Part III: Habitats

Chapter 18

Vulnerability of pelagic systems of the Great Barrier Reef to climate change

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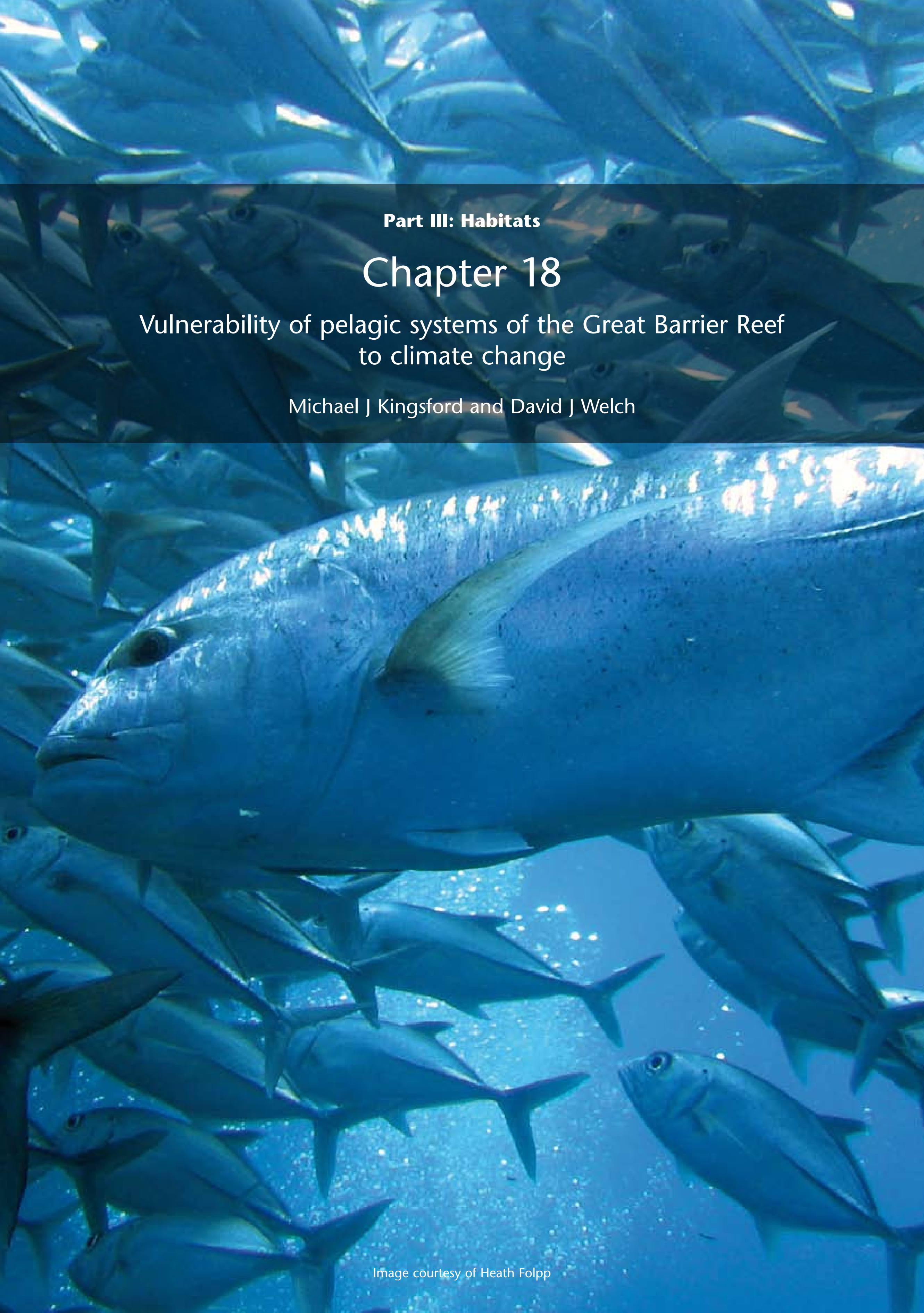

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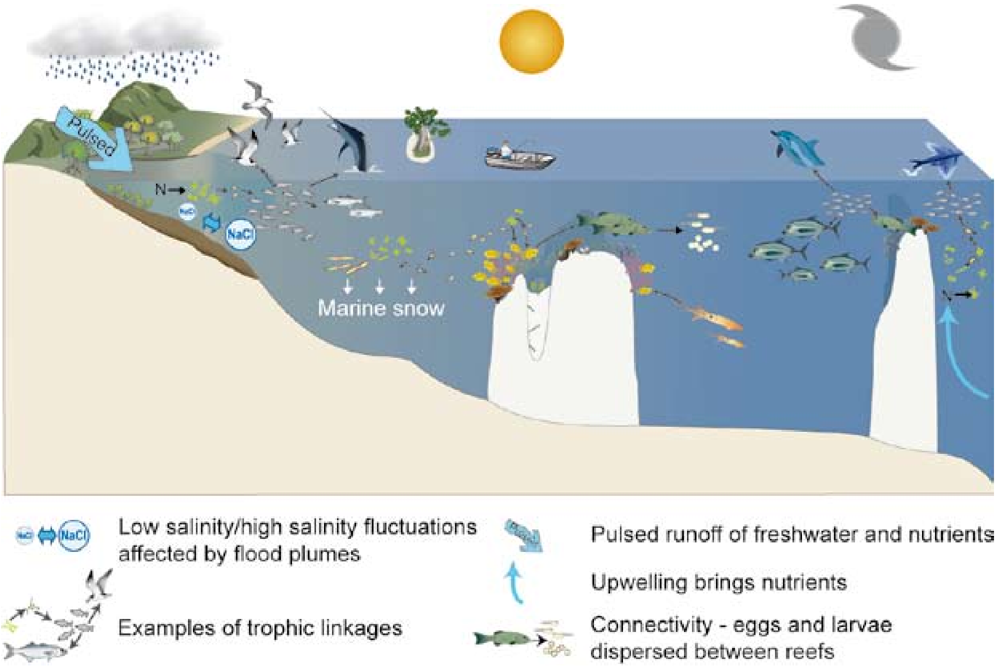
18.1 Introduction

It is well known that physical forcing, through changes in climatic conditions, has a great influence on terrestrial[58] and marine ecosystems[4,86]. Most research in this area has focused on dominant climatic signals on scales of tens of years and at spatial scales of kilometres to thousands of kilometres for the El Niño-Southern Oscillation (ENSO) in the Pacific and the North Atlantic Oscillation. Some changes in the biogeographic patterns of pelagic assemblages, on a scale of decades, have been related to ocean warming[6]. However, there are few reliable data on long-term change and the responses of organisms to changes in pelagic environments, especially in tropical latitudes. The challenge is to extrapolate beyond relatively short time scales to climate change and its consequences for pelagic ecosystems over the longer term. How will environmental baselines change and how will organisms respond or adapt to change?

This review focuses on pelagic environments. The oceanography of the Great Barrier Reef (GBR) is dynamic and is the physical template to which organisms respond. Planktonic assemblages are the basis of pelagic food chains and they provide a rich supply of food for high trophic groups (eg fishes, birds and whales) as well as the larvae and adults of benthic assemblages (Figure 18.1). Changes in pelagic systems, therefore, cannot be viewed in isolation from other habitats (such as coral reefs). Plankton ranges from tiny viruses (less than 1 micron) and bacteria, to larger plant (phytoplankton) and animal plankton (zooplankton). Jellyfish are the giants of the plankton world and can reach

Figure 18.1 Profile of the GBR from inshore to offshore showing key organisms of the tropical pelagic food chain, and physical features of the pelagic environment that influence organisms (eg upwelling and riverine runoff)



metres in size. Planktonic assemblages support a wealth of predators. Consumers of plankton (eg small planktivorous fishes such as sprats and pilchards) support larger consumers such as squid and fishes (eg mackerels, tuna, sharks), seabirds and whales. Plankton feeders are not always small in tropical waters of Australia and the world's largest shark (whale shark), largest rays (manta rays) and marine turtles (leatherbacks) feed on plankton. Changes in planktonic assemblages, therefore, can have an impact throughout the food chain and include organisms of all sizes.

Phytoplankton are called 'autotrophs' because they use sunlight to photosynthesise sugars that are essential for life. Consumers ranging from microscopic plankton to large fishes directly or indirectly depend on phytoplankton. Phytoplankton also has a major role in the recycling of carbon dioxide (CO_2). For these reasons anything deleterious that happens to phytoplankton will have a cascade effect through the entire food chain. Pelagic ecosystems are well known for trophic cascades and it is generally assumed that nutrient supply and subsequent growth of phytoplankton will result in 'bottom up' control of the whole food chain[134]. Top-down effects are also possible. This has been demonstrated in lakes[93] and marine ecosystems[95,42] where predators remove zooplankton grazers, relieving grazing pressure on phytoplankton resulting in an increase in phytoplankton biomass. Changes can happen very quickly in the plankton and this will affect populations of nektonic animals.

18.1.1 Scope of the chapter

The aims of this chapter are as follows:

i) Give an overview of the physical environment and biota of pelagic ecosystems of the GBR.

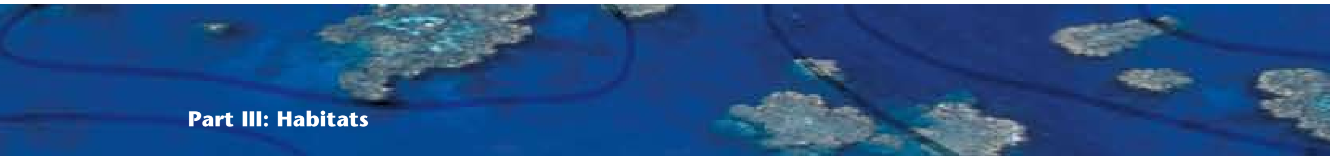
ii) Discuss the broader significance of pelagic organisms as links between habitats, connectivity among habitats such as coral reefs, and consequences of change to existing processes (eg survival of larvae).

iii) Assess the vulnerability of pelagic habitats to climate change.

iv) Discuss the implications for management and make recommendations.

In this volume useful background knowledge to this chapter can be found in Lough (chapter 2) who provides a detailed account of projected changes in climate in the GBR, and Steinberg (chapter 3) who provides an explanation of projected changes in oceanography of the GBR. From an organism-based view, we especially recommend reviews on phytoplankton and mesozooplankton assemblages (McKinnon et al. chapter 6), planktonic viruses and bacteria (Webster and Hill chapter 5), fishes (Munday et al. chapter 12), seabirds (Congdon et al. chapter 14) and marine mammals (Lawler et al. chapter 16).

