Coastal erosion and inundation due to climate change in the Pacific and East Timor

Synthesis report

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1 Executive summary

It is generally accepted that coastal margins and associated communities, particularly in low-lying atoll island states and river delta regions on some of the high islands in the Pacific region (including East Timor), will be particularly vulnerable to the impacts of climate change and sea-level rise. The fundamental physical aspects underpinning coastal-related vulnerabilities relate to land, water resource and food security issues, primarily due to potentially permanent erosion of the shoreline and loss of land, permanent inundation and increased frequency, magnitude and extent of episodic inundation of low-lying land areas, saline intrusion into freshwater groundwater lenses, and loss or reduction in coral reef biodiversity and productivity.

The magnitude of the inundation and shoreline changes and impacts that will be caused by climate change, including sea-level rise on Pacific coastal margins, will occur at a range of space and timescales, and vary between islands and different locations on islands. Such impacts will depend on:

- the complex interaction between the local physical drivers (waves and water-levels and in some cases river/stream outlets) that shape island shorelines and the impacts of climate change on these drivers
- how these drivers interact with the existing morphology and current biophysical characteristics
- rates of vertical land movement (as it is relative sea-level rise that needs to be adapted to at the local level, not the absolute global sea-level rise)
- sediment composition and balance between sediment inputs and losses on a particular coast
- the influence that humans have had or are having on the coast.

The effects of climate change on coastal inundation and change in the Pacific region and East Timor is likely to be felt first (and possibly most significantly) through possible changes in the impacts of episodic extreme weather events. Primarily changes in such impacts will be caused by:

- the gradual exacerbation of the effect of these events by sea-level rise (which raises the platform for dynamic wave and storm-tide processes to operate)
- potential ecological changes through temperature related and ocean acidification stressors, reducing the natural resilience and protection services provided by coastal ecosystems
- ongoing local human impacts such as nutrient run-off and overfishing on coral reef ecosystems, again impacting on the natural resilience and protection services provided by coastal ecosystems.

In the longer term, further changes in impacts could arise from climate change effects potentially altering the characteristics of these extreme events (e.g., storm frequency, seasonality and intensity).

Coastal inundation

Over the last decade, there have been increased reports of higher sea levels and subsequent coastal inundation episodes throughout the region. These can mostly be attributable to sea-level fluctuations arising from interannual cycles (e.g., El Niño Southern Oscillation or ENSO) and coinciding interdecadal cycles (e.g., Interdecadal Pacific Oscillation or IPO), whereas ongoing sea-level rise appears to have played a secondary role in these occurrences. In spite of climate variability being the primary cause of these recent events, what this pattern does indicate is that for many Pacific communities, settlements and infrastructure, even a few 10s of centimetres change in sea level is having an increasing effect on the frequency or magnitude of wave overtopping and episodic inundation of immediate coastal margins upon which present-day communities and associated infrastructure are now located. Such inundation effects from climate variability will only be compounded as sea-level rise accelerates during this century.

Changes in vulnerability to inundation for Pacific island communities are not only caused by changes in the occurrence or magnitude of inundation but are also due to economic and social changes. In many parts of the Pacific, vulnerability is also driven by population pressures, internal migration and high levels of urban sprawl in and around island capitals increasingly spreading into traditionally less populated locations or islands. These more recently developed locations are often more exposed to coastal-related hazards such as inundation than where the traditional or original settlements were established. Where vulnerability to coastal inundation has substantially increased in recent decades, it is in many cases primarily due to human-related land modification and development changes that are fundamental in driving this increasing vulnerability rather than simply a change in the hazard characteristics due to climate change and sea-level rise.

Despite this, the influence of the ongoing rise in relative sea-level rise, including vertical land movement, will increasingly become a fundamental driver changing the frequency, extent and magnitude of coastal inundation, and hence increased vulnerability to inundation in the future. However, over the near to mid-term (next 30–50 years), ENSO and IPO-related sea-level fluctuations will continue to play a major role in causing year-to-year and decade-to-decade variability in the magnitude and frequency of coastal inundation events. If historical patterns in the 20–30 year IPO cycle continue, it is possible that the heightened frequency of coastal inundation events experienced since 2000 may not change significantly, or only gradually, in the next few decades. It may not be towards the mid-part of this century, when the IPO next switches to a cool phase (as is being experienced at present), that significant changes to inundation occurrence will be more obviously attributable to ongoing sea-level rise.

Shoreline change

From most countries in the Pacific region there are many anecdotal reports that sea-level rise is already causing significant erosion and loss of land. On many ocean-side beaches there is near universal, but often ephemeral, evidence of erosion including beach scarps, undercutting of vegetation and coconut palms, and outcrops of beach rock that have become uncovered by shoreline changes. However, there is less reported evidence of erosion translating into a general net reduction in island area under sea-level rise rates experienced over the second half of the last century up to present. This reflects that sea-level rise is only one component that influences coastal change and that often erosion at one location tends to result in accretion at other locations.

Where significant erosion or loss of land does occur, it is often due to a particular storm event or a series or clustering of events, or a much more complex interaction of processes including episodic events, annual, interannual or interdecadal variations in sea levels and wave conditions, sea-level rise and anthropogenic impacts.

Despite shoreline change being a major concern to the Pacific region, there are few well-documented examples that have quantified the shoreline changes occurring, and fewer examples still that have attempted to assess the key drivers and driver interactions causing both past and potential future shoreline change.

The most significant coastal changes are likely to occur in river deltas and areas where shorelines are strongly influenced by river flows and fluvial sediment supply. Such areas will be particularly sensitive to a range of climate change impacts. Given the high population densities found in delta areas, this may become an early and significant socio-economic issue where there is little option but for communities and infrastructure to be relocated.

It is suggested that reef landforms have a greater degree of resilience than is commonly assumed, at least in the near- to mid-term (30–50 years). They will continue to undergo modification and change, which will vary from place to place and include combinations of both horizontal (profile) changes and 'longshore' or 'planform' changes. The sensitivity of reef islands and shorelines to change will depend on the interactions between a complex set of factors including coastal accommodation space (the area over which shorelines are free to flex), the present characteristics of coastal processes and sources and losses of coastal sediments, as well as global climate change and human impacts.

Whether global climate change and sea-level rise in the longer term (towards the end of the century and beyond) will result in environmental thresholds beyond which reef landform change becomes unstable or untenable for communities living there is less well understood. There is some suggestion of a sea-level threshold, based on the mid-Holocene sea-level 'highstand' and emergent levels of conglomerate platform, beyond which the extent of erosion may make many islands uninhabitable. For a high rate of sea-level rise over this century this threshold could be surpassed in the latter part of this century (2050–2080) and for a lower sea-level rise rate by early next century (2100–2160).

The impacts on the ecological functioning of reef carbonate systems caused by increasing sea-surface temperature, ocean acidification and ongoing local human impacts such as overfishing and nutrient run-off may result in other environmental thresholds being surpassed earlier than those associated with sea-level rise. Over this century, such ecological impacts may result in a much more significant impact on both the stability of shorelines and reef landforms, and the overall viability of communities located upon them, than sea-level rise.

2 Introduction

2.1 Overview of this report

It is generally accepted that the coastal margins and associated communities of Pacific islands, especially low-lying atoll island states, will be particularly vulnerable to the impacts of climate change and sea-level rise. The fundamental physical aspects underpinning coastal-related vulnerabilities relate to land, water resource and food security issues, primarily due to potentially permanent erosion of the shoreline and loss of land, permanent inundation of the lowest fringes and increased frequency, magnitude and extent of episodic inundation of adjacent low-lying areas, saline intrusion into freshwater groundwater lenses, and loss or reduction in coral reef biodiversity and productivity (Kench & Cowell, 2001).

The magnitude of the inundation and shoreline changes and impacts that will be caused by climate change and sea-level rise on Pacific coastal margins will occur at a range of space and timescales, and vary between islands and different locations on islands. Such impacts will depend on:

- the complex interaction between the local physical drivers (waves and water-levels) that shape island shorelines and the impacts of climate change on these drivers
- how these drivers interact with the existing morphology and current bio-geomorphological characteristics
- rates of vertical land movement (as it is relative sea-level rise that needs to be adapted to at the local level, not the absolute global sea-level rise)
- sediment types and balance between sediment inputs and losses on a particular coast
- the influence that humans have had or are having on the coast.

The effects of climate change on coastal inundation and change in the Pacific and East Timorese region is likely to be felt first (and possibly most significantly) through possible changes in the impacts of episodic extreme weather events. Primarily this will be caused by the exacerbation of the *impacts* of these events by both sea-level rise, and potential ecological changes through temperature-related and ocean acidification stressors on coral reef ecosystems, and secondly through potentially longer term climate change effects on the characteristics of such extreme events.

However, little specific work has been carried out to quantify the physical changes on hazard occurrence and magnitude and associated risk at island or community levels that may result due to different future emission scenarios. The small islands chapter (Mimura et al., 2007) in the Intergovernmental Panel for Climate Change Fourth Assessment Report (AR4) concluded that:

> A decade ago many small islands were the subject of vulnerability assessments to climate change. Such assessments were based on simplistic scenarios, with an emphasis on sea-level rise … Since then the momentum for vulnerability and impact studies appears to have declined,

such that in the present assessment we can cite few robust investigations of climate change impacts on small islands using more recent scenarios and more precise projections.

This report aims to provide a summary assessment of the potential impacts that climate change may cause on coastal inundation and shoreline change in the Pacific Islands and East Timor. In the following sections it focuses on:

- the physical drivers (and interactions between these drivers) that influence coastal inundation and shoreline change processes and how the relevant influence of these drivers vary across the region and impact on different island types
- the physical nature of Pacific island and East Timorese shorelines, their relative sensitivity and susceptibility to change, recovery and natural resilience mechanisms and how this may change in the future
- key human activities that exacerbate or impact this natural resilience.

The assessment is based on a review of existing publically available literature and information from various individuals and organisations involved in coastal hazard and climate change-related physical process work in the Pacific region.

This report is one of two prepared for the Department of Climate Change and Energy Efficiency with the other report focussing on *Anticipated climate change impacts on the coastal protection role provided by coastal ecosystems in the Pacific and East Timor* (Lundquist & Ramsay, 2011).

2.2 Island types and coastal landforms

The coastal margins of the Pacific islands display a wide range of morphological characteristics due to variations and interactions in geological, biological and climatic factors. In general terms, the variation in coastal geomorphology can be classified into three major island types (Nunn, 1994), which are described below. Within ocean plate settings, further differentiation of these three main types generally depends on the degree of subsidence or emergence that has occurred over geological timescales (e.g., Scott & Rotondo, 1983).

2.2.1 Volcanic islands

High volcanic islands range in size from large continental islands, such as Papua New Guinea to single volcanoes, such as Ono in southern Fiji. They are typically high islands, often slowly subsiding, surrounding by either fringing (e.g., Kosrae), or barrier reefs (e.g., Pohnpei and Chuuk), or a combination of the two (e.g., New Caledonia, Fiji, Samoa, Rarotonga) with coastal plains that generally developed during the fall in sea level in the late Holocene. These alluvial plains are typically narrow but can be wide, or have formed large deltas, around the larger river mouths (for example as found in PNG, Solomon Islands, Viti Levu and Vanua Levu in Fiji).

On low-lying coasts, beach systems typically front either mangroves, wetland swamps or a depositional coastal plain, and on steeper coasts, hard rock (Figure 2-1). Richmond (2000) summarised a number of distinct settings where beaches occur on high islands, including drowned river valley with bayhead beach, structural embayment with beach, pocket beach, coastal plain/cuspate foreland beach, delta beach and fringing beach. Typically such beaches are a relatively narrow strip of sand or gravel sediment flanked by the reef flat and the volcanic rocks of the island. More extensive deposits of sediment typically occur where there is a greater supply of terrestrial sediments, such as at deltas, river valleys or estuaries.

Figure 2-1: Examples of Pacific high island shorelines. A: Pocket beaches composed of carbonate sands constrained between volcanic rock outcrops, Matareva, Upolu, Samoa; B: Fringing gravel beach with sediment supplied be local rivers and streams, Bonegi Beach, Guadacanal, Solomon Islands; C: Narrow carbonate-derived sand and gravel fringing beach, Paonangisu, Efate, Vanuatu; D: Wide carbonate sand beach inshore of the barrier reef on the west coast of New Caledonia (Poe Beach); E: Barrier beach ridges fronting both a tidal channel and wetland at Walung, Kosrae, Federated States of Micronesia; F: Mangrove shoreline on the north coast of Viti Levu, Fiji.

2.2.2 High limestone islands

High limestone islands are typically found along convergent plate boundaries and have been uplifted (e.g., Banaba, Nauru and Niue). Makatea (composite volcanic and limestone) islands, found in the Southern Cooks (e.g., Mangaia and Atiu) and French Polynesia (Makatea) are similar raised islands but with a volcanic interior surrounded by a raised fringing reef (Figure 2-2).

Figure 2-2: Examples of raised limestone islands and associated coastlines. Top left: Alofi coastline of Niue; Top right: Oneroa coast of Mangaia, Cook Islands; Bottom: Southern (right) and northern (left) coastline of Tongatapu, Tonga showing the effects of island uplift and tilting on the coastal morphology.

High limestone island coastlines are typically characterised by cliffs or sloping limestone platform with little low-lying land close to the shoreline and only thin surficial beach or sediment deposits. The exception are islands with a more complex uplift history, for example Guam and Saipan, where well-developed beach systems and coastal depositional plains can be found. Similarly on Tongatapu, Tonga, island tilting has resulted in raised limestone cliffs along the southern coast, a much wider but lower-elevation coastal margin with intertidal and lagoon mangrove strands, along the northern coast (Figure 2-2), and on the open eastern and western coasts, both present-day and higher relic fringing beaches overlie the limestone platforms but rarely exceed 25 m in width (Roy, 1990).

2.2.3 Atoll and barrier reef islands

Atoll and barrier reef islands are low lying and comprise largely from unconsolidated biogenic sediments (e.g., all islands in Kiribati, Tuvalu, Tokelau and the Marshall Islands). In characterising the variability and diversity in reef island morphology, and their inherent morphological stability, a number of coral island classification schemes have been developed (e.g., Fairbridge, 1950; Stoddart and Steers, 1997), typically based on four criteria: sediment type, island location on the reef flat, island shape, and degree of vegetation cover. For Pacific atolls, Richmond (1992) characterised four types of islets (or *motu*) based on their morphology, sediment and rock characteristics, and location on the reef rim (Figure 2-3 and 2-4). Similar islet types also occur on the outer rims of barrier reefs:

- Type I: are small sand islets with little vegetation. They generally occur on the leeward side of atolls, adjacent to reef passages (e.g., Te Afualiku on Funafuti, Tuvalu), and on lagoon patch reefs.
- Type II: are usually the largest and exhibit the greatest long-term stability and typically occur on high wave-energy corners of atoll rims.
- Type III and IV have developed through deposition and reworking of sediments deposited on the reef surface due to storm or cyclone events and often have a series of beach ridges and topographical depressions reflecting historic storm events. Type III are usually narrow and elongated, often following the 'planshape' of the reef edge. Type IV can occur in a wide variety of shapes and have typically developed around raised reef, cemented rubble or storm deposits with an ocean-facing beach ridge of rubble and conglomerate and a sandy, lagoon-facing beach.

Despite their universally low surface elevation, there are subtle differences in surface topography of these islets related to location and how the islet evolved. In general terms three basic landform units are typically present on such islets: 1) an ocean or windward-side gravel beach ridge (or ridges), 2) a lower elevation sand beach and ridge on the lagoon or leeward-side and a central depression between the two (McLean, 1991). There can also be variations in topography along the length of the islet resulting in lower elevation surface topography, for example where more recent land accumulation has occurred, such as at the distal extents of islets (for example Atafu, Tokelau), or where subsequent inter-islet channel infilling has occurred (for example Tebunginako Village, on Abaiang, Kiribati (Webb, 2006b)).

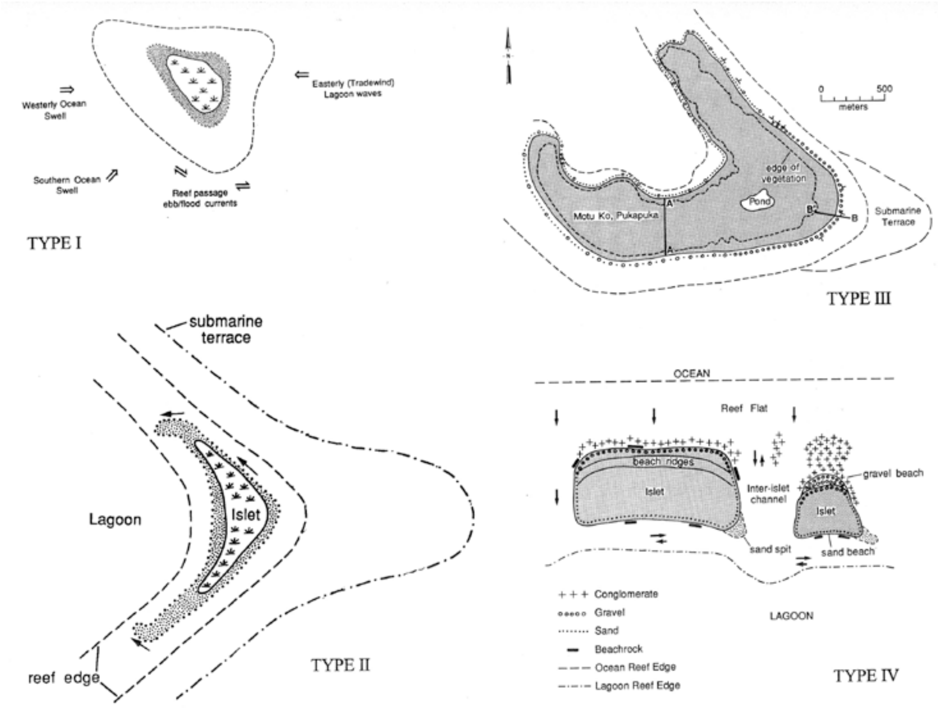


Figure 2-3: Atoll islet types. Richmond (1992).

Figure 2-4: Examples of atoll and barrier island shorelines. A: Te Afualiku islet (Type 1), Funafuti, Tuvalu; B: Vaitup, Tuvalu (Type II); C: South western extent of Funafuti lagoon (Types II and III); D: Eastern coast of Tarawa, Kiribati (Type IV).

2.3 Space and timescales of reef and shoreline change

Pacific island reef systems and their associated sedimentary islands and coastal margins are highly dynamic systems that can show visible changes in their morphology over hours to millennial timescales, and over spatial scales from a few metres to many kilometres. Kench (2011) summarised the responsiveness of the different components of a reef-based system as:

- development of coral reef platforms modulated by sea-level oscillations at millennium timescales
- reef island and shoreline development due to the interaction between the basement reef system, sediment supply and hydrodynamic regime at centennial timescales
- shoreline dynamics occurring at event to decadal timescales in response to wave energy input, sediment inputs, particularly from land-based sources, e.g., river systems, or human influences on the shoreline
- ecological transitions occurring at event to decadal timescales due to extreme weather or climatic events, or changes in ocean temperature, chemistry or local water quality.

This assessment is focussed on the second and third of the above components, with the first and fourth aspects addressed in the associated report (Lundquist & Ramsay, 2011) to this one.

3 Impact of climate change on the physical drivers of coastal inundation and shoreline change

3.1 Introduction to the drivers of coastal inundation and shoreline change

Coastal-related inundation and shoreline change on Pacific Islands tend to be caused by a range of interrelating forcing factors or ‘drivers’ operating over a range of temporal and spatial scales. Human impacts can also exacerbate these effects. Besides earthquakes and underwater landslides (which can cause tsunami or coastal subsidence), the main natural causes of coastal inundation and shoreline change typically arise from a combination of water levels and wave conditions related to ocean tides and extremes in weather such as cyclone events. Variability in climate, such as seasonal, interannual (e.g., El Niño Southern Oscillation (ENSO)) or interdecadal (e.g., Interdecadal Pacific Oscillation (IPO)) timescales also play an important role through influencing sea levels, wave climate and the occurrence and characteristics of storm and cyclone conditions. It is these weather and climate-related factors that will be altered most by climate change arising from global warming, and will tend to exacerbate existing coastal hazard problems within developed coastal margins.

3.2 Variability and change in mean sea-levels

3.2.1 Mean sea-level fluctuations

The sea level at any particular time is a combination of mean level of the sea (MLOS), astronomical tide, storm surge and wave conditions.

The astronomical tide (discussed in the next section) oscillates above and below the mean level of the sea (MLOS). The value of MLOS itself is continuously varying due to the influences of long-period (seasonal and >1 year) climatic influences that cause fluctuations in sea level. It is monthly or annual averages of MLOS that are analysed to assess long-term sea-level rise (see Section 3.2.2).

Seasonal fluctuations in MLOS, due to factors such as the annual warming and cooling cycle in each hemisphere, and seasonal movement in weather patterns and oceanic circulation are relatively minor over much of the region and are generally less than about ±25 mm. Slightly greater annual variability can occur around the Solomon Islands, PNG and East Timor.

The most significant influence on MLOS fluctuations over most of the Pacific Islands is due to the El-Niño Southern Oscillation (ENSO) cycle (Merrifield et al., 1999; Chowdehury et al., 2006). ENSO is a natural global climate fluctuation occurring over a two to four year cycle, classically characterised by the periodic development of unusually warm ocean waters along the tropical South American coast and out along the equator to the date line during an El Niño episode. El Niño and La Niña refer to opposite phases of the ENSO cycle, when major changes in the Pacific atmospheric and oceanic circulation and sea temperature swap around; e.g., cooler waters develop off the tropical South American coast during La Niña.

