Sea level

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Summary: Many Australians live near the coast but coastal regions and their valuable ecosystems are threatened by rising sea levels. Globally, sea level is now rising after several centuries of relatively stable values. The rate of rise increased from the 19th to the 20th century and during the 20th century. Since the early 1990s, the rate of rise is almost double the average for the 20th century. Sea levels are rising around Australia and the frequency of extreme high sea-level events that occur on annual to decadal timescales has increased by a factor of about three during the 20th century. Sea-level rise is a result of expansion of the oceans as they warm and the addition of mass to the ocean from glaciers and ice caps, and the ice sheets of Greenland and Antarctica. Sea level will continue to rise during the 21st century and beyond in response to increasing concentration of greenhouse gases. Including an allowance for the ice sheets, the IPCC projections are for a rise of 18 cm to 79 cm by 2095 compared to 1990. However, our current understanding of the response of ice sheets to global warming is inadequate and a larger rise is possible. Sea levels are currently rising at near the upper end of current projections. Rising sea levels will result in inundation of low-lying coastal regions and coastal erosion. Significant and urgent reduction in greenhouse gas emissions are required to avoid the most severe sea-level rise. However, even with a reduction in emissions some further sea-level rise is inevitable and adaptation will be necessary.

Introduction

Rising sea level is one of the major climate change risks facing Australia's coast. About 85% of Australia's population live within the coastal region (DCC 2009) and about half live within 7 km of the coast, with as many as 30% within 2 km of the coast

(Chen and McAneny 2006). Our coasts contain ecologically and economically important habitats such as tidal wetlands and seagrass beds, which may be at risk from sea-level rise. Sea-level rise contributes to coastal erosion and inundation of low-lying coastal regions as well as leading to saline intrusion into coastal waterways and water tables. These impacts can be exacerbated by local land motions, for example the compaction of sediments following the extraction of ground water or petroleum.

The response of coastal environments to sea-level rise will be complex and variable, depending upon the existing topography, sediment budgets, flooding and run-off regimes. Sea-level rise impacts on our coasts will be felt most severely during storm surges and storm wave events and at times of high tides. Where coastlines are highly developed, such as in much of south-eastern Australia and parts of south-western Australia, the ability of coastal habitats to naturally adapt to sea-level rise, and migrate landwards, is reduced; a process referred to as the 'coastal squeeze'.

Historical sea-level changes

Global-average sea-level rise

Sea level has changed dramatically through Earth's evolution. More than 35 million years ago when carbon dioxide concentrations were above 1000 ppm there were essentially no ice sheets on Earth and sea level was consequently much higher than present day values (Alley et al. 2005). As these carbon dioxide concentrations fell, the major ice sheets of Antarctica and the northern hemisphere formed. Over about the last 1 million years, sea level oscillated by more than 120 m as ice sheets waxed and waned on the northern European/Asian and North American continents (Rohling et al. 2009). These oscillations were paced by subtle changes in the Earth's orbit about the Sun and in the orientation of the Earth's axis, thus changing the distribution and the amount of solar radiation reaching the Earth. Changes in Earth's albedo and greenhouse gas concentration reinforced and amplified the initial solar-induced climate change.

At the time of the last interglacial, about 125,000 years ago, sea level was about 4 to 6 m higher than present day values with temperatures similar to those projected for the second half of the 21st century (Overpeck et al. 2006; Otto-Bleisner et al. 2006). Some geological indicators of sea level imply rates of sea-level rise of 1.6 ± 0.8 m/century at that time (Rohling et al. 2008).

Conversely, sea level was more than 120 m below present day values about 20,000 years ago near the end of the last ice age, primarily as a result of large ice sheets on North America and northern Europe/Asia. Sea level rose at rates of 1 m/century for many millenia, with peak rates potentially exceeding several metres per century (Fairbanks 1989; Lambeck et al. 2002; Alley et al. 2005). About six thousand years ago the rate of rise declined markedly and over the two millenia up to about 1900, the rate of sea-level rise has been at most a few tenths of a millimetre per year (a few centimetres per century).

The few long-term coastal sea-level records (the earliest dating from about 1700; Woodworth 1999) and sea-level records estimated from coastal sediment cores (e.g. Gehrels et al. 2005, 2006) indicate an increase in the rate of rise from the 19th to the 20th century. Estimates of global-averaged sea level indicate an acceleration in the rate of rise during the 20th century (Church and White 2006; Jevrejeva et al. 2006; Woodworth et al. 2009; Figure 1). Since 1993, the rate of rise has been over 3 mm yr^{-1} (Church and White 2006; Leuliette et al. 2004; Beckley et al. 2007) compared with the 20th century average of about 1.7 mm yr^{-1}; whether this represents a further sustained increase in the rate of rise is not yet clear (Church et al. 2008a).

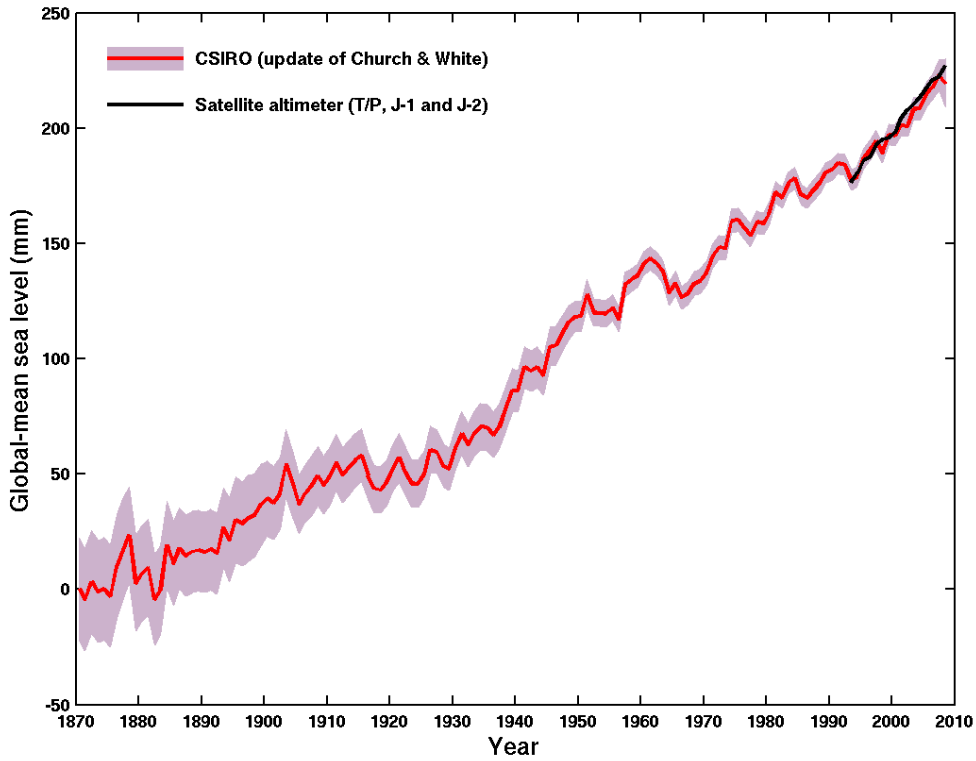

Figure 1. Global mean sea level from 1870 to 2008 with one standard deviation error estimates, updated from Church and White (2006, red), and the Topex/Poseidon/Jason-1 and -2 satellite altimeter global mean sea level (based on standard processing as in Church and White 2006) from 1993 to 2008 is in black. Both series have been set to a common value at the start of the altimeter record in 1993.

