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Critical Thresholds and the Vulnerability of Australian Tropical Coastal Ecosystems to the Impacts of Climate Change

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ABSTRACT

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Paleoenvironmental studies of tropical coastal ecosystems in northern Australia indicate past responses to sea-level changes, implying geomorphological resilience in the face of future sea-level rise. However, there are several critical thresholds beyond which abrupt change appears inevitable. Elevated temperatures have recently caused extensive coral bleaching and reefs appear threatened if the thermal tolerance of corals is exceeded. Many reef islands have accumulated on reef platforms under stable or falling sea level. Continued accretion seems likely under gradual sea-level rise, but may no longer be sustainable if the sea drowns the reef platform on which they have formed. Similarly, broad mangrove-fringed plains have prograded under stable sea level, predisposing them to inundation if sea level continues to rise rapidly. The resilience of coastal ecosystems is also threatened by the synergistic interaction with several other pressures.

ADDITIONAL INDEX WORDS: *Coral reefs, Mangroves, Sea-level rise, Climate variability*

INTRODUCTION

Climate change will have disproportionately large impacts on coasts. Sea-level rise has been the major concern, but there remains much uncertainty about global rates and regional and local factors such as crustal flexure, subsidence and compaction. Recently, other climate drivers, including sea-surface temperature (SST) and intensified storms, have also received attention because of the impacts they will have on coastal systems.

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. Vulnerability assessments have often emphasised the impacts that climate change will have on people, but metrics that assess vulnerability of coasts in terms of human costs are rarely appropriate for sparsely inhabited tropical coastlines. The response of tropical coastal ecosystems is frequently modelled simplistically; for example, identifying future shorelines using present-day contours as if the dynamic coastal landscapes will remain unaltered. In Australia, coral reefs, particularly the Great Barrier Reef (GBR), and coastal and freshwater wetlands (including the Kakadu World Heritage Area) have been recognised as particularly vulnerable.

This paper explores the resilience of these natural tropical systems, based on geomorphological investigations of past behaviour, and identifies critical thresholds beyond which abrupt change may occur in response to future climates and sea levels. Long-term threats to coral reefs, reef islands and mangrove shorelines with their associated wetlands, are described using paleoenvironmental reconstructions to infer where natural adaptive capacity may be exceeded.

CORAL REEFS AND THERMAL STRESS

Global warming threatens coral reefs as temperatures exceed the thermal tolerance of corals, resulting in expulsion of the symbiotic algae (zooxanthellae) and paling of the coral surface (HOEGH-GULDBERG, 2005). Coral bleaching occurs when SST exceeds ~1° C above the seasonal monthly maximum. Corals may recover, but if SST remains at these high levels for prolonged periods, or exceeds 2° C above the threshold, coral mortality is likely. Considerable variability occurs in both time and space because different corals have different susceptibilities and recoveries, with local effects such as reduced bleaching at greater water depths. Widespread bleaching occurred in 1998 and 2005, the two hottest years on record. Bleaching on an unprecedented scale occurred in the Indian Ocean in 1998; bleaching occurred on much of the GBR in 2002, and reefs in the Caribbean were widely affected in 2005, although many were already in decline as a result of the effects of multiple stresses (MCWILLIAMS *et al*., 2005).

Modelling implies that threshold temperatures at which corals bleach will be exceeded more often in the future, with recurrent bleaching at frequencies that reefs cannot sustain (HOEGH-GULDBERG, 2005; DONNER *et al*., 2005). Whether corals are able to adapt or acclimatise has been hotly debated (Figure 1). There is limited ecological and genetic evidence for adaptation of corals to warmer conditions (LITTLE *et al*., 2004). Changes have been recorded in the combination of coral host and symbiotic algae, creating ‘new’ ecospecies with more temperature-tolerant algae. One clade of symbiotic algae, *Symbiodinium* D, has been shown to be particularly thermotolerant and coral may shuffle algal symbionts, thereby improving thermotolerance.

