12

# Sea-level Rise

*John Church, Neil White, John Hunter, Kathleen McInnes, Peter Cowell and Siobhan O'Farrell*

Most Australians live near the sea, with all of the state capitals being located on the coast. The modern 'sea change' phenomena is seeing even more people moving to the coast, leading to rapidly growing populations in such areas as the Gold and Sunshine Coasts in South-East Queensland, and the northern New South Wales coastal region. Chen and McAneney (2006) estimate that about half of Australia's population lives within 7 km of the coast, with as many as 30%, or about six million people, within 2 km of the coast. They also estimate about 6% of Australian addresses are situated within 3 km of shorelines in areas with elevations below 5 m above mean sea level.

The coastal margins are intimately affected by the level of the sea, which varies over a wide range of time scales. Sea level is influenced by ocean waves, twice-daily and daily tides, meteorological fluctuations over days to weeks, and seasonal, inter-annual, decadal and multi-decadal variations. Superimposed on these variations, there has been an overall rise at a rate of just less than 2 mm per year in global mean sea level during the 20th century. This rise was caused predominantly by rising global temperatures (Bindoff *et al.* 2007; IPCC 2007). Coastal vulnerability is affected by an increase in ocean volume causing a rise in globally averaged sea level, redistribution of ocean mass associated with changing climate and by vertical movement of the land. There are large-scale vertical motions of the Earth's crust associated with past and ongoing changes of surface loads on the earth (glacial isostatic adjustment) and local tectonic motions (particularly subsidence) in some coastal regions. The combination of these effects causes the sea level to rise relative to the land ('relative sea-level rise').

The impacts of sea-level rise include coastal inundation and erosion, higher waves at the coast, and salt water intrusion into estuaries, wetlands and aquifers. In some regions, beaches and coastal wetlands become squeezed between the hard barrier of coastal developments and the landward migration of the coastline. If not protected in some way, the natural environment may be lost. Virtually all of these impacts are felt most acutely during extreme high sea-level events and storms (storm surges) when substantial inundation of low lying areas and rapid coastal erosion can occur. Much of Australia's (and the world's) coastal development over decades and centuries has occurred during a period of stable sea levels, with little concern for any potential changes in future sea levels. With sea levels now beginning to rise as one component of anthropogenic climate change, both coastal infrastructure and some of Australia's iconic coastal environments are threatened.

## Global mean sea-level change

### Historical rates of global sea-level change

Globally, the sea level has varied by more than 120 metres over glacial/interglacial cycles. At the time of the last interglacial, the sea level is thought to have been 4 to 6 metres above present day level, with a significant contribution coming from a partial deglaciation of Greenland (Stirling *et al.* 1998; Overpeck *et al.* 2006). At that time, temperatures over Greenland are estimated to have been several degrees warmer than today's values (Otto-Bleisner *et al.* 2006), and perhaps similar to temperatures projected for the end of the 21st century (IPCC 2007). For roughly the 100,000 years following the



in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

last interglacial, sea level fell by over 120 metres as major ice sheets were formed in northern America, Europe and Asia and the Antarctic ice sheet grew. From the last glacial maximum about 20 thousand years ago until about 7000 years ago, sea level rose by over 120 metres at an average rate of about 10 mm per year (1 metre per century), with peak rates as high as 40 mm per year (4 metres per century) (Fairbanks 1989; Lambeck *et al.* 2002). Over the last 7000 years, the rate of sea-level rise has been substantially slower (Lambeck 2002). The height of ancient Roman fish tanks built about 2000 years ago indicate there has been little net change in sea level between then and the start of the 19th century (Lambeck *et al.* 2004).

Sediment cores collected from coastal salt marshes in the western and eastern North Atlantic Ocean (Donnelly *et al.* 2004; Gehrels *et al.* 2005; Gehrels *et al.* 2006) indicate an increase in the rate of sea-level rise in the 19th to early 20th century, consistent with the few available long tide-gauge records, the longest of which date back to about 1700 (Woodworth 1999). (This technique has recently been applied on the east coast of Tasmania to determine a relative sea-level curve for the past few centuries, but the results are not yet available.)

Since 1993, there have been high-quality satellite-altimeter observations of sea levels over most of the globe (about 66°N to 66°S), allowing accurate estimates of both globally averaged and regional sea-level change. Global correlation patterns (called *empirical orthogonal functions*) estimated from the satellite altimeter record have been combined with coastal and island tide-gauge data (corrected for glacial isostatic adjustment) to estimate globally averaged sea levels since 1870 (Church and White 2006). The results show that, from 1870 to the present, global sea level has risen by about 20 cm, at an average rate of 1.7 mm per year during the 20th century, with an increase in the rate of rise over this period (Figure 1). Jevrejeva *et al.* (2006) and Holgate and Woodworth (2004) used quite different techniques to analyse historical tide-gauge data and found quite similar historical rates of sea-level rise. For the modern satellite period (1993 to present), sea level has been rising more rapidly at an average rate of a little greater than 3 mm per year (see, for example, Beckley *et al.* 2007). Note that these rates of increase are an order of magnitude faster than the average rate of rise over the previous several thousand years.

### Australian historical mean sea-level change

The oldest surviving Australian sea-level observations were made at Port Arthur, Tasmania from 1841 to 1842 (Hunter *et al.* 2003). They indicate that, from 1841 to 2002, local sea level rose about 14 cm relative to the land, or about 17 cm allowing for vertical land motion. This value is consistent with the estimate of global sea levels from 1870 to 2001 (Figure 1).

Monthly averaged sea-level variations (Woodworth and Player 2003) for the period 1920 to 2000 for Australian locations (Church *et al.* 2006) were compared with the sea levels estimated from a reconstruction of sea levels (Figure 2) on a global 1° by 1° grid using the technique of Church *et al.* (2004). Note that both the observed and reconstructed sea levels are *relative* sea levels; that is, they are the height of the sea surface relative to coastal benchmarks as required for understanding the local impacts of sea-level rise.

The observed inter-annual sea-level variability is strongest at locations along the north-western and western Australian coast and southern Australian coast. This variability is clearly related to El Niño-Southern Oscillation (ENSO) events and is transmitted through the Indonesian Archipelago from the equatorial Pacific Ocean and then anticlockwise around Australia, getting weaker as it progresses. The inter-annual variability on the east Australian coast is generally smaller in magnitude.

The observed records also show a long-term trend of rising sea levels. This trend is well reproduced in the reconstructed sea levels, with two exceptions. Firstly, the Gulf St Vincent site is a composite record from three sites near Adelaide (Port Adelaide Inner Harbour, Port Adelaide Outer Harbour and Port Stanvac). Compaction of sediments with a subsequent sinking of the coastal tide gauge is known to be occurring in this region leading to a larger relative sea-level rise (Belperio 1993). This larger local sea-level rise is not reproduced in the reconstructions. Secondly, the short section of data around 1970 at Brisbane appears anomalous compared with the reconstruction and other sea-level time series, and is suspected to be associated with a change in the datum of the tide gauge

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

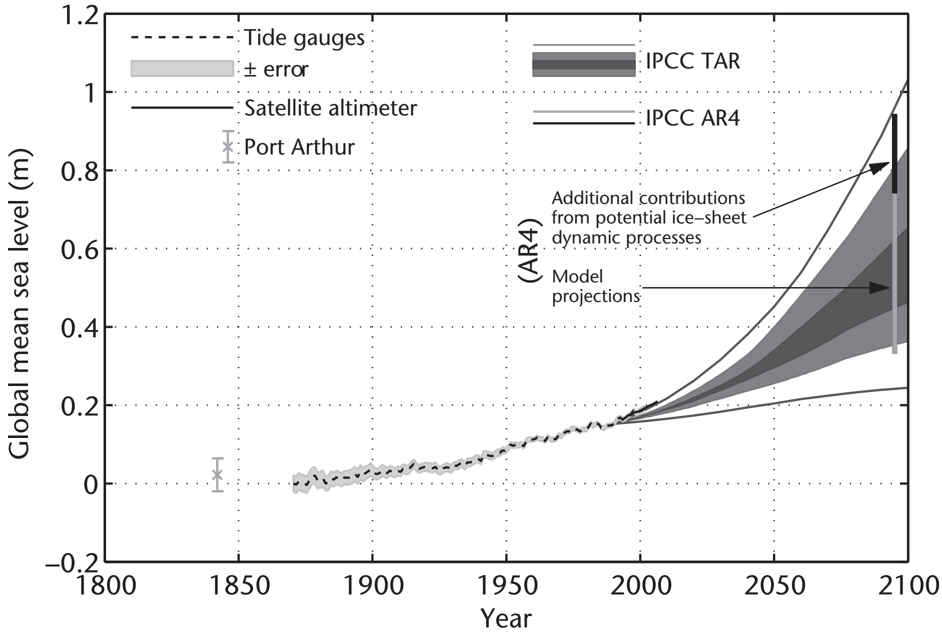


**Figure 1:** Sea levels from 1800 to 2100. The dotted line from 1870 to 2006 indicates the global average sea level and the black line from 1993 to 2006 indicates the modern satellite altimeter record. The curves from 1990 to 2100 are the IPCC 2001 projections and the bars at 2095 are the IPCC 2007 projections. The estimated local sea level (compared with present day local sea level and corrected for land motion) at the Port Arthur (Tasmania, Australia) benchmark in 1840 (Hunter *et al.* 2003) is shown in grey. The error bars on these estimates are one standard deviation.

between the two segments of data (John Broadbent, personal communication).