Sea-level rise in the Australian region

The two longest (near) continuous records from Australia (both in excess of 90 years in length) are from Sydney and Fremantle, on opposite sides of the continent. They show observed rates of sea level rise relative to the local (land-based) height datum of 0.9 ± 0.2 mm yr^{-1} and 1.4 ± 0.2 mm yr^{-1} over the periods 1914 to 2007 and 1897 to 2007. Church et al. (2006) examined sea level around the Australian coastline and estimated that from 1920 to 2000 the average rate of relative sea-level rise was 1.2 mm yr^{-1}.

One of the oldest tide gauge benchmarks in the world is at Port Arthur in south-east Tasmania. When combined with historical and recent sea-level observations, it shows that relative sea level has risen by 13.5 cm from 1841 to 2000 (Hunter et al. 2003).

Rates of sea-level rise from the Fremantle and Sydney gauges appear low when compared to the global mean. This difference is partly a result of global-scale changes in the Earth's shape resulting from changes of loading of the Earth over recent ice age cycles.

Satellite altimeters have, since 1992, provided an alternative way to measure sea level variations on a global basis. The rate of recent sea-level rise in the Australian region (Figure 2) has a considerable degree of spatial variability, with a maximum of sea-level rise to the north of Australia in the western equatorial Pacific. This feature is dominated by the change from more El Niño-like conditions at the start of the record to more La Niña-like conditions near the end of the record. These high rates of sea-level rise are transmitted through the Indonesian Archipelago to the eastern Indian Ocean and the north and north-west of Australia and decay counter-clockwise around the Australian coastline. Off south-east Australia, there is a maximum at latitudes of about 35°S in the Tasman Sea. This is consistent with the spin-up of the South Pacific subtropical gyre by increased wind stress curl (Roemmich et al. 2007). The minimum in the rate of sea-level rise off the east coast at about 25°S is likely to be a dynamic response associated with the southward movement of water and a shallowing of the subtropical thermocline at these latitudes.

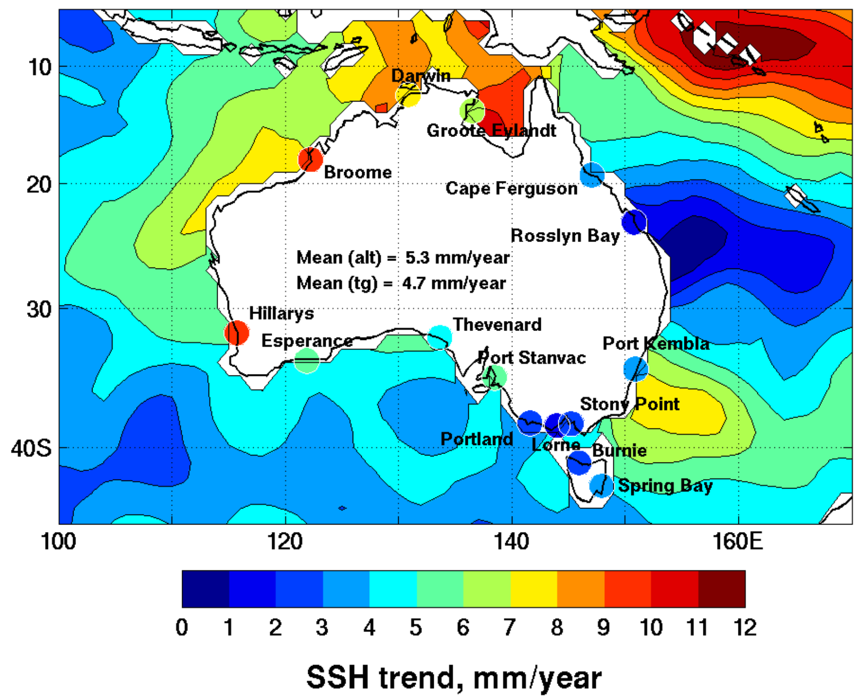

Figure 2. Sea-level rise during 1993-2008 in the Australian region. The offshore linear trends of sea-level rise (units in mm yr^{-1}) are determined from T/P, Jason-1 and-2 altimeter data over the period January 1993 to December 2008. The altimeter data has all standard corrections applied except that there is no adjustment for atmospheric pressure changes. The linear trends in coastal sea-level data over the same period are shown by the coloured circles (data from the national Tidal Centre). To remove the influence of Glacial Isostatic Adjustment (GIA), a small (~0.4mm yr^{-1}) adjustment has been applied to both data sets. See the text for a discussion of a comparison of the coastal and offshore rates.

Since the early 1990s, the National Tidal Centre has measured sea levels around Australia with an array of carefully quality-controlled acoustic tide gauges, the Australian Baseline Array (Figure 2; http://www.bom.gov.au/ntc/IDO60202/IDO60202.2009.pdf). The coastal sea-level data have both significant similarities and some striking differences to the offshore satellite record. On the north and north-west coasts of Australia, sea level rose during this period at rates of up to 9 mm yr^{-1}, well above the global average of about 3.4 mm yr^{-1}. The altimeter data also show a high rate of rise offshore. At Darwin and Broome the offshore and coastal rates of sea-level rise are within about 2 mm yr^{-1} of each other. At Groote Eylandt the coastal rate was only 6 mm yr^{-1} while the altimeter recorded a rise of 9 mm yr^{-1}. Hillarys (115.7°E; 31.8°S) recorded a rise of about 9 mm yr^{-1} compared with the offshore rate of about 5 mm yr^{-1}. It is thought that the high rate at Hillarys is a result of compaction of the sediments at this coastal sandy location following significant ground-water extraction in the region (Tregoning, pers. comm.). There is also about a 3 mm yr^{-1} higher sea-level trend at Hillarys compared with Fremantle (less than 30 km to the south with the Fremantle tide gauge situated on a raised limestone reef), consistent with implied sediment compaction near the Hillarys tide gauge.

On the south eastern and eastern Australian coastline, the rates of sea-level rise are typically 2 to 4 mm yr^{-1}, similar to the global-averaged rate of rise. Strikingly, sea-level rise at Port Kembla (150.9°E; 34.5°S) is close to the global average at about 3 mm yr^{-1} and shows little indication of the offshore peak in sea-level rise of (7 mm yr^{-1}) that is prominent in the satellite data at about 35°S in the Tasman Sea. Recent analysis (Hill et al. 2008, 2009) shows that the strength of the EAC, particularly its southward extension, varies considerably on interannual time scales and strengthened over the 1993−2003 period. Thus the strong sea-level zonal gradient across the southward flowing EAC has increased over this period, consistent with the different offshore and coastal rates of sea-level rise at this location (Deng et al. 2010).