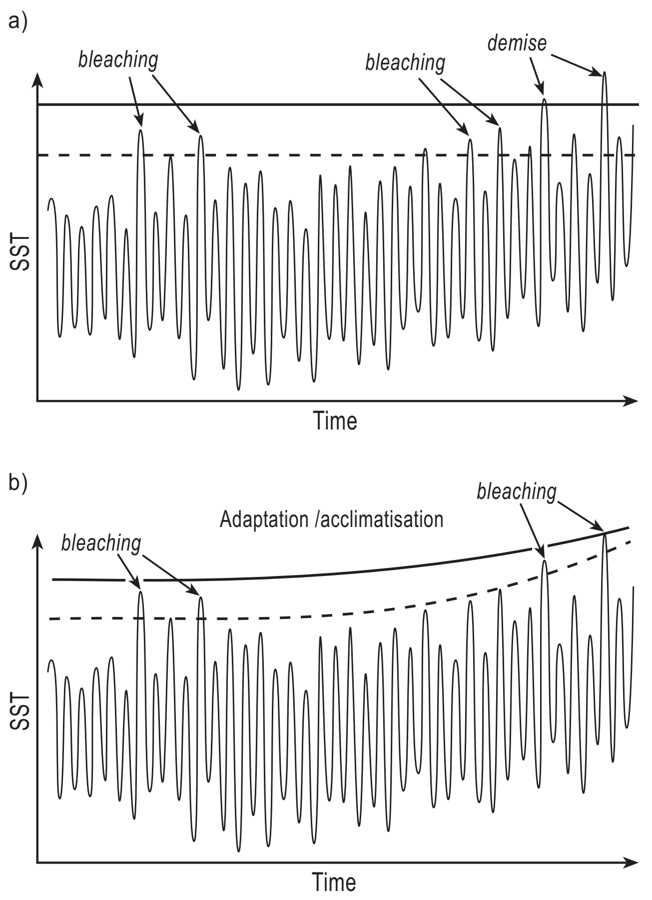

Figure 1. Response of corals to SST threshold: a) invariant SST threshold for bleaching (dashed line) and mortality (solid line); b) elevated thresholds if corals adapt or acclimatise to increased SST (based on HUGHES *et al.*, 2003).

The paleoenvironmental record does not appear to record former recurrent bleaching episodes, although past temperature fluctuations can be detected using geochemical analyses of coral skeleton. However, the future ability of reefs to absorb impacts due to climate change, and to recover, depends upon the extent to which they are already degraded and their resilience undermined, as well as timing between events.

Additional threats to coral reefs include ocean acidification, sea-level rise and the effects of storms. The concentration of CO_2 in the ocean is increasing, although lagging behind atmospheric CO_2 because of mixing, and this will result in a fall in pH leading to decreased calcification in several major groups of organisms, weakening corals to erosion (KLEYPAS *et al*., 1999). In addition to these climate impacts, many coral reefs have deteriorated as a result of the synergistic effects of various others pressures, particularly human impacts such as overfishing and pollution from adjacent land-masses (HUGHES *et al.*, 2003).

REEFS, REEF ISLANDS AND SEA LEVEL

The response of reefs to sea-level change has received particular attention through stratigraphic and radiometric dating studies of the Holocene evolution of reefs (NEUMANN and MACINTYRE, 1985), and can be broadly categorised into the responses shown in Figure 2. Although individual corals can grow at rates of 10 mm a^{-1} to 100 mm a^{-1}, reef growth occurs more slowly, in the range 1-10 mm a^{-1}. If rates of sea-level rise are very rapid, the reef is drowned. At slightly slower rates the reef backsteps. If rates of sea-level rise decelerate, the reef can catch up with sea level and if the rate of rise is similar to, or less than, the rate of reef growth a reef can keep up with sea level. If sea level is stable the reef progrades, building a broad horizontal reef platform as has occurred over much of the GBR. An emergent reef flat is formed if there is a relative fall of sea level, as is common on many Indo-Pacific reefs (DICKINSON, 2004). These various sea-level and reef-growth scenarios illustrate the range of responses that reef morphology can show to variations in the rate of sea-level change. Sea-level rise appears unlikely to threaten reefs in the immediate term and might even result in recolonisation of Indo-Pacific reef flats by corals as these presently less productive surfaces become available for coral growth (HOPLEY, 1993). However, a rise in sea level does seem likely to have implications for the low-lying reef islands on top of reef platforms and the people who live on them.

