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Sea-Level Rise and Allowances for Coastal Councils around Australia – Guidance Material

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1 Introduction

This report provides information to aid in the interpretation and use of sea-level rise projections and allowances that have been developed for NCCARF's CoastAdapt portal. The projections are consistent with those developed for the National Resource Management Project, available at http://www.climatechangeinaustralia.gov.au/en/climate-projections/coastal-marine/marine-explorer/ (see also McInnes et al., 2015) and the IPCC (Church et al., 2013a,b) but have been developed here for all coastal councils in Australia and contain projections at decadal time intervals up to 2100.

Sea levels change on a broad range of time and space scales. These time-scales range from seconds for surface waves, to hours/days for tides and storm surges, days/months/years/decades and longer for regional variability, seasonal variations, natural climate variability and the response to anthropogenic climate change. On a global scale, anthropogenic climate change is causing an increase in the volume of the ocean (and a rise in global mean sea level; Figure 1) through the expansion of ocean waters as they warm and an increase in mass of the ocean as glaciers and ice sheets lose mass (Church et al., 2013a). The mass of the ocean also changes as water is exchanged with terrestrial environment from the impacts of climate variability and change and through anthropogenic activities such as the storage of water in reservoirs and the depletion of groundwater (which subsequently makes its way to the ocean).

Locally, sea level changes not only because of the global change in volume of the ocean but also from a series of regional factors. Changes in regional sea level are dynamically linked to local and regional changes in the density of the ocean (which is dependent on temperature and salinity) and changes in ocean currents and as a result of air-sea interactions (winds and fluxes of heat and freshwater between the oceans and the atmosphere). Because of the dynamical coupling, changes in sea level at one location are linked to changes elsewhere in the ocean. For example, during El Niño events that bring drought to Australia, sea level is high in the eastern equatorial Pacific and low in the western equatorial Pacific, with the opposite occurring during La Niña events. The Interdecadal Pacific Oscillation and other climatic modes of variability affect regional sea level at higher latitudes and generally on longer decadal time scales. As water is added to the ocean, the sea-level signal propagates rapidly (within days) around the globe such that sea level also rises at locations distant from the initial mass addition (Lorbacher et al. 2012).

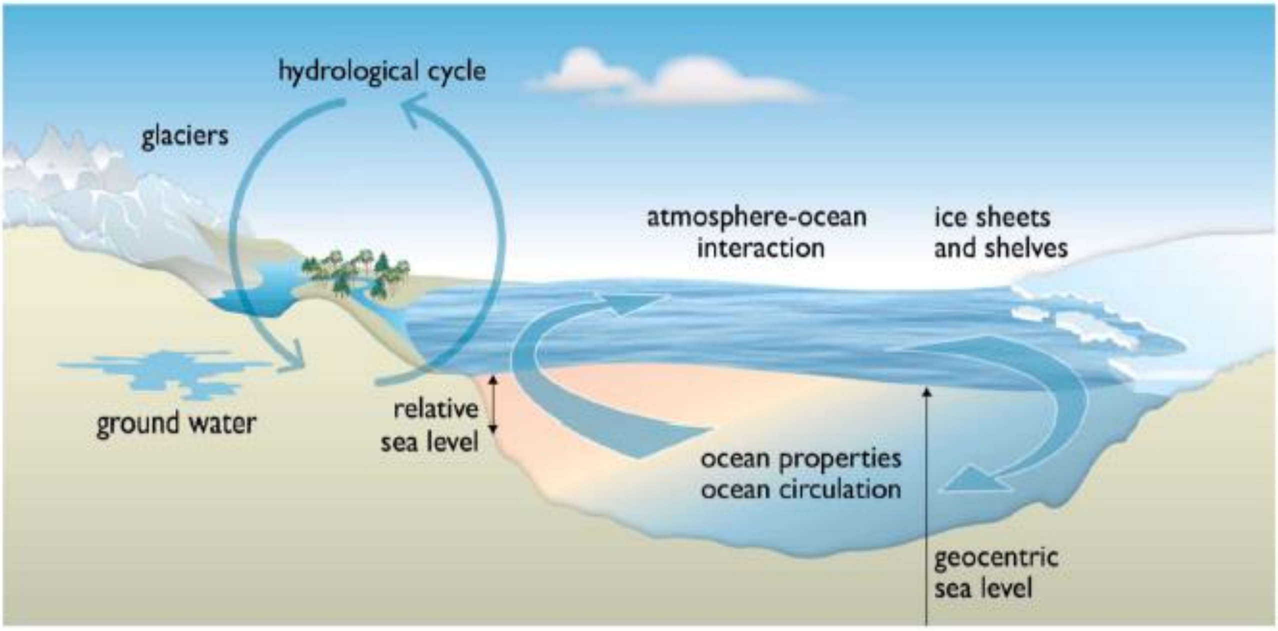

Figure 1. Climate-sensitive processes and components that can influence global and regional sea level. The term 'ocean properties' refers to ocean temperature, salinity and density, which influence and are dependent on ocean circulation (source: Church et al., 2013a).

Sea level relative to the land (relative sea level, as measured by a coastal tide gauge) also changes if the land is moving. This land motion can occur because of ongoing global scale movements of the land in response to changes in the distribution of ice on the Earth since the last ice age (the last glacial maximum occurred about 20 thousand years ago), or local land motion associated with earthquakes or other tectonic effects such as sediment compaction (particularly in deltaic regions and where ground water or petroleum is withdrawn from the sediments). Contemporary changes in the mass of glaciers, ice sheets and the terrestrial storage of water also change the gravitational field and rotation of the Earth resulting in a global redistribution of sea level (a greater than average relative rise far from the region of loss of mass and a reduced rise and even a fall in relative sea level close to the region of loss of mass). In contrast to tide gauges, satellite measure sea level relative to the centre of mass of the Earth/ocean/ice system (geocentric sea level).