Why does sea level change?

Relative sea level (i.e. sea level measured relative to the nearby land) changes both as a result of changes of the ocean surface or changes in the height of the land. Ocean surface height changes on a range of temporal and spatial-scales. The total volume of the ocean can change as a result of changes in ocean mass (addition of water to the ocean from the land) or expansion/contraction of the ocean water as it warms/cools. From 1961 to 2003, the upper 700 metres of the global oceans absorbed about $16 \pm 3 \times 10^{22}$ Joules, increasing global mean sea level (GMSL) at a rate of about 0.5 ± 0.1 mm yr^{-1} (Domingues et al. 2008). Warming deeper in the ocean has also contributed to sea-level rise (perhaps at the rate of order 0.2 mm yr^{-1}) over this period, but the sparseness of the available data means the estimates are poorly known. The next largest contribution to sea-level rise comes from the melting of glaciers and ice caps (e.g. Dyurgerov and Meier 2005; Cogley 2009), with smaller contributions from the ice sheets of Greenland and Antarctica and from changes in terrestrial storage (Lemke et al. 2007). Domingues et al. (2008) approximately explained the observed rise over 1961 to 2003 by combining these various contributions. Recent observations indicate growing Greenland and Antarctic Ice Sheet contributions to sea level rise (Velicogna, 2009; Rignot et al. 2008).

The height of the land can change as a result of large scale changes in the shape of the earth as a result of changes in the surface loading of the earth, particularly as ice sheets or other water loading of the land and the ocean changes. The earth is still responding to changes in the extent of ice sheets since the last glacial maximum (Glacial Isostatic Adjustment, GIA). For much of Australia's coastline, the GIA is of order 0.3 mm yr^{-1} (upward motion) and partially offsets the larger 20th century sea-level rise as a result of changes in the ocean's volume. Ongoing changes in the mass of the ice sheets (Mitrovica et al. 2001, 2009) also result in sea-level change but the impact of these on Australia to date is likely to be small and have not yet been explored. Local land motion can also occur as a result of sediment compaction (particularly following water or petroleum withdrawal). Examples include the Gippsland coast of Victoria, in the Perth region (affecting the sea level measurements at Hillarys, see above) and at some of the sea-level measurement sites near Adelaide.

Sea level extremes and impacts

Sea level rise will be felt most severely in response to storm driven wave and surge events. Such events have the potential to cause inundation and wave induced erosion of coastal landforms.

Observed changes to sea level extremes

Analysis of sea levels at both Fremantle and Fort Denison, Sydney shows that sea-level rise during the 20th century has already had a significant impact on the average recurrence interval (defined as the average time between exceedance events of a given height; Church et al. 2006). The rise in sea level has caused extreme high sea-level events that occur on annual to decadal timescales to increase their frequency of occurrence by a factor of about three during the 20th century. The change in the frequency of sea-level extremes may also change as a result of a change in the variability of sea level about the mean, as well as changes in mean sea level. However for both locations, 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.

Wave induced erosion is dependent on the water elevation relative to the height of the fronting beach face. The water level depends on the mean sea level, a tidal component, any storm surge component, and an increase in water level produced by waves, including both set-up and run-up. Larger waves are therefore more easily able to erode the shoreline. In addition to the impacts of wave height, the rate at which beach material is redistributed along the shore is also dependent on the angle at which waves arrive in the coastal zone. Therefore, coastal morphology depends strongly on the wave climate to which the coast is exposed. Changes to the wave climate, such as a shift in wave direction or increase/decrease in wave heights, may change the sediment budget at the coast, which may lead to accretion or erosion.

There are a number of examples of coastal erosion around the Australian coastline (see for example Church et al. 2008b for a more complete discussion). Perhaps the most well known is the Gold Coast, Queensland, following major coastal tourist development. However, here the major component leading to erosion was a result of the Tweed River entrance training walls that interrupted the northward flow of sand along the coast. The chronic beach erosion along Adelaide's coast is thought to have a sea-level rise component. However, significant uncertainties in estimates of alongshore sand transport (Coastal Engineers Solutions 2004) make it difficult to evaluate the contribution of sea-level rise (Church et al. 2008b). Coastal erosion at Byron Bay in the 1960s was at least partially associated with the construction of a car park on the active beach. Recent storms have resulted in further coastal erosion at Byron Bay. For virtually all locations, coastal development occurring too close to the shoreline and with little regard to sea-level rise and the active shoreline (including in some cases inappropriate protection measures) has exacerbated the impacts of coastal erosion.

Potential future impacts

The most robust projections of 21st century sea-level rise are the Assessments of the Intergovernmental Panel on Climate Change (IPCC). Projections of sea level rise for the 21st century made in the IPCC Third Assessment Report (TAR; IPCC, 2001) and the Fourth Assessment Report (AR4; IPCC 2007) are shown in Figure 3. The average of the TAR model projections for the full range of greenhouse gas scenarios for 2100 relative to 1990 is about 30–50 cm (dark shading in Figure 3). The range of all model projections over all scenarios is about 20–70 cm (light shading). The full range of projections, including an allowance for uncertainty in estimates of contributions from land-based ice, were for a sea-level rise of 9–88 cm (outer black lines). The AR4 model projections are composed of two parts and are for 2095 relative to 1990. The first part consists of the estimated sea-level rise (with a 90% confidence range) from ocean thermal expansion, glaciers and ice caps, and modelled ice sheet contributions and is for a sea-level rise of 18–59 cm to 2095 (the magenta bar). The second part consists of a possible rapid dynamic response of the Greenland and West Antarctic Ice Sheets, which could result in an accelerating contribution to sea-level rise, roughly estimated to be 10–20 cm of sea-level rise (using a simple linear relationship with projected temperature; the red bar). However, there is currently insufficient understanding of this dynamic response, and IPCC (2007) clearly stated that a larger contribution can not be excluded.

The TAR and AR4 projections of sea-level rise for the 21st century are similar, especially at the upper end of the projected range. An estimate of the AR4 projections for each decade during the 21st century (Hunter 2009) are also available at http://www.cmar.csiro.au/sealevel/sl_proj_21st.html. Note that sea level is currently tracking near the upper end of the projections (Rahmstorf et al. 2007) and that some of the simple statistical models trained against observations of 20th century sea-level rise and using global average temperature projections have resulted in somewhat larger projections for the 21st century (Rahmstorf 2007; Horton et al. 2008; Grinsted et al. 2009; Siddall et al. 2009a, b). These observations do not necessarily indicate that sea level will continue to track this upper limit - it may diverge above or below this upper limit. However, the ice sheet uncertainties referred to above are essentially one-sided – i.e. they could lead to a significantly larger sea-level rise than current projections (as some of the above simple statistical models suggest) but are unlikely to lead to a significantly smaller rise. Note also that greenhouse gas emissions are now tracking at about the highest of the emission scenarios used in the IPCC TAR and AR4 for calculating sea-level projections (Raupach et al. 2007; Canadell et al. 2007; http://www.globalcarbonproject.org/) and that none of these projections lead to a stabilisation concentration of 450 ppm CO_2 equiv or less.

