Information for Australian Impact and Adaptation Planning in response to Sea-level Rise

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Sea levels along Australia's coastline are influenced by natural climate variability and anthropogenic climate change. Projections of sea-level rise (SLR) for 2090 for the Australian coastline are similar to the global mean sea-level projections. The global and regional projections are almost independent of the Representative Concentration Pathways (RCPs) for greenhouse gas emissions chosen for the first decades of the 21st century, but they begin to diverge significantly from about 2050. For the business-as-usual scenario (RCP8.5), the rates increase steadily through the 21st century, reaching almost 12 mm yr^{-1} by 2100 at all locations. For the intermediate scenarios of RCP 6.0 and RCP 4.5, the rates stabilise in about 2090 and 2060 at about 7-8 and 6 mm yr^{-1}, respectively. For the strong mitigation scenario (RCP 2.6, requiring significant and urgent mitigation of greenhouse gas emissions), the rate of rise stabilises much earlier than the other scenarios and then reduces slightly to about 4 mm yr^{-1}. On the north and west coasts of Australia, the observed sea-level trends from the start of the projections in 1996 to 2010 are larger than the model projections as a result of the combined effect of SLR and internal modes of climate variability.

The impacts of SLR will be felt most profoundly during extreme sea-level events. The meteorological and climate processes that contribute to extreme sea levels around the coast of Australia are highly regionally heterogeneous. Allowances were calculated that provide estimates of the height that present assets or their protective measures would need to be raised to ensure that the likelihood of exceedance of those levels in the future does not change from the present climate. These allowances vary according to SLR projections, their uncertainties and the variability of extreme sea levels. For 2030, when the uncertainty surrounding future SLR scenarios is small, the allowances are approximately the median projected SLR. However by 2090, the larger uncertainties associated with the projections lead to allowances that typically lie towards the upper end of the range of projected SLR.

Introduction

Sea-level rise (SLR) is a significant concern for Australia with about half the population living within 7 km of the coast (Chen and McAneney, 2006) and a significant amount of industry and infrastructure located in the coastal zone. Between 22 and 35% of residential dwellings in Australia have been identified as potentially exposed to flooding under a SLR scenario of 1.1 metres (Department of Climate Change, 2009).

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Coastal infrastructure and coastal ecosystems are most at risk during extreme sea-level events, caused by storm surges and other contributing factors such as astronomical tides. It is therefore of vital importance that credible and robust up-to-date information on SLR projections and the impacts on extreme events are available for coastal planning and adaptation.

The Intergovernmental Panel for Climate Change (IPCC) assessments are a major source of SLR information, with each successive assessment providing improved understanding of the contributions to past sea-level change, future projections and their associated uncertainties. In the Fifth Assessment Report (AR5), Church et al. (2013b) reported significantly improved understanding of the contributions to sea-level change over the past few decades and the 20th century as a whole. For the first time, the IPCC provided regional projections, incorporating contributions from all components of sea-level change: oceans, glaciers, ice sheets, land water and large-scale vertical land motion from ongoing glacial isostatic adjustment (GIA), and projected changes in the distribution of mass on the Earth. Thus for the first time in an IPCC Assessment, the AR5 provided credible spatially-specific information on sea-level change. Furthermore, new methods for combining SLR scenarios and their uncertainties with extreme sea-level information were used to provide expected changes in the frequency of extreme sea-level events and policy-relevant information on appropriate sea-level allowances suitable for adaptation planning (Wong et al., 2014). These assessments did not consider tectonic factors that affect local sea level. Following these advances, it is timely to consider the implications of the improvements in these global assessments for Australia.

The specific goals of the paper are to:

- provide regionally specific and credible relative SLR (sea level relative to the land) projections around Australia for the 21st century,
- review recent studies on extreme sea levels, their causes and projections, and
- provide a means for interpreting SLR projections, uncertainty and extremes by the use of sea-level "allowances".

We build upon both the recent IPCC assessments (Church et al., 2013b, Wong et al. 2014) and also recent assessments of sea levels in Australia (White et al. 2014). This allows us to provide an overall assessment of observed 20th century and projected 21st century sea levels. This paper underpins the methods used to provide quantitative information for the Natural Resource Management regions of Australia in CSIRO and Bureau of Meteorology (2015).

We begin by reviewing global and Australian historical sea-level change (Section 2) and then present global and Australian sea-level projections for the 21st century and beyond (Section 3). We consider sea-level extremes in Section 4 and then combine the projected range of SLR together with information on extreme sea levels around Australia to provide information relevant for adaptation planning. We end with a discussion of the major results and their implications.

Historical Sea-level Change

Global mean sea level (GMSL) varies as a result of changes in the density of the ocean (ocean thermal expansion or contraction) and changes in the mass of the ocean through exchanges with the cryosphere (glaciers and ice sheets) and the terrestrial environment (soil moisture, terrestrial reservoirs, lakes, ground water, etc.) (Church et al., 2011b; Gregory et al., 2013; Moore et al., 2011). In addition to the global averaged SLR, regional sea level varies as a result of changes in ocean dynamics (ocean currents related to surface winds, air-sea fluxes of heat and freshwater and internal variability; Gregory et al. 2001), changes in the Earth's gravitational field (from the redistribution of water and ice on the Earth) and vertical motion of the land (Church et al., 2011a; Church et al., 2013b; Slangen et al., 2012; 2014b).

Global Context

Over the last 1 million years, sea level has varied by over 100 m as the mass of ice sheets has waxed and waned through glacial cycles (Lambeck et al., 2002; Foster and Rohling, 2013; Rohling et al., 2009). During the last interglacial (129 to 116,000 years ago), sea level was likely to have been between 5 and 10 m higher than present (Dutton and Lambeck, 2012; Kopp et al., 2009; Kopp et al., 2013; O'Leary et al., 2013). These higher sea levels occurred under different orbital (solar) forcing and when global-averaged temperature was up to 2°C warmer than preindustrial values and high latitude temperatures were more than 2°C warmer for several thousand years (Masson-Delmotte et al., 2013). Over the following 100 thousand years sea levels fell as major ice sheets formed over northern America, Europe and Asia (Lambeck and Chappell, 2001). Since the peak of the last ice age (about 20,000 years ago), sea level rose by more than 120 m (Lambeck et al., 2002), until about 6,000 years ago, after which contributions from the decaying ice sheets reduced considerably. Over the last several thousand years, global-averaged sea levels have been comparatively steady with fluctuations not exceeding 0.25 m on time scales of a few hundred years (Masson-Delmotte et al., 2013; Woodroffe et al., 2012). Estimates of relative sea level from salt marshes (Gehrels and Woodworth, 2013) and available long tide-gauge records (Jevrejeva et al., 2008; Woodworth, 1999) indicate a transition from these low rates of change (order a few tenths mm yr^{-1}) to 20th century rates (order mm yr^{-1}) in the late 19th to early 20th century.

Between 1900 and 2010, tide-gauge estimates of GMSL (Church and White, 2011; Church and White, 2006; Jevrejeva et al., 2006; Jevrejeva et al., 2008; Ray and Douglas, 2011; Wenzel and Schroeter, 2014) indicate a long-term average rate of rise of 1.7 ± 0.2 mm/yr. With the exception of Wenzel and Schroeter, these estimates indicate significant variations in the rate of rise during the 20th century, with large rates in the 1920 to 1950 period and post 1993. The relatively large rate of rise since 1993 has been confirmed by the satellite-altimeter data (Church and White, 2011; Masters et al., 2012) and is related to changes in natural and anthropogenic forcing (Church et al. 2013a,b; Slangen et al. 2014a). The Church and White and the Jevrejeva et al. analyses indicate accelerations (about 0.01 mm yr^{-2}) in the rate of rise from the start of the analysis in the late 19th century. While Ray and Douglas and Wenzel and Schroeter found no significant acceleration for the 20th century alone, Hay et al. (2015) proposed a smaller rate of rise prior to 1990 (1.2 mm/yr, compared with the assessed rate of 1.5 mm/yr; Church et al. 2013b) and a larger acceleration during the 20th century.

A large transfer of mass from the ice sheets to the ocean changes the surface loading of the Earth and induces an ongoing response of the viscous mantle of the Earth. As a result, over the 20th century relative sea level has been falling in locations of former ice sheets, rising at faster than the global average rate in the immediately adjacent regions (for example New York). In many locations distant from the locations of former ice sheets (including Australia), the rate of rise is slightly less than the global average (Lambeck and Chappell, 2001; Peltier, 2001) and in some parts of Australia there were periods of higher sea levels (compared to present day) of about a metre or more several thousand years ago. The ongoing response of the Earth's mantle and lithosphere means that relative sea level around Australia is rising at about 0.3 mm yr^{-1} less than it otherwise would (Lambeck, 2002).

Australian Context

Modern sea-level measurements began in Australia with the first sea-level benchmark at Port Arthur in about 1840 (Hunter et al. 2003), followed by the installation of tide gauges in Fort Denison (Sydney) in 1886 and Fremantle in 1897 (Figure 1). After 1966, there is sufficient data for the assessment of mean sea-level trends for all sectors of the Australian coastline, with high quality satellite altimeter data also available since 1993.

Two complementary assessments of sea level in the Australian region (Burgette et al., 2013; White et al., 2014a) show monthly sea-level anomalies around the Australian coastline are highly correlated with each other and with the Southern Oscillation Index, and propagate from the equatorial western Pacific Ocean through the Indonesian Archipelago to north-western Australia and then anticlockwise around Australia, decreasing in magnitude with distance from Darwin (see White et al. 2014 for a review, with key points reproduced here). Over 1966 to 2009, the tide-gauge data indicate an average relative SLR around Australia of 1.4 ± 0.2 mm yr^{-1}, ranging from 0.8 mm yr^{-1} at Sydney and Victor Harbor to 2.6 mm yr^{-1} at Darwin. When the signal related to the Southern Oscillation Index is removed, the average trend is 1.6 ± 0.2 mm yr^{-1}. This average is less than the global mean trend of 2.0 ± 0.3 mm yr^{-1} over the same period, mainly because of the effect of GIA and a smaller contribution from an increase in atmospheric pressure at a number of locations, which depresses local sea levels (White et al. 2014). If it were not for these factors, the average trend around Australia would be larger at 2.1 mm yr^{-1}, ranging from 1.3 mm yr^{-1} at Sydney to 3.0 mm yr^{-1} at Darwin. From 1993 to 2009, the average rate of rise was 4.5 ± 1.3 mm yr^{-1} and this reduces to 3.1 mm yr^{-1} after the signal correlated with the Southern Oscillation Index is removed and an allowance for GIA and atmospheric changes included. For comparison, the GMSL trend over 1993 to 2009 is 2.8 mm yr^{-1} estimated from the tide-gauge records and 3.4 mm yr^{-1} estimated from satellite altimeters and 3.2 mm yr^{-1} for the period 1993 to 2013. The point here is that after correcting for GIA and atmospheric pressure changes, White et al. (2014) demonstrate the average of the Australian tide-gauge trends is similar to, and shows a similar increase in rate as the trend in GMSL. Also, the recent trends are larger than the GMSL trend in northern Australia but similar to the GMSL trend in southern Australia.

