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POSITION ANALYSIS:  
climate change,  
sea-level rise and  
extreme events:  
IMPACTS AND  
ADAPTATION  
ISSUES



Australian Government  
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and Water Resources  
Australian Antarctic Division



Australian Government  
Bureau of Meteorology





*Position Analysis: Climate change, sea-level rise and extreme events: impacts and adaptation issues.*

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*Requests and enquiries concerning reproduction rights should be addressed to:*

*The Manager  
Communications  
Antarctic Climate & Ecosystems  
Cooperative Research Centre*

*Private Bag 80  
Hobart Tasmania 7001  
Tel: +61 3 6226 7888  
Fax: +61 3 6226 2440  
Email: enquiries@acecrc.org.au  
www.acecrc.org.au*



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# 1. introduction

This position analysis outlines recent developments in the science of sea-level rise and its influence on the effects of extreme events such as high tides and storm surges.

It also identifies some of the key issues around the potential impacts of sea-level rise and extreme events and the consequences they will have for Australia and its neighbours.

The aims of this position analysis are to:

1. inform Australian governments and community about recent results in the science of sea-level rise and associated events that are a consequence of climate change;
2. outline some of the likely impacts of these changes on Australia and neighbouring countries in the South Pacific and Indian Ocean regions; and
3. identify issues that will need to be considered in developing policies to respond to sea-level change and its impacts.

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This position analysis draws heavily on papers by Dr John Church *et al.* (2001; 2006a) and Dr John Hunter (2007) of the ACE CRC, and the Third and Fourth Assessment Reports (TAR and AR4) published in 2001 and 2007, respectively, by the Intergovernmental Panel on Climate Change (IPCC).

The term 'extreme sea-level events' in this document refers to events during which the sea level exceeds some specific fixed level.

## 2. the science of sea-level rise

Climate has changed throughout Earth's history, varying through four cold (glacial) cycles over the past 400,000 years (IPCC 2007, Ch 6).

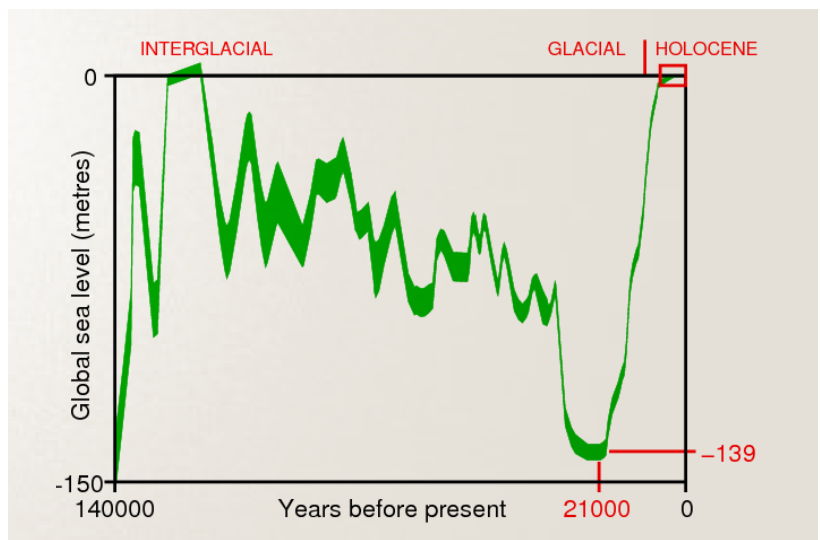
These cycles are believed to have been driven by, among other things, small changes of the Earth's orbit that caused subtle changes in the amount and timing of incoming solar radiation. This small effect was amplified by a number of processes, such as changes in the reflectivity of the ground when covered by ice or snow, or removal of carbon dioxide (a greenhouse gas) from the atmosphere into the ocean or by marine plants.

Accompanying this climate change have been large changes in sea-level as the Earth's climate oscillated between the glacial periods and warmer (inter-glacial) periods over thousands of years.

This sea-level change was driven predominantly by melting and freezing of ice on land. Cooling during the glacial cycles led to the build-up of ice on land, primarily in the Northern Hemisphere. This locked up water as land-based ice rather than water in the ocean, resulting in sea-level falls of more than 100 m. When the atmosphere warmed again, much of the land ice melted and flowed into the ocean, resulting in a rise in sea level (Figure 1). There would also have been some warming and cooling of the ocean, resulting in expansion of a warmer ocean (termed thermal expansion) and contraction of a cooler ocean.



Photo: Simon Marsland



**Figure 1. ▲**  
History of global sea level over the past glacial–interglacial cycle relative to modern-day levels (indicated by the horizontal line at 0 on the graph).

The thickness of the green line represents the uncertainty. The red rectangle (top right) indicates the period shown in Figure 2. After Lambeck and Chappell, 2001; Lambeck et al., 2002; Lambeck, 2002; Lambeck et al., 2004.

## 2. the science of sea-level rise



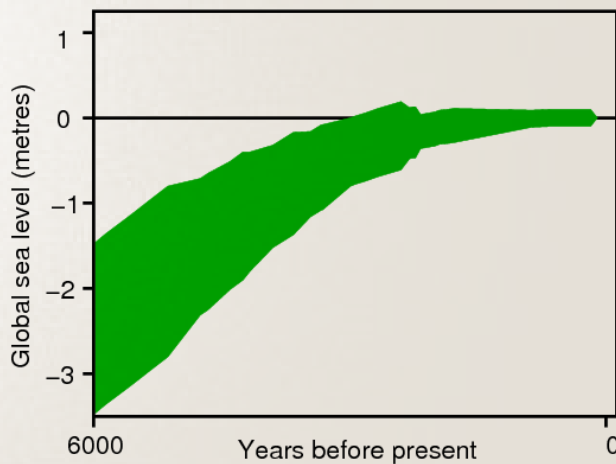
Following the peak of the last ice age 21,000 years ago (the 'glacial maximum') sea level rose by as much as 4 m per century (Church *et al.*, 2001) as the climate warmed and land-based ice melted and drained into the ocean. Around 2,000 years ago, sea-level rise had almost stopped (Figure 2) and from 1,000 years ago to the late 19th century, sea-level was relatively stable, varying by less than about 0.2 m over the whole period.