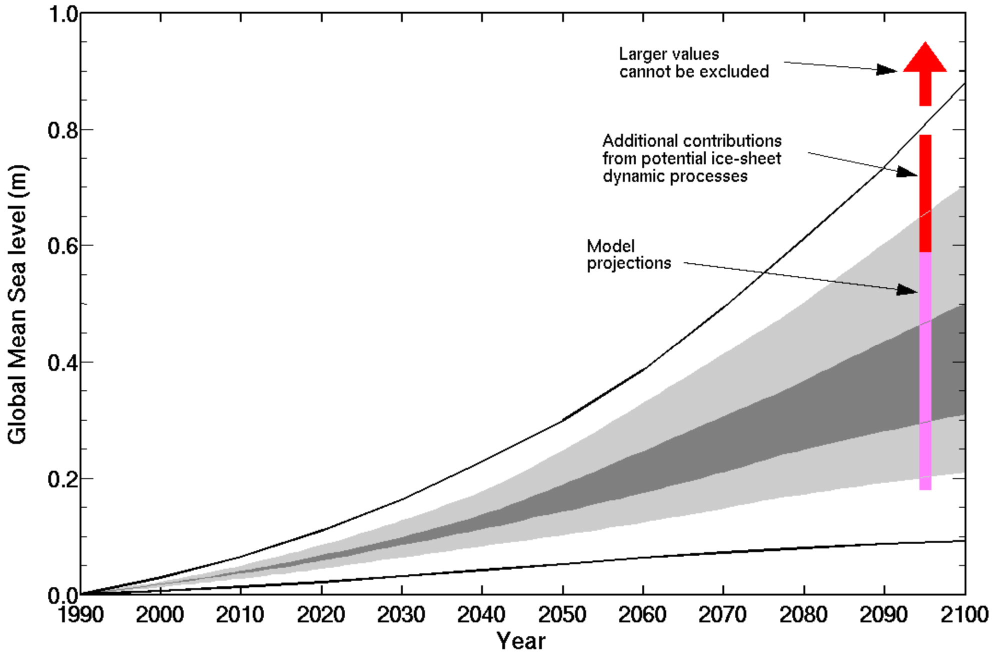

Figure 3. Projected sea-level rise for the 21st century. The projected range of global-averaged sea-level rise from the IPCC (2001) assessment report for the period 1990–2100 is shown by the lines and shading (the dark shading is the model average envelope for the range of greenhouse gas scenarios considered, the light shading is the envelope for all models and for the range of scenarios, and the outer lines include an allowance for an additional land-ice uncertainty). The AR4 IPCC projections (90% confidence limits) made in 2007 are shown by the bars plotted at 2095, the magenta bar is the range of model projections and the red bar is the extended range to allow for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic Ice Sheets to global warming. The red arrow indicates 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''; updated from Church et al. 2008a).

Sea levels will continue to rise long after 2100. In particular, ocean thermal expansion will continue for centuries, even after greenhouse gas concentrations in the atmosphere have been stabilised. The eventual sea-level rise would be dependent on the ocean and atmospheric temperatures, which in turn depend on the concentration of greenhouse gases. The Antarctic and Greenland Ice Sheets are the biggest concern for longer term sea-level rise. The area and mass of melt from the Greenland Ice Sheet (which contains enough water to raise sea level by about 7 m) is increasing. Model simulations indicate that surface melting of the Greenland Ice Sheet will increase more rapidly than snowfall, leading to a threshold stabilisation temperature above which there is an ongoing decay of the Greenland Ice Sheet over millenia. This threshold is estimated as a global-averaged temperature rise of just 3.1 ± 0.8 (standard deviation)°C (Gregory and Huybrechts 2006) above pre-industrial temperatures. With unmitigated emissions of greenhouse gases, the world is likely to pass this threshold during the 21st century. In addition, both the Greenland and Antarctic Ice sheets are showing signs of a dynamic response (for example Rignot et al. 2008; Velicogna 2009), potentially leading to a more rapid rate of rise than can occur from surface melting alone.

Sea-level rise during the 21st century and beyond is not expected to be spatially uniform. However, there is as yet little agreement in climate models of this regional distribution. The average from 17 climate model simulations for the A1B SRES Scenario for the Australian region suggest a higher than global average sea-level rise off the south-east coast of Australia and in a band stretching across the Indian and southern Pacific oceans at about 30°-45°S as indicated in the following plots for the A1B SRES Greenhouse Gas Scenario. Regional sea-level projections are currently not available for the A1FI scenario.

For both 2030 and 2070, these plots show the departure of the projected regional sea-level rise from the global-averaged projections. Thus to estimate sea-level rise at particular locations, these distributions need to be added to projections of the global-averaged rise. Note that these are results taken directly from the results of the World Climate Research Programme Coupled Model Intercomparison Experiment 3 as used in the IPCC AR4 (2007). The models are mostly relatively coarse resolution (1° or greater). Thus the majority of the models do not represent some coastal features well.

Regional sea level rise in 2030

Figure 4 shows the projected departures from the 2030 global-mean sea level from the average of 17 SRES A1B simulations. To facilitate estimation of projected coastal sea level, the top panel of Figure 5 below shows the difference between projected sea level and the global average, plotted around the Australian coastline.

Regional sea level rise in 2070

Figure 6 and 7 shows projected departures from the 2070 global-mean sea level from the average of 17 SRES A1B model simulations.

