Sea level

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What is happening

Sea levels are rising around Australia, with the fastest rates currently in northern Australia. New analyses of sedimentary records from the east coast of Tasmania confirm slow sea-level change over 1000s of years until the early 20th century, when there was a significant acceleration in the rate of sea-level rise. High sea-level events on annual to decadal timescales have increased by a factor of three during the 20th century.

What is expected

Sea level will continue to rise during the 21st century and beyond, and result in inundation of low-lying coastal regions and coastal recession.

What we are doing about it

Satellite altimeters and the Australian Baseline Sea Level Monitoring Array have provided a comprehensive picture of sea level around the Australian coastline since the early 1990s. Adaptation planning will be informed by national and regional assessments of coastal inundation and recession due to future changes in sea level and wave climate.

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
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the 20th century and during the 20th century. The average of global-averaged sea-level rise during the 20th century was about 1.7 mm yr⁻¹. The current rate (1993 to present) is about 3.1 ± 0.4 mm yr⁻¹. 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 such as 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.

Historical sea-level changes

Global-average sea-level rise

Sea level has changed dramatically through Earth’s evolution and a brief introduction was given in the 2009 report card. Since 2009, there have been new assessments of sea level at the time of the last interglacial. The assessment by Kopp et al. (2009) found that it is very likely that sea level was more than 6.6 m above today’s level but unlikely to have been more than 9.4 m above today’s level. When sea level was within 10 m of the present day values, the maximum rate of rise was very likely to have been greater than 5.6 m/millennium but less that 9.2 m/millennium. However these rates are representative of changes coming out of the previous glacial period rather than of changes during the interglaciation.

There have also been new paleo estimates of coastal sea level over the last few hundred years on the east coast of Tasmania (Gehrels et al. 2012) and the east coast of
the USA (Kemp *et al.* 2011). These studies confirm low rates of sea-level change until the late 19th century/early 20th century when there was a significant acceleration in the rate of sea-level rise.

**Figure 1.** Global mean sea level from 1880 to 2011 with one standard deviation error estimates, updated from Church and White (2011, blue), and the Topex/Poseidon/Jason-1 and -2 satellite altimeter records from 1993 to 2011(red). Both series have been set to a common value at the start of the altimeter record in 1993. Note the altimeter have been corrected such that the rise presented here represents an increase in global ocean volume.
Figure 2. Global mean sea level from satellite observations from 1993 to 2011. The light blue line shows monthly values, the dark blue line is the 3 month running mean and the red line is the linear trend. Note the altimeter have data been corrected such that the rise presented here represents an increase in global ocean volume.

An update of the estimated global averaged sea level since 1880 (Church and White 2011, Figure 1) is in general agreement with earlier estimates and confirm a 20th century rate of sea-level rise of 1.7 ± 0.3 mm/yr. Church and White (2011) find a slightly weaker, but still significant, acceleration of the rate of sea level rise compared with their earlier analysis (Church and White 2006). A recent study (Ray and Douglas 2011) produces global mean sea level time series similar to that of Church and White (2006, 2011), but does not find a significant 20th century acceleration. Satellite altimeter data continues to show sea level rising. However, in 2011 there was a rapid fall in global mean sea level associated with the La Niña event and floods in Australia, Asia and America. The resultant terrestrial storage of water has been directly estimated with satellite gravity measurements (Carmen Boenning, personal communication 2012). At the end of 2011, sea level appears to be approaching the long-term trend line again.

Sea-level rise in the Australian region

Satellite altimeters and the Australian Baseline Sea Level Monitoring Array have provided a comprehensive picture of sea level around the Australian coastline since the early 1990s (Figure 3). The rate of recent sea-level rise in the Australian region (Figure 3) continues to have a considerable degree of spatial variability, with a maximum of sea-level rise to the north of Australia in the western equatorial Pacific.
These high rates of sea-level rise in the western equatorial Pacific Ocean 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). There is a lower rate of sea-level rise at the coast (about 3 mm yr\(^{-1}\)) probably because of an increased southward flow of the East Australian Current. The minimum in the rate of sea-level rise off the east coast (2-3 mm yr\(^{-1}\)) 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.

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 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

**Figure 3.** Sea-level rise during 1993-2011 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 2011. The altimeter data has all standard corrections applied. The linear trends in coastal sea-level data over the same period are shown by the coloured circles (data from the National Tidal Centre). The data is all relative sea level – that is, no corrections for atmospheric pressure effects, or Glacial Isostatic Adjustment (GIA) have been made to either data set. See the text for a discussion of a comparison of the coastal and offshore rates.
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 and with the 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. Sea-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/cool.

