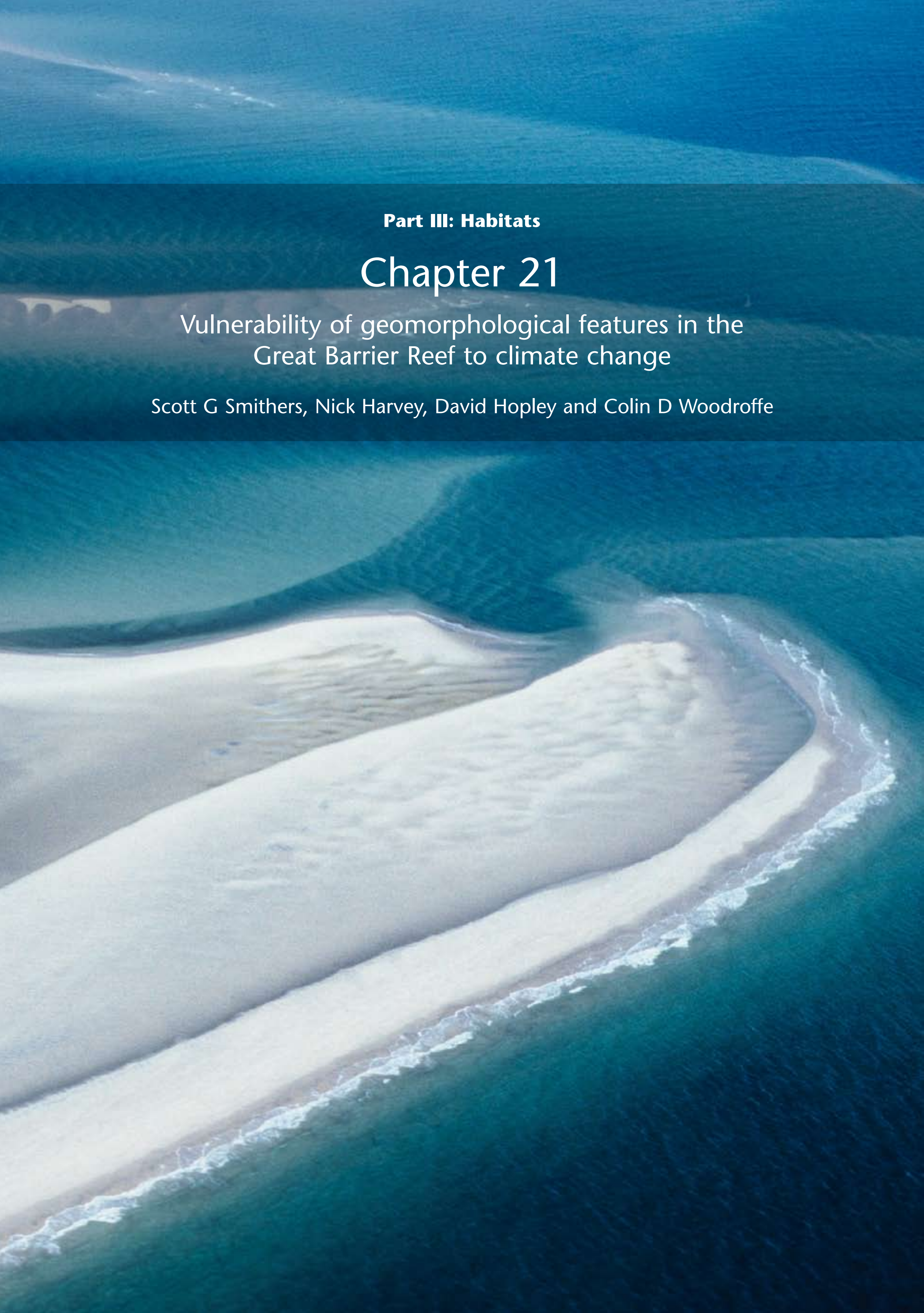

Part III: Habitats

Chapter 21

Vulnerability of geomorphological features in the Great Barrier Reef to climate change

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21.1 Introduction

The Great Barrier Reef (GBR) is the largest contiguous coral reef ecosystem in the world[81,49]. That it is possibly the largest geomorphological structure ever created by living organisms is less widely appreciated. The GBR extends through approximately 15 degrees of latitude and more than 2100 km along the northeast Queensland coast, covering an area of 344,500 km[282]. It includes more than 2900 reefs of varying types (eg fringing, patch, cresentic, lagoonal, planar), dimensions and stage of growth, which together occupy greater than 20,000 km^2, or about 5.8 percent of the total area of the GBR[81,82]. Three hundred or so coral cays, and more than 600 continental or high islands occur within the GBR. The mainland coast, which can be broadly separated into sandy shorelines and mangrove-lined muddy coasts and estuaries (rocky coasts are far less common)[80], is another important and dynamic geomorphological component of the GBR.

The geomorphology and ecology of the GBR are strongly interdependent – the reefs are almost entirely the skeletal remains of a myriad of calcium carbonate secreting fauna and flora. A suite of organisms and ecological processes are involved in the production, consolidation, modification and redistribution of these products to form many of the GBR's geomorphological features. Conversely, geomorphological features are important to reef ecology. They physically structure habitats for various biota and influence the distribution of physical processes (such as waves and currents) important to many reef organisms. At a larger scale, outer reefs separate the inner lagoon and open ocean, and control cross-shelf hydrodynamic energy gradients important for many species. Biogeographic and other influences are important[156], but the extraordinary habitat complexity and biological diversity found on the GBR can be largely attributed to the geographical opportunities of latitudinal and cross-shelf gradients provided by its impressive scale.

This chapter provides an overview of the vulnerability to climate change of five of the GBR's major geomorphological features: i) coral reefs, ii) reef islands, iii) high island beaches and spits, iv) mainland sandy coasts, and v) mainland muddy coasts. The vulnerability of biota associated with these features is assessed in other chapters (Lovelock and Ellison chapter 9, Hoegh-Guldberg et al. chapter 10, Congdon et al. chapter 14, Fabricius et al. chapter 17, Sheaves et al. chapter 19 and Turner and Batianoff chapter 20). Vulnerability is defined as the degree to which a system or species is susceptible to, or unable to cope with, the adverse effects of climate change[1].

Vulnerability assessments for geomorphological features are complicated because exposure to different climate change stressors varies geographically, and sensitivity can differ according to the rate and nature of predicted changes relative to contemporary and past patterns of exposure (Table 21.1). For example, a reef island's sensitivity to sea level rise would vary according to tidal range, late Holocene relative sea level history, and exposure to other sea level fluctuations such as those associated with El Niño–La Niña cycles. Complex feedbacks throughout the system present additional challenges, as do the differing timescales at which many ecological and geomorphological processes operate, and the variable significance of changes at different spatial scales. Our evaluations of the potential impacts, adaptive capacity and the vulnerability of geomorphological features are thus by necessity rather generalised, speculative, and have varying application across the GBR.

Table 21.1 *Possible conditions affecting the exposure and sensitivity of different geomorphological features of the GBR to climate change factors*

Climate change factor	Exposure and sensitivity affected by:
Rising sea level	*Late Holocene relative sea level history:* Has late Holocene relative sea level fall and emergence provided a buffer? *Rate of relative sea level change:* Is rate of rise faster than vertical accretion rate or can the feature keep up with sea level rise? What are the consequences of increased depth (eg increased wave penetration, remobilisation of surficial sediments)? *Tide range:* How do projected rates of rise compare with tidal fluctuations? Are changes of mm per year significant where tidal ranges can be more than 7 metres? *Total depth range:* What depth range can the feature survive in, and how precisely are these limits constrained?
Rising sea surface temperatures	*Late Holocene relative sea level history:* Has late Holocene relative sea level fall and emergence already exposed shallows to higher temperatures via ponding, etc? *Exposure to ameliorating phenomena such as mixing, upwelling etc:* Mixing by currents, turbulence or upwelling with cooler waters will reduce potential for thermostratification and excessive heat build-up *Existing thermal regime:* What is the magnitude of critical temperature change compared to the existing thermal regime, and how will changes influence critical sediment production, stabilisation or transport processes? *Tide range:* Areas of higher tide range and tidal currents will generally be better mixed and less vulnerable to excessive temperatures
Increased tropical cyclone activity and surge	*Late Holocene relative sea level history:* Is the feature emergent and lithified? *Tide range:* How does projected surge compare with tidal range? *Existing exposure to cyclone impacts:* Is the geomorphological feature already adjusted to high-energy conditions? *Position across shelf:* Outer shelf reefs are generally more exposed to higher wave energy than inner reefs, but variations in this pattern do occur *Coastal configuration, shelf gradient and depth:* Are coastal configuration and shelf bathymetry likely to enhance storm surge potential?

Climate change factor	Exposure and sensitivity affected by:
Enhanced or reduced rainfall	*Proximity to the coast:* Inshore areas are more exposed to flood impacts and changed sediment/ contaminant delivery to the GBR lagoon *Degree of enclosure:* Enclosed settings with poor mixing more exposed to lowered salinities *Nature of rainfall pattern change:* How do projected changes compare with existing rainfall patterns? *Degree of oceanic mixing:* Influence ameliorated where waters well mixed
Ocean acidification	*Temperature and aragonite saturation state:* Acidification is likely to vary within the GBR as a function of temperature and alkalinity (see chapter 17)

An appreciation of the nature and rates of past environmental changes on the GBR provides an important starting point for assessments of how it might respond to climate change and of the significance of any adjustments. The geological record documents numerous cycles of sea level change of greater magnitude and pace than those predicted for the future, through which corals have survived and the GBR has repeatedly re-established[158]. Of course, optimistic assessments of coral reef resilience to predicted environmental changes based on past survival must be tempered by acknowledgement of the extra pressures most now endure[85,124,45]. These issues are central to a longstanding debate about whether reefs are robust (a geological perspective) or fragile (an ecological position). Reviews of this debate generally conclude that both positions are valid, with each having merit at appropriate temporal and spatial scales (eg Done[38], Grigg[57]). Geomorphology is uniquely positioned to offer an integrative perspective of reef condition that is at a scale appropriate for many climate change assessments.

21.2 Geomorphological features discussed in this chapter

21.2.1 Coral reefs

Numerous definitions of a coral reef exist, with varying emphasis on ecological and geomorphological attributes[132,92]. Coral reefs are commonly defined geomorphologically as biologically influenced, wave-resistant structures composed of coral framework and carbonate sediments[70]. Most coral reefs are dominated by calcium carbonate produced by corals, although coralline algae, molluscs, foraminiferans and various other organisms can be significant contributors. For a 'true' coral reef to develop the skeletal remains of these organisms must accumulate to form a deposit stable enough to resist dispersion by waves and currents. Biological influence on coral reef geomorphology is not limited to skeletal carbonate production – reef organisms also erode, transport, bind and consolidate reef materials[51,84]. The above definition emphasises coral framework as an important structural element, but detrital facies are recognised as volumetrically more important on many reefs[110,82]. The production and transport of detrital materials during storms is an important constructive geomorphological process for many reefs[109,136], including those on the GBR[30,142,82].

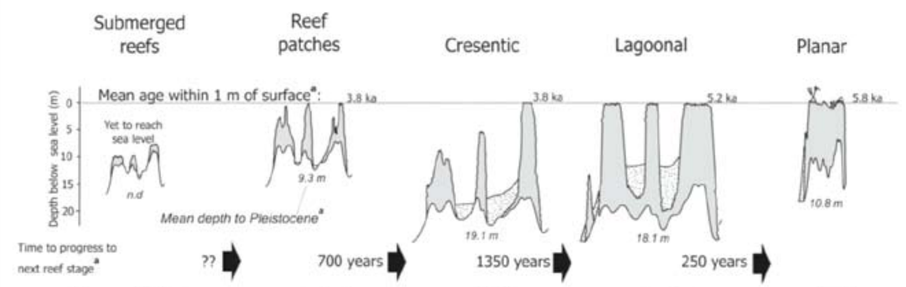
The modern GBR began to grow after the last ice age when rising seas flooded the continental shelf. For many years it was believed that modern reef growth on the GBR started within a 'narrow take-off envelope' between 8300 and 7500 years ago[31], but re-interpretation of detrital sediments at the base of reef cores suggests a much broader initiation interval beginning as early as 9900 years ago[82]. Outer- and mid-shelf reefs typically established on the limestone remnants of reefs formed during previous sea level highstands, the last of which occurred around 125,000 years ago[94]. Significantly, conditions amenable for reef growth have existed on the central GBR shelf for about 15 million years[32], but reef cores suggest that coral growth began on the northern GBR only 600,000 years ago, and growth equivalent to modern reef growth did not begin until 450,000 to 360,000 years ago[158]. As reviewed by Pandolfi and Greenstein (chapter 22), conditions suitable for reef growth have been the exception rather than the rule for much of the GBR's history. For most of the time, reef growth was restricted to the deeper shelf edge by low glacial sea levels[70,82]. Just five or six highstands (each lasting less than 10,000 years) during which reef growth comparable to present could flourish have occurred during the GBR's history[158]. Fluctuating sea level and associated environmental changes (often rapid and abrupt) have dominated the GBR's past (see chapter 22).

Comprehensive accounts of the tremendous geomorphological diversity observed across and between individual reefs within the GBR are available in Hopley[70] and Hopley et al.[82]. This variety largely reflects the ecological and geomorphological zonation of environmental parameters across reefs, and across the shelf and latitudinally[74,36,37]. Reef zonation is dynamic, changing as reefs grow or conditions change. The concept of reef geomorphology progressing through an evolutionary sequence was introduced by Darwin[29] for mid-ocean reefs, and was offered as a reason for the 'gradational nature' of GBR shelf reefs by Maxwell[114]. Hopley[70,72] extended Maxwell's work and developed a morphogenetic classification that explains differences in reef morphology as a function reef evolutionary stage. At the simplest level three broad classes were identified, each largely determined by the depth and size of a reef's foundations, and its relative sea level history:

- Juvenile reefs: reefs not yet at sea level, perhaps because they have risen from deep foundations or started growing late.
- Mature reefs: reefs with established reef flats but retaining a lagoon, possibly because reef foundations were larger or deeper than for senile reefs.
- Senile reefs: reefs with infilled lagoons and planar reef tops, usually formed over small and shallow foundations subject to late-Holocene sea level fall (Figure 21.1).