When neither El Niño nor La Niña is occurring, (usually referred to as ‘neutral’ or normal conditions), trade winds blow westward across the Pacific, piling up warm surface water so that Indonesian sea levels are about 50 cm higher than those in Ecuador. During classic El Niño events the trade winds weaken—resulting, amongst many other things, in a fall in mean sea level and increase in westerly wind conditions and hence waves over the central and western Pacific region (and conversely an increase in sea level in the eastern Pacific; for example, by up to around 0.3 m at Christmas Island in the Line Islands). During La Niña events, the trade winds strengthen, and the pattern is a more intense version of the 'normal conditions' with higher-than-normal mean sea levels experienced over the central and western Pacific. During the 1990s and 2000s there have been frequent occurrences of a maximum warm sea surface temperature anomaly in the central equatorial Pacific with cooler anomalies to the east and west. This has been variously termed the El Niño Modoki, date line El Niño, central-Pacific El Niño or warmpool El Niño (see Lee & McPhaden, 2010, for a review).

Figure 3-1 shows how monthly and annual MLOS has varied at five Pacific Island locations since 1974 based on the available sea-level datasets and the variation of the Southern Oscillation Index[1] over the same period. The effect of the strong El Niños in reducing MLOS in 1983 and 1997–98 in these Western Pacific locations can be clearly seen. ENSO influence can vary monthly sea level by around 0.5 m but the increase above normal due to a strong La Niña phase is typically less than 0.2 m. Conversely the drop in sea level during a strong El Niño can be greater; for example, during the 1997–98 El Niño event the mean level of the sea was around 0.35 m lower in Tuvalu in March and April of 1998, but had returned to a normal level by November of that year (Bureau of Meteorology, 2010). In Tarawa, since 1974 the influence of ENSO has caused variations in monthly average sea levels that range up to 0.43 m (Ramsay et al., 2010). While monthly MLOS and SOI are strongly correlated, MLOS response tends to lag SOI by a few months with the lag time varying across the region.

A further pattern of Pacific climate variability, the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO) shifts phases interdecadally over a period of 20–30 years, and also has an influence on MLOS fluctuation. The two are similar, but not exactly the same phenomena, and affect the two hemispheres differently. The PDO refers to shifts in sea-surface temperatures (SST) in the north Pacific centred near the date line at 40ºN (Mantua et al., 1997), whereas the IPO is a wider Pacific sea-surface temperature pattern incorporating also SST patterns in the Southern Hemisphere (Power et al., 1999; Folland et al., 1999; Salinger et al., 2001; Folland, 2008). A recent analyses of SST modes in the Pacific indicate that the IPO may be derived largely from decadal variability in ENSO in the South Pacific but in the northern hemisphere combines with a North Pacific mode to form the PDO (Messie & Chavez, 2011).

The SST pattern of the IPO is similar to ENSO but differs in several ways, including symmetry about the equator, less variability in the eastern Pacific and more variability in the extra tropics (Folland, 2008). The matching atmospheric sea-level pressure pattern is one of an east/west seesaw at all latitudes, but again centred over the North Pacific. Over the last century a positive (warm) phase occurred between around 1925–46, a negative (cool) phase (1947–76), a positive phase (1977–98) and a return to a negative phase since the turn of this century (Mantua et al., 1997; Messie & Chavez, 2011).

[1] The Southern Oscillation Index (SOI) is one of the measures of the occurrence and strength of El Niño and La Niña and is derived from the difference in mean sea level pressure difference between Tahiti and Darwin. El Niño occurs when SOI is persistently lower than -1 and La Niña when the SOI is persistently greater than +1.

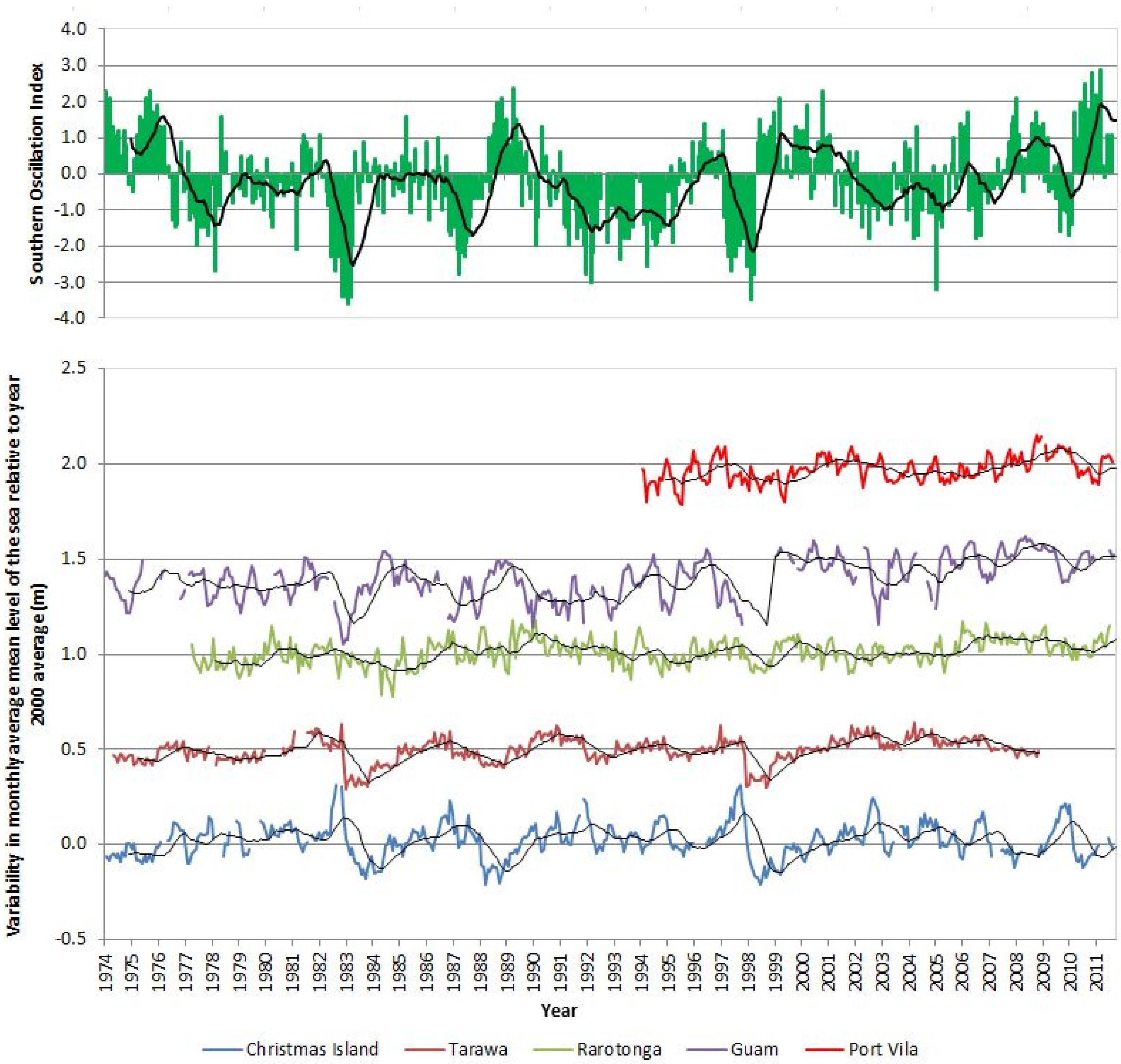


Figure 3-1: Southern Oscillation Index (top) and monthly mean level of the sea for five Pacific Island locations (bottom) between 1974 and 2007. The coloured bars/lines show the monthly Southern Oscillation Index/mean level of the sea respectively, with the black line the 12 month running mean. Variability in monthly mean level of the sea for each station is relative to the average mean level of the sea for the year 2000. Each mean level of the sea plot has been offset by 0.5 m for clarity.

The IPO is a significant source of decadal climate variation throughout the South Pacific but also modulates ENSO climate variability over the region (Salinger et al., 2001). During positive (warm) phases of the IPO, such as occurred between 1977 and 1998, there is an increased tendency for prolonged and stronger El Niño events, and during negative (cool) phases more neutral or La Niño events tend to occur. Since the recent cool phase began in around 1999–2000, there has been an increase in neutral or La Niña events relative to the previous two decades.

During positive (warm) phases of the IPO the increased tendency for El Niño events tends to suppress sea levels in the Western Pacific with the opposite happening during negative (cold) phases. This increased rate of sea-level rise in the Western Pacific appears to be related to the influence of the trade winds with Merrifield (2011) suggesting that there has been an increase in the strength of the trades since the early 1990s over and above natural variability. However, Messignac et al., (2012) conclude that there is a 25–30 year pattern in such sea-level fluctuations and that they are still dominated by natural variability within the ocean–atmospheric coupled system. While any influence of anthropogenic forcing could not be ruled out, any such effects are currently barely detectable.

Applying this in a simple way to IPO-related ENSO modulation, Figure 3-2 shows the annual mean level of the sea record for Kwajalein in the Marshall Islands, one of the longer sea-level datasets for the Pacific Islands, along with the average annual sea level over each IPO phase[2]. Transiting from a cool to a warm phase, the increase in mean sea level, due to global warming, is suppressed in the western Pacific including over the period of the warm phase due to the influence of El Niño events. Conversely the transition from a warm to cool phase occurs abruptly with a 'jump' in decadal average sea levels in the western Pacific as more neutral or La Niña conditions occur (and hence a higher sea level over a cool IPO phase). This 'jump' in mean level of the sea over the last decade is a significant factor in the increased number of reports that tidal inundation is becoming more common in the western Pacific, particularly in places such as Kiribati, Tuvalu and the Marshall Islands that lie largely outside the main cyclone belt and where extreme sea level occurrence is highly correlated with periods of higher mean level of the sea.

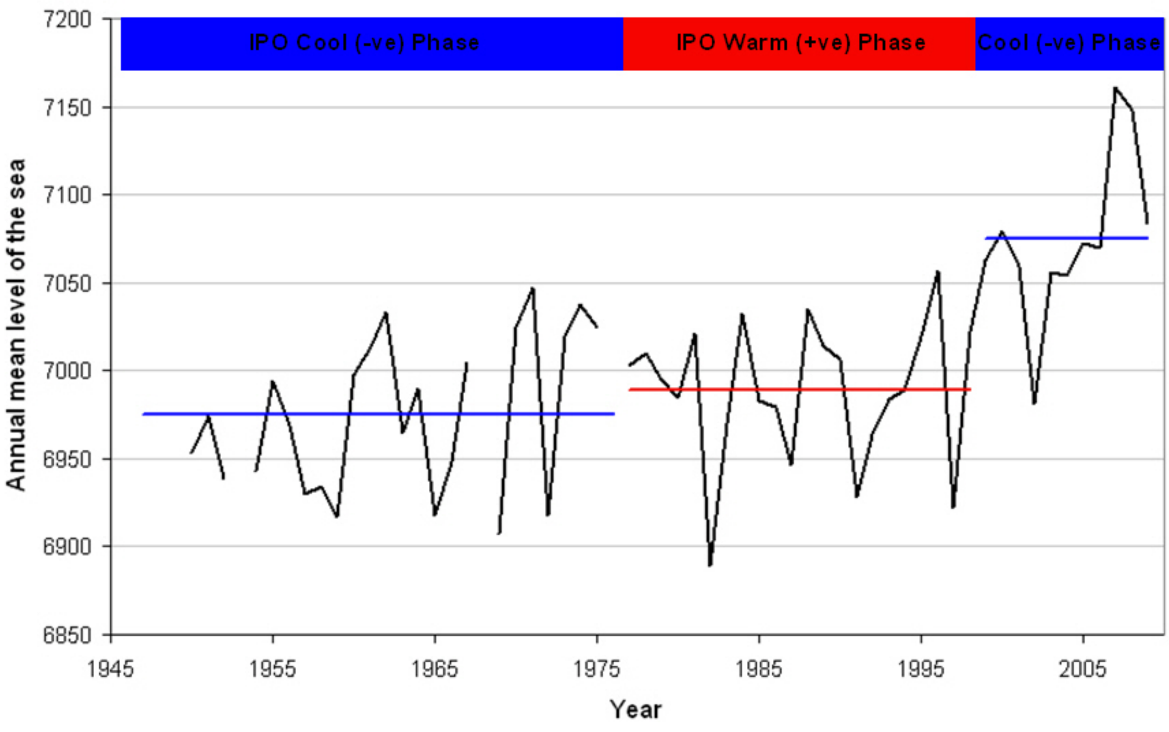


Figure 3-2: Annual mean level of the sea for Kwajalein between 1947 and 2009 and showing average mean sea level over each IPO phase.

[2] This same pattern between IPO warm and cool phases on mean sea level is also seen on longer sea-level time series in the Pacific region, such as the 110-year dataset from the sea-level gauge at the Port of Auckland.

The IPCC AR4 noted that the nature of ENSO has varied considerably over time (Trenberth et al., 2007) over both decadal and longer timescales. The role of global climate change on ENSO characteristics over this last century is still uncertain, with a suggestion of increased ENSO activity over the last 50 to 100 years (Vecchi & Wittenberg, 2010; Fowler et al., 2012). However, other studies have suggested that such changes are within the range of natural variability (Power & Smith, 2007) and while there have been suggestions that such increases could be due to increased atmospheric and sea surface temperatures associated with global warming, no attribution has yet been established.

The IPCC AR4 also noted that all model projections showed continued ENSO interannual variability (Meehl et al., 2007) throughout the 21st century. While current global climate model projections tend to show a pattern of change in tropical Pacific sea-level pressure that is more El Niño-like, the projections also show a range of between a 30 per cent reduction to a 30 per cent increase in ENSO variability (van Oldenborgh et al., 2005). AR4 concluded that presently there was no consistent indication of discernible future changes in ENSO amplitude or frequency and this conclusion has not changed subsequently.

El Niño and La Niña events will continue to occur in the future (Vecchi & Wittenberg, 2010) and will continue to be a dominant interannual influence on mean sea-level fluctuations. Assuming that there are no substantial changes in ENSO/IPO characteristics over the next few decades and the same general patterns from the last century continue, it is suggested that this current IPO cool phase is likely to continue for another 10–20 years and that the average mean level of the sea over the entire cool phase may not differ significantly to the average experienced over this last decade. Over a subsequent 20–30 year warm-phase sea levels in the western Pacific would then be suppressed somewhat. Hence it could be when the IPO next flips from a warm to a cool phase, possibly sometime between 2040 to 2050 that another substantial ‘jump’ in decadal-average mean level of the sea occurs, and the next substantial increase in the observed frequency or magnitude of tidal or storm-tide inundation occurs.

3.2.2 Mean sea-level change

Long-term changes in mean sea level, particularly over the late Holocene, have played a dominant role in the reef morphology and associated landforms and coastal margins that we see in the Pacific region today. However, it is the relative stability in sea levels over the last few millennia that have helped enable extended human occupation of reef islands and present-day low-lying coastal margins.

Increasing global sea levels are a well-established consequence of global climate change. Measurements of mean sea-level changes over the last two centuries have primarily come from long-term data from tide gauges mounted on land, supplemented since around 1993 by measurements made by satellites. The longest records suggest that the rate of rise of global mean sea levels began to increase from around the early to mid-1800s compared with a relatively stable sea level in the preceding century. Over the 20th century, global mean sea levels have increased by on average 0.17 m ±0.05 m (1.7 mm/year ±0.5 mm/year). Between 1963 and 2003, global sea-level rise rate was 1.8 mm/year (1.3–2.3 mm/year) and between 1993 to 2003, 3.1 mm/year (2.4–3.8 mm/year) (Bindoff et al., 2007). In the most recent analysis, Church & White (2011) show the global-average trend up to 2009 rose slightly from 1.7 mm ± 0.2 mm/year (starting from 1900) up to 1.9 mm ± 0.4 mm/year (starting from 1961).

Figure 3-3 summarises net absolute sea-level rise measured by satellites over the period October 1992 to July 2011. This spatial variability in the Pacific is largely due to trade wind and oceanographic influences and is similar to the horseshoe pattern of higher sea levels (and SST) around both hemispheres of the western Pacific characteristic of the Pacific-wide negative phase of the IPO which changed regime around the turn of the century. While there is some suggestion of change in trade winds since 1990 being a factor (Merrifield, 2011) the recent larger-than-global-average rise in the rate of sea-level in the Western Pacific for the satellite period from 1993 onwards may be predominantly attributable to interdecadal variability (Meyssignac et al., 2012).

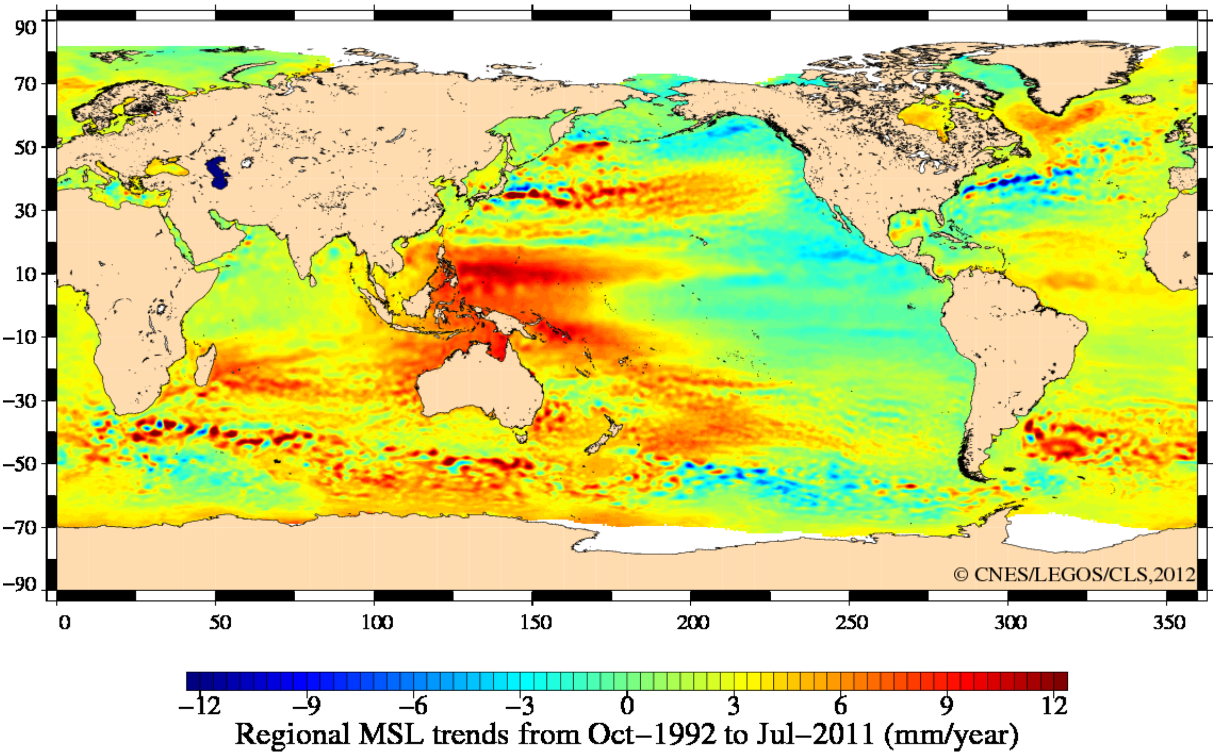


Figure 3-3: Global distribution of the rates of absolute sea-level rise between October 1992 to July 2011 as measured from satellite altimeter data. Source: http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/index.html

Both the available South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) and satellite sea-level records are too short for obtaining reliable sea-level trend estimates. A longer reconstruction of sea levels was undertaken by Church et al. (2006) to estimate the pattern of sea-level rise over the period from January 1950 to December 2001 and concluded an average rate of 2.0 mm/year over this period for the Pacific region, close to the estimates of the global rate of rise.

More recently Becker et al. (2012) assessed the total rate of sea-level rise between 1950 and 2009 due to climate variability and change in the western tropical Pacific using a reconstruction of global sea levels over this period. When global mean sea-level rise, low frequency regional sea level variability and vertical ground movements were accounted for this indicated a highly variable rate of relative sea-level rise over the 60-year period over the region (Figure 3-4). The assessment also confirmed the strong modulating effect of ENSO events on interannual sea-level variability in the western tropical Pacific and the additional influence of multi-decadal variability. It is likely that the magnitudes of the trends will continue to be influenced somewhat for some time by mean sea-level variability and regional differences from the global mean.

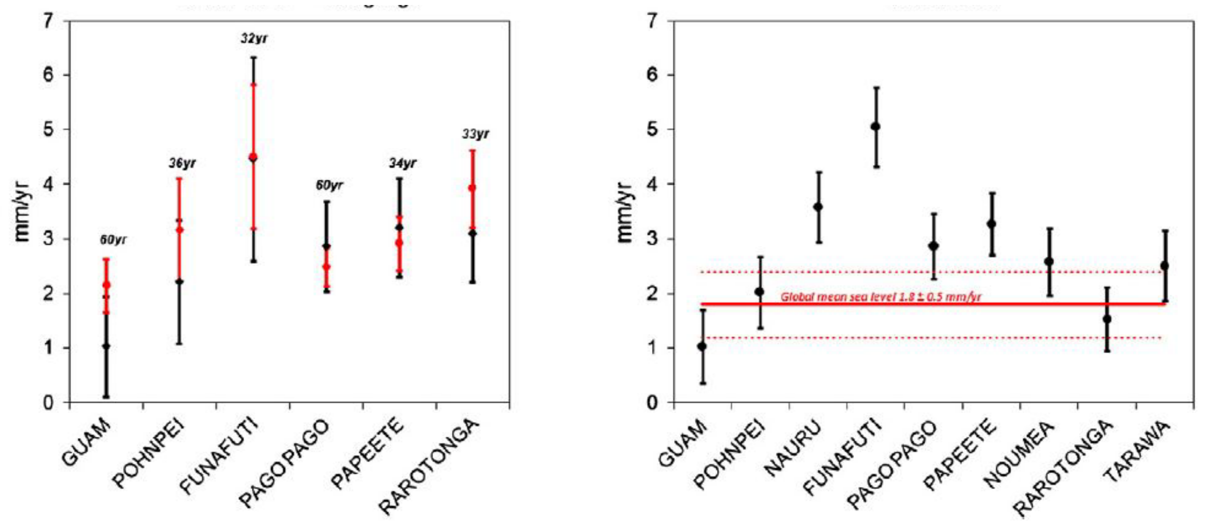


Figure 3-4: Relative sea level rise as measured by selected tide gauges (left) and from annual reconstructed sea level between 1950-1009. Source Becker et al., (2012.)

