



# REPORT CARD

## Sea-Level Rise 2012

# ACE CRC Report Card

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**Dr John Hunter**, Oceanographer, ACE CRC - [John.Hunter@acecrc.org.au](mailto:John.Hunter@acecrc.org.au)

**Dr Ian Allison**, ACE CRC, Honorary Research Professor, University of Tasmania - [Ian.Allison@acecrc.org.au](mailto:Ian.Allison@acecrc.org.au)

**Tessa Jakszewicz**, Deputy CEO, ACE CRC - [Tessa.Jakszewicz@acecrc.org.au](mailto:Tessa.Jakszewicz@acecrc.org.au)

An earlier draft of this report card was reviewed by Dr John Church, FAA, FTSE, CSIRO Fellow, Centre for Australian Weather and Climate Research (a partnership between CSIRO and the Bureau of Meteorology).

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

Miranda Harman  
Communications and Media Manager  
ACE CRC  
Private Bag 80  
Hobart  
Tasmania 7001  
Tel: +61 3 6226 7888  
Fax: +61 3 6226 2440  
Email: [Miranda.Harman@acecrc.org.au](mailto:Miranda.Harman@acecrc.org.au)  
[www.acecrc.org.au](http://www.acecrc.org.au)

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Takuu Atoll, Papua New Guinea, includes islands vulnerable to sea-level rise.  
Photo: John Hunter

## ACE CRC Report Card Sea-Level Rise 2012

### Introduction

Any warming of our planet will inevitably lead to a higher sea level due to thermal expansion of ocean water and melting of ice stored on the land in glaciers and ice sheets. Sea level has been rising slowly over the past 100 years. Rising sea level impacts coastal regions both by inundation and by causing the shoreline to recede through erosion. It will have a major impact on human societies because of the significant concentration of communities and infrastructure in coastal regions.

Understanding the contributions to present sea-level rise, and their causes, is crucial to projecting what might happen in the future.

The aims of this document are:

1. To update the Australian Government and the community on the latest developments in sea-level rise research, particularly those since 2008 when the ACE CRC produced *Briefing: a post-IPCC AR4 update on sea-level rise*;
2. To explain the components of sea-level rise and summarise our knowledge of how these could influence sea-level rise in the future; and
3. To inform policymakers, planners and infrastructure developers on the tools available to assist with adaptation to future sea-level rise.

## Past and Present Sea-Level Rise

Earth's climate has changed throughout the past. Over the past 800,000 years it has varied with ice-age cycles, each of which has lasted around 100,000 years. Prior to 1.3 million years ago each ice-age cycle lasted about 41,000 years. These cycles are initiated by the Earth's orbital variations, which cause small changes in the amount and timing of radiation from the sun. This small effect is amplified by a number of natural feedback processes.

Large changes in sea level, driven predominantly by melting and freezing of land-based ice sheets in the Northern Hemisphere, have accompanied these climate oscillations.

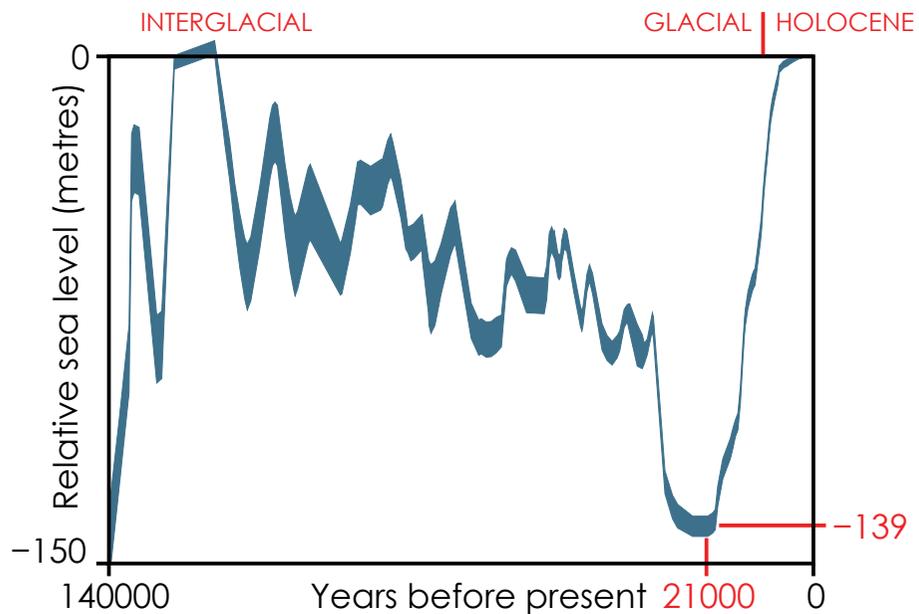
When the atmosphere cooled during these oscillations, land-based ice sheets locked up water from the ocean, resulting in sea-level falls of more than 100 m. When the atmosphere warmed again much of the land ice melted, returning water to the ocean and resulting in a rise in sea level. The evidence for these large changes comes from a number of sources, such as wave-cut shorelines and beach deposits, and the ratio of isotopes in fossils present in the sea bed.

As the climate warmed after the peak of the last ice age about 21,000 years ago (the last 'glacial maximum'), sea level rose by as much as 2 m per century (Fig. 1). However, by around 6,000 years ago, the rate of rise had fallen to less than 3 mm per year (0.3 m per century). Over the last 2,000 years until the late 19th century, sea level was stable to within about 0.2 m and the rate of change remained substantially below 3 mm per year (Lambeck and Chappell 2001, Lambeck et al 2002, Lambeck 2002, Lambeck et al 2004, Stanford et al 2010). This is the period when human populations started to grow and societies developed.