**But we are now living in a world in which the climate is being substantially modified by human activity, and it is happening at a pace that the Earth has not experienced for at least 5,000 years.**

Increases in greenhouse gases in the atmosphere during and since the 19th century, caused primarily by human-induced emissions, have contributed substantially to warming of the atmosphere.

Global atmospheric temperature increased by 0.76°C from 1850–1899 to 2001–2005 (IPCC, 2007) resulting in both warming of the oceans and melting of ice on land. The sea level rose significantly during the 20th century, at a rate that has not been experienced for the past 5,000 years (Figure 3 on page 6).

Church and White (2006) used a combination of tide-gauge records and satellite altimeter data to estimate sea levels from 1870 to 2004 and showed a global average rise of 0.17 m during the 20th century. Figure 3 also shows that the sea-level rise for Australia (the light blue line) was only slightly less than the global average.



**Figure 2. ▲**  
Global sea level over the past 6,000 years relative to modern-day levels (indicated by the horizontal line at 0 on the graph).

The thickness of the green line represents the uncertainty. The plotted record ends at about 1900. After Lambeck and Chappell, 2001; Lambeck *et al.*, 2002; Lambeck, 2002; Lambeck *et al.*, 2004.

# 2. the science of sea-level rise

The analysis also suggests that sea level has risen faster over the past decade than at other times in the last century, a conclusion supported by other analyses using only tide-gauge data (Holgate and Woodworth, 2004; Jevrejeva *et al.*, 2006).

Unlike the sea-level changes associated with the glacial-interglacial cycles, recent sea-level rise has increasingly been driven by a warming ocean and the corresponding thermal expansion.

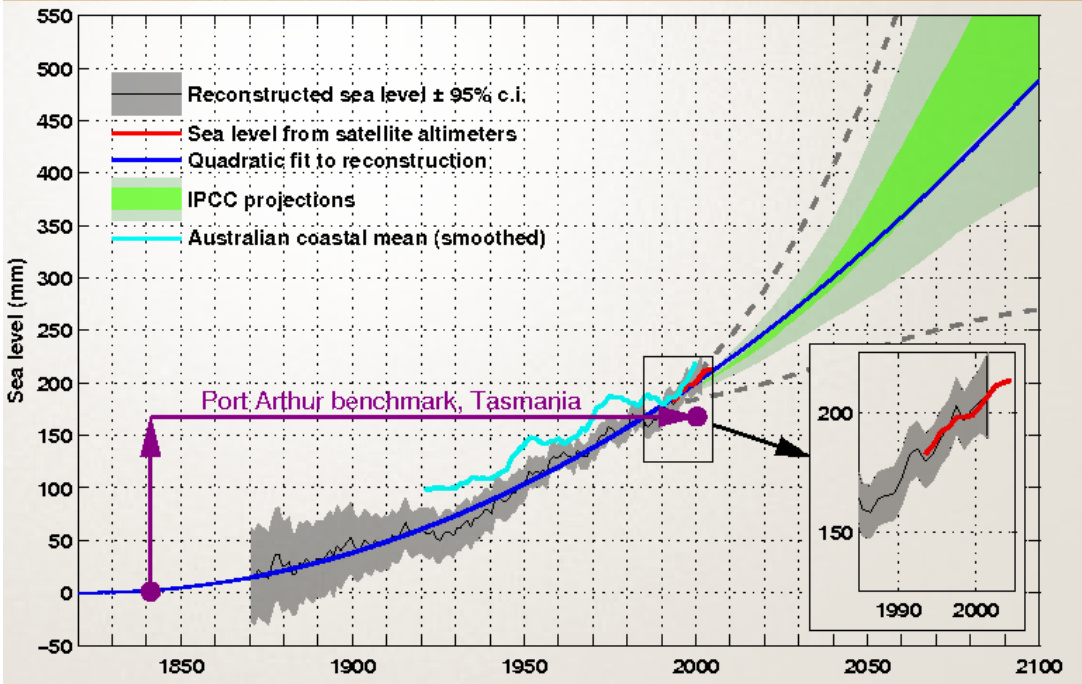
Thermal expansion and the melting of glaciers and ice caps (excluding the Greenland and Antarctic ice sheets) contribute similar amounts to current sea-level rise (IPCC 2007). Domingues *et al.* (2008) have recently shown that ocean thermal expansion contributed 50% more to total sea level rise for the second half of the 20th century (1961–2003) than estimated by the IPCC (2007).

Extremes of high sea-level events depend on changes in long-term average sea level as well as fluctuations around that

average caused, for example, by tides, atmospheric pressure and storm surges. Any changes in these periodic events will also have effects on the extremes of sea level experienced at the coast. Even without any increase in weather-related events, a rise in the average sea level will mean that extreme sea levels that currently cause occasional inundation or wash-over at a given location will do so with increasing frequency in the future, causing increasingly severe impacts on coastal communities, infrastructure and habitats.

**Figure 3. ▼**  
**Sea-level reconstruction of Church and White (2006).**

Historical sea-level reconstruction is shown by the thin black line, with grey shading indicating  $\pm 95\%$  confidence limits. Magenta dots and arrows indicate the estimate of sea-level rise from 1842–2001 from Port Arthur, Tasmania (Hunter *et al.* 2003). Dashed grey lines indicate the upper and lower limits of sea-level projections (1990–2100) from the IPCC Third Assessment Report (Church *et al.*, 2001). The darker green shading indicates the range in projected sea-level rise under different greenhouse gas emissions scenarios averaged across several global climate models, whilst the broader pale green shading shows the range of projected sea-level rise across all models and emissions scenarios, excluding allowance for changes in land-based ice. The red line indicates the sea level measured by satellite altimeters, which shows that observed sea level has been tracking the upper limit of projections since 1990. The light blue line shows the estimate of relative sea level around Australia (Church *et al.*, 2006a). The dark blue curve is a quadratic fitted to the sea-level data from 1870 to 2001. Figure courtesy Neil White, CSIRO.