Sea levels will continue to rise over the 21st century and beyond, primarily because of thermal expansion within the oceans and losses from polar ice sheets and glaciers or ice caps on land. The basic range of projected global mean level rise estimated in the AR4 is for a rise of 0.18 m to 0.59 m by the decade 2090–2099 (mid 2090s) relative to the average sea level over the period 1980–1999 (Meehl et al., 2007), Figure 3-5. These projections (light blue shading in Figure 3-5) did not include contributions due to changes in the dynamics of ice-sheet discharge (which is less well understood and likely to be an increasing factor particularly if greenhouse gas emissions are not reduced). Instead IPCC provided an estimated rise in the upper ranges of the emission scenario projections (dark blue shading) that would be expected with ‘scaled-up ice sheet discharge’ if contributions to sea-level rise were to grow linearly with global temperature change for each emission scenario. This was estimated within the IPCC AR4 as varying between an additional 0.09–0.17 m (depending on emission scenario) but was rounded up in the IPCC (2007) Synthesis Report to an additional 0.1–0.2 m rise. It was also clearly stated that larger contributions from the Greenland and West Antarctic ice sheets over this century could not be ruled out.

Since the 2006 cut-off point for science publications to be considered within the IPCC Fourth Assessment Report process, further scientific papers on sea-level rise projections have been published. These add to the array of information on potential future sea-level rise over this century and include consideration that sea levels are tracking close to the upper bound of projections from the previous IPCC Third Assessment Report (Rahmstorf et al., 2007) and confirmation that the loss of mass from Greenland and Antarctic ice sheets may be occurring more rapidly than from surface melting alone (e.g., Rignot et al., 2008; Shepherd and Wingham, 2007; Bamber et al., 2007) although recent studies by Wu et al. (2010) and summarised by Bromwich and Nicolas (2010) show that present-day ice sheet mass loss previously calculated from GRACE satellite measurements has been overestimated by a factor of two (due to a revised estimate of vertical land movement from past glaciation) although there remain uncertainties due to the sparse network of coastal GPS measurements. The increasing component of present-day sea-level rise due to ice-sheet losses has led to a number of more recent estimates of sea-level rise over the 21st century (Rahmstorf, 2007; Horton et al., 2008; Grinsted et al., 2010'; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010).

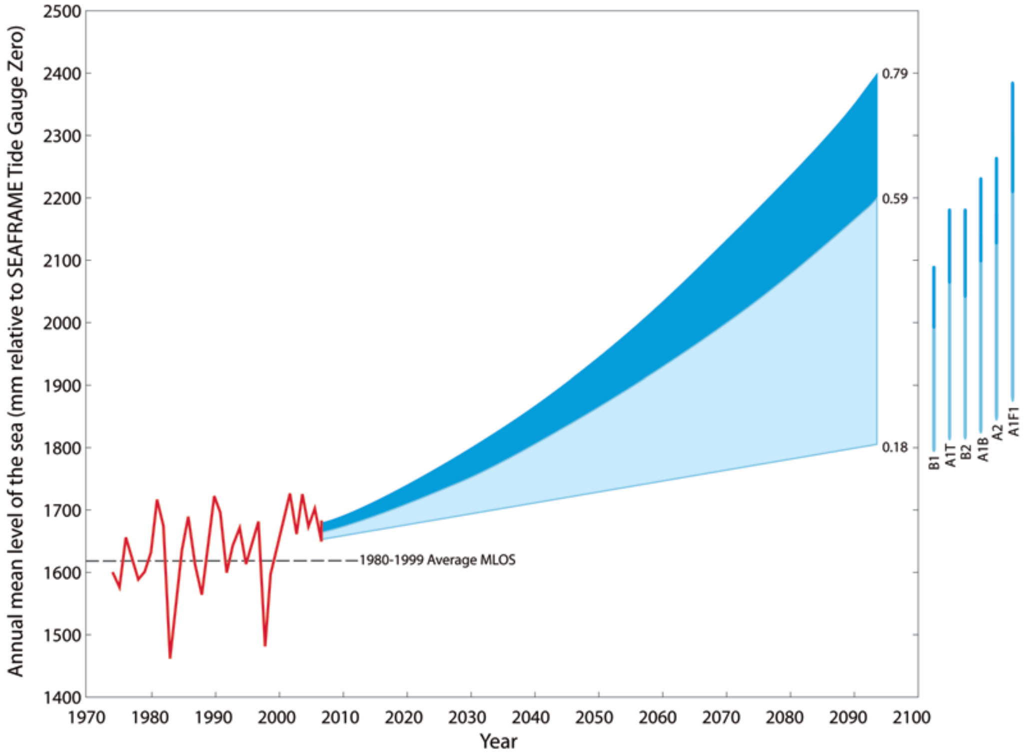


Figure 3-5: Range of AR4 global mean sea level rise projections to the mid-2090s in the context of mean annual sea level measurements at Tarawa since 1974. The red line is the annual mean level of the sea measured by the various tide gauges at Tarawa between 1974 and 2007 (Ramsay et al., 2010). The light blue shading shows the projected mean sea level out to the 2090s for six SRES emission marker scenarios. The dark blue shading shows the potential additional contribution of up to 0.2 m from ice sheets due to scaled-up ice discharge. The vertical lines on the right-hand side show the range in projections for the six emission scenarios, with the dark blue line above each, the potential additional scaled up ice sheet discharge for each scenario.

The ranges of these more recent sea-level rise estimates by 2100 or 2090s (2090–2099) are summarised in Figure 3-6. However, there is still debate over the robustness of the methodologies adopted in making these projections (Holgate et al., 2007; and summary in IPCC, 2010). Pfeffer et al. (2008) considered that the glaciological conditions required for a sea-level rise of two metres by 2100 are very unlikely to occur and that a more plausible, but still accelerating, ice sheet contributions lead to sea-level rise by 2100 of about 0.8 metres. Price et al. (2011), using a three-dimensional dynamic ice-flow model for Greenland that accounts for periodic variability, determined that the dynamic mass flow contribution from Greenland ice sheet would be up to 0.45 m by 2100 (half the upper bound estimate for Greenland by Pfeffer et al., 2008), but also including the time-varying change in ice-sheet surface mass balance raises this to 0.85 m by 2100. More recently Rignot et al. (2011) summarised recent accelerations in ice sheet loss over the last 18 years and conclude that if present trends in ice sheet accelerations continue they would contribute around 0.56 m by 2100 and become the dominant contributor to sea-level rise this century.

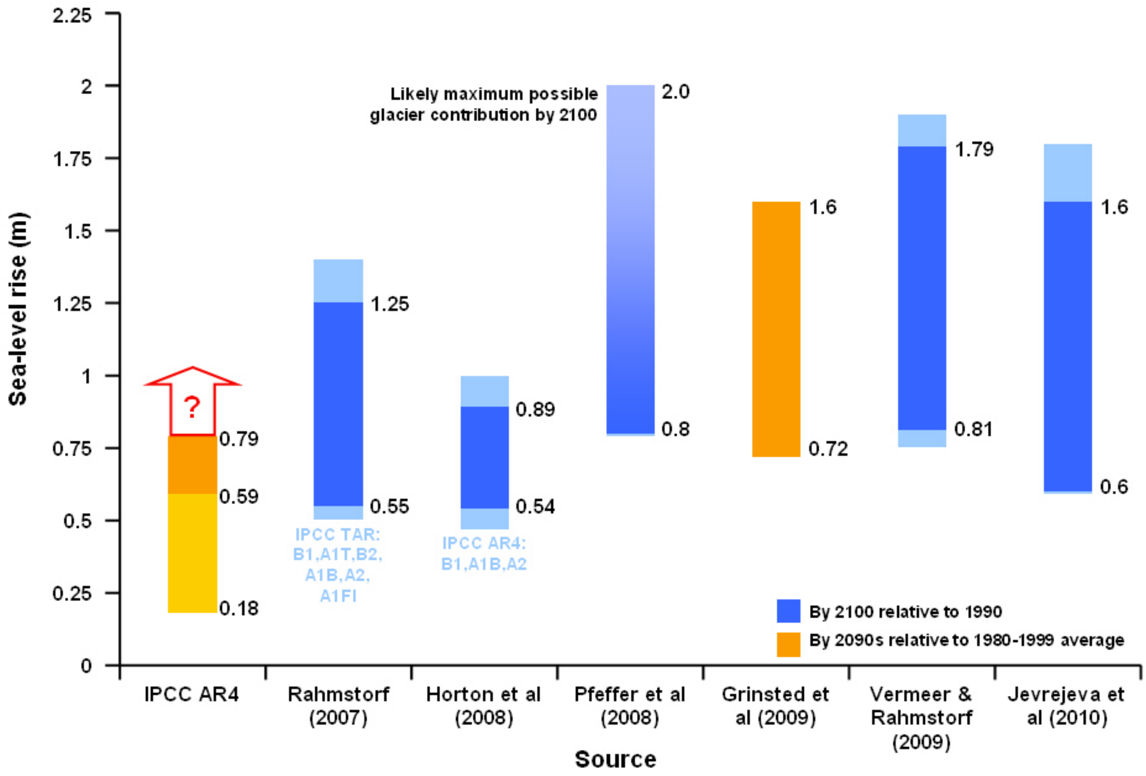


Figure 3-6: Summary of a selection of sea-level rise estimates from recent science publications. The dark blue bars show the range of projections for the various emission scenarios used. The light blue bars show the upper and lower error margins.

Initial multi-model ensembles of the SRES A1FI emission scenario suggest that long-term variability in regional sea-level rise across the tropical Pacific region is unlikely to be greater than ±0.05 m relative to global average sea-level rise by the 2090s (Meehl et al., 2007). Similar variability is shown for the A1B emission scenario by CSIRO for 2030 and 2070 (Figure 3-7). However, this modelling does not include all sea-level contributions from the two main polar ice sheets including gravitational redistribution which can result in a lower relative sea level near the decaying ice sheet and a larger rise, of up to 20 per cent, further away (Church et al., 2010). Further modelling is being conducted, for example as part of the Australian-funded Pacific Climate Change Science Program, to determine regional variation in future sea-level rise under different climate change scenarios. However, such variability is likely to be small relative to the current uncertainties in global sea-level rise associated with future ice-sheet loss.

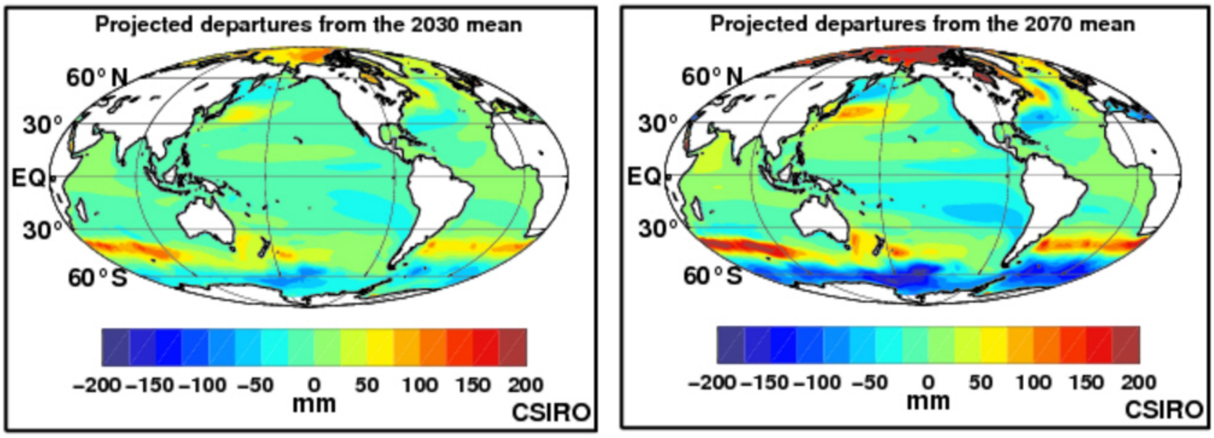


Figure 3-7: Multi-model mean of the departure of the projected regional sea-level rise from the globally averaged (SRES A1B) projection for 2030 and 2070. Source: http://www.cmar.csiro.au/sealevel/sl_proj_regional.html.

3.3 Variability and change in astronomical tides

For most Pacific islands, the main component determining the severity of a particular inundation event is the astronomical tide. The tide oscillates about the mean level of the sea, and can be predicted many years in advance. Tide levels can elevated or lowered due to mean sea-level fluctuations and over the long term will rise due to sea-level rise (see previous sections).

In the Pacific and East Timor, mixed (one high tide higher than the other each day) semi-diurnal (twice daily) tides are dominant, with periods of mixed diurnal (once-daily) tides experienced in parts of PNG and the Solomon Islands. Mean High Water Spring (MHWS) range varies across the region from less than 0.6 m in French Polynesia and the Cook Islands, to approaching 2 m in eastern Micronesia.

Tide ranges and high tide levels vary over different time frames (e.g., daily, the two weekly Spring-Neap tidal cycle, seven-monthly perigean-spring cycle and seasonally with higher tide ranges often experienced in the December to February period). There are also longer term cycles which influence the tide range, and hence the magnitude of the highest tides, in any year. This includes:

- The 8.85-year complete cycle of lunar perigee which influences high tides on a 4.4-year cycle (Haigh et al., 2011); for example, in Kiribati (Figure 3-8) and Tuvalu.

- The 18.61-year lunar nodal cycle, which is particularly evident in annual peak high tides in northern PNG, central Micronesia, Guam, Marianas and Solomon Islands and to a lesser extent Vanuatu, Fiji and Tonga. This variability in high tide level can be up to about 0.15 m, influences year to year variability in maximum sea levels and has been in the upper part of the cycle over the latter part of last decade.

Deep-ocean tidal characteristics, and hence tidal characteristics around oceanic islands, are unlikely to be significantly altered by climate change or sea-level rise. Some minor changes in tide range could occur in the inner parts of shallow lagoons, harbours, river mouths or estuaries, particularly around some of the larger Melanesian Islands. Any changes in tide range will be site-specific and is likely to be relatively minor over the sea-level rise rates expected over the coming century.

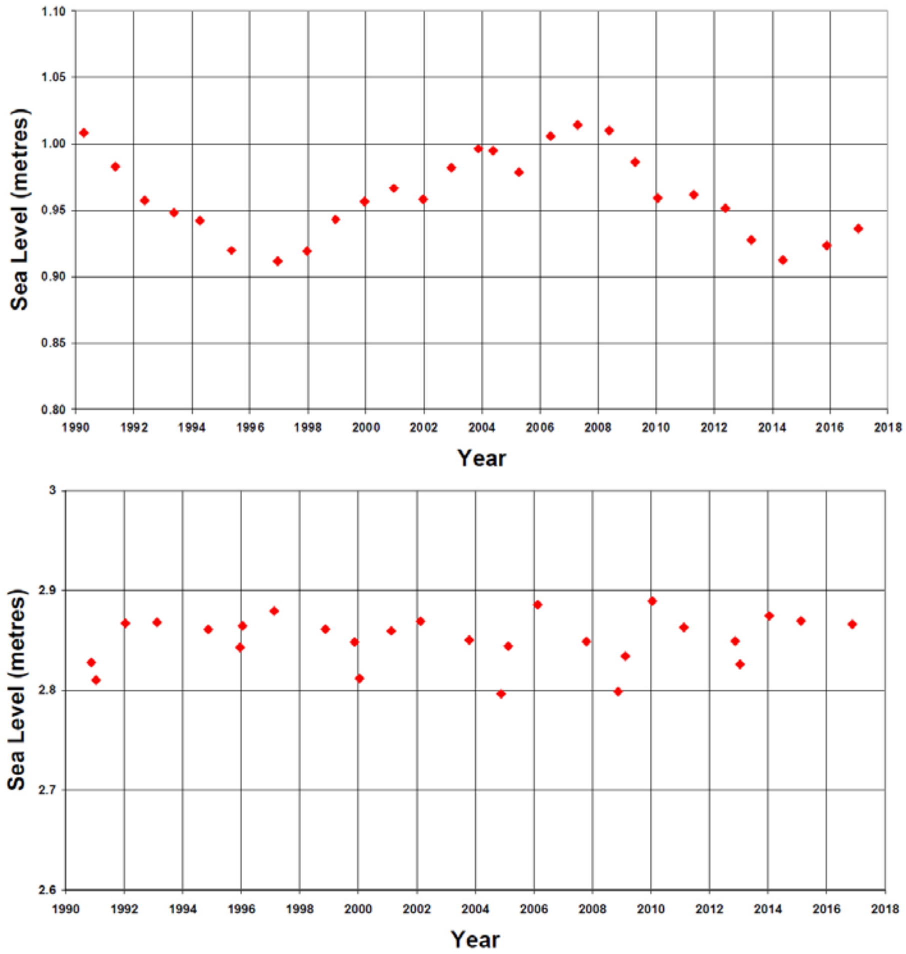


Figure 3-8: Predicted highest tide level each year for the period 1990 to 2018 for Honiara, Solomon Islands (top) and Tarawa, Kiribati (bottom). Source: South Pacific Sea Level and climate Monitoring Project Country reports for Kiribati and the Solomon islands available at: http://www.bom.gov.au/pacificsealevel/picreports.shtml

However, tidal range does play a role in compounding coastal impacts of sea-level rise across the region, with the effect of sea-level rise on high tide exceedences likely to be proportionately greater on margins subject to small tidal ranges (Bell, 2010). Figure 3-9 shows high tide exceedence curves for Tarawa (Kiribati) and Rarotonga (Cook Islands) relative to the mean level of the sea, with spring-tide ranges of 1.8 m and 0.7 m respectively. These curves have been derived from a 100-year prediction of high tides (excluding sea-level rise) based on tidal constituents extracted from sea-level measurements from the South Pacific Sea Level and Climate Monitoring Project (SPSLCMP). Assuming that tide range characteristics do not change in future, the entire high-tide exceedence curve can be raised vertically by the equivalent sea-level rise added to the present day mean level of the sea (in this case 0.5 m and 0.8 m sea-level rise).

Figure 3-9 shows that for a high tide level presently exceeded by 10 per cent of all high tides (MHWS10)[3] at Tarawa a 0.5 m sea-level rise would result in this level being exceed by 62 per cent of all high tides, and for a 0.8 rise in sea level by 93 per cent of all high tides. For Rarotonga, which has a much smaller tide range, sea-level rises of 0.5 m and 0.8 m would both cause all high tides to exceed the current MHWS10 level. It would only require 0.37 m of sea-level rise to for all future high tides to exceed this present-day level. Figure 3-10 shows the variability across the Pacific of the minimum sea-level rise required for 100 per cent exceedence of the present day MHWS10 level.

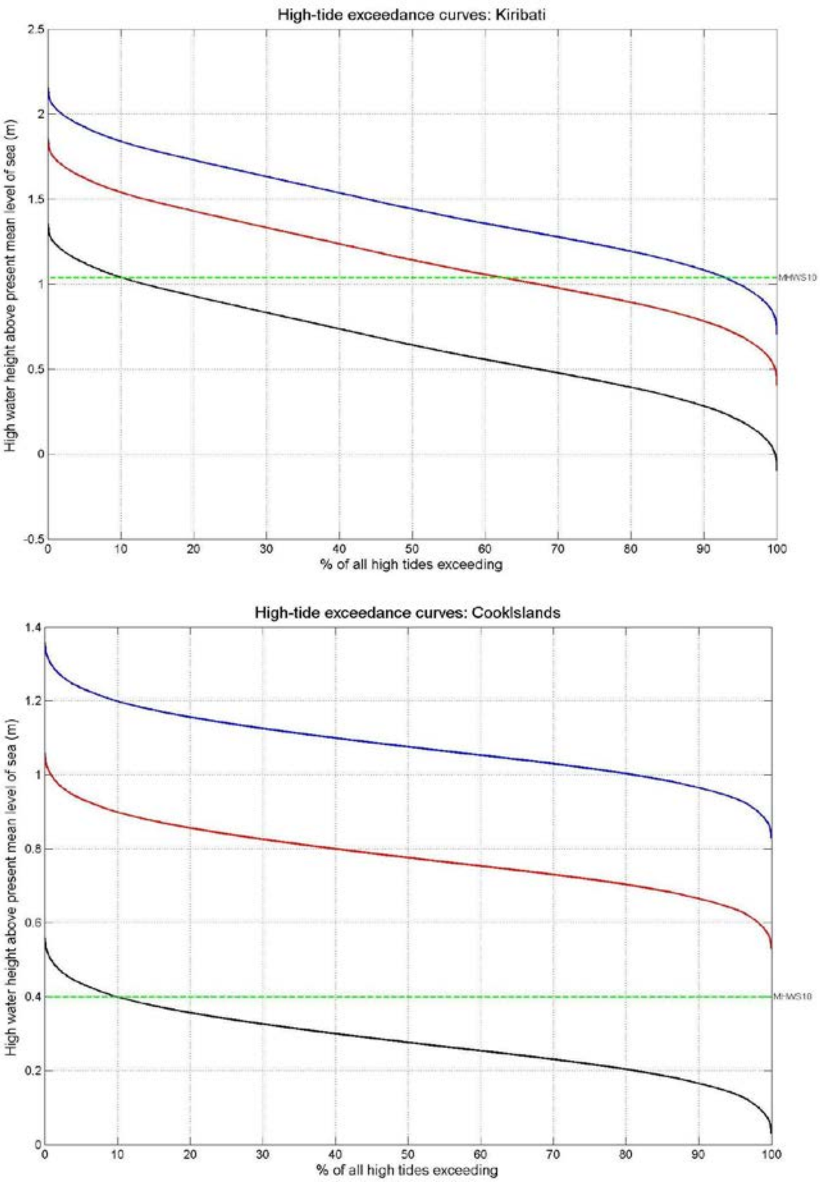


Figure 3-9: High tide exceedance curves for Tarawa, Kiribati (top) and Rarotonga, Cook Islands (bottom) for present sea level (black) and for sea-level rise of 0.5 m (red) and 0.8 m (blue). The green dashed line shows the present-day high tide level exceeded by 10 per cent of high tides (MHWS10).