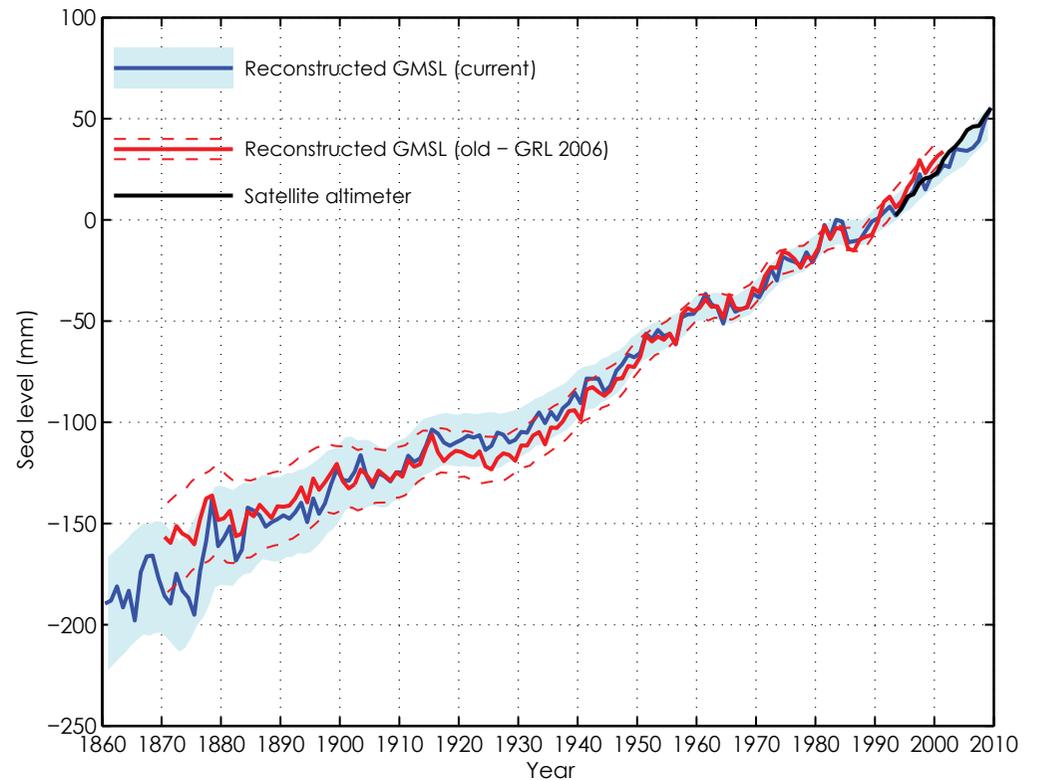
Increases in greenhouse gases in the atmosphere during and since the 19th century, caused primarily by human-induced emissions, have contributed substantially to warming of the atmosphere, especially since 1950 (IPCC 2007). Global atmospheric temperature increased by 0.76°C from 1850–1899 to 2001–2005 (IPCC 2007) resulting in both warming of the oceans and melting of ice on land. Sea level has risen significantly during the 20th century (Fig. 2) at a rate that has not been experienced for the past 6,000 years. This present sea-level rise is due to a combination of thermal expansion of a warming ocean and the melting of glaciers and ice sheets.

Ice shelf in East Antarctica. Such ice shelves are vulnerable to warming, which may lead to their melting, the acceleration of the glaciers that feed them and consequent sea-level rise.  
Photo: Simon Marsland





**Figure 1.** History of global sea level over the most recent glacial-interglacial cycle relative to modern-day levels (indicated by the horizontal line at 0 on the graph). The thickness of the blue line represents the uncertainty (after Lambeck and Chappell 2001, Lambeck et al 2002, Lambeck 2002 and Lambeck et al 2004).



**Figure 2.** Reconstruction of global mean sea level (GMSL) from 1860 to 2009 (blue line). Earlier estimates for 1870–2001 (Church and White 2006) are shown by the red solid line. Satellite altimeter data since 1993 is shown in black (Church and White 2011). Shading and dashed lines are one standard deviation errors.

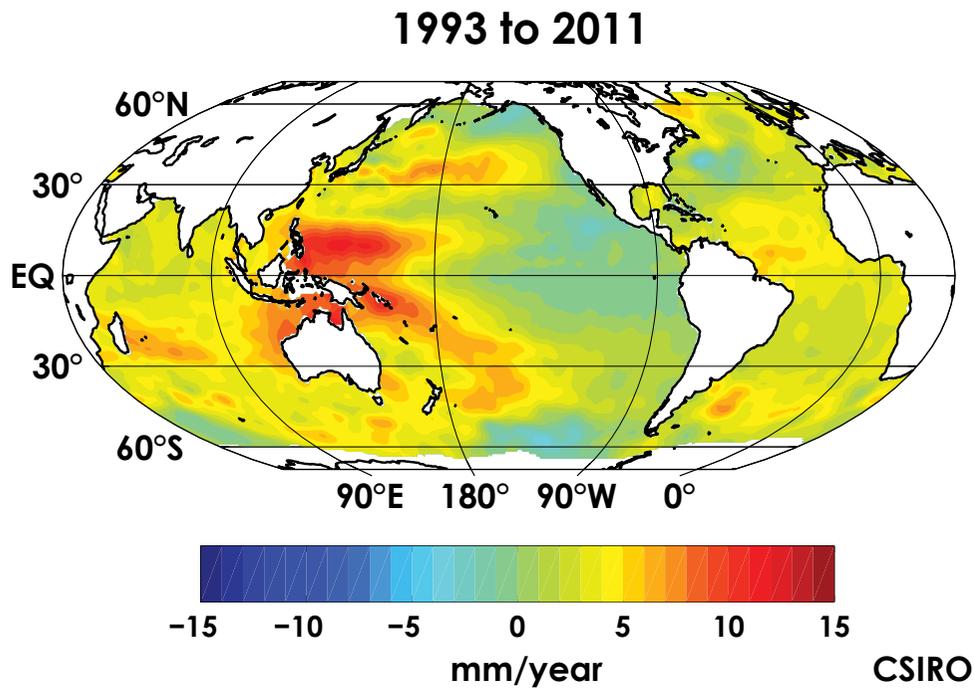
The issue and why it matters	What we know	What we need to know and how to find out
<p><b>How did global sea level change in the distant past?</b></p> <p>Understanding the causes of past, natural sea-level change provides insight into the sensitivity of the climate and sea-level systems to man-made changes.</p> <p>Knowing the sea level during the last interglacial (the warm period around 125,000 years ago, before the most recent ice age), when temperatures were broadly similar to the present, helps us better project future sea-level rise in response to global warming.</p>	<p>The paleo sea-level record from ocean sediments, ancient shore-line features and other sources shows there have been large changes in sea level over geological time scales. For about the last 800,000 years, sea level has fluctuated by more than 100 m during ice-age cycles with a periodicity of about 100,000 years (Fig. 1). These changes were driven predominantly by the melting and freezing of ice sheets.</p> <p>At the peak of the last interglacial temperatures are thought to have been around 2°C warmer and sea level at least 4-6 m higher than at present.</p> <p>This period was followed by the last glacial maximum (about 21,000 years ago), after which sea level rose rapidly for more than 10,000 years at rates as high as 2 m per century (Lambeck and Chappell 2001, Stanford et al 2010). This rise gradually stabilised until the seas began rising again in the late 19<sup>th</sup> century.</p>	<p>Was the change in ice-age cycles from a periodicity of 41,000 years to 100,000 years triggered by interactions between climate and biochemistry, and in particular a decrease in atmospheric CO<sub>2</sub> content? A very deep ice core from Antarctica with an age of 1.2 million years or more could provide a record of past temperatures and atmospheric CO<sub>2</sub> that would help answer this.</p> <p>Are the large and rapid sea-level fluctuations during the last ice age related to regional changes in the North Atlantic ocean circulation?</p>
<p><b>How has sea level changed in the recent past, and what does the instrumental record tell us about this change?</b></p> <p>Understanding the variations in sea-level over the 20<sup>th</sup> century, and comparing these with modelled data, improves our understanding of the processes and therefore our ability to project the future.</p>	<p>Tide gauge records have been reconstructed back to 1860 (Fig. 2 and Church and White 2011). They show a global average rise of 0.17 m (1.7 mm per year) during the 20<sup>th</sup> century.</p> <p>The rate of sea-level rise was lower in the 1960s (in fact sea level fell 10 mm between 1961 and 1966). This is consistent with enhanced dam building and retention of water on land, which is estimated to have offset about 30 mm of sea-level rise during the latter half of the 20<sup>th</sup> century (Chao et al 2008). Volcanic events, which cause short-term</p>	<p>We do not fully understand the high rate of sea-level rise from 1920 to 1960.</p> <p>New techniques such as the analyses of coral micro-atolls, salt marshes and archaeological indicators are increasingly being used to investigate the historical changes in sea-level rise. Salt-marsh data from the past 2000 years are especially important as they overlap the tide-gauge record.</p> <p>The Gravity Recovery and Climate Experiment (GRACE) has measured gravity perturbations over</p>