Also shown in Figure 2 is an estimate of the Australian-average relative sea-level change (excluding the anomalous Gulf St Vincent record). When examined over the complete 80 year period, these trends show a rise in relative sea level of about 1.2 mm per year. There are suggestions in both the Australian mean time series and in a number of the individual records (for example, Fremantle) that the rate of sea-level rise was at a minimum from the mid-1970s to the mid-1990s. This minimum in the rate of rise occurs during the period of more frequent, persistent and intense ENSO events, as evidenced by the Southern Oscillation Index since the mid-1970s (Folland *et al.* 2001). It is also consistent with global analyses for the period 1950 to 2000, which show a global minimum in sea-level rise in the western equatorial Pacific and in the eastern Indian Ocean (Church *et al.* 2004) over this period. It is important to note that the global analysis gives a global increase in ocean volume equivalent to a sea-level rise of 1.8 mm per year over the period 1950 to 2000 despite these regional areas of lower rates of sea-level rise. The longer records (Fremantle and Fort Denison), the reconstructed sea levels and the Australian Baseline Sea Level Monitoring Array (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml) suggest that this period of low rate of rise has now passed.

The modern satellite-altimeter data indicate that, since 1993, the rate of rise has not been uniform around the globe, with significantly larger rates of rise in the western Pacific and eastern Indian Ocean and as a consequence around much of the Australian coastline, particularly the coast of Western Australia. This is consistent with the larger rates of relative sea-level rise recorded in the tide-gauge records in the last decade or so, as discussed above, and is a result of both the variable (time and space) pattern of sea-level rise and also the increase in the rate of global-averaged sea-level rise. The large rates of rise since 1993 in the western Pacific/eastern Indian Oceans are again a signature of climate variability – there was a period of sustained El Niño-like conditions and low sea levels in the western Pacific at the start of the altimeter record.

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

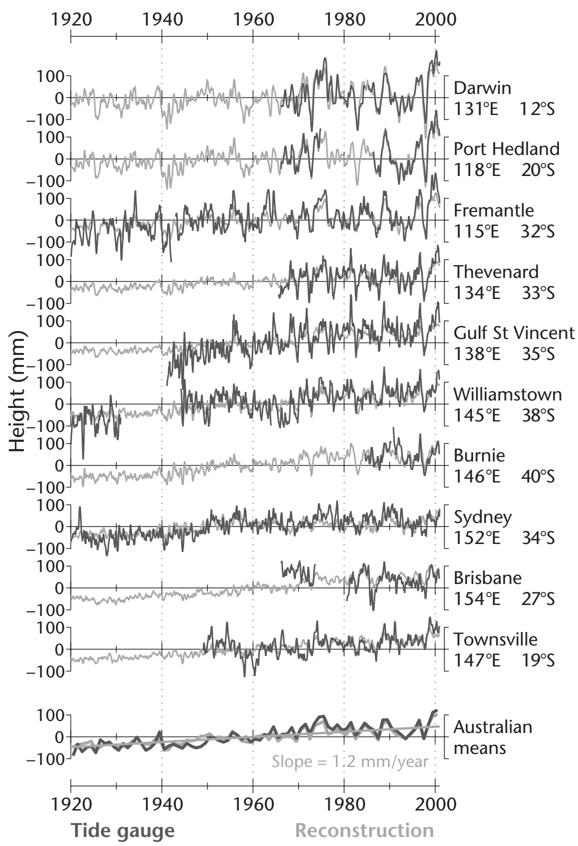


**Figure 2:** Observed (with coastal tide gauges) and reconstructed sea levels for the period 1920 to 2000. The observed tide-gauge records are monthly average values and can be obtained from the PSMSL website. The Gulf St Vincent site is a composite record from three sites. The bottom panel shows the average observed and reconstructed sea-level record for all Australian sites (with the exception of the Gulf St Vincent site) around the Australian coastline. (Source: after Church *et al.* 2006.)

## Projections of global averaged sea-level rise

The two major reasons for sea-level rise are expansion of ocean waters as they warm (and an associated decrease in ocean density) and an increase in the ocean mass, principally from land-based sources of ice (glaciers and ice caps, and the ice sheets of Greenland and Antarctica). Global warming from increasing greenhouse gas concentrations is a significant driver of both contributions. The amount of thermal expansion is non-uniform due to the influence of ocean currents and spatial variations in ocean warming.

The Intergovernmental Panel on Climate Change (IPCC) provides the most authoritative information on projected sea-level change. The IPCC Third Assessment Report (TAR) projected a global averaged sea-level rise of 9 to 88 cm between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios, a range of climate models and an additional uncertainty for land-ice changes (Church *et al.* 2001). The IPCC's Fourth Assessment Report (AR4; IPCC, 2007) used a larger range of models to project a sea-level rise of 18 to 59 cm (with 90% confidence limits) over the period from 1980–1999 to 2090–2099 (Meehl *et al.* 2007). This rise in sea level is mainly a result of thermal expansion of the upper ocean and from the melting of glaciers and ice caps. In these projections, the ice sheets of Greenland and Antarctica together contribute little to sea-level rise during the 21st century. Increased snow fall on Antarctica partially offsets positive sea-level contributions from other components. However, it is recognised that current ice sheet models are incomplete and do not allow for a rapid dynamic response of the ice sheets, as indicated in some recent observations. To allow for ice sheet uncertainties, IPCC AR4 increased the upper limit by 10 to 20 cm and stated that 'larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise.' The end result is that the upper values given in the IPCC TAR and AR4 projections (Figure 1) are similar.

From the start of the IPCC projections in 1990 to 2006, observed sea level has been rising more rapidly than the central range of the IPCC model projections and near the upper end of the total range of the projections (Rahmstorf *et al.* 2007), suggesting that one or more of the model contributions to sea-level rise is underestimated.

Sea-level rise over the early 21st century has largely been determined by past emissions of greenhouse gases. However, sea-level projections closer to, and beyond, 2100 are critically dependent on future greenhouse gas emissions, with both ocean thermal expansion and the ice sheets potentially contributing metres over centuries for higher emission scenarios. There is increasing concern about the longer term contributions of the ice sheets. For example, for the Greenland Ice Sheet, a sustained global average temperature increase relative to pre-industrial values of greater

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

than 3.1°C (with a 90-percentile range of 1.9°C to 4.6°C) would lead to surface melt exceeding precipitation, resulting in an ongoing wastage of the Greenland Ice Sheet for centuries and millennia (Gregory and Huybrechts 2006), consistent with sea levels in the last interglacial being several metres higher than today's value. This temperature increase could potentially be crossed late in the 21st century if effective greenhouse gas mitigation measures are not adopted. A second cause for concern is associated with the poorly understood dynamic responses of the Greenland and West Antarctic Ice Sheets, which could lead to a significantly more rapid rate of sea-level rise than from surface melting alone.

### Projections of mean sea-level rise in the Australian region

Sea-level rise during the 21st century is not expected to be uniform around the globe. This is a result of changing atmospheric conditions (in particular, surface winds) and ocean currents (Lowe and Gregory 2006). The oceans surrounding Australia are influenced by a number of climate variability patterns: for example, the El Niño Southern Oscillation (ENSO), the Southern Annular Mode (SAM) and the Indian Ocean Dipole. These climate variations overlay the global mean sea-level rise, resulting in significant regional variability in the magnitude and trend of sea-level rise in the oceans surrounding Australia. For example, ENSO results in sea-level variability in the tropical Indian and Pacific Oceans, while the SAM is a major driver of sea-level variability in the Southern and mid-latitude Indian and Pacific Oceans. The impact of climate variability results in a regionally complex pattern of sea-level rise and variability in the Indian and Pacific Oceans.

The strongest spatial signatures of sea-level rise projections from 16 atmosphere-ocean models, used for the IPCC AR4, are a minimum in the Southern Ocean south of the Antarctic Circumpolar Current, and a maximum in the Arctic Ocean (Meehl *et al.* 2007). The next strongest features are maxima in sea-level rise at latitudes of about 30° to 40°N in the Pacific and to a lesser extent the Atlantic Ocean, and at about 40° to 50°S in all of the southern hemisphere oceans, at the poleward extremities of the subtropical gyres. This band of maximum sea-level rise in the southern hemisphere is connected to an above average sea-level rise (about 0.2 m above the global average) off the east coast of Australia.

For the Australian region, the spatial pattern of sea-level rise by 2070 was investigated for a number of the climate models. The patterns of thermal expansion for 17 of the AR4 models are shown in Figure 3 for the A1B (mid-range) emissions scenario (CSIRO and Bureau of Meteorology 2007). Each model's globally averaged thermal expansion has been subtracted so that the diagrams represent the regional variation of sea level either above or below the global average sea-level rise projection. Although there is wide variation in the amount of projected sea-level rise, there are also similarities in some regions. For example, in 13 of the 17 models, the thermal expansion along the east coast of Australia south of 30°S is positive relative to the global average values, leading to an additional rise of around 10 cm above the global average change. This feature is attributed to a strengthening of the East Australian Current, which results in the movement of warmer water along the east coast and is caused by a southward shift in wind patterns in the 21st century simulations in the models. More work is required before there is confidence in these regional patterns of sea-level rise.