## 2. the science of sea-level rise

Studies of extreme sea levels from many locations around the world have indicated that sea-level rise is generally the dominant cause of more frequent extreme sea-level events (IPCC 2007; Woodworth and Blackman 2004). The long tide-gauge records from Fremantle and Fort Denison (Sydney) show that the return period<sup>1</sup> of flooding that occurred on a yearly to decadal basis pre-1950, decreased by a factor of about three from the pre-1950 period to the post-1950 period (Figure 4, Church *et al.*, 2006a). This was mainly caused by sea-level rise.

The relatively small rise in sea level that has occurred during the 20th century has therefore already caused a significant change in the frequency of extreme sea-level events around Australia's coast.

Sea level will continue to rise during the 21st century. Mitigation of greenhouse gas emissions might attenuate sea-level rise in the long-term but we are already locked into significant sea-level rise during this century.

Global sea levels are likely to rise by around 0.03 m in the next decade and by 0.2–0.8 m by the end of this century (IPCC, 2007).

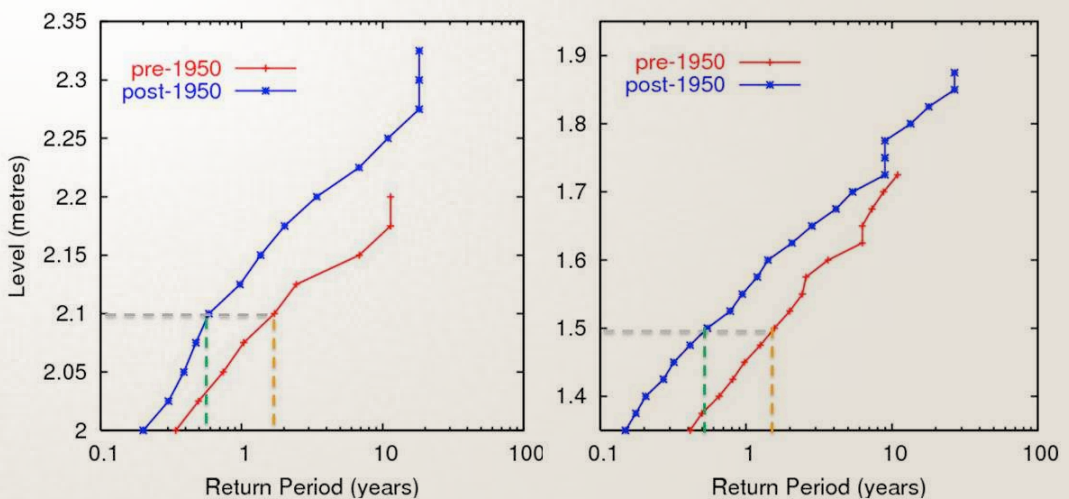
Even a moderate rise in sea level of 0.2–0.5 m will have serious implications for coastal zone management, including for communities, infrastructure, planning schemes, aquaculture, and coastal ecosystems – in Australia, the Indian Ocean and South Pacific regions – and globally.

**Sea-level rise is a significant long-term climate change issue that has important implications now and into the future for us all, internationally, nationally and locally.**

**Figure 4. ▼**  
**Change of return period for extreme high levels from pre-1950 to post-1950 conditions.**

Plots for Fort Denison (left) and Fremantle (right) show the return periods (on a logarithmic scale on the horizontal axis) for sea-level events of specific levels (vertical axis) prior to 1950 (red lines) and since 1950 (blue lines). The shift of the curves to the left (from red to blue) indicates that events of given levels (examples indicated by horizontal dashed grey lines) have happened approximately 3 times more often on average since 1950 (vertical dashed green lines) than before 1950 (vertical dashed orange lines). Source: Church *et al.*, 2006a.

<sup>1</sup> The return period (or average recurrence interval) is the average period between extreme events of a given height.



# 3. contributions to sea-level rise

There is still much uncertainty surrounding what contributes to the sea-level rise we are seeing today. In particular, the significance of the Antarctic contribution is not known with confidence, highlighting the gaps in our knowledge about the mass balance of the Antarctic ice sheet, especially over central and east Antarctica, both now and in the future.

While the total of the contributions statistically agrees with sea-level rise observed by satellites for 1993–2003, three caveats are important:

1. The uncertainties are quite large, about 25% of the total.
2. There are now better estimates of the ocean thermal expansion (Domingues *et al.*, 2008) than cited in Table 1. Future estimates of thermal expansion are likely to further improve the agreement between the total of the sea-level rise contributions and the satellite observations.
3. Land-based (terrestrial) storage<sup>2</sup> of water is possibly a significant influence on sea-level rise but has been omitted from the contribution to sea-level rise listed in Table 1. This land storage was estimated to contribute  $-0.35 \pm 0.75$  mm/year to mean sea levels during 1910–1990 by the IPCC Third Assessment Report. It was omitted from the Fourth Assessment Report because it is “poorly known” and because “...indirect evidence from considering other contributions to these sea-level budget... suggests that the land contribution either is small ( $<0.5$  mm/yr) or is compensated for by unaccounted or underestimated contributions.” (IPCC, 2007). The Fourth Assessment Report also concluded that “...our assessment of the land hydrology contribution to sea-level change has not led to a reduction in the uncertainty compared to the IPCC Third Assessment Report” (IPCC, 2007).

The two largest contributions to present sea-level rise are thermal expansion of the ocean and glacier/ice cap melt. Melting ice from Greenland and the West Antarctic Ice Sheet will become more and more important in coming decades to centuries.

The East Antarctic Ice Sheet could well gain mass over its interior despite a warmer global climate, but there remains great uncertainty about the prognosis for rates of discharge from the margins of the ice sheet as the surrounding oceans warm.

**The Greenland and the West Antarctic ice sheets hold enough grounded ice to raise sea level by 7 m and 6 m respectively if they melted entirely (Church *et al.*, 2001; IPCC, 2007).**

Surface melting alone is likely to lead to shrinkage of the Greenland Ice Sheet if global temperatures rise by at least 2.3–3.9°C above pre-industrial values (Gregory and Huybrechts, 2006). If these warmer temperatures were maintained over the coming centuries to millennia, sea level would rise by 7 m. It has been estimated that this temperature threshold will be reached by 2100 even under a mid-range emission scenario (IPCC, 2007, Section 10.5.4.6) and likely sooner under the high-impact scenario we are currently tracking.