Under stable sea level conditions reefs will develop through this sequence to a natural point of senescence. Approximately 2080 of the GBR's 2900 named reefs are easily classified with this morphogenetic scheme (ribbon and fringing reefs cannot), with around half at the juvenile stage (submerged and patches), and 25 percent at both the mature (crescentic and lagoonal) and senile (planar) stages. The spread of reef types at various stages in the evolutionary sequence is therefore suitable for the continued maintenance and development of habitat diversity and function. However, broad regional patterns in foundation depth, relative sea level history, and thus reef stage and morphology occur[70,81,82]. Therefore some reef types are spatially concentrated and are vulnerable to critical changes in these geographic areas (see section 21.3.1.1).

Figure 21.1 *Shelf reef classification and summary statistics (after Hopley et al.[82])*



	Submerged reefs	Reef patches	Cresentic	Lagoonal	Planar
Mean area[b]	6.2 km²	9.1 km²	16.8 km²	15.7 km²	4.1 km²
Number of reefs[b]	566	446	254	270	544
Percent of total number[b]	19.5	15	8.7	9	18
Percent of non-fringing reefs[b]	27	21	12	13	26
Unvegetated reef islands[c]	0	42	14	11	135
Vegetated reef islands[c]	0	4	2	0	83
Total number of reef islands on this reef type[b,c]	0	46	16	11	218
Percent of this reef type with reef islands[b,c]	0	9.4	6	5	40

[a] based on radiocarbon data set (see Tables 8.1-3, Hopley et al., 2007); [b] based on Table 5.3 Hopley et al., 2007; [c] based on Table 5.8 Hopley et al., 2007

Radiocarbon ages from reef cores and reef flat microatolls indicate that reefs can rapidly move through the evolutionary sequence. For example, many inner northern GBR reefs progressed from submerged reef patches to planar reef tops in a few thousand years[153,137]. Simple models using present-day carbonate production rates suggest very small lagoonal reefs may become planar reefs in under 500 years, and larger reefs of 20 km diameter (greater than 300 km² area) with 10 metre deep lagoons can reach senility in less than 6000 years[82]. Significant environmental and ecological change would accompany this intrinsic geomorphological development. Well-flushed submerged 'catch-up' reefs[116] with luxuriant growth over the platform would become increasingly enclosed and dominated by detrital sediments. The outer reefs had their most vigorous period of growth between approximately 8500 and 5500 years ago, since then their structural and ecological diversity has progressively declined[82]. As noted above, about 25 percent of GBR shelf reefs are near the end of this sequence.

Fringing reefs cannot be easily classified using Hopley's[70] evolutionary scheme, and due to their proximity to land are widely perceived as especially vulnerable to changes in terrestrial conditions. Clearly, however, many fringing reefs on the GBR have long been exposed to a range of terrestrial influences, and their sensitivity to these may actually be relatively low. Smithers et al.[143] noted that the many fringing reefs in the GBR underwent a period of active growth between about 7500 and 5500 years ago, but later 'turned off' as accommodation space was exhausted. The histories of these reefs are relevant to assessments of future vulnerability in several ways. First, they 'turned off' due to intrinsic

factors, although climate fluctuations were argued to modulate reef growth rates. Second, several of these senile reefs have not significantly changed size for thousands of years despite supporting healthy coral communities in historical times. These results demonstrate the long-term resilience of coral reef structures through prolonged periods of diminished carbonate production, and the pitfalls of assuming simple relationships between coral community condition and reef growth and maintenance.

21.2.2 Reef islands

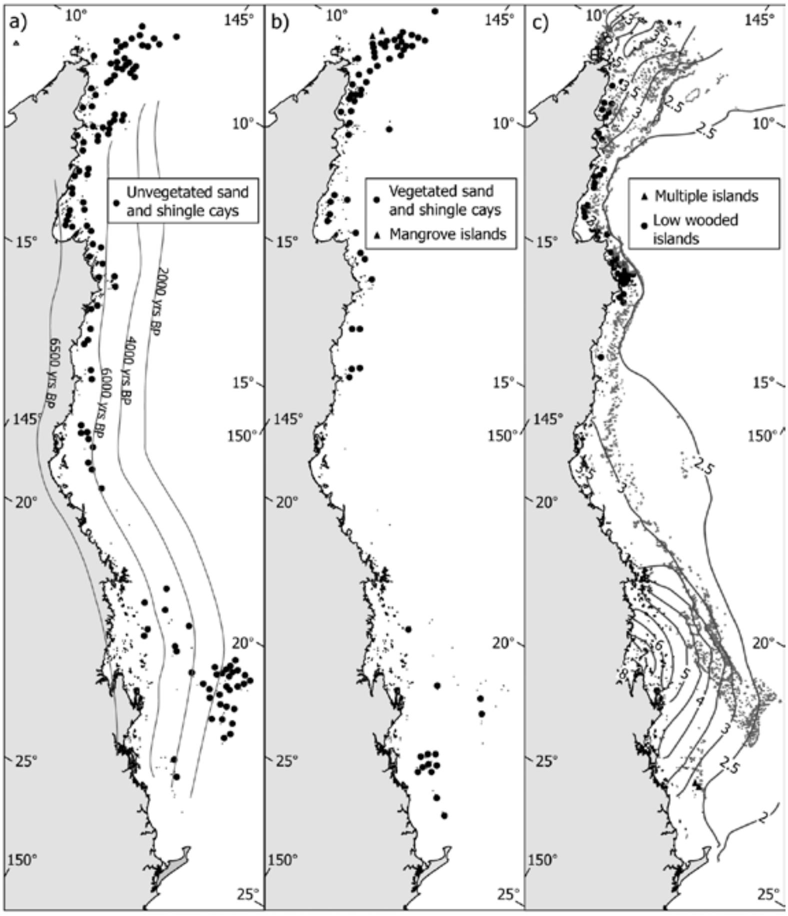
Reef islands (cays) are low-lying accumulations of reef-derived sediments, portions of which may be lithified, deposited on reef platforms at or close to sea level. They form where waves refract around and over reefs and converge at a focal point on the reef platform where sediments are deposited[54,79]. Cays are generally absent from larger reefs or those with a geometry that impedes centripetal wave refraction. The long-term development of reef islands in areas of dense reef network is similarly constrained, as low ambient wave energy cannot effectively concentrate sediment deposition[54]. Sand cays formed under ambient wave and climate conditions typically accumulate near the leeward edge of the reef platform, whereas those composed of coarser sediments moved during storms usually form closer to the windward reef edge. Gourlay[54] presents an excellent summary of reef island formation processes.

The geomorphology of reef islands on the GBR is varied, reflecting the range of latitude and climate, the variable geometries and relative sea level histories of the reefs on which they form, and the diversity of sediments of which they are composed[79,82]. Detailed descriptions of the reef islands found on the GBR are presented in Hopley[70,79] and Hopley et al.[82]. Unvegetated sand or shingle cays are the simplest reef islands geomorphologically, and usually the youngest and most dynamic. The complex low wooded islands composed of a windward shingle island, a leeward sand cay, and varying degrees of mangrove development over the intervening reef platform, are typically the most complex and stable. Surprisingly few reef islands on the GBR have been subject to detailed geomorphological investigations.

Most (72.7%) reef islands on the GBR occur on planar reefs that are concentrated north of 16° S and between 21 and 22° S, including almost all (97.6%) vegetated cays and low wooded islands. Importantly, approximately 60 percent of planar reefs presently do not support reef islands, and reef islands are not restricted to planar reefs. For example, 42 unvegetated cays occur on reef patches. Figure 21.2 shows the distribution of the major types of reef island on the GBR. More than 70 percent of reef islands on the GBR are unvegetated cays, with most located north of Cairns. They are also particularly common on the Swain Reefs between 21 and 22° S. A few unvegetated cays are located on the outer reefs (eg Sand Bank numbers 7 and 8), but only where protection exists[70]. Unvegetated cays are not found between Wheeler Reef in the central GBR south to the northern Pompey Reefs (a distance of 315 km). This absence probably reflects the high tidal range (approximately eight metres near Broad Sound; see section 21.3.1), and greater exposure to both normal and cyclonic waves on this section of the reef[70,127].

There are fewer vegetated cays than unvegetated cays on the GBR, but their distribution is similar. Most occur on planar reefs in the northern GBR, with a group of mostly larger vegetated cays located in the southern GBR (Capricorn Bunker Group). Vegetated cays also occur in the Swain Reefs and inner reefs in this area (Bell Cay and Bushy Island). No vegetated cays exist between Bushy Island, around 70 km east of Mackay, and Green Island offshore from Cairns, more than 600 km north.

Figure 21.2 *Distribution of different types of reef islands in the GBR (after Hopley et al.[82]). Isobase lines indicate approximate time when modern sea level was reached in panel a, and approximate tidal range in panel c.*



Several vegetated cays are located on the far northern outer barrier (Tydeman Cay, an unnamed cay on a reef at 13° 22′ S, Moulter Cay and Raine Island), but none exist on outer barrier islands outside this province. The distribution of complex low wooded islands is strongly associated with the location of smaller planar reefs with emergent reef flats that are concentrated on the inner shelf north of Cairns. Ninety-four percent are within 20 km of the mainland, and all lie west of (inside) the zero hydro-isostatic isobase and have experienced relative sea level fall since the mid-Holocene[21,71] (see section 21.3.1).

The confinement of GBR reef islands inside the zero hydro-isostatic isobase raises the question of whether relative sea level fall is required for reef islands to form. Kench et al.[89] suggested that some Maldivian cays began to accumulate prior to reef flats reaching sea level, and West Indian cays have formed where sea level has risen gradually to present since the mid Holocene and continues to rise[167].

Radiocarbon-dated fossil microatolls underlie many of the reef islands investigated on the GBR[106,147], suggesting that most developed after the reefs had reached sea level[18,21]. Reef islands on the Cocos (Keeling) Islands, Indian Ocean, similarly exist over fossil reef flat foundations that became emergent as sea levels fell during the late Holocene[170]. Dickinson[35] proposed that wave-resistant emergent palaeoreef flats strongly influenced the development of stable reef islands on many Pacific atolls, but acknowledged that less stable 'unpinned' reef islands are common on reef flats that remain flooded by lower tides.

If radiocarbon chronologies are correct, rapid sand production, delivery, and cay deposition occurred on many planar reefs of the GBR between 4000 and 3000 years ago, with only relatively minor modifications since. However, AMS radiocarbon dating of a sandy reef island in Torres Strait indicates that mid-Holocene ages may be an artefact of age determination on bulk sand samples; ages of molluscs indicate sustained incremental accretion of Warraber Island over the past 3000 years[172]. Island nuclei deposited during this earlier accumulation phase are often indicated by the presence of mature vegetation and greater soil development (eg Douglas Island and Masthead Island[63]), although Woodroffe and Morrison[169] found no clear relationship between soil development and age at Makin Island, Kiribati. Significantly, most stable reef islands form over reefs in or entering the *senile* stage of geomorphological development. Factors that promote reef advance through the evolutionary sequence are therefore important drivers of reef island formation. Reef island formation has not ceased on the GBR, and new reef islands will form if reef growth and sediment production continues. Excluding the ribbon, incipient fringing and true fringing reefs (which are not easily accommodated in Hopley's[70] morphogenetic classification), about 26 percent of reefs on the GBR are planar, 13 percent are lagoonal, 12 percent are cresentic, 21 percent are patches and 27 percent are submerged (Figure 21.1). Average estimates of the time required to progress through this sequence were discussed in the preceding section, but we emphasise that small shallow lagoonal reefs can transform into planar reefs in as few as 250 years[82]. Thus, where sediment supply is adequate and reefs are of suitable elevation, geometry and energy exposure exist, reef islands may form quite rapidly.

Reef island morphology and location on a reef platform can be sensitive to changes in wave energy and direction, associated with both normal variability in ambient conditions and infrequent extreme events such as cyclones[47,48]. Island responses vary from total obliteration, shifts in size, shape and position, or shifts between predictable morphological states. Changes in sediment type, supply or erosion, and in the extent of lithification, may also modify reef island morphology[149,178]. Almost all descriptions of unvegetated cays on the GBR note that they can rapidly and markedly change shape, size, elevation and position[152,69,70,3]. Compact unvegetated sand cays are especially dynamic, with several disappearing in historical time. Hopley[70] reported the example of a cay on Pixie Reef, near Cairns that was about 45 metres in diameter in 1928, but had split into two cays 65 metres apart by 1929. Reef top sediments at Pixie Reef in the early 1980s were completely dispersed, with not even a discrete sand bar visible.

The most detailed account of compact unvegetated cay behaviour on the GBR exists for Wheeler Cay[69], a normally oval cay, around 80 by 50 metres in size, located over an area of sanded reef flat (170 by 250 metres). Between 1969 and 1977, including 1971 when Tropical Cyclone Althea struck, Wheeler Cay varied markedly in shape, size and location, moving over 11,000 square metres of reef flat during this period. The highest point on Wheeler Cay migrated as much as 13 metres in a day that

included a three-hour storm with gusts to 60 knots, and the whole cay moved six metres on another day under light winds of less than 10 knots. Wheeler Cay had moved and changed shape again by 1980, but remained within the original sanded reef flat area[3].

The most stable reef islands typically occur on small to medium-sized reefs, with larger cays usually more stable than smaller ones. Vegetation is indicative of some stability and may also improve or maintain stability in various ways. Relatively large cays on the GBR are unvegetated compared to other reef areas in the world. For example, Waterwitch Cay is 2.8 hectares was unvegetated when visited in 1973, but all cays larger than 0.1 hectare on the Belize barrier are vegetated, and at Kapingamarangi Atoll all islets greater than 0.01 hectare support terrestrial plants[146]. This difference may reflect the larger tidal ranges, cyclone exposure, and possibly greater mobility of reef islands on the GBR. These constraints are particularly limiting on the central GBR.

Many stable reef islands are partially lithified, a process requiring at least temporary stability to occur[145,147], and which may impart improved stability in the longer term[137]. Beach rock is common on GBR reef islands, and forms a hard shoreline resistant to erosion. However, even large islands with extensive beach rock can be destabilised. For example, at Waterwitch Cay massive beach rock outcrops suggest previous periods of moderate stability, but at present the cay is barren, undoubtedly mobile, and disjunct from these lithified former shorelines. The cementation of cay sediments by phosphate solutions derived from guano to form phosphate rock is another lithification process that can improve reef island stability. Phosphate rocks mainly form above the high tide mark and in island interiors where birds may congregate. Where phosphate rock is well developed, such as at Raine Island, the island core becomes hardened and prospects for enduring island stability are improved, although unconsolidated beaches may remain dynamic.

