine Region and provides habitats for a wide range of marine communities. Light penetration through clear, shallow waters stimulates high levels of benthic primary production (macroalgae) whilst bacterial production is generated by leakage of nutrients from hydrocarbon seepage from below the surface sediments. This allocthonous carbon is known to support different benthic microbial communities than those reliant on light for primary production.

Channels shoal towards the shelf edge and terminate in about 90 m water depth. The deeper channels are thought to provide important refuge for a number of fish species and a source of cold water nutrients to the banks. Channels generate strong tidal movements and localised upwellings at the end of channels support detectable surface water chlorophyll concentrations that are the basis of planktonic food webs. Wave action is also likely to be significant and may influence communities and re-distribute materials on the banks.

Algal beds of *Halimeda* species are likely to be a dominant biological component of this subsystem. *Halimeda*-derived carbonates have played a key role in building the banks and contribute substantial carbonate sediments to surrounding basins. These communities rank amongst the highest in terms of carbon fixation (see Heyward *et al*., 1997). The *Halimeda* banks also support a range of invertebrate communities including sponges, soft corals, hard corals, bryozoans, ascidians and other sessile filter feeders. Foraminifera are a common component of the benthic fauna.

Whilst nutrient rich upwellings from deep cold oceanic waters have been canvassed as a theory to support the region’s productivity, an alternative microbial food web supported by hydrocarbon seepage from the underlying sedimentary deposits may also exist and warrant further research. Fisheries data validate the subsystem’s highly productive fish communities particularly within the deeper channels. Pelagic line fisheries (mackerel) are linked to localised planktonic food webs at ‘upwelling sites’ around channels and would suggest important trophic linkages that are as yet not documented but may indicate consistent sources of nutrients from localised upwellings. Trap fisheries (red snapper) are more likely to be associated with complex habitats (refugia) amongst banks and channels (figure 11).

The presence of oceanic cetaceans has been reported in the region (see WWF, 2003), however, their movements are poorly understood and further research is needed. It may be that the shelf acts as a barrier to some migratory species though deep water cetaceans may be present in the channels and deeper waters. There is evidence that supports the presence and foraging activities of olive ridley turtles on the banks and shoals of the Van Diemen Rise.

The shelf-edge/slope region supports very distinct biodiversity that is most likely to be influenced by tidal and ocean current upwelling activities. This area may provide habitat for a number of species, including marine turtles and a connecting point across deeper waters to the Indonesian Sea.

Seasnakes are very common marine reptiles in sub-tropical and tropical Australian waters and occupy a wide range of habitats, extending from the coast offshore to the reefs and banks of the Sahul Shelf. Although their specific occurrence in Joseph Bonaparte Gulf has not been documented, seasnakes are expected to be very common, with as many as 15 species known to occur in the region (see Storr *et al*., 1986).

Localised plankton productivity (upwelling hot spots) → juvenile fish → line fisheries

Carbonate Banks → *Halimeda* beds → consumers → trap fisheries

Hydrocarbon leakage from sediments → BMA → invertebrates → trap fisheries

Figure 11 Conceptual diagram of trophic relationships in the Van Diemen Rise subsystem

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APPENDIX 1 CURRENT RESEARCH AND INFORMATION RESOURCES

Gulf of Carpentaria

- CSIRO Land and Water Remote Sensing, classified satellite imagery with surface water characteristics
- Queensland Environment Protection Authority, marine turtle database
- CSIRO, food web models
- CSIRO, fish by-catch on trawl grounds
- CSIRO, SW corner impact assessment of trawl system
- CSIRO (Rothlisberg), estuary classification
- NRETA seagrass, marine turtle and seabird database
- QDPIF seagrass, marine turtle and seabird database
- Queensland/Northern Territory, database in fish trawl (access with permission)
- Geoscience Australia, OzEstuaries and Marine Sediments (MARS) databases
- NT Museum, invertebrate and vertebrate fauna
- NT Herbarium
- NRETA, west coast database
- NT Fisheries, fishing data (access restrictions)
- Australian Fisheries Management Authority, Northern Prawn Fishery logbook data