2 Historical Global and Australian Sea-Level Rise

Over the last 1 million years, sea level has varied by more than 100 m as ice sheets waxed and waned through glacial cycles. The paleo data indicates sea level was metres higher than present in times of a warmer climate (Dutton et al. 2015). About 20 thousand years ago sea level was about 130 m below present day sea level because of large ice sheets covering northern America and northern Europe, and a larger Antarctic Ice Sheet. Sea level then rose rapidly at rates of about 1 m/century for many millennia, and with peak rates of over 4 m/century. Sea level began to stabilise about six thousand years ago. From 1400 years ago up to the 19th century centennial rates of global sea-level changes were small (less than about 0.2 mm/yr; Kopp et al. 2016). In the 19^{th} century, the rate of rise began to accelerate (Kopp et al. 2016; Church and White 2006, 2011; Jevrejeva et al. 2008; Church et al. 2013a). From 1900 to 2010, estimates of the rate of sea-level rise vary between about 1.4 and 1.9 mm/yr (Hay et al. 2015 Rhein et al. 2013). Satellite altimeters provide the first nearly global observations of sea level and indicate a rate of rise that is generally accepted to be 3.2 ± 0.4 mm/yr (Masters et al. 2012), although a recent comparison with tide gauges suggest that the rate could be between 2.6 ± 0.4 mm/yr and 2.9 ± 0.4 mm/yr, with a small (but not significant) acceleration from 1993 to present (Watson et al. 2015). The satellite data indicates a non-uniform rate of rise from 1993 to 2015, with rates of rise to the north of Australia several times the global average and near zero rates in the eastern equatorial Pacific (for example, see Rhein et al. 2013).

Sea levels along most sections of the Australian coastline have been observed since 1966 (Figure 2). There is significant interannual variability, much of which is related to the Southern Oscillation Index (SOI; White et al. 2014) and the Interdecadal Pacific Oscillation (Zhang and Church 2012). White et al. (2014) removed the variability directly related to the SOI. For the periods 1966 to 2009 and 1993 to 2009, White et al. estimated the average trends of relative sea level around the coastline was 1.4 ± 0.3 mm yr^{-1} and 4.5 ± 1.3 mm yr^{-1} (with the largest rates in this latter period on the north and west coasts of Australia), which become 1.6 ± 0.2 mm yr^{-1} and 2.7 ± 0.6 mm yr^{-1} after the signal directly correlated with ENSO was removed. After further correcting for GIA and changes in atmospheric pressure (Figure 3), they found the corresponding trends were 2.1 ± 0.2 mm yr^{-1} and 3.1 ± 0.6 mm yr^{-1}, with the average close to the global-mean trends, including the increased rate of rise since the early 1990s. For Australia's two longest records (Fremantle and Sydney), they found both records showing larger rates of rise between 1920 and 1950, relatively stable mean sea levels between 1960 and 1990 and an increased rate of rise from the early 1990s.

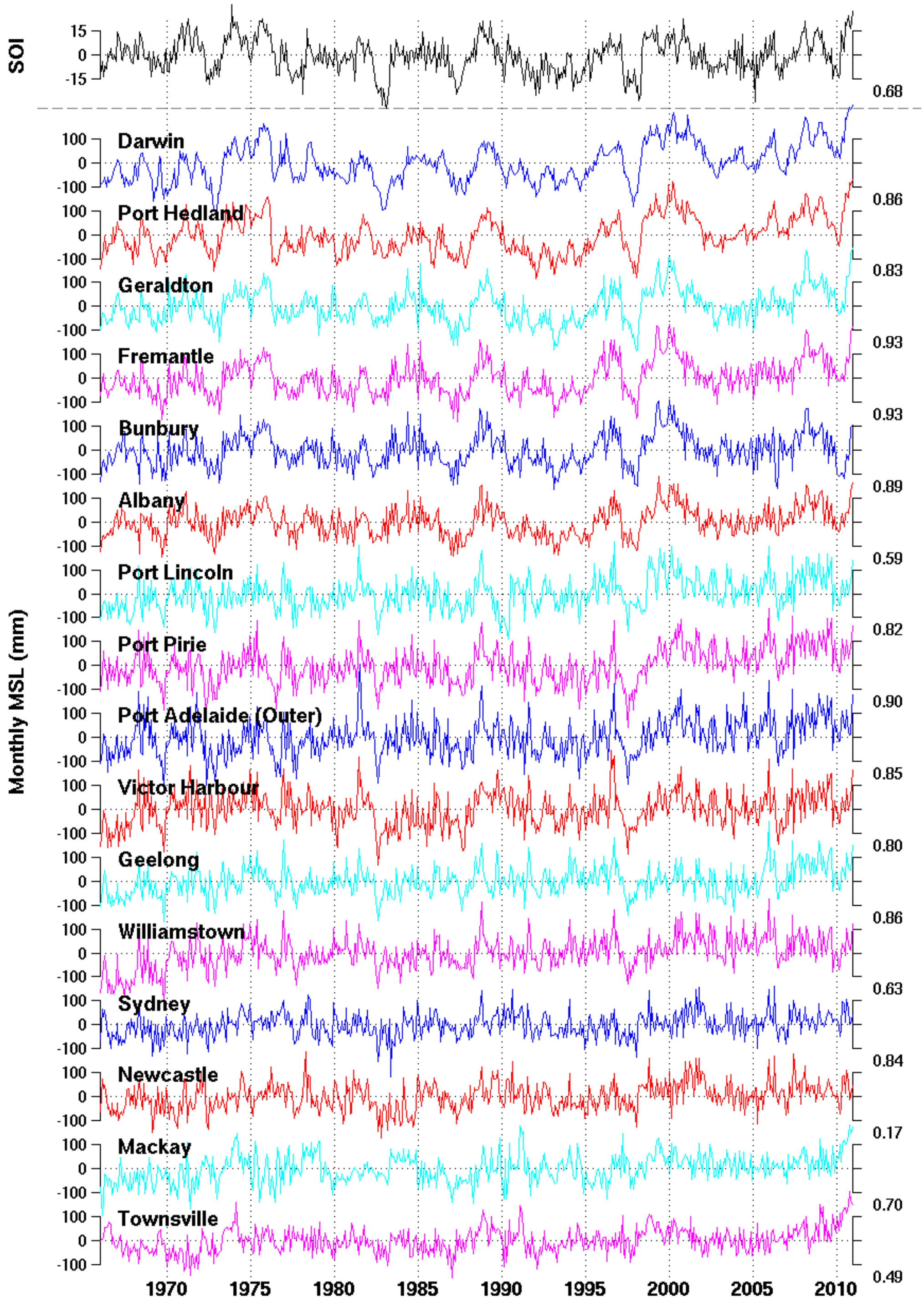

Figure 2. Monthly RMSL time series for the 16 near-continuous records available since 1966, from Darwin in the north, anticlockwise to Townsville in the northeast. The SOI is also shown. Cross-correlations between adjacent time series are shown on the right. The cross-correlation between Townville and Darwin is shown below Townsville (source: White et al., 2014).