21.2.3 High island beaches and spits

More than 600 high islands – continental outcrops separated from the mainland when the sea flooded the continental shelf after the last ice age – occur within the GBR. Many high islands have beaches, particularly in leeward embayments. Some of these beaches are fringed by reef and dominated by carbonate sediments (eg northwest end of Curacoa Island). Others are dominated by terrigenous sediments and have no fringing reef offshore (eg Horseshoe Bay, Magnetic Island). Beach rock is common on carbonate rich beaches, with lithified sediments varying from sands through to coarser shingle and rubble.

Many high islands, especially in the central GBR, have large leeside spits, many features of which are similar to the low wooded islands. The spit at Dunk Island, for example, extends more than 1200 metres along its central axis. Spit morphology is generally consistent with wave refraction around the islands and surrounding reefs. Most spits are dominated by terrigenous sediments, including boulders deposited during high-energy events. Hopley[73] concluded that larger spits were not Holocene deposits, but were multi-generational features formed over several previous sea level highstands. The soil development and elevated interiors of many spits are compatible with greater antiquity and formation during previous highstands when sea levels were higher than at present[94]. Many of these higher surfaces are well vegetated, and phosphatised (eg Dunk Island). Holocene carbonate deposits are also associated with several spits, with some developing prograding sequences of shingle ridges

(eg Curacoa Island and Rattlesnake Island). These ridges preserve a history of severe (greater than category 3) cyclone impact extending back to the mid-Holocene. These records show that severe storms affect most places on the GBR on average every 200 to 300 years, and that this recurrence interval has not significantly varied for the past 6000 or so years[61]. Nott and Hayne[120] have argued that this recurrence interval is significantly shorter than that calculated from instrumental records (and used in IPCC climate change projections), and suggests severe storms occur frequently enough to significantly influence coral communities and reef development.

21.2.4 Mainland sandy coastlines

Much of the mainland coast inside the GBR is sandy, composed of siliciclastic sediments derived from coastal catchments. Most of the sandy coastline may be geomorphologically described as either beach ridge plain or coastal sand barrier, with coastal dunes locally associated with both. Beach ridges are coastal sand ridges emplaced by waves, with sequences developing as successive ridges are emplaced on a prograding coast[150,151]. The mechanisms of beach ridge formation are debated, with pulsed sediment supply[2] and storm emplacement[119] the two main theories. Barrier systems may be broadly described as coastal sand deposits worked onshore by the transgression, but separated from the hinterland by an estuary or wetlands.

Beach ridges trail north from the mouth of almost every stream along the coast, typically forming a plain around 500 metres wide of up to 10 ridges. Much wider sequences have developed adjacent to major rivers. At the Haughton River, for example, a beach ridge plain of greater than 100 ridges is more than five kilometres wide. Beaches on exposed parts of the central Queensland coast typically develop a steep, coarse-grained, reflective upper profile and a lower gradient, fine-grained, dissipative lower profile. North of Cairns, wave energy is reduced because the barrier reef is closer. Sandy beaches with narrow beach ridge plains (generally less than one km) separated by rocky headlands occur along this coast. Most beach ridges on the GBR coast are Holocene in age, but some remnants of Pleistocene barriers exist[65].

High wave energy and lower tidal ranges are normally associated with barrier development, but more than 30 barrier systems occur on macrotidal sections of the central Queensland coast. Further north, near Kurrimine, a multiple barrier system up to 12 km wide occurs, in which at least three phases of progradation can be recognized from the orientation of ridge crests[56]. Ridges exposed to prevailing south-easterly winds commonly develop a dune cap, with higher ridges developing at the north of exposed beaches.

Several of the largest coastal dune fields in tropical Australia occur on Cape York, especially at Newcastle Bay, Orford Bay, Cape Grenville (400 km^2), Cape Flattery (700 km^2), and Cape Bedford. These dune fields are located where weathering of Mesozoic sandstone yields abundant sand, and the coast is exposed to south-easterlies that mobilise them during the dry season. Elongate parabolic dunes up to 5 kilometres long and over 100 metres high have developed which are now largely, but not fully, stabilised beneath heath or rainforest. Large dunes, rising to 60 metres, also occur on the northern end of Hinchinbrook Island. Smaller dune fields occur further south on Whitsunday Island, Curtis Island, and north of Yeppoon. Weathering features indicate that larger dune fields are of considerable age, formed during previous sea level lowstands[128,101].

Most of the beach ridge and barrier systems on the mainland GBR coast underwent a phase of active accretion and progradation during the late-Holocene[56], which did not continue to present in some locations. For example, mangrove muds of 2000 to 3000 years age interpreted as being originally deposited in the lee of seaward beach ridges now locally outcrop on exposed sections of the central and northern GBR coasts[175]. These muds have been uncovered by coastal retreat, which clearly should not be assumed to be a recent phenomenon, or anthropogenically forced.

Carbonate sediments occur on beaches adjacent to mainland fringing reefs, which are mainly concentrated around the Whitsunday Islands and further north around Cape Tribulation. Carbonates are subordinate to siliciclastic sediments even at these locations. Massive beach rock like that on offshore reefs and high islands may form where carbonates are well represented, such as at Hydeaway Bay in the Whitsunday region, but is relatively uncommon.

21.2.5 Mainland muddy coastlines

Muddy shorelines on the mainland coast are most common in north-facing bays protected from the prevailing south-easterly winds. In these areas the inshore sediment prism, a body of fine sediment trapped in the nearshore zone, can encroach onto the shoreline. On exposed coasts resuspension prevents the landward edge of the prism extending further inshore than the five metre isobath[97]. A series of characteristic geomorphological zones develop on these muddy coasts[42] (see chapter 9). Broad salt flats usually dominate the supratidal and upper intertidal, with freshwater marshes developing in higher rainfall areas. Sequences of shelly or coarse sandy ridges (known as cheniers) occur on many salt flats, a legacy of episodic cyclones in these normally low-energy environments[19,8]. At Princess Charlotte Bay, Chappell et al.[21] estimated that storms capable of depositing a chenier have occurred about every 80 years since the mid-Holocene. Near Sandfly Creek in Cleveland Bay (central GBR) at least four ridges can be identified within one kilometre of the active mangrove muds. The rear ridge is around 3700 years old and the most seaward 1400 years old, yielding a late Holocene progradation rate of about 0.5 metres per year[17]. Seaward of the salt flats a mangrove fringe usually occurs, the exact elevation of which varies locally. At Cocoa Creek, near Townsville, it lies between the mean low and high water spring tide levels[173]. Seaward of the mangroves are broad bioturbated mudflats, often with significant seagrass meadows. Tidal creeks incise back into the salt flats in many areas. Heap et al.[62] provide excellent descriptions of many of these systems on the GBR coast.

Chronostratigraphic studies suggest that these environments have typically developed as mangroves colonised the shoreline in the later part of the transgression and migrated landward with sea level until the mid-Holocene highstand. Seaward migration of the living mangrove fringe and salt flat development over the earlier mangrove deposits then occurred as sea levels fell to present during the late Holocene. Muddy shorelines are impressive sinks of fine sediment on the inner GBR, and as discussed by Lovelock and Ellison (chapter 9), they are major nutrient stores. Sedimentation patterns on muddy coastlines may vary according to the relative importance of tidal currents and terrestrial runoff in sediment supply, and thus climate and sea level changes may significantly affect sedimentation in mangrove forests and adjacent salt flats[162].

21.3 Exposure and sensitivity to major climate change stressors

21.3.1 Sea level rise

21.3.1.1 Post glacial sea level history.

Understanding sea level history is important for evaluating the vulnerability of the GBR to climate change for several reasons. First, detailed sea level histories can inform interpretations of how future sea level changes on the GBR might differ from predicted average global rates. Second, they provide a context for interpreting previous reef development and how reefs may respond to future change. Third, identification of features formed at higher sea levels, such as emergent palaeoreef flats[35] (section 21.2.2), allows recognition and consideration of physiographic regions and possibly process thresholds for inclusion in climate or sea level change response models. Reported rates of historical and future sea level change are generally global averages derived from a globally aggregated instrumental data set. A rate of rise around 1.7 mm per year is typically quoted for the past century, accelerating since 1993 to around 3 mm per year[25]. Assessments of the exposure and sensitivity of geomorphological features of the GBR to possible future sea level changes should consider the regional pattern of relative sea level change as this is the sea level signal to which the system will respond. Regional and global signals may differ due to a variety of mostly dynamic earth (isostatic) and ocean (temperature, density, wind and atmospheric pressure) factors.

The precise details of elevation and chronology vary spatially, but sea level was close to present by around 6500 years ago along much of the inner GBR, before rising a further metre or so by 6000 years ago and then falling to its present level[68,21]. Subtle flexure of the continental shelf in response to loading with seawater during the postglacial transgression (hydro-isostasy) produces this pattern[115]. Hydro-isostatic flexure occurs about a hinge line (the zero isobase[20]), to the east of which the shelf has subsided and relative sea level has risen, and to the west of which the shelf has flexed upward and relative sea level has fallen. This history has two major implications for assessments of future vulnerability. First, the inner GBR has experienced relative sea level fall for several thousand years, with intertidal communities formed in the mid-Holocene often elevated around a metre above their modern equivalents[21]. Second, different locations across the shelf have different sea level histories that may affect their response to future climate changes[71,115].

Geomorphological responses to postglacial sea level changes prior to the mid-Holocene highstand are also relevant to vulnerability assessments. During the last deglaciation at least two periods of rapid and sustained sea level rise forced by ice-sheet decay and melt-water discharge occurred. The two best-known events are melt-water pulse 1A (MWP-1A) and melt-water pulse 1B (MWP-1B)[46,4]. MWP-1A is accepted as 'a real feature of the postglacial eustatic sea level history'[159], beginning about 14,500 years ago, after which sea level rose by 40 to 55 mm per year for around 500 years[46]. The details of MWP-1B and other melt-water pulses[179,26,10] are less certain[138,6,174]. Reef growth on the GBR was limited to the continental slope during both MWP-1A and 1B by low sea levels, and thus they did not affect the contemporary GBR. Shelf reefs had established by 7600 years ago, but no convincing evidence of the melt-water pulse speculated then exists on the GBR[82]. Although direct evidence from the GBR is lacking, reefs clearly survived rapid sea level rise during MWP-1 events at Barbados and Tahiti[46,5], confirming the capacity of healthy reefs to endure sustained episodes of sea level rise at rates exceeding those predicted for the next century.

21.3.1.2 Tide range and wave exposure

The sensitivity of geomorphological environments to sea level changes in the order of millimetres per year is influenced by the variability of the ambient water level signal to which they are adjusted. Generally, 'noisy' environments – such as where waves and or tidal range are high – are less sensitive (Lovelock and Ellison chapter 9). Within the GBR, tidal range varies with latitude and across the shelf, ranging between 3.6 and 2.5 metres from Torres Strait to Cairns, but exceeding eight metres at Broad Sound on the southern GBR coast (refer to Figure 21.2c). The spring tidal range at the shelf edge is typically about three metres. The present-day wave climate is similarly variable, with smaller waves where the outer barrier is best developed and where fetch inside the barrier is limited. The hydrodynamics of the GBR are summarised in detail in Hopley et al.[82]. We emphasise that contemporary conditions are not always the same as those that have prevailed in the past, or during important periods of ecosystem or geomorphological development. For example, Hopley[73] suggested that boulder beaches and spits inside the central GBR were reworked by larger waves during the 'Holocene high-energy window' – a short interval in the mid-Holocene when the outer barrier lagged sea level and oceanic waves entered the GBR lagoon. Tidal ranges within the GBR have also been modified as sea level, reef, and coastal configurations changed through time.

21.3.1.3 Other background sea level variability

Superimposed over longer-term sea level fluctuations, and shorter ones such as tides, are other ocean-atmosphere phenomena with a range of frequencies and amplitudes, such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation, and the Interdecadal Pacific Oscillation. For example, sea level in the Western Pacific can oscillate by about 0.5 metres as the ENSO shifts from El Niño to La Niña over cycles as short as four to six years[177,60]. Such variations are another source of natural variability that may temper sensitivity to slower rates of predicted sea level change.

21.3.1.4 Depth range, bathymetric relief and topography

The exposure and sensitivity of geomorphological features will vary according to the breadth of the depth range in which they form. For example, coral reefs capable of flourishing within a 30 to 50 metre depth window are less sensitive to rising seas than reef islands, which form and persist within a much narrower vertical range. Especially on low gradient parts of the GBR, it is important to recognise that marked lateral shoreline translations may accompany sea level rise. In some areas shorelines may simply migrate across similar deposits emplaced in the late Holocene, but complex re-organisation of the coastal zone may ensue elsewhere.

21.3.2 Rising sea surface temperature

The exposure and sensitivity of geomorphological features on the GBR to rising sea surface temperature (SST) will mainly be influenced by the thermal regime presently experienced, whether projected increases will be mitigated or made worse at various locations, and the sensitivity of key biota to thermal stress. Broad regional variations in SST within the GBR are summarised in chapters 2 and 17. Rising SSTs may affect some geomorphological processes such as cementation and lithification by increasing the speed of reactions, but thermal stress of key organisms – which will vary between groups, and between and within species – will be the main impact.

Thermal stress will not be uniform across the GBR, or across habitats at smaller scales (eg reef front compared to lagoon). It will vary according to tolerances developed in response to the present-day thermal regime, with tolerance to three–day hot spells most critical for coral bleaching[9]. The magnitude and rate of temperature changes over the past century may also be important (Lough chapter 2, Lovelock and Ellison chapter 9, Fabricius et al. chapter 17), with corals in the south of the GBR experiencing warming by 0.7°C since 1903 – almost double the 0.4°C experienced on the northern GBR[64] (Fabricius et al. chapter 17). This geographic difference is further revealed by comparison of the mean maximum SST for both the northern and southern GBR for 1910 to 1919 and 1990 to 1999. This analysis shows a 0.6°C SST rise on the southern GBR but no change in the northern GBR (Lough chapter 2).