## Extreme events in the Australian Region

### Historic extreme events

Sea-level records show high and low extremes related to both tides and meteorological effects—the latter being generally referred to as 'surges'. Australia experiences a wide variation of tidal types and magnitudes. In western and north-eastern Australia, the tides occur approximately once per day (they are 'diurnal') while in north-western, eastern and south-eastern Australia, and in the Great Australian Bight and Bass Strait, they occur twice per day (they are 'semidiurnal'). Elsewhere the tides are 'mixed' and have both diurnal and semidiurnal qualities. Figure 4 (Bureau of Meteorology 2004) shows the tidal range (defined here as twice the sum of the amplitude of the $M_2$, $S_2$, $K_1$ and $O_1$ tidal constituents) around Australia,

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

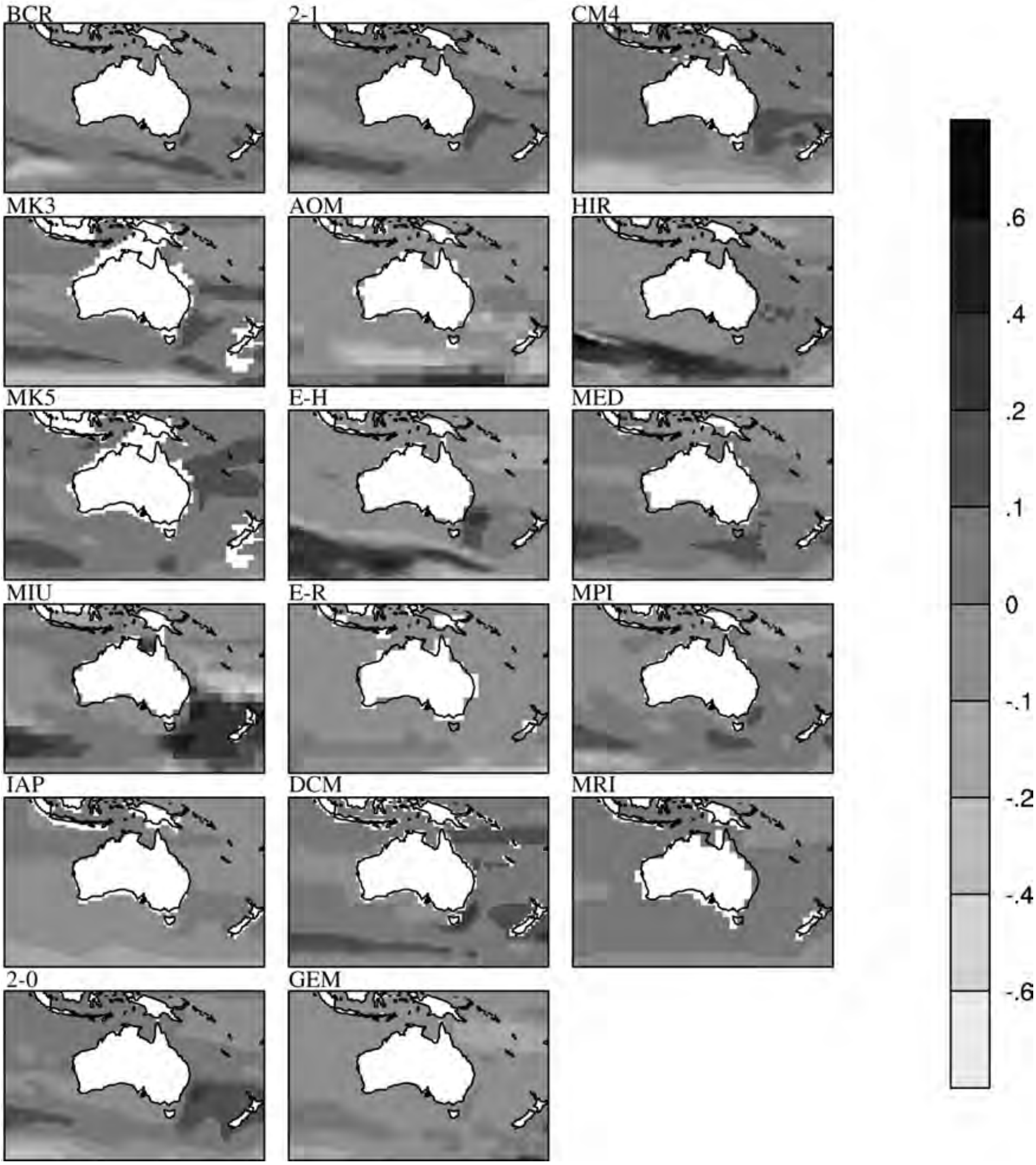


**Figure 3:** Projected regional contribution of thermal expansion by 2070 to sea level relative to the globally averaged value for each model showing the high degree of variability between models, but the general indication that rises on the east coast of Australia may be higher by about 10 cm than the global average rise though to 2070. Calculations are based on the sub-set of AR4 models that provided sea level data to PCMDI. Units are metres. Simulations used IPCC Scenario SRES A1B.

indicating that the largest tides occur in northern Australia (maximum range about 11 m) and in Bass Strait (maximum range about 3 m). The weakest tides occur off south-western Australia with ranges as small as 0.7 m.

Sea-level rise is often experienced through its effect on extreme levels: high (flooding) sea-level events getting higher, and extremes of a given height becoming more frequent. Figure 5 shows the effect of sea-level rise during the 20th century on

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

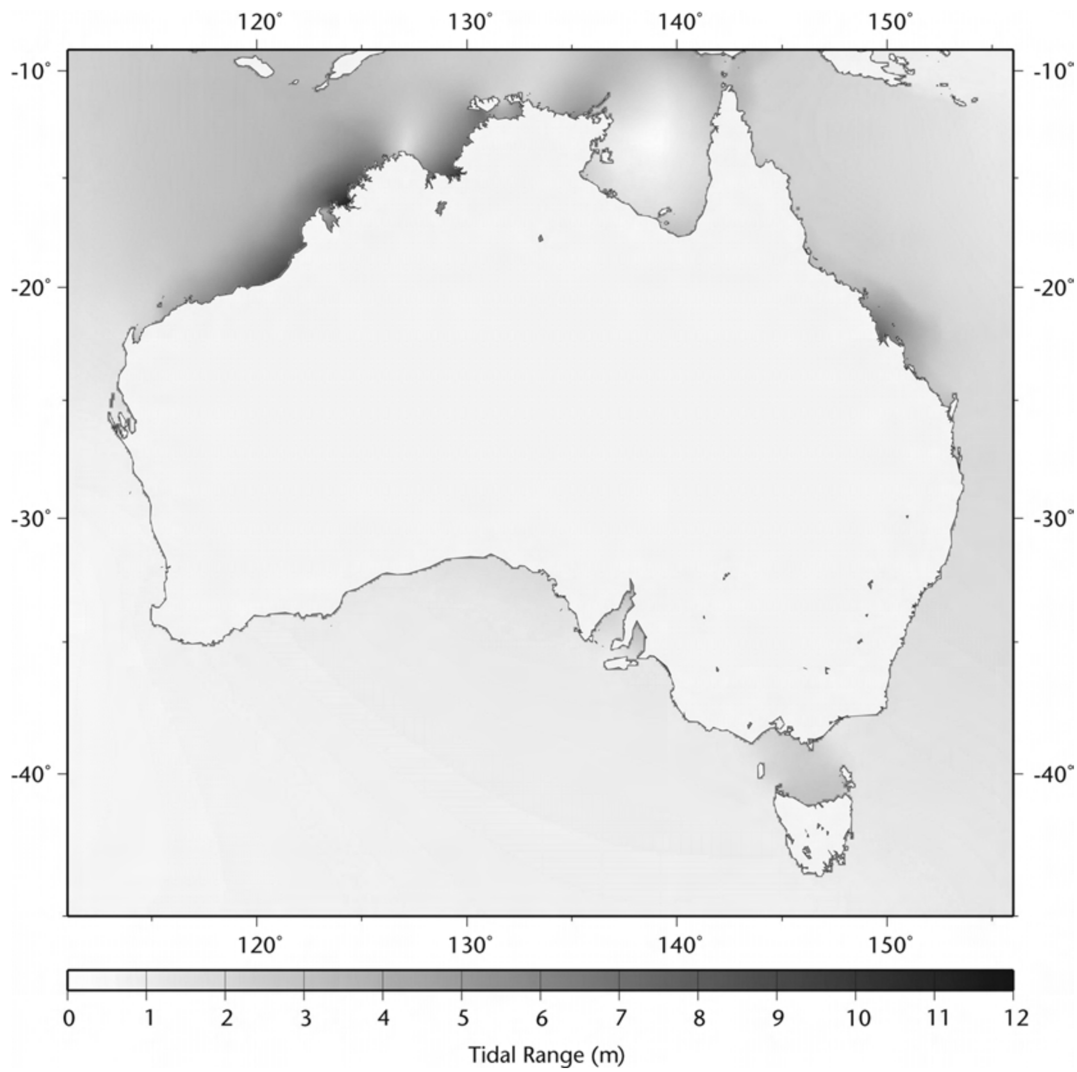


**Figure 4:** Tidal range around Australia (Source: Bureau of Meteorology 2004).

extremes observed at Fremantle, Western Australia (after Church *et al.* 2006). The curves indicate the levels of extremes with a certain average recurrence interval (defined as the average time between exceedance events of a given height), for data prior to 1950 (black) and after 1950 (grey) (the data starts in 1897 and ends in 2004). The post-1950 curve has been displaced upwards by about 0.1 m, which represents the overall sea-level rise between the two subsets of data. This displacement caused extremes that occurred on annual to decadal timescales to increase their frequency of occurrence by a factor of about three during the 20th century. A similar factor was found for Fort Denison, Sydney, which also has an approximately century-long record (Church *et al.* 2006).