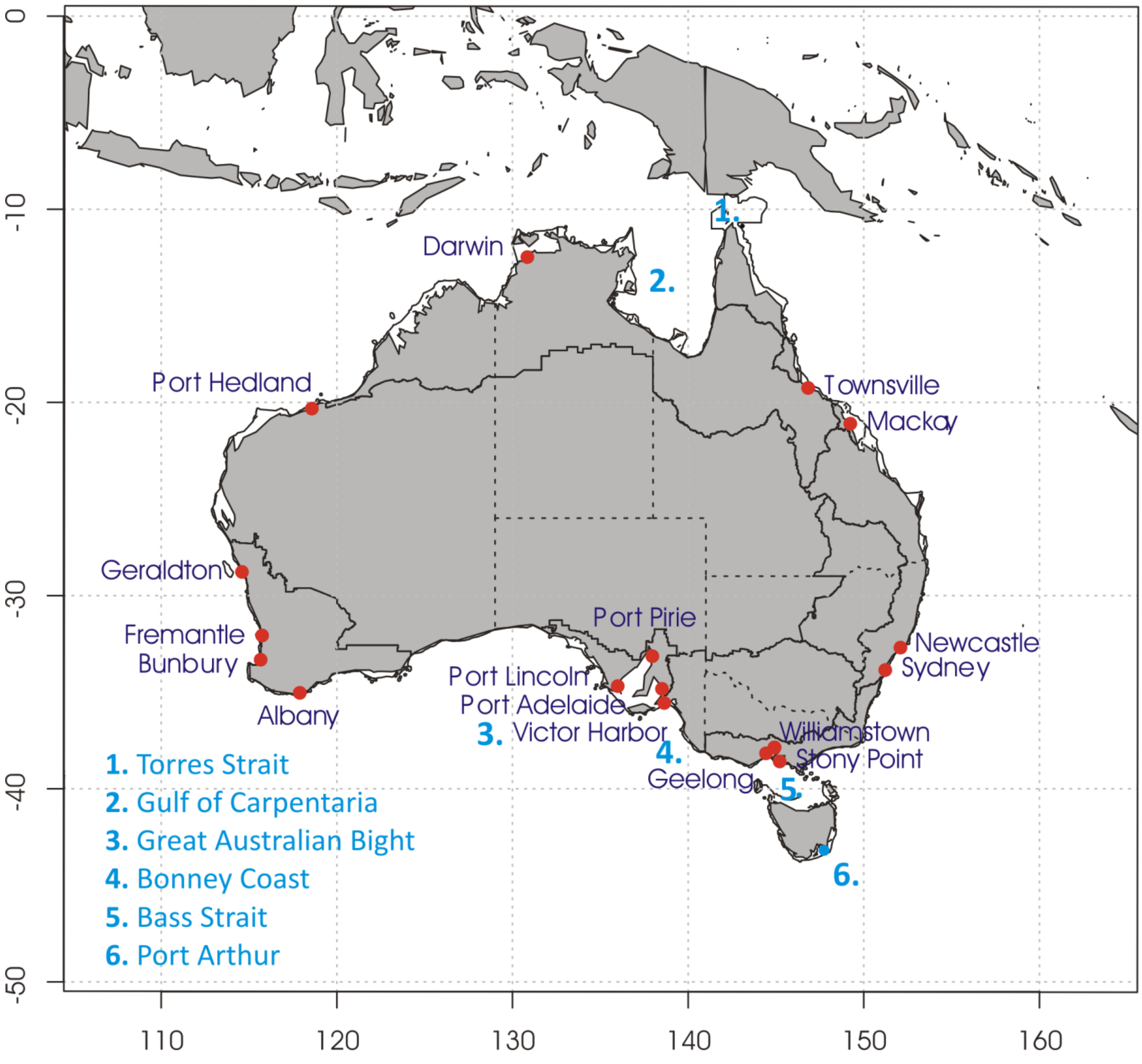
Sea-level Projections

Ocean thermal expansion and glaciers and ice caps are the main contributors to global mean sea-level change during the 20th century (Church et al., 2011b; Gregory et al., 2013; Moore et al., 2011) and are expected to be the major contributors during the 21st century (see below), with additional contributions from loss of mass from ice sheets, and changes in the mass of water stored on land.

Global Projections

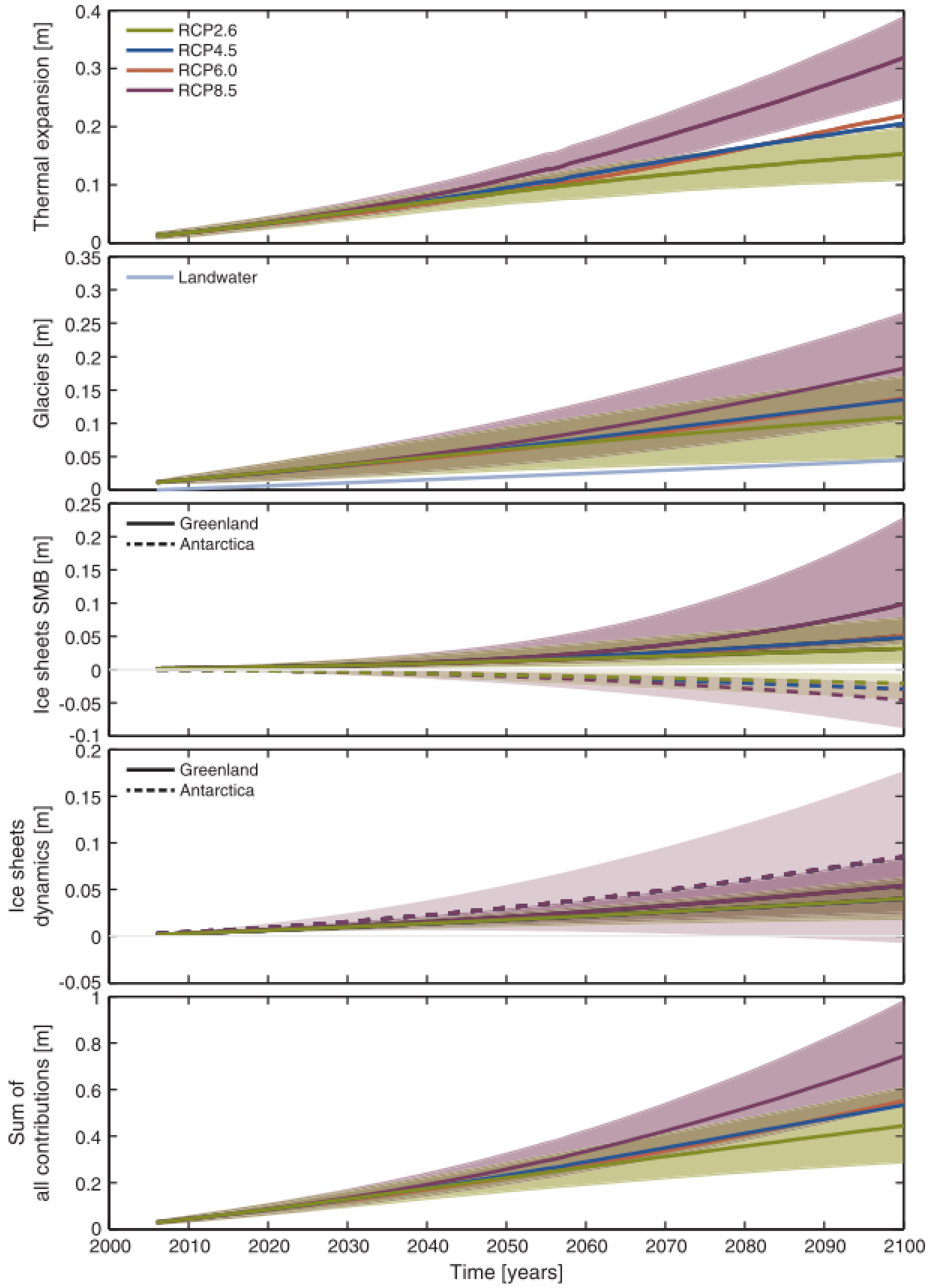
To estimate future sea-level changes, we combine projected contributions from changes in ocean density and circulation (available directly from available CMIP5 GCMs) (Figure 2) with contributions derived from purpose-built models designed to estimate additional sea-level contributions from the loss of mass from glaciers, the surface mass balance of the Greenland and Antarctic ice sheets and the dynamic response of the Greenland and Antarctic ice sheets and changes in land water storage (Church et al., 2013b). How these contributions and associated uncertainties are combined to form global mean sea level can be found in the supplementary materials of chapter 13 of the IPCC Fifth Assessment Report (Church et al., 2013b).

Figure 1 Map indicating the location of the tide gauges and locations referred to in the text. Also shown are the Natural Resource Management boundaries within Australia (solid lines) and state boundaries (dashed lines).



The contributions to global mean sea-level change for four different Representative Concentration Pathways (RCPs) of future greenhouse gas emissions are given in Figure 2. Projected global mean SLR by 2090 relative to 1986–2005 varies from 26–55 cm for the RCP 2.6 (strong mitigation scenario) to 45–82 cm for the RCP 8.5 (high emissions scenario), where the range for each scenario represents 90 percent of the model range. For RCP 8.5 and 6.0, the rate of GMSL rise increases throughout the 21st century, whereas for RCP 2.6 and 4.5, the rate of rise decreases after about 2030 and 2070, respectively. The IPCC AR5 assessed that the global mean sea-level change was *likely* to fall within the 5–95 percentile range of model results. However, because of uncertainties in climate sensitivity and other parameters, this model-based range is considered to only cover 66% of actual possibilities. A larger global mean SLR could occur prior to 2100 as a result of the marine ice sheet instability of the West Antarctic Ice Sheet (Church et al, 2013b; Rignot et al, 2014), but there is currently insufficient scientific evidence to assign a specific likelihood to values larger than the likely range defined above. Any additional contribution from the potential collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, was assessed to not exceed several tenths of a metre of SLR by 2100 (Church et al., 2013b). Recent observations (Rignot et al., 2014) indicate increased loss of ice from west Antarctica and recent modelling (Favier et al., 2014; Joughin et al., 2014) has been able to simulate the increased flow of individual West Antarctic Ice Sheet glaciers. Projections of mass loss in these studies are consistent with the Antarctic contribution used in the IPCC AR5 and here. Nevertheless, understanding of the relevant ocean-ice sheet processes (Alley and Joughin, 2012; Willis and Church, 2012) is still incomplete and the possibility of higher rates of SLR cannot be excluded.

Figure 2 Contributions to 21st century sea level rise (thick coloured lines) calculated using the results of individual climate models for all four emission scenarios. (a) Global-averaged ocean thermal expansion. (b) Glacier mass loss. (c) Changes in the surface mass balance of the Greenland and Antarctic ice sheets, (d) Ice sheet dynamical contributions (e) the sum of all contributions. For the RCP 8.5 and RCP 2.6 scenarios the multi-model mean values with 5 to 95% model ranges (shaded areas) are shown but for RCP 6.0 and RCP 4.5 scenarios, only the multi-model mean values are shown.