[3] This would be a level typical of a perigean-spring or “king tide”. A king tide is a popular name referring to any high tide or sea level that is well above an average height.

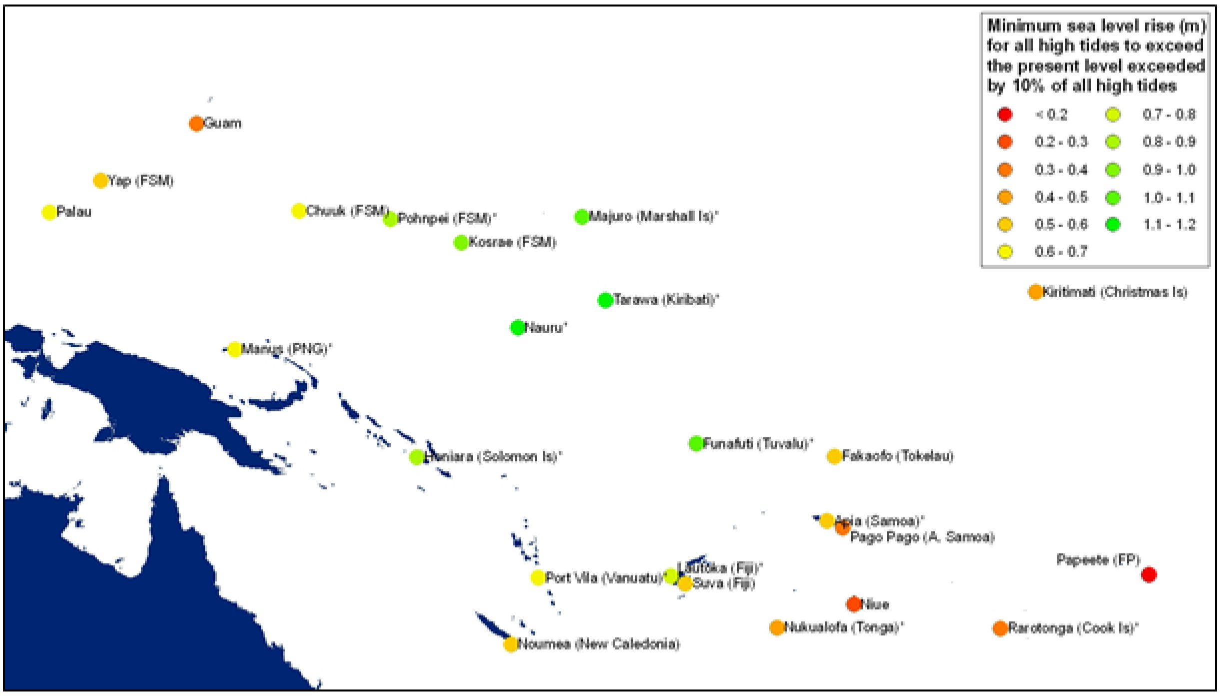


Figure 3-10: Minimum sea-level rise required for all high tides to exceed the present pragmatic MHWS10 level at each location. For the twelve SPSLMCP sites (marked by *) this is based on an analysis of tidal constituents extracted from the data. For other sites this is based on a limited set of eight tidal constituents from a global ocean tide model (Andersen et al., 2006).

These results show that Islands with lower tide ranges will be exposed to more frequent inundation, relative to the upper tide mark that historically guided coastal development. This compounding factor arising from smaller tide ranges relative to sea-level rise means waves and storm surges will more often coincide with high tides that will be above the present MHWS10 or maximum tide marks.

3.4 Variability and change in extreme conditions

3.4.1 Tropical cyclone variability and change

For much of the tropical Pacific region (7º to 25º north and south of the equator), tropical cyclone events are a primary cause of extreme water levels and wave conditions that can cause substantial inundation and shoreline change.

The South Pacific region experiences on average nine cyclone events each year (Figure 3-11) with the North-West Pacific on average 26 events[4]. Year-to-year variability in cyclone characteristics is due primarily to ENSO in both regions. In the North-West Pacific, ENSO-related variability includes a tendency for a south-eastward displacement in cyclone tracks with more cyclones forming in the central North Pacific region during El Niño phases (e.g., Clark & Chu, 2002); a non-linear relationship between ENSO and the number of cyclones, particularly when ENSO is strong (e.g., Wang & Chan, 2002); and greater intensity and lifetime of cyclones during El Niño (Camafgo & Sobel, 2004). Similarly in the South Pacific region, cyclone activity is greater during strong ENSO events (Basher & Zheng, 1995). During El Niño periods there is an eastward elongation of the normal pattern of cyclone

[4] Tropical Cyclone Category 1 or greater

frequency with increased occurrence in most Polynesian countries (and a lower-than-normal occurrence in PNG, Solomon Islands and Vanuatu and Eastern Australia) and vice versa during La Niña conditions (Figure 3-12).

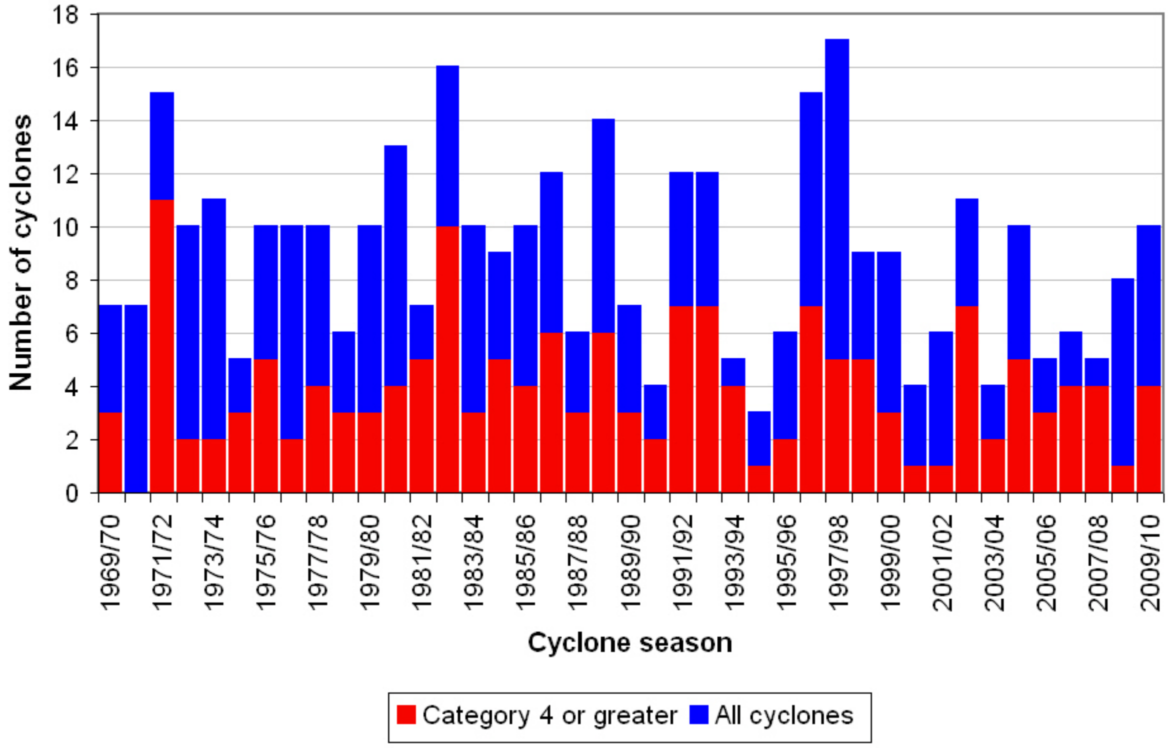


Figure 3-11: Number of cyclones between 1969/70 and 2009/10 in the South Pacific region.

Whether there is any current long-term trend in tropical cyclone frequency or intensity is still unclear with multi-decadal variability and uncertainties in the historical record making it difficult at present to detect any trends in all cyclone regions. In the Pacific region, Webster et al. (2005) concluded there was a large increase in the proportion of category 4 and 5 events over the period 1990–2004 compared to the period 1975–1989 with a doubling in the numbers in the south-west Pacific region (between 155ºE and 180ºE) and a 30 per cent increase in the north-west Pacific, with Emanuel (2005) reaching a similar conclusion in the north-west Pacific. However, uncertainty remains due to changes in both observation technologies and analysis techniques (e.g., Landsea et al., 2006). Despite this, the occurrence of significant trends in sea surface warming in the north-west Pacific cyclone region (and western tropical Pacific warm pool region) where cyclones form and intensify does raise the issue that changes in tropical cyclone activity could potentially be occurring. However, more recently Kuleshov et al. (2010) concluded that there was no apparent trend in the total numbers of tropical cyclones (minimum central pressure less than 995 hPa) between 1981–82 to 2006–07, nor in the number of severe tropical cyclones (< 970 hPa) in both the South Pacific region and Southern Indian Ocean. A positive trend in the number of cyclones of 945 hPa and 950 hPa was observed in the Southern Indian Ocean, which could have been influenced by data quality, but not in the South Pacific. Similar conclusions were reached by Terry and Gienko (2010) from an analysis of cyclone tracks between the 1969–70 to 2007–08 seasons from the archives held by the Regional Specialised Meteorological Centre in Nadi. Despite analogous periods of cyclone behaviour no overall long-term trends were detected in the data. Given the dominant influences of interannual fluctuations on cyclone and track characteristics it may well yet be some decades yet before any clear statistical trend due to climate change can be identified or not.

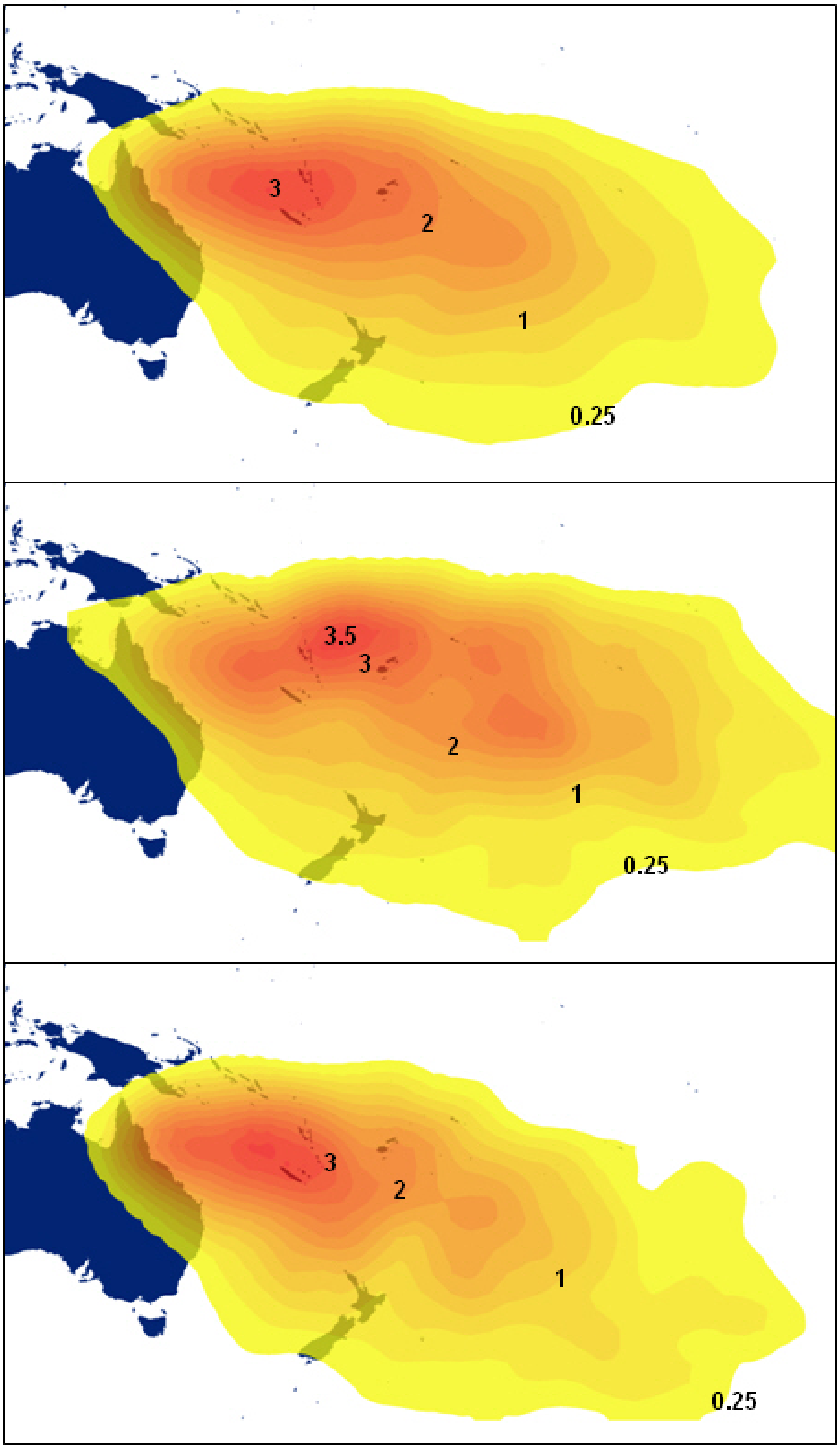


Figure 3-12:Tropical cyclone occurrence in the South Pacific region per 2.5 degree sector between 1969–70 and 2009–10. The top plot shows the occurrence of cyclones for all cyclone seasons, the middle plot for El Niño seasons, and the bottom plot for La Niña seasons.

Identifying potential changes in tropical cyclone activity in the future is challenging as, with identifying any trends over the last few decades, any changes will tend to be small compared with interannual and interdecadal variability. Such anomalies will continue to have a much more dominant influence on cyclone temporal patterns than potentially gradual changes in long-term average cyclone activity due to climate change (Terry and Gienko, 2010). Despite this, future projections, based on both theory and high resolution modelling suggest (e.g., Knutson et al., 2010; Emanuel et al., 2008):

- The global frequency of tropical cyclones will either decrease or stay unchanged. However, there is little confidence in projected changes in any individual basin, given the variability between models. In the Southern Hemisphere there is some indication of a decline in frequency, except in small regions east of Indonesia and in the far west of the south Indian Ocean, and indications of slight increase in frequency in the north-west Pacific.
- It is likely there will be some increase in the mean maximum wind speed of tropical cyclones (2–11 per cent) but increases may not occur in all tropical regions.
- There is expected to be an increase in the frequency of the most intense (Category 4 and 5) storms in some regions. Generally in the Southern Hemisphere, whether there will be an increase in intensity is presently indeterminate, but with some indication that in the Australian region there may be an increase of about 15 per cent in the mean decadal number of Category 4 and five cyclones during the period 2000–2050 relative to 1970–2000 (Leslie et al., 2007). There is more indication of a potential increase in the North-West Pacific.
- Model projections show wide, large-scale changes in tropical cyclone genesis-location, duration and areas of impact, although there is a tendency towards decreased duration in the Southern Hemisphere.
- Rainfall rates are likely to increase in the order of +20 per cent within 100 km of the tropical cyclone centre.

While there is presently no consistent indication of discernible future changes in ENSO amplitude or frequency (see Section 3.2.1), any anthropogenic-related changes in ENSO characteristics may be most noticeable in tropical cyclone activity towards the margins of cyclone occurrence. For example, the southern Marshall Islands and eastern islands in FSM in the Northern Hemisphere, and East Timor, Tuvalu, Tokelau, and eastern Polynesian islands in the Southern Hemisphere.

3.4.2 Extratropical cyclones

Mid-latitude storms (located outside the tropical region between 30º and 60º) can cause inundation damage to the tropical Pacific islands through long-period swell generated by low-pressure storm systems which then propagates southward (for North Hemisphere storms) or northwards (for South Hemisphere storms) through the tropical Pacific region. An example is the inundation event that occurred over the 8–9 December 2008 that effected northern coastlines of islands in the Northern Marianas, FSM, Marshall Islands and Papua New Guinea (see Box 1).

The AR4 concluded a likely pole-ward shift in the tracks of extra-tropical cyclones since the 1950s and a likely increase in the frequency and intensity of the most extreme events (Trenberth et al., 2007) which may in part be due to anthropogenic warming. The AR4 also noted a potential continued pole-ward shift in storm tracks in both hemispheres under a warmer climate with fewer mid-latitude storms in each hemisphere (Meehl et al., 2007). In the mid-latitude northern Pacific a reduction in winter storm activity is projected along with a possible north-eastern movement of storm tracks (e.g., Favre & Gershunov, 2009). In the southern hemisphere a reduction in storm frequency and intensity in the mid-latitudes is projected (Lim & Simmonds, 2009). However, there is still considerable variability and uncertainty around storm trends in regional-scale projections, with no indication how such changes could influence long-period swell events across the tropical Pacific region.

3.4.3 Variability and change in storm surge and extreme sea levels

Changes in extreme sea level will be influenced by changes in mean sea-level (Section 3.2) and changes in cyclone-related storm-surge characteristics.

Storm surge is the rise in sea level over and above that of the predicted astronomical tide and the mean level of the sea at the time creating a storm tide. Storm surges are caused by low atmospheric pressure and strong winds during cyclone conditions. Storm surge is usually a major component of extreme sea levels in the cyclone region of the Pacific, between 7º to 25º north and south of the equator, particularly when in coincides with high tide levels. For island nations close to the equator, such as Kiribati, storm surge is not a significant component and has little influence in causing extreme sea levels.

The storm surge experienced at any particular island location is complex and can vary over short distances along a coast, as it is highly sensitive to the cyclone characteristics, such as storm intensity, forward speed, cyclone size, angle of approach to the coast and central pressure, and the shape and characteristics of the coast. Any long-term changes in any of these characteristics could be expected to change storm-surge characteristics and potentially trends in extreme water levels at a particular location. However, given the episodic nature and natural variability in such events it will likely require many more decades of monitoring before any such changes could be identified. At present there is no conclusive evidence of any change in storm-surge magnitude or frequency across the tropical Pacific.

Despite this, over the last decade in particular, there has been frequent anecdotal accounts in the Pacific of increasing frequency and magnitude of extreme sea levels resulting in increased coastal flooding. The AR4 concluded that trends in global extreme sea levels across the globe tend to reflect the trend in mean sea level (Bindoff et al., 2007), and that it is largely mean sea-level rise rather than changes in storm-surge characteristics that is predominantly contributing to increasing extreme sea levels globally. This conclusion is confirmed by more recent studies (e.g., Mendendez and Woodworth, 2010).

Menendez and Woodworth (2010) estimated global tidal and non-tidal residual extremes from tide gauge records, grouping locations where astronomical tide conditions dominate extreme sea levels (such as the Marshall Islands, Kiribati, Tuvalu), and where non-tidal residuals (e.g., storm surge) dominate (such as French Polynesia, Cook Islands, Guam and Saipan)—the same regional pattern as shown in Figure 3-10.

For tide-dominated extreme sea levels, variability in both annual mean and extreme sea levels is strongly correlated with ENSO (Figure 3-13) with longer period tidal components that are not reflected in mean level of the sea, for example the quasi-4.4-year periodicity in perigean-spring tides evident in the highest percentile sea levels in Tuvalu and Kiribati and the 18.61-year nodal cycle also an influence (Woodworth, 2009; Haigh et al., 2011). While tidal and climate-related variability can result in decadal or longer trends in extreme sea levels that can be different (in both direction and magnitude) to mean sea-level trends, long-term changes in extreme sea-level rise and variability will likely continue to be similar to mean sea-level rise trends, at least over much of this century.