Sea-level extremes may also change as a result of a change in the variability of sea level about the mean. For Fremantle (and for Fort Denison, Sydney), this effect has so far been of secondary importance—the dominant change in extremes being due to the rise in mean sea level. This is not, and will not, necessarily be the case in all regions. For example, in the North Sea, where large storm surges are experienced, an increase in winds can have a larger impact than mean sea-level change on the extreme height of storm surges, at least in the near term. Of course, for larger rises in sea level, the

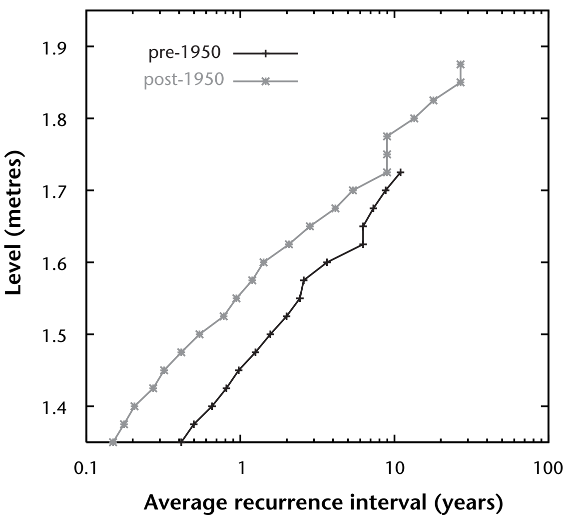


**Figure 5:** Changes in the average recurrence intervals for Fremantle for the period 1897–2004 (Source: Church *et al.* 2006).

change in the mean value dominates over changes in the height of surges about this mean value.

### Future changes in the frequency of extreme events

The severity and frequency of extreme sea-level events in the future will increase with rising sea levels and may also change as a result of changes in the frequency and intensity of the meteorological drivers of storm surge. It may be seen from either curve in Figure 5 that the sea level varies approximately logarithmically with the average recurrence interval, indicating that the extremes approximately follow a Gumbel distribution. The increase in the frequency of extreme high levels, caused by a future increase in mean sea level, may be estimated from the slope of such curves. If a sea-level rise of $h$ increases the frequency of occurrence by a factor $r$, then, a sea-level rise of $H$ increases the frequency of occurrence by a factor $r^{H/h}$ (this is a consequence of the form of Gumbel distribution), which can become very large, even for modest increases in sea level. Figure 6 shows the estimated increase in the frequency of occurrence of extreme high levels, caused by a sea-level rise of 0.1 m, for the 29 Australian tidal records that are longer than 30 years. This multiplying factor has a range of 1.8 – 5.8 and a mean of 3.1, which is broadly consistent with the 20th century observations for Fremantle and Fort Denison, Sydney (Church *et al.* 2006). For a mid-range 21st century rise of mean sea level of 0.5 m (see above), the mean multiplying factor for Australia would therefore be $3.1^{0.5/0.1}$ or 286, indicating that events which now happen every 10 years would happen more than once a month in 2100. Figure 6 shows that even larger increases in the frequency of extremes would occur around Sydney, Brisbane and in Bass Strait, with smaller increases off the north-west and north-east coasts, and off South Australia.

The meteorological drivers of sea-level extremes in Australia include cyclones in the tropics north of 30°S, westerly winds associated with cold fronts along the south coast and a combination of cyclones of tropical and mid-latitude origin on the east and west coasts south of 30°S. Storm surges occur more commonly during the warmer months in the north and during the colder months in the south. The effect of climate change on these systems has been summarised recently in a report by the CSIRO and the Bureau of Meteorology (2007). Studies of tropical cyclones in the Australian region indicate a likely increase in the number of tropical cyclones in the more intense categories, but a possible decrease in the total number of cyclones. They also indicate a poleward extension of tropical cyclone


**Figure 6:** Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameters of the discs), caused by a sea-level rise of 0.1 m.

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

tracks. For example, Leslie *et al.* (2007) found a poleward shift of over 2° in latitude of the genesis region of tropical cyclones and of the tropical cyclone tracks. Abbs *et al.* (2006) found a poleward shift of 0.7° in the tropical cyclone genesis region across Australia and of 3° in the decay location of cyclones on the east coast.

The projected large-scale change to wind patterns that will affect the incidence of storm surges in mid-latitude regions is one of a poleward shift of the mid-latitude westerlies, bringing weaker winds to the southern Australian coast to the west of 140°E during the colder months. However, increasing wind speeds are more likely over the Victorian, Tasmanian and southern NSW coasts. This is likely to be associated with a southward extension of the East Australian Current, which brings warmer water further southward along the east coast and enables a greater intensification of storm systems in this region. In a climate model simulation in which this pattern of EAC intensification occurs, it was found that east coast low pressure systems with central pressures of 990 hPa or deeper were 60% more frequent in 2070 (McInnes *et al.* 2007b).

There have been two broad approaches for evaluating storm-tide return levels under current and future climates in Australia: one that is used in tropical regions and another that is used in the mid-latitude regions. The basis for these approaches lies with the frequency of occurrence of the storm-surge generating weather systems and whether the associated storm surges have been well captured by the tide-gauge network. In the tropics, the infrequency of tropical cyclones together with their small spatial scale (of order 100 km or less), and hence the small spatial scale of the storm surge, means that the observational record of storm-surge occurrence is poor. This precludes an estimation of the storm-surge recurrence intervals from observational records. Instead, an approach in which a hydrodynamic model is used to simulate the cyclone-induced storm surges from synthetically generated tropical cyclone wind and pressure fields have typically been used (for example, McInnes *et al.* 2003; Hardy *et al.* 2004). The population of synthetic cyclones is derived from the characteristics of the observed cyclones in the region of interest. On the south coast of Australia, the methods developed to evaluate storm-surge return periods exploit the frequency and coherence of storm-surge events along the southern coastline. Previous studies have shown that these events are coherent over thousands of kilometres and are a response of coastal-trapped waves to the atmospheric forcing (Church and Freeland 1987). Therefore methods to quantify storm-tide return periods in this region have involved using a hydrodynamic model to simulate an observed population of extreme sea-level events identified in tide-gauge records ( McInnes *et al.* 2007a). In both approaches, statistical methods are used to estimate storm-surge recurrence intervals from the population of modelled events.

The effect of climate change on storm-surge recurrence intervals has been investigated in several studies around Australia. The tropical studies of McInnes *et al.* (2003) for Cairns in northern Queensland and Hardy *et al.* (2004) for a number of locations along the Queensland coast considered an increase in mean sea level (0.25 m and 0.3 m, respectively) and a 10% increase in the intensity of all cyclones. Hardy *et al.* also considered a southward shift of cyclone tracks of 1.3 degrees (about 140 km). They found that sea-level rise provided the largest contribution to the future increase in extreme sea levels, with cyclone intensity changes and the southward movement of tracks having a negligible impact on the height of the 1 in 100 year storm surge. On the other hand, McInnes *et al.* found that an increase in the intensity of tropical cyclones increased the 1 in 100 year storm surge by around 0.3 m. A key difference in the two approaches is in the way tropical cyclones were selected for the hydrodynamic modelling. Hardy *et al.* use an autoregressive model whose coefficients were derived from observed tropical cyclones over the Coral Sea from 1969 to 2001. McInnes *et al.* used extreme value statistics fitted to cyclones dating back to 1908 to evaluate the cyclone probabilities and this approach includes more intense cyclones than have been observed in the last few decades (Church *et al.* 2006).

Along the eastern Victorian coast, the study of McInnes *et al.* (2007a) evaluated the possible change to storm surge recurrence intervals by considering the range of wind speed change in 13 climate models over Bass Strait. Although the changes in wind speed were found to increase in the majority of

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

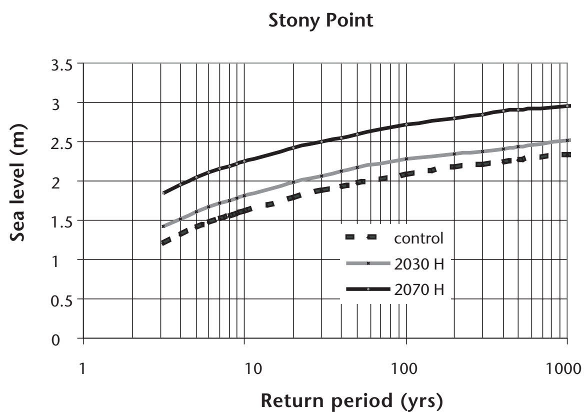


**Figure 7:** Storm-tide return-period curves for Stony Point under the high climate-change scenarios for 2030 and 2070. Note that a high scenario comprises a high wind-speed scenario combined with a high sea-level rise scenario. The 1 in 100 year storm-tide height in 2070 is around 0.7 m higher than the control value. Of this increase, around 75 to 80% is due to sea-level rise, while the remainder is due to wind speed increase. The frequency of the extreme events increases in the two scenarios shown also with the control climate 1-in-100-year event being exceeded on average once every 30 years in 2030 and once every 5 years in 2070.

models, the response of the various models ranged from a decrease of 5% to an increase of 10% by 2070. These low and high wind-speed changes were applied uniformly to the wind fields for each modelled storm-surge event. For a storm-surge height of 0.75 m—which represents roughly a 1 in 100 year storm surge along much of the eastern Victorian open coast—the wind speed changes induced water-level changes of –0.075 m to +0.15 m (that is, twice the percentage change in wind speed). The changes in extreme sea levels from potential wind-speed changes are somewhat smaller than those that can occur from mean sea-level rise, which may be as high as 0.49 m by 2070 in these simulations. An example of the return periods of extreme sea level under current and future conditions is given in Figure 7 for Stony Point on the Victorian coast.