Sea-level Projections for Australia

To determine the regional changes in sea level around the Australian coastline, we combine the global mean change with the dynamic ocean sea-level distribution (changes in sea level from ocean-circulation changes), regional changes associated with contemporary changes in mass of glaciers and ice sheets and the gravitational response in the ocean, and an ongoing GIA from the visco-elastic response of the Earth to the redistribution of ice-sheet mass since the last glacial maximum (Church et al., 2011a, 2013b; Slangen et al., 2012; 2014b).

Each of the components associated with a change in mass implies changes in the Earth's gravitational field and vertical movement of the crust (sea-level fingerprints). The resulting 'fingerprints' of sea-level change consist of a larger than global average rise far from the regions of mass loss and a sea-level fall in the immediate vicinity of the regions of mass loss. These projections use the fingerprints calculated by Mitrovica et al., (2011), based on the loss of mass during the latter half of the 20th century, as estimated by Cogley, (2009b). While the 21st century pattern of glacier mass loss may differ from that assumed by Mitrovica et al. (2011), the resultant changes in the Australian region are likely to be small. The Greenland fingerprint around the Australian coastline is insensitive to details of the exact location of mass loss from the Greenland Ice Sheet. With regard to Antarctica, we assume that the mass gain from increased accumulation of snow is assumed to be uniformly distributed over the continent whereas the dynamic loss is expected to be from the West Antarctic Ice Sheet. The projected small changes in the mass of water stored on land in reservoirs and aquifers are here assumed to result in a uniform change in sea level around the globe.

Note the regional projections included here are slightly different to those in Church et al. (2013b). Here, the projections are low passed filtered (by averaging 20 years of results) to focus on the climate change signal. We also use a different model for estimating the GIA: we use results from the pseudo-spectral algorithm of Kendall et al., (2005) which takes into account time-varying shorelines, changes in the geometry of grounded marine-based ice, and the feedback into sea level of Earth's rotation changes, and the ice-load history is from the ICE-5G model (Peltier, 2004). We have not included the impact of projected changes in atmospheric pressure, likely to have an impact at about the 1-cm level over Australia. These and other minor differences in the way regional sea levels are computed likely result in only trivial differences in the projections.

The regional distribution of relative SLR for projections at 2090 relative to the period 1986 to 2005 for each of the four scenarios is shown in Figure 3. The amount of regional SLR is largest for the RCP 8.5 scenario and smallest for the RCP 2.6 scenario, with RCP 4.5 and 6.0 being of intermediate magnitude. On the larger scale, climate models simulations (Hall and Visbeck, 2002; Sen Gupta and England, 2006) indicate a robust southward shift of the Antarctic Circumpolar Current (ACC) associated with an intensification of the circumpolar circulation (Wang and Cai, 2013). This change is reflected in high sea-level anomalies north of the axis of the ACC, with low anomalies to the south (Figure 3). Strengthening of the subtropical gyre circulation of the South Pacific Ocean is projected to lead to a larger rise off the south-eastern Australian coastline, as shown by Zhang et al., (2013) for CMIP3 simulations. This pattern intensifies with higher emissions. However the current low-resolution models may not adequately represent how these higher offshore sea levels are expressed at the coast. Present indications are that intensification of the East Australian Current (EAC) at least partially prevents these larger offshore anomalies from reaching the coast. The GIA readjustment leads to lower rise along the Australian coastline compared to offshore. For RCP 8.5 by 2090, the difference in magnitude between on- and offshore GIA-induced rise is a few centimetres, reaching about 10 centimetres in the Gulf of Carpentaria.

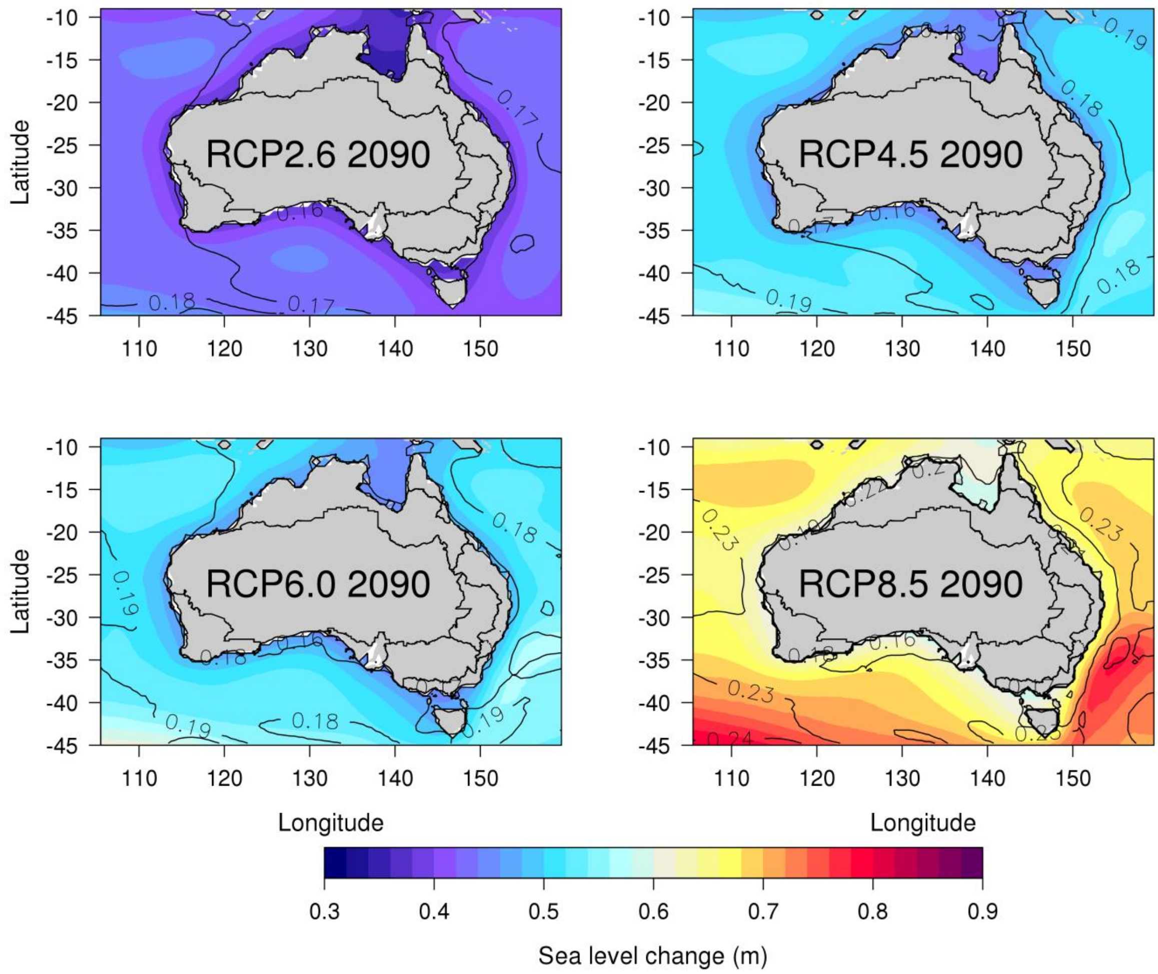
Sea-level projections for the Australian coastline (Table 1, Figure 4) are similar to the GMSL projections. This is a balance between the fingerprint patterns which result in a larger than global-averaged rise far from the regions of glacier and ice sheet mass loss offset by the GIA signal that led to a smaller than global-averaged SLR around Australia during the 20th century. The global and regional projections are almost independent of the RCP chosen (Table 1, Figures 2 and 4) for the first decades of the 21st century, but they begin to differ significantly from about 2050. Significant interannual variability of monthly sea levels (as seen in the observations) has been effectively removed in forming the ensemble-average projections and the low-pass filtering. However, the interannual variability will likely continue through the 21st century and beyond. An indication of its magnitude is given by the dashed lines plotted above the top and below the bottom of the projections in Figure 4, indicating the 5 to 95 percent uncertainty range of the detrended historical records.

The projected rates of regional rise (Figure 5) increase from the current GMSL value of just over 3 mm yr^{-1}. For RCP8.5, the rates increase steadily, reaching almost 12 mm yr^{-1} by 2100 at all locations. For the intermediate scenarios of RCP6 and RCP 4.5, the rates stabilise in about 2090 and 2060 at about 7-8 and 6 mm yr^{-1}, respectively. For the strong mitigation scenario, the rate of rise stabilises much earlier than the other scenarios and then reduces slightly to about 4 mm yr^{-1}.

Evaluation of the regional projections

There has been considerable progress in understanding the 20th century global-averaged SLR including an increase in the skill of sea-level models (Church et al., 2013a; Slangen et al., 2014a). However, regional projections have only recently been developed (Church et al., 2011a,b; 2013b; Slangen et al., 2012; 2014b) and require a combination of several different component models to produce results across the globe. Even though the component models have been evaluated individually, there has not yet been a thorough evaluation of the ability of the combination of these models to project future regional sea-level change. As a step towards such an evaluation, we compare regional results for 16 locations identified in Figure 4 and listed in Table 1 with observations from both tide gauges and altimeters (Figure 6).

Figure 3 The regional distributions of sea level change (four emissions scenarios) for the period centred on 2090 compared to 1986 to 2005. The projections (shadings) and uncertainties (solid lines) represent the contributions from the changes in terrestrial ice, the gravitational response of the ocean to these changes, and an ongoing GIA.