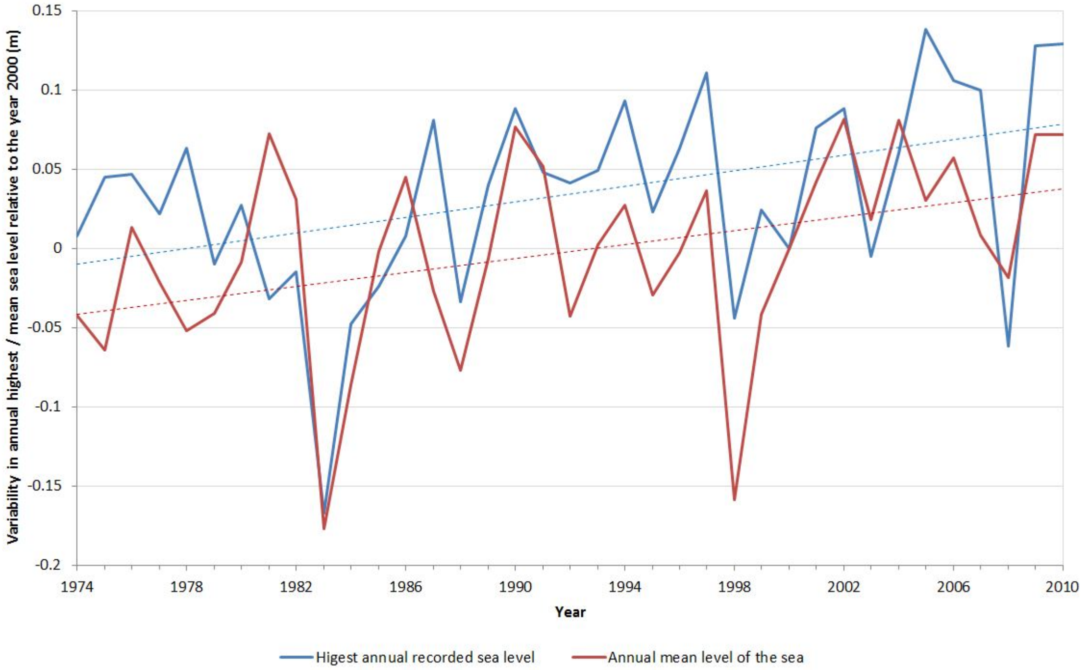


Figure 3-13: Variability in the highest annual hourly and annual mean level of the sea relative to the year 2000 recorded at Tarawa between 1974 and 2010. The corresponding dashed lines are the linear trend over the period for both.

Where non-tidal residuals dominate extreme sea levels, long-term trends will depend on the effect that any potential decrease in overall cyclone frequency and increase in intensity of the most severe storms has on long-term storm-surge characteristics, with any such effect likely to vary from location to location. At present there is little information available from modelling activities in the Pacific region on how storm surge and extreme water levels may respond to such changes in tropical cyclone activity. Initial work conducted in Mangaia and other islands in the Cook Islands as part of the Pacific Adaptation to Climate Change project suggests that the effects of cyclone changes on offshore extreme wave and water-level joint probabilities (Figure 3-14) may be modest relative to ENSO-related variability (with changes in resulting wave conditions at the shoreline, wave run-up, overtopping and inundation likely to be influenced to a much greater degree by sea-level rise) (Stephens and Ramsay, 2012). However, for northern Australia, McInnes et al. (2005) concluded that a 10 per cent increase in intensity of cyclone events (but no change in frequency) would result in a 1-in-100 year event becoming a 1-in-70 year event and that the areal extent of inundation could more than double.

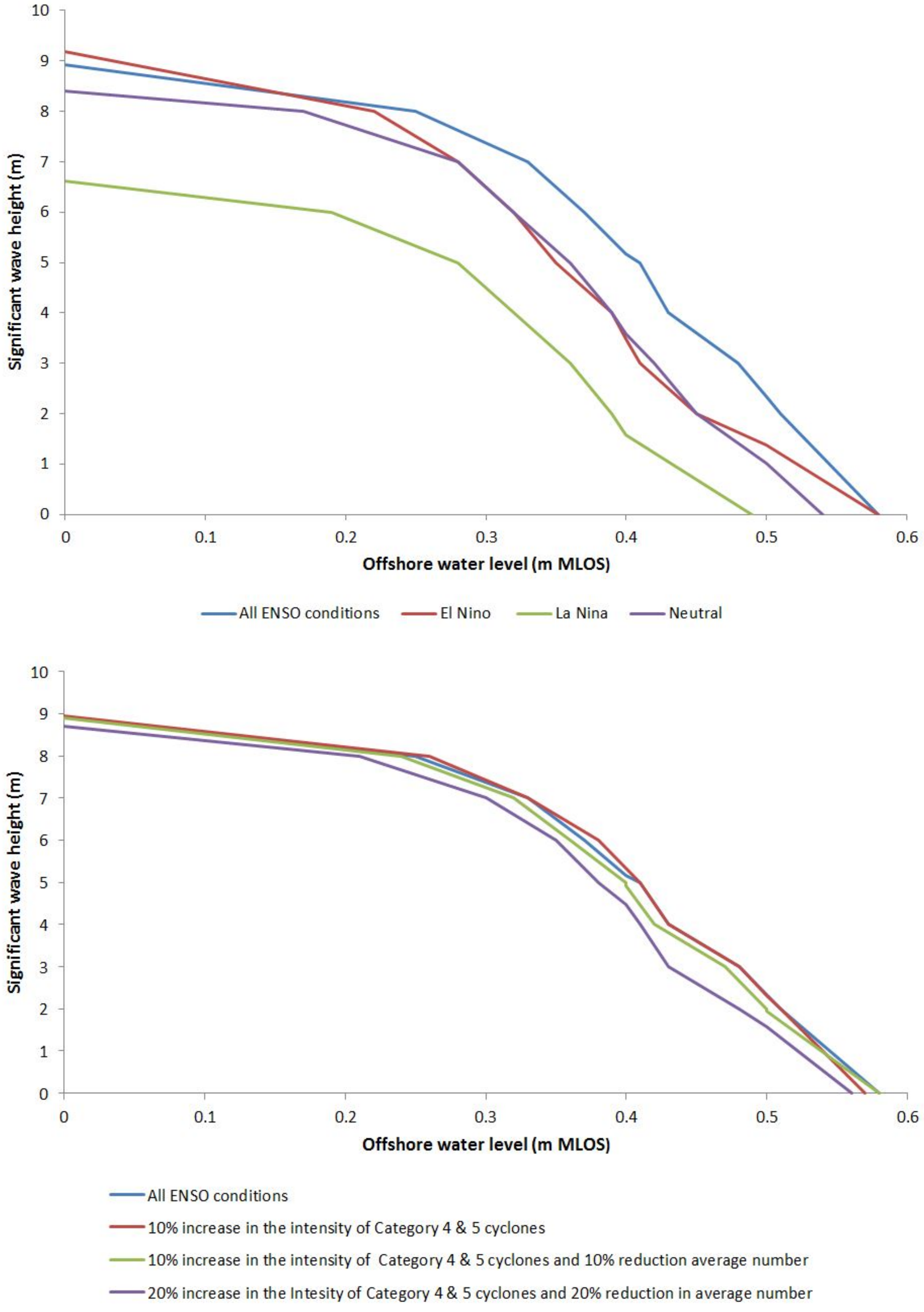


Figure 3-14:Present and future wave-water level joint occurrences for Rarotonga for an average recurrence interval of 10 years. The top figure shows the variability in present-day extreme cyclone conditions associated with different ENSO phases with the bottom figure showing the influence of potential changes in cyclone average annual number and intensity due to climate change (not including sea-level rise) (Stephens & Ramsay, 2012).

3.5 Variability and change in wave climate

Waves, typically acting during a high tide or storm tide, are generally the dominant cause of significant coastal inundation and shoreline change. The changes in variability and any long-term trend in the wave climate will have an influence on the characteristics of coastal inundation and may have a significant influence on the patterns and rates of shoreline change.

Waves are generally characterised by their height, period and directional spectrum and all have influence on inundation and shoreline change processes. In the Pacific region the most damaging wave conditions typically occur due to:

- extreme wind conditions during tropical cyclone events resulting in high wave heights of low to moderate wave period
- large swell of moderate wave period radiating out from slow-tracking cyclone events
- distantly generated long-period swell that travels from lower latitudes in both the southern and northern hemispheres
- strong locally generated wind waves within lagoons occurring during extremely high tides or sea levels.

However, the general wave climate, and variability and changes in this climate, can also be important particularly where longshore sediment transport is an important process influencing shoreline change.

Seasonal effects and the influence of ENSO on trade winds and hence wave conditions in the south-west Pacific are well established with higher significant wave heights[5] observed during El Niño periods (Figure 3-15) (e.g., Gorman et al., 2003; Hemer et al., 2010). During the 1997–98 extreme El Niño event, significant wave heights (specifically the wind wave rather than swell component) increased by up to 50 per cent in the region, due to the northward shift in the South Pacific Convergence Zone, with other ENSO events producing similar changes (Vega et al., 2010). Over the Western Pacific Ocean there is also a significant correlation between wave direction and ENSO events, particularly where prolonged El Niño events result in a weakening of the easterly trades and increase in wind from the western quadrant, with a clockwise rotation of wave direction occurring during El Niño periods (Hemer et al., 2010).

Many studies have suggested significant trends in wave heights in different oceanic regions but most relate to the mid to upper latitudes and the northern hemisphere (for example, see Lowe et al. (2010) for a summary), with very few studies available for the tropical Pacific region. The AR4 concluded (Trenberth et al., 2007) that there had been positive trends in significant wave height over the period between 1950 and 2002 over most of the mid-latitudes in the northern hemisphere but a decrease in other areas, including the eastern coast of Australia and the Coral Sea (e.g., Gulev and Grigorieva, 2004; Hemer et al., 2010) and close to the equator in the Northern Hemisphere west of 180º (Gulev et al., 2006).

[5] The significant wave height is the average of the highest one third of wave heights over a period of time.

Using projected winds from a 20 km resolution general circulation model to drive a 1.25º resolution wave model, Mori et al. (2010) showed a clear latitudinal dependence on averaged significant wave height change, with most significant change occurring in the mid- and upper latitudes (Figure 3-16). For the Pacific region this suggested that average significant wave height on the equator would decrease by about 7 per cent, corresponding to a 0.1 m decrease.

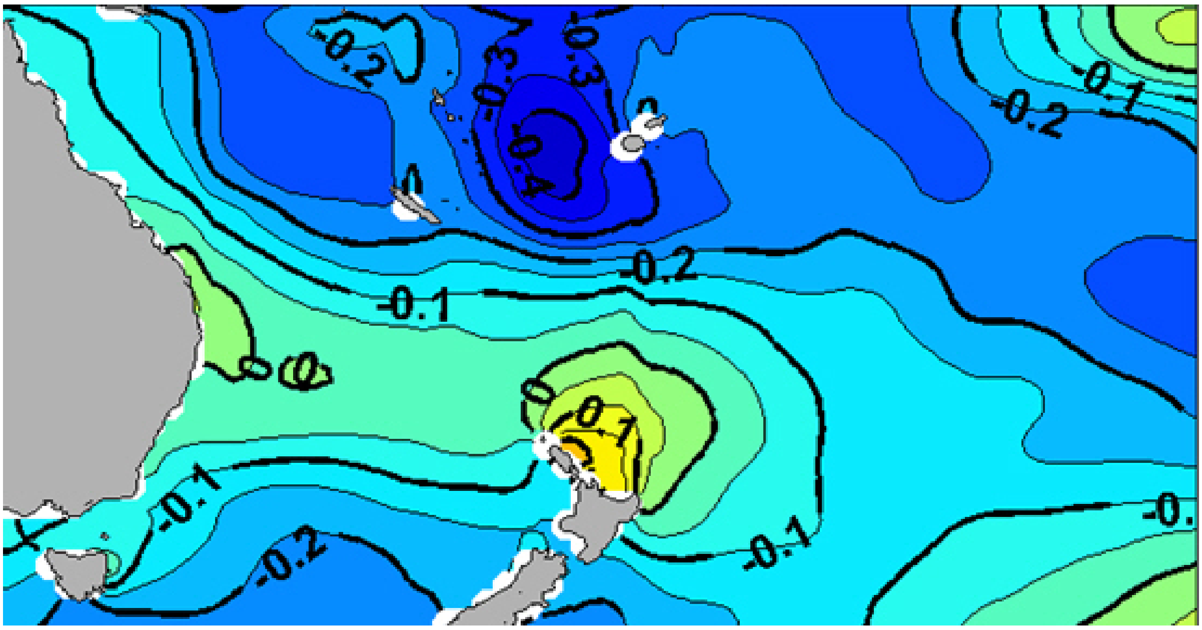


Figure 3-15:Correlation between the Southern oscillation Index and significant wave height in the South West Pacific. Based on a 20-year hindcast (1978–1998). A negative correlation indicates wave heights are higher during El Niño phases, with a positive correlation indicating higher wave heights during La Niña phases (Gorman et al., 2003).

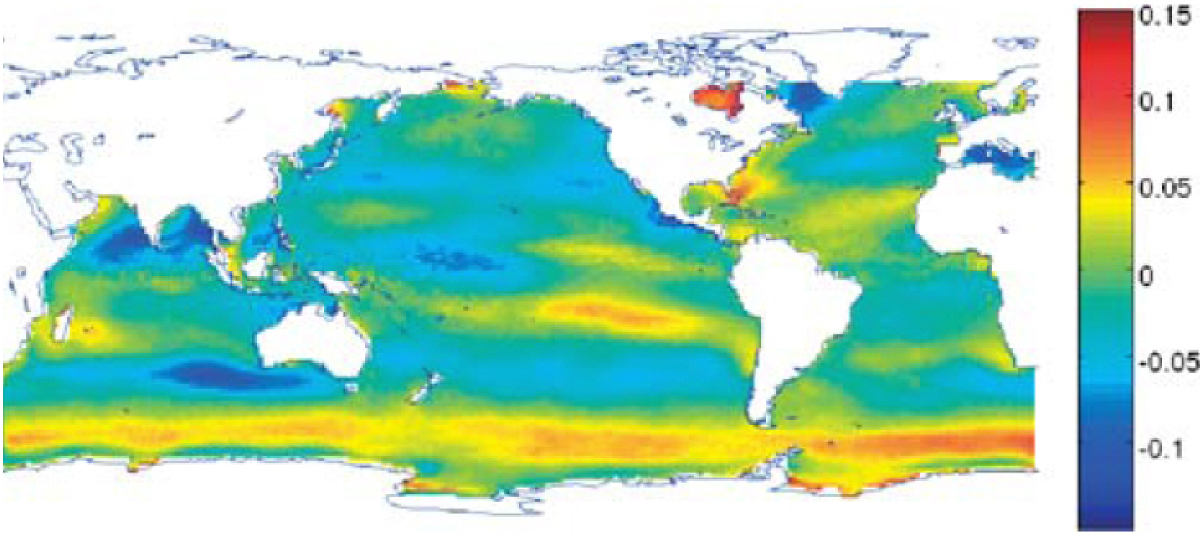


Figure 3-16:Normalised difference (future minus present, divided by the present) in average significant wave height. The present is for the period 1979–2004 and the future, 2075–2100, (Mori et al., 2010).

There are few other projections of future wave climate in the Pacific, with a lack of consistency between general circulation models in wind projections. McInnes et al. (2011), compared change in extreme and mean wind speeds for 2081–2100 relative to 1981–2000 from 19 models. For the Pacific region, model agreement suggested a mean wind speed increase during June–August in the tropical Pacific but a decrease from the equator northwards, with an increase in extreme winds of up to five per cent between 10º and 20ºS. However, despite the consistency between models, the projections and their associated implication for changes in wave climate and extremes in the tropical Pacific region need to be treated with caution because the model grids employed still do not adequately resolve tropical cyclone and other small-scale weather phenomena well. At present for the Pacific region no information is available on potential future changes in wave direction and period (which may have a greater impact on shoreline change than small changes in average wave heights).

3.6 Shoreline wave and water level processes

How potential changes in oceanic mean and extreme wave and water levels translate into changes in shoreline water levels, wave conditions, changes in wave run-up, overtopping and inundation is extremely complex and highly variable depending on how these processes and changes to these processes interact with local morphological characteristics and changing characteristics of each section of coastline.

After the astronomical tide, wave set-up (Figure 3-17), due to wave breaking on the edge of fringing or barrier reefs, can be the most significant factor raising water levels over reef flats. In some cases, such set-up can be half the offshore wave height. Wave breaking, wave set-up, the transformation of waves and wave-induced flows over the reef to the shoreline or lagoon are heavily influenced by the shape of the reef profile and how it varies along the coast. The magnitude of wave set-up tends to increase with increased wave height and is very sensitive to wave period. It is also heavily dependent on the tide or storm-tide level at the time, with increasing influence exerted by the reef top topography as the depth of water over the reef flat decreases (with wave set-up generally decreasing with increasing water depth over the reef).

The total water level (mean level of the sea + astronomical tide level + any storm surge + wave set-up) over the reef flat also determines the size of the waves that can translate over the reef flat, with the width and characteristics of the reef flat or lagoon surface determining the amount of decay in wave energy through friction effects between reef edge to the shoreline.

Few studies have attempted to assess the correlations between waves and water levels, how they relate to conditions at the shoreline, and how they may change due to sea-level rise or coral reef mortality (e.g., Sheppard et al., 2005), and resulting wave run-up and overtopping, which is the primary pathway for most episodic inundation (see next section). As both wave run-up and overtopping of beaches and coastal defences can be extremely sensitive to small changes in water levels and wave conditions reaching the shoreline, even small changes in water depths over reef flats can have a significant impact on the frequency and volume of inundation (as is seen presently during periods of higher mean level of the sea during La Niña phases).

Hence sea-level rise and resulting increased water depths over reef flats, and shallow lagoon areas where larger waves tend to be depth-limited, will tend to result in an increase in wave energy reaching the shoreline, and a non-linear response in wave run-up and overtopping. However, in the long term this will depend on the health and vertical response of coral or coralline algal growth at the reef edge (which influences how much wave energy is dissipated in wave breaking), and the characteristics and vertical response of the reef flat (which influences how much wave energy is dissipated as waves propagate over the reef flat to the shoreline).

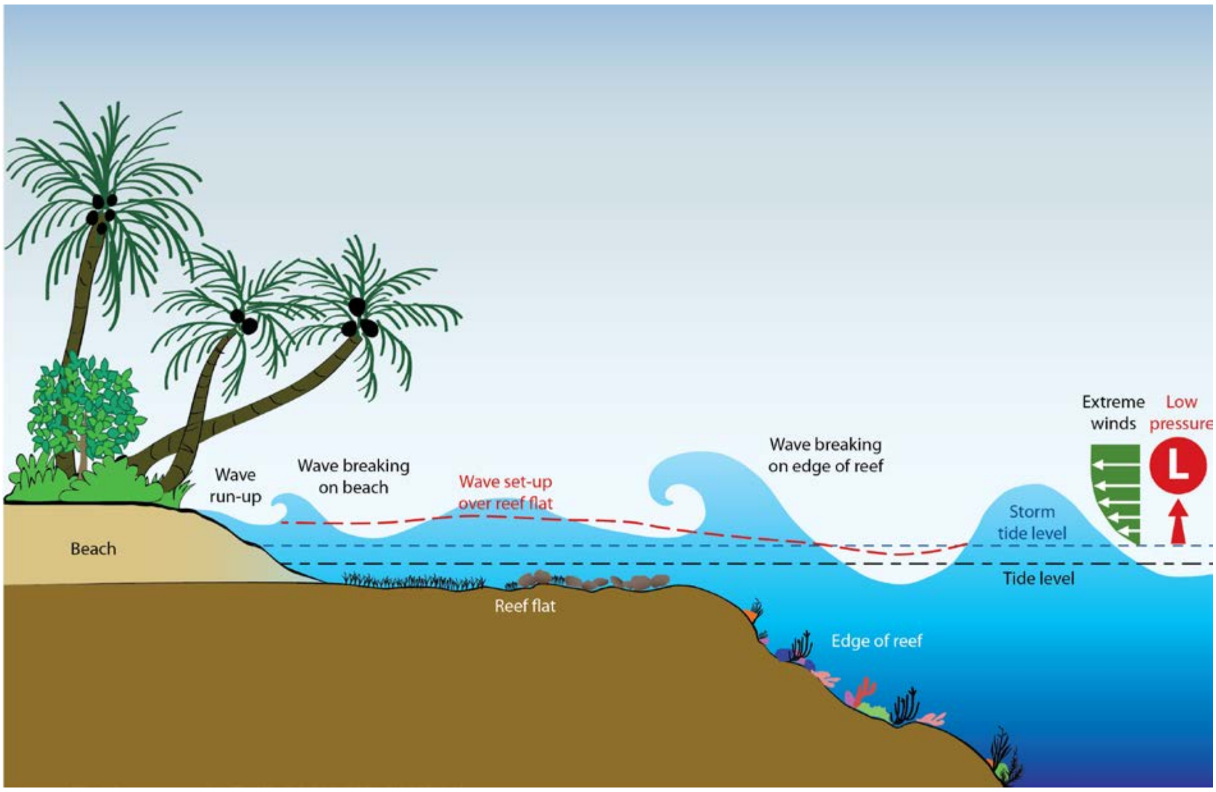


Figure 3-17: The main components of extreme water levels over a fringing reef.

4 Impact on coastal-related inundation

4.1 Inundation processes

For most Pacific countries, weather and climate-related inundation is typically episodic in nature resulting in normally dry, but low-lying coastal margins being occasionally flooded by seawater. The relative influence of the drivers of inundation can vary from event to event, between island locations and between differing island shorelines (e.g., lagoon and ocean shoreline), but typically occur due to a combination of wave conditions coinciding with high tides (Box 2):

- periods when the mean level of the sea is raised during strong La Niña phases (in the Western Pacific) or El Niño phases (in the Eastern Pacific, e.g., Kiritimati) resulting in higher than normal high tide levels. This in itself can inundate very low-lying areas during high spring tides or in combination with coincident wave conditions.
- periods when larger than normal storm waves or large swell conditions from distant cyclones or mid-latitude storms coincide with a high tide
- extreme weather events such as cyclones resulting in a high storm tide, where storm surge (due to low atmospheric pressure and strong winds) acts on top of any tide level and mean level of the sea at the time, along with large wave conditions.

High sea levels can also affect the magnitude and extent of river flooding in low-lying margins adjacent to estuaries, river mouths and delta areas.