## Coastal erosion around Australia

### Factors Influencing Coastal Erosion

Geomorphic and stratigraphic evidence from field and model investigations in Australia and elsewhere, summarised in Roy *et al.* (1994), clearly show massive coastal change of tens of metres in response to sea-level variations during the last 10,000 years of the Holocene Epoch. Confidence is gained from these studies that advanced numerical models are capable of reproducing observed geomorphic responses to the complete range of factors responsible for coastal change, including effects of sea-level rise (Cowell *et al.* 1995, 2003; Stolper *et al.* 2005). However, despite the historical increase in mean sea level around the Australian coast during the 20th century, other factors causing coastal erosion have to date masked any local response to sea-level trends and it has not been possible to unambiguously attribute an erosion signal to sea-level rise, in the presence of other anthropogenic activities.

Geomorphic impacts can be characterised by changes in location of shorelines. Shoreline change has particular significance to society through land loss and effects of erosion on property and infrastructure. Shoreline movements are a manifestation of horizontal and vertical translations in the *shore face* due to changes in sea level, sediment availability or geometry of the shore face (Cowell *et al.* 1995). Erosion, deposition and sediment transport rates generally decrease in deeper water due to the weakening of wave motions with water depth. (The shore face comprises the beach and bed of any coastal water body, extending from the landward limit of sedimentary processes associated with wave run-up, out to the offshore limit of sediment transport; Cowell *et al.* 1999.)

The tendency for the coast to erode or accrete depends on the combined effects of four factors:

1. a gradual rise in mean sea level, which causes a landward recession of the coast wherever it comprises loose sediments or friable bedrock (Roy *et al.* 1994)
2. changes in the magnitude of transient storm-erosion events (Zhang *et al.* 2004; McInnes *et al.* 2007b)
3. supply and loss of sediments from nearby sources and sinks (List *et al.* 1997; Stive and Wang 2003)
4. realignment of shorelines due to changes in directional statistics of wave fields (Ranasinghe *et al.* 2004; Goodwin *et al.* 2006), which can be expected if wave refraction patterns are

altered by sea-level rise or there are other changes in climate.

The first of these mechanisms may be simply understood by consideration of the transport of sediment by incoming ocean waves. Under equilibrium conditions, the shape of the shore face is governed by a balance between onshore/offshore transport of sediment by surface waves. Under a given level of wave activity, the shore face takes on a particular offshore profile. If the sea level rises, the onshore/offshore transport changes until the shore face returns to its original profile and equilibrium is re-established under conditions of raised sea level. However, in this new equilibrium, the shoreline has been moved upwards and onshore resulting in recession of the shoreline. This mechanism was formalised in a very simple way by Bruun (1962; see following Section) and later re-formulated to allow for changes in profile equilibrium through time (for example, Cowell *et al.* 2006).

Generally, the most common experience of acute coastal erosion in Australia has been associated with transient erosion due to storm events involving high waves and abnormally high water levels, especially when storm surges coincide with spring tides. These conditions occurred in south-east Australia during the strong La Niña of May–June, 1974, and the resulting storm erosion that caused destruction of houses at Narrabeen and Bilgola on the Sydney coast has become a benchmark in coastal-hazard planning.

While dramatic property losses during such storm events capture the attention of coastal managers and the public alike, extreme storms that have recurred historically do not represent an increased threat. Nor are they *necessarily* indicative of more serious chronic erosion problems. Coasts recover from these transient events through the return of sand to beaches and dunes following its temporary displacement offshore during storms. Only with an increase in magnitude of erosion events will related storm impacts penetrate further inland. Historically, Australia has generally been free of chronic coastal erosion problems, except where such problems were triggered by coastal engineering. For the most part, property and infrastructure losses associated with extreme storms to date reflect the inappropriate development of assets within dynamic coastal environments that were mistakenly thought to be stable under existing and historical conditions.

At present, the strength of non-sea-level rise factors driving erosion, and uncertainty in quantifying these drivers, generally makes detection of the sea-level rise response signal problematic. Almost all the chronic coastal-erosion hotspots around Australia lie in regions where alongshore sand transport is a dominant process and the erosion is largely due to disturbances in the alongshore transport gradient or the existence of local sinks that cause sand loss from the littoral environment. In most cases, the disturbance to littoral transport has been induced through coastal engineering works.

The possibility of shore-face sand supply to beaches has further obscured the geomorphic signal of sea-level rise over recent decades (Figure 8a). Evidence for sand supply to beaches from the lower shore face is surprisingly ubiquitous around much of the Australian coast (Figure 8b) and is likely to be common on most coasts with shore faces comprising a concave up cross-shore profile due to onshore skewness in the amplitudes of water velocities under shoaling waves. For example, results from geological investigations in south-east Australia (Cowell *et al.* 1995) and sediment-transport modelling on the central Netherlands coast indicates that sand supply from the lower shore face fully compensates for the effects of significant relative sea-level rise (Beets *et al.* 1992). Strong evidence of shore-face sand supply also exists in field data from the Columbia River littoral cell in the US north-west Pacific (Cowell *et al.* 2001).

## Historical coastal erosion

One of the best known examples of coastal erosion is the result of the Tweed River entrance training walls interrupting the alongshore sand feed from northern NSW to the Gold Coast beaches (Boak *et al.* 2001). Coastal erosion occurred immediately following initial construction of the training walls in the early 20th century, and again in the late 1960s when the walls were lengthened. The latter phase occurred after massive tourist development on the Gold Coast, so the ensuing erosion attracted much more attention. The publicity was not enough to prevent similar costly mistakes being made elsewhere, such as in Victoria at Portland (Gourlay

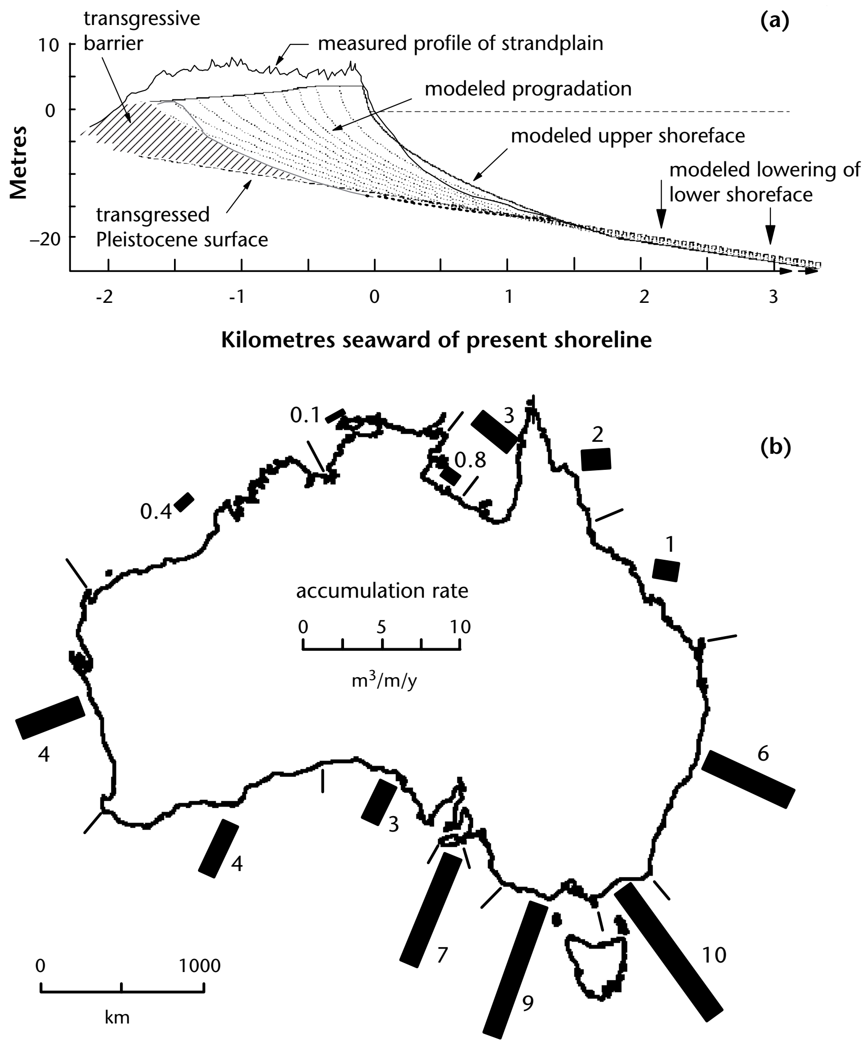


**Figure 8:** Sand supply for barrier progradation from the shore face: (a) modelled and measured supply from Tuncurry, south-east Australia (Source: adapted from Cowell *et al.* 2003); (b) volume estimates for segments of the Australian coast (Source: Short 2003).