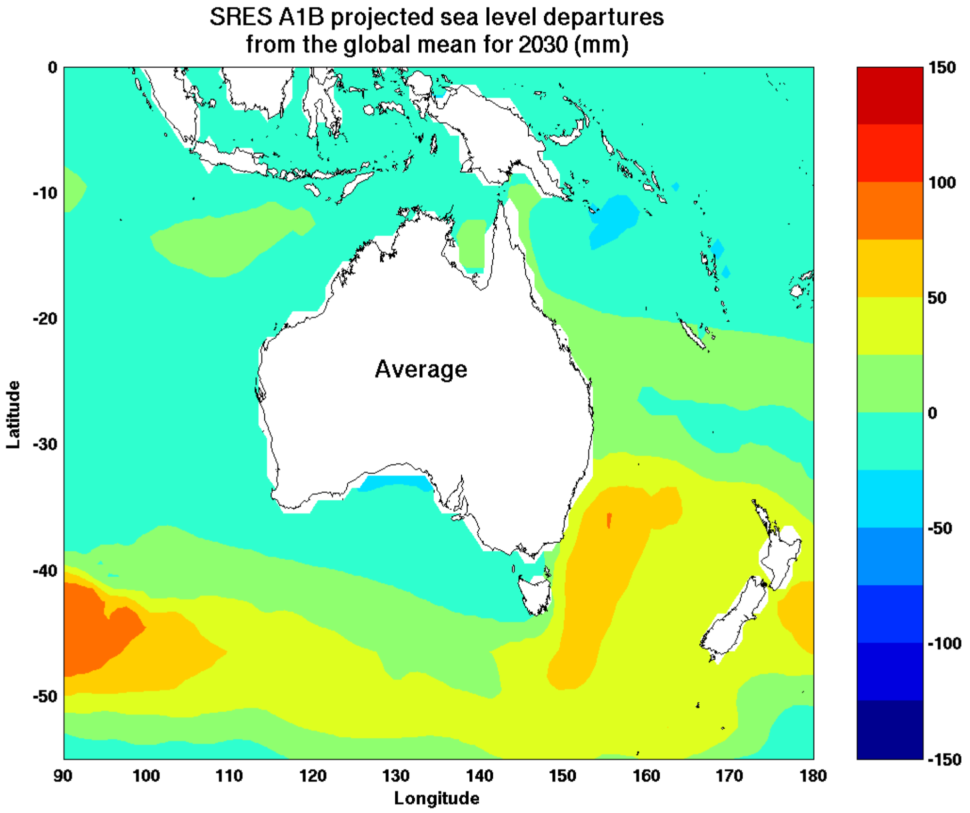

Figure 4. SRES A1B projected average sea level departures from the global mean for 2030 (mm)

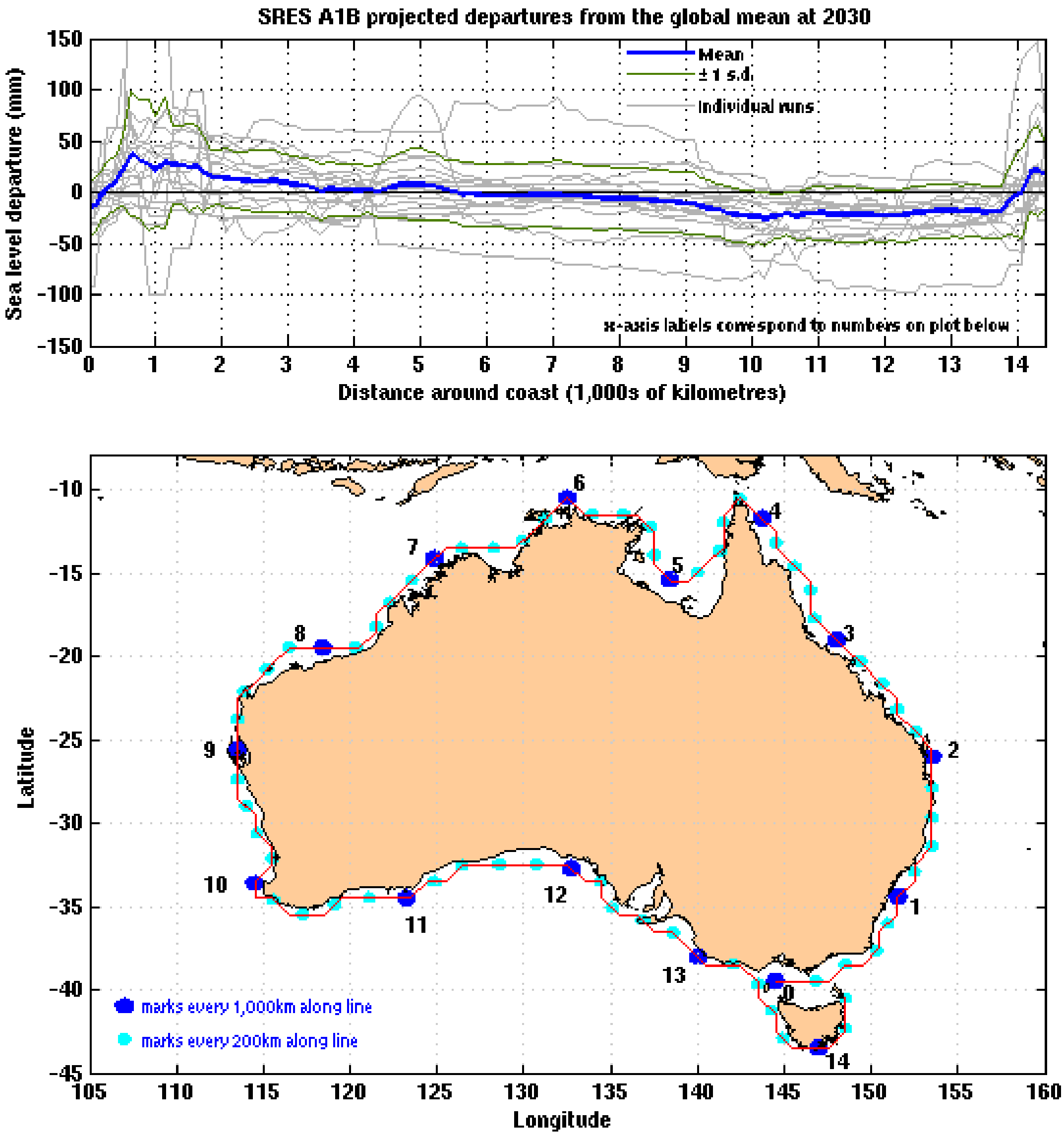

Figure 5. The x-axis on the top panel corresponds to distance along the coastline (bottom panel), starting in western Bass Strait, going east, then anti-clockwise around the Australian coast. The top panel shows the average of all models (heavy blue line), the results of the individual models (grey lines) and the model spread (plus- and minus one standard deviation; green line). The bottom panel allows the identification of individual locations adjacent to the coastline. **NOTE THAT THESE ARE DEPARTURES FROM THE 2030 GLOBALLY-AVERAGED MEAN PROJECTION FOR THE A1B SRES SCENARIO.**