4.2 Recent evidence of changes in coastal inundation

4.2.1 Recent changes in high sea levels

Increasing high sea levels and associated wave overtopping and coastal flooding events, particularly over the last decade in atoll nations such as Tuvalu and Kiribati are often cited as evidence of, or are directly attributed to, sea-level rise.

Global-average mean sea-levels have increased by approximately 0.17 m over the last 100 years. However, identifying whether sea-level rise over this last century has resulted in changes in occurrence or magnitude of inundation events at any location is difficult as over such timescales significant morphological and human-induced interactions and changes have also taken place, and in certain areas such as part of Melanesia, also significant vertical land movements. All influence inundation processes and associated risks.

Increasing sea-level rise will be an exacerbating factor where inundation has a history of occurring. This will be most noticeable in terms of being a factor in any changing frequency of inundation events in some of the most vulnerable locations, such as some of the very low-lying atolls in PNG, Solomon Islands and Vanuatu (which are also influenced by tectonic movements; Box 2) and in low-lying river delta areas primarily in Melanesia. However, to date there is little recorded evidence of current sea-level rise *alone* causing notable change to coastal inundation characteristics within the Pacific region.

Box 1: Examples of recent coastal inundation events

Majuro, Marshall islands

Wave overwashing of the coastal margins has been occurring around high spring tides over the December 2010 to February 2011 period resulting in flooding of low-lying parts of Majuro. The strong La Niña phase being experienced caused mean level of the sea to be raised by around 15 cm above normal, resulting in high tide levels being raised by a similar amount. Fortunately when the highest spring tides were expected in late February, unusually light winds and little long-period swell occurred for the time of year reducing the magnitude and extent of inundation.

Information and photo courtesy of Murray Ford, Coastal Processes/Management Extension Agent, University of Hawaii Sea Grant College Program

Kosrae, Federated States of Micronesia

Over 8–9 December 2008, the north coast of Kosrae experienced damage due to coastal flooding caused by a mid-latitude storm system well to the north of Kosrae. This resulted in large long-period swell conditions tracking south. Despite it coinciding with a neap tide, the swell resulted in large wave set-up, raising water levels over the reef flat and allowing larger wave conditions to reach the shoreline—causing wave run-up, overtopping and inundation of the immediate coastal margins. Inundation problems were also experienced on northern coastlines of other islands in the FSM, Marshall Islands, Palau, Marianas and a day later, as the swell waves propagated south, resulted in over 50,000 people being evacuated from coastal margins of PNG. Similar events causing substantial inundation on the north coast of Kosrae are known to have occurred in 1979, 1969 and 1961.

Photo courtesy of the Kosrae Island Resource Management Authority

Nukunonu, Tokelau

On 25 February 2005 Cyclone Percy affected the three atolls of Tokelau. The cyclone resulted in widespread damage, with wave overwashing and inundation experienced over much of the inhabited island on Nukunonu. Inundation was also on issue on parts of Atafu and Fakaofo. The occurrence of the cyclone and magnitude of the inundation experienced was influenced by: 1) a strong El Niño event, 2) the cyclone coinciding with a spring tide, 3) storm surge and wave set-up resulting in a storm tide that inundated the lower lying land areas, and 4) large waves acting on the back of the storm tide overwashing the atoll from ocean to lagoon side.

Photo courtesy of the Office of the Council for the Ongoing Government of Tokelau

Rather, the recent evidence of increased inundation is presently more attributable to long-term interannual (e.g., ENSO) and decadal (e.g., IPO) sea-level fluctuations coinciding with larger high tides at the peaks of the 4.4- or 18.6-year lunar cycles (See Section 3). At decadal scales, upon which anecdotal perceptions or evidence of change often tend to be based, the magnitude of climate change-related sea-level rise over recent decades has much less of an influence on inundation occurrence or magnitude than sea-level fluctuations due to climate variability. This is particularly the case in atoll nations such as Kiribati and Tuvalu where the tide range, and the raising and lowering of the tide range due to ENSO and longer-period tidal components, are the primary contributors to recent high sea levels and the occurrence of inundation events.

However, what these recent observations of increasing coastal inundation occurrence do indicate is that for many Pacific communities, settlements and infrastructure, even a few tens of centimetres change in sea levels is having a significant impact on the frequency or magnitude of wave overtopping and episodic inundation of immediate coastal margins upon which present-day assets and associated infrastructure are now located. As mentioned in Section 3.3, these impacts will be compounded for those Pacific islands with smaller tide ranges.

Box 2: Vertical tectonic movements and coastal flooding in the Torres Islands of Vanuatu (Ballu et al., 2011)

A coconut plantation on Loh Island in the Torres Island group flooded by seawater; photo: V Ballu, IRD

Rising sea levels around the six Torres Islands at the northern end of the Vanuatu since the late 1990s resulted in considerable headlines about the first climate change refugees, after Lataw village on Tegua Island was moved several hundred metres inland as part of an adaptation project. This followed concern about seawater extending further inland during high tides and stormy weather.

The Torres Islands are located close to the convergent plate boundary between the Australian and Pacific Plates. They have a long history of vertical land movements, particularly uplift, due to the frequent earthquakes that occur in this region.

After a magnitude Mw 7.8 earthquake in April 1997, villages noted a significant rise in sea level, which was actually caused by subsidence of between 0.5 to 1 m of the islands. Although changes in coastal flooding were noted soon after the earthquake, flooding increased in extent over subsequent years.

This gradual increase in flooding was considered to be due to global climate change. However, other factors after the 1997 earthquake are likely to have been more significant, including further lowering of the islands due to post-seismic deformation, changes in local hydrodynamics, coastal erosion and loss of shoreline barriers due to the initial subsidence and/or the tsunami that occurred due to the earthquake. Precise survey data suggest that, between 1997 and 2009, absolute sea levels rose by 150 mm (±20 mm) and the islands subsided by 117 mm (±30 mm) thereby almost doubling the rate of total or observed sea-level rise over this period. These rates exclude the sudden subsidence associated with the April 1997 earthquake.

The study emphasises the importance of accounting for vertical land movements when assessing sea-level related hazards in tectonic regions in the Pacific.

Source: Ballu et al. (2011)

4.2.2 Recent changes in vulnerability to inundation

Changes in vulnerability to inundation for Pacific Island communities are not only caused by changes in the occurrence or magnitude of inundation but are also due to economic and social changes (Yamano et al., 2007). In many parts of the Pacific it is population pressures, internal migration and high levels of urbanisation in and around island capitals increasingly resulting in development creep, with urban communities increasingly spreading into traditionally less populated locations or islands (particularly over the last half century). These recently settled locations are often more exposed to coastal-related hazards, such as inundation, than where the traditional or original settlements were established (Figure 4-1).

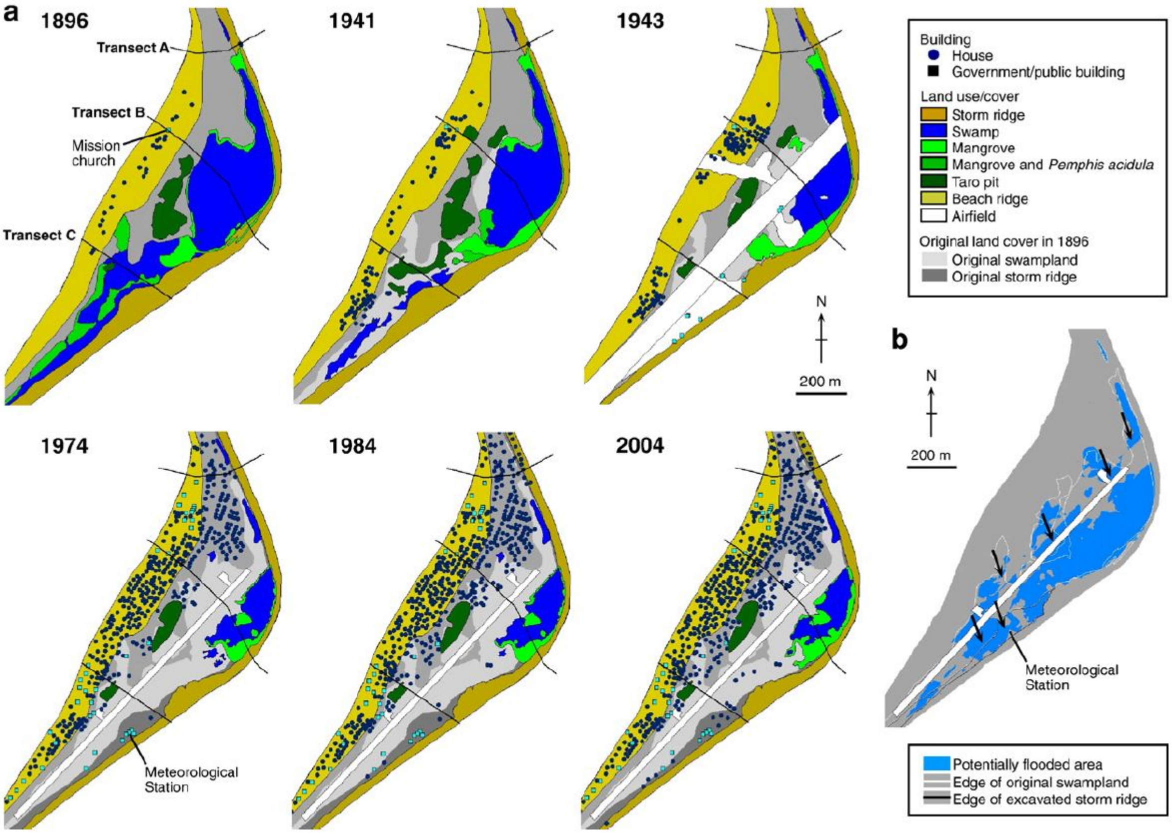
Where vulnerability to coastal inundation has substantially increased in recent decades, it is in many cases due to human-related land modification and development changes that are fundamental in driving this increasing vulnerability rather than simply changes in the hazard characteristics due to climate change and sea-level rise. In the case on Fongafale in Tuvalu, Yamano et al. (2007) provides a detailed example, incorporating consideration of existing landforms, the history of land modification, human settlement changes and economic conditions that have led to higher vulnerability to inundation (Box 3). Other recorded examples of where development has increased community vulnerability include Tebunginako village on Abaiang, Kiribati (Webb, 2006b), the Delap-Uliga-Djarrit area of Majuro, and Ebeye on Kwajalein, Marshall Islands (Spennemann, 2006).

Figure 4-1: Popua settlement in Nuku'alofa, Tonga where reclaimed land and associated development are barely above present-day high tide levels.

4.3 Future changes in coastal inundation

Climate change–related sea-level rise to-date has, in most parts of the Pacific, been a limited driver of changing vulnerability to inundation events within Pacific Island communities. However, the influence of ongoing and accelerated mean sea-level rise over the remainder of this century and beyond will increasingly become a fundamental driver that will substantially change the frequency, extent and magnitude of coastal inundation. However, there are still very few robust examples in the region where climate-change impacts on changing inundation characteristics have fully accounted for the relative influence of and interactions between the various drivers of inundation.

Box 3: Changes in land use cover and distribution of buildings in the central part of Fongafale Islet, Tuvalu from 1896 to 2004 (Yamano et al., 2007)



The central part of Fongafale Islet is typical of many atoll landforms with a high storm ridge along the ocean margin of the islet, a lower beach ridge along the lagoon side, and a low-lying area in the central part of the islet. In 1896 this low-lying area was dominated by swamplands containing mangroves with land levels below high tide levels. During high spring tides, water was observed seeping up through the swamp, ponding in low-lying depressions, and draining away during the ebb.

By 1974 an increasing population and limited land area on the beach ridge resulted in the population expanding into the central depression. Despite much of the original swampland being reclaimed for the construction of the runway in 1942, which also resulted in excavation of the storm ridge around the location of the Tuvalu Meteorological Office, some parts of the low-lying central area are still below high tide levels and still flood during high tides, such as around the Meteorological Office.

While sea-level rise over this last century will have had some influence in potentially increasing the number of high tides that cause seepage and ponding water in the low-lying areas, the vulnerability of the area is due to the original nature of the landform, and the human modifications and patterns of development within this areas that have occurred particularly over the last few decades.

The figures (a) show the changes in land use/cover and distribution of buildings over the last century, with (b) showing the distribution of swampland in 1896, with the arrows showing the locations of present flooding during high tides.

Source: Yamano et al., 2007.

4.3.1 Timing of coastal inundation changes

Inundation due to cyclone and severe storms events aside, at both interannual and interdecadal scales ENSO- and IPO-related sea-level fluctuations will continue to play a major role in moderating coastal inundation events, at least in the near to mid-term (30–50 years). If patterns in the 20–30 year IPO cycle seen historically continue, it is possible that the general characteristics of coastal inundation experienced (cyclone-related inundation events aside) since 2000 may not change significantly or only gradually in the next few decades:

- If the current cool (negative) phase of IPO continues for another 10–20 years with a similar pattern of increased neutral or La Niña phases, with higher-than-normal mean sea levels over much of the central and western Pacific, then inundation characteristics will continue to be similar to those experienced over this last decade.
- Subsequently, when IPO reverts back to a warm (positive) phase with a bias towards El Niño phases, mean sea-levels will become depressed again over much of the central and western Pacific. This may result in the long-term rate and effects of climate change-related sea-level rise to be somewhat masked over much of the next warm IPO phase.
- For the central and western Pacific it may well be towards the mid-part of this century, when the IPO next flips back into a cool (negative) phase, that significant changes to inundation occurrence will occur due to cumulative sea-level rise coinciding with the characteristic jump in sea level as the IPO phase switches back. This will be more obvious in locations outside the main cyclone zones, such as Kiribati and Tuvalu, where the astronomical tide and mean sea-level fluctuations are the dominant contributors to high sea levels. In such locations, developed islands with a smaller tide range will tend to be more vulnerable than those with higher tide ranges.

Most significant occurrences of inundation will continue to be driven by extreme weather events such as cyclones or other regional or remote storms, particularly where storm surge and larger-than-normal waves or swell coincide with reasonably high tides. Over much of this century it is likely that the strong but irregular fluctuations of such events will remain the dominant feature influencing their occurrence—and hence resulting inundation occurrence—at any particular location, more so than possible gradual changes in long-term average cyclone activity (Terry and Gienko, 2010).

4.3.2 Changes in inundation frequency, magnitude and extent

Irrespective of the normal temporal and spatial patterns of sea-level fluctuations from climate variability, over this century, particularly the latter half, increasing mean sea levels will be most evident in terms of an ever-increasing frequency of:

- encroachment of seawater at high spring tides into low-lying coastal and estuarine areas. Areas most at risk include the large delta areas that occur at the mouths of major rivers in Melanesia (Box 4), estuarine areas, low-lying areas behind natural beach/storm berms (e.g., Box 3) or embankment coastal defences, and poorly planned land reclamations.
- wave overtopping events of the natural beach/storm berm or coastal defences and associated inundation. Both wave run-up and overtopping of beaches and coastal defences is extremely sensitive to small changes in water levels and wave conditions reaching the shoreline. Changes in the frequency of wave overtopping will be a very obvious indicator of sea-level changes (Box 5). In

atoll environments sea-level rise related increases in overtopping on lagoon shorelines and related inundation are likely to be more frequent than on the ocean shoreline, due to the generally lower beach berm along lagoon shorelines.

However, wave overtopping events, particularly on ocean shorelines not constrained by coastal defences, play a role in building up land levels. As waves overtop they also deposit sand and coral rubble onto the land, building up the storm berm but also, on occasions, land levels behind the berm. Over time this can result in significant increases in land elevation. For example, on Tokelau archaeological surveys (Best, 1988) found evidence of communities on Fakaofo and Atafu atolls around 1000 years ago living on land levels between one to two metres lower than they are today and at the time much more vulnerable to wave overwashing.

- river- and drainage-related flood events, including reduced performance of surface and storm water drainage and sewerage systems in low-lying urban areas. Changes in the frequency and magnitude of river- and drainage-related flood events may well be already occurring in some areas and will be one of the more obvious indications of climate change due to the influence of both increased intensity or rainfall events and higher downstream sea levels. Areas at greatest risk include delta areas (Box 4) and near coast flood-plains and low-lying coastal urban areas.

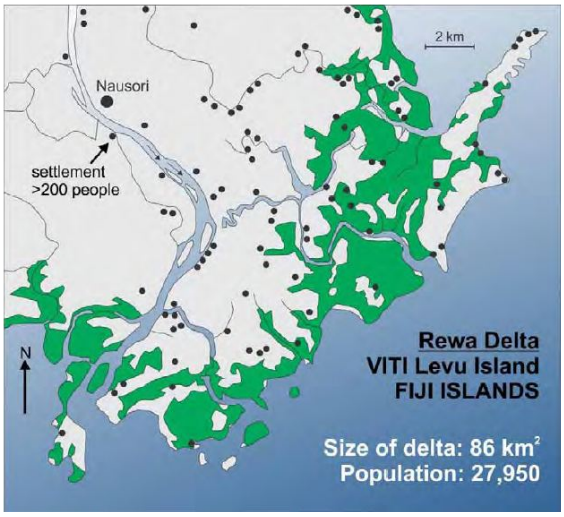
Changes in the magnitude and extent of coastal inundation in many cases will also increase but will be much more site-specific, depending on the morphology or occurrence of coastal defences in the area.

4.4 Barriers and issues related to improving the identification of inundation-prone areas

Despite the vulnerability of communities and associated infrastructure in the Pacific region to coastal-inundation hazards and one where the frequency, extent and magnitude will progressively change due to climate change and sea-level rise, there are few examples from the region where detailed coastal inundation assessments have been carried out and coastal hazard mapping conducted. This is recognised as a major impediment to better informing disaster risk reduction, land use and infrastructure planning activities and decision-making.

The most significant barrier is the lack of high-resolution land elevation information (topography) in every country in the Pacific. While relatively robust assessments of extreme wave and water levels can be derived and how these may change under different climate change scenarios, the weak link in the process is how these extreme conditions translate into potential areas impacted by inundation and how that may change in terms of frequency, extent or depth of inundation with climate change.

Box 4: Impact of climate change on delta areas in the Pacific



Location of the main communities, existing shoreline and mangrove areas (green shaded areas) on the Rewa delta in south-east Viti Levu, Fiji, (Latu and Nunn, 2011)

Delta regions on some of the larger high Pacific islands are densely populated, with large towns and key infrastructure located on them, and are often important productive agricultural areas. Major deltas in the region include:

- PNG: Sepik, Fly
- Solomon Islands: Lungga
- Vanuatu: Sarakata
- Fiji: Nadi, Rewa, Labasa
- Samoa: Vaisigano.

Human impacts affect all deltas, changing the flood regime and sedimentary processes. Impacts include:

- subsidence and compaction of the delta surface with problems exacerbated by groundwater extraction
- clearing of protective mangrove stands
- catchment forest clearing and river dams, changing water and sediment regime.

Climate change will result in increasing-intensity rainfall and higher sea levels. Both these factors, along with the existing human impacts, will result in delta areas experiencing increasingly much more frequent and severe river and coastal flood events.

In many cases there will be few options but for increasingly vulnerable communities to progressively relocate from the areas most at risk. Given the high population densities, this may become an early and significant socio-economic issue.

Indicative position of the shoreline (red line) based on present day topography for sea-level rises of 0.4 m (left), 0.8 m (centre) and 1.2 m (right). For details see Lata and Nunn (2011).

Sources: Nunn (2011), Lata and Nunn (2011).

Box 5: Impact of future sea-level rise on wave overtopping of the Dai Nippon Causeway in Tarawa, Kiribati

The *Climate Information for Risk Management* component of the Phase II of the Kiribati Adaptation Project attempted to develop risk-based information on nearshore wave and water levels and associated processes to help underpin 'climate-proofing' of future infrastructure and development.

The project conducted a detailed assessment of extreme wave and water level conditions, and how they are correlated, for both lagoon and ocean shorelines on Tarawa. A spreadsheet tool was developed to allow simple assessments (based on the approach of Sheppard et al., 2005) to be made, using the wave/water level information of the effect that climate change and sea-level rise would have on site-specific nearshore processes, including wave set-up, wave translation over the fringing reefs and sandflats, wave run-up on beaches and defences, and overtopping discharge of coastal defence structures.

As an example, the potential changes to overtopping rates of the Dia Nippon causeway were assessed. Assuming offshore wave and water level combinations associated with a 10 per cent annual exceedence probability (10-year return period) event, and a mean sea-level rise of 0.35 m by the 2050s and 0.79 m by the 2090s:

- Corresponding water levels over the reef flat during such an event would increase by 0.31 m and 0.66 m by the 2050s and 2090s respectively compared to the period between 1980 and 1999. Due to the increase in water depth from sea-level rise, wave set-up is reduced slightly (assuming no change in reef morphology).
- The significant wave height at the shoreline for the event would increase by 19 per cent and 41 per cent respectively.
- Mean volume of water overtopping the causeway on the ocean side would increase by 252 per cent and 611 per cent respectively.
- The number of waves overtopping the causeway from the ocean side over one hour would increase by 189 per cent and 255 per cent respectively.

This example assumes no change in elevation of the reef edge and reef flat topography from the present day and no change in offshore wave conditions.

In terms of overtopping performance of the causeway, due to the interaction between water levels and wave translation over the reef, to maintain the same present day overtopping performance of the causeway would require the entire causeway profile to be raised by twice the amount of sea-level rise.

Source: Ramsay et al. (2010).