By necessity this review utilises findings from all over the world. Many paradigms concerning pelagic habitats have come from high latitude studies in the northern hemisphere[50,115] and the relevance of these to tropical pelagic habitats could be questioned. However, there are significant similarities between temperate and tropical pelagic habitats. At low latitudes, planktonic assemblages are characterised by small variations in biomass, low standing crop and high turnover rates; rather than high variation in biomass, sometimes-high standing crop and high turnover rates found at higher latitudes[133]. Although more knowledge is needed about tropical pelagic habitats, it is true that all pelagic systems are characterised by rapid change, and variation in the physical environment can have a great influence on all taxa in pelagic assemblages.



18.2 Description of pelagic systems

18.2.1 Physical environment – oceanography of the GBR

Oceanography affects the GBR at large and small spatial scales[145]. At the largest spatial scales (thousands of kilometres), major oceanic currents of the Pacific bath the GBR, affecting patterns of flow and the movement of warm and cool waters. At small spatial scales (centimetres to metres), small-scale turbulence can affect the settlement patterns of organisms such as corals. The South Equatorial Current that flows from east to west affects the oceanography of the GBR. The South Equatorial Current weaves its way as 'jets' around Vanuatu and New Caledonia before bifurcating at the central GBR. Waters flow north and south as the East Australia Current. The South Equatorial Current often enters the reef matrix, especially where the density of reefs is low[12], and influences flow within the GBR lagoon. Tides (2 to 5 metres in amplitude) flow on and off the shelf and often dominate transport of water. Complex topography generates jets, eddies and convergences and the position of these features will vary with direction of flow[70]. Wind varies in direction and strength with time of year and influences water movement and the resuspension of sediments, especially in shallow water. Wind generated movement and destructive waves can be catastrophic during cyclones. Variation in vertical physical structure (ie thermoclines and haloclines) and the input of freshwater from coastal sources also have an effect on water transport and associated particles. Across the shelf, nearshore waters are often impacted by freshwater and runoff of nutrients whereas outer shelf waters are more affected by upwelling of cooler nutrient-rich waters[35]. Anthropogenic impacts are greatest near shore where delivery of sediments, nutrients and pesticides from agricultural activities varies according to freshwater flow from rivers. Nearshore waters are most turbid due to wind related turbulence in shallow water and riverine inputs[34].

18.2.2 Pelagic assemblages of the GBR

18.2.2.1 Viruses to jellyfishes

Tropical pelagic assemblages are diverse and there is great variation in body size from viruses to whales. Plankton includes tiny viruses, bacteria, cyanobacteria (eg *Trichodesmium*), dinoflagellates, diatoms, copepods, larvaceans, arrow worms, larval forms of invertebrates and fishes, and tiny jellyfishes to those that are metres in length (McKinnon et al. chapter 6). The relative abundance of autotrophs varies with nutrient input and, at some latitudes, time of year. Although seasons are often ignored in tropical environments, the latitudinal range of the GBR is extensive (10 to 24° S) and seasonal change in the composition of plankton is therefore considerable.

Phytoplankton is a critical food source for zooplankton. Zooplankton include many larvae that are temporary members of the plankton (meroplankton) and those that spend their whole life as plankton (holoplankton). A multitude of developmental forms that include nauplii, intermediate stages (eg copepodites) and adult holoplankton are found. Copepods (subclass Copepoda) often dominate zooplankton samples (up to 80% of catches and there are at least 193 species on the GBR). Common genera in waters of the GBR include: medium sized *Acartia, Paracalanus, Temora* (approximately 0.7 to 1.1 mm adults), and larger *Candacia, Undinula, Eucalanus, Centropages, Labidocera, Pontella* of the order Calanoida (approximately 1 to 3.0 mm); small to medium sized *Oithona* and *Oncaea* (approximately 0.7 to 1.1 mm adults), of the orders Cyclopoida and Poecilostomatoida respectively;

and *Euterpina* and *Microsetella* of the order Harpacticoida. Other important members of the phylum Crustacea that are found in net plankton include *Penilia* (order Cladocera).

Critical links between benthic and pelagic assemblages occur through the larval forms of reef-associated organisms such as corals, crabs, crown-of-thorns-starfish, sea urchins and fishes. Invertebrates and fishes release eggs or larvae in the water column[14] and pre-settlement phases can last from about nine days for clown fish to months for taxa such as surgeon fishes and tropical lobsters. At times of the year when animals are spawning, larvae can constitute a major component of total plankton. This is especially the case for corals that have 'mass spawning' and benthic algae that have mass releases of spores into the water column[21,140]. Larvae range from the small and ciliated planula larvae of jellyfish and corals (about 0.5 mm) and the transparent brachiolaria larvae of starfish, to large and essentially nektonic pre-settlement reef fishes. The pelagic phase of surgeonfish can be over 50 mm (standard length, SL) at settlement and tank tests have demonstrated they may swim up to 120 km without food. Although some larvae do not feed in the plankton[151], most are planktotrophic and depend on planktonic food to survive. Although the larvae of many tropical taxa can be found throughout the year[73], distinct spawning seasons are typical of most invertebrate and fish taxa[87]. The majority of taxa spawn late spring to summer, the period of time when GBR waters are most likely to be impacted by warm water anomalies (Lough chapter 2).

There are few data on broad scale (ie kilometres to hundreds of kilometres) abundance patterns of plankton on the GBR. Some data indicate total plankton is most abundant in nearshore waters, followed by mid-shelf then outer waters[138]. This corroborates with a concentration of schooling planktivorous fishes that concentrate in nearshore waters[18], but the persistence of these patterns within and between years is unknown.

Gelatinous megazooplankton are spectacular predators of the zooplankton and can have a great influence on pelagic food chains. Although jellyfish are a natural part of the ecosystem their abundance is sometimes related to the health of an ecoystem, be that thermal or nutrient related[64]. For example, abundance of some jellyfish flourishes in eutrophic conditions[77]. The phylum Cnidaria includes the class Scyphozoa, represented by many large jellyfish, some of which have tentacles that extend over three metres in length (eg *Cyanea, Desmonema*; lions mane jellyfish) and they can weigh more than 10 kilograms. Others have stumpy tentacles, such as *Catostylus*, and fisheries target some of these taxa for sushi grade jellyfish (adults are up to five kg wet weight). One of the most common jellyfish in coastal waters is *Aurelia* (moon jelly), which is harmless and like most jellyfish can be found in great numbers. Densities of jellyfish can be so great at times that they are referred to as 'blooms'[77]. The deadliest jellyfish belong to the class Cubozoa and include stingers and multiple types of jellyfish that are responsible for the medical condition called Irukandji syndrome (eg *Carukia barnesi* and *Pseudoirukandji* spp.). Little is known about the ecology of cubozoans, except chirodropids (eg stinger *Chironex fleckeri*) that are abundant in nearshore waters. Polyps of chirodropids are in estuaries and the release of small medusae is thought to coincide with rain events[150]. The carybdied *Carukia barnesi* is found nearshore, while very dangerous Irukandji syndrome medusae, such as *Pseudoirukandji* spp., are most common kilometres from mainland Australia (L Gershwin and J Seymour pers comm). Anecdotal accounts suggest that the incidence of stings and observations of dangerous cubozoans has increased over the last decade and there is strong evidence for global increases in jellyfish and other gelatinous zooplankton worldwide[13,90].

Other gelatinous zooplankters have important roles in pelagic ecosystems. Siphonophores are voracious predators of plankton and are solitary or form long strings (colonies) that drift and swim by hydraulic pumping of seawater. In bloom conditions jellyfish siphonophones and comb jellies (Ctenophora) can have a significant effect on concentrations of holoplankton and meroplankton[111,112]. Other gelatinous zooplankters that form strings, but are unrelated to siphonophores, are the salps and doliolids (phylum Chordata, class Thaliacea; nine species on GBR; McKinnon et al. chapter 6). Salps can also bloom and their filtration of the water column can have a great effect on tiny plankton that form the food of larvae and other large holoplankton[152,153]. Gelatinous zooplankters are not only predators, they can provide shelter for small fishes and some invertebrate larvae[72].

Tropical waters are generally clear and low in nutrients. In contrast to temperate systems, there is generally consistent and high turnover of plankton[92]. It is often estimated that the entire biomass of phytoplankton turns over every two days (McKinnon et al. chapter 6). There are localised exceptions to low biomass, particularly with respect to blooms of plankton that are the result of riverine input and sometimes upwelling[34]. Riverine plumes, in particular, are well known for causing great variation in concentrations of plankton and related feeding conditions for larvae[45] and larger pelagic predators such as fishes[18].

18.2.2.2 Nekton

There is great diversity of highly mobile marine organisms in the GBR. There are approximately 12 species of squid, approximately 1500 species of bony fishes and sharks, six species of marine turtles, eight species of marine snakes (of 50 species in the Indo-Pacific), 35 species of dolphins in tropical seas, and 11 on the GBR (of which spinner (*Stenella longirostris*) and bottlenosed dolphins (*Tursiops truncates*) are the most common), one species of dugong and 16 species of whales (of which the humpback whale and dwarf minke whale would be the most common) (Munday et al. chapter 12, Lawler et al. chapter 16). Although seabirds are not technically nekton, they are regular visitors to pelagic habitats and many can dive tens of metres below the surface to capture prey (usually fishes, squid or plankton; Congdon et al. chapter 14). Although the majority of fishes are resident in the GBR, many large vertebrates are only temporary visitors that move freely in and out of the GBR depending on the time of year and the conditions they experience.

Squid are common in tropical waters (eg *Sepioteuthis lessoniana, Loligo chinensis, Loliolus noctiluca*)[62]. They are voracious predators that feed on plankton and fishes, and reproduce and die young[97]. No tropical squid lives for longer than one year[62]. Small squid have been collected at all distances across the continental shelf of the GBR[98], but knowledge of their ecology and movements on and off the shelf is poor. However, distributional data would suggest that some taxa never leave shelf waters (eg *Idiosepius pygmaeus*).

A range of small fishes, both open water and reef-associated, feed on plankton and in turn provide critical food for a broad range of bony fishes, elasmobranchs, seabirds and cetaceans. Small fishes of the families Clupeidae (herrings and sprats), Engraulididae (anchovy), Carangidae (trevallies and scad), Scombridae (mackerels) and Caesionidae (fusiliers) are important as bait fish at all latitudes on the GBR (Figure 18.2). These small fishes are the prey of larger fishes that include: scombrid (eg *Scomberomorus commerson*, narrow barred spanish mackerel; *Scomberomorus semifasciatus*, grey mackerel; *Euthynnus affinis*, mackerel tuna; *Thunnus tonggol*, longtail tuna), carangid (*Elegatis bipinnulata*, rainbow runner;

Figure 18.2 *School fish and piscivores: a predatory spanish mackerel hunting hardy heads (Photo credit: Robert Torelli, Blue Water International)*

Caranx ignobilis, giant trevally; *Carangoides fulvoguttatus*, gold-spotted trevally), Coryphaenidae (eg *Coryphaena hippurus*, dolphinfish) and at the largest end of the fin-fish tree the sailfish and marlins of the family Istiophoridae (eg *Istiophorus platyerus*, sailfish; *Makaira mazara*, black marlin).