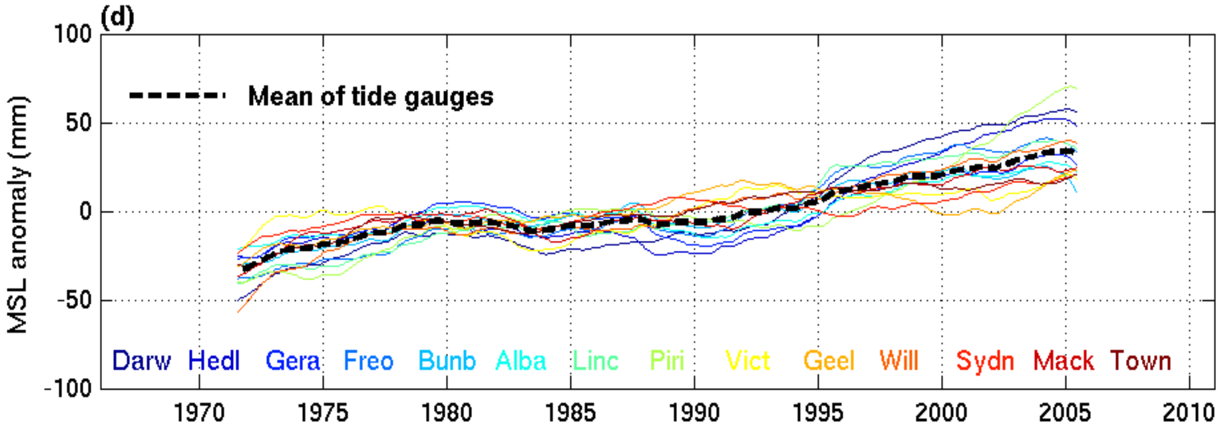

Figure 3. The tide gauge data (after the signal linearly correlated with the SOI has been removed and the results smoothed with a ten year running average) for the 14 tide-gauge records (different colours) and the average (black dashed; source: White et al., 2014).

3 Understanding Historical Global Mean Sea-level Rise

Understanding the reasons for historical sea-level rise has been a conundrum for several decades. However, over the last five years there has been significant progress in providing a quantitative explanation for the observed sea-level rise from observations of the individual contributions, particularly since 1970 when more data are available (Church et al. 2011a; Moore et al. 2011), and also since 1900 using a combination of observations and models (Gregory et al. 2012; Church et al. 2013a,b). The two largest contributions come from ocean thermal expansion and the loss of mass from glaciers. The surface mass balance (SMB) of the Greenland Ice Sheet has been making an increasing contribution to sea-level rise since 1990. Part of this Greenland SMB contribution since 1990 appears to be related to anthropogenic climate change with part related to natural variability in the North Atlantic region (Church et al. 2013a). There is thought to have been a Greenland SMB contribution (Kjeldsen et al. 2015; Slangen et al. 2016) and a glacier contribution in the first half of the 20th century (Marzeion et al. 2014, Church et al. 2013a,c) that is also related to natural variability in the North Atlantic region.

The contributions from the ice sheets of Greenland and Antarctica related to rapid changes in discharge of ice into the oceans remains poorly determined, although it is thought that the 20th century contribution is small (Kjeldsen et al. 2015). There are now observations of the total mass balance changes of both ice sheets since the early 1990s using multiple techniques (Shepherd et al. 2012) and new models of the projected ice discharge for the 21st century for both the Greenland (Nick et al. 2013) and Antarctic ice sheets (Levermann etal. 2014; Favier et al. 2013; Cornford et al., 2015; Ritz et al. 2015; De Conto and Pollard 2016).

There are also long term (and non-trivial) contributions from the depletion of ground water (Konikow 2011; Wada et al. 2012) and the storage of water in reservoirs (Chao et al. 2008; updated by Wada et al. 2012). The storage of water on land related to natural variability is thought to be small over multidecadal periods (Ngo-Duc et al. 2005) but it is becoming increasingly clear that it is important over multi-year periods (Boening et al. 2012; Dieng et al. 2015; Reager et al. 2016).

When models of all of these contributions are combined there is now reasonably good agreement between the simulated and observed global mean sea level, especially since 1970 and 1993 when improved observations are available.

Recent attribution studies have demonstrated that natural climate forcing or variability cannot explain the observed trend in ocean thermal expansion since 1970, although it is responsible for some of the decadal variability (Slangen et al. 2014b). The modelled response from the combined climate forcing from greenhouse gases and aerosols is in reasonable agreement with the observed trend since 1970 (Marcos and Amores 2014; Slangen et al. 2014b). For the glacier contribution, Marzeion et al. (2014) demonstrated that the response to past climate variations was an important contribution to the glacier contribution in the first half of the 20th century, but that anthropogenic forcing was responsible for the majority of the glacier contribution during the latter half of the 20th century.

Slangen et al. (2016) completed a comprehensive analysis of the causes of 20th century global mean sea-level (GMSL) rise. They found that the sum of all modelled contributions explains 74 ± 22% (± 2σ) of the observed GMSL change over 1900-2005. Natural radiative forcing makes little contribution over the 20th century but combined with the ongoing response to past climatic variations explains 67 ± 23% of the observed rise prior to 1950, but only 9 ± 18% after 1970. In contrast, the anthropogenic forcing (primarily a balance between a positive sea-level contribution from greenhouse gases (GHG) and a partially offsetting component from anthropogenic aerosols) explains only 15 ± 55% of the observations before 1950, but increases to become the dominant contribution to sea-level rise after 1970 (69 ± 31%).

While uncertainties remain, particularly for the first half of the 20th century, the ability to explain the observed GMSL changes and the reasons for these changes gives greater confidence in our understanding of sea-level change and our ability to project future change.