Since 2009, there has been progress in understanding the reasons for sea-level rise. From 1972 to 2008, the observed global-average sea-level rise (1.8 ± 0.2 mm yr\(^{-1}\) from tide gauges alone and 2.1 ± 0.2 mm yr\(^{-1}\) from a combination of tide gauges and altimeter observations) agrees well with the sum of contributions (1.8 ± 0.4 mm yr\(^{-1}\)) in magnitude and with both having similar increases in the rate of rise (Church et al., 2011a). The largest contributions come from ocean thermal expansion (0.8 mm yr\(^{-1}\)) and the melting of glaciers and ice caps (0.7 mm yr\(^{-1}\), with Greenland and Antarctica contributing about 0.4 mm yr\(^{-1}\). The cryospheric contributions increase through the period (particularly in the 1990s) but the thermosteric contribution increases less rapidly. An improved estimates of aquifer depletion (0.3 mm yr\(^{-1}\), partially offsets the retention of water in dams and giving a total terrestrial storage contribution of -0.1 mm yr\(^{-1}\). Wada et al. (2012) estimate a slightly larger aquifer depletion term such that the total terrestrial storage over this period is close to zero. Very recently, Pohkrel et al. (2012) argue for a substantially larger terrestrial storage contribution, at variance with other studies.

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 20\(^{th}\) century sea-level rise as a result of changes in the ocean’s volume. Ongoing changes in the mass
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of the ice sheets (Mitrovica et al. 2001, 2009) also result in sea-level change. 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 impacts

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 may 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 as sea level rises. 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. 2008 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. 2008). Coastal erosion at Byron Bay in the 1960s was at least partially associated with the construction of a car
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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 for sea-level rise and the active shoreline has exacerbated the impacts of coastal erosion.

Potential impacts by 2030s and 2100s

The most robust projections of 21st century sea-level rise are reported in the Assessments of the Intergovernmental Panel on Climate Change (IPCC). Projections of sea-level rise based on the Fourth Assessment Report (AR4; IPCC 2007) are shown in Figure 4 (Church et al. 2011b). These projections are composed of two parts. The first part consists of the estimated sea-level rise (with a 5 to 95% confidence range) from ocean thermal expansion, glaciers and ice caps. The second part uses a simple linear relationship with projected temperature to estimate a possible rapid dynamic response of the Greenland and West Antarctic Ice Sheets to sea-level rise. However, there is currently insufficient understanding of this dynamic response, and IPCC (2007) clearly stated that a larger contribution cannot be excluded.

The inability of models to reproduce the observed rise during the twentieth century, our lack of ability (until recently; see Church et al. 2011a) to adequately explain sea-level rise over decadal periods, and the observation that sea level is currently rising near the upper end of the IPCC AR4 projections (Rahmstorf et al., 2007; Church et al. 2011b; Figure 4b) has led to concern that the IPCC projections for the twenty-first century may be underestimated. This concern has, in turn, led to the development of so-called "semi-empirical Models" (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) in an attempt to bypass our lack of process understanding. These semi-empirical models scale observed sea-level rise to some other physical parameter such as global averaged temperature or radiative forcing. They give higher rates of rise and a wider range of projections (about 50-180 cm) by 2100. A number of concerns have been raised about these semi-empirical projections, one of which is that, although semi-empirical models represent the observed rise over the period of calibration, there is little available information to quantitatively test their predictive skill over decadal periods. Note that some of the projections are approaching the value of 2 m and that Pfeffer et al. (2008) argued that rises above this value were physically untenable. In summary, although semi-empirical models give a warning that larger sea-level rises than suggested by current process-based models may be possible, they should be used with caution until the concerns about their value are adequately evaluated and addressed.
Figure 4. Projected sea-level rise for the 21st century. (a) Projections of global-averaged sea-level rise for the greenhouse gas scenarios from the IPCC Special Report on Emission Scenarios (SRES) are shown to 2100 with respect to 1990. The shaded region shows the full (5- to 95-percentile) range of projections, without scaled-up ice sheet discharge. The outer light lines show the full (5- to 95-percentile) range of
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 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 may 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 and a lower threshold for the ongoing decay of the Greenland Ice Sheet. (Robinson et al. 2012).

Sea-level rise during the 21st century and beyond is not expected to be spatially uniform. While there is as yet little agreement in climate models of this regional distribution, progress is being made towards making better regional projections (Church et al. 2011a and Slangen et al. 2011)). These projections include an allowance for changes in the gravitational field associated with the changing distribution of surface mass (Gomez et al. 2010) as glaciers and ice sheets change, as well as dynamic ocean changes.
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Figure 5. The regional distribution of the projections of sea-level change for 2090 compared to 1990 for the A1B scenario, combining the global average sea-level projections, the dynamic ocean departure from the global average and the regional changes associated with the changing mass distribution in the cryosphere. The black contour is the "average" value at 2090 of 38 cm dividing those regions with above and below average sea-level rise.