Contributions to sea-level rise (mm/yr) 1993-2003	
Thermal expansion	1.6 ± 0.5
Glaciers & ice caps	0.77 ± 0.22
Greenland ice sheet	0.21 ± 0.07
Antarctic ice sheet	0.21 ± 0.35
<b>Total</b>	<b>2.8 ± 0.7</b>
Observed from satellites	3.1 ± 0.7

**Table 1: ▲**

The IPCC Fourth Assessment Report summarised the major contributions to sea-level rise over the period 1993–2003. Note: the errors quoted are at 90% confidence intervals. Source: IPCC 2007, *Technical Summary*, p 50.

<sup>2</sup> Terrestrial storage refers to liquid water stored on the land surface or as groundwater.

<sup>3</sup> The AR4 defines ‘likely’ as a better than 66% chance of occurrence, or a 66% chance of being within a specified range.



## 3. contributions to sea-level rise

Even if atmospheric greenhouse gas concentrations are stabilised at 550 ppm (CO<sub>2</sub> equivalent), there is about a 50% change of melting of the Greenland Ice Sheet (possibly irreversibly). This is because the critical temperature increase for Greenland of 2.3–3.9°C falls well within the likely<sup>3</sup> range of global temperature expected if greenhouse gas concentration is stabilised at 550 ppm (CO<sub>2</sub> equivalent) (IPCC, 2007, Section 10.7.2; Stern, 2006).

Two other causes of faster polar ice sheet decay have gained recognition only in the last decade, but are not yet adequately included in our climate models:

- water from melting surface ice during summer may percolate through crevasses to the bases of ice sheets and 'lubricate' the contact between the ice sheet and the bedrock. The result would be to speed up the flow of ice sheets into the sea (Zwally *et al.*, 2002).
- ice shelves floating in the ocean where ice sheets flow off land masses appear to act as 'buttresses', slowing the flow of the ice sheets into the ocean. Disintegrating ice shelves (eg the Larsen B Ice Shelf in 2002) have resulted in glaciers behind the ice shelves flowing more quickly to the sea (Rignot *et al.*, 2004). It is likely that these buttressing ice shelves will become increasingly prone to thinning, fracture and collapse as they are warmed from above by a warming atmosphere and from below by warming oceans.

So it is likely that current projections of the rate of increase in sea level attributable to loss of ice from the Greenland and Antarctic ice sheets are under-estimates, and that sea level may rise more quickly than recent projections.

Gaps in our knowledge of these two processes led the IPCC to add 0.1–0.2 m to the upper limit of the model projections for sea-level rise to 2090–2099 in the Fourth Assessment Report and to add the caveat that "...larger values cannot be excluded..." (IPCC, 2007).

Photo: John Hunter

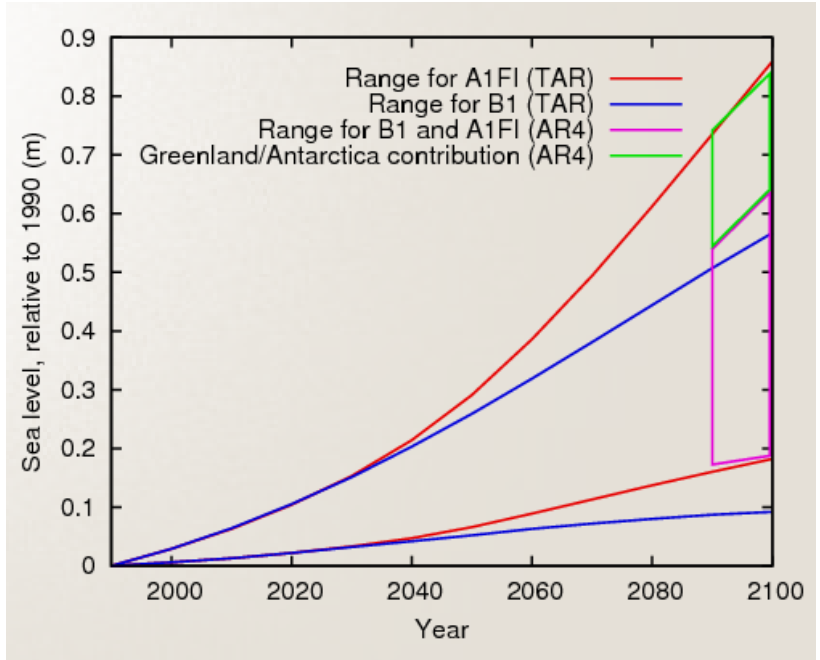


# 4. questions and uncertainties

Computer models are used to make projections of climate and sea levels over future decades to centuries.

Although model projections are based on the best available understanding of climate processes and potential future levels of greenhouse gas emissions, which are now known to affect climate change, these projections are imperfect for three reasons:

- although we understand climate processes reasonably well, our knowledge of all the processes that determine climate is not complete. This can be considered as ‘knowledge uncertainty’.
- it is usually difficult or impossible to completely capture reality in a computer model, and different models represent climate in slightly different ways. Variation between model representations of climate, combined with the underlying knowledge uncertainty, is sometimes referred to as ‘model uncertainty’.
- we cannot know for sure what will be the future scenario for levels of greenhouse gas emissions. This is called ‘scenario uncertainty’. We don’t know today what will be the future social, economic and environmental development of the world, and the consequent greenhouse-gas emissions.



**Together, these uncertainties create limitations on our statements about likely climate conditions and sea level at any time and the uncertainty generally increases the further into the future we look.**

The scenario uncertainty is dealt with by modelling a range of possible futures, or emissions scenarios<sup>4</sup> to capture a credible range of possible future climate conditions, including sea level.

**Figure 5. ▲ Projections of sea-level rise relative to 1990.**

Figure shows sea-level projections from the IPCC’s Third Assessment Report (TAR) and the Fourth Assessment Report (AR4), for the B1 (low impact) and A1FI (high impact) scenarios. Source Church et al., 2001, IPCC 2007

The model uncertainty, which in effect encapsulates both our knowledge uncertainty and the variation in how we represent climate in computer models, is captured in climate projections that combine results from several models.

Figure 5 shows the minimum and maximum model projections of sea level relative to 1990<sup>5</sup> for two emissions scenarios, a ‘low-emission’ (B1, blue lines) and ‘high-emission’ (A1FI, red lines) scenario. The upper and lower lines for each scenario show the range of results from different climate models when run with that scenario.