Open water sharks of the GBR are broad ranging[57] and have a diverse diet that includes squid, small and large bony fishes and other sharks[53] (Chin and Kyne chapter 13). Whaler sharks (Carcharhinidae) are common in open water and fast-moving sharks of the Lamnidae (eg *Isurus oxyrinchus*, mako shark) will feed on fish as large as marlin. Large but relatively docile planktivores include whale sharks (*Rhincodon typus*) and manta rays (*Manta alfredi*). Many of these large elasmobranchs have been demonstrated to move outside the GBR and sometimes between countries (eg whale sharks move from Ningaloo Reef in Western Australia to Indonesia). Juvenile whale sharks are thought to aggregate off Ningaloo Reef during the Austral autumn to feed on a rich supply of euphausids and other planktonic food such as coral spawn[130,142]. There is some evidence that numbers of sharks are influenced by ENSO, where numbers are greatest during La Niña conditions[141]. Large rays such as manta rays may also have large-scale movements that relate to reproduction, similar to cownose rays in Atlantic waters[5], but there are no data on this.

Large mammals use tropical waters of the GBR and many species of dolphin and whale are found in GBR waters (Lawler et al. chapter 16). Dolphins focus on bait fish as a food source and are found in nearshore to offshore waters over the continental shelf. Although some dolphin populations are resident on scales of less than 10 km^2, many whales only use reef waters at certain times of the year. Humpback whales give birth during the Austral winter before mating and returning to Antarctic waters. Similar migrations have been discovered for Arnold's minke whales that are common in mid- and outer-shelf waters of the GBR. Baleen and toothed whales (Odonticeti) are sometimes observed feeding on schools of bait fish (Lawler et al. chapter 16).

18.3 Significance of pelagic organisms in the GBR

18.3.1 Food for larvae

Trophic cascades in pelagic ecosystems are likely to be strongly bottom-up with ample evidence in different environments for strong linkages between phytoplankton, zooplankton and fish populations[103]. Larval invertebrates, squid and fishes from all environments on the GBR as well as those from coastal systems, and perhaps the deep seas adjacent to the shelf, have to survive their early life history in the plankton. Some larvae will grow and eventually settle in benthic environments such as reefs, while others will grow into pelagic juveniles. Great focus has been given to understanding how organisms survive early life because it is a fundamental determinant of input to and the viability of populations[124]. It is clear that abundance of food and predators can be critical determinants of survival in the plankton (Table 18.1). The timing, types and amount of plankton produced are all important. The combination of plankton and suitable oceanographic conditions can also be critical to concentrate prey to levels required by larvae to survive.

Table 18.1 *Examples of hypotheses on factors in pelagic habitats that affect numbers of larvae that survive to recruit to adult populations. Hypotheses focus on the importance of planktonic food, predators, oceanography or a combination of factors*

Hypothesis	Scenario	Source
Match-Mismatch	The survival of fish larvae is greatest when production of larvae through spawning of adult fish matches the production of larval food	Cushing[26]
Vertical stability	Thermoclines are essential to aggregate planktonic food into concentrations that allow fish to survive	Lasker[85]
Upwelling/turbulence	Level of upwelling and disturbance influences encounter rates of larvae with food which will influence survival of larvae	Cury and Roy[25]
Stable retention areas	Oceanographic features retain larvae so that they recruit to adult populations. Retention areas prevent expatriation of larvae and the size of retention areas influences population size. The presence of a retention area is more important than concentrations of food.	Sinclair[123], Lobel and Robinson[88]
Larval transport by internal waves	The frequency and location of internal waves will determine the number of invertebrates and fish larvae that return to coastal environments	Pineda and Lopez[109], Shanks and Wright[120]
Ctenophore predation	Introduced ctenophore blooms in the Black Sea and predation on clupeid fish larvae cause recruitment failure of fish	Kideys and Moghim[69]

Hypothesis	Scenario	Source
Jellyfish predation	The number of larvae surviving correlates with number of predators (ie more jellyfish means less larvae survive, regardless of the size of adult fish stock)	Moller[96]
Jellyfish predation and competition	Jellyfish consume many larvae, but they are also significant competitors for larval food	Lynam et al.[89]
Salp predation	Salps consume food for larvae so that larvae starve. Survival rates of larvae are higher in the absence of salps.	Zeldis et al.[153]

18.3.2 Food for benthic assemblages

Plankton supports a diversity of organisms in coastal, inter-reef and pelagic habitats. Sponges, corals, anemones, ascidians and other suspension feeders feed on plankton and are critical for the input of nutrients to reefs and other habitats[116]. Many small reef fishes also feed on plankton. The densities of these fishes and their abundance has coined the term 'wall of mouths'[48], and in tropical and temperate regions they can have a measurable effect on plankton[76] and provide and important input of nutrients to reefs[118]. Important reef-associated taxa include fishes of the families Pomacentridae, Caesionidae, Serranidae (especially Anthids) and fishes that have a more facultative relationship with reefs such as the Carangidae and Scombridae. Munday et al. (chapter 12) and Hoegh-Guldberg et al. (chapter 10) provide discussion on coral reef fishes and corals. The fall-out of plankton and faeces from the water column to the benthos is also a critical component of marine sediments that deposit feeders such as sea cucumbers feed on; often called 'marine snow'[39]. Variation in the pelagic environment, therefore, will manifest itself on the substratum as variation in the input of food.

18.3.3 Predators

Predators of a wide range of sizes are found in the pelagic environment. Some of these organisms have the ability to influence population sizes of autotrophs or consumers and, therefore, variation in predator numbers will have a great influence on pelagic environments. Tiny plankton feed on each other. Of great significance to organisms from all environments on the GBR is predation of larvae. In many parts of the world, it is argued that numbers of predators determine the number of larvae that survive the larval phase (Table 18.1). The abundance of jellyfishes, ctenophores and siphonophores for example may have a great influence on the survival of fish larvae. Large gelatinous organisms also have other roles in pelagic ecosystems such as providing shelter for a host of larval invertebrates and fish[72]. It has been argued that there is a positive relationship between the abundance of large predatory jellyfish and the recruitment of small fishes that utilise the jellyfish as shelter[49]. Jellyfish predation can also result in top-down effects, for example Fock and Greve[32] modelled a pelagic food web where small ctenophores and copepods are known to eat a dinoflagellate responsible for red tide (*Noctiluca scintillans*). The model indicated that predation by scyphozoan jellyfish on ctenophores and copepods reduced predation pressure and this could facilitate blooms of the dinoflagellate.

There is experimental evidence for this in Australia (K Pitt and Kingsford unpublished data). This type of cascade could become more common with global increases in numbers of gelatinous zooplankton in coastal waters[13].

Large predators from the pelagic environment affect other environments and generate complex trophic links. Piscivorous fishes (especially from the Carangidae and Scombridae) and dolphins, for example, commonly prey on reef and estuarine associated fishes. Some large predators are closely associated with reefs (eg Serranidae[71]) and consume pelagic prey while others are open water taxa that often move in response to food and/or temperature[86] where these two factors are sometimes correlated. Intense predation by both reef-associated and open water taxa can have significant effects on populations of prey.

18.3.4 Bait fish: a critical resource

Bait fish are a critical resource for many consumers including squid, fishes, seabirds and marine mammals[18]. Small planktivorous school fish are found across the GBR and they are a critical resource to larger fishes from all environments[71]. There are 'hot spots' or billfish grounds in the GBR lagoon where large numbers of planktivorous school fish aggregate. Mangrove-lined bays adjacent to the GBR lagoon are highly productive and are called Effective Juvenile Habitats[28]. These grounds are considered important for a range of taxa and include the following regions: Cairns (16.8° S, 145.7° E), Dunk Island (17.8° S, 146.2° E) and Cape Bowling Green Bay (19.3° S, 147.4° E). Nutrient rich waters from mangroves and associated creeks enter coastal waters and enhance primary and then secondary production. Coastal eddies entrain this production and maintain the geographic stability of nursery areas.

Bait fish move throughout the GBR lagoon during the year. In winter, great aggregations of clupeid, carangid and scombrid bait fish and teleost, elasmobranch, avian and cetacean predators occur in billfish grounds[18]. Juvenile black marlin and adult sailfish target large surface aggregations of bait fish. Gut content data demonstrate that northern pilchard (*Amblygaster sirm*) and golden-lined sardines (*Sardinella gibbosa*) compose 95 percent of the diet in the majority of black marlin. Sailfish also consume many pilchards (57% of the diet), as well as larval monacanthids and balistids[18]. Marine mammals such as dolphins and whales also focus on large schools of small planktivorous fishes (Lawler et al. chapter 16). Many of the larger piscivores move outside the GBR once they have spawned or grown large enough to leave GBR nursery areas, thus connecting with open ocean environments. These predators are therefore reliant on adequate supplies of bait fish as their primary food source and represent an important link at the top of the food chain (Figure 18.3), and many species in turn support fisheries of importance on the GBR.

Seabirds such as terns, mutton birds, shearwaters and boobies are abundant on coral cays and granite islands of the GBR (Congdon et al. chapter 14) and use these locations as roosting and breeding sites. Near and abundant prey is usually a prerequisite for the successful survival of chicks where they feed on small clupeid fishes such as *Spratelloides robustus* as well as anchovies (*Engraulis* spp.). Adults make long distance forays from isolated reefs inside and outside of the GBR where complex topography facilitates good conditions for feeding[36].

***Figure* 18.3** *Baitfish are a critical source of food for piscivores: Golden trevally patrolling a school of bait fish (hardy heads) (Photo credit: Robert Torelli, Blue Water International)*

18.3.5 Fisheries

Fishers are effective predators in multiple habitats of the GBR. In some parts of the world overfishing has resulted in fishing down the food chain[64]. Overfishing has a direct effect on fishes, but can also cause trophic cascades in pelagic systems. For example, overfishing of plankton feeding fishes along the coast of Angola resulted in great population growth of gelatinous zooplankton that thrive on the additional prey[90]. Commercial and recreational fishers take fishes from the GBR lagoon and adjacent habitats such as estuaries. Reef fish, pelagic fish and fish from coastal environments are taken (Table 18.2). Fisheries have a direct ecological impact on target species and potential indirect positive affects on prey taxa. In addition, they are of considerable social and economic significance to the region.

Several commercial fisheries on the GBR target pelagic species ranging from net fisheries near the coast to line fisheries operating throughout much of the GBR. Spanish mackerel represents an important line fishery on the GBR worth approximately A$2 million annually with an annual harvest of about 600 tonnes (Table 18.2). GBR line fisheries also take shark mackerel, mostly as bycatch, and not currently in significant quantities. Other commercial fisheries that take pelagic species on the GBR are net fisheries operating in nearshore environments and take species such as grey mackerel, carangids, queenfish, pilchards, sardine, garfish and several shark species.