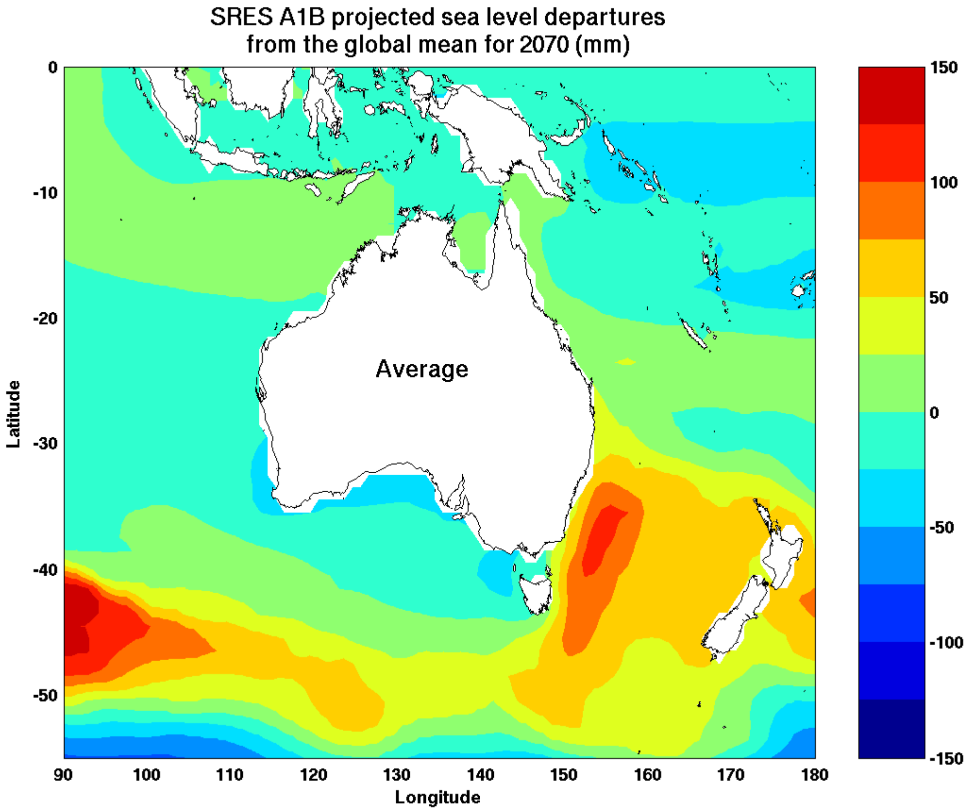

Figure 6. SRES A1B projected average sea level departures from the global mean for 2070 (mm)

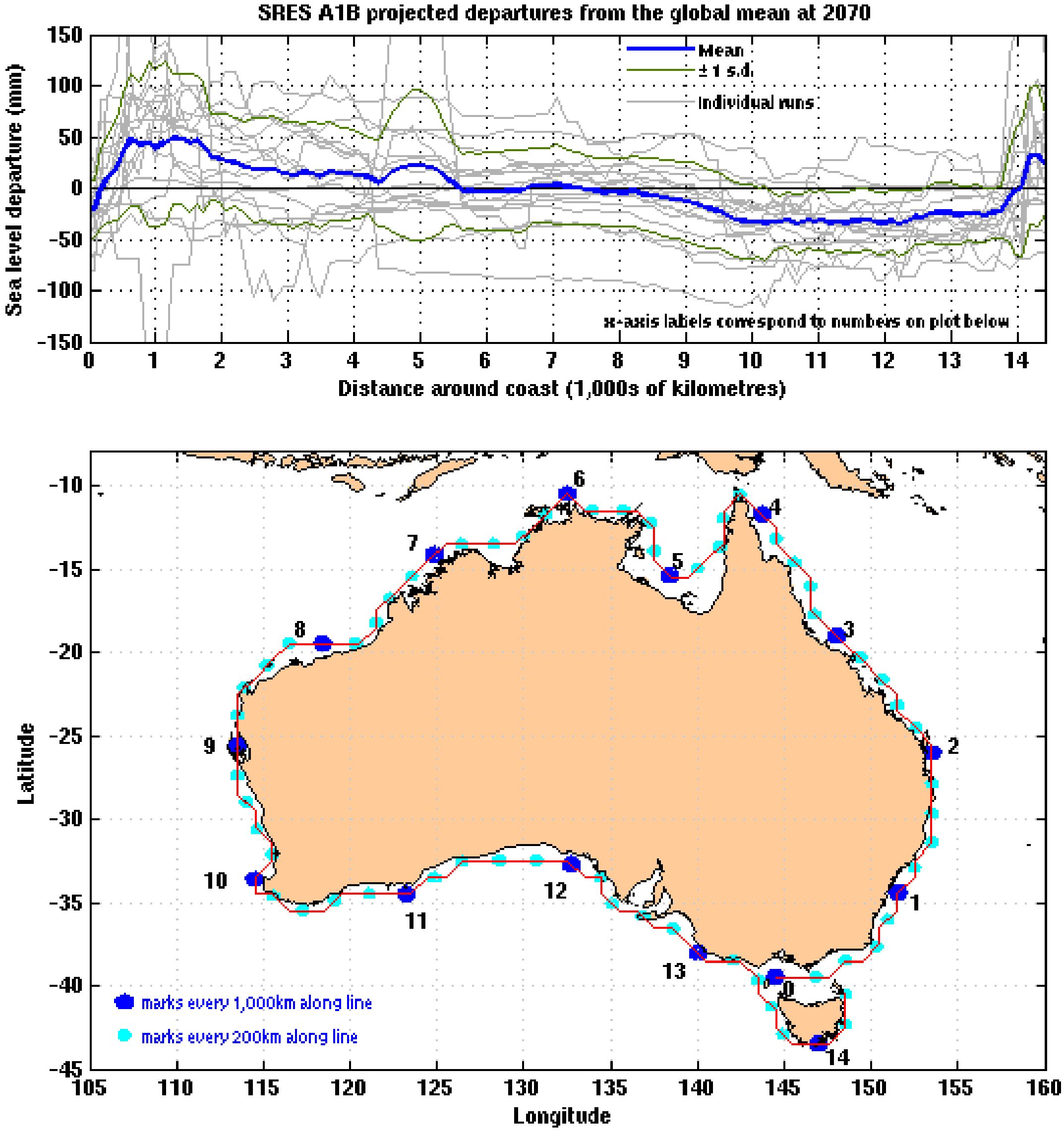

Figure 7. As Figure 5 but for 2070.

Note, these distributions do not include a quantitative assessment of the impacts for Australia of changes in the Earth's gravitational field or in the shape of the Earth as a result of changes in the mass of ice stored on land (Mitrovica et al. 2009; Bamber et al. 2009).

Future extreme sea level changes

Sea level rise will be felt both through changes in mean sea level, and, perhaps more importantly, through changes in extreme sea level events. Even if there are no changes in extreme weather conditions (for example, increases in tropical cyclone intensity), sea-level rise will result in extreme sea levels of a given value being exceeded more frequently. This change in the frequency of extreme events has already been observed at

Fremantle and Sydney. The increase in frequency of extreme events will depend on local conditions, but events that currently occur once every 100 years could occur several times per year by 2100 (Figure 8).