Surface water heating is the main cause of thermal stress, and greatest exposure occurs where surface waters are weakly mixed by waves and currents, have longer residence times, and do not receive cooler upwelling. However, it is important to note that for coral reefs, for example, bleaching is most highly correlated with three–day hot spells rather than mean or median conditions[9], and thus only short-term exposure is required for significant stress impacts to occur. At smaller scales, organisms living where water may stagnate, such as in enclosed embayments, lagoons or ponded reef flats, may experience more critical stresses than on reef fronts and flanks where active hydrodynamic mixing takes place. The physiologically damaging effects of ultraviolet-A and ultraviolet-B radiation[164] will also vary spatially due to mediation associated with hydrodynamic mixing and water column properties. Inshore turbid zone reefs may be less exposed than those in clearer waters where damaging radiation can penetrate to greater depths[78].

The sensitivity of different organisms to rising SSTs is a common theme in preceding chapters. Geomorphological features that rely directly or indirectly on 'sensitive' organisms to produce materials, or to undertake or facilitate important geomorphological processes are most exposed and sensitive to these impacts. The sensitivity of most features has not been adequately established, but coral reefs are an obvious example. Corals have bleached repeatedly in recent decades due primarily to elevated SSTs, and projections suggest that the capacity of reefs on the GBR to maintain significant coral communities will be largely lost as SSTs rise[40]. Although this outcome may be catastrophic ecologically, and will inevitably produce some geomorphological modification, the medium- to long-term geomorphological significance of these changes remains unquantified. With other stresses (eg acidification, increased storm frequency) rising SST will probably lead to increased mortality and availability of a new pulse of sediment on many reefs (see Sheppard et al.[139]).

21.3.3 Increased cyclone activity

Tropical cyclones have two major impacts on geomorphological features of the GBR: i) direct damage through storm waves, and ii) extreme cyclonic rainfall that generates floods delivering freshwater, sediments and nutrients to the GBR (exposure and sensitivity to rainfall are discussed in section 21.3.4). Tropical cyclones can devastate coral and other communities, but they are important constructional events for several geomorphological features. Storm blocks, shingle ramparts, and detrital facies are common geomorphologic features that document a long-history of storm exposure on the GBR[136]. Cheniers and beach ridges along the mainland coast similarly record episodic cyclone impacts in the recent geological past[119]. Severe tropical cyclones have occurred about once every 200 to 300 years on average for the last 6000 or so years over most of the GBR[24,61,120], and these events may be mechanically destructive to depths below 20 metres[155].

Many tropical coastal habitats are adapted to periodic cyclonic disturbances, with robust communities and structures in higher-energy settings better able to physically withstand periodic cyclonic impacts[27]. Exposure to physical destruction by cyclone waves thus tends to show strong cross-shelf variation, being lowest where reef configuration limits fetch and/or attenuates waves as they cross the shelf. However, this decline in exposure occurs against a corresponding increase in sensitivity. Corals on inshore reefs tend to have weaker skeletons and can be less firmly attached to the reef structure. The reef structure may also be weakly consolidated[142,125], and potentially more sensitive and vulnerable to damage.

An increase in the destructiveness and intensity of cyclones in recent decades has been argued and linked to climate change[44,160], although the completeness of the underlying data is questioned[95,96]. Increased cyclone activity will raise the exposure of more frequently affected reefs. The physical sensitivity of structures should not vary markedly from the present-day pattern in the short term, but accompanying changes in community structure are predicted which may have variable effects. Reefs dominated by fragile forms will be most sensitive initially, but as community structure changes and massive and encrusting corals with a higher probability of surviving wave damage dominate[39], this effect may diminish. Geomorphological features reliant on sediments produced by fragile assemblages will be sensitive to this structural transformation. Coral shingle is an important contributor to many geomorphological features (eg ramparts and beaches), and with a high surface area to volume ratio may be a major and relatively dynamic producer of coral sands. Projected general reductions in calcification and simplification of coral communities may significantly modify sediment budgets, especially where post-event community recovery slows and the interval between storms shortens. Under this scenario, geomorphological features that have historically been constructed by cyclones may be eroded in the longer-term future.

Patterns of exposure and sensitivity for inter- and supratidal geomorphological features like reef islands and sandy beaches differ from those of reefs, and are likely to be affected more by factors such as tidal range and late Holocene sea level history. For example, many reef islands on the inner northern GBR are located over emergent reef platforms (see section 21.3.1), and are protected by lithified ramparts. These islands are less exposed and sensitive to changed cyclone activity than unconsolidated cays on lower reef flats. By their very nature, sandy beaches are sensitive to changes in hydrodynamic environment and sediment supply, and move toward an equilibrium profile that is largely a function of these two parameters.

21.3.4 Enhanced rainfall

Climate change projections suggest that increased cyclone activity will produce more frequent high intensity rainfall events against a more general drying of most coastal catchments (Lough chapter 2). This change may expose geomorphological features to three interrelated impacts: i) increased frequency of freshwater flood plumes, ii) increased delivery of sediments to the coast, and iii) increased exposure to elevated nutrients and contaminants. Inshore geomorphological features will be most exposed, however as these environments have been episodically affected by similar events in the past their sensitivity should be relatively low. However, water quality has declined historically in many parts of the inner GBR[33,11,45], and it is uncertain whether past resilience to plume impacts has been maintained.

More frequent large plumes may extend further offshore and increase the exposure of offshore reefs. Cyclonic rain produced a large flood plume from the Fitzroy River in 1992 that lowered salinity over shallow reefs on the Keppel Islands and reduced live coral cover by 85 percent[155]. The sensitivity of inshore communities other than coral reefs have been discussed in other chapters, and will affect the sensitivity of associated geomorphological features such as sandy or muddy coastlines. As an example, reductions in mangrove or seagrass cover may affect patterns of sediment deposition, erosion and transport[70,154].

Changes in both sediment availability and transport potential may affect sediment delivery to the coast. Terrestrial and marine records in the region indicate that sediment yields are highest when dry conditions are followed by episodic high intensity rain events, especially where drought reduces vegetation cover and increases catchment vulnerability to erosion[103]. The sensitivity of inshore communities to increased supply of fine sediments should be low, as they already experience high turbidity due to wind and wave resuspension of the inshore sediment prism[98,99]. Where excessive sediment is delivered, currents may struggle to transport it all away and some smothering may result. This is most likely in sheltered locations, or near stream mouths[163]. Where flood plumes deliver suspended sediments beyond their present range, sensitivities may be higher. Delivery of sand to the coast may also increase, but this will take longer, and the amount of new sediment delivered will still be relatively small compared to the amount accumulated over the last 6000 years[97]. Sands are unlikely to be transported far offshore, but may be redistributed alongshore[7,126], possibly renewing beach ridge progradation in some areas.

21.3.5 Reduced rainfall

A major impact of reduced general rainfall but episodic high intensity events will be reduced vegetation cover and an increase in terrestrial erosion, with accompanying water quality reductions if nutrient and contaminant yields during floods remain high. The sensitivity of geomorphological features to reduced rainfall will also be influenced by the extent to which attributes such as vegetation that rely on regular freshwater are involved in enhancing stability or other important processes. For example, where insufficient rain falls to replenish aquifers or keep vegetation alive, cays may become more vulnerable to erosion, or less likely to become vegetated with the stability that brings.

21.3.6 Ocean acidification

Atmospheric carbon dioxide (CO_2) concentrations are expected to rise from pre-industrial levels of 280 parts per million to 540 to 970 parts per million by 2100[86] (Lough chapter 2). Carbon dioxide entering the ocean reduces the capacity of calcifying organisms to produce calcium carbonate skeletons[131], with obvious potential impacts for geomorphological features reliant on these materials. Future changes in seawater pH are anticipated to reach levels not experienced for several hundreds of millions of years[16]. Critically, carbonate ion availability is estimated to fall below that necessary for calcification by corals when atmospheric concentrations of CO_2 exceed 500 parts per million[50,58] (Hoegh-Guldberg et al. chapter 10), a level at the lower end of future projections.

It has been argued that negative impacts of ocean acidification on calcification will be offset by positive impacts of temperature increases on the same process[107]. Although calcification is highly correlated with temperature in GBR corals[102], it is unlikely that this would persist in a warming world[93].

21.4 Potential impacts, adaptive capacity and vulnerability

Predictions of the potential impacts, adaptive capacity and vulnerability of projected climate change on geomorphological features of the GBR are complicated by the diversity of each of the major geomorphological features, and uncertainties regarding the nature of projected climate changes, geomorphological responses, and of synergistic effects of climate change, natural variability and human activities. Nonetheless we can be certain that the entire GBR and adjacent coast experienced massive and repeated environmental changes beyond anticipated projections in the recent geological past, as glacial-interglacial cycles forced sea levels through more than 100 metres of vertical range, and forced shorelines to migrate laterally over tens of kilometres. The adaptive capacity of most geomorphological features – even under sub-optimal conditions – is therefore self evident, and the long-term vulnerability of many would appear demonstrably low. However, confidence in this conclusion is reduced where biological productivity is important and the survival of critical organisms is threatened by climate driven changes, compounded by pressures associated with other anthropogenic activities. Coral reefs are clearly in this category.

In this section we infer the adaptive capacity of major geomorphological features from knowledge of their morphological behaviour to natural cycles (some with limits that exceed the extremes of future projections), including those observed from outside the GBR and those that have occurred in the historical and geological past.

21.4.1 Coral reefs

21.4.1.1 Sea level rise

Potential impacts of climate change on the geomorphological structure of coral reefs are summarised in Table 21.2 and schematically shown in Figure 21.3. Despite earlier concerns, the consensus is now that rising sea levels alone will not present significant difficulties for healthy reefs, as projected rises are within the range of natural variability and geological precedent. Projected rates of sea level rise are well below published rates of coral growth, which are commonly around 10 to 12 mm per year for massive corals and as high as 180 mm per year for branching species[22]. However, coral and reef growth rates are not synonymous. Reef accretion – the rate at which the reef grows vertically – is not only a product of coral calcification, but is also affected by factors including sediment production by other reef organisms (eg foraminiferans, molluscs, etc), bioerosion, and sediment redistribution[84]. Spencer[144] calculated average rates of vertical accretion for the northern, central and southern GBR at 14, 10, and 12 mm per year respectively, again suggesting that projected sea level rise will not be problematic for healthy reefs.

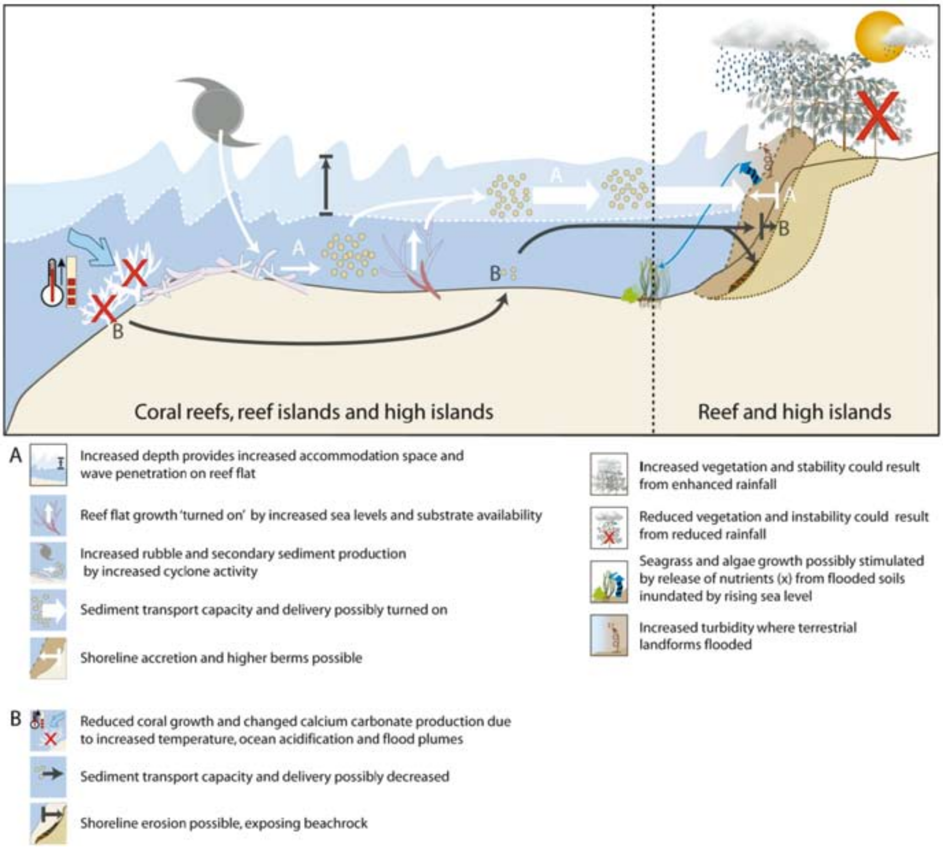
Many reefs on the GBR reached sea level in the mid-Holocene[82], after which continued vertical and luxuriant reef growth was 'turned off' by stresses associated with a lack of accommodation space[14]. Hopley[77] argued that where coral growth rates have not been diminished by human activities, the more rapid projections of future sea level rise (0.5 metres by 2100) may reinvigorate or 'turn on'[14] at least some of these reefs by providing new accommodation space into which they may grow. Kinsey and Hopley[90] estimated that the current calcification rate of about 50 million tonnes per year on the GBR may increase to 70 million tonnes per year if presently senescent reef flats are recolonised. Production declines at depth due to rising sea level are unlikely to be significant.