Islands throughout the Indo-Pacific appear to have formed as a result of deposition of sediment over the late Holocene, with onset of deposition on many islands triggered by a slight relative fall of sea level (DICKINSON, 2004). Most reef islands form when reefs are in the ‘mature’ stage of geomorphological development, when lagoons are largely infilled and sediment-covered reef flats have developed. Future sea-level rise may have several effects over such reef flats. Increased wave activity may mobilise more sediment, moving it towards existing reef islands (HOPLEY, 1993). Increased wave run-up might build higher beach crests. Alternatively, increased wave energy across the reef flat, especially following disintegration of degraded reefs after bleaching, may induce shoreline erosion (SHEPPARD *et al*., 2005). Erosion of islands is predicted by application of the Bruun rule and using a modified shoreline translation model (KENCH and COWELL, 2001), but such equilibrium models are not designed for application on reefs where the lower shoreface is a solid reef flat.

Figure 3 implies a sea-level threshold in reef-island response. Individual reef platforms differ in terms of their vulnerability to erosional forces, depending on the degree of emergence of the reef platform and the resilience of the island. Emergence is widespread on reefs in the Indo-Pacific region. It has led to formation of a conglomerate that acts as an anchor on which islands sit, and a site-specific sea-level threshold beyond which islands will experience net erosion. Partially lithified islands on emergent reefs, such as those near the mainland coast on the GBR will not experience the same degree of erosion as unconsolidated islands on reefs presently at sea level, or those incipient cays formed on reefs that are in catch-up mode and have not yet reached sea level.

Reef flats may be recolonised by coral and undergo further keep-up growth, but reef islands do not seem to have kept pace with rapid sea-level rise. That islands can form under gradual rates of sea-level rise is clear from the occurrence of sand cays on Caribbean reefs where the sea has been rising at a decelerating rate over past millennia. However, there is no paleoenvironmental record of islands persisting under rapid rates of sea-level rise. It seems likely that there is a threshold, beyond which reef islands may experience more frequent overtopping and may be less desirable places to live than they have been while sea level has been falling or stable.

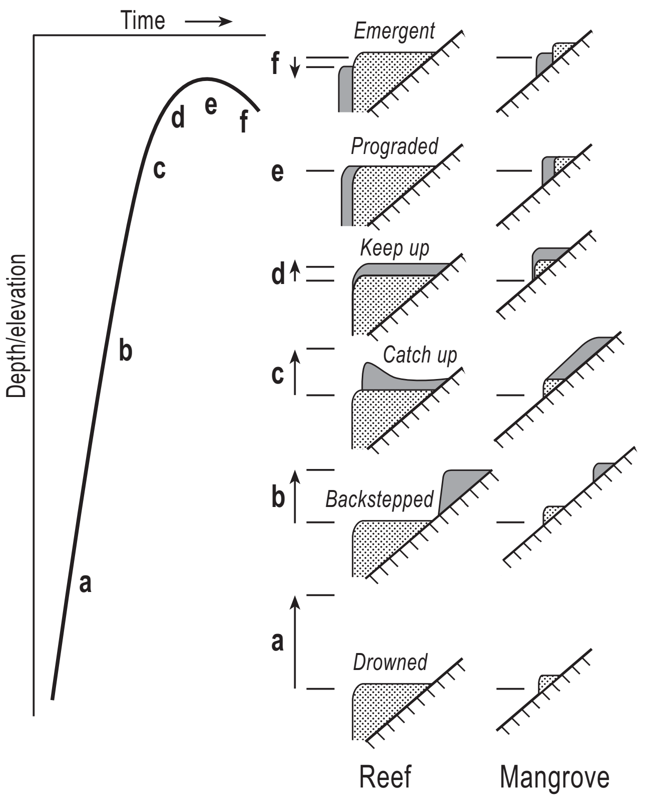

Figure 2. Response of reefs and mangrove shorelines to variations in Holocene sea-level change.

Geomorphological investigation of reef islands indicates that they are more resilient than is generally recognised, having formed in various situations under a range of conditions (WOODROFFE *et al*., 1999; KENCH *et al*., 2005). For example, sand cays persist under varying wave conditions and even unvegetated islands have a capacity to persist over time. Islands vary from unvegetated sand cays (more than 70% of islands on the GBR, particularly north of Cairns), to vegetated cays, to the more complex low-wooded islands, where much of the reef flat contains shingle storm ridges with mangrove forests in their lee. Different islands can be anticipated to differ in their resilience. Vegetation gives greater resilience, whereas lithification, whether beachrock, cay sandstone, phosphate rock or conglomerate platform, increases resistance. Islands are spatially heterogenous and the degree of lithification varies around the shoreline. There will also be different behaviour according to tidal range, the surface of the platform (whether it contains shingle ridges and/or mangrove vegetation as on the low-wooded islands of the GBR), as well as size and shelter of individual platforms and the frequency and intensity of extreme events (and human factors). Clearly much more research is needed on the processes that operate on these platform reefs (and atolls) to understand the quasi-equilibrium that has been possible for more than 3000 years and their morphological persistence. If sea-level fall provided the conditions for islands to begin to accumulate, even though it is not the same set of processes in reverse, it seems likely that each island may have an individual threshold beyond which it will change from accretion to erosion and perhaps a further threshold sea level beyond which it cannot persist.