Recreational fishing is a significant pastime on the GBR with Queensland residents spending approximately 4.6 million days fishing during the period May 2000 to April 2001[52]. Recreational fishers using the GBR contribute about A$623 million to the Australian economy annually[2]. Mackerel species represent one of the most highly targeted recreational species groups. Commercial and recreational GBR fisheries also target a suite of reef and inshore species representing significant social and economic importance (Munday et al. chapter 12, Sheaves et al. chapter 19, Fenton et al. chapter 23).

Table 18.2 *Commercial and recreational catches of fishes and invertebrates taken on the GBR*. Catch in tonnes (unless specified), value in millions of Australian dollars; commercial data from 2005[a], except data for coral trout from 2005–2006 and sourced from ABARE[1]; year for recreational data as listed[16,52,113]. No data available designated by nd*

Common name	Species	Commercial Catch ($)	Recreational Catch (year)
Pelagic taxa			
Spanish mackerel	*Scomberomorus commerson*	249.3[†] ($1.746)	406 (2003)
Grey mackerel	*Scomberomorus semifasciatus*	181.1 ($1.087)	12 (1995)
School mackerel	*Scomberomorus queenslandicus*	29.6 ($0.178)	43
Spotted mackerel	*Scomberomorus munroi*	27.8 ($0.167)	70
Garfish	Hemiramphidae	74.3 ($0.446)	5.2 (2001)[§]
Shark mackerel	Grammatorcynus bicarinatus	43.2 ($0.259)	nd
Pilchards/Sardine	*Sardinops* sp.	6.1 ($0.012)	nd
Trevally unspecified	Carangidae	90.8 ($0.363)	235.2 (2001)[§]
Queenfish	*Scomberoides* sp.	78.2 ($0.235)	nd
Reef taxa			
Coral trout	*Plectropomus leopardus*	1134.0[‡,§] ($34.020)	386 (2005)[§]
Red throat emperor	*Lethrinus miniatus*	300.0[#] ($1.501)	118 (2005)[§]
Red emperor	*Lutjanus sebae*	29.3 ($0.264)	232 (2005)[§]
Spangled emperor	*Lethrinus nebulosus*	16.9 ($0.102)	nd
Snapper	*Lutjanid* sp.	23.0 ($0.184)	approx. 850 (2005)[§]
Tropical rock lobster	*Panulirus ornatus*	210.0 ($4)	nd
Reef, inter-reef and open water			
Shark	*Unspecified*	657.7 ($3.946)	approx. 105 (2001)[§]
Coastal Taxa			
Blue swimmer crab	*Portunus pelagicus*	29.8 ($0.192)	200 (1999)
Mud crab	*Scylla serrata and Scylla olivacea*	539.9 ($5.669)	1000 (1999)
Barramundi	*Lates calcarifer*	199.9 ($1.399)	275 (1999)
Tiger prawn	*Penaeus esculentus*	1619.1 ($24.287)	nd
Eastern king prawn	*Penaeus plebejus or latisulcatus*	1331.1 ($14.857)	nd
Banana prawn	*Penaeus merguiensis*	348.0 ($3.132)	nd

* Most of these taxa are important in the recreational fishery but there are few data on catches

† From 2004 Total Allowable Commercial Catch (TACC) capped at 619.5t

‡ from 2004 TACC capped at 1350t

from 2004 TACC capped at 700t

§ estimates for all QLD

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[a] Queensland Department of Primary Industries and Fisheries commercial logbook data, http://chrisweb.dpi.qld.gov.au/chris/

Collectively the commercial and recreational fishing catch and effort for pelagic species on the GBR is relatively modest by international standards. However, locally they represent important industries both socially and economically. Just as impacts on the pelagic environment attributable to climate change may have an impact on the populations of bait fish species and those that prey on them, there would also be flow-on impacts to fisheries that target these species either commercially or recreationally. Unless these fisheries are monitored closely over the coming years of climate change, impacts on pelagic species populations may develop unchecked.

Some bony fishes and sharks have very large home ranges or are highly migratory. Consequently they are often fished immediately outside of the GBR by Australian and international vessels[74]. Fishing impacts or climate stressors outside of the GBR therefore, may affect the size of pelagic populations within the GBR. This is certainly true of large pelagic fishes such as marlin and some sharks.

18.3.6 Tourism

Many pelagic organisms represent the charismatic megafauna of tropical marine ecosystems and often are a focus of GBR tourism, which as part of regional tourism contributes AU$6.1 billion to the Australian economy[2]. Tourist operations have tours to sites such as the 'cod hole' on the northern GBR to observe large site-attached serranids. Sites with abundant reef sharks are also popular (eg Osprey Reef in the Coral Sea). Open water fauna including sharks and mammals also attract significant tourism attention. Tourists keenly seek observations of whales and operators take them to observe migrating humpback and minke whales.

18.4 Physical environment effects on pelagic organisms

Pelagic organisms interact with the physical environment. Therefore, it is not surprising that the physical environment has a great influence on fauna and variations in physical aspects of the environment will alter assemblages (Table 18.3). This is especially true where organisms are intolerant of variation outside a narrow range of conditions (eg temperature: stenothermal organisms). The physical environment can influence patterns of growth, mortality, movement, reproduction, recruitment and assemblage composition. Key physical factors include: oceanography (current strength and direction), sea level, sea temperature, ocean chemistry, ultraviolet radiation, nutrient enrichment, rainfall, salinity, wind and cyclone events. For the purposes of this chapter we are nesting rainfall (and related salinity changes), upwelling, winds and cyclones within nutrient enrichment, as all of these physical factors will have an impact on nutrient levels. Rainfall not only affects nutrient levels through runoff but can also cause low salinity waters that can kill some organisms. For example, benthic phases of some jellyfishes die in salinities of less than 12 practical salinity units (psu)[77]. Cyclones can also have significant destructive effects on reef habitats and associated organisms.

Table 18.3 *Physical changes to pelagic habitats of the GBR that can affect biota. Some of the sources of change listed correlate with each other (eg cyclones will alter rainfall). Indication of predicted changes are in short (next 20 years) and long term (beyond 20 to 100 years) (Source Lough chapter 2)*

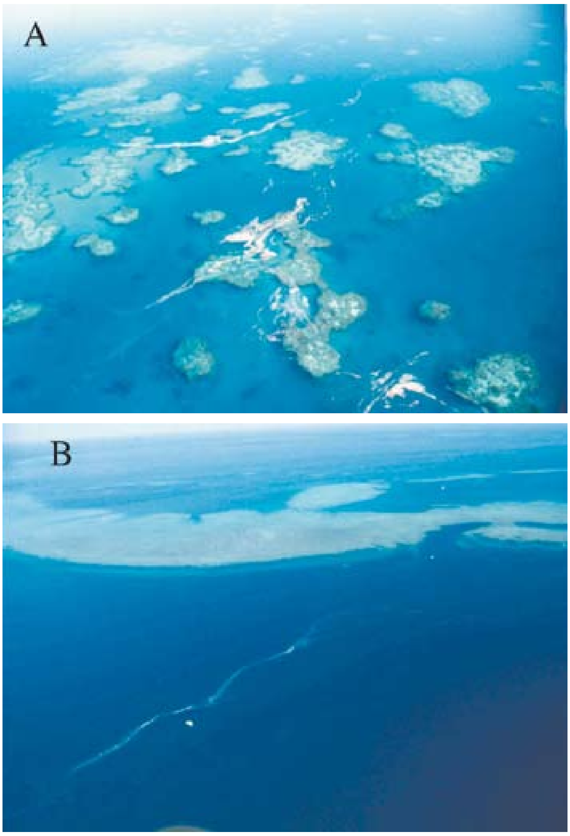
Source of change	Scenario
Oceanography	Changes in current strength and direction; some changes in current strength are expected.
Change in sea level	Inundation of established coastal habitats such as mangroves and seagrass beds. An increase of up to one metre is expected in the long term. Current rates of increase are 2.9 mm per annum, but sea level would increase significantly with catastrophic melting of ice caps.
Temperature	Changes in average temperature will influence the size and duration of hot spots. Average increases of 1.6°C long term. There are no predictions on hot spots.
Acidification	A reduction in pH as a result on increased levels of dissolved CO_2. Decrease of 0.5 pH units is expected over the next 100 years.
UV radiation	Increased exposure to UV radiation; variation in short and long terms not expected to be great.
Rainfall and clouds	Increased residence time of warm water on the GBR could result in increased evaporation and accumulation of clouds. Onshore winds would result in greater rainfall and input of low salinity water; but predictions do not suggest a great increase in rain.
Upwelling	Upwelling frequency, duration and intensity along the shelf break; no predictions, but wind would affect upwelling.
Wind	Changes in strength and direction of wind would alter currents, upwelling and rainfall. No predicted change in wind for the short or long term, but see cyclones.
Cyclones	Increased intensity and frequency of cyclones. Changes in wave height and increased potential for habitat destruction; extreme rainfall and freshwater input to coastal environments which is toxic to many organisms (low salinity), increased mixing of surface layers resulting in localised change in temperature. Long- and short-term predictions show little change in cyclone behaviour.

18.4.1 Oceanography

Currents connect habitats on the GBR through the transport of larvae and nutrients, and influence the movements of patches of planktonic organisms. In addition, currents influence the genesis of planktonic assemblages. For example, upwelling will transport nutrient rich waters into the photic zone. The subsequent growth of phytoplankton will in turn influence production of consumers (McKinnon et al. chapter 6).

Most benthic organisms have a larval stage that spends time in the pelagic environment. Currents can favour repatriation to areas where larvae were spawned (source) or expatriate them (sink). Oceanography clearly affects the connectivity of benthic habitats such as reefs that are separated by expanses of shelf waters. This is seen dramatically during the mass spawning of corals[101,140] where many reproductive products are dispersed among reefs separated by hundreds of metres to kilometres (Figure 18.4). Although models have predicted that larvae can disperse over great distances[65,137], it is clear that the probability of broad dispersal will depend on currents as well as the mobility and sensory capability of larvae[78]. Recent studies have indicated that a substantial proportion (20 to 30%) of at least some taxa may return to source reefs[66,67]. Despite high rates of settlement to source reefs by some taxa[37], there is still some dispersal among clusters of reefs[24]. The strength and direction of currents will influence the position of source and sink reefs[20] and a change in currents may require a response by managers to consider marine protection regimes.