1996) and Port Fairy (BMT-WBM 2007), and in Western Australia along down-drift beaches flanking Fremantle Harbour (Searle and Semeniuk 1985), the Peel Inlet at Mandurah, and the Port Geographe marina entrance near Busselton. Such training-wall installations interrupt alongshore sand transport, thereby inducing positive alongshore transport gradients on down-drift beaches, causing systemic erosion. The walls also tend to promote sequestration of sand by estuarine sinks, causing sand losses from adjacent beaches.

A chronic-beach erosion history along Adelaide's coast is thought to have a sea-level rise component. However, significant uncertainties in estimates of alongshore sand transport (Coastal Engineering Solutions 2004) make it difficult to evaluate the contribution of sea-level rise. As with erosion hotspots elsewhere, erosion may be as much to do with development having encroached too close to the shoreline, thus interrupting littoral transport, making it difficult to identify the response to the sea-level rise.

Similar coastal management issues play a significant role in beach erosion at Byron Bay in NSW. Construction of a car park and its revetments on the active beach in the 1960s caused a realignment of the down-drift coast, contributing to coastal erosion. The coastal realignment problem is compounded by fluctuations in the rate of sand bypassing Cape Byron. These fluctuations occur with ENSO and longer interdecadal climate variations that affect the wave regime, causing fluctuations in coastal alignments (Ranasinghe *et al.* 2004; Goodwin *et al.* 2006). Coastal realignments due to engineering works and climate fluctuations have been especially significant when the transient erosion they cause is compounded by severe storm-erosion events. In 1974, these combined effects caused the destruction and permanent abandonment of Sheltering Palms—a village immediately north of the Brunswick River entrance-training walls on the Byron Bay coast.

On the central and south coast of NSW, the highly embayed coastline features and prominent headlands extending into deep water means that leakage of sand to adjacent beaches is negligible (Roy and Thom 1981). Under such conditions, the closed littoral sediment budgets eliminate the main source of contamination in the potential geomorphic signal in beach response to sea-level rise. The resulting opportunity for detection of this signal is, however, somewhat diminished due to sand contributions to beaches from the lower shore face. The Collaroy–Narrabeen Beach in Sydney probably represents the greatest exposure to imminent property loss due to coastal erosion at present in Australia (Hennecke *et al.* 2004). Here again, the problem relates to coastal development of land subdivided almost 100 years ago on what is now known to be the historically active beach zone. The available evidence indicates that the beach has been historically stable in terms of mean-trend changes, and that erosion episodes have been transient throughout the historical past (Thom 1974).

### Projected coastal erosion

While local disturbances and changing wave conditions have been the dominant contribution to detectable, systematic coastal change at erosion hotspots on the Australian coast to date, sea-level rise and changes in storms will become significant and begin to dominate over several decades, particularly if the upper range of sea-level projections and intensification of storms eventuate. Current erosion hotspots will probably be the first places to suffer serious impact from erosion induced by increased sea level.

Coastal recession tendencies due to sea-level rise are the result not only of inundation but also systematic patterns of bed erosion and sedimentation (see above). These geomorphic effects can be expected in all marine littoral environments, including wave-dominated and protected oceanic settings, as well as in estuaries, coastal lakes and wetlands. Stive (2004) demonstrated from consideration of shore-face translation and sediment-mass continuity that the rate of shoreline retreat, $c_R$, can be expressed as

$$c_R\,(h_* + h_d) = \frac{\partial S}{\partial t} L_* + \frac{\partial Q_y}{\partial y} - Q_x - V \qquad (1)$$

where $\frac{\partial S}{\partial t}$ is the rate of sea-level rise; $L_*$ and $h_*$ are the distance and water depth defining the offshore limits of the active zone; $h_d$ is the height of the dune or friable cliff; $Q_x$ is the time-averaged shoreward sediment flux into the active zone from the lower shore face; $Q_y$ is the alongshore sediment flux integrated over $L_*$; $V$ is a local sediment source or sink (such as a delta or estuary); and $x$ and $y$ are across-shore and alongshore dimensions. The *active zone* is the upper-shore-face region in which rates of fluctuation in bed elevation, due to cycles of erosion and deposition, are larger than the rate of sea-level rise.

Equation 1 is general, especially if the source/sink term, $V$, incorporates any changes in the maximum transient-erosion volume due to storms. Such changes can be expected if systematic variation occurs in storm magnitudes and frequencies. For the special case, in which sources, sinks, net littoral transport and shore-face supply of sediments can all be ignored, equation 1 reduces to the widely applied *Bruun Rule* (Bruun 1962):

$$c_R = \frac{\partial S}{\partial t}\left(\frac{L_*}{h_* + h_d}\right) \qquad (2)$$

Equation 2 is widely applied because of its practical simplicity, whereas equation 1 demands use of numerical models (Cowell *et al.* 2006). Unfortunately, the special-case conditions underpinning equation 2 seldom arise in nature, so application of the Bruun Rule as the sole explanation for observed or projected changes is generally invalid. One of the few field studies to have validated equation 2

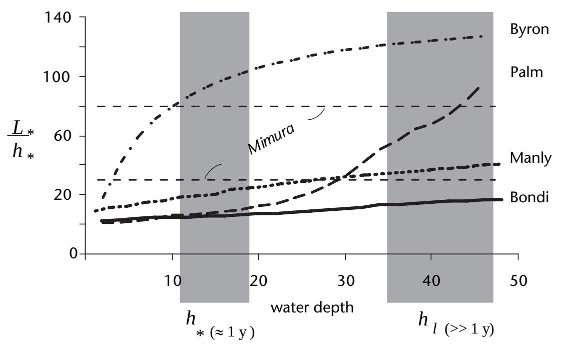


**Figure 9:** Variability of shoreface slope in equation 2 ($L_*/h_*$), for five iconic beaches in south-east Australia, in relation to water depths indicative of limiting depths of the active zone ($h_*$), and the slowly evolving lower shoreface ($h_l$) on the annual time scale (Hallermeier 1981): $h_*$ is the limiting depth of detectable changes in bed elevation, and $h_l$ characterises the limiting depth of significant sand movement. Although Hallermeier's $h_*$ has been used often to calibrate application of the Bruun Rule, Hallermeier recommended that $h_l$ is more appropriate in place of $h_*$ in equation 2 because significant sand movement during a typical year makes consequential bed-level changes possible on the multi-decadal time scale.

demonstrated that applicability existed along coastal tracts free of tidal-inlet effects and littoral transport gradients, which comprised more than 30% of the US coastline studied from South Carolina to Long Island NY (Zhang *et al.* 2004). Another study, in which validity of equation 2 was evident, involved dominance by strong relative sea-level rise (Mimura and Nobuoka 1995). More generally, under conditions of weak sea-level rise, the other terms in equation 1 tend to dominate coastal change (Roy *et al.* 1994).

These field studies also demonstrate the weakness of the rule-of-thumb that $c_R$ is on the order of 50 to 100 times the rate of sea-level rise. For example, variability in the reciprocal slope term characterising the shore face, $L_*/h_*$, is illustrated in Figure 9 and demonstrates the effect that choice of $h_*$ has on estimates obtained via the Bruun Rule. Taking uncertainty about choice of $h_*$ into account gives erosion factors ($L_*/h_*$) ranging from 44 to 64 for Manly, 29 to 99 for Palm Beach and only 28 to 39 for Bondi Beach (Figure 9). These factors correspond poorly to the 50–100 range proposed for coasts elsewhere (for example, Mimura and Nobuoka 1995). On this basis, for example, the response of Manly Beach to an increased sea level by 2100 of 0.28–0.79 m (see above) would involve an expected horizontal erosion distance of between 12 and 51 m. This range of estimates does not, however, take into account uncertainties at Manly related to future changes in shore-face geometry, effects of rock reefs, and a seawall. Application of more appropriate simulation modelling to deal with these uncertainties provides a probabilistic basis for projecting coastal erosion at Manly in response to sea-level rise and possible changes in the wave climate (Figure 10).

The simulations upon which the Manly recession risk estimates were based take into account the additional factors included in equation 1, but excluded from equation 2. For example, the possibility of sand supply from the shore face ($Q_x$ in eq.1) introduces the possibility that the beach may undergo time averaged accretion rather than recession despite sea-level rise, although the probability that this will occur is estimated to be less than 10% (Figure 10). Because Sydney beaches, including Manly, are not subject to significant alongshore transport of sand, projections of coastal recession do not involve effects of disturbances in littoral sediment budgets. In coastal regions subject to these effects, described above in relation to the historical erosion hotspots, erosion risk is much greater than illustrated in Figure 9.