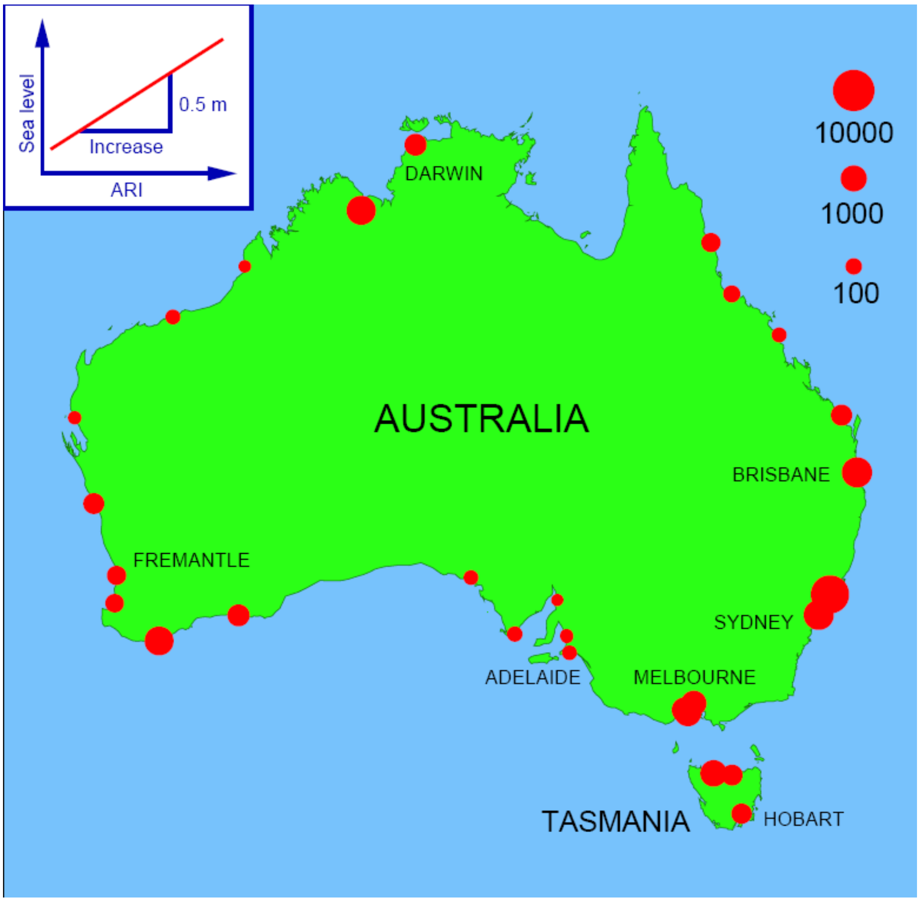

Figure 8. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameters of the discs), caused by a sea-level rise of 0.5 m (modified Church et al. 2008b). Note that these factors only consider changes in mean sea level and not changes in variability about the mean.

Potential inundation

Mean sea-level rise and possible changes in extreme weather conditions due to climate change are likely to increase the frequency and intensity of extreme coastal sea levels and the consequent inundation of low-lying coastal terrain. In Cairns in northern Australia, numerical modelling of the inundation caused by the extreme sea levels from storm tides (the combination of the storm surge and astronomical tide) under a 10% increase in the intensity of tropical cyclones was found to increase the average area of inundation around Cairns from the top 5% of storm tide events (those with a return period of 100 years or greater) by a factor of more than two (McInnes et al., 2003).

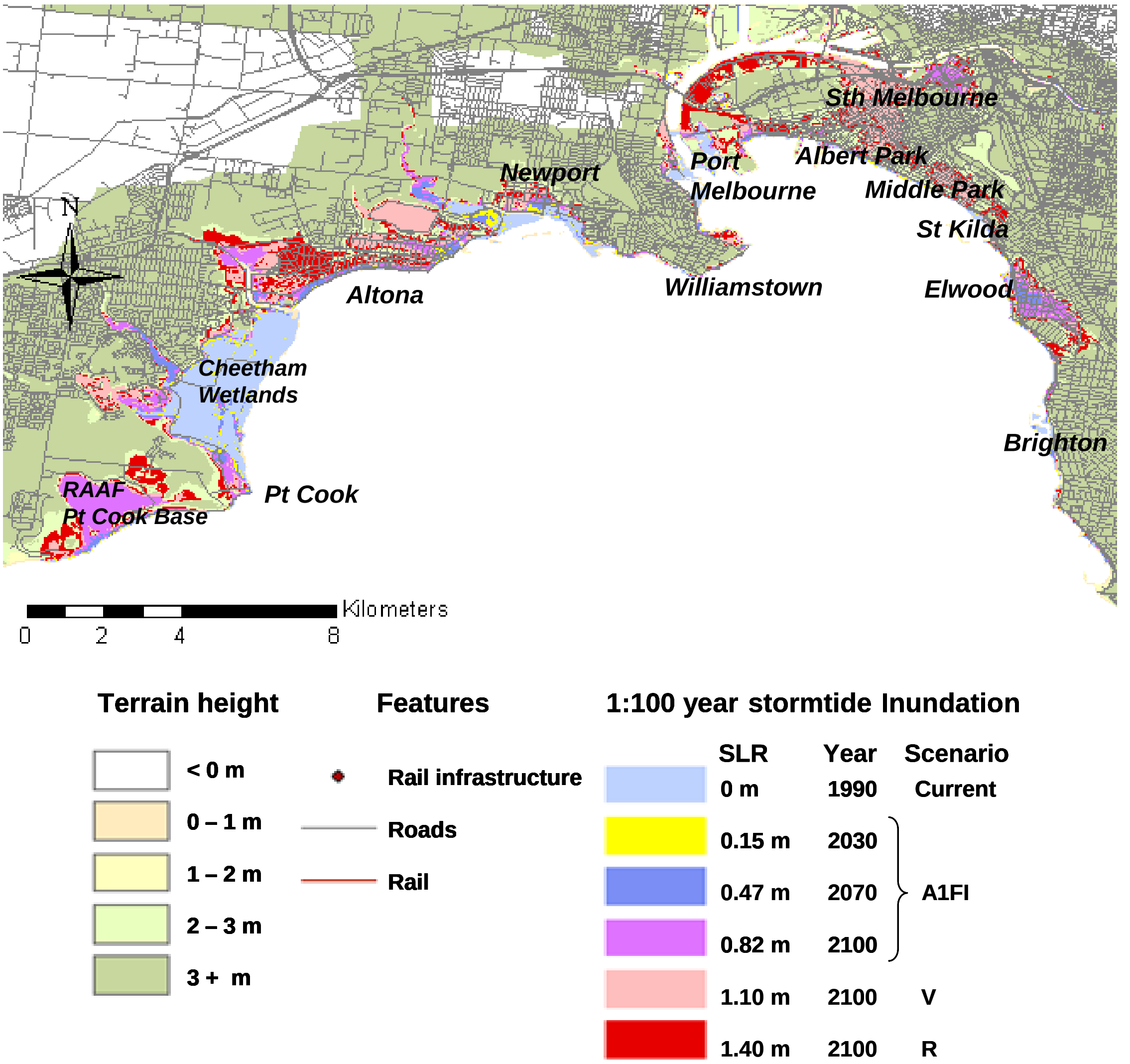

Figure 9. Land vulnerable to inundation during a 1 in 100 year storm tide under current climate conditions and various scenarios of future sea level rise for Melbourne suburbs from Point Cook to Brighton. A1FI refers to a scenario for the emissions of greenhouse gases from Nakićenović and Swart (2000) with associated sea level estimates from Hunter (2009), V and R refer to alternate estimates for sea level rise for 2100 from Vellinga et al. (2009) and Rahmstorf (2007) respectively.