Figure 18.4 *Connectivity of reproductive products among reefs on the central GBR.*
A. Patch reefs in the lagoon of Bowden Reef (altitude 300 metres), coral spawn among reefs separated by tens to hundreds of metres, slick area 200 to 500 metres long
B. Stanley reef (altitude 1500 metres), coral spawn slicks among reefs, shown boat is eight metres long and the slick is two to three km long (Photo credit: Bette Willis)



Oceanography will also influence the distribution of patches of plankton. For example, larvae of pelagic fishes are transported by currents that are important for retaining or transporting larvae to suitable nursery areas. Thermal signatures of patches may correspond to a unique plankton assemblage on and off the shelf[44], while nekton may respond to thermal structure[86], a potential sign that conditions are good for feeding. Climatic factors that change the direction and strength of currents therefore, would alter patch dynamics on the GBR.

Stratification of the water column influences the distribution and abundance of plankton and can have a great influence on the distribution of planktonic food and the nekton that feeds on it. Although shelf waters of the GBR are often well mixed, stratification can result from freshwater input and waters are stratified immediately off the shelf break (Steinberg chapter 3). Changes in stratification can alter patterns of plankton biomass[122] and the degree of stratification is influenced by climatic factors.

18.4.2 Sea level

Sea level changes with phase of the tide and, tidal ranges of 1.7 to 6 metres are typical on the GBR. Tides combined with bathymetry are primary drivers of the physical oceanography of the GBR and influence transport of nutrients, plankton and nekton and the advection of larvae as well as influencing organisms with intertidal distributions (Lovelock and Ellison chapter 9). However, the entire tidal base-line can alter with changes in sea level.

Organisms of the GBR have dealt with previous changes in sea level. Five thousand to twelve thousand years before present the current continental shelf was not immersed and as recently as 1000 years before present sea level was one metre higher than it is now. It is predicted that sea level will rise approximately one metre within the next 100 years. Organisms with narrow nearshore depth ranges would be most affected. Benthic organisms such as mangroves have moved seaward or further inland with historical changes in sea level[144]. For pelagic organisms, changes in nearshore sea level could have a great affect on nearshore production levels, the effectiveness of nursery areas, turbidity and changes in currents due to alterations to bathymetry and related water movement.

18.4.3 Temperature

Variation in water temperature affects many aspects of the biology of pelagic organisms, including: timing and duration of phytoplankton blooms; spawning of adults (eg fishes[121], egg size[82], survival of larvae[75], duration of larval phase[43]); growth of larval, juvenile and adult forms (eg squid[63], tropical wrasse and other reef fishes[127]); and movements and distribution of adults[86]. Temperature has also been shown to influence the distribution, abundance and growth of mesozooplankton and phytoplankton[115], the abundance and distribution of planktonic pathogens, and the occurrence and virulence of disease (Webster and Hill chapter 5).

Biogeographic patterns and growth of most marine organisms are affected by temperature[22]. Range changes in response to increases in temperature, have been demonstrated for marine fishes elsewhere[107]. In summer, normal latitudinal temperature variation from Torres Strait to the southern GBR can be 4 to 5°C (ie 25.5 to 29°C). Temperature varies with time of year, especially at high latitudes on the GBR, so some tolerance of variation in temperature is apparent. On the southern

GBR, temperatures range from 18 to 29°C during the year. Local effects that influence temperature include warming in lagoons[3], upwelling and the input of freshwater[145]. Upwelling will generally cause low temperature anomalies, while freshwater can be either warmer or cooler than the ocean and this generally depends on the time of year. Patches of warm water can pool at various locations for days to weeks based on activity of the South Equatorial Current and related ENSO effects, as well as interaction with local tides. Over the last two decades, patches of water greater than 31°C have been resident on coral reefs for long enough to cause coral bleaching.

Patches of warm water affect the distribution and recruitment of nekton. The distribution and abundance of pelagic fish species are strongly linked to temperature regimes. For example, highest catches of skipjack, the world's most prolific tuna species with respect to fisheries, comes from a 'warm pool' in the western equatorial Pacific. Further, spatial shifts in skipjack populations have been linked to large spatial displacements of this warm pool that occurs during ENSO events[86]. This has also been found for other tuna and billfish[148].

The shift in the distribution of round sardinella (*Sardinella aurita*) in the western Mediterranean Sea has been shown to correlate with changing sea temperatures, with temperature also explaining areas of high abundance and high fisheries landings[119]. Perry et al.[107] also demonstrated similar changes in a number of exploited and non-exploited North Sea fish species with changes in distribution by both latitude and depth. There are also indications of this occurring in the Bering Sea with a northward shift in the range of some fish, bird and mammal species[128].

Large pelagic species tend to show a consistent vertical stratification with dolphin fish occupying surface layers, marlin in the surface mixed layer, yellowfin tuna in the thermocline layer, bigeye tuna below the cooler thermocline and swordfish in the deeper cold waters[56]. Patterns in the geographical and vertical distribution of tuna and billfish species are strongly linked to temperature (eg Pacific bluefin[79,80], yellowfin tuna[106,27], skipjack[106], black marlin[46,17]. Worm et al.[148] concluded that sea surface temperature was the strongest predictor for pelagic predator diversity and density globally.

Spanish mackerel (*Scomberomorus commerson*) represent the most significant pelagic fishery in GBR waters. As an epipelagic shelf species, spanish mackerel are found the length of the GBR and are thought to carry out seasonal migrations along the GBR coast[131], with their range extending south during warmer months. Movements are thought to be related to food supply more than temperature, and the east coast population appears to tolerate a wide range of water temperatures. Other smaller mackerel include spotted (*S. munro*i), grey (*S. semifasciatus*) and shark mackerel (*Grammatorcynus bicarinatus*) that are important epipelagic predatory fish associated with reef and inshore waters and are important recreational and commercial species. Spotted mackerel are known to carry out seasonal northerly migrations during winter[7] suggesting that water temperature may be an important factor. Little is known of the influence of temperature on grey and shark mackerel. Temperature has been shown to be a significant determinant of distribution and movements of other fish species elsewhere including similar mackerel species (eg Atlantic mackerel, *Scomber scombrus*[99]).

Peck et al.[105] found that small scale variations in sea surface temperature of the southern GBR affected the foraging success of wedge-tailed shearwaters during their breeding season, providing evidence of fine scale mechanisms driving the coupling of breeding success of seabirds with pelagic prey distribution and ENSO events.

18.4.4 Ocean chemistry

Stable pH is critical for most marine organisms. Many species of marine plankton rely on optimal ocean chemistry conditions for development of calcareous shells, plates and skeletons[102]. Ocean chemistry can also affect the subcellular functions and physiology of respiration, growth and reproduction in marine organisms[114]. However, studies on the impact of changes in ocean chemistry on pelagic organisms are sparse.

Several studies have examined the effects of changes in water chemistry in the pelagic environment on the early development of some species but few data exist on the physiological regime requirements for individual species. It is significant though, that from geological records, current levels of ocean pH (and CO_2) are inferred to have been stable during the past 300 million years[15]. There has been some change over the last 200 years (a reduction of 0.1 pH units), probably due to industrialisation[114]. Development of pelagic eggs and larval stages of various marine organisms have been shown to be sensitive to changes in water CO_2 concentration and pH levels[47], however responses can differ among species and life stages. Ishimatsu et al.[61] examined a range of different species types and found that silver seabream (*Pagrus major*) and Japanese sillago (*Sillago japonica*) larval development was disrupted, particularly at the cleavage and juvenile stages with increased levels of CO_2. The authors also found that adults of the pelagic Japanese amberjack (*Seriola quinqueradiata*) died within eight hours of being exposed to seawater equilibrated with five percent CO_2 levels. Kurihara and Shirayama[83] found that fertilisation rates and development of two species of pelagic spawning sea urchins decreased with increasing CO_2 concentrations.

Photosynthesis in marine phytoplankton has been shown to decrease under increased levels of CO_2 (and reduced pH) resulting in lower phytoplankton biomass[136]. From experiments between latitudes of 11 and 44° N in the western north Pacific Ocean, copepod mortality increased under increasing levels of CO_2[135]. Although not conducted in the southern hemisphere, these studies found tolerance to CO_2 concentration changes was lower in shallow water, sub-tropical copepods.

Some subcellular functions, such as ion exchange and protein synthesis, are reduced under conditions of elevated CO_2 levels, more so in invertebrates than fish[110]. This can affect growth and survival and so ocean acidification impacts may vary between species. There are also potential negative synergies to organisms with increases in CO_2 concentration and increased exposure to ultraviolet radiation.

18.4.5 Ultraviolet radiation (UVR)

Ultraviolet radiation (UVR) is damaging, particularly to the DNA of organisms. UVR is long wavelength and can penetrate seawater to depths of 30 to 40 metres. There has been concern for phytoplankton and zooplankton at high latitudes where ozone depletion is greatest[51]. Ultraviolet B (UVB) exposure has been shown to inhibit photosynthesis in phytoplankton[84], but there is evidence that phytoplankton is more vulnerable at high latitudes than at low latitudes[51]. UVR is known to influence the composition of zooplankton communities in freshwater systems[108] and vulnerability to UVR is greatest at high latitudes.

18.4.6 Nutrient enrichment – upwelling, rain, winds and cyclones

Upwelling, rain, winds and cyclones can all influence levels of nutrient enrichment and will, therefore, affect primary productivity in the pelagic environment. Areas of upwelling, around the globe, are

where the highest biomass of pelagic organisms is found from plankton to large nekton. Nutrient rich waters are advected into the photic zone where the producers (phytoplankton) can utilise them during photosynthesis. Concentrations of nutrients are relatively low near the break of the GBR when compared to other parts of the world[145], but are of considerable biological importance to reef, inter-reef and pelagic habitats. Upwelling is of greatest biological relevance along the shelf break of the GBR where cold tongues of water are advected onto the shelf and in some cases may extend to mid shelf reefs[35] (Steinberg chapter 3).

Wilson et al.[143] showed that upwelling associated with El Niño conditions resulted in high chlorophyll abundance (phytoplankton) and high abundance of meso- and macrozooplankton. While down-welling associated with La Niña conditions resulted in the opposite community structure in the plankton. Further, differences between surface and deep macrozooplankton assemblages were more pronounced during down-welling conditions.

Wind direction and strength will influence the location of upwelling and the duration of upwelling. Thus, any changes in wind could perturb spatial and temporal patterns of biology (eg distributions and productivity). Wind has a major influence on the transport of waters near the surface (Ekman Layer) and this can influence the transport of larvae and other plankton as well as patterns of nutrient enrichment[145].

Cyclones impact on the surface layers of the ocean through increased mixing and alteration of water temperature, at least in the path of the cyclone, and significant damage can occur to the habitats of reef-associated organisms. In January 1998 on the southern Northwest Shelf in Western Australia, the passage of Cyclone Tiffany resulted in changes to the physical characteristics of the water column and in plankton communities[91]. Changes in both water temperature and salinity occurred but differed depending on proximity to the coast (shelf position). Changes to plankton included increased abundance and biomass of phytoplankton with higher primary production, changes in the composition of copepod species, and increased presence of larval fish species that were previously rare or absent. On the GBR, Cyclone Justin traversed the coast for several weeks in March 1997 and resulted in anomalous localised decreases in water temperature. No studies were conducted coinciding with this event that were able to detect changes in the pelagic environment, however resultant changes in catches of the two primary target species of the GBR line fishery were evident[139].