Table 21.2 *Potential impacts of global climate change on coral reef geomorphological features of the GBR*

Process(es) or Parameter(s) affected	Potential impact	Important factors
Rising sea level		
Water depth Inundation extent Sediment transport and deposition Substrate availability Water quality	Lower irradiance for deeper corals and possibly slower growth or even 'drowning' Increase accommodation space into which depth-constrained reef communities may extend Shoreline retreat may present additional habitable substrate Flooding and erosion of terrestrial landforms may elevate inshore turbidity, nutrient and contaminant loads Greater depths and openness on the inner GBR may improve flushing and water quality in some areas Increased depth and potential for wave-generated sediment transport across shallow reefs	Rate of rise critical[77] Tidal range relative to rise rate Late Holocene sea level history important Turbidity impacts
Rising sea surface temperature		
Community structure Photosynthesis/ Autotrophic activities Calcification rates and contributing calcifiers Primary production Erosion (including bioerosion) and disease Reef strength	Increased coral bleaching and loss of sensitive species Coral reef calcification rate and sediment budget modified (composition, texture, amount, and durability of sediments) Reef growth rate may change – construction may shift more to detrital than framework growth Balance between primary calcification production and secondary sediment yield may be modified Increased bare substratum for colonisation by algae and accessible to disease and bioeroders Physical strength of coral reef structures reduced, and stability as substratum for colonisation possibly altered	0.8°C rise causes bleaching, 2 to 3°C rise causes coral death Three-day hot spells are most critical for corals, not average temperature increases[9] Genotypic variation (coral and zooxanthellae) in sensitivity Ameliorating factors (eg upwelling) and warming patterns (enclosed lagoons etc) will affect spatial patterns

Process(es) or Parameter(s) affected	Potential impact	Important factors
Increased tropical cyclone activity and surge		
Wave climate and exposure	Greater exposure to larger waves Physical destruction of corals and other living benthos Shifts toward more storm tolerant taxa and modification of sediment types and rates of production Increased erosion and secondary sediment production Episodic production and transport of coral rubble/shingle Reduced structural complexity, strength and possibly long-term wave resistance	Existing exposure to high energy storms and associated geomorphological characteristics Tide range and reef depth relative to wave base Skeletons weakened by bioerosion, crystal poisoning, etc, more vulnerable
Enhanced rainfall		
Fluvial and groundwater inputs into GBR lagoon Runoff quality Inshore water quality Salinity Coral reef growth	Increased number, duration and extent of flood plumes Reefs further offshore affected more often by flood plumes Increased delivery of sediments, nutrients and contaminants by flood plumes Increased benthic algae and reduced coral cover Increased probability of low salinity mortality events in enclosed lagoons, moats and settings with restricted circulation and mixing Increased bioerosion	Proximity to mainland and/or larger high islands Catchment size and land use
Reduced rainfall		
Inshore and surface water salinity Inshore water quality	Reduced number, duration and extent of flood plumes Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs Reduced delivery of sediments, nutrients and contaminants by flood plumes Increased coral cover Reduced bioerosion	Proximity to mainland and/or larger high islands Catchment size and land use
Ocean acidification		
Calcium carbonate production and fixing	Reduced coral and other biotic calcification	Full ramifications likely to be significant but limited knowledge

Figure 21.3 *Key processes and potential impacts of predicted climate changes on coral reefs, reef islands and high islands*



Rapid rates of sea level rise will improve transmission of wave and current energy over reef surfaces, producing several effects. Depth is a critical control of energy available for sediment transport, which is likely to increase over reef flats as sea level rises. The inner part of the wide reef flat at Warraber in the Torres Strait is now around one metre above the live reef as a result of regional hydro-isostatic adjustment[171], similar to many reef flats inside the zero isobase on the GBR[71,115]. Recent work by Kench and Brander[87] showed that the reef flat at Warraber is geomorphologically inert for most of the time at present, with waves above 0.05 metres occurring on the outer reef for less than 30 percent of each spring neap tidal cycle. Larger waves will propagate further across the reef flat over a larger proportion of the tidal cycle under higher sea level scenarios. Where sediments are available, either residual from earlier production or as reinvigorated primary production, they may be more efficiently transported by the increased wave energy. This may benefit both the maintenance and growth of geomorphological features composed of detrital materials such as reef islands and beaches, and primary production of carbonate where sediment accumulation is limiting (ie where sediments are smothering substrates suitable for productive communities).

21.4.1.2 Rising sea surface temperature

Projected sea level rise may have some positive outcomes for reefs, but it is increasingly unlikely that they will outweigh the negative impacts of other climate change stressors. Rising temperatures are predicted to cause more widespread, severe, and frequent bleaching (Hoegh-Guldberg et al. chapter 10), resulting in reduced live coral cover and structural complexity, and modified reef sediment budgets. Branching *Acropora* corals are likely to be affected first and gradually decline, but massive corals will be increasingly affected as SSTs continue to warm (Hoegh-Guldberg et al. chapter 10). Diminished coral cover and fecundity of survivors will reduce recovery of bleached communities, producing an increasingly bare substratum dominated by fleshy algae[34]. The general decline in Acropora and other primary framework builders will reduce primary reef framework construction; fewer living *Acropora* and reduced shingle sediment production will be amongst the most rapid changes. However, the dynamics are complex; it has been argued that warmer sea surface temperatures will (up to a limit) produce faster growth but lower calcification[107,108,93], so that material produced is more fragile and easily broken down[139]. More shingle will initially be produced as declining thickets are disturbed more often, leading to at least a short period of accelerated reef evolution as lagoons are infilled by detrital sediments, however diminished recovery and thicket growth will ultimately reduce the production of this material.

Some reefs may shift toward an erosional regime, with unstable frameworks and reduced structural integrity, but again such effects are likely to be variable. Well-preserved reef surfaces and even corals formed thousands of years ago (eg fossil microatolls) suggest that this may be a very slow process and not a major problem in many areas. Conversely, however, fringing reefs in the Seychelles are now far less efficient dissipaters of wave energy than they were prior to the 1998 bleaching event and subsequent coral mortality and disintegration[139].

21.4.1.3 Increased cyclone activity

Increased cyclone activity will have variable effects, with negligible impact on reefs or reef habitats in high-energy settings, but potentially large impacts on those not adapted to such events. Reefs composed of unbound detrital material, as is common for many inshore reefs[142], are vulnerable to stripping and possibly structural collapse. As for other climate stressors, the negative effects of community composition changes will be reinforced by slow and increasingly limited recovery between events. Resultant morphological changes are likely to mirror those associated with rising SSTs, with initial loss of fragile components. This loss may be hastened by skeletal weakening associated with eutrophication and crystal poisoning (where contaminants are incorporated into the skeletal structure and reduce skeletal strength[130]). Greater bioerosion associated with increased benthic algae and plankton may also increase the rate of coral loss. The diminution of coarse primary carbonates to sands may be accelerated by these processes, but not enough is known to confidently predict this outcome.

Although corals are important components on most healthy reefs, other organisms are also significant contributors to reef construction (section 21.2). As coral vigour is reduced by climate change stress, other contributors, for example, molluscs, foraminiferans or coralline algae may compensate if suitable substrates and conditions are available. *Halimeda*, for example, has formed large banks in areas of the GBR affected by nutrient rich upwellings[41], and may become a more widespread and significant contributor to reefs affected by eutrophication. Nutrients released as soils were reworked

by rising seas after the last ice age were linked to flourishing *Halimeda* by Hopley[76], and are a useful analogy for possible future changes. Carbonate sediments produced by different organisms vary markedly in important properties like durability and hydrodynamic behaviour, and shifts in producers can alter sediment transport and depositional dynamics. The impacts of such changes on various reef environments are poorly understood.

21.4.1.4 Enhanced rainfall

Increased exposure to low salinity flood plumes fed by enhanced rainfall may cause greater mortality than occurs at present, but the most significant impacts of a changed hydrological regime will probably be associated with increased nutrient and contaminant loads rather than freshwater runoff *per se*. Modern reef growth occurred as the coastal plain was actively prograding (eg Belperio[7], Graham[56]), suggesting that floods themselves are unlikely to limit reef growth.

21.4.1.5 Ocean acidification

Increased ocean acidification will pose a critical threat to continued reef development as calcifying organisms, particularly those secreting aragonite, struggle to form skeletons[131]. Kleypas et al.[91] suggested that doubling pre-industrial CO_2 by 2050 would lower the ocean's aragonite saturation state by 10 to 30 percent, with dire consequences for reef construction. How these changes will affect existing reefs is uncertain. Existing reefs will remain as geological structures, but the probability of continued vigorous reef growth seems low. Ecological and aesthetic reef values will also likely be diminished as detrital sediments increasingly dominate.

21.4.2 Reef islands

The potential impacts of climate change on reef islands of the GBR will, like the islands themselves, be diverse. Anticipated potential impacts are summarised in Table 21.3 and schematically presented in Figure 21.3.

21.4.2.1 Sea level rise

Early concerns that sea level rise will simply drown reef islands have been shown to be incorrect, with island response being the result of the complex interplay of a variety of physical, biological and chemical factors. Changes in sediment production and delivery must be considered, and the possibility that some islands will actually expand, at least in the short to medium term, is now widely accepted[106,75,77,88].

Rising sea level may improve sediment transport across reef platforms by allowing larger waves to propagate further through more of each tidal cycle (section 21.4.1.1). Inner shelf reefs experienced a relative sea level fall of about a metre during the late-Holocene, allowing sediments to build up over reef flats that are immobile except during storms. Shallow depths over these reef platforms limit sediment transport and delivery to reef islands[77,87], and rising sea levels might ameliorate this impediment by allowing more wave energy across the reef platform. Hopley[75] suggested that a sea level rise of just 0.5 metres would remobilise reef flat sediment deposits and move them shoreward. Many reef geomorphologists agree that projected sea level rise will substantially re-work unconsolidated sediments, at least enough to maintain reef island mass[104,75,88].

Table 21.3 *Potential impacts of global climate change on reef island geomorphology of the GBR*

Process(es) or Parameter(s) affected	Potential impact	Important factors
Rising sea level		
Water depth Inundation extent Sediment transport and deposition, erosion Reef island stability	Increased accommodation space for reef communities to grow into Increased depth and potential for wave-generated sediment transport across shallow reef flats Larger waves possible at reef island shores, with greater shoreline modification Higher berms Changed reef island morphology	Rate of rise critical[77] Tidal range relative to rise rate Late Holocene sea level history important Degree of lithification will mediate effects Vegetation will stabilise Likely to be regional patterns
Rising sea surface temperature		
Community structure Calcification rates and contributing calcifiers Sediment production Erosion (including bioerosion) Reef construction Reef strength	Increased coral bleaching Reduced coral calcification and modified sediment budgets (composition, texture, amounts, and durability of sediments) Reef growth rate may change – construction may shift more to detrital than framework growth Balance between primary calcification production and secondary sediment may be modified Increased bare substratum for colonisation by algae and accessible to disease and bioeroders More rapid diminution of sediment size Structural integrity reduced, and stability as substratum for colonisation altered More rapid cementation of beach materials	0.8°C rise causes bleaching, 2 to 3°C rise causes coral death Three-day hot spells appear most critical for corals rather than average or median temperature increases[9] Genotypic variation (both coral and zooxanthellae) in sensitivity Ameliorating factors (eg upwelling, etc) and probably warming patterns (enclosed lagoons, etc) will affect spatial patterns
Increased tropical cyclone activity and surge		
Wave climate and exposure Depth during cyclones increased by surge	Greater exposure to larger waves Physical destruction of corals and other living benthos – production of reef rubble, shingle, sands and finer sediments Shifts toward storm tolerant taxa and modification of the types and rates of sediment produced More erosion (including bioerosion) and increased secondary sediment production Episodic transport of coral rubble/shingle Reduced structural complexity, strength and long-term wave resistance Inundation and higher level erosion during surge events Higher berms	Existing exposure to storms Tide range and reef depth relative to wave base Shelf bathymetry and coastal configuration will affect surge potential Complexity of reef network will affect fetch and capacity for longer period waves to develop Reef platform shape will affect wave refraction and influence sediment dispersion versus concentration properties of storm waves

Process(es) or Parameter(s) affected	Potential impact	Important factors
Enhanced rainfall		
Fluvial and groundwater inputs into GBR lagoon Runoff quality Salinity Freshwater aquifers Establishment and survival of reef island vegetation	Increased number, duration and extent of large flood plumes Reefs further offshore affected more often by flood plumes Increased delivery of sediments, nutrients and contaminants by floods Increased benthic algae and reduced coral cover Increased bioerosion and disease Increased low salinity mortality events in enclosed lagoons, moats and poorly mixed settings Improved reef island stability where vegetation establishment and survival improved Reduced reef island mobility and vulnerability to climate variations	Significant local variation likely between GBR catchments Proximity to mainland and island size Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event
Reduced rainfall		
Inshore and surface water salinity Freshwater aquifers Establishment and survival of reef island vegetation	Reduced number, duration and extent of flood plumes, but possibly more very large ones Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs Improved autotrophic calcium carbonate production Increased sensitivity to episodic floods Reduced delivery of siliclastic sediments, nutrients and contaminants by flood plumes More difficult for island vegetation to establish and survive and reduced potential for vegetation enhanced stability Islands more mobile and vulnerable to storms and climate fluctuations such as wind shifts etc	Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event
Ocean acidification		
Calcium carbonate production and fixing	Reduced calcification Reduced primary production of carbonate sands and reef island sediments Possible that increased erosion of standing reef framework may initially yield higher secondary reef sediments	Full ramifications likely to be significant but limited knowledge Surface area to volume – will smaller sediments, like sands, which dominate many reef islands, be aggressively dissolved?

Once sediments stored on reef flats are exhausted by transfer to the reef island or possibly off reef, the amount of new sediment available will depend on the rate of sea level rise if current calcification rates in different geomorphologic zones can be sustained. Hopley[77] modelled carbonate budgets for an idealised atoll reef flat responding to a 0.5 and 1.8 metre rise by 2100, and demonstrated that almost all reef zones would vertically accrete and reef morphology would not change if sea level rose at the more modest rate. However, the algal zone transformed to coral cover at the higher rate of rise, and calcium carbonate production substantially increased. Some of this enhanced carbonate productivity would yield sediments suitable for reef island construction, and because greater depth allows waves competent to transport sediments shoreward to occur more often, Hopley[77] concluded that a higher rate of sea level rise may ironically be more beneficial for reef island sustainability than a slower rate.

Cay build-up is largely controlled by the characteristics of waves reaching the beach, with berm height – the height of the beach above mean high water – dependent on wave run-up. Run-up increases with wave height, wave steepness, beach slope, shape of the beach profile and roughness and permeability of the beach material. Gourlay and Hacker[55] found that wave run-up height varied reliably with the ratio of the breaker height to water depth over the reef flat at Raine Island, because wave heights are limited by shallow water breaking conditions. They indicated that the height of the four metre beach berm was controlled by the wave run-up height during the highest spring tides. Gourlay and Hacker[55] calculated that with a 0.6 metre rise in sea level, 1.6 metre waves could reach the cay, and would increase berm height from 4 to 4.8 metres, and that 0.5 metre waves reaching the cay at lower tides would increase berm height by 1.2 to 5.2 metres. These results reveal that reef islands may vertically accrete by an amount larger than the sea level rise if the reef flat lags and larger waves can reach the beach.