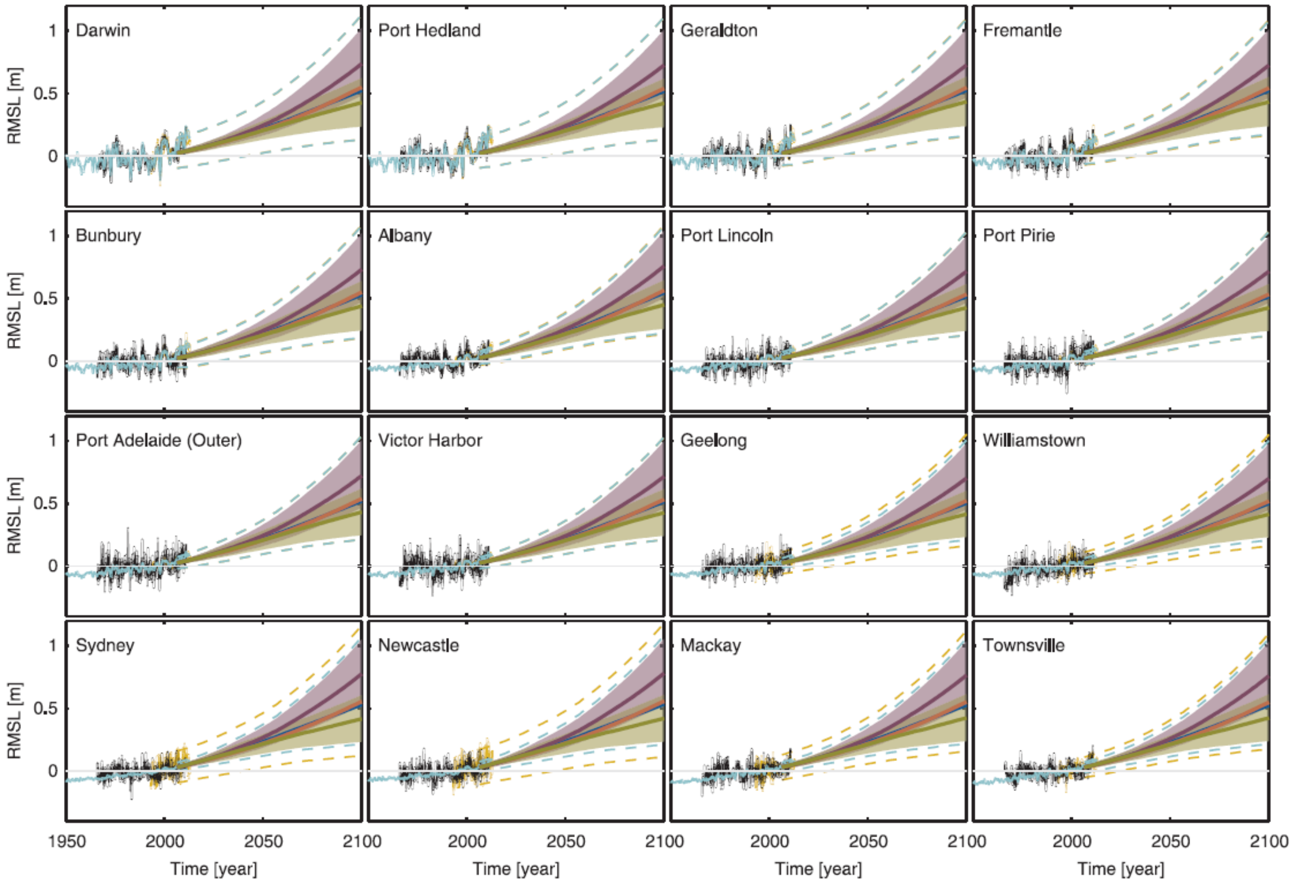


These regional projections represent the average results from a number of climate models. Interannual to decadal signals combine destructively in the multi-model averages since internal variability in individual model runs are unlikely to be synchronized across models. Also, the model averages have been low-pass filtered to reduce the natural variability to focus on the climate change signal. Therefore, the projections from 1996 (Figure 4 and 6) comprise smooth trends with a slight upward curvature (a small acceleration). An indication of the expected magnitude of the natural variability (estimated to cover 90% of the observations using 1.65 standard deviations of the sea-level data from the historical tide-gauge records over 1966 to 2010) is indicated by the dotted lines above and below the projections in Figure 6. This range is larger on the north and west coasts and on broader shelves and smaller in the east and south coasts and on narrow shelves. For all locations, the model-based SLR is consistent with the observed sea-level records allowing for natural variability. We have computed trends for the observed and projected SLR. However, the observed trends are sensitive to the exact start and end dates because of the large decadal variability and the short period available for a direct comparison. In general, the observed trends are larger than the projected trends on the north and west coasts of Australia, and generally similar to the projected trends elsewhere. This may reflect the impact of decadal scale variability such as the transition from a positive (higher sea level in Eastern Pacific) to a negative phase (higher sea level in Western Pacific) of the Pacific Decadal Oscillation (Zhang and Church, 2012). A more rigorous comparison of the model projections will require longer comparison periods, improved understanding of decadal and interannual variability and of the future prediction of interannual and decadal variability.

Table 1 Median values and the 5-95% model range of projected regional sea level rise and allowances for 2050 and 2090 relative to 1986 to 2005 under RCP emission scenarios 2.6, 4.5 and 8.5 for selected locations along the Australian coastline.

Stations	*Scenarios*	*2050*		*2090*	
		Sea Level Rise (m)	Allowance (m)	Sea Level Rise (m)	Allowance (m)
Darwin	RCP2.6	0.21 (0.13-0.28)	0.21	0.38 (0.22-0.55)	0.43
	RCP4.5	0.22 (0.14-0.30)	0.23	0.46 (0.29-0.65)	0.52
	RCP8.5	0.25 (0.17-0.33)	0.26	0.62 (0.41-0.85)	0.71
Port Hedland	RCP2.6	0.20 (0.13-0.28)	0.21	0.38 (0.22-0.55)	0.43
	RCP4.5	0.22 (0.14-0.30)	0.23	0.46 (0.28-0.64)	0.52
	RCP8.5	0.24 (0.16-0.33)	0.26	0.61 (0.40-0.84)	0.70
Geraldton	RCP2.6	0.21 (0.13-0.29)	0.22	0.39 (0.22-0.56)	0.49
	RCP4.5	0.22 (0.14-0.30)	0.24	0.46 (0.28-0.65)	0.57
	RCP8.5	0.24 (0.16-0.33)	0.27	0.61 (0.40-0.85)	0.78
Fremantle	RCP2.6	0.21 (0.13-0.29)	0.22	0.39 (0.22-0.56)	0.47
	RCP4.5	0.22 (0.14-0.30)	0.24	0.46 (0.28-0.65)	0.56
	RCP8.5	0.24 (0.16-0.33)	0.26	0.61 (0.39-0.84)	0.76
Bunbury	RCP2.6	0.21 (0.13-0.29)	0.22	0.40 (0.23-0.57)	0.47
	RCP4.5	0.22 (0.14-0.30)	0.24	0.47 (0.29-0.65)	0.55
	RCP8.5	0.25 (0.16-0.34)	0.27	0.62 (0.40-0.85)	0.75
Albany	RCP2.6	0.22 (0.14-0.30)	0.24	0.41 (0.24-0.58)	0.50
	RCP4.5	0.23 (0.15-0.31)	0.25	0.48 (0.31-0.66)	0.59
	RCP8.5	0.26 (0.17-0.34)	0.28	0.64 (0.43-0.87)	0.81
Port Adelaide	RCP2.6	0.21 (0.13-0.29)	0.24	0.39 (0.23-0.55)	0.50
	RCP4.5	0.22 (0.14-0.30)	0.25	0.46 (0.29-0.63)	0.59
	RCP8.5	0.25 (0.16-0.33)	0.28	0.61 (0.40-0.84)	0.81
Victor Harbor	RCP2.6	0.21 (0.13-0.28)	0.21	0.38 (0.23-0.55)	0.43
	RCP4.5	0.22 (0.14-0.30)	0.22	0.45 (0.28-0.63)	0.50
	RCP8.5	0.24 (0.16-0.33)	0.25	0.60 (0.39-0.83)	0.69
Stony Point	RCP2.6	0.20 (0.12-0.28)	0.21	0.37 (0.22-0.53)	0.43
	RCP4.5	0.20 (0.12-0.28)	0.22	0.45 (0.27-0.63)	0.51
	RCP8.5	0.24 (0.15-0.32)	0.25	0.59 (0.38-0.81)	0.70
Sydney	RCP2.6	0.22 (0.14-0.29)	0.24	0.38 (0.22-0.54)	0.48
	RCP4.5	0.24 (0.16-0.31)	0.26	0.47 (0.30-0.65)	0.59
	RCP8.5	0.27 (0.19-0.36)	0.30	0.66 (0.45-0.88)	0.84
Newcastle	RCP2.6	0.22 (0.14-0.30)	0.24	0.38 (0.22-0.54)	0.49
	RCP4.5	0.24 (0.16-0.32)	0.26	0.47 (0.31-0.65)	0.60
	RCP8.5	0.27 (0.19-0.36)	0.30	0.66 (0.46-0.88)	0.86
Mackay	RCP2.6	0.21 (0.14-0.29)	0.22	0.38 (0.22-0.55)	0.43
	RCP4.5	0.23 (0.16-0.31)	0.24	0.47 (0.30-0.64)	0.53
	RCP8.5	0.26 (0.18-0.35)	0.28	0.64 (0.44-0.87)	0.73
Townsville	RCP2.6	0.21 (0.14-0.29)	0.23	0.38 (0.23-0.54)	0.44
	RCP4.5	0.23 (0.16-0.31)	0.24	0.47 (0.30-0.64)	0.53
	RCP8.5	0.26 (0.18-0.34)	0.28	0.64 (0.44-0.86)	0.74

Figure 4 Observed and projected relative sea level change in metres for the 16 locations in Figure 1. The observed sea level records are indicated in black, with the satellite record (since 1993) in mustard and tide gauge reconstruction (which has lower variability) in cyan. Multi-model mean projections (thick purple and olive lines) for the RCP8.5 and RCP2.6 emissions scenarios with likely model ranges are shown by the purple and olive shaded regions from 2006 to 2100. The olive dashed lines represent estimates of interannual variability combined with the range of the projections. Thick dark blue and orange lines represent multi-model mean projections for the RCP 4.5 and 6.0 scenarios, respectively.



Limitations of the regional projections

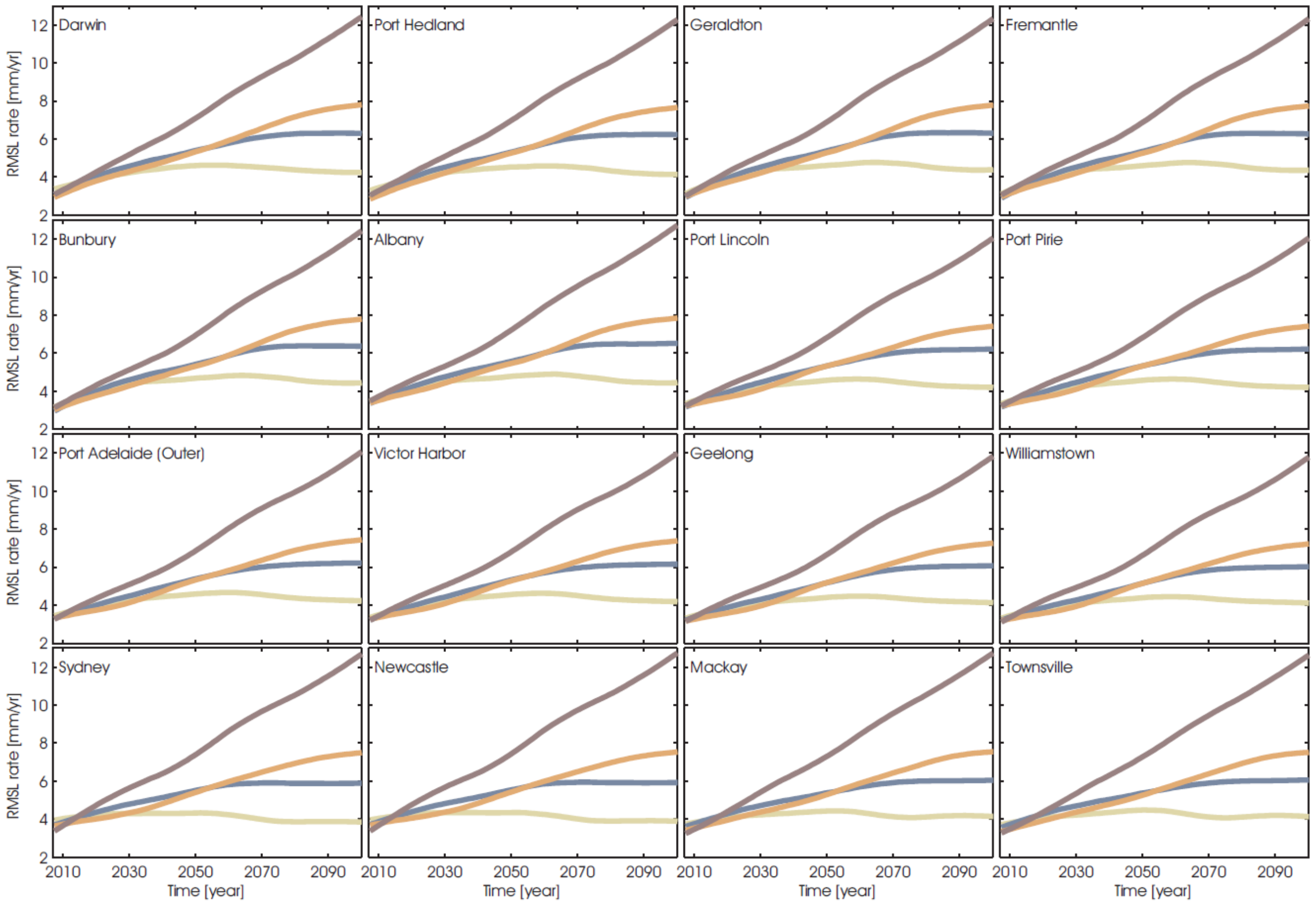
The current generation of global climate models have horizontal resolutions of the order of 1° and therefore do not fully resolve the details of ocean currents such as the East Australian Current and its eddies and the representation of deep-ocean/continental shelf interactions. As a result, the coastal response of sea level to climate change contains uncertainties in addition to those associated with the atmospheric/climate response. These additional uncertainties are not expected to change the large-scale results qualitatively, but may result in slightly higher or lower sea levels than projected here.