<sup>4</sup> The main emission scenarios used for IPCC modelling are described in the Special Report on Emission Scenarios (SRES) (Nakicenovic, et al., 2000). These scenarios do not allow for any specific greenhouse mitigation activities. The lower emission SRES scenarios, such as B1, represent emission reductions that may be expected simply from ‘cleaner’ environmental policies, and fall somewhat short of what is required for stabilisation of greenhouse gas concentrations at what Stern (2006) suggested was an ‘acceptable’ level. The impacts discussed earlier are therefore those which we should expect in the absence of any significant mitigation policies.

<sup>5</sup> Strictly, the TAR related projections to 1990, while the AR4 related projections to the average over the period 1980–1999.

## 4. questions and uncertainties

Photo: John Hunter



The upper red line and lower blue line bound almost completely the full range of emissions scenarios used for climate modelling by the IPCC to date. The plotted red and blue lines represent results from modelling reported in the IPCC Third Assessment Report (Church *et al.*, 2001). The magenta box at the far right of the figure shows the range of model projections of sea level over the period 2090–2099, reported in the AR4 (IPCC 2007), for the same low- and high-emission scenarios excluding some aspects of Greenland and Antarctic Ice Sheet dynamics that were included in the earlier projections. The green box represents the additional estimated potential rise in sea level (up to 0.2 m) to be added to the upper limits of the later projections of sea level to account for these omissions. Importantly, the upper limits of the projections of sea level in the Third and the Fourth Assessment Reports (with ice sheet uncertainty added) are in good agreement at 2090–2099, while the lower limit is roughly 0.1 m higher for the Fourth than for the Third Assessment Report. It should be noted that the Fourth Assessment Report adds the caveat that “...larger values cannot be excluded...”

### **The range of projected sea level at 2090–2099 is 0.18–0.79 m above that in about 1990.**

Although these results are an extensive assessment of present climate science, some scientists have suggested that the

sea-level projections may have been underestimated. Rahmstorf (2006) used the relationship between global average temperature and sea level during the 20th century to project sea level into the 21st century based on the model temperature projections. He suggested a rise of 0.5–1.4 m above 1990 levels by 2100. One extreme projection (Hansen 2007) suggests that a rise of 5 m over the 21st century is not completely beyond question. However, Pfeffer *et al.* (2008) demonstrate that such a rapid rise is not consistent with glacier dynamics. Rahmstorf *et al.* (2007) showed that since 1990, global temperature and sea level have both been tracking the upper limits of the model projections (see Figure 3), again suggesting that most of the model projections may be underestimating actual changes. Raupach *et al.* (2007) and Candell *et al.* (2007) showed that global greenhouse-gas emissions are now tracking well above the high-impact (A1FI) emissions scenario, and that the world is not yet taking any effective mitigation measures. It is therefore reasonable to assume that the higher projections are plausible.

There is significant uncertainty in the projections of sea-level rise during this century and beyond, stemming partly from the model and scenario uncertainties described earlier, but also because of our poor understanding of the fundamental process that determine the dynamics of the large ice sheets over Greenland and Antarctica.

An additional uncertainty in the projections of sea level is that present models of sea-level rise do not include climate-carbon cycle feedbacks. This is not the case for models used to project temperature change.

There are also differences between models concerning the spatial variation of sea-level rise during the 21st century. Some models project that sea level will rise by smaller-than-average amounts in the Southern Ocean and by larger-than-average amounts in the Arctic. In these models, the sea-level rise in these regions typically deviates by 0.1–0.2 m from the global average over the 21st century.

Another common but not ubiquitous feature of the projections is pronounced sea-level rise of up to about 0.2 m above the global average in a narrow band stretching across the Indian and southern Atlantic and Pacific oceans. Sea-level rise also tends to be higher at 30°–45°S and 30°–45°N (IPCC, 2007).

Variation in the locations of higher- and lower-than-average sea-level rise will influence the vulnerability of different regions to the effects of rising sea level. Resolving this uncertainty will be particularly important for planning local responses to likely sea-level rise.

## 5. physical impacts

### Extremes

A rise in mean sea-level on its own will mean that we will experience more frequent extreme sea-level events above a given fixed reference point, even if the variation about that mean does not change.

The frequency of extreme events can increase many times for even modest changes in mean sea level. Figure 6 shows the estimated increase in extreme sea-level events caused by a mid-range (0.5 m) sea-level rise over the 21st century for 29 Australian locations where we have good tidal records that are longer than 30 years. The figure indicates that events that happen every few years now, are likely to occur every few days in 2100 if mean sea-level rises by just 0.5 m. Larger increases in the frequency of extremes may occur in many places, including around Sydney, Brisbane and in Bass Strait.

It is likely also that tropical cyclones will become more intense (IPCC, 2007), bringing with them higher storm surges that will affect sea-level extremes most in the northern parts of Australia. Storm tracks may move towards the north and south poles, bringing changes in wind and surge events around southern Australia.

Winds and surges may also increase in some regions around south-eastern Australia associated with significant ocean warming. Increases in these meteorological events is likely to exacerbate the effect of rising sea level on the frequency of extreme events, effectively making the orange discs in Figure 6 larger, though the exact size of such additional effects remains uncertain.