Although residual sediment may be stored on emergent reef flats (due to both their greater elevation and relative age), the positive benefits of sea level rise depend on increased reef flat depth, which will take longer to manifest on higher reef flats. Interactions between the buffer against rising sea levels afforded by late Holocene emergence and the timing of re-invigoration of reef flat sediment transport and productivity are fundamental to accurate predictions of reef-island response to climate change, but are poorly known and require further investigation. Sea level changes may also modify reef-top habitats and the contributions of different carbonate producers, affecting the rate of sediment delivery to reef islands, and thus reef island dynamics.

21.4.2.2 Reduced carbonate production

Several studies suggest that cays in the GBR and Torres Strait accumulated most of their mass prior to 2000 years ago, with only limited accretion since[13,166]. On the northern inner GBR this early phase of accretion corresponds with the generally more substantive and elevated inner island core, which is usually replete with soils and mature vegetation. A lower peripheral terrace is associated with recent accretion[147]. Whether the distinction between these two surfaces is a function of sediment supply or falling sea level (and thus reduced sediment delivery to the island) is unresolved, but both possibilities are closely connected. Chronological data are available for very few islands. Those that are available and the terraced morphology evident on others suggest that many cays of the inner GBR: i) are formed of sediments produced several thousand years ago, ii) appear to have accumulated a significant proportion of their bulk long ago, and iii) have not received significant recent carbonate

production. Projected collapses in carbonate productivity may thus have limited immediate impact on these islands, especially as many are significantly lithified which should improve resistance to erosion if sediment deficits arise.

It would be unwise to assume that all reef islands on the GBR have developed as described above, or that they have similar potential resilience to climate-change impacts. As indicated, GBR reef islands are geomorphologically diverse, the geomorphologies of few are known in detail, and establishing reef island accretion chronologies is technically difficult. For example, Lady Elliot Island has continued to accrete at a relatively constant rate since the mid-Holocene[24], and similar chronology has recently been established for Warraber based on selective Accelerator Mass Spectrometer radiocarbon dating of gastropod sediments[172]. Gastropods inhabit the reef flat close to the island, and derived sediments are transported quickly onshore so that death and depositional ages are close. This new chronology suggests that Warraber has grown at a reasonably constant rate since the mid-Holocene[135], differing from a previous chronology based on dating bulk sediment samples which suggested rapid accretion soon after the mid-Holocene and relative senescence thereafter[166]. A comparable accretion history was determined for Makin, Kiribati by Woodroffe and Morrison[169]. An important difference between Makin and Warraber however, is that Makin is mainly composed of foraminiferans produced on the outer reef flat that are quickly moved onshore.

This close connection between outer reef flat production and reef island accretion occurs at Makin despite partial emergence of the reef-top during the late Holocene. Woodroffe and Morrison[169] implied that sea level fall may have initiated rather than impeded reef island growth by creating abundant foraminiferan habitat and presenting a slightly elevated foundation over which foraminiferan sediments could accumulate. Yamano et al.[178] determined that foraminiferans are also the main contributors of recent sediment at Green Island on the GBR, and suggested that this dominance arose because relative sea level fall in the late Holocene increased foraminiferan habitat and reduced that of other carbonate producers. Earlier sedimentological work by one of the authors (DH) at Green Island indicates that foraminiferans are a very recent addition to cay sediments (see Hopley et al.[82]). Green Island is actually inside the zero-isobase and thus has not experienced relative sea level fall inferred as the driver for expanded habitat and representation of foraminiferans at this location. Nevertheless, modern foraminiferans at Green Island also live near the reef edge, with tight coupling between foraminiferan production and delivery to the cay attributed to the hydraulic traits of foraminiferan tests, which are relatively easy to entrain and transport[178].

Where reef islands are younger, the future may be less positive. Sediments comprising these islands have probably been produced more recently on reef flats nearer to sea level than those on the inner shelf. Lithification to form beach rock and conglomerate will aid stabilisation, but they are nonetheless more vulnerable to climate change in several ways. First, the reef flats on which they form are deeper than those of the inner shelf, and thus the islands are more sensitive to changes in wind and wave conditions, including those that may move sediments off the reef platform. Shoreline mobility associated with this sensitivity can also inhibit lithification and longer-term stability. Second, less sediment is likely to be stored on these reef flats for reworking toward the islands as sea level rises. Finally, active carbonate production and reef island accumulation are more tightly coupled on less emergent reef flats, with efficient transfer of products to the zone of accumulation. In these circumstances diminished carbonate productivity and sediment supply will have more immediate effects on island sediment budgets and morphologies.

Reef islands near the zero isobase are particularly vulnerable to these effects, as are those where the tidal range is relatively large (allowing larger waves across reef flats at neap and higher tides) or where the outer barrier provides less protection from large waves. That these conditions limit reef island development and stability is demonstrated by the lack of reef islands through the central GBR (section 21.2.2). Bushy Island (20° 57' S, 150° 05' E) is an exception, able to endure because it is located inside the zero isobase on an elevated reef flat encircled by a large algal rim and moat that mediates the destabilising effects of high tidal range and wave exposure[70].

21.4.2.3 Increased cyclone intensity

The impacts of increased cyclone intensity are difficult to predict, as the relationship between geomorphologic work and cyclone intensity is poorly understood. Changes in cyclone duration and frequency may be more significant. Cyclones have clearly caused significant erosion on some reef islands, especially unvegetated cays (section 21.2.2) but they can also be important accretion events. On Lady Elliot Island, concentric ridges increase in age toward the island interior and document the progressive growth of the island during storms[24]. On the northern GBR, storm-emplaced features such as shingle islands, and shingle and rubble ramparts are common on the low wooded islands[147,148]. Materials must clearly be available for accretion to occur, and hence cays on reefs where carbonate productivity has declined and sediment supplies have become limited are most vulnerable to erosion during cyclones.

Broad spatial patterns of vulnerability to cyclone impacts may be inferred from observations of contemporary patterns of island occurrence, mobility, and stability. Islands of the inner GBR located over emergent reef flats are least vulnerable. Many are protected by lithified ramparts, conglomerates or beach rock outcrops and a metre or so of emergent, often sediment veneered, reef which buffers the negative impacts of rising sea level and or reduced carbonate production. However, inshore reefs are potentially exposed to higher storm surges than those further offshore, which could offset this buffer. Storm surge on mid-shelf and offshore reefs is usually small, for example, the surge produced by cyclone Emily in 1972 (central pressure 985 hectopascal) at Gladstone was two metres but at Heron Island, over which it directly passed, the surge was less than 0.8 metres[66].

As noted above, reef islands are rare through the central GBR, and climate change will not enhance their prospects for development in this area. In the southern GBR, more intense cyclones may affect reef island formation and stability in areas such as the Swain and Pompey Reefs. Here, a complex reef network impedes the development of discrete focal points for wave refraction and island accumulation under prevailing south-easterly winds. Reef islands in these areas appear particularly vulnerable to disturbance by cyclones approaching from variable directions that may redistribute sediments over the reef top and require a long time to recover. Many cays in the Capricorn Bunker group lie on more symmetrical reef platforms and have developed on well-confined focal points. Several are large, well vegetated, and partially lithified by both phosphatisation of sediments in the island interior and beach rock formation on the shoreline. Although the present high mobility of the distal tails of the more elongate cays will continue and possibly increase, the long-term stability of these islands is good.

21.4.2.4 Changed rainfall patterns

Changed rainfall regimes will have different impacts depending on island size. Higher rainfall on small, mobile, arid islands presently lacking a freshwater lens may improve prospects for vegetation establishment and stability. This benefit would be reduced if rainfall remains highly seasonal or mainly associated with extreme events. Reduced rainfall will be problematic for vegetation survival, and possibly reduce stability of islands with freshwater aquifers requiring regular recharge. According to the layered aquifer model of reef island ground water retention[15], a threshold island width of 120 metres is needed for a freshwater lens to develop. Oberdorfer et al.[122] suggested that if island size remains above this level, rising sea level has a counter intuitive effect on the total freshwater resource of islands possessing a layered aquifer. An increase in sea level makes available more low permeability Holocene materials for freshwater retention, increasing the total freshwater resource. Hence, a rise in sea level may not be disastrous for island ground water resources, but may actually increase if islands become larger, especially if rainfall also increases.

21.4.3 High island beaches and spits

The potential impacts of climate change on high island beaches will be similar to those on reef islands and mainland sandy coasts (Table 21.4, Figure 21.3). Only specific differences are described in detail here.

21.4.3.1 Sea level rise

Most high islands on the GBR are west of the zero isobase and have experienced late Holocene emergence. Many have developed broad leeward reef flats over which spits have accumulated. Beaches are most common on leeward embayed shorelines. As on reef islands, rising sea level will increase depth and wave penetration across shallow inshore areas, mobilising and transporting stored sediments shoreward. Larger waves will run-up higher on the beach, producing an increase in berm height that may exceed the rise in sea level if adequate sediment is available[55].

The interiors of large spits are often elevated up to several metres above peripheral Holocene deposits, and inundation of higher surfaces is unlikely in the short to medium term. However, if they were flooded, nutrients may leach onto the reef flat[23]. Leached nutrients may boost algal and seagrass growth, possibly affecting coastal sediment dynamics. Seagrass meadow expansion on the reef flat at Green Island trapped sediments on the reef flat and reduced sediment supply to the cay beach, causing erosion[70,154].

21.4.3.2 Reduced carbonate production

Where sea level rises quickly, presently unproductive reef flats may be recolonised by calcifiers and carbonate production may increase[77], although as discussed for coral reefs and reef islands, if projections of ocean acidification are correct calcifying organisms will struggle to survive[93]. Rising SSTs and increased bleaching will affect coral community structure, but the geomorphologic impacts are difficult to predict. Sheppard et al.[139] showed that wave energy at the beach increased due to a loss of reef structure caused by bleaching mortality, but many fringing reefs on the GBR have persisted without significant accretion for several millennia and still appear structurally robust[143].

Table 21.4 *Potential impacts of global climate change on high island spit and beach geomorphology of the GBR*

Process(es) or Parameter(s) affected	Potential impact	Important factors
Rising sea level		
Water depth Inundation extent Sediment transport and deposition Water quality	Increased accommodation space for reef communities to grow into Shoreline retreat may present additional substrate for colonisation by coral reefs Flooding and erosion of terrestrial landforms may elevate inshore turbidity, nutrient and contaminant loads Increased depth and potential wave-generated sediment transport across shallow reefs Mobilisation of reef flat or shallow inshore sediments New 'high-energy window'? Period when many spits in the central GBR were reworked	Rate of rise critical[77] Tidal range relative to rise rate Late Holocene emergence provides a buffer
Rising sea surface temperature		
Community structure Calcification rates Sediment production	Impact on coral beaches with increased bleaching events as carbonate sediment budget Modified primary sediment production – change in dominant producers of sand-sized carbonate sediments Increased bare surface for algal colonisation – possible switch to mollusc dominated sediments?	0.8°C rise causes bleaching, 2 to 3°C rise causes coral death Three-day hot spells appear most critical for corals rather than average temperature increases[9] Genotypic variation (both coral and zooxanthellae) in sensitivity
Increased tropical cyclone activity and surge		
Wave climate and exposure Depth during cyclones increased by surge	Significant erosion of beach and backing dunes or land Loss of beach and erosion buffer Physical destruction of corals and reef Episodic production and transport of coral rubble/shingle Higher spit mobility/lower stability Larger waves at reef island shores, greater shoreline modification Exposure of beachrock or other cemented deposits	Frequency and intensity of storm events impacts will affect recovery Some smaller spits and exposed beaches may erode beyond point of recovery Sediment characteristics and availability will be important controls

Process(es) or Parameter(s) affected	Potential impact	Important factors
Enhanced rainfall		
Fluvial and groundwater inputs into GBR lagoon Runoff quality Salinity Freshwater aquifers Establishment and survival of littoral vegetation	Increased number, duration and extent of large flood plume Reefs further offshore affected more often by flood plumes Increased delivery of sediments, nutrients and contaminants by floods Increased benthic algae and reduced coral cover More low salinity mortality events in enclosed lagoons, moats and poorly mixed settings Increased bioerosion Improved chances of vegetation establishment and survival Improved spit and beach stability	Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event
Reduced rainfall		
Inshore and surface water salinity Freshwater aquifers Establishment and survival of reef island vegetation	Reduced number, duration and extent of flood plumes, but possibly more very large ones Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs Improved autotrophic calcium carbonate production Increased sensitivity to episodic floods Reduced delivery of siliclastic sediments, nutrients and contaminants by flood plumes More difficult for littoral vegetation to establish and survive and reduced potential for vegetation enhanced stability Spits more mobile and vulnerable to storms and climate fluctuations such as wind shifts etc	Local variation likely between GBR catchments Proximity to mainland and island size Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event
Ocean acidification		
Calcium carbonate production and fixing	Reduced calcification Reduced primary production of carbonate sands and reef island sediments Possible that increased erosion of standing reef framework may initially yield higher secondary reef sediments	Full ramifications likely to be significant but limited knowledge Reduction in carbonate production and representation in features

In the Seychelles, Sheppard et al.[139] noted that many reef flats had become rubble dominated, and this may occur on some GBR fringing reefs as sands are preferentially winnowed. Greater wave access across reef flats under higher sea level may increase spit mobility, particularly at distal unconsolidated ends, and especially during storms. Some lithification is common if spit or beach sediments contain significant carbonate, with beach rock or conglomerate often exposed. These indurated deposits improve stability, but they can be outflanked and stranded off the active beach. Where sediment supply is exhausted and shorelines retreat, lithified shorelines resist erosion more effectively than unconsolidated deposits. However, shorelines dominated by lithified deposits may not provide critical ecosystem services formerly satisfied by unconsolidated beaches, such as turtle nesting habitat.

21.4.3.3 Changed rainfall patterns

Modified rainfall regimes have several potential impacts on bigger islands with larger catchments and creeks. Extreme floods fed by more intense cyclones may lead to episodic salinity stress near creek mouths, although this would be localised and rare. If rainfall generally declines but extreme events become more frequent, vegetation cover may decline and sediment yields increase, possibly compensating for reduced carbonate productivity in some areas.