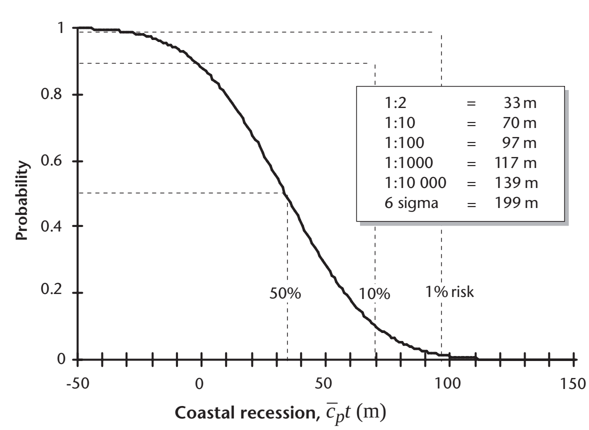


**Figure 10:** Probability of shoreline recession by year 2100 due to climate-change impacts at Manly Beach, Sydney, based on simulations in which model variables were sampled from probability distributions for each of 2000 repetitions. Negative recession values imply time averaged accretion of the coast (Source: based on Cowell *et al.* 2006).

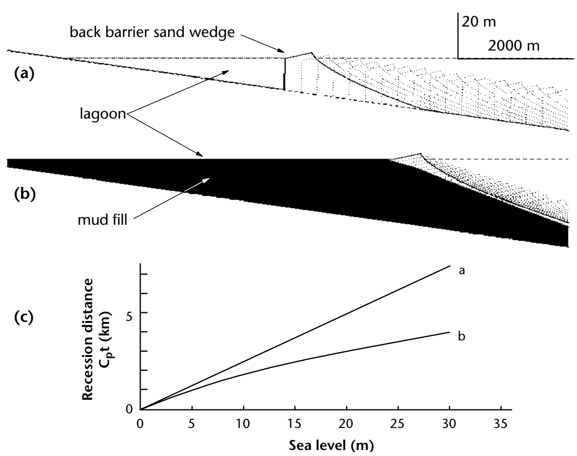


**Figure 11:** Moderating effects on rate of coastal recession due to deposition of fine sediments in a barrier estuary under constant rates of sea-level rise: (a) barrier rollover with no estuarine mud deposition, for which the rate of recession is identical to the rate of simple inundation on a sloping plane; (b) effect of mud accumulating vertically at the same rate as sea-level rise; and (c) comparative rates of horizontal recession of the shore face (Source: adapted from Cowell *et al.* 2003).

For the next few decades, the role of estuaries, including river mouths and lagoons, as sinks for beach sand is unlikely to be significant. Exceptions will exist in the vicinity of entrances that are artificially deepened for navigation. If sea levels continue to rise in subsequent centuries, the resulting deepening of estuaries and tidal inlets will tend to cause a progressive loss of sand to estuarine sinks from adjacent beaches (Figure 11).

Deposition of sediments other than marine sand (including fine sediments, such as estuarine muds and bay-head (fluvial) delta sands; Roy, 1994) within estuaries and coastal wetlands due to either natural processes or artificial fill plays a significant role in reducing the potential sink capacity of estuaries (Figure 11). Such sedimentation reduces the sink volume and thus limits sand demand exerted on the adjacent coast.

## Conclusion

A substantial body of evidence indicates sea level has risen at a significantly larger rate during the 20th century than over the previous several millennia. This is true both globally and around Australia, with evidence coming from geological data, in situ instrumental data and, most recently, satellite-altimeter data. This rise will continue during the 21st century and beyond because of the long time scales associated with the deep ocean and the ice sheets. The IPCC projections indicate a global-averaged sea-level rise of 18 to 79 cm from 1990 to 2095, with recent observations indicating a rise closer to the upper end of the range. In addition, regional variations from this global averaged rise are expected. The projected sea-level rise will require significant adaptation.

Rising sea levels will be felt most acutely through extreme events. The rise in mean sea level has already led to an increase in the frequency of high sea-level events of a given magnitude, by a factor of about three on both the east and west coasts of Australia. The logarithmic relationship between the height and return period of high sea-level extreme events means that by late in the 21st century, events that now occur once every 10 years could be occurring once every few weeks and the present one-in-a-hundred-year event could occur several times a year. In addition, the most severe high sea-level events will have a greater impact. Again, these changes will require significant adaptation and planning for many regions around the Australian coastline.

Urgent and effective mitigation is required if the world is to significantly decrease the risk of multi-metre sea-level rise from ice-sheet contributions. Paleogeomorphic data indicate that, when temperatures were similar to those we can expect in 2100 if efforts to mitigate greenhouse gas emissions fail, the sea level was several metres higher than today's. We presently have insufficient understanding of the response of ice sheets to both atmospheric and oceanic warming to determine whether such a rise would occur over decades to centuries through a rapid dynamic ice-sheet response, or would occur over millennia from surface melting alone. These rises would have major impacts on virtually all regions of the Australian coastline.

As well as inundation from extreme events, coastal erosion will be an important issue. To date, erosion hot spots have occurred as a result of coastal developments on active dune areas. While it is likely that sea-level rise has not yet produced a detectable impact on coastal erosion, it will become a dominant contributor during the 21st century, with the existing hot spots the first (and probably

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

the most severely) regions to be affected. As sea levels continue to rise, coastal erosion will be felt more broadly along the Australian coastline.

Adaptation strategies will be required and include (Church *et al.* 2007):

- **accommodation** through forward planning and appropriate use of low-lying coastal regions (for example, to ensure escape and emergency routes are available for future flooding events, and to increase the resilience of coastal developments and communities)
- **protection** via 'hard' measures such as sea walls (for example, 10 million people who live below sea level in the Netherlands are protected by dykes and levees) and 'soft' measures such as increased beach nourishment
- **(planned) retreat** through planning instruments, such as implementation of no-build areas or building setbacks for areas susceptible to flooding and erosion.

Adaptation plans must not only consider modern urban development, but also allow for the protection of historical sites, sensitive environmental areas and ecosystems. Developing management policies that simultaneously tackle these potentially conflicting goals presents a major challenge. However, with proactive planning, we can substantially lessen the impact of 21st century sea-level rise.

## References


Abbs DJS Aryal S, Campbell E, McGregor J, Nguyen K, Palmer M, Rafter T, Watterson I and Bates B (2006). 'Projections of extreme rainfall and cyclones'. A report to the Australian Greenhouse Office, Canberra, Australia, 97 pp. Bureau of Meteorology, Canberra.

Beckley BD, Lemoine FG, Lutchke SB, Ray RD and Zelensky NP (2007). A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geophysical Research Letters* **34**, L14608 <doi:10.1029/2007GL030002>.

Beets DJ, van der Valk L and Stive MJF (1992). Holocene evolution of the coast of Holland. *Marine Geology* **103**, 423–443.

Belperio AP (1993). Land subsidence and sea level rise in the Port Adelaide estuary: implications for monitoring the greenhouse effect. *Australian Journal of Earth Sciences* **40**, 359–368.

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa, K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD and Unnikrishnan A (2007). Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis KB Averyt, M Tignor and HL Miller). Cambridge University Press, Cambridge, UK and New York.

BMT-WBM (2007). 'Port Fairy East Beach coastal erosion engineering and feasibility study'. Report prepared for Moyne Shire Council BMT WBM Pty Ltd, Brisbane.

Boak L, Jackson LA, McGrath J and Brosnan M (2001). Proceedings 15th Australasian Coastal and Ocean Engineering Conference. In: *An Overview of Gold Coast Coastal Management 1960–2001*. The Institution of Engineers, Australia, Barton ACT.

Bruun P (1962). Sea-level rise as a cause of shore erosion. *Journal of Waterways Harbors Division* **88**, 117–130.

Bureau of Meteorology (2004). 'Modelling of tides and tsunamis'. National Tidal Centre, Bureau of Meteorology, Australia.

Chen K and McAneney J (2006). High-resolution estimates of Australia's coastal population. *Geophysical Research Letters* **33**, L16601. <doi:10.1029/2006GL026981>.

Church JA and Freeland HJ (1987). The energy source for the coastal-trapped waves in the Australian Coastal Experiment region. *Journal of Physical Oceanography* **17(3)**, 289–300.

Church JA and White NJ (2006). A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* **33**, L01602. <doi:10.1029/2005GL024826>

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D and Woodworth PL (2001). Changes in sea level. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Eds. JT Houghton, Y


in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

Ding DJ Griggs, M Noguer PJ van der Linden, X Dai, K Maskell and CA Johnson) Cambridge University Press, Cambridge, UK and New York.

Church JA, White NJ, Coleman R, Lambeck K and Mitrovica JX (2004). Estimates of the regional distribution of sea level rise over the 1950–2000 period. *Journal of Climate* **17**, 2609–2625.

Church JA, Hunter JR, McInnes KL and White NJ (2006). Sea-level rise around the Australian coastline and the changing frequency of extreme events. *Australian Meteorological Magazine* **55**, 253–260.

Church JA, Nicholls R, Hay JE and Gornitz V (2007). Ice and Sea-level Change, In *Global Outlook for Ice and Snow*. (Ed. J Eamer) United Nations Environment Programme, New York.

Coastal Engineering Solutions (2004). 'Coastal processes study of Adelaide beaches'. Report for Department for Environment and Heritage, Natural and Cultural Heritage Coastal Protection Branch, Adelaide.

Cowell PJ, Roy PS and Jones RA (1995). Simulation of large-scale coastal change using a morphological behaviour model. *Marine Geology* **126**, 45–61.