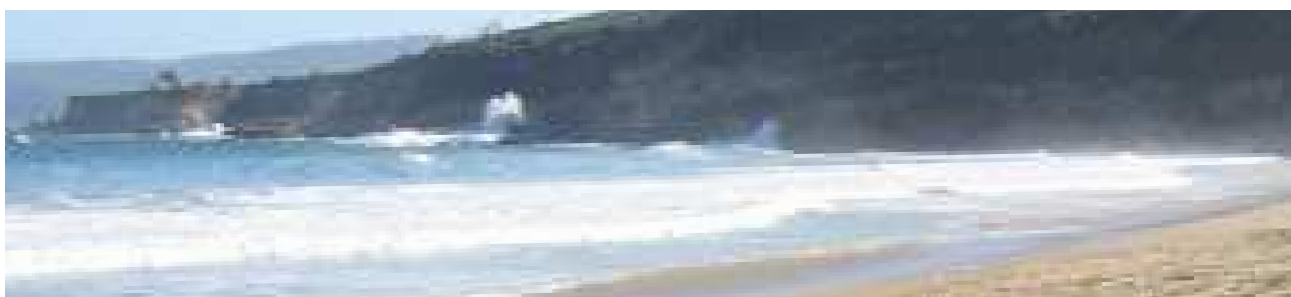
### Shoreline recession

It is well-established that sea-level rise generally leads to erosion and causes the shoreline to retreat landwards (shoreline recession) especially on sandy coasts. Today, 70% of the world's beaches are eroding and less than 10% are extending seawards (Bird 1993). The amount of such erosion caused by sea-level rise can be approximated by the Bruun Rule (Bruun 1962; but see also Pilkey and Cooper 2004; Nicholls and Stive 2004) which says that shoreline recession happens at a rate in the order of 100 times the amount of sea-level rise. This equates to around 50 m landward erosion for a sea-level rise of 0.5 m. Erosion of this magnitude will have significant impacts on coastal ecosystems, infrastructure, land tenure and public beaches.

It is important to note that this rule of thumb applies to specific circumstances (eg sandy shores with no long-shore transport of sediment and a certain wave environment). It has been noted that the ratio of recession to sea-level rise will be far higher (some estimate as high as 800:1) in some areas (eg, high energy exposed coasts such as around much of southern Australia) and lower in others (eg, very low energy or embayed coasts across much of tropical Australia).

### Flooding of low-lying islands

Low-lying islands are particularly vulnerable to sea-level rise. The low profile of many islands exposes them to flooding from higher sea levels and more frequent high sea-level events. They also often cover only a small area, with little opportunity for communities to retreat in the face of rising sea levels or receding shorelines. Small islands such as coral atolls are by their nature vulnerable to small changes in the environment. A coral atoll is generally sustained by a balance between accumulated material eroded from fringing coral reef and sediment lost through erosion. Sea-level rise is just one factor that can disturb this balance – others being changes in the patterns of winds, waves or currents and human impacts such as sand mining or dredging.



## 5. physical impacts

**Figure 6. ► Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events.**

The multiplying factor for the increase in the frequency of occurrence of high sea-level events caused by a sea-level rise of 0.5 m is indicated by the diameter of the discs. *Source: Hunter (unpub).*

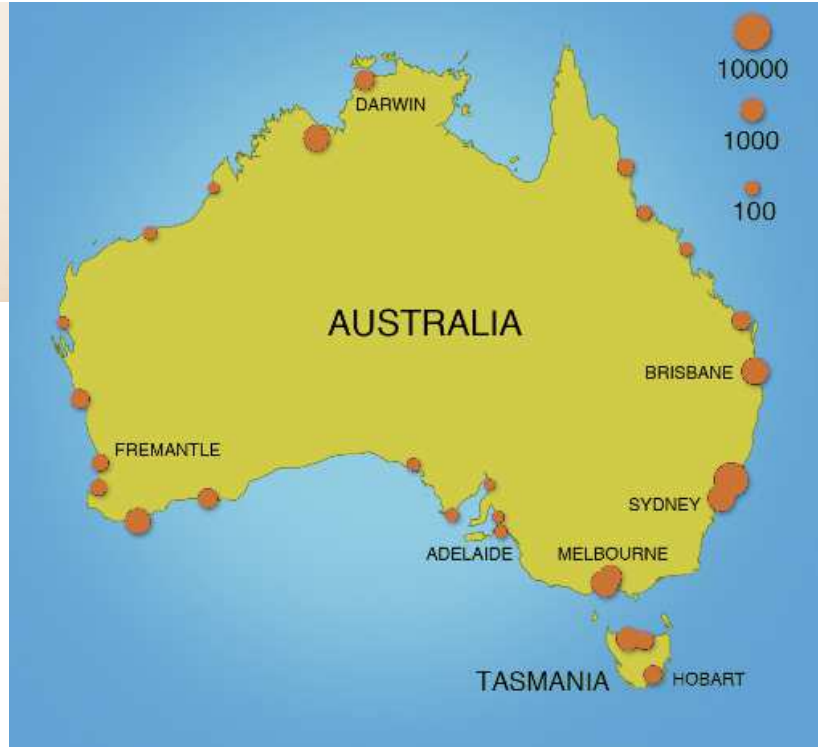


Photo: John Hunter

## 6. regional impacts

Changes in sea-level rise and the frequency and intensity of extreme events have potentially significant environmental, social, cultural and economic consequences for vulnerable coastlines in Australia, and for low-lying coastal regions and islands in the Indian and South Pacific Oceans (Church *et al.*, 2006b).

In Australia, local, state and national governments are concerned about the risks and costs associated with potential damage to housing and infrastructure in vulnerable coastal areas. The insurance and business sectors have also expressed similar concerns. It is now recognised by local, state and federal governments, communities and some industries that strategic planning, decision-making and planning guidelines will need to take into account projected impacts of sea-level rise and associated events.

A report published by the Australian Greenhouse Office (AGO, 2007) outlines the potential impacts of climate change in six areas of local government functions and responsibility: infrastructure and property services; health services; planning and development approvals; natural resource management; water and sewage services; and recreational facilities. The report notes that where coastal development is permitted in areas vulnerable to sea-level rise, councils are likely to have to bear responsibility, costs, legal liability and possibly compensation for decisions that allow developments to proceed (AGO, 2007).

The Australian Government and state and territory governments are also accountable for decisions taken to address, or not to address, the impacts of climate change. For example, Queensland has developed a State planning policy for climate change to ensure that climate change risks and issues – such as vulnerable and threatened areas and the type of development suitable for use – are incorporated into Queensland's planning and development systems (Queensland Government 2007a, 2007b). The goal is to enhance Queensland's resilience to the impacts of climate change, including impacts on the marine



## 6. regional impacts



Photo: John Hunter

ecosystems of the iconic Great Barrier Reef and its associated fisheries and tourism industries. This will require a collaborative approach by the Australian and Queensland governments to their jurisdiction and management responsibilities.