The issue and why it matters	What we know	What we need to know and how to find out
	<p>cooling, have also contributed to fluctuations in the sea-level record.</p> <p>Since 1961 the tide-gauge record has shown an average sea-level rise of 1.9 mm per year (Church and White 2011).</p> <p>Global-average sea level varies with the El Niño /La Niña cycle, being higher during an El Niño event and lower during La Niña (CSIRO/ACE CRC 2012). A possible reason for this is increased rainfall and storage of water on land during La Niña.</p>	<p>the past decade using a pair of satellites. Longer records from this will improve our understanding of changes in the distribution of water on land and in the ocean and their relationship to the El Niño/La Niña cycle.</p>
<p><b>What is the present rate of sea level change?</b></p>	<p>Global sea-level monitoring using satellite altimeters has been routinely available since 1993. This provides a sea-level rise estimate that is consistent with the tide-gauge record within the error limits of both techniques. From 1993 to 2009, the reconstructed data shows a rise of 2.8 mm per year and the satellite altimeter data shows a rise of 3.2 mm per year (Church and White 2011). The increase of the 1993-2009 average over the 1961-2009 average is not necessarily indicative of a present acceleration in sea-level rise, as there has been significant decadal variability in the trend over the 20<sup>th</sup> century.</p> <p>Some recent fluctuations in the rate of sea-level rise are linked to short-term cooling caused by the injection of aerosols into the stratosphere from volcanic events, for example Mt Agung in Bali (Church et al 2011a).</p>	<p>Satellite and tide-gauge sea-level time series are corrected to allow for glacial isostatic adjustment (or GIA, the allowance made for vertical motion in the Earth's crust caused by the redistribution of the water from past ice sheets).</p> <p>Our understanding of GIA is improving with better and longer records of sea level and vertical land motion (for example, with the use of GPS).</p> <p>Better estimates of the temporal and spatial patterns of these GIA corrections will improve present estimates of changes in ocean volume, and future projections.</p>

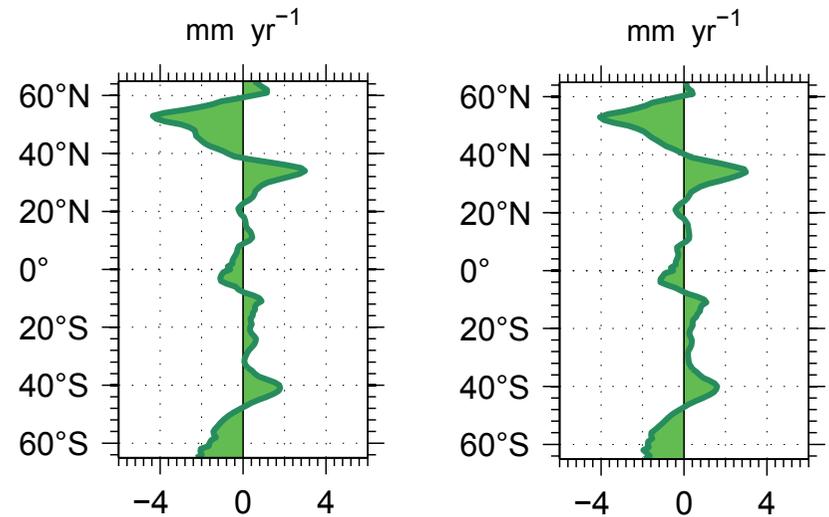
The issue and why it matters	What we know	What we need to know and how to find out
<p><b>How is sea-level rise distributed regionally across the globe?</b></p> <p>Impacts of sea-level rise occur at a regional scale and need to be known for appropriate adaptation.</p> <p>Regional sea-level rise is mainly determined by the distribution of change in ocean temperature. It is also influenced by the distribution of sources of melting ice.</p>	<p>Fig. 3 shows the regional distribution of sea-level rise from 1993 to 2011, much of which may be attributed to ocean warming (Fig. 4).</p> <p>Changes in the salinity of the ocean, as well as temperature, are important for the regional distribution of sea-level change, but not for the global total.</p> <p>Melting of ice on land causes a redistribution of mass on the Earth's surface. This, in turn, causes vertical movement of the Earth's crust, changes of gravity and consequent regional changes in sea-level rise.</p> <p>These effects can be modelled and used to improve our understanding of the past and present, and our projections of the future.</p>	<p>There is a need for comparisons between recent models of global and regional sea-level rise and reconstructions from observations (for example, from Church and White 2011). There is also a need to better understand the reasons for the differences between the projections from different models.</p>

Gold coast infrastructure potentially at risk from coastal flooding. Photo: Patrick Oberem; Community-based surveying of the shoreline as part of the TASMARC project, Tasmania. Photo: Nick Bowden; Flooding event, 6 February 2004, caused by Cyclone Meena at Rarotonga, Cook Islands. Photo: Geoff Mackley, [www.geoffmackley.com](http://www.geoffmackley.com)





**Figure 3.** Distribution of sea-level trend from 1993 to 2011 (CSIRO/ACE CRC 2012).



**Figure 4.** Left, rate of sea-level rise relative to the mean for different latitude bands, January 1993 – December 2001, from satellite altimeter data. Right, average thermal expansion of the upper 700 m of the ocean for the same latitude bands (Church et al 2008). The similarity of these shows the strong influence of ocean warming on regional sea-level rise.