For Pacific Islands and East Timor, at best available topography contours are at one-metre elevation intervals, and in other places five-metre or ten-metre intervals. For example, for Tarawa in Kiribati, land-level contours were derived from aerial photography in 1998 and are available at one-metre vertical intervals (but with a potential error of +/- 50 cm). At best, this can enable some indicative assessment of areas at risk from coastal inundation but is too coarse to assess the incremental increase in potential inundation due to climate change, particular for land areas with low relief.

Barriers to improving inundation hazard mapping also relate to:

- the complexity of inundation processes: 1) it is rarely caused by one factor alone but a combination of wave, storm and sea level variations and changes, and in some cases compounded by river/drainage processes, 2) the process and interactions between waves and water levels as waves cross nearshore and fringing reef systems and towards a shoreline, and 3) the dynamic nature of inundation, particularly the mechanism of how seawater inundates a certain land area.

- the modelling tools available and simplifications in approach that need to be made to accommodate the inundation processes outlined above
- the gap in effort between adopting a simple indicative approach to something more quantitative that considers joint probabilities of the various factors. Improving understanding of the frequency, extent and depth of inundation and how climate change will impact in a robust quantifiable way is likely to be justifiable in key sensitive areas or where there are a large number of property and infrastructure assets potentially at risk.
- the lack of data on vertical land movement in tectonically active parts of the region.

A further challenge in developing information on how coastal inundation may change over time is to ensure that they can be communicated and understood at all levels, from communities to government planners, and applied to inform decision-making. Again the current uncertainties around the potential magnitude of future sea-level rise make this a considerable challenge, but can be somewhat circumvented by an adaptive management approach to staging community adaptation.

5 Island and shoreline morphological response

5.1 Shoreline change

Sedimentary coastal margins and islands are highly dynamic systems that can show visible changes in their morphology over hours to centennial timescales, and over spatial scales from a few metres to many kilometres. They are in continual readjustment as episodic events, and variability and change in the hydrodynamic drivers, interact with the morphological characteristics of the coastal margin or island, and variability and change in the relative balance of sediment supply and losses. Around the Pacific plate boundary, tectonic factors influencing coastal uplift or subsidence can also significantly influence shoreline change (Box 2). Finally, human-related activities that impact on natural coastal physical processes have also played a significant role in influencing shoreline change and susceptibility to inundation in every nation in the Pacific and East Timor.

Morphological adjustments in coastal margins and islands include shoreline erosion and accretion, sediment wash-over, shoreline realignment and island migration (Kench et al., 2009). These adjustments are predominantly influenced by both the prevailing and extreme wave climates and how wave processes interact with the coral reef system over the range of sea levels experienced at any location. Climate change and sea-level rise will influence shoreline change predominantly due to changes:

- in wave conditions reaching the shoreline, through either increasing sea-level rise or changes to the oceanic wave climate or extremes resulting in reworking and redistribution of shoreline sediments
- in coral-reef morphology
- in sediment supply (predominantly changes in carbonate sediment budgets or catchment-derived sediment input from rivers on high islands).

5.2 Recent coastal erosion and shoreline changes

5.2.1 Shoreline variability and change

The most commonly assumed impact of sea-level rise on all sedimentary coastlines in the Pacific is that of shoreline erosion which, in the case of atoll environments, is implicated to lead to instability and eventually complete loss of islands.

From most countries in the region there are many anecdotal suggestions that sea-level rise is already causing significant erosion and loss of land with the rationale that increased sea levels cause higher water levels across reef surfaces, enabling increased wave energy to reach the shoreline, which results in increased cut-back of the shoreline (Sheppard et al., 2005).

Despite shoreline change being a major concern to the Pacific region, there are few well-documented examples that have quantified the shoreline changes occurring, and fewer examples still that have attempted to assess the key drivers and interactions causing such change.

Figure 5-1: Examples of shoreline change on Pacific Islands. *Top left*: Long-term eroding coastline on the south-east coast of Kosrae, FSM. *Top right*: Approximate increase (shown by red shading in land area of some acres after a cyclone in 1914 in Atafu, Tokelau. *Middle*: Sediment washover on Kili Island, Marshall Islands in January 2011 due to high tides coinciding with long-period swell resulting in gravel being washed up to 40 m inland (Murray Ford, pers. comm.). *Bottom (left)*: Shoreline change on Paava and Fualifeke Islets on Funafuti atoll between 1984 and 2003 (the 1984 shoreline position is shown by the pink line) (Webb, 2006a). *Bottom right:* Coastal protection along the Naitonitoni frontage on Viti Levu, due to long-term loss of land, potentially partly due to changes in sediment supply to the frontage caused by a combination of dredging of the Navua River and construction of groynes to keep drainage outlets open.

On many ocean-side beaches there is near-universal, but often ephemeral, evidence of erosion including beach scarps, undercutting of vegetation and coconut palms, and outcrops of beach rock that have become uncovered by shoreline changes (Woodroffe, 2008; Stoddart & Steers, 1997). In one of the few assessments of shoreline change in the region, covering 27 atoll islands over a 19–61 year period, Webb and Kench (2010) also found that ocean-side erosion was more common than accretion, which they suggest may be indicative of shoreline readjustments due to increased wave energy at the shoreline as a result of increased sea levels over this period. Despite this, such changes did not translate to a general net reduction in island area, with the majority of the islands showing considerable stability with either no change or an increase in overall area. On Majuro in the Marshall Island, Ford (2012) also found over a 34–37 year period that 93 per cent of urban and rural areas had increased in size. The most significant change was in urban areas due to land reclamation. Much lower rates of shoreline change were experienced in rural areas, with the lagoon shoreline generally eroding and the ocean-facing shoreline accreting.

There is also little evidence of extended periods of sea-level rise over a number of years directly resulting in increased patterns of general erosion in the region. For example, in Kiribati (Figure 3-1), and over much of the western Pacific, short-term mean sea levels rose rapidly (of the order of 0.1 m/year in Kiribati) over an approximate three-year period between late 1998 and 2002 as a strong El Niño phased changed into a La Niña and coincided with a regime shift in the IPO. Such rapid change in sea level over several years did not result in an identifiable increase in ubiquitous erosion or loss of land. This reflects that sea-level rise is only one component that influences coastal change and that erosion at one location tends to result in accretion at other locations; for example:

- In atoll situations erosion of an ocean-facing shoreline results in lagoon-side progradation (Webb and Kench, 2010).
- Along both ocean and lagoon-facing shorelines of atolls, and fringing beaches of high islands, changes in longshore planform occur due to temporal and spatial variability in littoral drift.
- In delta coastlines on high islands, fluctuations in erosion and accretion can be substantial and typically depend on the interactions between variable fluvial sediment supply to the coast and how this sediment is redistributed and reworked by coastal wave and current processes.

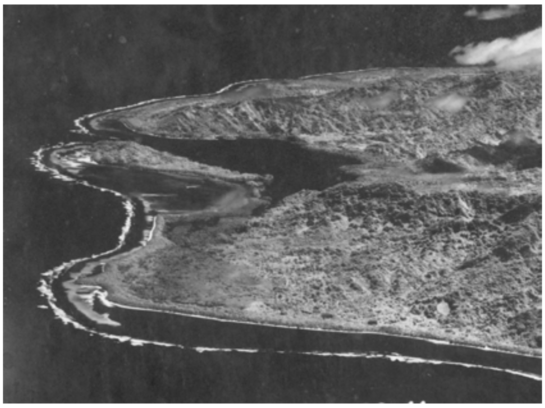
5.2.2 Storm response and recovery

Where significant erosion or loss of land does occur, it is often due to a particular storm event or a series or clustering of events, or a much more complex interaction of processes—including episodic events, annual, interannual or interdecadal variations in sea levels and wave conditions, sea-level rise and anthropogenic impacts (Box 6).

Cyclone events in particular play both an important constructional and erosional role on shorelines of reef environments, with the response depending on how frequently such events occur (e.g., Bayliss-Smith, 1988) and on the type of shoreline (Figure 5-4).

Box 6: The influence of historic cyclones and human activities on long-term shoreline changes on the east coast of Kosrae

The island of Kosrae, the easternmost island in the Federated States of Micronesia, is a high volcanic island surrounded by a narrow fringing reef and, along less exposed sections, well-developed coastal mangroves. Coastal erosion leading to a loss of land has intensified over the last 50 years leading to a landward retreat (between five and 50 m) of the shoreline, particularly along the eastern coast. This retreat is of concern as much of Kosrae's development and infrastructure is located on the coastal berm along this eastern side of the island.



Aerial photograph from 1944 looking south along the east coast of Kosrae. The rubble banks on the fringing reef flat along the east coast are still substantial features on the eastern facing reef flat over 50 years after the cyclone that created them.

Remnants of the rubble bank in 2011.

To understand why these coastal changes are occurring, it is necessary to look back to the end of the 19th century. Kosrae is rarely affected by cyclone events, with the main tracks located to the north and west of the island. The last major cyclone was in 1905 but it was a cyclone in 1891 that resulted in a bank of coral rubble being deposited on to the reef flat along much of the eastern coastline. In places it was so high that the breaking waves could not be seen (Buck, 2005).

This bank of coral rubble acted as a breakwater blocking a substantial amount of the incident wave energy that would have normally reached the shoreline. This sheltered environment in the lee of the rubble rampart enabled the shoreline to gradually build out and fringing reef mangrove strands to develop at the mouths of streams over much of the early to mid-part of the last century.

Over the subsequent decades these rubble banks gradually broke down but continued to provide a substantial level of protection to the eastern shoreline.

However, it was in the decades after World War II when considerable development commenced, including the circumferential road, and the widening of a causeway. These projects utilised large amounts of coral rubble sourced from these banks.

The removal of such a large amount of rubble from the banks both accelerated the breakdown and shoreward migration of the remaining coral rubble but also substantially reduced the protection provided to the shoreline. The increase in wave energy reaching the shoreline has subsequently resulted in a loss of the fringing mangroves and long-term and ongoing readjustment of the shoreline along much of the eastern coastline with much higher rates of erosion than has been occurring on any of the other shorelines around Kosrae.

Along fringing reef ocean shorelines (on both atoll and high islands) that experience storm and cyclone events, a coarse rubble or shingle ridge tends to occur. Single cyclone events can generate large volumes of coral rubble that are deposited on to the reef surface and can subsequently increase the land area through:

- subsequently reworking of the rubble bank onshore to the island shoreline. The rubble ridge that was created by Cyclone Bebe in 1972 along the south-eastern coastline of Funafuti (Tuvalu) is one of the best documented examples which resulted in an increase of around 10 per cent of the land area of the atoll (Margoes et al., 1973; Baines & McLean, 1976) (Figure 5-3). In atoll environments where longshore transport of material is also occurring, either during or after the event, this can also result in elongation of the island; for example, the substantial increase in land area at the southern end of Atafu, Tokelau, after a cyclone in 1914 (Figure 5-1).

- subsequent beach accretion in the lee of rubble ramparts due to changes in local wave-induced longshore beach sediment transport.

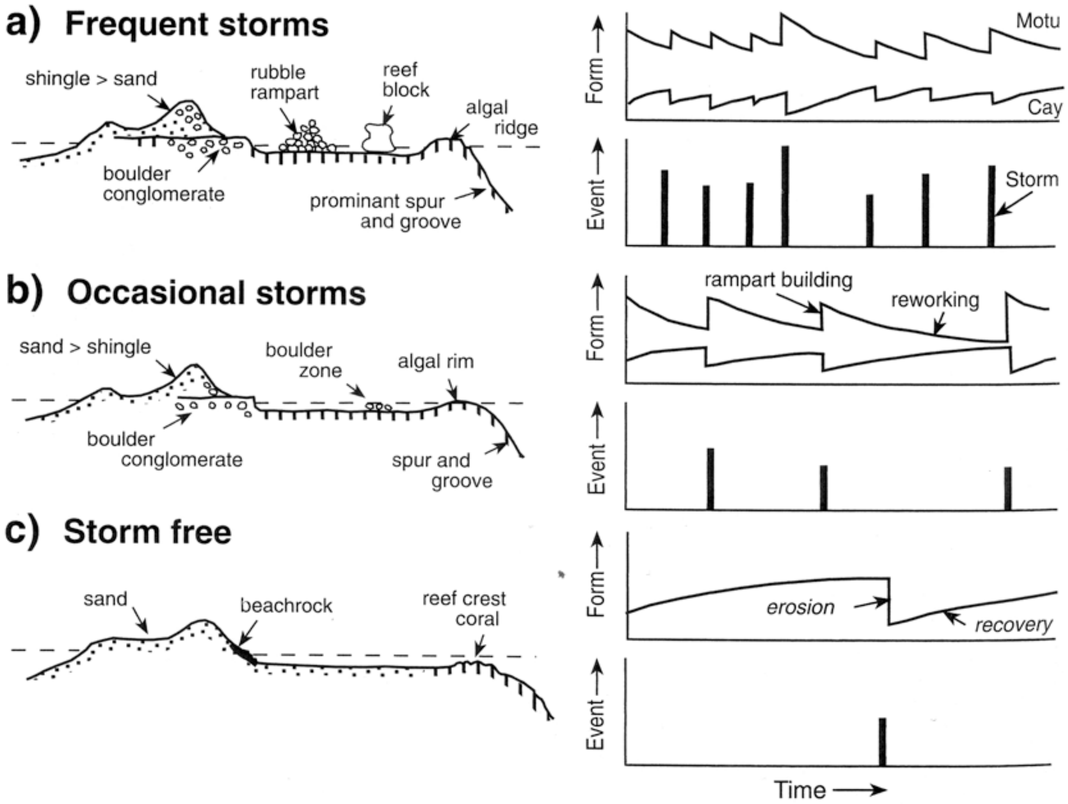


Figure 5-2: Response of ocean-facing fringing reef and sand (cay) and motu (gravel) beach systems to different storm frequency. McLean & Woodroffe (1994).

Figure 5-3: Increase in land area of Funafuti, Tuvalu due to Cyclone Bebe in 1972. The picture on the left shows the rubble bank following the cyclone (Baines and McLean, 1976) with the picture on the right (from opposite direction) showing the remnants of the rubble bank now part of the landmass of Fongafale on Funafuti in 2003.

In island locations that rarely experience cyclone or severe storm events, such as Kiribati, the island shorelines tend to be formed by sand, or with a rubble veneer in the more exposed shorelines or where there are narrower fringing reefs. In these locations storm events, particularly when they coincide with a high spring high tide, tend to result in erosion occurring. On open-lagoon or ocean shorelines, cutback of the beach and loss of front line coconut, for example, during such events does not necessarily mean that long-term erosion is occurring as often the beach will build back up after the event, but gradually and over a much longer period. The rate of recovery depends on:

- the frequency of storm events over a period of time (relative to the rate of recovery)
- where the eroded beach material has been moved to and whether it can be moved back onto the beach. For example whether it has been moved onto the reef flat and can still be transported back to the beach by wave action or whether it has been lost into deeper water; for example, over the edge of the fringing reef or into a lagoon.
- the rate of supply of new sediment to the particular beach system which depends on the types of beach sediments; for example, carbonate-derived sediments (see Lundquist & Ramsay, 2011), fluvial sediments from rivers on high islands, and the redistribution of beach sediment due to longshore transport
- the effect that humans are having on the coastal system; for example, pollution affecting carbonate sediment production, sand mining removing sediment from the beach or reef flat system, on coastal defences that affect the natural movements of beach sediments (see next section).

In high-island depositional environments where coastal margin sediments are predominantly derived from fluvial sources, such as deltas, estuarine bayhead and embayment beaches, cyclone events when they do occur can result in substantial erosion and loss of land. Recovery can be highly variable, again depending on the supply to, and redistribution of sediment along the shoreline (Box 7).

5.2.3 Shoreline response to climate variability

Cyclic trends in patterns of erosion and accretion also occur due to annual, interannual and interdecadal variability in wave climate influencing the longshore movements of beach sediments and can be a feature of both lagoon and ocean shorelines. However, given the lack of regular monitoring of shoreline movements across the Pacific there is little recorded information on such cycles. Solomon and Forbes (2006) and Forbes and Hosoi (1995) suggested that ENSO variability in winds and hence wave conditions was a factor in cycles of erosion and accretion at locations of Tarawa, although at some of the locations the likelihood of ENSO being the main contributing factor influencing erosion was subsequently questioned (Webb, 2006).

Substantial cyclic changes in shoreline position related to annual monsoonal variability on winds and hence waves have been monitored on reef islands in the Maldives (Kench and Brander, 2006). Similar annual and interannual changes have been anecdotally observed in

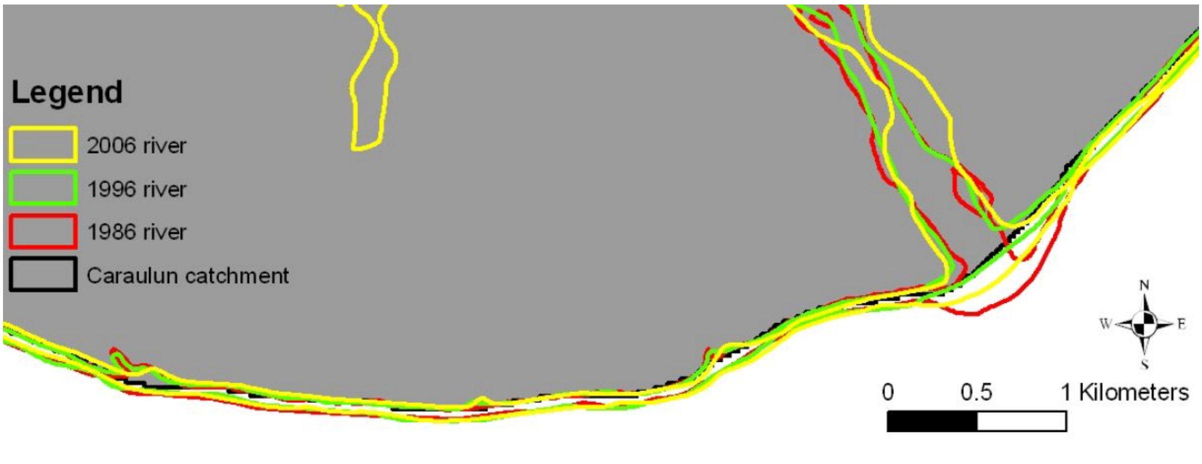
Tuvalu. For example, on Niutao, a small, near-circular patch reef atoll, there is generally a wider beach on the western side of the island due to the influence of the north-easterly trade winds. However beach sediments tend to be moved back to the eastern end of the atoll during the three-month period each year when westerly winds are more prevalent, with this effect more pronounced during El Niño phases when there is an increase in westerly wind conditions. This creates a cyclic pattern of beach erosion and accretion around the island but likely little net change in actual island area.

Box 7: Catchment changes and shoreline change in Timor Leste (Alongi et al., 2009)

The north coast of Timor Leste is characterised by narrow fringing coral reefs with embayment sandy beaches and narrow mangrove strands between rocky headlands. The south coast has a much wider and shallower shelf than along the north coast and this, along with persistent onshore current and wave conditions, has led to the development of areas of beach ridge plains parallel to the shoreline with the sediment supplied for the formation of these beach ridges predominantly from the catchments that drain to the coast. Lagoons can occur landward of the beach ridges and are colonised by mangroves.

In the Laclo catchment (that drains to the north coast) and Caraulun catchment (that drains to the south coast), catchment erosion is now up to 20 times higher than it was in historical times due to land-use change, particularly the removal of vegetation from riverbanks. This has increased the sediment loads in the rivers causing shallowing and widening in their lower reaches resulting in increased bank erosion and flooding, and more erratic river flows as channels have widened and braided.

The increased sediment loads have also supplied more sediment to the coastline. Off the Laclo River on the northern coast this sediment has largely been deposited in deeper water offshore with little impact on the adjacent coastline (which experiences relatively little variability in shoreline movement) and mangroves. However, the increased sediment supply has resulted in more rapid seaward growth of the Caraulun delta with mangroves also being partly buried on the delta due to the high loads. The clearance of vegetation in different parts of the catchment at different times is thought to be a significant factor in the patterns of erosion and accretion at the river mouth and along the adjacent sections of coast. Mapping of these changes over recent decades suggests that the area of coastline has not changed much between 1986 and 2006 but that there have been considerable changes (of the order of many tens to hundreds of metres) in the shape of the coastline, with some sections of coast showing both periods of retreat and advance of the shoreline with other areas experiencing only retreat or advance. However, understanding these patterns of shoreline change (and how they may change in the future including due to the added effects of climate change) is extremely complex given the interactions between river flows and sediment loads reaching the coast, and the coastal processes acting on the southern coast.



Coastal change in the Caraulun delta and adjacent coast (Alongi et al., 2009)

5.2.4 Human influences on coastal erosion

While natural factors influence changes in shoreline position over varying temporal and spatial scales, where erosion has been severe over the last half century it has often been caused, or significantly influenced, by human activities. These human impacts diminish the resilience of the coastal protection function of the natural beach system and limit its ability to recover from natural disturbances, such as storm events.

Human influences on shoreline change are often relatively localised, have a direct impact, and are linked to rapidly increasing populations, urban development and development-related changes in construction practices requiring a source of construction aggregate. The most detrimental practices influencing erosion of Pacific Island coastlines include:

- removal of coral rubble from the reef flat surface (Box 5). This removes a future source of coral rubble to the adjacent shoreline, reduces the dissipation of wave energy propagating over the reef resulting in larger wave conditions reaching the shoreline, and can also remove habitat for sand-producing organisms such as foraminifera.
- removal of sand and shingle from the beach (Figure 5-4). There is a finite reservoir of sediment on reef islands and coastal margins dominated by carbonate sediments. Removal of sand from the beach for construction or other activities is a loss from the beach system and a direct cause of erosion.
- reef-flat dredging with the resulting dredge pits or reef channels acting as a sediment trap and causing loss of beach sediment and erosion of adjacent shorelines (Figure 5-4)
- alterations to the position of river, stream or drainage outlets resulting in readjustments of the adjacent sections of shorelines
- dredging of rivers for navigation and flood alleviation which reduces fluvial sediment supply to adjacent coastlines (Figure 5.1)
- changes in catchment land-use and vegetation clearing (see Box 7)
- construction of causeways across intertidal channels which can cause both accretion and erosion of adjacent shorelines (Figure 5-4)
- construction of inappropriate coast defenses, land reclamation, or other structures over the active beach that impact on the longshore movements of beach sediments (Figure 5-4)
- clearing of shoreline mangroves or vegetation from the immediate backshore.