Cowell PJ, Stive MJF, Roy PS, Kaminsky GM, Buijsman MC, Thom BG and Wright LD (2001). Shoreface sand supply to beaches. In *Proceedings of the 27th International Conference on Coastal Engineering*. pp. 2495–2508. American Society of Civil Engineers, Sydney.

Cowell PJ, Stive MJF, Niedoroda AW, Swift DJP, De Vriend HJ, Buijsman MC, Nicholls RJ, Roy PS, Kaminsky GM, Cleveringa J, Reed CW and de Boer PL (2003). The coastal-tract (Part 2): Applications of aggregated modelling to lower-order coastal change. *Journal of Coastal Research* **19(4)**, 828–848.

Cowell PJ, Thom BG, Jones RA, Everts CH and Simanovic D (2006). Management of uncertainty in predicting climate-change impacts on beaches. *Journal of Coastal Research* **22(1)**, 232–245.

CSIRO and Bureau of Meteorology (2007). 'Climate change in Australia'. Technical report. <www.climatechangeinaustralia.gov.au>.

Donnelly JP, Cleary P, Newby P and Ettinger R (2004). Coupling instrumental and geological records of sea-level change: Evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters* **31**, L05203. <doi: 10.1029/2003GL018933>.

Fairbanks RG (1989). A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* **342**, 637–642.

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlemans J, Salinger MJ and Wang S-W (2001). Observed climate-variability and change. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Eds JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, X Dai, K Maskell and CA Johnson), Cambridge University Press, Cambridge, UK and New York.

Gehrels WR, Kirby JR, Prokoph A, Newnham RM, Achterberg EP, Evans H, Black S and Scott DB (2005). Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews* **24**, 2083–2100.

Gehrels WR, Marshall WA, Gehrels MJ, Larsen G, Kirby JR, Eiríksson J, Heinemeier J and Shimmield T (2006). Rapid sea-level rise in the North Atlantic Ocean since the first half of the nineteenth century. *The Holocene* **16(7)**, 949–965.

Goodwin ID, Stables MA and Olley JM (2006). Wave climate, sand budget and shoreline alignment evolution of the Iluka–Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. *Marine Geology* **226**, 127–144.

Gourlay MR (1996). History of coastal engineering in Australia. In *History and Heritage of Coastal Engineering* (Ed. NC Kraus) pp. 1–88. American Society of Civil Engineers, New York.

Gregory JM and Huybrechts P (2006). Ice-sheet contributions to future sea-level change. *Phil. Trans. R. Soc.* A **364**, 1709–1731.

Hallermeier RJ (1981). A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering* **4**, 253–277.

Hardy T, Mason L and Astorquia A (2004). 'Queensland climate change and community vulnera-

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

bility to tropical cyclones: ocean hazards assessment – Stage 3', Report to Queensland Government, 56 pp. <www.longpaddock.qld.gov.au/ClimateChanges/pub/>

Hennecke WG, Greve CA, Cowell PJ and Thom BG (2004). GIS-based coastal behaviour modelling and simulation of potential land and property loss: implications of sea-level rise at Collaroy/Narrabeen Beach, Sydney (Australia). *Coastal Management* **32**, 449–470.

Holgate SJ and Woodworth PL (2004). Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters* **31**, L07305. <doi:10.1029/2004GL019626>.

Hunter J, Coleman R and Pugh D (2003). The sea level at Port Arthur, Tasmania, from 1841 to the present. *Geophysical Research Letters* **30**, 7, 1401. <doi:10.1029/2002GL016813>.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller). Cambridge University Press, Cambridge, UK and New York.

Jevrejeva S, Grinsted A, Moore JC and Holgate S (2006). Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research* **111**, C09012. <doi:10.1029/2005JC003229>.

Lambeck K (2002). Sea level change from mid Holocene to recent time: an Australian example with global implications. In *Ice Sheets, Sea Level and the Dynamic Earth*, Geodynamics Series 29, pp. 33–50. American Geophysical Union, Washington DC.

Lambeck K, Yokoyama Y and Purcell T (2002). Into and out of the Last Glacial Maximum: sea-level change during Oxygen Isotope Stages 3 and 2. *Quaternary Science Reviews* **21(1–3)**, 343–360.

Lambeck K, Anzidei M, Antonioli F, Benini A and Esposito A (2004). Sea level in Roman time in the Central Mediterranean and implications for recent change. *Earth and Planetary Science Letters* **224**, 563–575.

Leslie LM, Karoly DJ, Leplastrier M and Buckley BW (2007). Variability of tropical cyclones over the southwest Pacific Ocean using a high resolution climate model. *Meteorology and Atmospheric Physics (Special Issue on Tropical Cyclones)*, in press.

List JH, Sallenger AH, Hansen ME and Jaffe BE (1997). Accelerated relative sea-level rise and rapid coastal erosion: testing a causal relationship for the Louisiana barrier islands. *Marine Geology*, **140(3–4)**, 347–365.

Lowe JA and Gregory JM (2006). Understanding projections of sea level rise in a Hadley Centre coupled climate model. *Journal of Geophysical Research* **111**, C11014. <doi:10.1029/2005JC003421>.

McInnes KL, Walsh KJE, Hubbert GD and Beer T (2003). Impact of sea-level rise and storm surges on a coastal community. *Natural Hazards* **30(2)**, 187–207.

McInnes KL, Hubbert GD, Macadam I and O'Grady JG (2007a). Assessing the impact of climate change on storm surges in southern Australia. *MODSIM 07* conference, Christchurch, New Zealand, 10–13 December.

McInnes KL, Macadam I, Abbs DJ, O'Farrell SP, O'Grady J and Ranasinghe R (2007b). Projected changes in climatological forcing conditions for coastal erosion in NSW. *Coasts & Ports 2007* conference, Melbourne, Victoria, 18–20 July.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ and Zhao ZC (2007). Global climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller). Cambridge University Press, Cambridge, UK and New York.

Mimura N and Nobuoka H (1995). Verification of Bruun Rule for the estimate of shoreline retreat caused by sea-level rise. In *Coastal Dynamics 95* (Eds WR Dally and RB Zeidler) pp. 607–616. American Society of Civil Engineers, New York.

Otto-Bleisner BL, Marshall SJ, Overpeck JT, Miller GH, Hu A and CAPE Last Interglacial Project members (2006). Simulating Arctic climate

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.

warmth and icefield retreat in the last interglaciation. *Science* **311**, 1751–1753.

Overpeck JT, Otto-Bliesner BL, Miller GH, Muchs DR, Alley RB and Kiehl JT (2006). Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* **311**, 1747–1750.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE and Somerville RCJ (2007). Recent climate observations compared to projections. *Science* **316,** 709. <doi:10.1126/science.1136843>.

Ranasinghe R, McLoughlin R, Short A and Symonds G (2004). The Southern Oscillation Index, wave climate, and beach rotation. *Marine Geology* **204**, 273–287.

Roy PS (1994). Holocene estuary evolution - Stratigraphic studies from southeastern Australia. In *Incised-Valley Systems: Origin and Sedimentary Sequences* (Eds RW Dalrymple, BA Zaitlin and R Boyd). pp. 241–263. SEPM (Society for Sedimentary Geology), Tulsa, Oklahoma.

Roy PS and Thom BG (1981). Late Quaternary marine deposition in New South Wales and southern Queensland – an evolutionary model. *Journal of the Geological Society of Australia* **28**, 417–89.

Roy PS, Cowell PJ, Ferland MA and Thom BG (1994). Wave dominated coasts. In *Coastal Evolution: Late Quaternary Shoreline Morphodynamics* (Eds RWG Carter and CD Woodroffe) pp. 121–186 Cambridge University Press, Cambridge, UK.

Searle P and Semeniuk V (1985). The natural sectors of the inner Rottnest Shelf coast adjoining the Swan Coastal Plain. *Journal of the Royal Society of Western Australia* **67**, 116–136.

Short AD (2003). A survey of Australian beaches. In *Coastal Sediments 2003, Proceedings of the International Conference, Clearwater Beach, Florida* (Eds RA Davis, A Sallenger and P Howd). World Scientific Publishing, River Edge NJ.

Stirling CH, Esat TM, Lambeck K and McCulloch MT (1998). Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth, *Earth Planetary Science Letters* **160**, 745–762.

Stive MJF (2004). How important is global warming for coastal erosion? *Climatic Change* **64(1–2)**, 27–39.

Stive MJF and Wang ZB (2003). Morphodynamic modeling of tidal basins and coastal inlets. In *Advances in Coastal Modeling*, (Ed. C Lakhan) pp. 367–392. Elsevier, Amsterdam.

Stolper D, List JH and Thieler ER (2005). Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behaviour model (GEOMBEST), *Marine Geology* **218 (1–4)**, 17–36.

Thom BG (1974). Coastal erosion in Eastern Australia. *Search* **5**, 198–209.

Woodworth PL (1999). High waters at Liverpool since 1768: the UK's longest sea level record. *Geophysical Research Letters* **26(11)**, 1589–1592.

Woodworth PL and Player R (2003). The Permanent Service for Mean Sea Level: an update to the 21st century. *Journal of Coastal Research* **19(2)**, 287–295.

Zhang K, Douglas BC and Leatherman SP (2004). Global warming and coastal erosion. *Climatic Change* **64**, 41–58.

in Transitions: Pathways Towards Sustainable Urban Development in Australia, ed. P. W. Newton, CSIRO Publishing, Australia, 2008.