Many companies in the reinsurance industry in particular, and in the private sector, have already expressed concern about the likely impacts of climate change and sea-level rise. They are taking active measures to ensure that their assets are protected and their potential liabilities are addressed. Corporations with an eye on the future realise that they cannot afford to wait for scientific precision before they act, as the cost of not acting will exceed the costs of acting now. The influential Australian Business Roundtable on Climate Change, which includes big companies such as IAG, Origin, Swiss Re and Visy, has already voiced this concern (Henry, 2007).

In the Pacific and Indian Oceans, key direct consequences of sea-level rise are accelerated erosion of vulnerable coastal regions and saltwater intrusion into the freshwater areas of low-lying islands. Other potential consequences of sea-level rise in these regions include: flooding of low-lying areas along coasts and waterways; damage to key coastal infrastructure such as ports, tourism developments and industries such as agriculture, aquaculture and coastal fisheries; and displacement of local communities and the social, cultural and economic costs this brings.<sup>6</sup>

Less well-known and indirect consequences of sea-level rise include: changes in the nature and patterns of health and wellbeing, as well as the social, cultural and economic effects of community dislocation. Examples of the latter include: abandonment of affected neighbourhoods and islands and disruption to and destruction of, primary food sources such as agricultural crops, coastal fisheries and aquaculture. These consequences are likely to be borne out as shortages of staple foods, conflicts associated with issues of food and fresh water security, and the movement of environmental refugees away from affected regions to other destinations, both within the region and to neighbouring countries such as New Zealand and Australia.

In this context, sea-level rise has implications for Australia's international aid programs. For example, changes in sea-level rise have significant implications for communities and economies that rely on agriculture, fisheries and aquaculture both as domestic food resources and as products for export. Responding to increased frequency of extreme weather events, together with expected sea-level rise will also involve logistics, assets, and personnel from the Australian Defence Force.

<sup>6</sup> Solomon Islands Foreign Minister Pateson Oti told a 2007 news conference that "members of the Alliance of Small Island States faced a future of more violent storms, depleted fish stocks, bleached coral reefs and even annihilation if the world fails to deal with climate change." [www.planetark.com/dailynewsstory.cfm/newsid/44508/story.htm]

## 7. policy options



Photo: John Hunter

The scientific evidence is clear: global sea levels are projected to rise significantly by the end of this century.

The IPCC estimates the maximum sea-level rise this century to be around 0.8m, with a caveat that higher levels might be reached. More recent published work, however, suggests that a rise of up to 2 m is possible.

The impacts of climate change and sea-level rise create significant policy issues for all levels of government in Australia and internationally. As in all policy areas, decisions about sea-level rise are developed in an atmosphere of uncertainty. Addressing sea-level rise and the associated extreme events in the context of climate change means that policy options have to be developed in conditions of higher uncertainty than usual for the more traditional policy areas. Three policy options can be considered:

- do nothing
- mitigate
- adapt

### Option 1 (do nothing)

While this option is theoretically possible, it is not likely to be politically sensible. By 'doing nothing' governments risk relinquishing control of the sea-level rise policy agenda and outcomes to non-government interests. A 'status quo' option would centre on arrangements other than those of the Australian Government to influence behaviour. For example, economic structures such as premiums and loans designed to relate the risk of an activity to sea-level rise, would have to involve the insurance and finance industries. 'Doing nothing' brings significant risks for governments at all levels.



## 7. policy options

**Scientific and policy evidence indicates that the status quo is no longer a policy option as the costs of 'doing nothing' – economic, social, environmental and political – are likely to outweigh any perceived benefits of inaction.**

### Option 2 (mitigation) and Option 3 (adaptation)

The scientific evidence is that sea-level rise and an increase in the frequency and intensity of associated extreme events are connected to the rise in greenhouse gas emissions. Some argue that mitigation and adaptation are two separate options, but developing and adopting both mitigation *and* adaptation measures will be necessary.

Current projections indicate that potentially severe impacts of rising sea levels are now almost a certainty, that the current trend in global warming will continue, and that sea levels will continue to rise, even with immediate mitigation measures to actively reduce greenhouse gas emissions.

Mitigation measures are highly unlikely to significantly reduce the sea-level rise and extreme events in the short to medium term. Any mitigation measures would have to include regulations that are linked to economic structures, such as renewable energy targets, carbon pricing and trading regimes.

The first stage in adaptation to sea-level rise is developing climate change risk and vulnerability assessments. Adaptation strategies and action plans might then be targeted as key tools to address the impacts of sea-level rise, initially at those areas most vulnerable in the near future. A number of local and state governments in Australia and countries in the South Pacific Region, including Kiribati and Samoa, have begun this process. The Pacific Islands face major adaptation challenges and Australia is well-placed to assist these countries to develop appropriate adaptation measures, including through Australian international aid policies and funding programmes.

There are several possible adaptations to the likely impacts of sea-level rise in any location, but crucial to developing a portfolio of potential approaches is an initial vulnerability and risk management assessment. Options such as protection, setback provisions, retreat and/or abandonment of vulnerable areas (Rigby, 2005) may all need to be considered, both in Australia and in neighbouring, low-lying countries. Each of these strategies requires a substantial financial investment and the issues and costs associated with liability and compensation will need to be considered.

The complex question of liability in the event of accidents or damage to property from sea-level rise becomes even more difficult when hazards and risks are poorly defined and extend well into the future (Rigby, 2005).

More legislative exemptions offer some protection from liability for the affected planning authorities, but Rigby notes that "...such exemptions are not, however, absolute, and case law indicates that the spectre of liability remains for local planning authorities" (Rigby, 2005). These are complex policy questions that need to be carefully considered by policy and decision-makers.

Changing exposure to inundation may result in changes in access to or feasibility of areas for various coastal activities, including inshore fisheries, aquaculture or lowland agriculture, resulting in consequential changes in agricultural, fishing and aquaculture operations. This is likely to have significant implications for existing agriculture, tourism, fisheries and aquaculture in the South Pacific and Indian Ocean regions as well as some areas around Australia, including the Torres Strait islands. For example, how will agriculture develop sustainably if fresh water resources and arable land in coastal areas deteriorate or disappear? What will sea-level rise mean for tourism and the revenue it brings to the regions? What are the implications for sustainably managing coastal fisheries and aquaculture? Will landholders, tourism operators, holders of fishing and aquaculture leases or licences seek compensation for losses incurred? If so, from whom will they seek compensation?