A major source of nutrient enrichment in the marine environment is from riverine inputs[38,45,145]. The input of terrestrial sediments and nutrients is known to affect the recruitment of fishes and prawns, and it is often argued that recruitment is enhanced through increased primary and secondary production as rainfall and associated riverine input increase. In addition, as riverine input increases associated flood plumes become increasingly effective as retention areas for larvae. Thus, a combination of factors may contribute to good recruitment, including high growth rates of larvae that can minimise the time they are affected by small planktonic predators. Inshore waters of the GBR are regularly exposed to riverine inputs and nutrient related biological impacts are likely to be greatest inshore and on wide ranging nekton that utilise inshore areas. Other biological effects of freshwater input can be mortality of some taxa through low salinity and high levels of turbidity that can reduce light penetration to the benthos[34].

A combination of climate factors will often affect organisms. For example, Bergenius et al.[10] concluded that UV radiation, along-shore winds and rainfall during early larval growth of fish on the GBR may influence growth, larval duration and settlement.

18.5 Vulnerability of pelagic systems to climate change

This chapter has described how the physical environment affects organisms and how changes in the physical environment can have multiple impacts (Table 18.4). Some aspects of the physical environment have shown little variation in the last few thousand years, but climate change has altered this pattern and will continue to do so. Changes that are significant for the pelagic environment include ocean acidification, ocean warming and resultant thermal expansion of water causing sea level rise of as much as one metre in the GBR region by 2100, which will inundate some low-lying coastal and coral reef environments. Inundation will be greater if there is catastrophic melting of the ice caps, where significantly higher sea level rise would be experienced. The exposure of organisms to UV light (a DNA destructor) will potentially change with loss of global protection through ozone depletion, though predictions for the next 100 years suggest little change in the tropics (see also McKinnon et al. chapter 6).

18.5.1 Spatial and temporal scales of impact

Climatic factors vary in space and time and this variation will have a great influence on the response of pelagic organisms. Although discussions often focus at global or GBR regional scales, some climatic perturbations will at times only affect some regions (eg northern or southern regions), certain distance strata (eg temperature induced coral bleaching is often greatest near the mainland; Hoegh-Guldberg et al. chapter 10), or clusters of reefs within a distance strata. Temperature is a good example of a stressor that varies in space (eg patches of warm water) and the duration of exposure will vary depending on the size of the patch and how fast it is being advected. Bender et al.[9] identified two kinds of perturbations, 'pulse' and 'press'. A 'pulse' is a relatively instantaneous alteration after which the system returns to its previous state (eg a warm patch of water in an area for hours to a few days). A 'press' is a longer-term fluctuation that is sustained and can lead to significant impacts and possibly the elimination of some taxa (eg warm water resident in an area for weeks). An example of a press event on a scale of tens of square kilometres was experienced in the Keppel Islands in 2006 where there was substantial bleaching of corals. The ability of populations of pelagic and benthic organisms to recover will depend on the frequency and duration of events. It is highly likely that localised pulse and press events would be the first stage of climate change on the GBR for stressors such as temperature. Therefore, detection of climate change impacts over the next 100 years needs to consider spatial monitoring on the GBR.

18.5.2 Climatic stressors on the GBR

There are multiple projected changes in the physical environment with climate change and scenarios vary by physical variable and years from present (Lough chapter 2). Climate change is expected to alter current patterns in the GBR and the connectivity of populations between habitats. Sea level rise of up to two metres or more is possible and this will immerse shallow habitats, alter patterns of nearshore

Table 18.4 *Biological responses to changes in the pelagic environment. Many potential responses and the ability to adapt will depend on rates of change (Sources Kingsford and Gray[75], Hays et al.[50], Wolanski and De'ath[146])*

Exposure	Oceanography	Temperature	Acidification	UV	Nutrient enrichment (Upwelling, winds, rainfall, cyclones	Sea level
Sensitivity	• All taxa with larvae are sensitive (the majority of fish and invertebrates on the GBR	• Thermal tolerance • Viability of reproductive products • Survival of larvae • Patterns of growth	• High for pelagic organisms with calcium skeletons or shells (eg fishes, molluscs)	• High for some phytoplankton and zooplankton, which is the foundation of pelagic food chains • Viability of pelagic eggs	• High for organisms with low tolerance for variation in nutrient levels	• Nekton that use coastal habitats for recruitment or feeding • Organisms with historical spawning sites that are topographically distinct and will be altered with sea level change
Potential impacts	• Changes in larval transport • Changes in connectivity among reefs and coastal environments (ie estuaries). • Species replacements	• Range shifts • Changes in spawning location and success • Long-term viability of some pelagic populations • Successional change in ecosystem (ie increase in jellyfishes)	• Change in planktonic assemblages that provide food for nekton (ie quantity and quality)	• Change in plankton community (diversity and abundance)	• Change in planktonic assemblages and food sources for larvae and nekton • Changes in larval survival (positive for some negative for others) • Changes in distribution • Increased harmful blooms	• Alter nearshore habitats that are nursery areas fro pelagic taxa • Change input of nutrients from coastal environments (eg detrital food chains)

production and alter currents. Mean sea temperature and the size and duration of temperature hotspots will increase on the GBR and expose pelagic organisms to temperatures that are known to stress corals and could affect pelagic organisms (Table 18.4). Projected changes in sea temperature are +0.4 to 0.5°C to 2020 and 1.1 to 1.5°C by 2050 (Lough chapter 2). Changes in wind will contribute to changes in oceanography, altering patterns of connectivity, transport and nutrient enrichment factors such as upwelling and rainfall. Projections suggest that patterns of rainfall will remain similar with seasonal rain in the northern and far northern regions of the GBR, and stochastic rainfall in central and southern regions (Lough chapter 2). The magnitude of droughts and high intensity rainfall events are likely to be greater. For example, the stochastic element of rainfall may increase if there is a higher frequency of category 4 and 5 cyclones. Cyclones will generally affect relatively small areas of the GBR (eg a swath of 100 km), but this can result in significant local destruction of benthic habitats and changes in nutrient enrichment and temperature, especially through rainfall.

Projections suggest that currents are likely to remain similar in direction but with increases in the speed of key currents that influence the GBR likely (eg the East Australian Current; Steinberg chapter 3). Therefore the direction of connectivity of populations is likely to remain the same, but increases in current speed will influence local patterns of upwelling. Greatest variation in upwelling would be experienced on the shelf break. If current direction does change, patterns of larval connectivity will also change along with biogeographic patterns. Increased speed of the GBR lagoon current that flows from the central GBR to the southern GBR is likely to move temperature hotspots to the south faster. Currents in the northern and far northern regions of the GBR are generally slower behind reefs and longer residence times of temperature hotspots would be expected. Inshore, central and northern reefs are generally impacted to the greatest extent in bleaching events and pelagic assemblages may experience greater press perturbations of temperature as average sea temperatures and frequency of hotspots increase. The risk of ponding warm water masses is greatest on the northern GBR. Although bleaching has been recorded in the southern GBR, faster flowing currents in the GBR lagoon may move patches more quickly. Sea level rise will also change local currents, especially near the mainland where large expanses of low-lying coastal land would be inundated and local retention areas altered.

Average change of physical perturbations at GBR or global scales is not indicative of exposure for local populations. For example, warm seawater anomalies usually manifest themselves on the GBR as warm patches that only affect some parts of the ecosystem. The duration of a hotspot will vary from a pulse of a few hours to days, to a press lasting weeks to months. These anomalies can result in changes of up to five degrees (eg 26 to 31°C) that can affect pelagic organisms. It is likely in the next 20 to 50 years that some of the greatest impacts on organisms will be in patches rather than GBR-wide. Over longer time scales, the combination of increase in average temperature combined with an increase in the number, size and press duration of hotspots has the potential for greater impacts on pelagic populations.

Projections of atmospheric CO_2 concentrations show increases from current 380 parts per million to concentrations ranging from 540 to 970 parts per million by 2100[60]. As a result of CO_2 exchange with sea water[102], pH and concentrations of carbonate in sea water will change. The relationship for the absorption of CO_2 in sea water is also influenced by temperature[81] and there is the potential for calcification to facilitate a negative feedback on atmospheric levels[117]. A drop of 0.5 pH units over the next 50 to 100 years is predicted. This has the potential to affect intracellular processes and the

physiology of organisms and especially pelagic organisms with calcium carbonate (as for corals) or calcium phosphate in their skeleton. Plankton (ie foraminifera, coccolithophores), molluscs (eg pteropods, heteropods and squid), crustaceans (eg copepods) and fishes have calcium carbonate in their skeletons and fishes and marine mammals have calcium phosphate as bone. All of these organisms therefore, are at risk from ocean acidification[102]. We have already described how the environment affects pelagic organisms, and physical changes will also affect the biota of pelagic ecosystems (Table 18.4).

18.5.3 Empirical models – correlations between climatic factors and abundance

Empirical models are simple correlations between physical variables (eg temperature) and population parameters (eg abundance and recruitment). Empirical models[124] of recruitment levels versus oscillation indices have been published for a wide range of taxa including algae, benthic fishes and pelagic fishes. Based on these correlations, many have concluded that climatic forcing has a strong influence on populations and assemblages. Pattern seeking of this type requires data sets that encompass long periods if they are to relate with a wide range of climatic conditions (eg El Niño to La Niña). Data sets of greater that 10 years have shown strong relationships between climatic indices and recruitment.

Attrill and Power[4] concluded that climatic forcing (over 16 years, North Atlantic Oscillation) was consistently the most important parameter explaining variation in assemblage composition, abundance and growth of juvenile marine fishes during estuarine residency. The recruitment of West Australian rock lobsters correlates strongly with the Southern Oscillation Index, where recruitment is highest in La Niña conditions (over 18 years[19]). Interestingly, direction of correlations varies according to taxa. For example, Caputi et al.[19] found a negative correlation between the Southern Oscillation Index and recruitment of lobsters while there was positive relationship for bivalves. Parrish and MacCall (in Sissenwine[124]) could explain 60 to 86 percent of the variation in recruitment of Pacific mackerel to a survival index. Empirical models do not explain the processes influencing recruitment, but provide a hypothesis-generating platform for further investigation. Furthermore, robust models can be used to make accurate predictions of levels of recruitment to populations or movement that includes important commercial stocks[86]. Parrish and MacCall[104] argued that 84 percent of their survival index was due to zonal Ekman transport. This oceanography transports larvae from offshore spawning grounds to inshore nursery areas.

Empirical models are not causal since the physical variable is only a proxy for an underlying biological process. For example, the Southern Oscillation Index may correlate with current flow that influences the transport of larvae, or correlations of abundance with increased temperature may be indicative of good feeding conditions.