At the regional scale, compaction of sediments in deltaic regions and land reclaimed from the sea, subsidence exacerbated by ground water extraction, and changes in sediment supply to the coast as rivers become more managed could increase the relative SLR and coastal erosion at some locations. Examples of this effect in Australia include Hillarys in Western Australia and Port Adelaide in South Australia. These local geological effects could lead to significant local departures from the projected sea-level changes. Also, we do not consider processes such as fluvial and wave erosion and sediment transport that also affect coastal accretion/erosion.

Beyond 2100

At the end of the 21st century, global and regional sea level is projected to continue rising in all scenarios (Figures 2, 4 and 5), with the rate in the high emission RCP8.5 scenario equivalent to the average rate experienced during the deglaciation of the Earth following the last glacial maximum, and much larger than the late 20th century rate. In contrast, the projected rate for RCP2.6 is only marginally larger than the late 20th century rate and slowly declines thereafter (Figure 5). Global mean (Church et al. 2013b) and Australian sea levels are projected to increase beyond 2100, with thermal expansion contributions (proportional to the degree of warming) continuing for many centuries. In contrast, mountain glacier contributions per degree of warming show a tendency to slow as the amount of glacier ice available to melt decreases. Mass loss from the Greenland ice sheet is projected to continue if global average temperatures cross a threshold estimated to be between 1° and 4°C, leading to about a 7 m rise over millennia (Church et al. 2013b). This threshold could be crossed during the 21st Century, depending on the emissions pathway chosen by society. It is not yet possible to quantify the timing or amount of a multi-century contribution from the dynamic response of the Antarctic ice sheet to future ocean and atmosphere warming and thus the above long-term rates may be underestimated. Longer term SLR will also depend on future emissions (Church et al. 2013b).

Figure 5 The central values of the projected rates of relative SLR for 2005 to 2100 in mm yr^{-1} for the 16 locations in Figure 4. Thick olive, blue, orange and purple lines represent multi-model mean projections for RCPs 2.6, 4.5, 6.0 and 8.5, respectively.



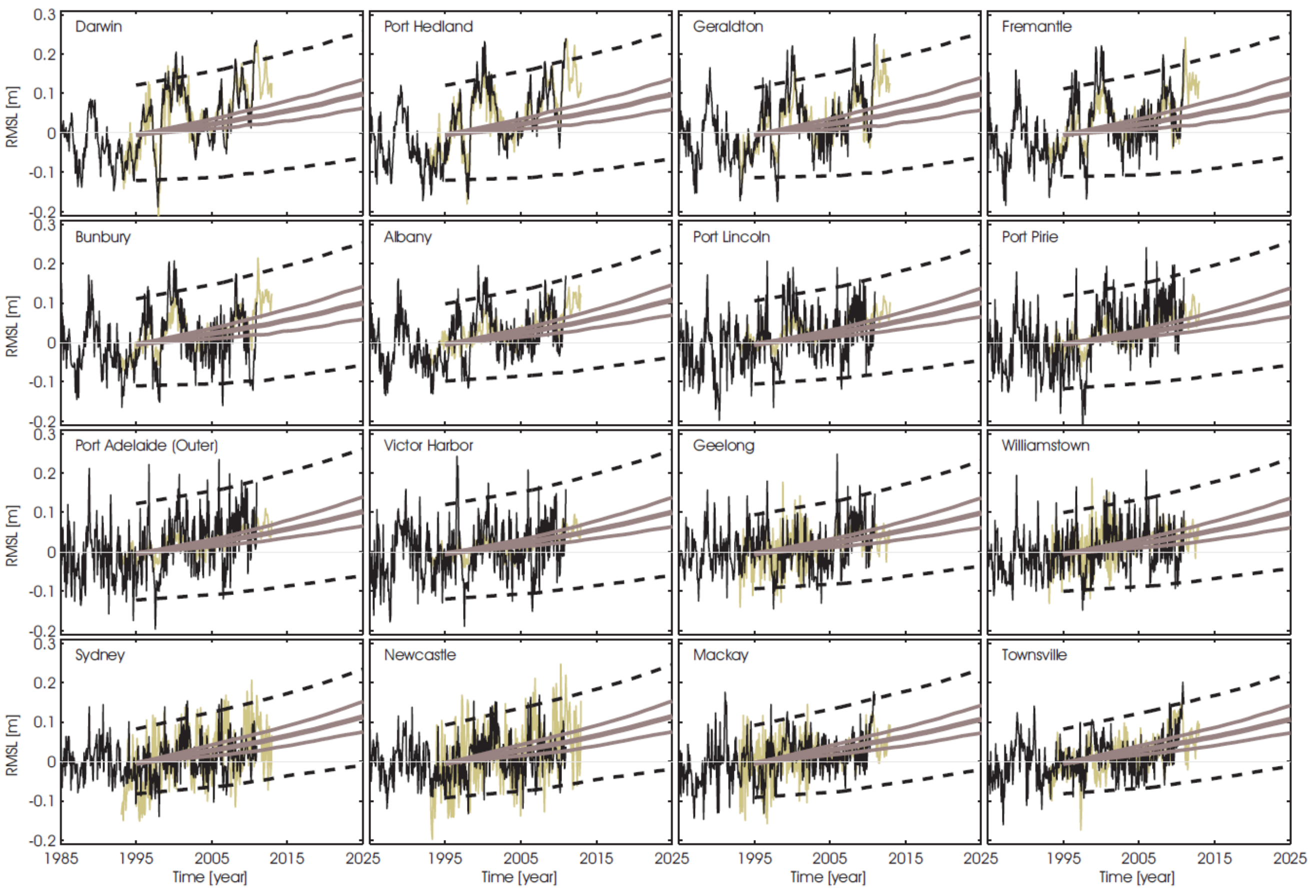
Extreme Sea Levels

Extreme coastal sea levels are caused by several factors including astronomical tides, storm surges and wind waves. It will be during these periods of sea level extremes that the effects of mean SLR will be felt most acutely. Climate change can affect sea level extremes through a change in mean sea level (i.e. with mean SLR, a lower storm surge at high tide would be sufficient to produce a sea level high enough to cause flooding) and through changes in the storms that cause storm surges. This section reviews the causes of extreme sea levels around Australia and how these may change in the future due to weather and circulation changes. It then describes a method by which sea level projections together with information on extreme sea levels can be used to derive an allowance to guide adaptation to future SLR.

Extreme Sea Levels in Australia

Storm surges arise from the passage of weather systems and their associated strong surface winds and falling atmospheric pressure. The term storm tide refers to the combination of storm surge and astronomical tides. Wave breaking in the surf zone can further increase coastal sea levels through wave setup; the temporary elevation in sea levels due to the cumulative effect of wave breaking, and wave runup; the maximum elevation up the shore that is reached by an individual breaking wave. In general, storm surges tend to be higher in coastal regions with relatively wide and shallow continental shelves which, in Australia, includes the tropics, Bass Strait and the Great Australian Bight (Figure 1). This is illustrated by the results from Haigh et al., (2014) (Figure 7) which shows the 1-in-100 year storm tide heights evaluated from a hydrodynamic model hindcast over the period 1949 to 2009. The heights vary around the coastline due to variations in the tidal range, the prevailing meteorology of the region and coastline features such as shelf width and coastal orientation in relation to prevailing meteorology (the 150 m isobath is also shown in Figure 7 to indicate the continental shelf width). The highest storm tides occur on the northwest shelf due to the amplification of tides and surges over the wide shelf region. Lower storm tides occur on southwest and southeast coastlines and the Bonney coast (Figure 1) due to the narrower continental shelf and smaller tidal range. In these narrow shelf margins, higher wave energy reaches the coast.

Figure 6 Observed and projected relative sea level change in meters for 1965 to 2015 for the 16 locations in Figure 4. The observed sea level records are indicated in black, with the satellite record (since 1993) in mustard. Multi-model mean projections (thick purple) for the RCP8.5 and RCP2.6 emissions scenarios with model ranges are shown by the thin purple lines.