# 8. conclusion

Science has demonstrated that sea-level rise is a significant consequence of increased greenhouse gas emissions and global warming.

Sea-level rise brings with it more frequent and severe extreme events, which will have direct and indirect environmental, social, cultural and economic impacts on coastal Australia and on low-lying islands in nearby regions. Domestic implications for Australian governments at all levels include the need to integrate information from ongoing climate science into strategic and development planning.

It is highly likely that a range of policy options, including abandonment, will need to be considered within years to decades for some locations in coastal Australia, low-lying islands (for example in the South Pacific and Indian Oceans) and large coastal areas across Asia. It is also likely that fresh water sources and staple food production in some island communities, including those of the Torres Strait, will be adversely affected and that populations will need to be evacuated as a result of the inter-related effects of climate change and sea-level rise, possibly within a few rather than many decades.

Australia will be involved in an increasing range of humanitarian and disaster relief activities, involving Australian government agencies and non-government organisations.

There are a number of reasons for suspecting that present IPCC projections for sea-level rise during the 21st century may be under-estimated. Improved projections of sea-level rise over coming decades remains a major requirement for determining the most effective strategies for responding to a changing sea level.

## Contacts

Dr Rosemary Sandford  
Policy  
rosemary.sandford@ace.org.au

Dr John Hunter  
Sea-level Rise  
john.hunter@acecrc.org.au

Dr Ian Allison  
Ice Sheets  
ian.allison@acecrc.org.au

## References

- Australian Greenhouse Office, 2007. *Climate Change Adaptation Actions for Local Government*. Australian Greenhouse Office, Department of Environment and Water Resources, Commonwealth of Australia, Canberra.
- Bruun, P., 1962, Sea-level rise as a cause of shore erosion. *Journal of Waterways and Harbors Division*, 88, 117–130.
- Canadell, J., C. L. Quéré, M. Raupach, C. Field, E. Buitenhuis, P. Ciais, T. Conway, N. Gillett, R. Houghton, and G. Marland, 2007. Contributions to accelerating atmospheric CO<sub>2</sub> growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences* 104, 18866–18870.
- Church, J.A. and White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33, L01602, doi:10.1029/2005GL024826.
- Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D. and Woodworth, P.L., 2001. *Changes in Sea Level*. [In IPCC, 2001: *Climate Change 2001: The Physical Science Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge United Kingdom and New York, USA, 881 pp.
- Church, J.A., Hunter, J.R., McInnes, K.L. and White, N.J., 2006a. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine*, 55, 253–260.
- Church, J.A., White, N.J. and Hunter, J.R., 2006b. Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, 53, 155–168.



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- Domingues, C., White, N.J. and Church, J.A., 2008. Improved ocean-warming estimates: implications for climate models and sea level rise. *Nature* 453. p1090-1093
- Gregory, J.M., and Huybrechts, P., 2006. Ice-sheet contributions to future sea-level change. *Philosophical Transactions of the Royal Society of London, Series A*, 364, 1709–1731.
- Hansen, J., 2007. Climate catastrophe. *New Scientist*, 28 July, 30-33.
- Henry, D., 2007. Households must act now to become energy efficient. *The Weekend Australian*, 24-25 March: 4. [Cited in Sandford, R. 2007 Antarctic Science in a Changing Climate: Challenges and Future Directions for Australia's Antarctic Science and Policy, in Kriwoken, L, Jabour, J., and Hemmings, A. (eds.) *Looking South*, Federation Press, Sydney, Australia.]
- Holgate, S.J. and Woodworth, P.L., 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* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B., Averyt, M. Tignor and H. L. Miller (eds)] Cambridge University Press, Cambridge United Kingdom and New York, USA, 996 pp.
- Jevrejeva, S., Grinsted, A., Moore, J.C. 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. Ice Sheets, Sea level and the dynamic earth. *Geodynamics Series 29*, American Geophysical Union, 33-50.
- Lambeck, K. and Chappell, J., 2001. Sea level change through the last glacial cycle. *Science*, 292, 679-686.
- 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) 343-360.
- Lambeck, K.L., 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.
- Nakicenovic, N. and 27 others, 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K.
- Nicholls, R.J. and Stive, M.J.F, 2004. Society and sea-level rise requires modelling. *Science* e-letter response, <http://www.sciencemag.org/cgi/eletters/303/5665/1781>.
- Pfeffer W.T., Harper, J.T. and O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, 321, 1340-1343.
- Pilkey, O.H. and Cooper, J.A.G, 2004. Society and sea level rise. *Science*, 303, 1781-1782.
- Queensland Government, 2007a. *ClimateSmart 2050: Queensland climate change strategy 2007*. Department of Natural Resources and Water, Queensland Government, Brisbane.
- Queensland Government, 2007b. *ClimateSmart Adaptation 2007-12*. Department of Natural Resources and Water, Queensland Government, Brisbane.
- Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 5810, 368-370.
- Rahmstorf, S, Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E. and Somerville, R.C.J. 2007. Recent climate observations compared to projections. *Science*, 316, 5825, 709.
- Raupach, M.R., Marland, G., Ciais, P., Le Quere, C., Canadell, J.G., Klepper, G. and Field, C.B., 2007. Global and regional drivers of accelerating CO<sub>2</sub> emissions. *Proceedings of the National Academy of Sciences*, 104, 10288-10293.
- Rigby, J., 2005. *Sea-level Rise and Coastal Settlements: An Analysis of Adaptive Decision Making Within Integrated Coastal Zone Management*, ACE CRC Technical Report No. 2, [www.acecrc.org.au/drawpage.cgi?pid=publications&aid=797039](http://www.acecrc.org.au/drawpage.cgi?pid=publications&aid=797039).
- Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A. and Thomas, R., 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters*, 31, L18401, doi:10.1029/2004GL020697.
- Stern, N., 2006. *The Economics of Climate Change*. Cambridge University Press, Cambridge, U.K.
- Woodworth, P.L and Blackman, D.L., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. *Journal of Climate*, 17, 6, 1190-1197.
- Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J. and Steffan, K., 2002. Surface melt-induced acceleration of Greenland Ice-Sheet flow. *Science*, 297, 218-222.