4 Projections of Global Mean and Regional Sea-level Rise

The improved understanding of 20th century sea-level rise and the factors leading to the regional differences in the rate of rise has led to the development of and improved confidence in techniques for projection of the global-averaged and the regional distribution of sea-level rise for the 21st century (Slangen et al. 2012; Church et al. 2011b). As a result, the Intergovernmental Panel on Climate Change provided probabilistic regional projections of sea-level rise for the first time in the Fifth Assessment Report (AR5; Church et al. 2013a,b). The regional projections for Australia presented here are based on the AR5 projections and the regional application of these as reported in McInnes et al. (2015).

The AR5 projections use scenarios of atmospheric greenhouse gas concentrations (Representative Concentration Pathways, RCPs) that range from high concentrations representing continued growth of emissions in a business-as-usual fashion (RCP8.5), to lower concentrations representing very strong mitigation and removal of carbon dioxide from the atmosphere in the second half of the 20^{th} century (RCP2.6) and two intermediate scenarios (RCP4.5 and RCP6.0; the number is the approximate radiative forcing in W m^{-2} from greenhouse gas increases by 2100). Note that of these four scenarios, only RCP2.6 is projected to result in a warming that is *likely* (66% probability) to be less than 2°C above preindustrial temperatures.

4.1 Global Projections

To estimate future sea-level changes, projected contributions from changes in ocean density and circulation (obtained directly from available climate models) are combined with additional sea-level contributions from the loss of mass from glaciers, the surface mass balance of the Greenland ice sheet and the dynamic response of the Greenland and Antarctic ice sheets and changes in land water storage (Church et al., 2013a). 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., 2013a).

The contributions to global mean sea-level change for the four greenhouse gas RCPs are given in Figure 4. Projected global mean SLR by 2100 relative to 1986–2005 varies from 28–61 cm for the RCP 2.6 (strong mitigation scenario) to 52–98 cm for the RCP 8.5 (high emissions scenario), where the range for each scenario was estimated to be *likely* (covering 66% of the probabilities). 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. A larger GMSL rise could occur prior to 2100 as a result of marine ice sheet instability in West Antarctica (Church et al., 2013a; Rignot et al., 2014), but there was insufficient scientific evidence at the time of the AR5 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 GMSL rise by 2100 (Church et al., 2013a). Recent observations (Rignot et al., 2014) indicate increased loss of ice from west Antarctica and recent modelling (e.g. Favier et al., 2014; Joughin et al., 2014; Levermann et al. 2014; Cornford et al. 2015; Ritz et al. 2015) simulates increased outflow from the Antarctic Ice Sheet. Projections of mass loss in these studies increases confidence in the *likely* Antarctic contribution used in the IPCC AR5 and reduces the probability of a rise above this range (Clark et al. 2015). Nevertheless, understanding of the relevant ocean-ice sheet processes (Alley and Joughin, 2012; Willis and Church, 2012) is still incomplete and a higher sea-level rise is possible. Indeed, recently De Conto and Pollard (2016) simulated the collapse of Antarctic ice shelves as the result of surface melting and hydro-fracturing, resulting in a sea-level rise for climate projections from one model at the upper end and even beyond the several tenths of a metre in the IPCC AR5 Assessment.

4.1 Sea-level Projections for Australia

To determine the regional changes in sea level around the Australian coastline, McInnes et al. (2015) combined 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 and rotational 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., 2011b, 2013a; Slangen et al., 2012; 2014b).