21.4.4 Mainland sandy coasts

Close links between form and process are confirmed by morphodynamic studies of many Australian sandy beaches[140], including several on the mainland coast inside the GBR[112,113]. These studies typically relate beach morphology to incident energy (wave and tide) and sediment supply and traits. Characteristic beach states develop for a given set of conditions, and beach state will change if conditions are altered[176,141]. Adjustments can occur over short timeframes at a local scale in response to events such as storms. However, longer-term studies are needed to detect more protracted cycles of erosion (cut) and accretion (fill)[105], and the influence of climatic events such as the El Niño-Southern Oscillation and the Interdecadal Pacific Oscillation at sub- and multi-decadal scales[129,52,53]. These influences must be filtered when reconstructing coastal change trajectories based on short records, and it is equally important to accommodate changes within these cycles in vulnerability assessments.

21.4.4.1 Sea level rise

The impacts of sea level rise on sandy beaches have traditionally been assessed using the simple two-dimensional Bruun Rule[12], which states that a beach will adjust its cross-shore profile to maintain an equilibrium form in response to a given sea level rise. This rule implies that sand moved from the upper beach is deposited lower on the profile as equilibrium adjustments are made, with limited loss to seaward. Various modifications of this basic rule have followed in subsequent years, including several that support Bruun's calculation that the ratio of shoreline recession to sea level rise is usually within the range of 50 to 200:1[100]. However, the application of the Bruun Rule as a universal predictor of beach response to sea level rise has been criticised[28]. Problems with its application to mainland sandy beaches inside the GBR include: the arbitrary selection of closure depth; it does not account well for rock outcrops; sediment deposition on land is not included; the impacts of storms are not accommodated; and longshore transport, complex currents, and the timeframe of sediment transport

are all ignored. Particular issues inside the GBR arise where morphological adjustment is not possible because the lower shoreface is lithified beach rock or conglomerate, or where hard reef flats lie offshore of the beach[88].

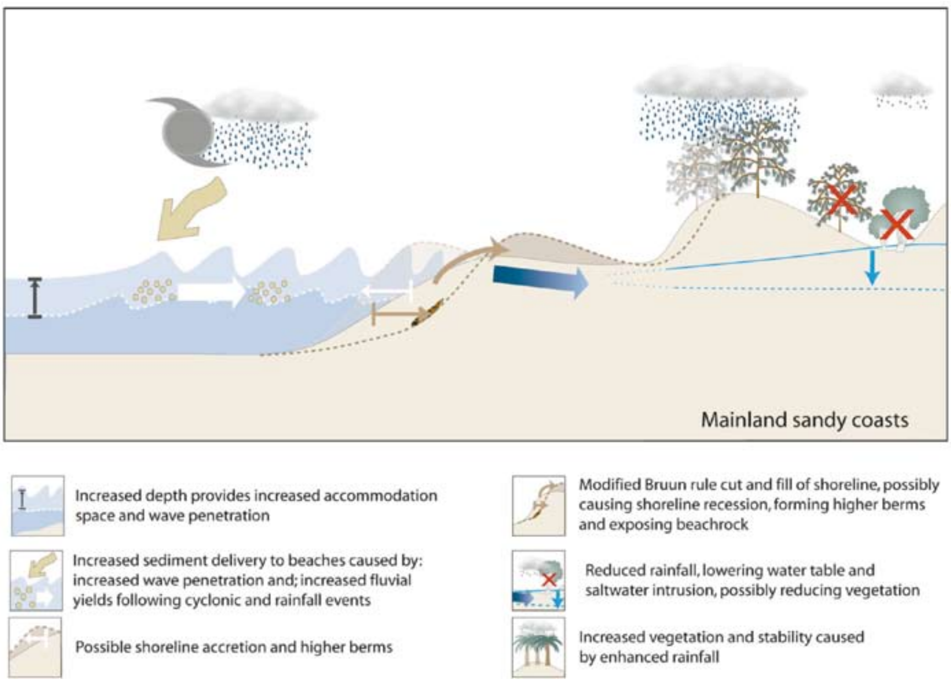
In the shorter term, rising sea levels will probably cause some coastal retreat as sediments are worked onshore by wave swash. Responses will vary with tidal range, exposure to wave energy, and sediment supply. The main potential impacts are summarised in Table 21.5 and Figure 21.4. In assessing the significance of any changes, it is important to note that shoreline recession over the past few millennia has been a common trend on many sandy coasts inside the GBR[175,142]. Isolating the impacts of climate change induced retreat from this longer erosion trajectory, and the various other cycles and events that may cause shoreline variation discussed earlier, is challenging. Although many beach ridge sequences have been eroding for the past few thousand years, most began to form around 6000 years ago[65,56], and large sand reserves remain onshore at most locations.

Table 21.5 *Potential impacts of global climate change on mainland sandy coast geomorphology inside the GBR*

Process(es) or Parameter(s) affected	Potential impacts	Important factors
Rising sea level		
Water depth Inundation extent Sediment transport and deposition Water quality	Morphodynamic adjustment of beach form Loss of beach width and beach amenity Elevated impact of waves Inundation of coastal lowlands Intrusion of saline water into freshwater sandy aquifers	Bruun rule applicability limited on GBR Late Holocene emergence on coast and significant progradation since mid-Holocene provides a buffer
Rising sea surface temperature		
Carbonate production	Minor potential impacts on carbonate rich beaches as bleaching events reduce primary carbonate productivity	Few beaches carbonate rich
Increased tropical cyclone activity and surge		
Wave climate and exposure	Significant erosion of beach and backing dunes or land Loss of beach width and beach amenity Loss of beach and erosion buffer Exposure of lithified shorelines Change to coarser beach Loss of nesting habitat	Energy difference between storm events and ambient conditions may hinder recovery to equilibrium form Storm frequency and intensity affects time available for beach recovery

Process(es) or Parameter(s) affected	Potential impacts	Important factors
Enhanced rainfall		
Vegetation cover Terrigenous sediment yield and delivery	Increased supply of siliclastic sediments to the coast Altered vegetation coverage of sand coloniser plants	Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event
Reduced rainfall		
Vegetation cover Terrigenous sediment yield and delivery	Reduction in coastal sediment supply Altered vegetation coverage of sand coloniser plants	Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event

Figure 21.4 *Key processes and potential impacts of predicted climate changes on the geomorphology of mainland sandy coasts*



21.4.4.2 Increased cyclone intensity

How mainland sandy coasts will respond geomorphologically to changes in cyclone intensity is unclear, and the potential impacts of more intense cyclones are thus difficult to predict. For example, severe Tropical Cyclone Larry (category 5) directly struck Mission Beach in March 2006 but caused only minor geomorphological change (personal observations), whereas a large proportion of North Queensland's sandy coast was significantly eroded during Tropical Cyclone Justin in 1997 (category 3). Justin was a large cyclone system that persisted for three weeks, including two spring tide phases[111]. The geomorphological impacts of cyclones on sandy shores vary according to many factors, but the stage of the tide (including storm surge) at which the cyclone strikes, the duration of cyclone activity, the size of the cyclone system, and sediment supply are among the most important.

Cyclone impacts can be significantly amplified by storm surge on the mainland coast, raising water levels and wave activity into higher parts of the coastal system less resilient to wave forces (eg dunes). Potential storm surge varies according to storm characteristics and paths (increasing with cyclone intensity – or as central pressure decreases – and as the approach direction is more perpendicular to the coast[118], but coastal configuration and offshore bathymetry also markedly affect surge height. Broad shallow bays with gently sloping offshore bathymetries generally produce the largest surge. Storm surges with calculated return periods of 100 years are around two metres above Australian Height Datum (AHD) north of Cairns, more than 4.5 metres above AHD at Broad Sound, and about three metres above AHD near Gladstone[82]. Models of surge with future climate change generally show the same spatial pattern, but suggest surge heights will increase by about one metre in the next century (eg Gutteridge, Hoskins and Davey[59]). Wave run-up also raises water levels and the zone of cyclone impact further above the shoreline. Inundation during several category 5 cyclones on the Western Australian coastline between 1998 and 2002 demonstrated run-up may add an extra 35 percent to surge elevation, and that erosion occurred to this level, not just that of the surge[121]. Central and southern parts of the GBR coast, where the outer reef is well offshore and waves are generally larger, are most vulnerable to these impacts under climate change scenarios.

21.4.4.3 Changed sediment supply

Where sediment supply is limited, sandy shorelines will erode during intense cyclones. However, where deposits exist to be mobilised by cyclonic waves and currents, they may be moved onshore, and a cyclone may be an accretionary event. It has been argued that beach ridges – an important geomorphological feature of sandy coasts inside the GBR – may form in this way[119] (section 21.2.4). If rainfall patterns are modified as predicted, sand supply to the coast may increase due to reduced vegetation cover and episodic but erosive rainfall events and floods. The dynamics of sediment availability and transport to the coast will vary with catchment physiography and hydrological response. If sufficient sediment accumulates inshore, a phase of coastal progradation may re-establish in some areas.

Siliciclastic sediments dominate mainland beaches inside the GBR. Carbonates are well represented on beaches behind some fringing reefs, but are still subordinate to siliciclastics. Where carbonates are a significant component, changes in the productivity of calcifying organisms may modify the supply of carbonate sediments. If projected increases in ocean acidification eventuate, continued supply of carbonate sediments to mainland beaches could be threatened. The most probable outcome for most mainland sandy beaches of reduced carbonate production is a slow decline in carbonate

representation and increase in the proportion of siliciclastics. Beaches with significant carbonate are generally located behind reefs and are relatively protected. Only minor changes in beach morphology would be expected because of changed sediment composition in these areas.

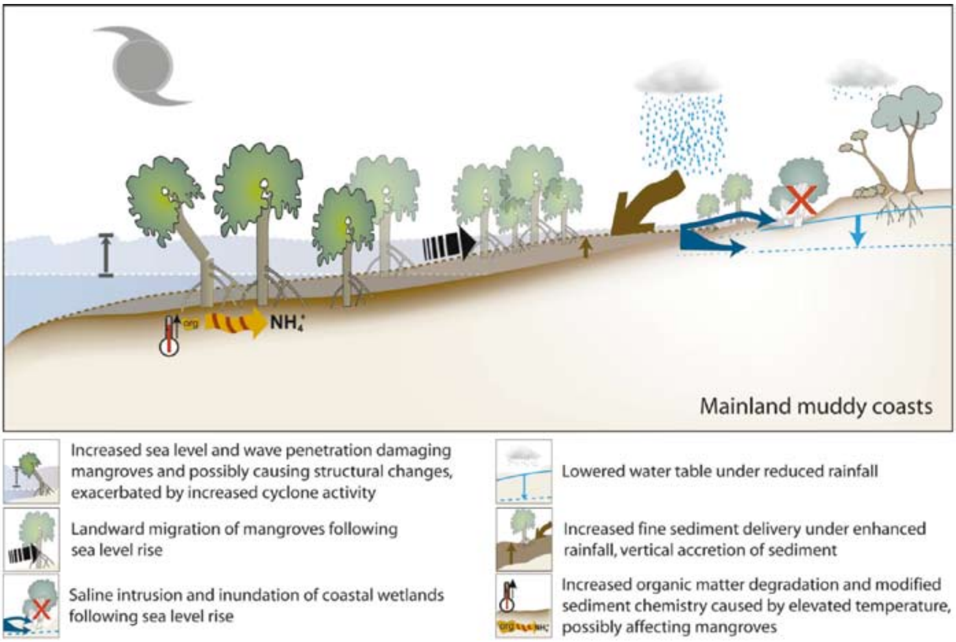
21.4.5 Mainland muddy coasts

Most mainland muddy coast inside the GBR occurs in north facing bays protected from the prevailing south-easterly winds. The geomorphology and potential impacts of climate change stressors are briefly outlined by Lovelock and Ellison (chapter 9), and are summarised in Table 21.6 and Figure 21.5.

***Table 21.6** Potential impacts of global climate change on muddy coastline geomorphology of the GBR*

Process(es) or Parameter(s) affected	Potential impact	Important factors
Rising sea level		
Water depth Inundation extent Sediment transport and deposition Water quality	Increased erosion and sedimentation Migration landward Altered vegetation cover	Response will vary depending on the relative rates of sea level rise and sedimentation, ground water conditions, tidal amplitude and mangrove vigour Late Holocene emergence on coast and significant progradation since mid-Holocene provides a buffer
Increased tropical cyclone activity and surge		
Wave climate and exposure	Increased erosion Saltwater inundation	Impact will vary with exposure, and degree stability or recovery affected by other climate change factors
Enhanced rainfall		
	Altered nutrient and sediment budgets Altered vegetation extent a nd coverage	Significant variation in present-day hydrological conditions in these systems between wet and dry tropics – may see shift in distributions. Dry tropics ecosystems more likely to be affected
Reduced rainfall		
	Reduced environmental flow – increased salinity Reduced sedimentation Altered vegetation coverage	Wet tropics systems more likely to be affected

Figure 21.5 *Key processes and potential impacts of predicted climate changes on the geomorphology of mainland muddy coasts*



21.4.5.1 Changed sediment supply and accretion

The ability of mangrove shorelines to maintain their current positions and geometries varies with mangrove stand composition and tidal range. Mangrove shoreline migration is a function of the rate of sediment accretion relative to the rate of sea level rise, with responses likely to reflect local sediment dynamics and to be highly site specific[165]. Ellison and Stoddart[43] suggested that modern mangroves would erode if sea level rose faster than 0.9 mm per year, but as indicated above, sediment supply and accumulation rates must also be considered. Muddy coasts near larger catchments are more likely to receive sediment supplies adequate to keep pace with projected sea level rise, but the supply of sediments to the inner GBR should not be limiting, with catchment yields argued to have increased five to ten fold over the last few centuries[103]. Sediment cores from Bowling Green Bay reveal a distinctive mercury horizon three metres down core associated with the onset of gold processing in the upper Burdekin catchment just over a century ago[157]. Recent research in southeastern Australia suggests that sedimentation accounts for less than 50 percent of surface elevation variability in some mangrove-salt marsh systems[133], but this work is yet to be replicated in tropical Australia.

21.4.5.2 Sea level rise

If sediment delivery is insufficient for vertical accretion to match sea level rise, mangrove communities and associated geomorphologic and ecological zones will probably migrate landward. Mangrove communities migrated rapidly landward as sea levels rose during the postglacial transgression[165], and continue to shift laterally where subsidence produces relative sea level rise today[134]. Along most of

the mainland muddy shorelines of the GBR this migration entails mangrove retreat over sediments deposited as late-Holocene sea levels have fallen. The landward advance of mangrove and associated wetlands would progress unless impeded by anthropogenic or topographic structures, in which case zones will become compressed and possibly lost. This process is referred to as 'coastal squeeze' where coastal defence structures restrict horizontal migration[117]. Topographic gradients on most mainland muddy coasts are gentle, and thus modest sea level rise can affect large areas.