MANGROVE-FRINGED PLAINS

The modern morphology and stratigraphy of wetlands associated with mangrove-lined coasts of northern Australia is known in greatest detail for the Alligator Rivers region, and the adjacent Mary River wetlands (WOODROFFE *et al*., 1993). Drilling, radiocarbon dating and pollen analysis indicate that a series of valleys draining north to van Diemen Gulf were inundated by the rising sea around 8000 years BP after which these macrotidal estuaries and the plains that flank them infilled rapidly with organic-rich muds. Since a ‘big swamp’ phase around 6000 years ago, mangrove forests in the Top End have been replaced by broad grass-sedgelands and the coastal plain has built seaward several kilometres. Saline mudflats dominate similar plains in semiarid areas (Western Australia), whereas forested wetlands occur in more humid areas (northeastern Queensland or the peat swamp forests of southeast Asia). Tidal flows are largely restricted to channels between muddy levees, although the plains are inundated by rain and freshwater runoff during the wet season. Numerous paleochannels record the former positions of tidal river courses,

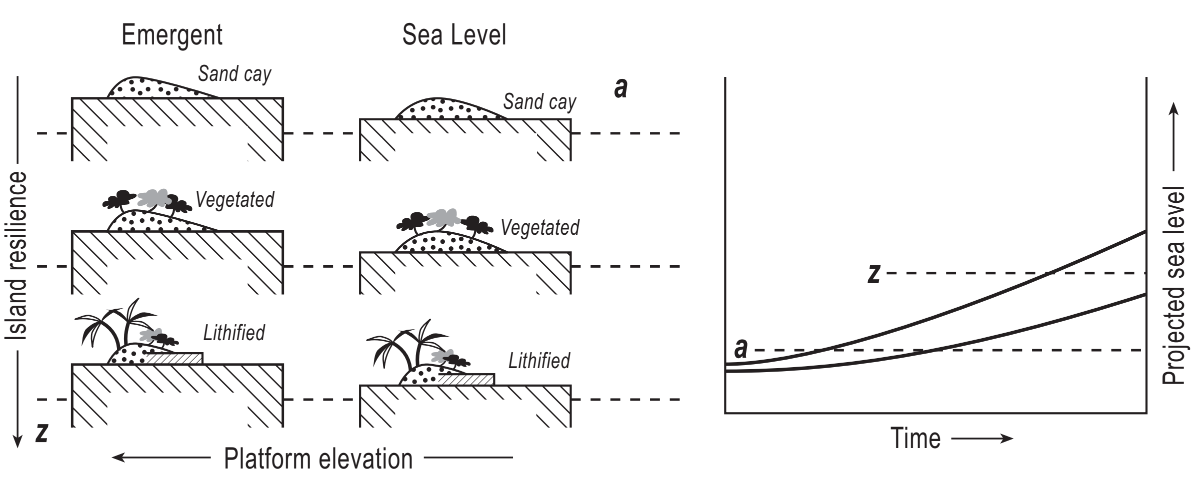

Figure 3. Variations in platform emergence and island resilience, and threshold sea levels beyond which individual islands are threatened