Table 18.4 presents information on the sensitivity, potential impact, adaptive capacity, and linkages and interactions that may result from exposure to multiple climatic factors. Stressors with greatest potential for impact are sea temperature and nutrient enrichment, followed by oceanography and sea level rise. Some of these stressors are not independent, for example, oceanography can alter patterns of sea temperature and nutrient enrichment. Changes in water chemistry have the potential for far reaching change. However, this is more likely at time scales beyond 50 years from present.

18.5.4 Oceanography

18.5.4.1 Exposure and sensitivity

All organisms that are dependent on pelagic food resources and the pelagic environment for larval transport will be exposed. Predictions are for only minimal changes in current direction and changes in current strength. However, some change to the oceanography of the GBR would be expected as a result of sea level rise that will influence local currents.

18.5.4.2 Potential and observed impacts

Changes in current direction and speed could alter patterns of connectivity and the ability of larvae to return to natal (ie source) reefs. For example, Cowen et al.[23] found that the return of larvae to a reef was dependent on depth stratified currents, where deep currents advected larvae onshore. Expatriation of larvae through adverse currents could have a large influence on populations[59]. Changes in currents could also influence the movement of pelagic larvae from spawning grounds to recruitment areas. The position of retention areas could change, influencing not only plankton but also the nekton that depend on them (eg bait fishes and predators).

18.5.4.3 Adaptive capacity

Unknown for plankton, but there is the potential for larvae to alter patterns of vertical migration in response to changes in currents. Large nekton may alter patterns of migration and patterns of biomass[86].

18.5.4.4 Vulnerability and thresholds

All taxa are vulnerable, but changes in currents are predicted to be small with some changes to currents nearshore due to sea level rise being the most significant. The interaction between currents and patches of different temperature water is likely to have the greatest effect on pelagic organisms and cause the greatest vulnerability.

18.5.5 Sea level rise

18.5.5.1 Exposure and sensitivity

Although the projected sea level rise is unlikely to cause great change over the continental shelf at mid and outer distances, there would be effects nearshore due to changed nutrient and sediment regimes and changes in size of estuarine and mangrove forest recruitment areas. Local sea levels will vary according to topographic channelling of tidal waters to adjacent basins (eg near Cairns sea level rise is not expected to be as great as two metres; J Nott pers comm). A catastrophic increase in sea level due to the melting of major ice caps may be too fast a change for nearshore production cycles to re-establish. Populations with restricted depth tolerances may struggle for physiological reasons or due to an inability to interact with organisms from other depths (ie competition and predation). A two to ten metre sea level rise will alter local currents for local populations with subsequent oceanographic influences.

18.5.5.2 Potential and observed impacts

There are likely to be changes in the size and quality of nursery areas that are critical to the recruits of many fishes and invertebrates. Some shallow water habitats would increase, as predicted for mangrove habitat on the mainland, while others may disappear due to steep sided islands, similar geomorphology and landward constraints by man made structures (Lovelock and Ellison chapter 9). Many changes due to sea level are likely to affect benthic rather than pelagic organisms, but most marine organisms have pelagic larvae and the composition of pelagic larval assemblages would change if intertidal assemblages changed greatly as a result of sea level rise. Sediment regimes may change and local levels of production (eg from detrital food chains) may alter and affect interactions with pelagic organisms. There is also the possibility that increased inundation of land will increase the input of pollutants to inshore waters of the GBR. The latter scenario may not be significant as the size of populated areas adjacent to the GBR is relatively small (ie there are only three cities with populations greater than 100,000). The inundation of beaches used by turtles for nesting may alter patterns of reproduction on the GBR and therefore that component of the pelagic environment.

18.5.5.3 Adaptive capacity

Some pelagic organisms may migrate away from areas that have been inundated or altered by sea level rise, and in some cases there may be local extinctions where water depth becomes too great. If the inundation of coastal habitats is slow then critical coastal and estuarine habitats should re-establish as they have done in the past (eg mangroves[144]). However, a sudden sea level rise due to the melting of polar ice caps would allow less time for relatively gradual changes of habitats.

18.5.5.4 Vulnerability and thresholds

Nearshore assemblages will be most vulnerable to changes in sea level, with the areas of greatest concern being nursery areas. There is an unknown component of vulnerability to sea level rise due to the possible melting of polar ice caps and a sudden sea level rise.

18.5.6 Sea temperature

18.5.6.1 Exposure and sensitivity

Plankton and nekton of the pelagic environment in the GBR will be highly exposed to the 1 to 3°C increase in mean sea temperature predicted. Temperature anomalies will be experienced as patches of warm water that remain in an area for a short (pulse) or long (press) time. Although warm water is low density and should float, a high level of mixing on the shelf would be facilitated through physical processes such as wind, tide and currents, so temperature incursions may be experienced at all depths.

18.5.6.2 Potential and observed impacts

Many pelagic organisms have the capacity for substantial vertical and horizontal migrations through the water column and this could encompass temperature ranges of greater than 3°C. It could be predicted, therefore, that the potential impact on pelagic organisms due to temperature increases in the next 100 years will be slight. However, for most organisms there are no data on response to upper critical levels of temperature (ie thermal tolerance above a temperature such as 31°C). Temperature tolerance may cause mortality but critically there may be sub-lethal effects on larvae and other plankton such as changes to growth, vulnerability to starvation and predation, behaviour and longevity[75]. Shifts in the structure of prey and predator communities is likely to be a major secondary effect on many plankters within the pelagic plankton as has been documented at other latitudes and this is likely to affect the growth, development and survival of larvae[6].

Higher water temperatures can improve growth rates in larvae of *Pomacentrus coelestis* on the tropical northwest coast of Western Australia[94]. Sponaugle et al.[127] found this was the case also for the tropical wrasse *Thalassoma bifasciatum*, and that recruitment was higher, although more variable, in warmer water conditions. Squid also grow faster in warmer water[33].

For nekton, variation in sea temperature is likely to change movements, particularly if prey are affected. There are demonstrated temperature limits that influence the distribution and abundance of the bait fish round sardinella (*Sardinella aurita*) in the Mediterranean Sea[119]. The movement of bait fish can also affect the movements and survival of fishes and birds that feed on them (Congdon et al. chapter 14).

Changes in planktonic assemblages have been demonstrated to vary with sea temperature. For example, warming in the north Atlantic has affected the composition of plankton[115] and the feeding environment for larval cod that are now thought to have poorer conditions for feeding[6]. It is also thought that the frequency of harmful toxic algae blooms that can affect nekton will increase[30]. In addition, warmer waters are likely to change the timing of phytoplankton and zooplankton blooms and influence the larval and older forms that are dependent on them[29]. Zeldis et al.[152] argued that salp outbreaks were more common in warm water and the feeding activity of the salps destroyed a suitable feeding environment for fish larvae[153]. Slight increases in water temperature have been shown to alter the balance between plankton autotrophic and heterotrophic communities in temperate environments[100,126].

Sea temperature has the potential to affect nekton. On Australia's east coast, Hobday[55] predicted that under the various IPCC assessment scenarios of climate change, the range of southern bluefin tuna (*Thunnus maccoyii*) would contract southwards, while yellowfin tuna (*Thunnus albacares*) will increase their distribution and abundance. Demographic changes have been noted in a number of North Sea fish species with altered distributions in response to recent changes in water temperature. Further, it is species with shorter life cycles that have shown the greatest response[107].

Humpback whales annually migrate to mid-GBR waters during the cooler winter months to give birth to calves. It is possible that with increases in temperature these migrations will contract further south (Lawler et al. chapter 16).

Increased ocean warming is likely to alter spatial distribution of primary and secondary pelagic production in the pelagic environment, with a cascade effect up the food chain, potentially placing greater stress on fish and mammal populations[115] (Lawler et al. chapter 16). Predicting the responses of pelagic communities to increasing water temperature is difficult given the complexities associated with the inter-relationships of different trophic levels and the multitude of different species within these levels.

18.5.6.3 Adaptive capacity

The ability of larval, juvenile and adult forms to alter thermal tolerances is poorly known. Lamnid sharks (eg mako and white sharks) are able to regulate their body temperature and so are more adapted to occupy a greater range of environmental temperature regimes (Chin and Kyne chapter 13). However, these species are infrequent GBR visitors. Lamnids and pelagic tunas and billfish are unique in that they can essentially regulate their body temperature via an internal countercurrent system and a structure called a *rete mirabile*. This essentially means that they have higher body temperatures and provides the ability for niche expansion[41]. These species are naturally suited to adapt to changes in sea temperature. Mobility is important for nekton, but changes in prey distribution may be more influential.

18.5.6.4 Vulnerability and thresholds

Planktonic organisms are highly vulnerable to environmental changes, which can result in a trophic cascade as observed in the northern hemisphere. In the medium term on the GBR this is likely to be restricted to sections of the GBR that are exposed to press events of warm water. Temperature thresholds are poorly known for tropical plankton and nekton. Nekton can move in response to changes in temperature but they may experience recruitment failure of larval habitat and juvenile nursery grounds may be compromised.

18.5.7 Ocean chemistry

18.5.7.1 Exposure and sensitivity

Climate change projections predict increased dissolved CO_2 accompanied by a reduction in the oceanic pH of 0.5 units by 2100 (Lough chapter 2). Calcifying zooplankton will be most susceptible to this change[102], but intracellular and physiological affects (eg changes in respiratory efficiency, growth and reproduction) are also likely to occur[114]. Pelagic eggs and larvae of fish and invertebrates will be exposed to these changes and are likely to be highly sensitive to them. It is unknown how local buffering effects of calcium carbonate reefs will affect the pelagic environment of the GBR.

If a rate of change of 0.5 units over 100 years is realised it will be the fastest rate of change experienced by marine organisms for about 400,000 years[114]. However, marine organisms have had to deal with ocean CO_2 concentrations that were three to four times higher than present about 100 million years ago (Cretaceous era[11]) and pH would have also been lower. However, many organisms that are critical in pelagic food chains today have a form of calcium carbonate in their skeletons called aragonite that is more susceptible to changes in pH than calcite, which was more abundant in the skeletons of organisms 100 million years before present. Not withstanding unknown buffering effects due to calcium carbonate stored in the dead matrix of coral reefs, organisms will have to deal with lower pH over time.

18.5.7.2 Potential and observed impacts

Adult pelagic species are likely to be less sensitive to predicted changes in ocean chemistry than early life history stages although few data are available. It is likely that selective removal or reduction in abundance of some taxa will result in trophic cascade effects with potential negative impacts on the pelagic food chain. Potential decreases in abundance of particular zooplankton, particularly calcifying species[117], will lower food reserves for planktonic larval species possibly lowering recruitment levels. Carbon flux to the substratum, through marine snow, would alter due to increases in polysaccharide production. The production of these complex sugars would increase with higher photosynthetic rates of phytoplankton cells, a response to increased levels of CO_2[31]. Changes in benthic assemblages can also link with pelagic ecosystems. For example, many molluscs have a critical role in releasing nutrients from sediments. If the mortality, growth and reproduction of these organisms are affected then nutrient exchange with the water column may be altered and this could in turn facilitate a trophic cascade. If coral reefs are compromised by reduced pH then this could change the habitats of many organisms that interact with and contribute to the pelagic environment through feeding and reproduction[40]. The oceans are critical in the global carbon cycle and changes in the ability of the ocean to absorb CO_2 could affect rates of global warming[114].