21.4.5.3 Increased cyclone activity

Cyclones can have catastrophic and long-lasting impacts on mangrove communities and environments. Most of the muddy mainland coastline inside the GBR typically experiences low wave energy[82], but chenier sequences document a history of episodic cyclone strike and significant geomorphologic impacts[119]. Quantitative data on cyclone impacts on muddy coasts in northern Australia are rare[168]. The geomorphological impacts of Tropical Cyclone Althea, including the generally minor changes to muddy coasts were described by Hopley[67], but we are unaware of any research that has quantified the effects of individual cyclones on muddy coasts deposits on the GBR.

Observational accounts indicate that cyclone impacts can be patchy, but the emplacement of large cheniers several kilometres long shows that periodic disturbances and geomorphologic adjustments on a large scale do occur. However, the relationship between these deposits and storm history is poorly understood. Dated chenier sequences show that not all storms are recorded, possibly because shell beds that provide the sediments require adequate time to recover between events[19]. At Princess Charlotte Bay, this would appear to be around 80 years[21]. In contrast, coral shingle ridges at several locations on the GBR record severe storms with an average recurrence interval of around 200 years[61,120]. Given these frequencies, chenier plains should contain more cheniers than shingle ridge sequences contain ridges, but this is not the case. For example, the chenier plain at Cocoa Creek in Cleveland Bay contains eleven discrete cheniers but the shingle ridge sequence at Curacoa Island, around 75 km to the north, contains more than 20 discrete ridge units[61].

Mangroves play an important role in protecting coasts from high-energy events. However, as discussed for the other geomorphological features, the influence of more intense cyclones on these environments remains unclear. Recent category 5 Tropical Cyclone Larry did remarkably little damage to mangrove communities in Lugger Bay, reinforcing the earlier thesis that intensity is often not highly correlated with geomorphologic effectiveness. Tidal stage when a cyclone hits is probably the biggest factor influencing the geomorphological effect of cyclones at any location, with reduced effects if the cyclone arrives at lower tides. Storm duration, tide range and surge potential may also be important controls of the potential for geomorphological change, but this is yet to be determined.

21.5 Linkages

Where climate changes affect geomorphological features they will often be accompanied by ecological change, and in some instances, vice versa. Such linkages are too numerous to identify individually, and the details and significance of many are poorly known. Examples of several important linkages are outlined below.

Coral and framework loss will reduce habitat complexity and availability for many species, but as outlined in previous chapters these interactions are variable and multifaceted. There will be shifts in habitat, organisms and the rate and nature of carbonate produced. This will have flow through effects on rates of reef growth, growth fabrics, structural integrity and persistence.

Reduced reef growth and possibly increased destruction coincident with sea level rise may alter the wave climate within the GBR lagoon, potentially affecting the mainland coast. For example, ambient inshore wave energy may increase on open coasts as greater depth allows larger waves over the outer barrier, causing shoreline morphologies to change. Higher inshore energy may also affect water quality, with more resuspension and a wider distribution of turbid water than occurs at present.

Changed reef island dynamics will affect bird and turtle nesting success. This may be more complex than first envisaged. For example, increased mobility may reduce *Pisonia grandis* climax vegetation on many GBR cays. Loss of *Pisonia* would have serious implications for many birds, but other cays with rudimentary vegetation would still be important nesting sites (eg Michaelmas Cay). Reef islands with partially lithified shorelines may remain moderately stable if hydrodynamic, sedimentary and storm regimes change, but may lose unconsolidated beaches, with major implications for some nesting species. In contrast, unconsolidated cays may be highly mobile over reef platforms, but could maintain beaches suitable for nesting success.

21.6 Summary and recommendations

Climate changes will prove difficult if not catastrophic for many organisms on the GBR. However, major geomorphologic features have repeatedly survived large climate changes in the past, and will endure into the future, but possibly in a modified state. The history of the GBR (and other reefs globally) demonstrates a remarkable capacity for adaptation to significant change, driven both by external and internal factors. Many of the likely responses of geomorphological features on the GBR are not simplistic and require an understanding of geomorphological history and processes, which for many parts of the GBR is incomplete. Reefs grow, mature and may potentially enter a decay phase as part of a natural cycle on longer than ecological scales. An appreciation of where in this cycle a particular reef is, and how observed changes relate to this, is critical to effective documentation and management of climate change impacts.

At shorter time scales, the intrinsic capacity of many geomorphological features on the coast to adapt to changes in the physical environment will confer some resilience, but this may wane if poorly understood thresholds are crossed under sustained climate change pressure. The remarkable morphological diversity developed by the major geomorphological features within the GBR provides a significant buffer against catastrophic loss across the entire system. Nonetheless, parts of the GBR are vulnerable to global climate change not because of the changing climate alone, but because of additional stress factors – many of which relate to anthropogenic activities – that may lower the thresholds at which catastrophic change occurs. Some of these additional pressures, like reduced water quality, are local and regional issues that may be addressed by management at various government scales. Others, like ocean acidification, are global problems and will be far more challenging to overcome.

21.6.1 Key vulnerabilities to climate change

21.6.1.1 Coral reefs

Ecological assessments of the adaptive capacity of GBR reefs in previous chapters concluded that offshore reefs in the northern GBR are least vulnerable to climate change, and those inshore and further south will be most affected. Geomorphological adaptive capacity will mostly be determined by the capacity of reef communities to produce sufficient calcium carbonate, or at the very least, for existing calcium carbonate products to be preserved. How carbonate production will change as communities change, and the immediacy and impact of these changes on coral reef geomorphology will be highly variable. Insufficient knowledge exists to confidently predict outcomes for even the simplest systems. Sheppard et al.[139] showed that responses can be rapid, but the geomorphology of many senile reefs on the GBR has changed little for millennia[70,21]. It is also possible that some reefs will be less vulnerable to some impacts of climate change due to changes in other parameters. For example, nearshore turbid reefs may be less vulnerable to the damaging effects of UV penetration, and the critical effects of SST may be mitigated around the submerged shelf edge reefs that may actually be exposed to cooler water if upwelling strength increases as has been predicted[82].

21.6.1.2 Reef islands

Concerns that reef islands will disappear as climate changes are often based on misunderstandings of their morphodynamic sensitivity (relatively rapid morphological response to hydrodynamic and sediment supply conditions). Ironically, it is this sensitivity that confers on many GBR reef islands an intrinsic adaptive capacity to adjust to and often benefit from predicted climate changes. Reef islands will continue to move and be periodically removed by naturally variable climatic and sea level conditions, but it is likely that at least some GBR reef islands will, in the short term, adjust to rising sea levels, more intense cyclones, and modified rainfall regimes by getting larger and higher. This is especially so for reef islands on the inner GBR where relative sea level fell over the late Holocene, with sediments stored on emergent reef flats that may be mobilised and worked shorewards.

Many reef islands on the GBR are less vulnerable to climate change in the short term than popularly portrayed. However, variable responses will occur that largely reflect differences in reef platform elevation, sediment supply, and hydrodynamic setting, and thus regional patterns may be expressed. Definitive prediction of vulnerability requires a balanced assessment of i) antecedent buffers against negative impacts (eg residual sediment, lithification, platform emergence, vegetation), ii) the more immediate impacts of disturbances such as intense cyclones, and iii) the longer-term consequences of severely reduced new sediment production as a result of ocean acidification. Unvegetated cays on exposed reefs in areas of high tidal range are most vulnerable to sea level rise and will probably switch to an erosion phase at the lowest thresholds. Vegetated cays with lithified shores and interiors on emergent reefs platform are likely to be more resilient.

Insufficient data of adequate quality exist to systematically assess reef island vulnerability to climate-change stressors or their cumulative effects by 2100. However, all must be viewed as vulnerable if sea level rise continues beyond 2100 (expected even if climate is stabilised – Wigley's[161] 'sea level commitment'), or if extreme and rapid sea level rise occurs as may transpire, for example, if the West

Antarctic Ice Sheet melts[123]. Predicted rates of sea level rise are lower than rates during the postglacial transgression, but are considerably higher than historical rates[60]. Houghton et al.[83] calculated that predicted rates of sea level rise are 2.2 to 4.4 times that of the global average for the last century.

21.6.1.3 High island beaches and spits

Spits and high island beaches will adjust to the impacts of climate-change stressors, with both environments changing little. Some beaches and spits may become more mobile and dynamic, and higher but narrower. Backing dunes may be lost, reducing storm erosion buffer and beach amenity, but neither environment is particularly vulnerable to large modification.

21.6.1.4 Mainland sandy coasts

An important difference between the erosion impacts of tropical cyclones on tide-dominated beaches inside the GBR and storm impacts on wave-dominated beaches is that higher ambient energy levels enable the latter to recover relatively rapidly to an equilibrium or stable profile. In low energy settings recovery can be prolonged, and geomorphological changes caused by extreme events can persist for many years. Scarped beach ridges near Pallarenda (north of Townsville) produced during Tropical Cyclone Althea (category 3) in 1971 are still visible. If intense tropical cyclones become more frequent, the prospects for full geomorphologic recovery or achievement of a stable 'equilibrium morphology' between events is increasingly unlikely. Thus although morphodynamic adjustments of beach form to prevailing energy conditions provides some basis for adaptive capacity under future climate change scenarios, where extreme events do significant geomorphologic work and ambient energy conditions are inadequate to achieve a readjustment, the geomorphological condition of some sandy coasts may in the future reflect extreme events more than they do at present.

21.6.1.5 Mainland muddy coasts

The almost exclusive occurrence of mainland muddy coasts in protected north facing embayments and the low gradient topography they commonly develop makes them especially vulnerable to the more frequent occurrence of high intensity cyclones and, where accretion rates are low, to sea level rise. As discussed by Lovelock and Ellison (chapter 9), mangroves and other plants play an important role in protecting these normally low-energy environments from destructive storms, how these communities respond to climate change, and to modified disturbance and recovery regimes is not yet resolved. Any destabilisation of vegetation communities is likely to also affect geomorphological stability.

Muddy coasts adjacent to smaller catchments or those, perhaps ironically, not affected by anthropogenically elevated yields of terrestrial sediment, are most likely to receive insufficient sediment supply for vertical accretion rates to match sea level rise. Where accretion lags behind sea level rise shoreline translation will occur, potentially affecting important wetlands (including saline flats) at the rear of many of these systems. Changes in rainfall associated with climate change may put further pressure on these environments.

21.6.2 Potential management responses

This and other chapters have identified the particular vulnerabilities of the GBR to climate change. A common conclusion is that climate changes have happened in the past and that reefs have survived, but never before have they occurred in conjunction with a range of additional anthropogenic stressors that now also affect many reefs. It cannot be assumed that the GBR will survive these combined stresses as it has survived the impacts of previous climate change episodes. As indicated in section 21.6, some of the major effects and impacts of global climate change on the GBR, for example increased SST and ocean acidification, are global and require international intergovernmental co-operation and agreements to fully address. Given current intransigence by key governments, including Australia's, such agreements are unlikely to be achieved in the near future. Nonetheless, a range of management responses could be more quickly implemented for positive benefit. These include:

i) Reduce additional anthropogenic pressures – management strategies aimed at relieving additional pressures such as overfishing and degraded water quality may improve resilience to climate change impacts. Some anthropogenic impacts may mitigate climate change effects (for example, increased turbidity due to sediment runoff may reduce the potential impacts of elevated ultraviolet exposure), and these interactions should be fully investigated.

ii) Intervention to protect critical geomorphological features – critical habitats may be protected or managed actively. For example, important nesting beaches may be artificially renourished, or groynes may be used to influence hydrodynamics to either reduce erosion or direct deposition. A variety of engineering options, both 'hard' and 'soft' are available to treat coastal issues in other environments, and these may be evaluated for critical management locations.

iii) Continued research to address knowledge gaps, more effectively predict future changes, and to assess their geomorphological, ecological and other significance. This is essential if scant resources are to be effectively assigned to systematically prioritised issues where enduring satisfactory outcomes can be achieved.

21.6.3 Future research

Knowledge gaps remain which limit capacity to predict the response of major geomorphological features to climate change. Conceptual models exist that link critical ecological, physical and geomorphological factors and processes, but these linkages have rarely been quantified and many of the basics remain unclear. Major knowledge gaps and priority areas for future geomorphological research include:

- Sediment budgets and links to landforms and processes in contemporary settings are poorly constrained, hindering modelling of future responses. This is true for environments reliant on biogenic and siliciclastic sediments.
- Palaeohistories are incompletely known, with relatively poor geographic and temporal coverage. High priority investigations to inform predictions of possible future responses include: i) establishing accurate palaeohistories of storm occurrence from a wider area of the GBR, ii) more and more detailed reconstructions of previous geomorphological response to sea level change, and different storm, hydrodynamic and climate regimes, and iii) more widespread and detailed histories of island accretion and dynamics.

- Bathymetric and topographic control is poor for many parts of the GBR. The paucity of high quality topographic data and geomorphological mapping means that valuable baseline information is commonly not available. Where it does exist, basic spatial data is often inadequate for sophisticated numerical modelling of geomorphic change under various climate change scenarios.
- The morphodynamic behaviour of many geomorphological features is poorly understood, particularly with respect to the quantification of natural variability, sensitivity to different physical, biological and chemical forcing functions, and thus potential thresholds for change. Understanding the nature of thresholds at which geomorphological features in the GBR will switch from accretion to erosion, or will have modified stability, is critical to their effective management. The significance of spatial variations in geomorphological sensitivity and vulnerability to the effective management of critical organisms dependent on geomorphological services should be systematically addressed.
- Identification of most appropriate sites for conservation management based on geomorphological history and growth trajectories (ie reefs at juvenile and mature stages with greatest structural complexity and habitat diversity), and most geomorphologically resilient to predicted climate change impacts.

A critical issue related to the preceding point is whether the intrinsic variability observed for most geomorphological features will remain and continue to satisfy ecosystem demands that can no longer be serviced on modified features. For example, if rising sea levels erode beaches and expose beach rock that is unsuitable for turtle nesting on some cays, will enough sandy cays or beaches remain to accommodate this displaced nesting effort? Although particular changes will be catastrophic for certain organisms, some geomorphological features and organisms will also undoubtedly benefit. Resolution of this issue, with an understanding of spatial and temporal variations these responses, is critical if limited management resources are to be effectively directed.

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