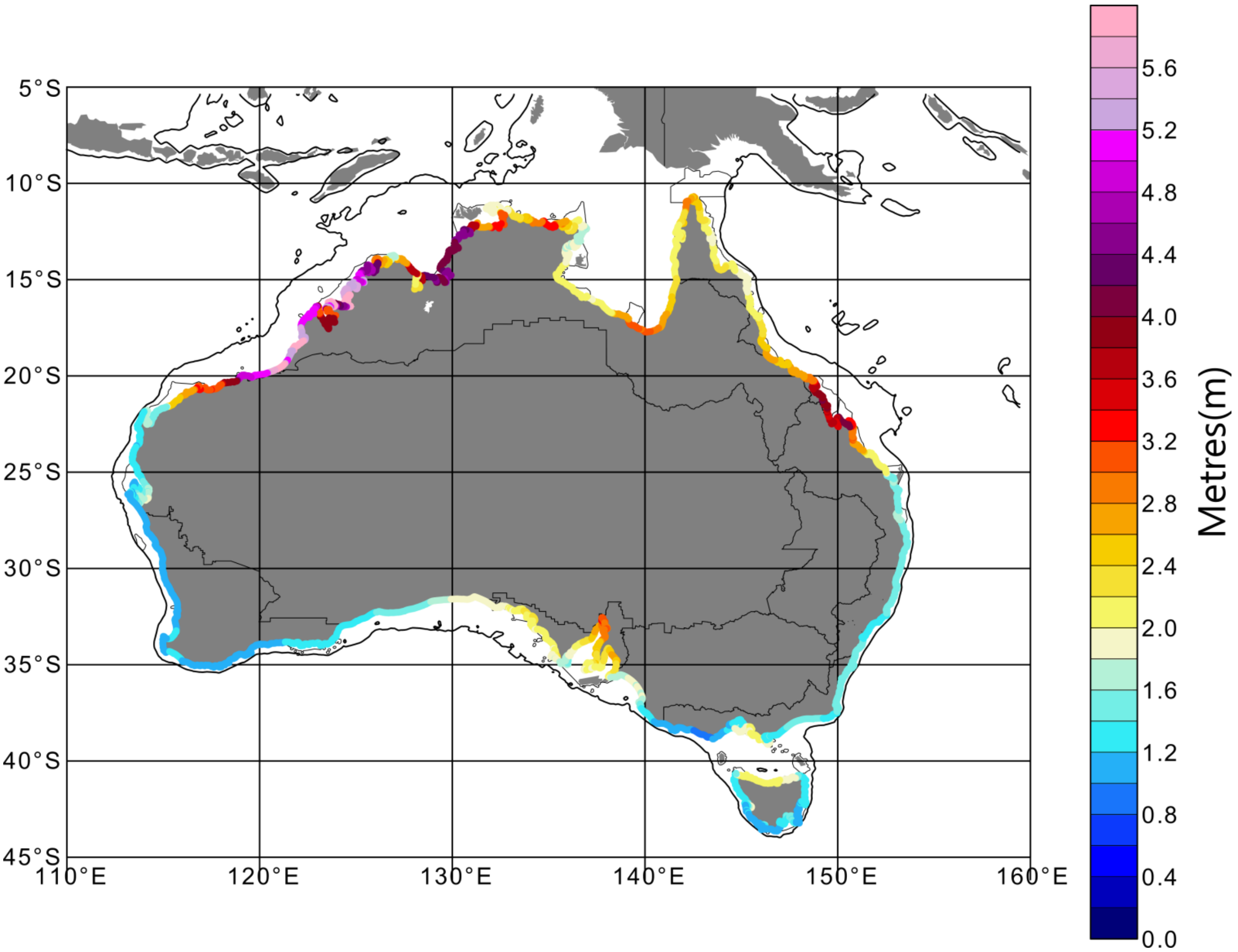


Different weather systems also influence storm surges. In Australia's north, tropical cyclones pose the most significant storm surge threat. Harper (1999) documents the occurrence of around 70 known instances of tropical cyclone-related storm tide events along the Queensland coast dating from as early as 1884. In the Gulf of Carpentaria the northwest monsoon during the austral summer months causes high sea levels (Oliver and Thompson, 2011), which can be significantly enhanced when cyclones occur (Smith et al., 2013). The Torres Strait Islands also experience storm tides during the northwest monsoon during austral summer and due to periods of strong sustained south-easterlies during the austral winter months (Green et al., 2010).

Storm surges experienced along the southwest WA coastline are caused primarily by easterly or northeasterly travelling extratropical storms or cyclones of tropical origin (Haigh et al., 2010). They are typically less than 1 m in height but since the tidal range in this region is also small (~0.5 m), they form a significant contribution to extreme sea level events (Haigh et al., 2010). Tropical cyclones have also been noted to generate coastally trapped waves (CTW) that propagate southwards around the WA coast (Hubbert et al., 1991; Pattiaratchi and Eliot, 2008).

Along the south coast of Australia, the majority of storm surges occur in conjunction with the passage of cold fronts, which occur year round but most frequently in the winter months (McInnes and Hubbert, 2003). Tide gauge observations reveal a highly coherent sea level signal along the south coast which is consistent with the propagation of CTWs, (e.g. Provis and Radok, 1979; Church and Freeland, 1987). Extreme sea levels on the east coast of Tasmania are highly correlated with those on the central and western Victorian coastline indicating that, similar to the mainland coast, elevated sea levels occur in conjunction with the passage of cold fronts. On the northern Tasmanian coast, elevated sea levels tend to occur when extratropical cyclones are located to the west of Bass Strait producing strong northerly winds over northern Tasmania (McInnes et al., 2012a). Although *storm surge* heights for a given return period are larger on the central to eastern Victorian and eastern Tasmanian coasts, *storm tide* heights for a given return period are larger on the central Victorian and northern Tasmanian coasts. This is due to the large tidal range in central Bass Strait (McInnes et al, 2009; 2012a; 2013).

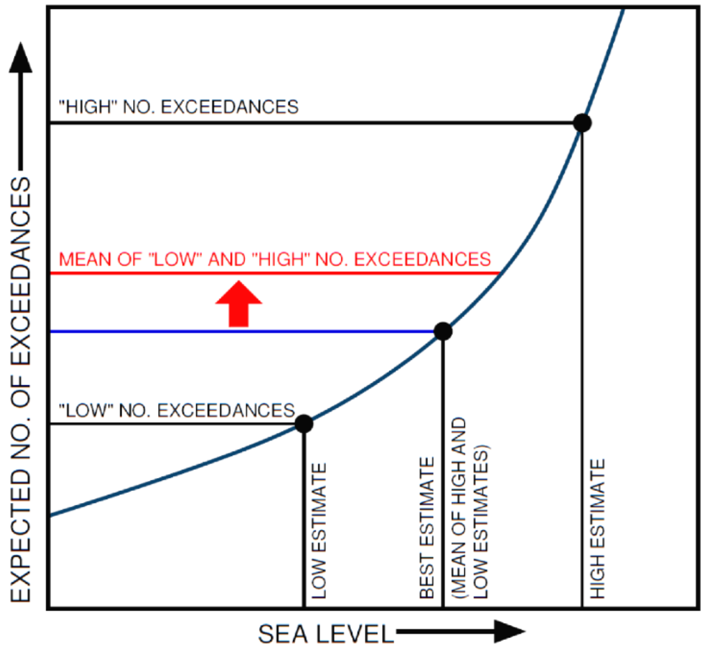
Figure 7 The 1-in-100 year storm tide height in metres (coloured dots) relative to mean sea level from the hydrodynamic modelling study of (Haigh et al., 2014). Also shown is the 150 m isobath. The return levels were estimated from modelled sea levels over the interval 1949 to 2009 by fitting a Gumbel distribution to the modelled annual maximum sea levels over the 61-year period.



Along Australia's east coast from New South Wales to Southeast Queensland a major cause of storm surges is East Coast Lows (McInnes and Hubbert, 2001). The coastline's exposure to high energy waves and swell means that wave setup and wave run-up are important contributing factors during these extreme sea level events (McInnes et al., 2012b).

Other factors such as ocean currents and climate variability can also contribute to variations in coastal sea levels on different timescales. For example, in the Gulf of Carpentaria, sea levels change by up to 1 m over a year, due to strong seasonal changes in wind associated with the monsoon over southeast Asia (see Figure 4 of Haigh et al., 2014). On the southwest WA coastline, the stronger southward flow of the Leeuwin Current in winter compared to summer leads to sea levels that are about 0.2 m higher at the coast due to current setup (Pattiarachi and Eliot, 2008). Over the East Coast region, warm and cool eddies from the East Australian Current can also contribute to local sea level changes of about 0.2 m (McInnes et al., 2012b). As discussed in section 2, ENSO can strongly influence background sea levels in northern Australia (White et al., 2014).

Figure 8 Curve showing the expected number of exceedances as a nonlinear function of sea level. The blue line shows the expected number of exceedances based on the best estimate of sea-level rise. The red line shows the mean of the expected number of exceedances based on "low" and "high" estimates of sea-level rise. The red arrow shows the increase in the expected number of exceedances caused by uncertainty.



Projected Changes to Extreme Sea Levels

Extreme sea levels may also change in the future due to changes in meteorological forcing. Colberg and McInnes (2012) used a hydrodynamic model forced by four different climate model simulations to generate sea levels along the coastline of southern Australia and Tasmania over the periods 2080 to 2099 and 1980 to 1999. Changes to annual maximum sea levels between the two periods were found to be small, amounting to a few centimetres at most (typically at least an order of magnitude smaller than the projected SLR for that scenario) and mostly negative (i.e. leading to a reduction in storm tides) along the south coast with small increases occurring in eastern Bass Strait and parts of Tasmania, mostly in winter and spring. The changes were consistent with the southward movement of the subtropical ridge (STR, Kent et al., 2013) bringing weaker winds to the southern mainland coast but stronger winds and higher variability over Tasmania.

An additional consequence of the projected southward movement of the STR is a projected decrease in wave heights and changes in the wave climate on the NSW coast (Hemer et al., 2013a,b; Dowdy et al., 2014). O'Grady et al. (2015) has shown that the change in both wind-driven currents and waves in south-eastern Australia may lead to complex seasonal changes in longshore sediment transport with subsequent impacts on the near shore region.

The change to storm tides arising from a projected increase of cyclone intensity has been investigated along the Queensland east coast using synthetic cyclone modelling approaches. Results reported in Harper et al. (2009) showed that a 10% increase in tropical cyclone intensity produced only a small increase in the 1-in-100 year storm tide, but a larger increase in 1-in-1000 year storm tides.

In summary, although future changes in weather conditions may also contribute to changes in future extreme sea levels, only a few hydrodynamic downscaling studies have investigated such changes for selected regions. In general, studies undertaken so far suggest that the influence of climate change on the storm tide levels typically considered for planning purposes (e.g. 1-in-100 year levels) may be smaller than the projected MSL change and therefore not included in the first order projections reported here. However, changes to coastal currents and waves may also affect littoral transport and shoreline response, but few studies to date have investigated these aspects.

Method for calculating SLR Allowances

A challenge in planning for SLR is dealing with the uncertainty in the SLR projections. This challenge has been addressed by 'vulnerability-based' approaches that consider the critical thresholds for SLR, which if exceeded would seriously compromise the assets and values being protected (IPCC, 2012). However, where SLR planning benchmarks have been developed for a particular future time period, the practice has often been to select a single and often precautionary value, informed by the high-end of the range of projected SLR (e.g. Department of Environment, 2010; Victorian Coastal Council, 2014).

Hunter (2012) proposed an objective method to derive an allowance, A, from a projected range of future sea levels to provide guidance for adaptation planning. This allowance is the vertical distance that current assets, or their protective measures (e.g. levees), would need to be raised so that the protection they provide in the future remains the same as the present. The allowance is independent of the current level of protection. For example, present day protection may be set at the 1-in-10 or the 1-in-1000 year (or more) level depending on the criticality of the assets being protected. The formula for A is given by

$$A = \Delta z + \sigma^2/2\lambda \tag{1}$$

where Δz is the mean sea level rise projection for a given scenario and future time period, σ is the standard deviation of the SLR projection uncertainty assuming a normal distribution and λ is the Gumbel scale parameter that describes the behaviour of extreme sea levels at the location of interest (Hunter et al., 2013). Here we provide a qualitative interpretation of the role of σ^2 and λ on the allowance. For completeness a summary of the mathematical derivation is given in the Appendix.