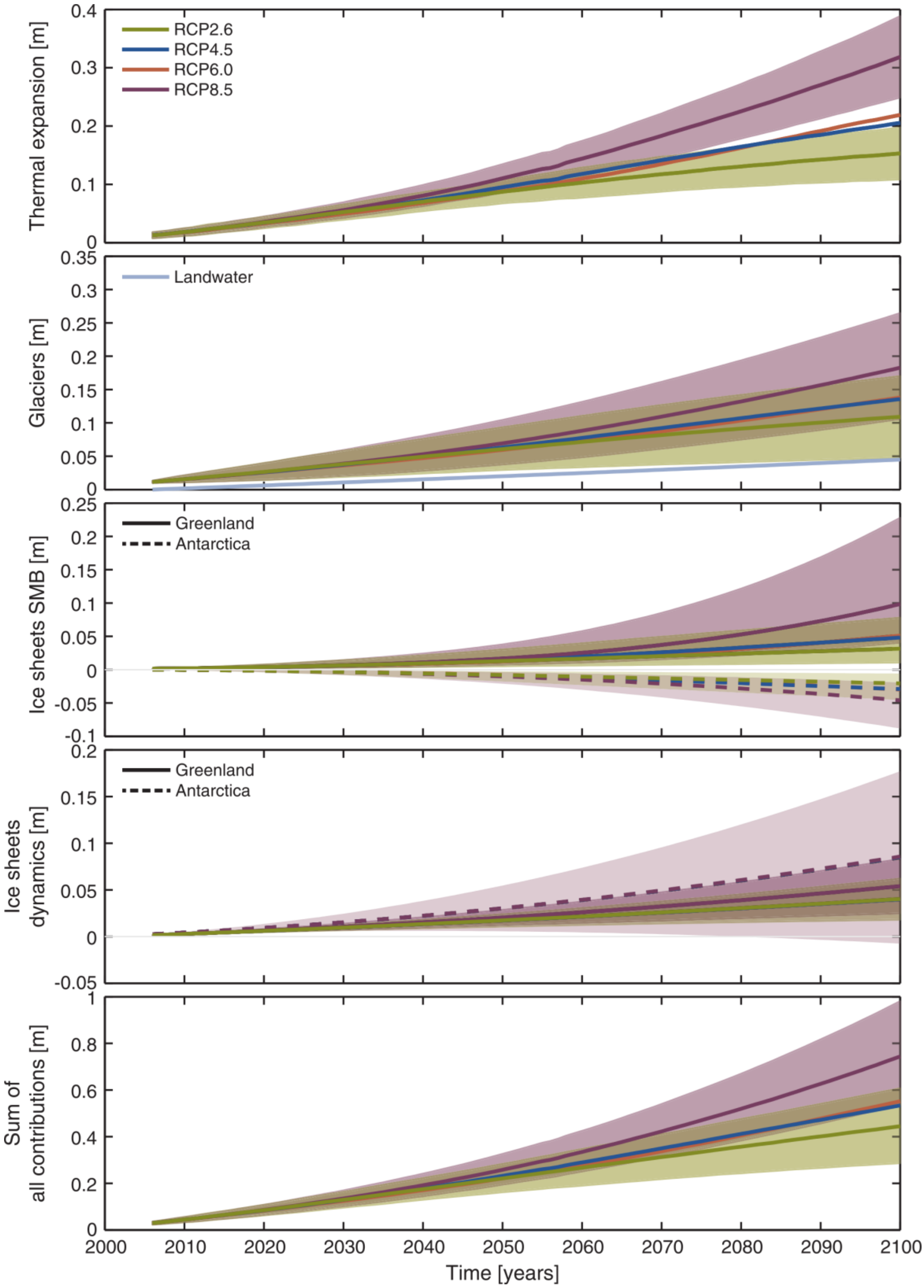

Figure 4. Contributions to 21st century sea-level rise (thick coloured lines) calculated using the results of individual climate models for all four RCPs. (a) Global-averaged ocean thermal expansion. (b) Glacier mass loss (c) Changes in the surface mass balance of the Greenland and Antarctic ice sheets, (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 multi-model mean values are shown (source: McInnes et al., 2015).

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. The Greenland fingerprint around the Australian coastline is insensitive to details of the exact location of mass loss from the Greenland Ice Sheet. For Antarctica, McInnes et al. assumed that the mass gain from increased accumulation of snow is 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 were assumed to result in a uniform change in sea level around the globe.

Note the regional projections of McInnes et al. are slightly different to those in Church et al. (2013a,b) in that they are low-pass filtered (by averaging 21 years of results) to focus on the climate change signal. They also use a different model for estimating the GIA (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)). McInnes et al. did not include 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 are likely to result in only trivial differences between the projections of McInnes et al. (2015) and Church et al. (2013a,b)

The regional distribution of relative SLR for projections averaged over 2081-2100 relative to the period 1986 to 2005 for each of the four scenarios is shown in Figure 5. 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 broader scale, 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. (2014). This pattern intensifies with higher greenhouse gas concentrations. 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 leads to lower relative rise along the Australian coastline compared to offshore.

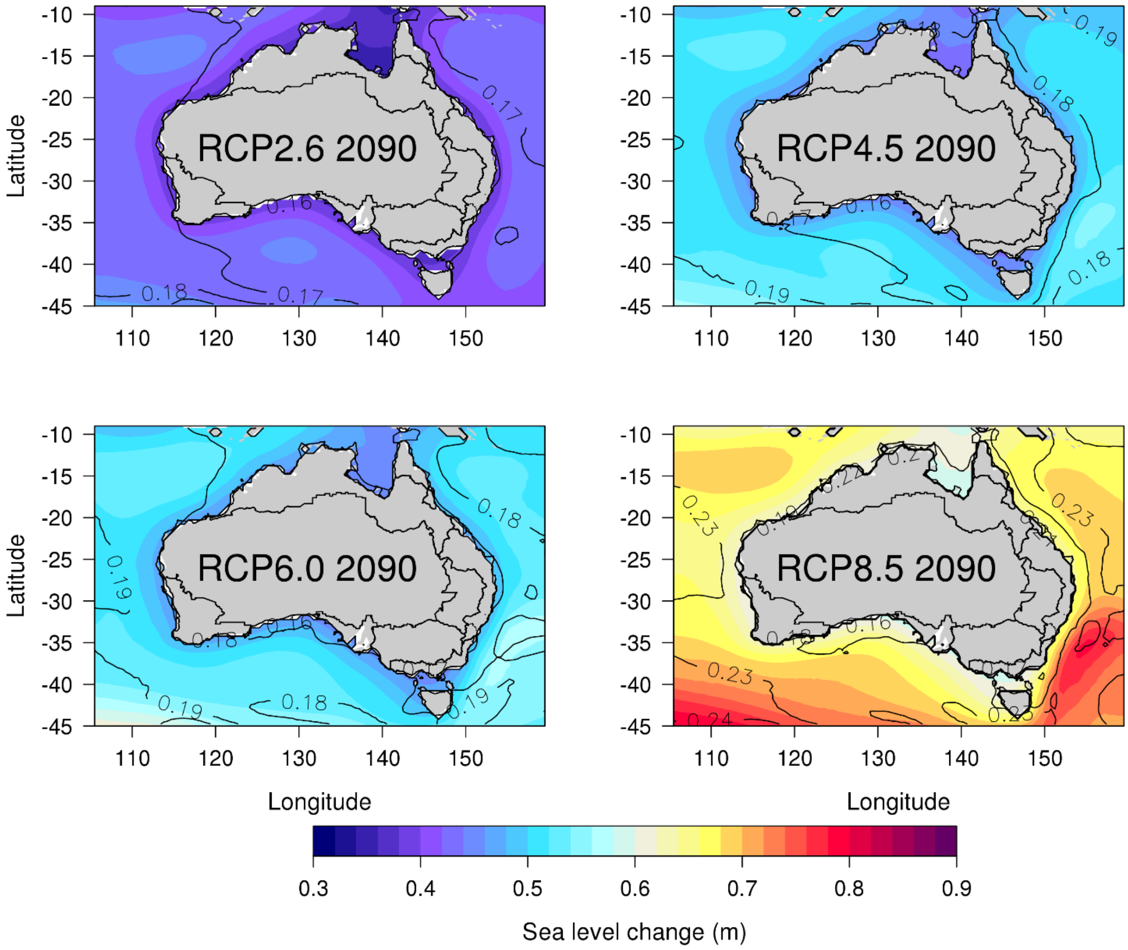

Figure 5. The regional distributions of sea-level change (four RCPs) for the period centred on 2090 compared to 1986 to 2005. The projections (shadings) and uncertainties (solid lines) represent the contributions from the changes in terrestrial ice, the gravitational response of the ocean to these changes, and an ongoing GIA (source: McInnes et al, 2015).