## Contributions to present sea-level rise

The major components of the present sea-level rise are thermal expansion of a warming ocean, melting of glaciers and ice-caps in mountainous and high-latitude regions, and ice loss from the ice sheets of Greenland and Antarctica. Depletion of water in aquifers is largely offset by the retention of water in dams, and the total contribution from terrestrial storage (i.e. all water on land except that stored as ice) is small.

The largest land reservoirs of water that can contribute to future sea-level change are the Greenland Ice Sheet (7.4 m of sea-level equivalent) and the Antarctic Ice Sheet (56.6 m of sea-level equivalent) (IPCC 2007). Over the last decade, the contribution to sea-level rise from melting ice has exceeded that due to thermal expansion of the ocean.

Components of sea-level rise	What we know	What we need to know and how to find out
<p><b>Thermal expansion</b></p> <p>When the ocean is heated, it expands, like the liquid in a thermometer.</p>	<p>About 90% of the extra energy retained by the earth system due to increased greenhouse gases is absorbed by the ocean, with more than 75% of this in the upper 700 m of the ocean.</p> <p>Recent corrections to biases in the measurement of ocean temperature since 1961, and the widespread use of robotic (Argo) floats to measure sub-surface ocean temperatures, have improved estimates of the increase in ocean heat.</p> <p>For the period since 1972, when a reasonably good distribution of ocean temperature data is available, warming of the upper 700 m of the ocean is estimated to have led to sea-level rise of 0.63 mm per year. Over the full ocean depth, including the impact of smaller changes in the abyssal ocean, the thermal expansion is equivalent to 0.80 mm per year (Church et al 2011b).</p> <p>For the satellite altimetry period, since 1993, upper ocean thermal expansion is equivalent to 0.71 mm per year of sea-level rise, and over the full ocean depth the expansion is equivalent to 0.88 mm of sea-level rise.</p>	<p>Ongoing deployment of Argo or similar systems to monitor sub-surface ocean temperatures will provide good future estimates of thermal expansion for most of the global ocean. However in polar regions, the sea-ice cover on the ocean surface requires development of different ocean monitoring technology.</p> <p>For the period before Argo deployments, only ocean models and relatively sparse ship-based observations of ocean temperatures are available to estimate the regional distribution of thermal expansion.</p>

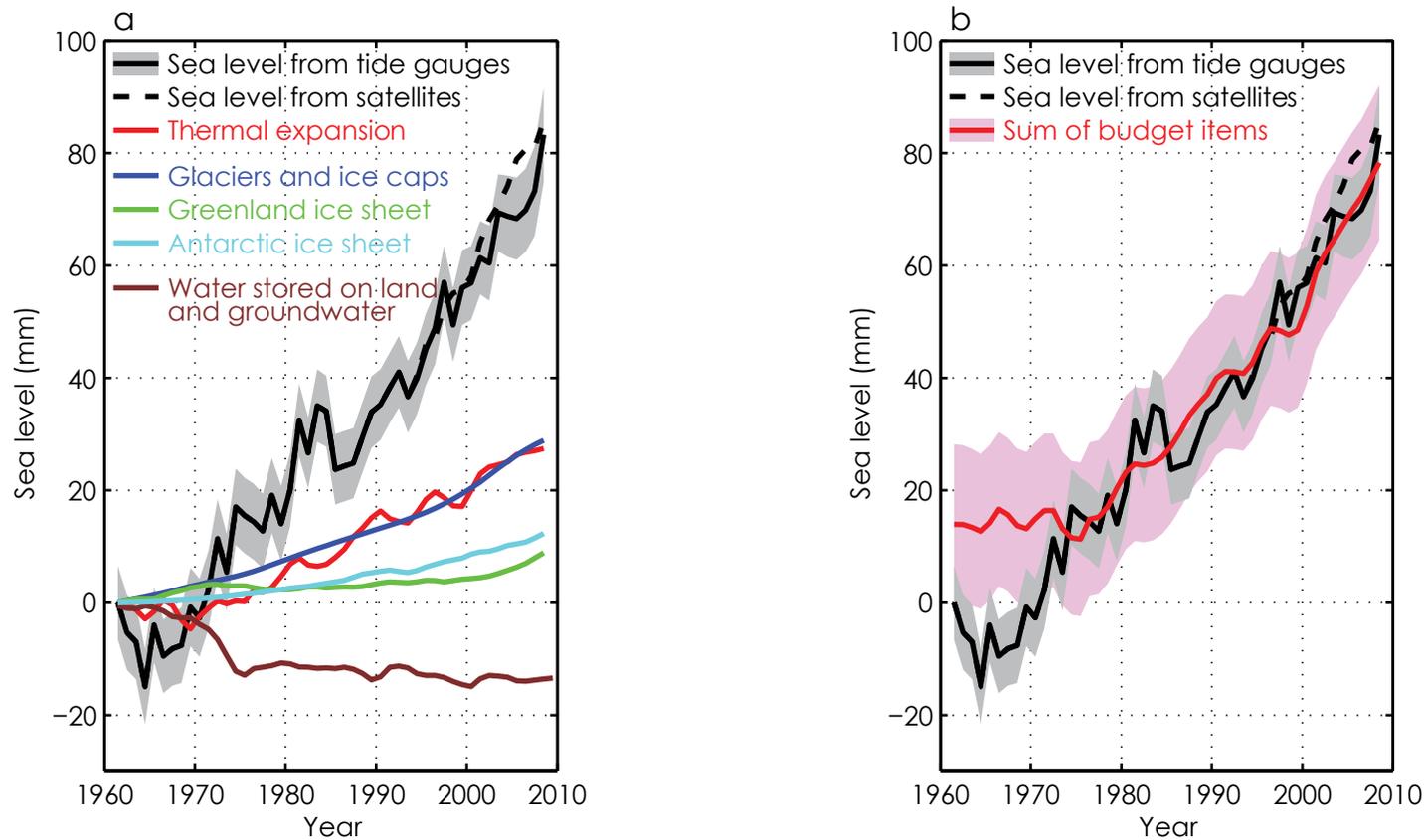
Components of sea-level rise	What we know	What we need to know and how to find out
<p><b>Glaciers and ice caps</b></p> <p>Glaciers and ice caps are perennial ice bodies on land, usually found at high elevation or high latitude. They originate primarily from compressed snow, and flow slowly downhill under gravity. An ice cap is a dome-shaped ice mass, usually covering a highland area.</p> <p>Glaciers and ice caps are of much smaller extent than ice sheets, which are of continental scale. However they are sensitive to changes in temperature and precipitation, and such changes directly affect global sea level.</p>	<p>Glaciers and ice caps, including those in Greenland and Antarctica but excluding the ice sheets, have been shrinking globally since about 1850. These are estimated to have contributed 91 mm to sea-level rise between 1850 and 2005, a rate of about 0.6 mm per year (Leclercq et al 2011). The rate of glacier contribution has increased since the 1990s and the most recent assessment shows a sea-level rise contribution from glaciers and ice caps, including those surrounding the Greenland and Antarctic ice sheets, of 1.2 mm per year for 2001-2005 (Cogley 2009).</p>	<p>The total sea-level equivalent held in the estimated 200,000 glaciers on Earth is about 0.6 m (Radic and Hock 2010), but is not accurately known.</p> <p>The estimated contribution of glaciers to sea-level rise is based on very few measured glaciers and extrapolated regionally and globally on the basis of glacier morphology and climate.</p> <p>New glacier inventories are being compiled from satellite-based glacier monitoring and other observations.</p> <p>More accurate knowledge of the relationships between changes in glacier surface area and volume is also needed to improve the estimates of present and future contributions of glaciers to sea-level rise.</p>
<p><b>Greenland and Antarctic ice sheets</b></p> <p>An ice sheet is a land-ice body of continental size that is sufficiently deep to cover most of the underlying bedrock topography. An ice sheet flows outward from a high central ice plateau. Today there are only two polar ice sheets, in Greenland and Antarctica, which together contain more than 60 m of sea level equivalent. During glacial periods there were other Northern Hemisphere ice sheets.</p>	<p>Three different and independent satellite-based methods have been available since 1992 to estimate the change of ice mass in Greenland. These are altimetry (for example, Sorensen et al 2011), gravity (for example, Velicogna 2009; Schrama and Wouters 2011; Chen 2011) and mass flux estimates (Rignot et al 2011).</p> <p>These different estimates give a consistent picture of the spatial and temporal variability of loss from Greenland, although there are some differences in the absolute values.</p> <p>Between 1992 and 2009, Greenland contributed 0.2 to 0.4 mm per year to sea-level rise, with the rate rising to 0.4 to 0.7 mm per year for the period 2002 to 2009.</p>	<p>The causes of the accelerated ice discharge from both ice sheets are not well understood. It is thought possible that the recent acceleration may be a result of thinning of ice shelves and floating ice tongues due to incursions of warmer ocean water, and reduction in the back-stress that these exert on the grounded ice (for example, Holland et al 2008).</p> <p>Better observations of ocean temperatures surrounding the ice sheets and improved models of these systems are needed to address this.</p> <p>There is greater uncertainty in the estimated ice loss from Antarctica than from Greenland. In particular, the state of balance of East Antarctica – whether increased snow accumulation in the interior is</p>