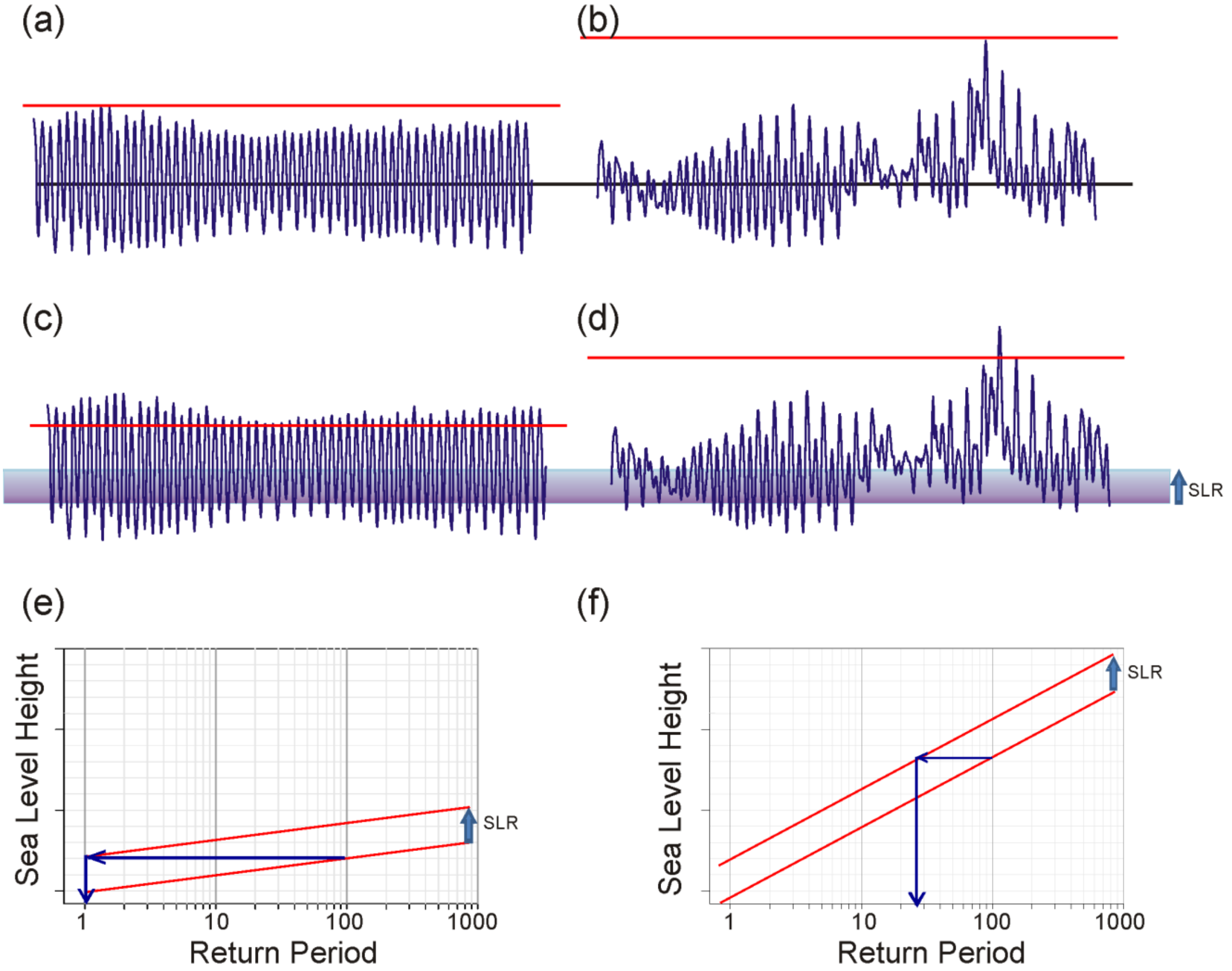
The larger the uncertainty (σ) associated with projected SLR, the larger A becomes. The relationship between σ and A can be understood by considering the non-linear relationship between the expected number of exceedances in a given time period and sea level (Figure 8). Every 10 cm rise in sea level does not increase the number of exceedances by the same amount. For example, the increase in the number of exceedances for a future 60 cm sea-level rise compared to 50 cm is larger than the decrease in the number of exceedances for a 40 cm sea-level rise compared to 50 cm. Therefore, taking a best estimate or average projected sea-level rise does not give the overall expected number of exceedances. A more appropriate way is to take the average of the expected number of exceedances for the high and low estimates of sea-level rise, which gives a value higher than the number of exceedances for the average value of sea-level rise. This is the essence of the allowance, which is larger than the best estimate of sea level rise by an amount which depends on the uncertainty (illustrated by the "high" and "low" estimates of sea level in Figure 8), and on the Gumbel scale parameter (λ), which determines the curvature of the line shown in Figure 8.

The Gumbel scale parameter λ represents the slope of the return period curve and relates to the variability of the extremes. The inverse relationship between A and λ in Equation (1) indicates that the steeper the slope of the return period curve, the smaller the value of A. The relationship between extreme sea levels and λ is illustrated in Figure 9a for a location that experiences weak modulation in tides and small storm surges, and hence little variability in extreme sea levels. The horizontal line represents a benchmark set to protect the location against all but the most extreme sea levels. Figure 9b represents a location that experiences large tidal modulation and/or large storm surges and accordingly a higher benchmark to afford protection against extreme sea levels. If the same SLR is applied to both locations, (Figures 9c and d respectively), the present day benchmarks will be exceeded more frequently and the number of exceedances will be greater at the location represented in Figure 9c compared to 9d. Therefore a larger value of A will be needed at the location represented by 9c to retain the current likelihood of exceedance. The return period curves for both locations are shown in Figures 9e and f respectively where it can be seen that the effect of a uniform rise in sea levels at both locations is to shorten the interval between extreme events more markedly for the situation shown in 9e than 9f.

Results

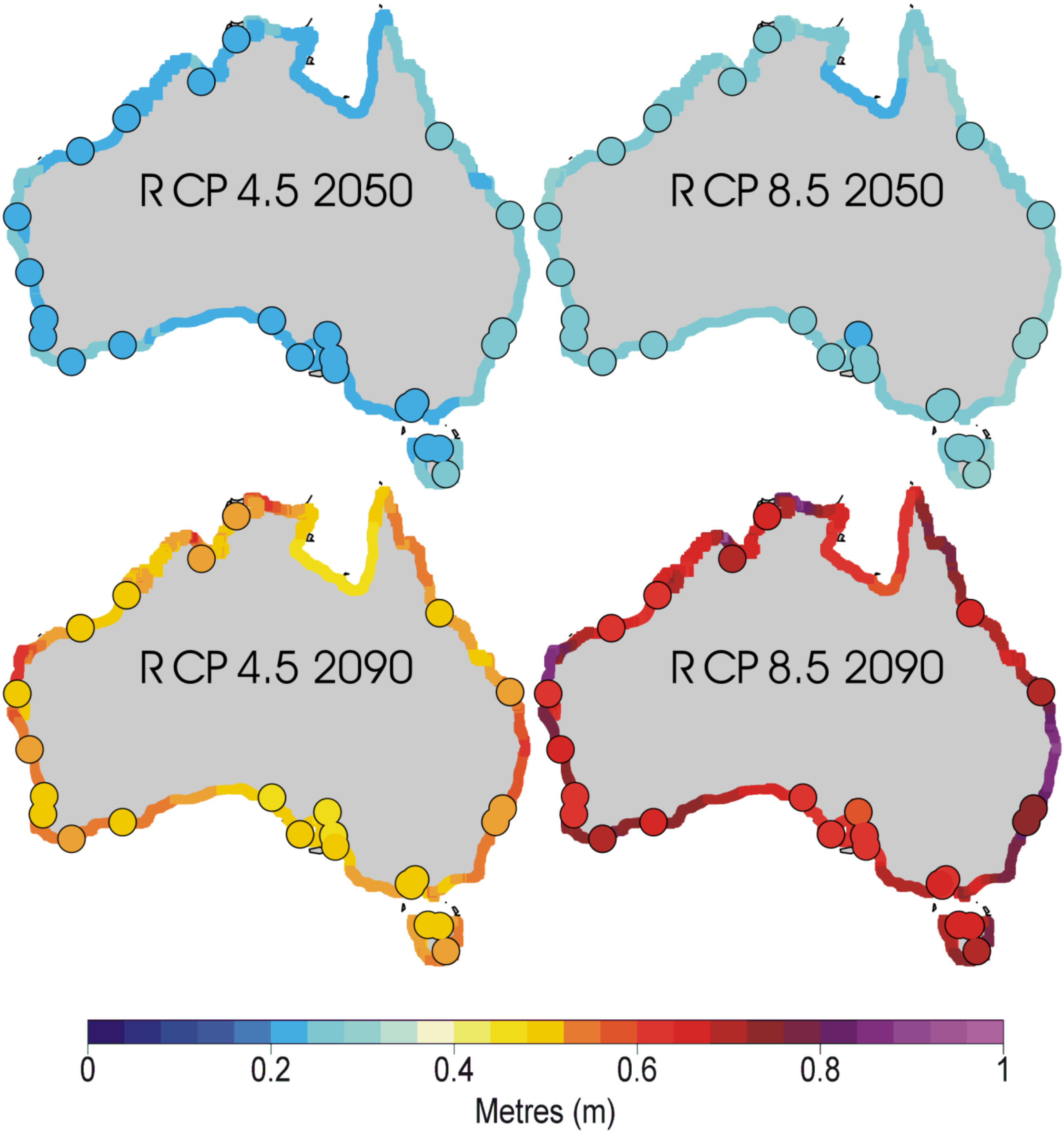
The allowances are calculated using the regional SLR projections presented in section 3.2 and the scale parameters generated by Haigh et al., (2014). For comparison, allowances calculated on the basis of scale parameters fitted to tide gauge data, as described in Hunter (2012), are also calculated. Values for 2050 and 2090 (relative to 1986 to 2005) under RCPs 2.6, 4.5 and 8.5 are shown in Figure 10. Allowances from the model-derived scale parameters of Haigh et al., (2014) are generally in good agreement with those based on Hunter (2012) although they tend to be slightly higher than those from the tide gauge. This is because the model underestimates the variability on some sections of coastline, such as along the southwest coastline from Geraldton to Esperance and the east coast from Sydney to Bundaberg. These are two stretches of coastline where wave effects are likely to also be important. The modelling study of Haigh et al., (2014) did not include the effects of waves (and therefore wave setup) and this may account for the larger differences between model-derived and observation-derived allowances in these locations. However, it should also be noted that tide gauges will generally not capture the full effect of waves either due to their typical situation within sheltered harbours where wave setup is considerably lower than on the adjacent exposed coastlines (e.g. McInnes et al., 2012b, Hoeke et al., 2013).

Figure 9 Diagram illustrating the relationship between variability in extremes and scale parameter. Example of water level variations for a location that (a) experiences weak modulation in tides and small storm surges (small scale parameter) and (b) large tidal modulation and/or large storm surges (large scale parameter). Red horizontal lines illustrate extreme sea level benchmarks predicated on the extremes that occur in both of these situations. (c) and (d) show the situation under a uniform sea level rise. The number of exceedances of the original planning benchmark is greater in (c) with the smaller scale parameter than (d). (e) and (f) show the respective slopes on a return period curve indicating that sea level rise will shorten the period of time between exceedances in the small scale parameter case (e) by a significantly larger amount than in the large scale parameter case (f).