The upper end of the sea-level projections for the Australian coastline (Figure 6) are slightly larger than the GMSL projections, the largest differences of 0.06 m occurring in the 95 percentile of the model values for RCP 8.5 at locations along the east coast of Australia. The higher-than-global-averaged values for the Australian coastline are primarily a result of the fingerprint patterns, which give a larger than global-averaged rise far from the regions of glacier and ice sheet mass loss. This larger rise is at least partially 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 (Figures 4 and 6) for the first decades of the 21st century, but they begin to differ significantly from about 2050. Significant interannual variability of monthly regional 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 6 indicating the 5 to 95 percent uncertainty range of the detrended historical records.

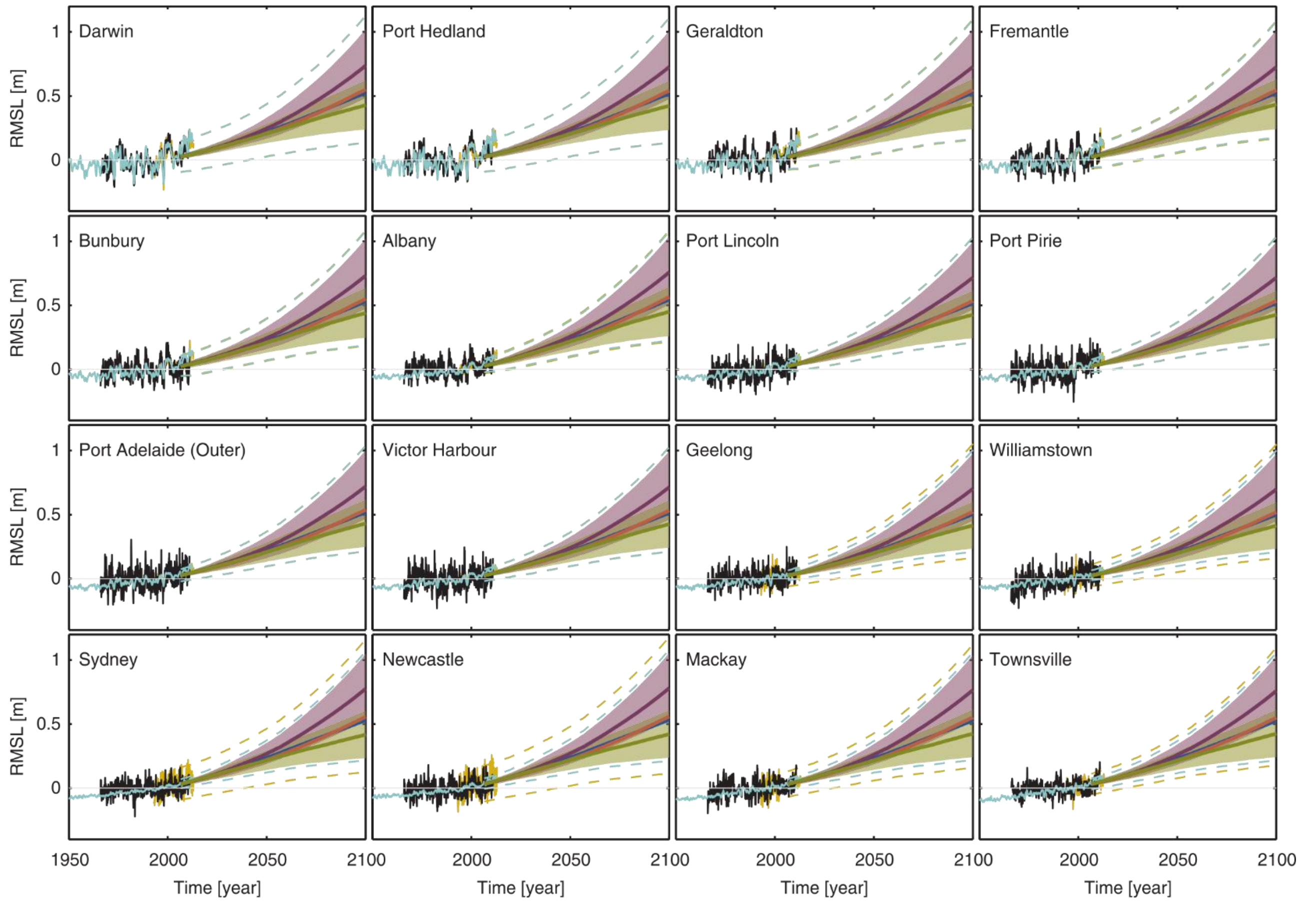

Figure 6. The observed sea-level records are indicated in black, with the satellite record (since 1993) in mustard and tide gauge reconstruction of Church and White (2011); which has lower variability) in cyan. Multi-model mean projections (thick purple and olive lines) for RCP8.5 and RCP2.6 with *likely* 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 (source: McInnes et al., 2015).

The projected rates of regional rise increase from the current GMSL rate 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}.

4.2 Evaluation of the regional projections

While there has been considerable progress in understanding the 20th century global-averaged SLR (Church et al., 2013a; Slangen et al., 2014a), regional projections have only recently been developed (Church et al., 2011b; 2013a,b; Slangen et al., 2012; 2014b,c) and require a combination of several different component models to produce results around 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, McInnes et al. (2015) compared regional results for 16 locations around the Australian coastline with observations from both tide gauges and altimeters (Figure 7).