A recent assessment of changes in potential inundation caused by 1 in 100 year storm tides was undertaken for selected low-lying locations along the Victorian coast. Numerical and statistical modelling was undertaken on a statewide basis to evaluate the height of the 1 in 100 year storm tide (McInnes et al, 2009a). Further modelling was then undertaken to evaluate the inundation likely under various sea-level rise scenarios using a high resolution digital elevation model (McInnes et al., 2009b,c). Results indicate that the land area vulnerable to inundation across the area shown in Figure 9 increases non-linearly with increasing sea level. For example, under an A1FI sea-level rise scenario for 2030, 2070 and 2100, the area vulnerable to inundation increases by 13%, 45% and 125% respectively. For the same set of sea-level rise scenarios, the number of land parcels that are potentially vulnerable to inundation, increases even more dramatically with 303 land parcels potentially vulnerable under present conditions increasing by 37% by 2030, quadrupling by 2070 and increasing by more than a factor of 11 by 2100. This study highlights thresholds of sea-level rise that are important in the context of vulnerability and adaptation.

A national assessment of coastal impacts has recently been released (DCC 2009).

Confidence Assessments

Globally and around Australia sea level has been rising during the 20th century. There is high confidence that sea level will continue to rise during the 21st century and beyond. The range of projections for 2100 cover a wide range but global-averaged sea level is currently tracking near the upper limit of these projections (Rahmstorf et al. 2007).

Sea level will not rise uniformly around the globe but there is not yet agreement on the appropriate regional pattern of sea-level rise. Note that the pattern of sea-level rise since the early 1990s should not be taken as an indication of the pattern of future sea-level rise.

There is high confidence that sea-level rise will lead to a significant increase in the frequency of coastal sea levels of a given height.

Increased sea levels are likely to lead to increased coastal erosion in many regions. However, there is as yet little knowledge of how surface waves will change and thus modify any pattern of coastal erosion.

For the purpose of formal risk assessment, the (quantified) uncertainty of sea-level rise may be combined with the present statistics of tides and surges to yield the overall likelihood of future flooding events (Hunter, 2009).

Adaptation Responses

Significant, urgent and sustained mitigation is required if the world is to avoid crossing the threshold leading to ongoing melting of the Greenland Ice Sheet and to limit contributions to sea-level rise from ocean thermal expansion and the Antarctic Ice Sheet.

Even with successful mitigation, adaptation to rising sea levels will be essential. It is critically important to recognize that during the latter part of the 20th century, global-averaged sea level moved outside the range of sea level over the last few centuries and much coastal development has occurred with little regard to future rises in sea level. During the 21st century, sea level will move substantially further outside the range experienced by our society. Appropriate adaptation can significantly reduce the impact of sea-level rise. Planned adaptation includes retreat from rising sea levels (involving planning and zoning of vulnerable regions), accommodation (i.e. modification of coastal infrastructure) and protection of highly valued coastal regions (i.e. the building of dykes or highly sophisticated barriers like the Thames Barrage protecting London and the Rotterdam storm surge barrier). Planned adaptation is more cost effective and less disruptive than forced adaptation in response to the impacts of extreme events. It is now clear that the most appropriate response to sea-level rise for coastal areas is a combination of *adaptation* to deal with the inevitable rise, and *mitigation* to limit the long-term rise to a manageable level.

Knowledge Gaps

The broad range of current projections of global-averaged sea-level rise for the 21st century is primarily the result of model uncertainty and to a lesser extent greenhouse gas concentrations, and there is currently inadequate understanding of the factors controlling the global-averaged sea-level rise and its regional distribution. Improving monitoring, understanding and modelling of the global oceans, glaciers and ice caps and of the Greenland and Antarctic Ice Sheets, and detecting early signs of any growing contributions of the ice sheet to sea-level rise are critical to informing decisions about the required level of greenhouse gas mitigation and for adaptation planning. Quantifying how the Greenland and Antarctic Ice Sheets will contribute to sea-level rise during the 21st century and beyond is currently the largest single uncertainty.

Today, early warning of extreme events through improved storm-surge modeling and its operational application is an important tool in some regions. These warning systems need to be improved and applied in regions where they do not currently exist and where substantial impacts are likely to occur in the future. Such warning systems will require the best bathymetric and near shore topographic data and will involve forecasts of the meteorological conditions, surface waves, storm-surge and detailed inundation mapping.

The understanding of sea-level rise and variability has progressed considerably over the last decade, largely as a result of dramatically improved *in situ* and satellite observational systems, improvements in the underpinning geodetic systems and improved models of the climate system. These observing systems need to be completed, improved and sustained, as described in the plans of the Global Climate Observing System, if we are to continue to reduce uncertainties. A summary statement of research and observational needs are available from http://wcrp.wmo.int/AP_SeaLevel.html.

Finally, the scientific information must be translated into practical adaptation plans and this requires the development and strengthening of partnerships between science, different levels of governments, business and the public.

Key Messages

What is happening

- Sea level: global sea levels have risen about 20 cm over 1870 to 2008 (HIGH Confidence).
- The current rate of global averaged sea-level rise is about 3.3 ± 0.4 mm yr^{-1}, compared to the average for the 20th century of about 1.7 mm yr^{-1}. This is near the upper end of the projections for sea-level rise since 1990 (HIGH Confidence).
- Extreme flooding events: There has already been a decrease in the average period between high coastal sea-level events of a given magnitude.

What is expected

- Sea level: Sea levels will continue to rise during the 20th century (HIGH Confidence). The range of the projections for 2095 compared to 1990, including potential ice-sheet dynamic processes, are for a rise of 18 to 79 cm (MEDIUM confidence). Higher sea-levels can not be excluded because of inadequate understanding of the response of the ice sheets to global warming (LOW Confidence).
- Extreme flooding events: The frequency of extreme flooding events may increase by a factor of one hundred or more, depending on the amount of rise and the local conditions.

Knowledge Gaps

- Sea level: There is currently a broad range of sea level projections for the 21st century and inadequate understanding of the ice sheets response to global warming. There is inadequate understanding of the regional distribution of sea-level rise
- Surface waves: There is in adequate knowledge of how wave conditions might change.
- Extreme flooding events and coastal erosion: There is inadequate knowledge of the regional and local impact of future changes in sea level, storm surges and wave conditions.

Further Information

This report draws heavily on a comprehensive book on sea-level rise that is currently in press (Church et al. 2010). Further information on sea-level rise and its causes can also be found at http://www.cmar.csiro.au/sealevel/index.html.

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