Human effects can also be indirect, impacting on the ecological functioning of the reef system which in turn can impact on nearshore wave- and water-level processes (Sheppard et al., 2005), and on sediment supply and composition to reef landforms. Key impacts include nutrient and sediment run-off from adjacent catchments, marine pollution, and overfishing of key grazing reef fishes (see Lundquist and Ramsay, 2011).

Figure 5-4: Examples of human impacts on shoreline changes. *Top left*: Sand mining from the beach on Tarawa. *Top right*: Dredged pits (dark blue areas) on the reef flat at Tafunsak, Kosrae resulted in rapid erosion of the adjacent coastline along Tafunsak village frontage. *Bottom left*: Build-up of land due to causeway construction of Tarawa. *Bottom right*: Downdrift erosion along the Sandy Beach Hotel frontage on Kosrae caused by coastal defence construction.

5.3 Key features of island morphology and processes and their sensitivity and resilience to change

It is generally accepted that the coastal margins of Pacific Islands (and East Timor), particularly low-lying atoll island states, and river delta regions on some of the high islands, will be particularly vulnerable to the impacts of climate change and sea-level rise.

However, an increasing number of studies suggest that reef islands and associated shorelines have some degree of natural resilience and adaptive capacity (Kench et al., 2005, Woodroffe, 2008; Kench et al., 2009; Webb & Kench, 2010), and that over recent rates of sea-level rise a significant number of atoll islands have shown little net change in land area, or have increased in area, with only a few showing loss of land area, over multiple decades. Despite the small net changes observed in land area, significant localised changes in shoreline position were noted as occurring in some cases as islands adjust their position on the reef platform (Webb & Kench, 2010; Ford, 2012).

Pacific Island shorelines and islands can be highly dynamic features that can change position and evolve over a range of timescales in response to the natural processes that drive such changes (waves and water levels and the effects that climate variability and change has on these processes), and human impacts. The form and magnitude of change in reef island and shoreline morphology, due to global climate change, will vary considerably from place to place.

A fundamental challenge for communities living in such environments is carrying out development in a way that both recognises and accommodates such change, and factors in that such change is likely to happen at a greater rate than has occurred over the last century.

5.3.1 Atoll and barrier reef islands

Changes to reef islands and shorelines will include combinations of both horizontal (profile) changes, summarised in Figure 5-5, and planform changes such as lagoon progradation, island migration on the reef platform, island expansion and extension (Webb & Kench, 2010).

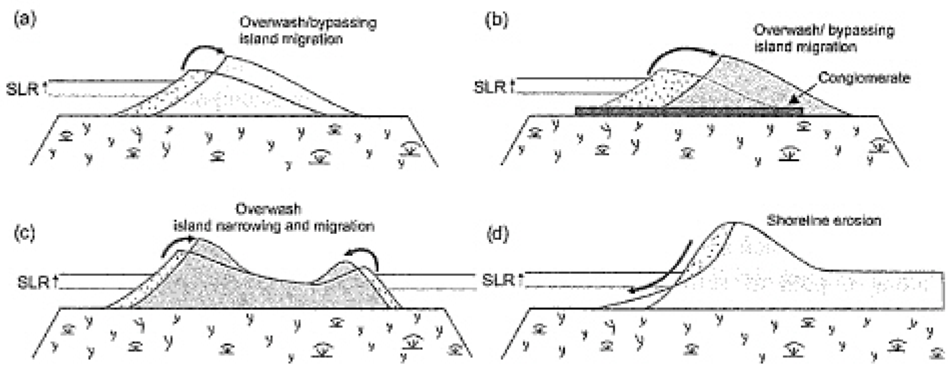


Figure 5-5: Summary of horizontal response of reef shorelines to increased sea-level rise assuming no change in sediment budget. Source: Kench & Cowell (2002).

These modes of change identified by Kench and Cowell (2002) identify a number features of morphological change related to sea-level rise:

- Morphological change of the order of 3 to 15 m was identified for a sea-level rise of 0.5 m.
- The mode and magnitude of change was very dependent on the present morphology, particularly island elevation, volume of sediment and accommodation space (the space available on a reef or lagoon sand flat to accommodate island movements).
- Horizontal movement of the shoreline did not necessarily imply erosion; rather, overwash of island and inlet bypassing results in migration of islands that can conserve and build up island sediment volume.
- Deposition from overwash can raise storm ridge and adjacent land levels.
- Beaches and the seaward vegetated island margins are susceptible to reworking but the vegetated cores of islands are likely to remain stable.

Based on Richmond's (1992) characterisation of atoll islets (Figure 2-3), their resilience to change can be summarised as:

More susceptible to change	Type 1:	Characterised by constant fluctuations in size and shape and shifting of position of the reef platform, but often with minimal change in land area. However, they are susceptible to significant modification during large storms and even complete destruction.
	Type III and IV	Over time they gradually reduce in size, with Type IV islets tending to migrate landwards until a cyclone or storm event of sufficient size to deposit coral rubble renourishes and rapidly increases the islet size. They can be reshaped considerably during such storm events.
Less susceptible to change	Type II	Can experience shoreline modification by infrequent catastrophic events but are in a state of dynamic equilibrium with land area gradually increasing. Typical planform changes include erosion on the ocean shoreline, island elongation and lagoon progradation towards the ends of the islet.

These adjustments provide an insight as to how reef shorelines and islands will continue to respond in the near- to mid-future, the rate of which will still be driven by event to decadal scale processes. The sensitivity of reef islands and shorelines to change will depend on the interactions between a complex set of factors including accommodation space, the present process regime, sediment supply and losses, as well as global climate change and human impacts (Kench et al., 2009). These factors and their influence are summarised in Figure 5-6 for atoll islets but are also generally applicable for most reef shorelines.

Where global climate change affects the reef-system sediment budget this is likely to drive significant shoreline change and potential instability in reef landforms, possibly more so than sea-level rise (Kench & Cowell, 2003), either through:

- changes in the sediment supply with even small negative shifts in the sediment budget being shown to accelerate change (Kench and Cowell, 2003). Given that both supply and composition of sediments can vary significantly in response to changes in reef growth and ecology, climate change impacts particularly related to sea-surface temperature rise and ocean acidification and ongoing human impacts such as excessive nutrient and sediment run-off, have the potential to significantly affect sediment budgets contributing to reef landform evolution.

- changes in the littoral budget with changes in net littoral sediment transport patterns (e.g., due to changing wave climate reaching shorelines), having considerable potential to reconfigure alongshore shoreline position.

The limited number of geomorphic and model studies conducted to-date suggest that reef landforms have a greater degree of resilience, at least in the near- to mid-term, than is commonly assumed. Reef landforms will continue to undergo modification and change with island persistence and resilience highest in those systems that can reorganise and establish new regimes while maintaining or increasing sediment deposits (Kench et al., 2009).

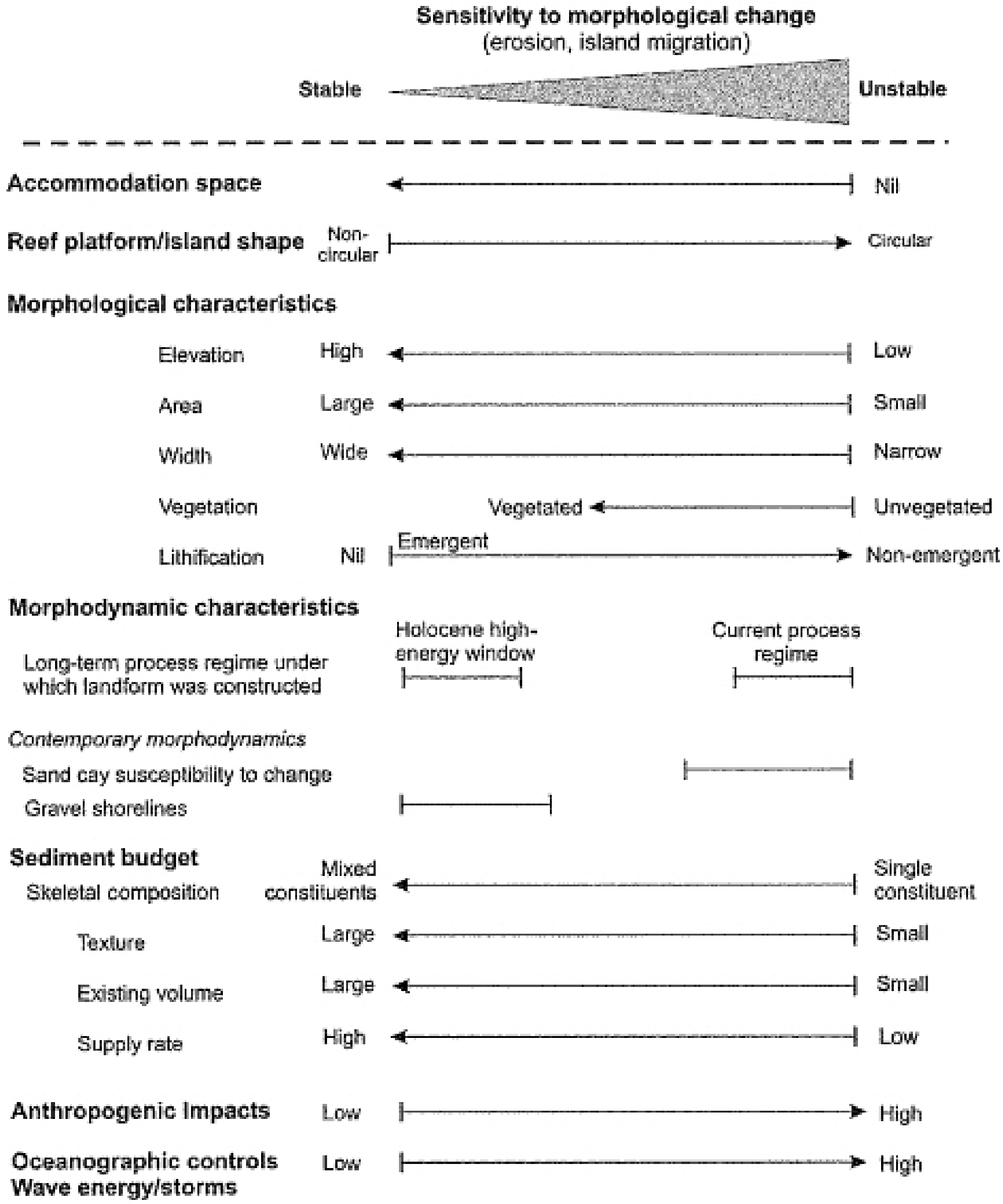


Figure 5-6: Factors influencing the future sensitivity of reef sedimentary landforms to geomorphic change. Arrows depict increasing values of each characteristic that makes landforms more or less susceptible to change (Kench et al., 2009).

However, whether global climate change and sea-level rise in the longer term (towards the end of the century and beyond) will result in environmental thresholds beyond which reef landform change becomes unstable or untenable for communities living there is less well understood. Dickinson (2009) suggests a threshold based on the mid-Holocene sea-level highstand and emergent levels of conglomerate platform. While these levels vary within the region, Dickinson suggests that for a high rate of sea-level rise over this century the threshold could be surpassed in the latter part of this century (2050–80) and for a lower sea-level rise rate by early next century (2100–60).

The impacts on the ecological functioning of reef carbonate systems caused by increasing sea-surface temperature, ocean acidification and ongoing local human impacts such as overfishing and nutrient run-off may result in other environmental thresholds being surpassed earlier than those associated with sea-level rise. Over this century, such ecological impacts may result in a much more a significant impact on both the stability of shorelines and reef landforms and the communities located upon them, than sea-level rise (Lundquist & Ramsay, 2011).

5.3.2 Volcanic islands

Many of the same factors (Figure 5-6) that influence change on atoll and barrier reef landforms also apply to shoreline change on the sedimentary coastal margins of high volcanic islands.

Where shoreline position is strongly dominated by inputs of fluvial sediments, such as deltas, estuarine bayhead and embayment beaches, shoreline change will continue to be highly variable (Box 7) with long-term changes dependent on the balance between volumes of sediment supplied to the coastal system relative to sea-level rise. Delta areas and areas adjacent to river mouths may well be the most sensitive coastal areas to shoreline change in the region.

On open sections of long fringing beach systems, and associated coastal features such as spits and cuspate forelands, changes in longshore transport patterns and rates may well have the most significant impact on changing patterns of erosion and accretion. Any retreat of shoreline position will also depend on hinterland characteristics; for example, elevation of land behind the immediate shoreline. Where the coastal margin is largely a storm berm backed by lagoon, mangrove or wetland swamp, such as found in Kosrae (Box 6), similar profile responses as shown in Figure 5-5a, b and d will occur. Where land levels behind the shoreline are higher or are rising, any rate of retreat would be expected to be relatively more modest.

5.3.3 High limestone islands

Given that high limestone island coastlines are typically characterised by cliffs or sloping limestone platform and little unconsolidated shoreline sediments or low-lying areas, such islands are relatively much more resilient to climate change-related shoreline change.

However, where uplift history is more complex, and low-lying coastal plains have developed, or islands are being tilted, such as Tongatapu (Figure 2-2), much more rapid erosion and loss of land could be experienced than in many other places, due to the combined influence of subsidence and sea-level rise.

5.4 Barriers and issues related to improving the understanding of shoreline change

Quantifying how the shorelines in the Pacific region and East Timor will be influenced by climate change is extremely difficult. Physical shoreline change is caused by a complex interaction of coastal hydrodynamics, morphology, ecology, geology, sediment supply and losses, sediment redistribution and reworking, and in many cases human influences or all interacting over multiple time and space scales.

To date there are few examples that have attempted to assess robustly how climate change will influence shoreline change in the Pacific region and East Timor, other than at an extremely simplistic level; for example, use of inappropriate empirical tools such as the 'Bruun Rule' (Bruun,1962) for many Pacific Island situations. There are two key factors that need to be addressed to enable more rigorous approaches to assess shoreline change over the timeframes that are of use for development planning:

- the lack of process-based approaches, in a Pacific context, that can simulate the complex influence that the drivers and interactions of the drivers, including climate change, have on how shorelines will change over the spatial and temporal scales of interest
- the lack of high-quality coastal observational information to understand the patterns and rates of shoreline changes and to better understand the relative influences of the drivers of these changes.

6 Conclusions

It is generally accepted that coastal margins and associated communities, particularly in low-lying atoll island states and river delta regions on some of the high islands in the Pacific region (including East Timor), will be particularly vulnerable to the impacts of climate change and sea-level rise. The fundamental physical aspects underpinning coastal-related vulnerabilities relate to land, water resource and food security issues, primarily due to potentially permanent erosion of the shoreline and loss of land, permanent inundation and increased frequency, magnitude and extent of episodic inundation of low-lying land areas, saline intrusion into freshwater groundwater lenses, and loss or reduction in coral reef biodiversity and productivity.

The magnitude of the inundation and shoreline changes and impacts that will be caused by climate change including sea-level rise on Pacific coastal margins will occur at a range of space and timescales, and vary between islands and different locations on islands. Such impacts will depend on:

- the complex interaction between the local physical drivers (waves and water-levels and in some cases river/stream outlets) that shape island shorelines and the impacts of climate change on these drivers
- how these drivers interact with the existing morphology and current biophysical characteristics
- rates of vertical land movement (as it is relative sea-level rise that needs to be adapted to at the local level, not the absolute global sea-level rise)
- sediment composition and balance between sediment inputs and losses on a particular coast
- the influence that humans have had, or are having, on the coast.

The effects of climate change on coastal inundation and change in the Pacific region and East Timor is likely to be felt first (and possibly most significantly) through possible changes in the *impacts* of episodic extreme weather events. Primarily changes in such impacts will be caused by:

- the gradual exacerbation of the effect of these events by sea-level rise (which raises the platform for dynamic wave and storm-tide processes to operate)
- potential ecological changes through temperature-related and ocean-acidification stressors, reducing the natural resilience and protection services provided by coastal ecosystems
- ongoing local human impacts such as nutrient run-off and overfishing on coral reef ecosystems, again impacting on the natural resilience and protection services provided by coastal ecosystems.

In the longer term, further changes in impacts could arise from climate change effects potentially altering the characteristics of these extreme events (e.g., storm frequency, seasonality and intensity).

Coastal inundation

Over the last decade, there have been increased reports of higher sea levels and subsequent coastal inundation episodes throughout the region. These can mostly be attributable to sea-level fluctuations arising from interannual cycles (e.g., ENSO) and coinciding interdecadal cycles (e.g., IPO), whereas ongoing sea-level rise appears to have played a secondary role in these occurrences. In spite of climate variability being the primary cause of these recent events, what this pattern does indicate is that for many Pacific communities, settlements and infrastructure, even a few tens of centimetres change in sea level is having an increasing effect on the frequency or magnitude of wave overtopping and episodic inundation of immediate coastal margins upon which present-day communities and associated infrastructure are now located. Such inundation effects from climate variability will only be compounded as sea-level rise accelerates during this century.

Changes in vulnerability to inundation for Pacific island communities are not only caused by changes in the occurrence or magnitude of inundation but are also due to economic and social changes. In many parts of the Pacific, vulnerability is also driven by population pressures, internal migration and high levels of urban sprawl in and around island capitals increasingly spreading into traditionally less-populated locations or island. These more recently developed locations are often more exposed to coastal-related hazards, such as inundation, than where the traditional or original settlements were established. Where vulnerability to coastal inundation has substantially increased in recent decades, it is in many cases primarily due to human-related land modification and development changes that are fundamental in driving this increasing vulnerability rather than simply a change in the hazard characteristics due to climate change and sea-level rise.

Despite this, the influence of the ongoing rise in relative sea-level rise, including vertical land movement, will increasingly become a fundamental driver changing the frequency, extent and magnitude of coastal inundation, and hence increased vulnerability to inundation in the future. However, over the near- to mid-term (next 30–50 years), ENSO- and IPO-related sea-level fluctuations will continue to play a major role in causing year-to-year and decade-to-decade variability in the magnitude and frequency of coastal inundation events. If historical patterns in the 20–30 year IPO cycle continue, it is possible that the heightened frequency of coastal inundation events experienced since 2000 may not change significantly, or only gradually, in the next few decades. It may not be towards the mid-part of this century, when the IPO next switches to a cool phase (as is being experienced at present), that significant changes to inundation occurrence will be more obviously attributable to ongoing sea-level rise.

Shoreline change

From most countries in the Pacific region there are many anecdotal reports that sea-level rise is already causing significant erosion and loss of land. On many ocean-side beaches there is near universal, but often ephemeral, evidence of erosion including beach scarps, undercutting of vegetation and coconut palms, and outcrops of beach rock that have become uncovered by shoreline changes. However, there is less reported evidence of erosion translating into a general net reduction in island area under sea-level rise rates experienced over the second half of the last century up to the present. This reflects that sea-level rise is only one component that influences coastal change and that often erosion at one location tends to result in accretion at other locations.

Where significant erosion or loss of land does occur, it is often due to a particular storm event or a series or clustering of events, or a much more complex interaction of processes including episodic events, annual, interannual or interdecadal variations in sea levels and wave conditions, sea-level rise and anthropogenic impacts.

Despite shoreline change being a major concern to the Pacific region, there are few well-documented examples that have quantified the shoreline changes occurring, and fewer examples still that have attempted to assess the key drivers and driver interactions causing both past and potential future shoreline change.

The most significant coastal changes are likely to occur in river deltas and areas where shorelines are strongly influenced by river flows and fluvial sediment supply. Such areas will be particularly sensitive to a range of climate change impacts. Given the high population densities found in delta areas, this may become an early and significant socio-economic issue where there is little option but for communities and infrastructure to be relocated.

It is suggested that reef landforms have a greater degree of resilience than is commonly assumed, at least in the near- to mid-term (30–50 years). They will continue to undergo modification and change, which will vary from place to place and include combinations of both horizontal (profile) changes and longshore or planform changes. The sensitivity of reef islands and shorelines to change will depend on the interactions between a complex set of factors, including coastal accommodation space (the area over which shorelines are free to flex), the present characteristics of coastal processes and sources and losses of coastal sediments, as well as global climate change and human impacts.

Whether global climate change and sea-level rise in the longer term (towards the end of the century and beyond) will result in environmental thresholds beyond which reef landform change becomes unstable or untenable for communities living there is less well understood. There is some suggestion of a sea-level threshold, based on the mid-Holocene sea-level highstand and emergent levels of conglomerate platform, beyond which the extent of erosion may make many islands uninhabitable. For a high rate of sea-level rise over this century this threshold could be surpassed in the latter part of this century (2050–80) and for a lower sea-level rise rate by early next century (2100–60).

The impacts on the ecological functioning of reef carbonate systems caused by increasing sea-surface temperature, ocean acidification and ongoing local human impacts such as overfishing and nutrient run-off may result in other environmental thresholds being surpassed earlier than those associated with sea-level rise. Over this century, such ecological impacts may result in a much more significant impact on both the stability of shorelines and reef landforms and the overall viability of communities located upon them, than sea-level rise.

7 References

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