Components of sea-level rise	What we know	What we need to know and how to find out
	<p>Less accurate estimates suggest that Greenland may have been contributing 0.0 to 0.3 mm per year since 1972 (Rignot et al 2008).</p> <p>About 50% of the loss from Greenland since 1992 has been due to increased melt and runoff, and about 50% due to increased glacier discharge to the sea.</p> <p>The same satellite-based techniques have been used to estimate the mass change from Antarctica. The average loss from Antarctica since 1992 has been about 0.1 to 0.3 mm per year of sea-level rise (Zwally et al 2005; Rignot et al 2011), and since 2002 the rate of loss has increased to 0.2 to 0.5 mm per year (for example Velicogna 2009; Ivins et al 2011; Chen et al 2009; Rignot et al 2011). All loss from Antarctica, except from the Antarctic Peninsula where melt is significant, is due to increased discharge of glacier ice to the sea. The major loss is occurring from West Antarctica.</p>	<p>occurring and may be balancing increased discharge is still ambiguous.</p> <p>Longer records from satellite altimeters and gravimeters are improving estimates of the magnitude and distribution of ice loss from both ice sheets. However uncertainty remains about ice-sheet changes before modern satellite measurements.</p>
<p><b>Others - land storage (aquifers, dams, etc.), ocean sedimentation</b></p>	<p>The rate of ground water depletion is estimated to have increased sea-level by 0.26 mm per year since 1972 (Konikov 2011), partially offsetting the storage of water in dams (-0.44 mm per year average since 1972). The total terrestrial storage of water (including natural changes) since 1972 is estimated to have contributed a lowering of 0.1 mm per year to sea-level rise (Church et al 2011b).</p>	

Components of sea-level rise	What we know	What we need to know and how to find out
<b>Overall budget</b>	<p>For the periods 1972 to 2008 and 1993 to 2008 the sum of the individual components of sea-level change equals the total estimated sea-level rise within the error limits of the various terms (Fig. 5). Since 1972, thermal expansion contributed about 45% to total sea level rise, glaciers and ice caps another 40%, with most of the remainder from the ice sheets. Since 1993 the contribution of the ice sheets to sea-level rise has increased to about 30% (Fig. 5 and Church et al 2011b).</p>	<p>For periods before 1972 the sea-level budget is not fully closed, indicating errors in some of the estimated contributions. The causes of some fluctuations in sea-level for the earlier part of the instrumental record cannot be fully explained.</p>

Grosser Aletschgletscher, Switzerland, at the glacier margin below Mt Mossifluo in October 2006. This glacier is showing recession. Photo: Juerg Alean, [www.glaciers-online.net](http://www.glaciers-online.net)