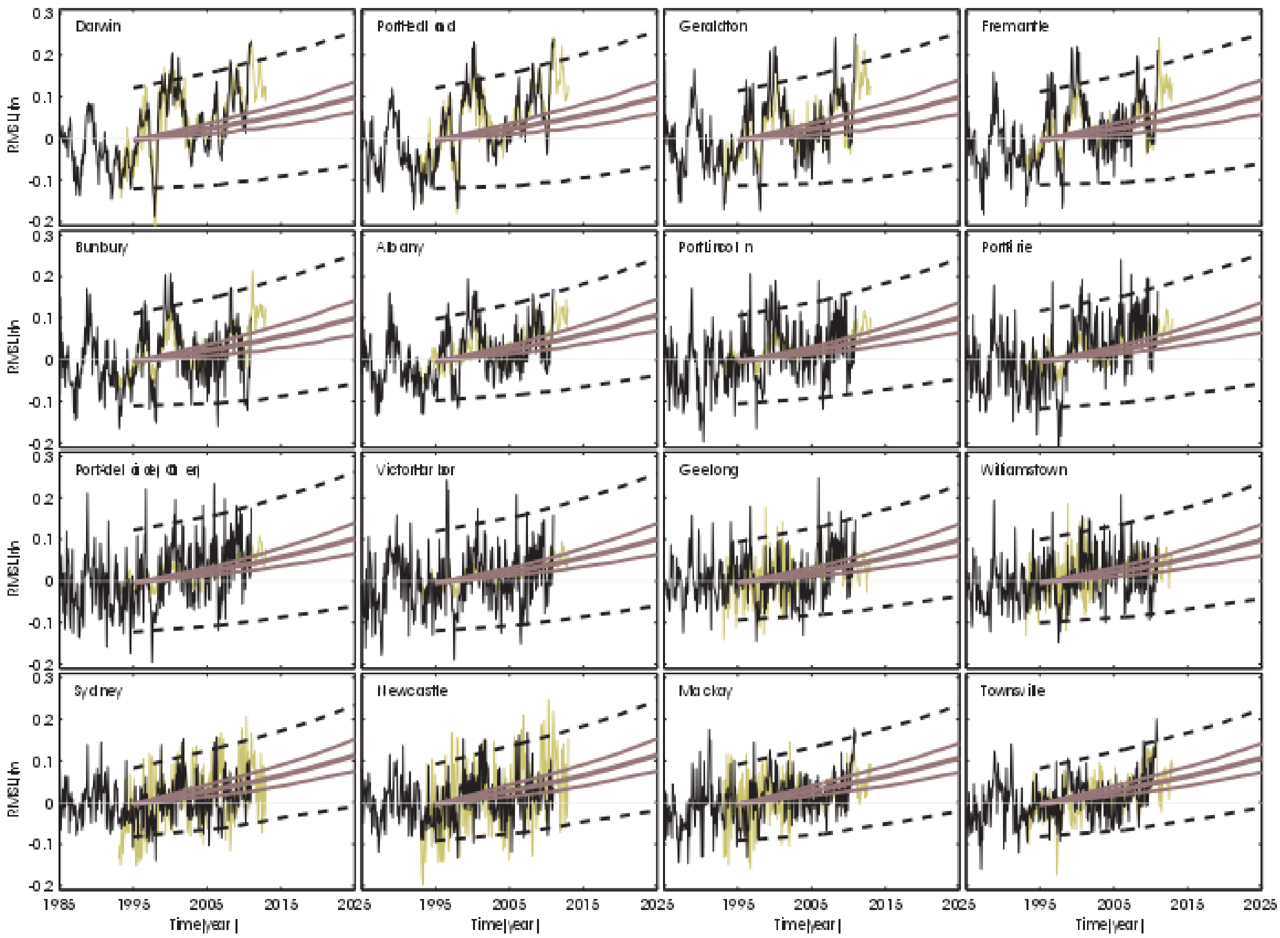

Figure 7. Observed and projected relative sea-level change in meters for 1965 to 2015 for the 16 locations in Figure 4. The observed sea-level records are indicated in black, with the satellite record (since 1993) in mustard. Multi-model mean projections (thick purple) for RCP8.5 and RCP2.6 with model ranges are shown by the thin purple lines (source: McInnes et al., 2015).

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 the 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 (Figures 6 and 7) 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 levels from the historical tide-gauge records over 1966 to 2010) is indicated by the dotted lines above and below the projections in Figures 6 and 7. 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 after allowing for natural variability. McInnes et al. computed trends for the observed and projected SLR. These 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 in the future prediction of interannual and decadal variability.

4.3 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 further investigation is required.

Note that these projections were assessed to represent the *likely* range (66% of probabilities), which was evaluated from the 5-95% range of the model results, and do not include the additional allowance of several tenths of a metre if there was significant collapse of the Antarctic ice sheet. Under such conditions, the projections would be somewhat higher.

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.

4.4 Beyond 2100

At the end of the 21st century, global and regional sea level is projected to continue rising in all scenarios, with the rate in RCP8.5 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 fractionally larger than the late 20th century rate. Global mean (Church et al. 2013a,b) 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. 2013a,b). 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 oceanic and atmospheric warming but is likely to be meters for higher emission scenarios. Longer term SLR will also depend on future emissions (Church et al. 2013a).

5 Sea-level Extremes and Allowances

The effects of sea-level rise will be felt most profoundly during episodes of extreme sea levels. Extreme sea levels can arise from singular oceanic phenomena such as tides or a storm surge but more commonly occur due to a combination of natural phenomena that individually may not be extreme. These phenomena occur on a range of time and space scales (Figure 8) in any given coastal location, and thus the contribution of each phenomenon to extreme sea levels varies. Breaking waves occur on the shortest time and space scales in the shoaling zone at the coast. Storm surges affect sea levels on the continental shelf on time scales from hours to several days while climate variability affects sea levels across the ocean basin on interannual time scales. A range of weather conditions cause storm surges and high waves including tropical cyclones and cold fronts. Sea-level extremes are also affected by coastal bathymetry and coastal alignment with respect to the forcing storm conditions.

For coastal engineering, planning and adaptation, the likelihoods of extreme sea levels, expressed in terms of return periods (i.e. the average time interval between events that exceed a particular height) or exceedance probabilities (the probability that an event exceeding a particular magnitude will occur in any given year) are of considerable importance in informing the design of built infrastructure and coastal protection. Figure 9 illustrates the relationship between extreme sea-level variability and return periods for two different coastal locations under present conditions. Location A represents a location with large variability in extreme sea levels due to large variations in tidal range between the fortnightly neap and spring cycles and the tendency for large storm surges to occur while location B represents a location with little variation in maximum tides throughout the month and a tendency for smaller storm surges when storms occur. In terms of return periods for storm tides (the combination of the storm surge and astronomical tide) the location on the left is characterised by a steeper return period curve compared to the right (lower panels). The statistical relationships that are represented in these return period curves in Figure 9 (lower panel) describe the probabilities that an exceedance event will occur in a given year.