18.5.7.3 Adaptive capacity

Given that ocean chemistry has been historically highly stable, it is unknown how pelagic organisms will respond to changes in ocean CO_2 concentrations and pH. Generation times of phytoplankton and zooplankton can be rapid suggesting good adaptive capacity for organisms such as copepods. The capacity of different organisms to respond to change is likely to be highly variable and is difficult to predict. Most experiments that have been done on tolerance to variation in pH are too short term (ie responding to pulse not press impacts) to be relevant[114].

18.5.7.4 Vulnerability and thresholds

Organisms in the plankton, including larval forms and crustacean stages, are likely to be the most vulnerable in the pelagic environment. Thresholds for tropical plankton species are poorly known and are likely to be highly variable across the myriad of species present.

18.5.8 Ultraviolet radiation

18.5.8.1 Exposure and sensitivity

Ultraviolet radiation levels on the GBR are not predicted to change significantly. Therefore, although many pelagic organisms occupy the upper 20 to 30 metres of the water column, they are not likely to be exposed to changes in UV radiation. Phytoplankton are known to be sensitive to increases in UVB exposure.

18.5.8.2 Potential and observed impacts

Should current predictions of UV radiation levels alter, a reduction in phytoplankton levels is possible which would result in changes in species abundance and composition at higher trophic levels. Zooplankton community composition may also be altered.

18.5.8.3 Adaptive capacity

Although it is known that some phytoplankton species can respond quickly to changes in UV exposure, few studies exist for tropical species (McKinnon et al. chapter 6).

18.5.8.4 Vulnerability and thresholds

Based on current predictions the pelagic environment is not considered to encounter changed UV radiation conditions over the next 100 years.

18.5.9 Rainfall, nutrient enrichment and cyclones

18.5.9.1 Exposure and sensitivity

Predictions of changes in rainfall and cyclones on the GBR are uncertain. However, it is predicted that although there may be no change in their frequency, the intensity of extreme events will increase. This will expose the pelagic environment of inshore areas to more intense events of increased nutrients associated with flood plumes. Exposure may also extend further offshore (depending on currents and wind) to mid- and offshore reefs where few flood events have been experienced in the past. This may mean that organisms further offshore are more sensitive than their inshore counterparts. More intense winds from cyclones would exacerbate the enrichment of pelagic waters through mixing of benthic layers with surface waters. Increased flooding will also reduce salinity and temperature. Changes in sea level may also cause changes in nutrient enrichment depending on how drainage systems change with increased inundation.

18.5.9.2 Potential and observed impacts

It is uncertain how ENSO events will alter in the face of climate change, if at all, so changes in upwelling and down-welling events on the GBR are unknown. An increase in nutrients would generate bottom-up responses of the pelagic food chain[134] and significant changes in planktonic assemblages would be expected. Impacts of high nutrient inputs to the GBR are likely to be greatest in inshore areas, however there will also be increased occurrence of nutrient rich flood waters on mid- and outer-shelf reefs. Recruitment of fish and crustacean species is likely to be enhanced and will possibly result in much higher inter-annual variability in recruitment of populations. This may have significant impacts on fisheries production but may also alter biological and fishery stability. Changes in nutrient regimes also have the potential to alter the recruitment of gelatinous zooplankton including dangerous cubozoans. Aside from increased risk to the public, abundant gelatinous zooplankton has the potential for top-down effects where other plankton proliferates, including those that can generate toxic blooms[32,30].

Cyclone events are likely to have more localised effects. Increased flood events and associated winds may also have lethal or sub lethal effects on organisms sensitive to low salinity or benthic organisms sensitive to turbid conditions and increased sedimentation. Increased intensity of rainfall, cyclones and nutrient enrichment is likely to result in a more variable ecosystem and impacts may vary spatially within the GBR.

18.5.9.3 Adaptive capacity

In response to rapid changes associated with storm and rainfall events, some organisms can move away if conditions become unfavourable. Benthic organisms will be less capable of responding to these events.

18.5.9.4 Vulnerability and thresholds

Changes in nutrient levels will cause fundamental changes in pelagic assemblages. The composition of plankton changes quickly in response to changes in nutrient levels and this will in turn affect nekton. Experimental perturbations demonstrate rapid change. In Kaneohe Bay, Hawaii, for example, nutrient enrichment occurred from sewage that was pumped into the bay from the 1950s to 1977. The major uptake of inorganic nitrogen and phosphorus was by phytoplankton and this supported abundant zooplankton. When the sewage was diverted, biomass of plankton decreased rapidly[125]. As with other stressors, plankton in the pelagic environment will therefore be most vulnerable to changes in nutrients. However, this will result in community changes at higher trophic levels as they respond to altered primary and secondary production as well as changes in species assemblages in the plankton. Some benthic organisms may be most vulnerable to these rapid changes.

18.6 Linkages, interactions and implications

It is clear that changes to pelagic ecosystems will result in trophic cascades from plankton to benthic assemblages. The supply of planktonic food affects invertebrates and fish alike. Suspension feeders depend on plankton and changes in plankton supply from currents, upwelling, riverine input and other sources will affect them.

Excess plankton (eg algal blooms) can result in deoxygenated waters and death of benthic organisms. This has happened with prolonged El Niño conditions and atypical temperatures in New Zealand where diatom blooms were generated and then collapsed to decompose near the substratum, killing invertebrates and fishes[129].

Most benthic algae, fishes and invertebrates have a pelagic phase to their life history. Algae have spores and marine animals generally have pelagic larvae and often pelagic eggs. Conditions in the water column, therefore, will affect the probability of survival of these organisms (Table 18.3). It will also affect connectivity and the ability of pelagic organisms to be transported or move between environments and detect suitable habitat for successful settlement and growth[37].

The pelagic habitat of the GBR links with open ocean systems through pelagic fishes and marine mammals that visit the GBR on occasion or have strong seasonal migrations[68]. The nature of these links will vary according to environmental variation such as sea temperature, which can be used as a proxy for good feeding conditions[86]. On the GBR, there are geographically stable aggregations of bait fish (section 18.3.4) that attract open water predators and act as Effective Juvenile Habitat for pelagic fish such as marlin. The climatic factors that affect the fidelity and size of these aggregations will have a great effect on the local pelagic food chain.

Variation in pelagic stressors will affect the whole food chain, and this was dramatically observed in Peru where an upwelling failure resulted in altered bait fish distribution, lower survival of fish larvae, the movement of large nekton such as tuna, whales and sharks away from the area and the starvation of birds and other animals that depend on bait fish. Fisheries and the communities that depend on them are also greatly affected when these events occur[54]. There is varying certainty about how climatic factors will vary in the GBR in the short and long term. Variation in sea temperature and

sea level are the most certain along with long-term changes in pH. Changes in nutrient enrichment and oceanography will occur at local scales. All of these stressors will affect biota at different spatial and temporal scales, will interact with each other and therefore require multiple approaches by environmental managers.

18.7 Implications for management and recommendations

The implications that come from this review are as follows:

i) Predictions of global change and related environmental stressors are often weak, especially at spatial scales of less than one hundred kilometres.

ii) Changes in environmental stressors will alter the pelagic environment and linkages with other environments (eg coral reefs).

iii) Pelagic systems are quickly influenced by bottom-up (eg nutrient input) and top-down processes (eg predation) while mobile nekton can move great distances in response to environmental change.

iv) Predictions of physical change suggest that within the next 50 years biological changes in pelagic systems are likely to occur in patches on the GBR, rather than the entire region. Managers will have to deal with impacts on scales of tens to hundreds of kilometres in the medium term and spatial scales of impact are likely to increase with time.

Our recommendations to managers are:

i) Reducing CO_2 emissions to the atmosphere is the only practical way to minimize the risk of large-scale and long-term changes to the oceans[114].

ii) Managers need to set up relevant monitoring programs and research taking into account regional variation in GBR physical and biological processes.

iii) Monitoring of pelagic and benthic assemblages provides early warning of change. Coral reefs are considered the canaries in the coalmine, but plankton are the silent sentinels of change, as demonstrated in the northern hemisphere[6].

iv) Monitoring changes in physical oceanography can also warn of potential change. A GBR network of sensors and satellite imagery would allow broad scale monitoring of physical changes in currents, water temperature, salinity, pH and upwelling. It is critical that climatic conditions on the GBR are monitored. It is also important that predictions and measurements are made of patches of water with a high stress rating (eg waters over 31°C) and the time they spend in an area (ie pulse or press).

v) Monitoring catches of key taxa such as bait fish and large piscivores will track changes in pelagic fish assemblages, which has proven useful in the northern hemisphere.

vi) Patterns of growth, movement, reproduction and biogeography of many taxa track the environment and should be researched and monitored.

vii) Monitoring of plankton is time consuming and research on plankton should be used to develop models that predict biological responses to changes in environmental stressors.

viii) Some changes in the environment may increase risk to the public through toxic blooms and dangerous jellyfishes. Monitoring of these groups would be judicious as would the development of predictive models.

ix) Few data are available to managers on the response of different organisms to stressors. Field and laboratory-based research is required to determine the impact of pulse and press type perturbations on organisms. Early life history stages are the raw material of marine populations and are likely to be most vulnerable[75]. Responses to stressors can be lethal or sublethal as well as acute or chronic and the literature on pollution provides a useful framework for this type of research (eg Underwood and Peterson[132]).

x) Marine Protected Areas (MPAs) and fisheries management don't protect against the impacts of climate change, but will reduce additional stress on habitats and organisms not attributable to climate change[8]. Current management of the GBR through MPAs and fisheries management are considered excellent by international standards, but protection of pelagic taxa is more challenging. One option, however, would be to have increased protection of bait fish where they regularly concentrate. Protected areas could include Effective Juvenile Habitats in coastal bays, which are critical for many game fish, as well as areas of upwelling.

xi) Pelagic 'predator diversity hotspots'[147] may be protected. The protection of diversity may allow ecosystems to recover from perturbations as the loss of diversity can impair normal ecosystems function[149].

With climate change and related variations in environmental stressors it is inevitable that there will be changes in the biogeography of benthic and pelagic organisms. Species replacements are possible, as recorded through times of historical environmental change, and fisheries managers of the GBR will need to monitor target taxa and review quotas. There is an element of wait and see, but vigilance and increased understanding of the response of organisms to stressors are the keys to considering options for adaptive management.

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