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 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. Figure 6 (a) shows the expected change in this frequency for a sea-level rise of 0.5 m. Typically, this means that flooding events that currently occur once every 100 years could occur several times per year by 2100. This increase in the frequency of flooding events may be avoided if coastal infrastructure is raised by an appropriate allowance for sea-level rise (Hunter, 2011). The allowance which preserves the frequency of flooding events as sea-level rises from 1990 to 2100 is shown in Figure 8(b), based on global-average projections from the IPCC AR4 and the A1FI emission scenario.

The effect of climate change on storm-induced sea level extremes has been investigated for southern Australia using a hydrodynamic model to simulate the sea level response from the atmospheric conditions of three climate model simulations for 2080-2099 compared to 1980-1999. It was found that the overall poleward movement of the mid-latitude storm belt simulated by the climate models and the associated changes in wind and weather patterns over Australia would mostly lead to declines in extreme sea levels (compared to mean sea level) along the southern coastline and
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Slight increases over parts of Tasmania by the end of the 21st Century. However the changes are small, typically within 5% of the extreme sea levels considered (Colberg and McInnes, 2012).

Figure 6. (a) Left: 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 Hunter, 2011). (b) Right: sea-level rise allowance (m) for 1990 to 2100 based on preserving the frequency of flooding events as sea level rises, based on global-average projections from the IPCC AR4 and the AIFI emission scenario (modified Hunter, 2011). Note that these results only consider changes in mean sea level and not changes in variability about the mean.

Potential inundation and erosion

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 for 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).
An 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, 2011). Results indicate that the land area vulnerable to inundation across the area shown in Figure 7 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...
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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 vulnerability was released (DCC 2009) that assesses coastal vulnerability to inundation and erosion due to sea level rise. A subsequent update (DCCEE, 2011) undertook a more detailed assessment of coastal vulnerability for selected population centres around Australia using higher resolution elevation data. However future patterns of erosion will also depend on future wave climate change and information on such changes under future climate conditions is only beginning to emerge (Hemer et al, 2011, 2012).

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 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; Church et al. 2011b).

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 exceeding a given height.

Increased sea levels are likely to lead to increased coastal erosion in many regions. However, there is as yet only limited 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, 2010, and the decision-support tool at www.sealevelrise.info).

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 as well as 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, the rate of global-averaged sea level exceeded the rate over the last few centuries when much coastal development occurred (with little regard to possible changes in sea level). During the 21st century, sea level will move 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.

**Knowledge Gaps**

The broad uncertainty 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. That is, there is currently inadequate understanding of the factors controlling the global-averaged sea-level rise and its regional distribution. Successful mitigation and adaptation depends critically on: (a) improving monitoring, understanding and modelling of the global oceans, glaciers, ice caps, and the Greenland and Antarctic Ice Sheets, and (b) detecting early signs of any growing contributions of the ice sheet to sea-level rise. 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 operational storm-surge modeling 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 in Church et al. (2010).

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

**Key Messages**

**What is happening**

- **Sea level**: global sea levels have risen about $21 \pm 3$ cm over 1890 to 2011 (HIGH Confidence).
- The global-averaged sea-level rise during the 20th century was about $1.7 \text{ mm yr}^{-1}$. The current rate (1993 to present) is about $3.1 \pm 0.4 \text{ mm yr}^{-1}$. This latter
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rate is near the upper end of the projections for sea-level rise since 1990 (HIGH Confidence).

- Extreme flooding events: There has already been an increase in the frequency of high coastal sea-level events of a given magnitude. (HIGH Confidence)

What is expected

- Sea level: Sea levels will continue to rise during the 21st century (HIGH Confidence).
- Extreme flooding events: The frequency of extreme flooding events will increase significantly, depending on the amount of rise and the local conditions. (HIGH Confidence)

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 climate change. There is inadequate understanding of the regional distribution of sea-level rise
- Surface waves: There is incomplete knowledge of how wave conditions might change.
- Extreme flooding events and coastal erosion: There is incomplete 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 (Church et al. 2010 and recent publications as cited). Further information on sea-level rise and its causes can also be found at http://www.cmar.csiro.au/sealevel/index.html.

References


Church, J., and N. White (2011), Sea-level rise from the late 19th to the early 21st century, Surveys in Geophysics, 1-18.


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