Arafura

- Dave Ramm, demersal trawl work in Central sub-system, 1987, with most results written up in Northern Territory Fisheries reports. Specimens held at NT Museum.
- Dave Ramm, demersal trawl video data applicable to the Central sub-system.
- Patrick Decker of ANU, has completed a study on where the Indonesian Throughflow may have distributed fine muds in the NMR.
- Wolanski, E. (ed), (2006), *The Environment in Asia-Pacific Harbours*, 497p., contains a food diagram for Darwin Harbour.
- Victor Gomelyuk (Marine Group, NRETA), video footage of fish species around Wessel Islands (Helen Larson is aware of it).
- Daryl Chinn (NT Government), contact point for spatial data mapping.
- Simon Townsend (NT Government), head of the water quality group.
- B. Edmeades and Peter Brocklehurst, mangrove and salt marsh mapping and wildlife database reports on seabirds, waterbirds and marine turtles.
- The Indian Ocean – South-East Asian Marine Turtle Memorandum of Understanding (IOSEA) website (http://www.ioseaturtles.org/), migration pathways of turtles
- Arafura Sea biological survey report.
- Peter Last (CSIRO), fish data.
- DEWHA's Marine and Migratory Species section, have copy of Lindsay Porter's (WWF-Hong Kong) report on cetaceans.
- Neil Gribble (QDPIF), reports on soft sediments, however not specific to this region.

Joseph Bonaparte Gulf

No current research or information resources listed for this system.

APPENDIX 2 INFORMATION GAPS

Gulf of Carpentaria

- Characterisation of soft bottom benthic communities, at least on eastern and western shores (preferably in each subregion)
- Information on pelagic dynamics
- Inshore biodiversity, process and habitat (<20 m water depth)
- Oceanographic connection with Papua New Guinea/Irian Jaya and Arafura/Timor Sea
- Land-sea interactions
- Connectivity
- Nutrients
- Genetics (including endemism)
- Demographics (including fish stocks)
- Connectivity between breeding grounds for migratory mega fauna
- Characterisation of the reef system
- Biology of non-commercial species
- Trophic dynamics
- Disturbance regimes and impacts (environmental forces)
- Juvenile bull sharks caught as illegal, unreported and unregulated catch and by-catch
- Reef systems are an area of further research (underway by Geoscience Australia?)
- Bottom fauna unknown (Vanderlins)
- No hard substrata invertebrate fauna sampling (NW Blue Mud Bay)
- No systematic seabird sampling (NW Blue Mud Bay)
- Feeding behaviour and seabird activity (Gulf of Carpentaria basin)
- Pelagic movement of marine turtles (Gulf of Carpentaria basin)
- Spatial dynamics of pelagic fish (Gulf of Carpentaria basin)

Arafura

- Characterisation of soft bottom benthic communities in coastal and offshore areas
- Oceanography of the offshore area, including grooves, currents and possible influence of the Indonesian Throughflow
- The depth of marine habitats represented in this sub-region also needs to be clarified (there are deep ocean fish, how does this relate to geomorphology?)
- Current strengths, tides, duration in inshore and offshore areas of the Region: David Williams indicated that a lot of data have been collected, but not collated and analysed. Not a lot known about tides as drivers within the system.
- Wessel Islands: need to know more on corals and reef life generally (species presence/absence). Charlie Veron and Helen Larson consider this a high priority for the Region.
- Physical and ecological consequences of changed land use upon marine environment: in particular, areas of significant river catchments and softer (terrestrial) sediments, such as to the west and east of the Arafura region
- Cobourg Peninsula: corals and reef life
- Patterns of fish distribution across central region (offshore) and relationship to benthic sediments
- *Halimeda* banks and shoals

Joseph Bonaparte Gulf

- Characterisation of soft bottom benthic communities in coastal and offshore areas
- Actual presence of *Halimeda* species
- Fuzzy Logic Model for fisheries productivity/geomorphology
- Phytoplankton production at ‘upwelling sites’
- Carbonate sand export to surrounding regions
- Influence and extent of upwellings
- Benthic communities/composition/diversity
- Role of channels
- Composition of substrate
- Distribution of beaked whales
- Boundary of coastal turbid water zone (Andrew Heap suggested the coastal boundary could be selected by overlaying maps of primary productivity with bathymetry. The *CSIRO Atlas of Regional Seas* includes estimates of primary productivity.)
- Food web linkages between coastal marine snow and fisheries (prawns)
- Substrate composition and habitats, including faunal surveys: need for high resolution bathymetry
- No biological information on this sub region, other than sea-surface chlorophyll concentrations
- Current flows and movement of mud in deep channels into and out of the basin
- Influence of other system drivers such as monsoonal conditions, cyclones, Indonesian Throughflow, upwellings and the nutrient source for productivity