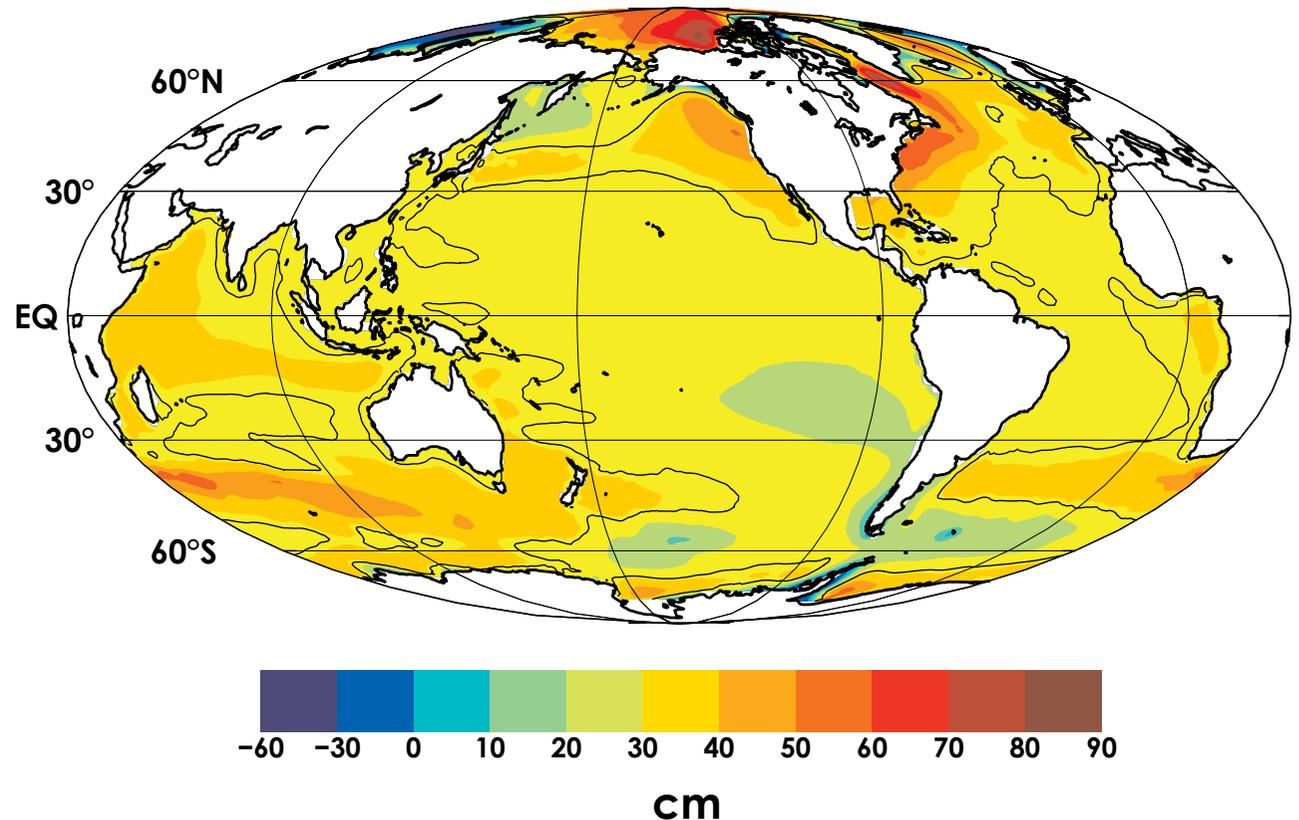
**Figure 5.** Global sea-level budget, 1961 to 2008 (after Church et al 2011b). (a) The observed sea level using tide gauges (solid black line) and the satellite altimeter data (dashed black line). The blue, red, green and brown lines show sea-level rise contributions from individual components. (b) The observed sea level and the sum of the components. In both (a) and (b), the estimated uncertainties (approximately  $\pm$  one standard deviation) are indicated by the shading.

## Future Sea-Level Rise

Projections of the future sea level are derived from atmospheric and ocean temperatures simulated by ocean-atmosphere-climate models, which are driven by different scenarios of atmospheric CO<sub>2</sub> and other greenhouse gases. Estimates of ocean temperature increase are used to calculate thermal expansion of the ocean and the melting of ice that is in contact with sea water. Estimates of atmospheric temperature and precipitation are used to derive the surface response of glaciers and ice sheets to warming.

These model-based projections can provide information on the geographical distribution of sea-level rise as well as the global average (Fig. 6). However there is considerable uncertainty in the projections because of unknown future greenhouse gas levels, differences between various climate models, and complexities in the response of glaciers and ice caps, even at a regional level. Considerable uncertainty also exists because processes that might cause increased discharge of large ice sheets into the ocean in response to warming (the "dynamic response") are largely unknown.

The last two IPCC assessments (2001 and 2007) have used this modelling technique to estimate sea-level rise over the next century (Figure 7). Although the spread of possible outcomes is large in both cases, the estimated mid-point and extreme values have not changed very much between assessments. The estimated minimum projected sea-level rise at 2100 has risen somewhat, from about 0.1 m to 0.2 m, but the upper projection remains at around 0.8 m, with significant uncertainty about any additional ice-sheet dynamic response.

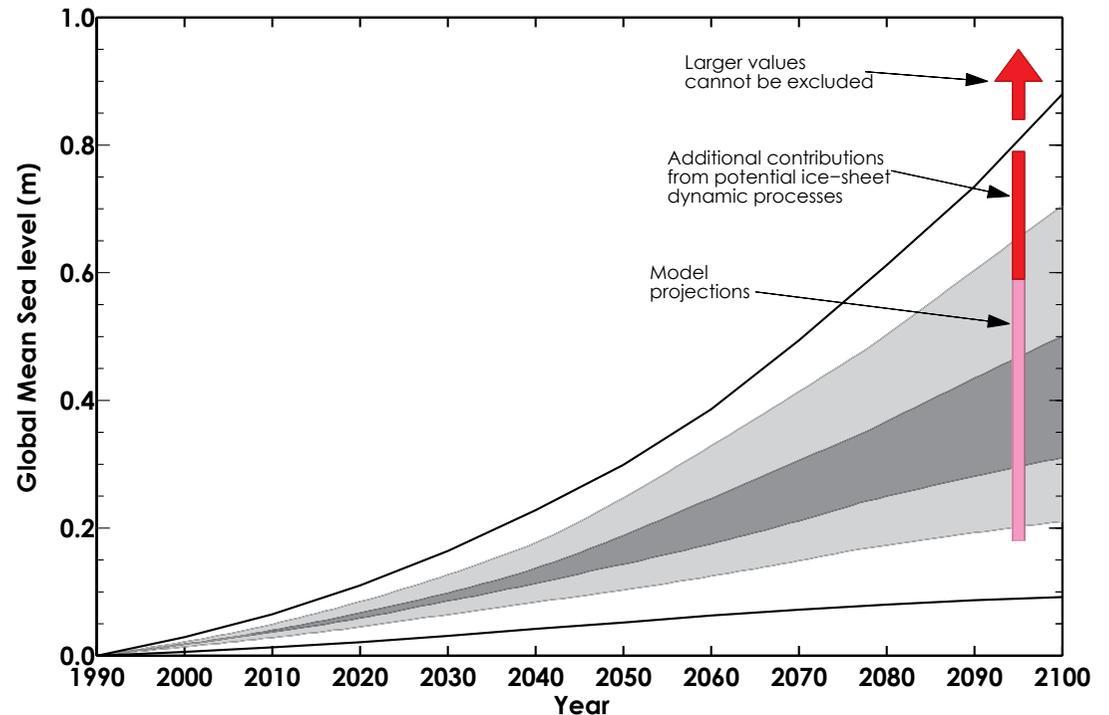


**Figure 6.** Regional distribution of sea-level change for a mid-range estimate of future greenhouse gas emissions for 2090 compared to 1990, including regional changes associated with changing mass distribution of ice. The global-average value at 2090 is 0.38 m (Church et al 2011a).