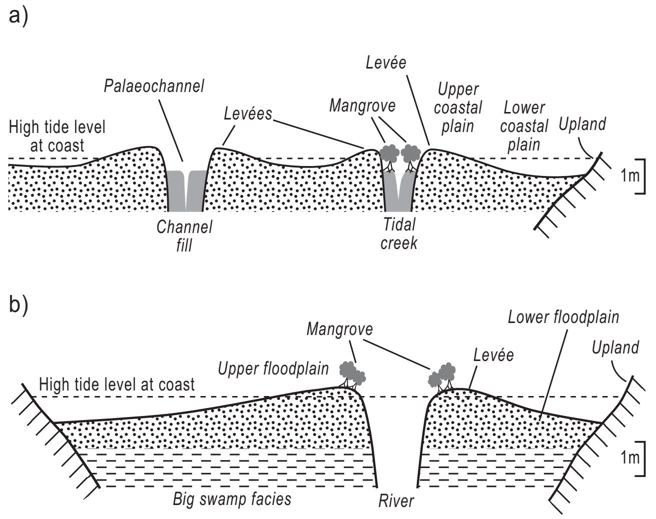

Figure 4. Typical topography across coastal plains of the Mary River (above) and estuarine plains of the Alligator Rivers (below).

many now abandoned and infilled (WOODROFFE, 1993).

Considerable areas of these plains are presently below the level reached by the highest tides at the coast (Figure 4). Several studies have documented patterns of change in tidal creeks with extension of new creeks into freshwater wetlands. The most spectacular of these has been on the Mary River where two creek systems, Sampan and Tommycut have increased exponentially, commencing since the 1940s, destroying vast areas of paperbark forest (KNIGHTON *et al*., 1991). These creeks, and similar though smaller creeks on the Alligator Rivers, have preferentially exploited lower-lying ground, particularly incompletely-infilled paleochannels (Figure 4). The cause of the onset of tidal creek expansion has not been determined unequivocally. Initial incursion coincided with feral buffalo populations and buffalo swim channels were implicated. Recently, following elimination of the buffalo, it has more frequently been contended that this might be a consequence of sea-level rise (WINN *et al*., 2006).

Whatever the cause, a paleoenvironmental legacy is clear. This can be seen in Figure 5 which shows that two creeks, Tommycut (T) and Sampan (S), have connected into paleochannels, and have undergone rapid extension, whereas a very similar unnamed creek (U) has undergone little change over the same period. Present, and future, behaviour is conditioned by contingent events in the past, such as paleochannel location. Increased tidal prism under sea-level rise will upset the relative balance of tidal flows in comparison with fluvial flows, implying that the estuarine sections of channels may enlarge (WOLANSKI and CHAPPELL, 1996). The natural system may have some ability to deposit sediments to maintain a tidal channel, but there appears an inevitable threshold beyond which wide-scale inundation of the plains by tidal flows will occur. The progradation of broad plains over the past 6000 years has preconditioned the area such that too rapid or too sustained a sea-level rise will result in saline incursion on a much broader scale than that presently observed.

Paleoecological studies indicate that mangrove systems can ‘keep up’ with sea-level rates of several millimetres a year, if there is available sediment and space for them to colonise (Figure 2). Mangrove forests colonised more landward environments as the sea rose. A constraint on future landward encroachment of mangrove (and other intertidal systems), commonly experienced in densely-populated regions, is that hinterland is inhabited, and protected, so that wetland loss occurs through coastal squeeze. The northern Australian situation is different; mangrove environments are separated from the bedrock hinterland by broad progradational plains. Some adjustment by the system is likely in future, and the fact that most tidal flows are accommodated within tidal river and creek banks implies a morphological equilibrium. If the sea rises, this system will demonstrate some natural resilience. However, there appears to be a threshold, already surpassed for the Mary River system, where tidal incursion into paleochannels triggers an exponential expansion of creek networks. The paleochannels provide a legacy and preconditioned the present-day landscape. Future tidal systems may inherit patterns from the past, as have the expanding networks of recent decades. Large areas are presently at elevations that make them susceptible. Individual breaches present single creeks with the opportunity to exploit the most vulnerable of the low-lying wetlands. A much more major and widespread threshold would be crossed if sea level rose to the extent that it overtopped the levee height along extensive parts of several adjoining systems. If sea level rises at faster rates than present, saline intrusion may be exacerbated and the pattern of creek expansion, already occurring in some places, may be seen more widely. Efforts to thwart creek expansion have proved difficult, although a considerable amount of local wisdom has been acquired where this has been attempted.