Selected allowance values around Australia are also provided in Table 1. These allowances show that when the uncertainty on SLR projections is small, as is the case for 2030, the allowances are close to the median SLR scenario. For example, for both Townsville and Albany the allowances for RCP 4.5 are calculated to be 0.13 m, the same as the median SLR scenarios in these locations (Table 1). However as the uncertainty becomes larger, as is the case for 2090, the allowances become larger and tend to lie between the median and 95th percentile SLR projection. For Townsville and Albany under RCP 8.5, the allowances become 0.74 and 0.81 m respectively, which are close in value to the upper end of the range of projected SLR for these locations of 0.86 and 0.87 m respectively. The relatively higher allowance at Albany compared to Townsville is because of the dependence on the behaviour of extreme sea levels, characterised by the steepness of the extreme sea level return period curves. In areas that do not experience large variability in sea level extremes, a given SLR will more dramatically increase the frequency of extreme sea levels occurring, than a location with a greater variability in extreme sea levels as discussed in relation to Figure 9. Sea level extremes in Albany are less variable than those in Townsville leading to a higher sea level allowance for Albany compared to Townsville.

Figure 10 Allowances for future periods (2050 and 2090) representing the vertical distance that an asset needs to be raised under a rising sea level so that the present likelihood of flooding does not increase. Allowances are calculated for two emissions scenarios (RCP 4.5 and 8.5) using the sea level rise projections presented in this paper. Small circles indicated values based on the model results of Haigh et al. (2014) while the large circles represent values based on tide gauge data reported in Hunter (2012).



Implications for Planning

Here we discuss the sensitivity of the derived allowances to assumptions about SLR projection uncertainty and implications for their use in planning. Here, the 5 to 95 percentile model range is assumed to represent the 5 to 95 percentile uncertainty range in projected SLR and the allowances calculated on that basis. This contrasts with the IPCC AR5 where the reported 5 to 95 percentile model-based range of SLR projections is considered to cover only 66 per cent of the full uncertainty in future SLR (Church et al., 2013b). In IPCC terminology this is referred to as the *likely* range. The effect on allowances of interpreting the modelled SLR range as representing only 17-83 percent of the total SLR uncertainty would to lead to allowances that are larger than reported here. For example, for RCP 8.5 they would become around 0.4 m larger. The most appropriate interpretation of the uncertainty of projected SLR for allowance calculations requires further analysis but it is clear that greater uncertainty and hence allowances would lead to greater challenges in planning for future sea level rise.

From an adaptation perspective, the large inherent uncertainties in projections of longer term SLR means that flexible approaches to planning are desirable. The 'adaptation pathways' approach affords this flexibility by characterising different adaptation strategies in terms of adaptation tipping points (points in time beyond which existing strategies are not longer effective). The crossing of tipping points triggers the initiation of alternative strategies and is independent of when in time the point is crossed. This approach favours flexible and reversible options and the delay of decisions to maximise future options (see Wong et al., 2014 and references therein). Internationally, the Thames Estuary 2100 plan for the management of future flood threat for London adopts the adaptation pathways principles. These involve maintaining the system for the first 25 years then upgrading and enhancing (i.e. selectively raising) the existing system over the next 25 to 60 years. Beyond this time, the need for a new barrier or even barrage would be assessed. The adaptation pathways approach requires monitoring to determine if and when critical decision points are reached (Wong et al, 2014).

In Australia, the state of South Australia has used a staged approach to protection against SLR since 1991, which is still in operation at the present time. All local council development plans incorporate SLR in their planning schemes. Current provisions for SLR in development plans allow for 30 cm over 50 years, plus the capability of being protected against further SLR of 0.7 meters, using measures such as sea walls and setbacks (Walsh et al., 2004).

Although the calculation of an allowance may be a useful approach for adapting the built environment to SLR, its relevance for the natural environment is less clear. Natural coastal systems require the ability and space to migrate landward with SLR. Protection of coastal environments through the building of levees is neither likely to be economically viable, nor appropriate for the healthy functioning of ecosystems that require periodic wetting and drying and hence connectivity to natural sea level variations (e.g. saltmarsh and mangroves). However the allowance approach may inform the minimum amount of setback that will be required to enable the future landward migration of ecosystems.

Summary and Conclusions

The projections provided here build on progress in understanding and building projections of sea level change over the last decade as summarised in the IPCC AR5 (Church et al., 2013b) and recent studies attributing ocean thermal expansion (Slangen et al., 2014a) and glacier mass loss (Marzeion et al., 2014) to SLR due to anthropogenic factors. Despite this progress, the largest uncertainty remains in the contribution of the Antarctic Ice Sheet to future SLR and the possibility of higher rates of SLR cannot be excluded.

Regional projections of SLR depend on many factors. During the 20th century, Australian rates of relative SLR were below the estimated global average rise because of upward relative land motion from GIA. This process will continue during the 21st century but will become relatively less important as other contributions increase, particularly larger contributions from glaciers and ice sheets with a larger than global-averaged fingerprint in the Australian region. The net effect is that the projected relative SLR around Australia by 2100 is similar to the global average. Avoiding the larger rises associated with the higher emission scenarios and large sea-level commitments beyond 2100 requires significant and urgent mitigation of global greenhouse gas emissions.

Variability in sea level from decadal and interannual climate variability will continue into the future, resulting in times when the sea level and the rates of rise will be measurably above or below the global-averaged and regional sea-level projections presented here. Observed sea levels and rates of rise off north and west coasts of Australia are currently above the projections as a result of this variability. This variability will continue to confound short-term evaluation of regional climate change projections. However, estimates are that the climate change sea-level signal, compared to the average over 1986 to 2005, will begin to emerge from this natural variability by 2030 off the east coast of Australia and 2040 off the west coast (Lyu et al., 2014) stressing the urgency for future planning and risk management to take account of the combined impact of SLR and natural variability signals. Seasonal sea-level predictions (up to nine months in advance) (Miles et al., 2014; McIntosh et al., 2015) may be a useful tool in helping to manage these risks.

Any change in the El Nino Southern Oscillation or other modes of variability have the potential to impact Australian sea levels. However, the regional pattern of dynamic ocean sea-level change remains inadequately understood. Further studies of interannual and decadal variability, and detection and attribution studies of sea-level variability and change are a priority to address these issues.

It is important to note that SLR around Australia will continue beyond 2100 in all of the scenarios considered. For the RCP8.5 scenario, the rates of SLR by the end of the 21st Century, will likely be well above the 20th Century rate and approaching average rates (1 m/century for many millennia) experienced during the last deglaciation of the Earth from 20,000 to 6,000 years ago.

Under future climate conditions, extreme sea levels are expected to change due to increases in regional sea level and changes in climate and weather events. Studies that have investigated the effect of projected changes in weather events suggest that the influence of climate change on the storm tides may be smaller than the projected MSL change and so were not included here. Nevertheless, potentially larger storm surges occurring in the future should be considered.

In terms of planning for and adapting to future SLR, the expected number of exceedances of defined thresholds in a specific time period provides more relevant information than the overall exceedance probability. Based on this, allowances were calculated that provide estimates of the height that present benchmarks would need to be raised to ensure that the expected number of future exceedances remains unchanged from the number that occur in the present climate. Values vary around the Australian coast depending on the mean GMSL, its uncertainty and characteristics of tides and storm surges. These allowances show that for 2030, the current rate of sea level exceedances can be preserved by adopting a median SLR scenario but by 2090, a value higher than the median SLR projection will be necessary. However, only moderate confidence is given to the actual allowance values provided since their calculation has utilised modelled extreme sea level data, which contains uncertainties, and the allowances do not take into account possible changes in the behaviour of extreme sea levels in the future. Therefore the uncertainty associated with future SLR may be larger than expressed by the 5 to 95% confidence limits.

The greater uncertainty in sea level projections towards the end of the 21st Century compared to those for 2030 implies that flexible strategies are needed for adaptation. The 'adaptation pathways' approach affords this flexibility by characterising different adaptation strategies in terms of adaptation tipping points. This approach favours flexible and reversible options and keeping options open to maximise the benefit of future adaption strategies.

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Appendix

The likelihood of an extreme event occurring within a time period T, is usually described in terms of average recurrence intervals (R) (or return periods), which describe the average time interval, T, between events of a particular magnitude. The probability of there being no exceedances during the interval T is described by a cumulative distribution function, F, where $\mathrm{F} = 1 - \mathrm{E}$ and E is the probability of at least one exceedance event in the period T . These terms are related by

$$F = 1 - E = exp\left(\frac{-T}{R}\right) = exp(-N) \tag{A1}$$

where N is the expected number of exceedances during T and it is assumed that exceedance events are independent (i.e. follow a Poisson distribution).

Extreme sea levels are generally well described by a Generalised Extreme Value distribution, and most sea level extremes can be described by the simplest of these, the Gumbel distribution (van den Brink and Können, 2011), which is expressed as

$$F = exp\left(-exp\left(\frac{\mu - z}{\lambda}\right)\right) \tag{A2}$$

where F is the probability that there will be no exceedances above z during time interval T, z is the height, μ is the 'location parameter' and λ is the 'scale parameter', which relates to the variability of the extremes.

We next assume that;

- $z = z_c$, is some critical asset height under present climate conditions
- mean sea level is raised by an amount $\Delta z + z'$ where Δz is the mid-range increase and z' is a random variable with zero mean and a distribution function $P(z')$
- the asset height is raised by an amount A to account for the rise in sea level.

Under conditions of uncertain SLR the total number of exceedances of $z_c + A$ during a period T is

$$N_{tot} = \int_{-\infty}^{\infty} P(z')\, exp\left(\frac{\mu - z_c + \Delta z + z' - A}{\lambda}\right) dz'$$

which noting from (1) that $N = \exp(\mu - z_c)/\lambda$, can be rearranged to give

$$N_{tot} = Nexp\left(\frac{\Delta z + \lambda\, ln \int_{-\infty}^{\infty} P(z') exp\left(\frac{z'}{\lambda}\right) dz' - A}{\lambda}\right) \tag{A3}$$

In other words, for the future total number of exceedances to be the same as the current number of exceedances, the allowance A must be equal to $\Delta z + \lambda ln \int_{-\infty}^{\infty} P(z') \exp\left(\frac{z'}{\lambda}\right) dz'$.

Hunter (2012) applies three different distributions that can be used to describe the SLR uncertainty. Of those the normal distribution is considered to represent a compromise between a tightly constrained distribution and a fat upper tail. Therefore here the normal distribution is assumed,

$P(z') = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(z')^2}{2\sigma^2}\right)$,

which substituting into (A3) and solving gives

$$N_{tot} = Nexp\left(\left(\Delta z + \frac{\sigma^2}{2\lambda} - A\right)/\lambda\right). \tag{A4}$$

The allowance simplifies to

$$A = \Delta z + \sigma^2/2\lambda \tag{A5}$$

where Δz is the mean SLR for a given scenario and future time period and σ^2 is derived from the 5–95 percentile range of the SLR projections. This equation shows that the amount that the allowance lies above the median SLR is a function of the uncertainty of the sea level projections and the inverse of the scale parameter λ. Since the scale parameter determines the slope of the return period curve, the less steep the curve, the greater the value of A.