An alternative approach to estimating future sea level, without detailed knowledge of the actual processes, is the use of semi-empirical models (for example, Rahmstorf 2007; Vermeer and Rahmstorf 2009). These use a scaling relationship between observed sea-level rise and another parameter, such as global average temperature, and assume that this relationship holds into the future. This method generally projects higher rates of sea-level rise over the next century (as much as 1.6 m or more). For a semi-empirical model to provide valid projections, the relative importance of the various processes contributing to sea-level rise (for example, thermal expansion, glacier melting) must be the same in the earlier "calibration" period as during the projection period; this may well not be the case.

There have been suggestions that, as a result of dynamic changes to ice sheets, sea-level rise over the next century could be as high as 5 m (Hansen 2007). However Pfeffer et al (2008) argue that there is a physical limit to ice sheet acceleration and, using the IPCC AR4 projections of ocean thermal expansion, they estimate maximum sea-level rise by 2100 to be in the range of 0.8 to 2.0 m.

Temperature in the abyssal ocean and ice sheets respond only slowly to air temperature changes, and sea level will continue to rise for several centuries, even if global temperature is stabilised. On these longer times, total sea-level rise will exceed several metres, and some of the changes may be irreversible (Solomon et al 2009).



**Figure 7.** Projected range of global-averaged sea-level rise from IPCC's Third (IPCC 2001) and Fourth (IPCC 2007) Assessment Reports relative to 1990. Lines and shading show projections from the Third Assessment Report (dark shading is model average envelope for all emission scenarios; light shading is envelope for all models and all emission scenarios; outer lines include additional uncertainty for changes in land ice and sediment deposition). Bars plotted at 2095 show projections from the Fourth Assessment Report. The magenta bar is the range (at 90% confidence) of model projections and the red bar is the extended range, allowing for a potential additional contribution from Greenland and Antarctic ice sheets. The red arrow indicates that the upper bound is poorly quantified (from Church et al 2009).

Components of future sea level rise	What we know	What we need to know and how to find out
<b>Thermal Expansion</b>	Climate models show some skill in simulating the present thermal expansion of the oceans (see above). The oceans will continue to expand as the world warms, but thermal expansion will become a relatively less important component as contributions from ice-melt increase.	Thermal expansion of the oceans depends both on the amount of heat added and the way in which it is distributed within the oceans (because the thermal expansion coefficient depends on temperature, salinity and pressure). Improved understanding of the way heat was taken up by, and distributed within, the oceans during the 20 <sup>th</sup> century will help improve models of future ocean thermal expansion.
<b>Glaciers and ice caps</b>	<p>Glaciers and ice caps will continue to decrease in volume and contribute to sea-level rise with rising temperature. The changes however will not be consistent, and there will be periods when individual glaciers go against the global trend.</p> <p>The total sea-level equivalent in all the Earth's glaciers is <math>0.60 \pm 0.07</math> m (Radic and Hock 2010). This includes <math>0.19 \pm 0.06</math> m of sea-level equivalent in the glaciers surrounding the Greenland and Antarctic ice sheets, but excludes the ice sheets themselves. Even at the upper level projections of warming, it will take several centuries for all this ice to melt.</p>	Changing glacier volumes will have impacts beyond sea-level rise, including impacts on river flows and natural hazards of relevance to human societies. Improved understanding of regional climate variations and the response of local glacier systems to these will be required for adaptation planning.
<b>Greenland and Antarctic ice sheets</b>	Both snowfall accumulation and surface melt and run-off over Greenland will continue to increase with further warming. The melt rate will however increase more rapidly than precipitation, to a point (estimated at a global temperature increase of 2-5° C) where the ice sheet loses more ice each year than it gains. If this temperature was maintained for millennia, the Greenland ice sheet could disappear almost completely (Gregory and Huybrechts 2006).	<p>The rate of future dynamic discharge from both Antarctica and Greenland is largely unknown. This is the largest cause of uncertainty in projecting sea-level rise over the next century (IPCC 2007). Is the present increase in dynamic discharge a transient process, will it continue to increase steadily, or accelerate?</p> <p>Better understanding of the processes in ice-shelf melt, iceberg calving and ice dynamics at the grounding line are required. These need to be</p>

Components of future sea level rise	What we know	What we need to know and how to find out
	<p>In Antarctica, ice-sheet surface temperature is mostly well below the melting point, and increased surface melt will not be a significant cause of mass loss for several centuries of warming (apart from on the Antarctic Peninsula).</p>	<p>incorporated into better models of the whole ice-sheet system that include full treatment of the interactions between ice sheets, ice streams and ice shelves. Several international consortia are working on such models. Improved data are also required on oceanographic conditions and changes of the margins of ice sheets. Sea-ice cover makes such observations difficult.</p>

Flooding event in Cairns, Queensland, January 2009. Photo: Cairns Regional Council



## Impacts

There are two major impacts of sea-level rise: coastal inundation and shoreline recession. Inundation is the process by which flooding is caused by a simple rise of water level over a static shore. In addition, sea-level rise may cause a landward motion of the shoreline through erosion of soft (sandy or muddy, for example) material – this process is called recession.

Sea-level-induced inundation proceeds in a similar way to many other processes related to a changing climate, by an increasing frequency in extreme events rather than through a steady increase in an otherwise constant state. Inundation and shoreline recession occur through the combined action of the tides and storm surges (storm tides), sea-level rise and wave action.

A further impact of sea-level rise is salination, which occurs when a saline water table (lying below a fresh water layer) rises in response to local sea level. This is important for small, low-lying islands and regions where people live close to the coast. It can lead to loss of drinking-water supplies and to crop damage. Changes in precipitation and water withdrawal also affect groundwater reserves.