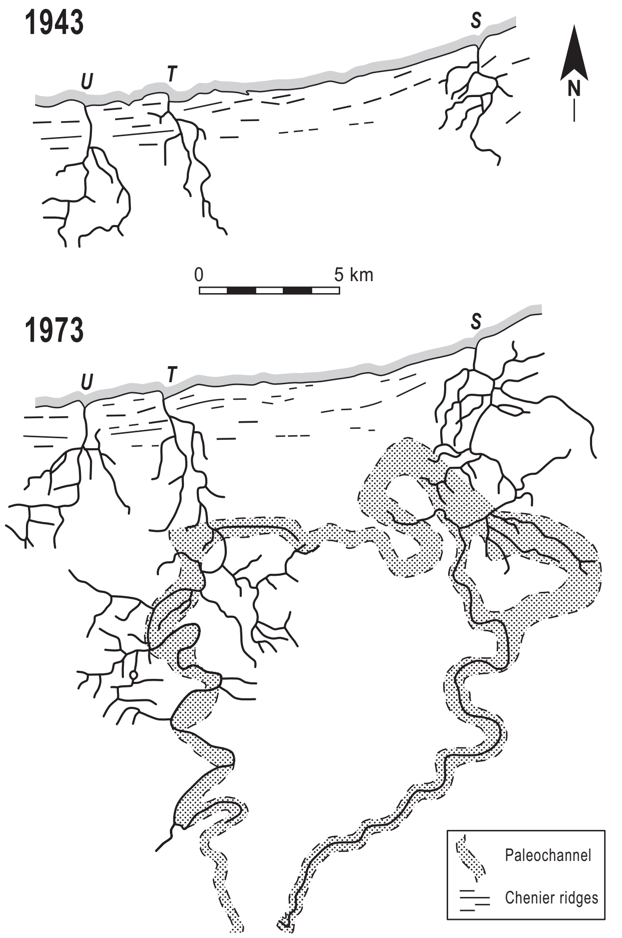

Figure 5. Rapid tidal creek expansion on the Mary River plains (after MULRENNAN and WOODROFFE, 1998).

CONCLUSIONS

Tropical coastal ecosystems show geomorphological resilience. They survived the vicissitudes of past glacial/interglacial cycles during which sea level varied through more than 100 m of vertical range and shorelines migrated 100s of kilometres. Their response to key environmental factors is often portrayed as a simple linear response to one factor, but responses are often multidimensional and non-linear. Paleoenvironmental records indicate considerable natural adaptive capacity; however, key thresholds exist beyond which the systems will abruptly alter their behaviour and they are threatened by the synergistic interaction of several factors.

Rising temperatures (SSTs) are already stressing corals, leading to bleaching and death. Bleaching has occurred on many reefs in the past, but recurrent bleaching episodes are not detectable in the fossil record using geochemical proxies. Current thermal limits for coral bleaching are forecast to be exceeded on many reefs in coming decades, with further reduction in both coral cover and diversity. The extent to which thermal thresholds might increase through adaptation or acclimatisation remains very uncertain. Tropical and subtropical reefs will remain in an early successional state or shift to communities dominated by organisms such as macroalgae. This will be exacerbated by additional stresses (such as reduced water quality and over-exploitation of key species) unless ecological resilience of reefs is better managed.

Sea-level rise seems unlikely to threaten corals, and may enable corals to recolonise emergent reef flats, which may provide both protection and a source of additional sediment. However, islands may only be stable until a threshold sea level is surpassed. Inundation of these reef platforms is not directly analogous to postglacial transgression, and understanding of the re-establishment of coral over reef platforms, or the sensitivities of island shorelines under rapidly rising sea level, is incomplete.

Postglacial sea-level rise caused mangrove ecosystems to migrate landwards. Mangroves can generally cope with moderate rates of sea-level rise, depositing both inorganic and organic sediment. Mangrove forests along prograded coasts are now at the seaward margin of broad progradational plains, and future accelerated sea-level rise will involve inundation of this Holocene sediment wedge, in contrast to postglacial transgression. There is much scope for more refined interpretation of paleo-environmental changes in order to discriminate natural changes and determine how rapidly accretion can occur. Paleoenvironmental study of these systems demonstrates their geomorphological resilience and their natural adaptive capacity, but evolution under stable, or falling, sea-level has predisposed them to abrupt changes should SST or sea level accelerate, and cross these critical thresholds.

The ecological consequences, should reefs bleach, reef islands be overtopped, and widespread tidal inundation of coastal plains eventuate, include lost revenue from tourism. However, still more vulnerable are similar reefs and low-lying coastal and deltaic plains of Southeast Asia. These support vast populations, in terms of fisheries, agricultural and aquacultural production and also some of the most rapidly expanding megacities in the world.

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