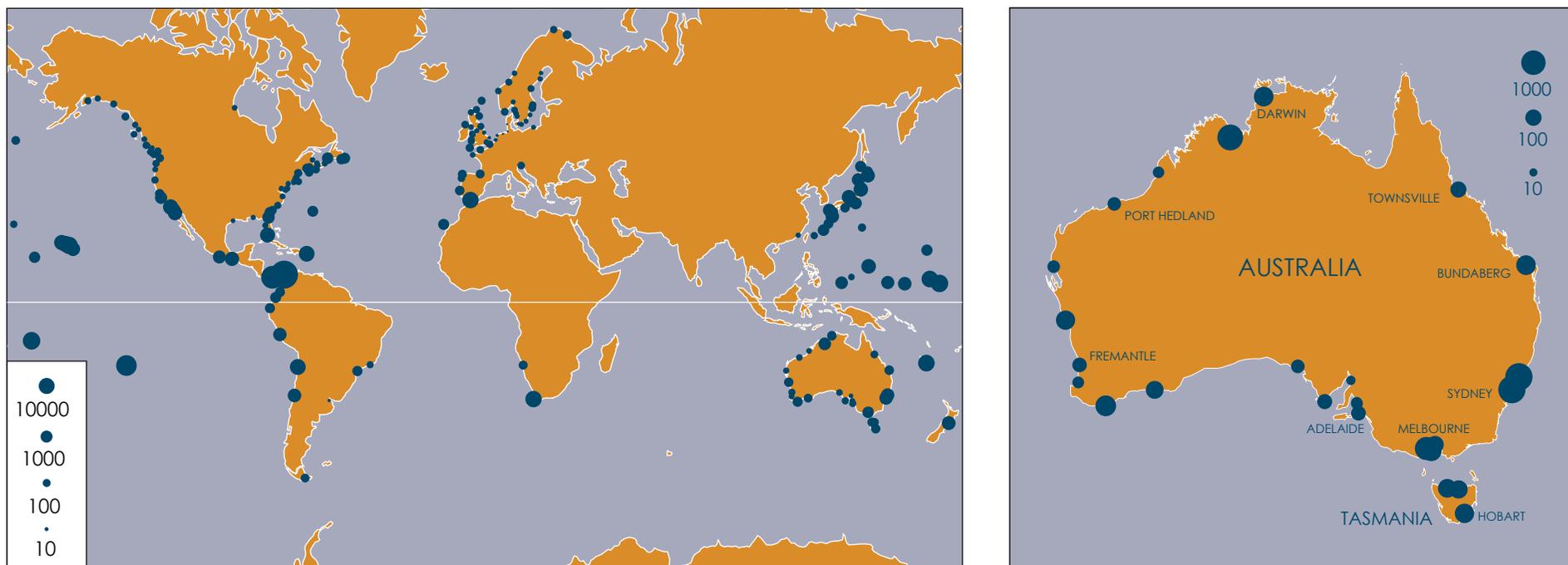
The issue and why it matters	What we know	What we need to know and how to find out
<p><b>Coastal flooding</b></p> <p>In the absence of changes in other factors (for example, storminess) sea-level rise causes an increase in the frequency of flooding events from the sea.</p>	<p>As a rule of thumb, a 0.1 m rise in sea level increases the frequency of flooding by about a factor of three. This effect is multiplicative so that even a relatively modest increase in mean sea level of 0.5 m will increase the frequency of flooding by a factor of roughly 300. This means that an event which presently only happens on average once every 100 years (the '100-year return event') will happen several times a year after sea level has risen by 0.5 m.</p> <p>Future sea-level rise is not known exactly. However, the uncertainty is quantifiable and may be used to estimate the increased likelihood of flooding events caused by sea-level rise (Hunter 2010).</p>	<p>The long-term statistics of storm surges and the way in which they might change in the future are not well known.</p> <p>Long-term statistics of surges are being improved by more and longer sea-level observations. Modelling is also improving these statistics and indicating future change.</p> <p>Wave action also contributes to coastal flooding. At present, future changes in wave properties are poorly known. This will be rectified by coupling global wave models to climate models.</p>

The issue and why it matters	What we know	What we need to know and how to find out
<p><b>Coastal recession</b></p> <p>Sea-level rise will, on average, cause soft shorelines to recede. This causes loss of land and infrastructure. If this loss is prevented by building a seawall, then the beach and the associated coastal habitat is lost on the seaward side of the wall – an effect known as 'coastal squeeze' (Doody 2004).</p>	<p>The vulnerability of soft shorelines increases with sea-level rise. On average, sandy shorelines recede horizontally at roughly 100 m for every 1 m of sea-level rise.</p> <p>Models are being developed to address these processes (for example, Roelvink et al 2009), but we are not yet able to successfully model long-term (decadal) shoreline recession.</p>	<p>Existing models are unable to predict with any reasonable accuracy the recession of a given beach under the combined impacts of rising sea-level and possible changes to currents and waves. These models need further development.</p> <p>Research is needed into the movements of shorelines during the past century, in order to better project future changes. A valuable source of such information lies in historic aerial photography, much of which remains to be analysed for shoreline motion.</p> <p>Increased research is needed into present and projected ocean waves at all spatial scales from global to individual beaches.</p>
<p><b>Salination</b></p> <p>In the vicinity of the shoreline, sea-level rise causes the saline water table to rise, causing problems for water supplies and agriculture (Gornitz 1991). This is a particular problem for small islands where, by necessity, people live and work close to the shoreline.</p>	<p>While the process of salination is quite well understood, it depends strongly on regional properties other than sea-level rise, such as storm tides, ocean wave conditions, local rainfall (and its future change), the hydrological properties of the aquifer and water withdrawal (Ferguson and Gleeson 2012). These are often poorly known.</p>	<p>In addition to requiring knowledge of storm tides, waves and sea-level rise, improved information is required on characteristics of coastal groundwater, regional projections of rainfall and water withdrawal by local communities.</p>
<p><b>Regional distribution</b></p> <p>The regional distribution of the flooding impact of sea-level rise depends on the spatial variations of not only sea-level rise, but also storm tides and the way in which these may change in the future.</p>	<p>Since the IPCC Fourth Assessment Report there have been significant improvements in our understanding of the regional variation in present and future sea-level rise (for example, through the inclusion of associated vertical movements of the Earth's crust and gravitational changes, Church et al 2011a). The development of regional storm-tide models and datasets of global sea-level observations has contributed to our understanding of the spatial variation of storm tides.</p>	<p>Our understanding of the regional distribution of future sea-level rise is still relatively poor (see above). There are also many regions of the world (for example, Africa) with few observations or models of tides and storm surges.</p> <p>It is important that existing high-quality tide gauges are maintained, and that the global network of gauges is expanded into data-sparse regions of the world. Modelling of storm tides should be extended</p>

The issue and why it matters	What we know	What we need to know and how to find out
	<p>The multiplication factor for the frequency of flooding events for a sea-level rise of 0.5 m (see above) may be estimated from a knowledge of the local storm tides. This factor is shown in Fig. 8 based on tide-gauge observations.</p> <p>Information from tide gauges and storm-tide models may be used to estimate the likelihood of future flooding from the sea, based on a range of possible sea-level rise projections (Hunter 2010 and <a href="http://www.sealevelrise.info">www.sealevelrise.info</a>). The same technique provides an objective method of estimating an appropriate vertical planning allowance for future sea-level rise (Hunter 2011).</p>	<p>on a consistent basis to cover all regions of the world. This may require an operational global storm-tide model.</p> <p>There is a need for more integrated regional planning tools that combine processes such as coastal inundation, coastal recession, riverine flooding, ocean waves and the costs of both adaptation and flood-related damage.</p>

Flooding event, 10 December 2008, Nukatoa on Takuu Atoll. Photo: John Hunter





**Figure 8.** Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m (Hunter 2011).

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