For the protection of built assets, it is customary to consider the heights associated with particular return periods (e.g. the height of the 1-in-50 or the 1-in-100 year event). These planning guidelines are illustrated in Figure 9 (top panel) for present climate conditions. Under a constant sea-level rise these planning heights will be breached far more frequently in location B compared to location A due to the nature of extreme sea-level variability (Figure 9 middle panel) and this is reflected by a more dramatic shortening of the time interval between exceedance events on the return period curves (Figure 9 lower panel).

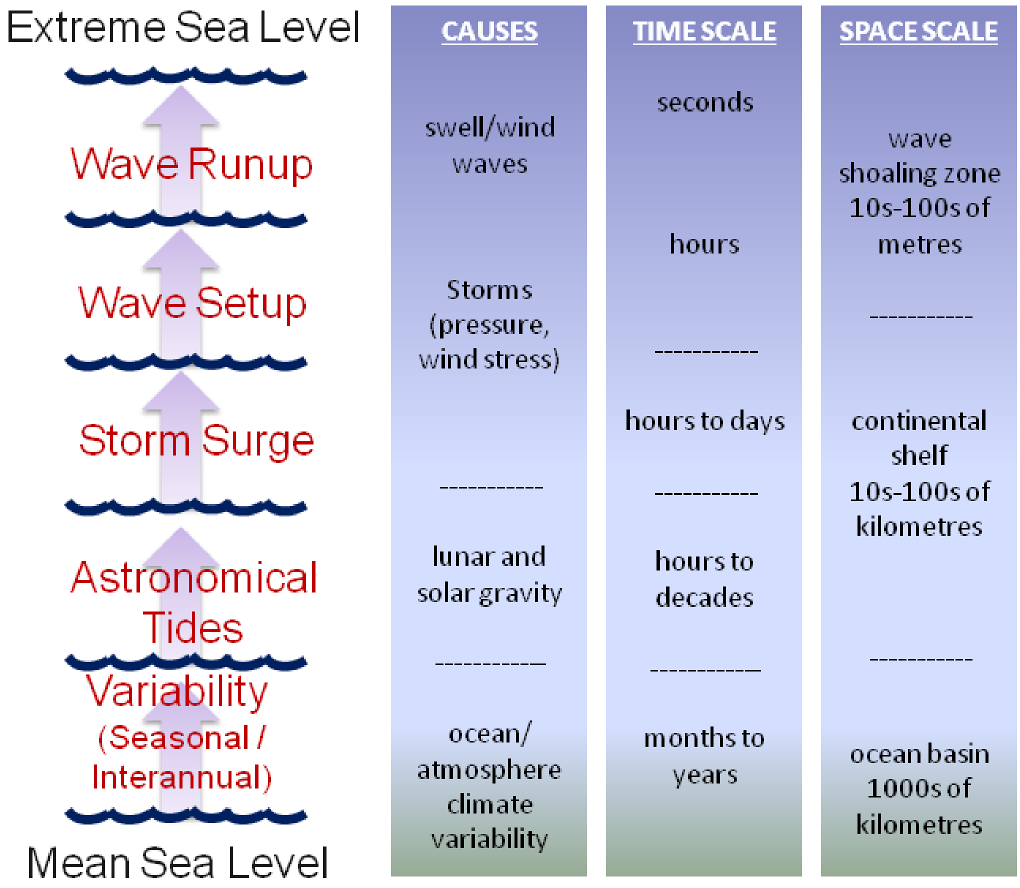

Figure 8. Oceanic phenomena that contribute to the total water levels at the coast during an extreme sea-level event, their causes and the time and space scales over which they operate (source: McInnes et al, 2016).

In consideration of planning for future sea-level rise and its associated uncertainty, Hunter (2012) proposed an objective method to calculate an allowance from a projected future sea-level range, that if added to current design values would mean that the expected frequency of exceedances at the future time with sea-level rise (including its assessed uncertainty range) would be the same as expected under current day conditions without the sea-level rise. In other words the performance of the mitigation measures would be as effective in the future as they are today. The mathematical derivation of the allowance is provided in different forms in Hunter (2012), Hunter et al, (2013) and also in McInnes et al, (2015). The form of the allowance used here is given by

$$A = \Delta z + \sigma^2 / 2\lambda \quad (1)$$

where Δz is the mean sea-level rise for a given scenario and future time period, σ^2 is derived from the 5-95% range of the modelled sea-level rise projections and λ is the scale parameter that describes the slope of the extreme sea-level return period curves as shown in the bottom panel of Figure 9. Allowances for the Australian coast have been calculated based on the sea-level rise projections presented here and scale parameters generated by the study of Haigh et al., (2014) in which a hydrodynamic model was used to simulate sea levels due to tides and storm surges and then statistically analysed to produce return periods. The allowances calculated from the model are generally in good agreement with those based on Hunter (2012) who used tide gauge data to calculate values of λ. There is a tendency for the allowances based on the scale parameters from the modelled data to be slightly higher than those from the tide gauge scale parameters (i.e. the models underestimate the variability) on some sections of coastline, particularly 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 (not considered in the Haigh et al. study) are likely to be important also.

Figure 10 presents examples of allowances for 2030, 2050 and 2090 (relative to 1986 to 2005) under RCPs 4.5 and 8.5. Sea-level projections and allowances for a selection of locations around Australia are provided in Table 1. These allowances show that when the uncertainty on sea-level rise projections is small, as is the case for 2030, the allowances are close to the median of the sea-level rise range. 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 sea-level rise 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 of the modelled sea-level rise range. For example, for Townsville and Albany under RCP 8.5, the allowances become 0.74 and 0.81 m respectively, which lie between the median and 95th percentile projections of both locations i.e. 0.62 [0.42-0.85] and 0.64 [0.44-0.87] respectively. The relatively higher allowance at Albany compared to Townsville is because of the dependence of allowances on the variability of extreme sea levels, characterised by the steepness of the extreme sea-level return period curves. In areas that do not experience large sea-level extremes (e.g. location B in figure 9) , a given sea-level rise will more dramatically increase the frequency of extreme sea levels occurring, than a location with a greater propensity for extreme sea levels (e.g. location A in Figure 9). Extreme sea levels in Albany are less extreme than those in Townsville leading to a higher sea-level allowance than for Townsville.

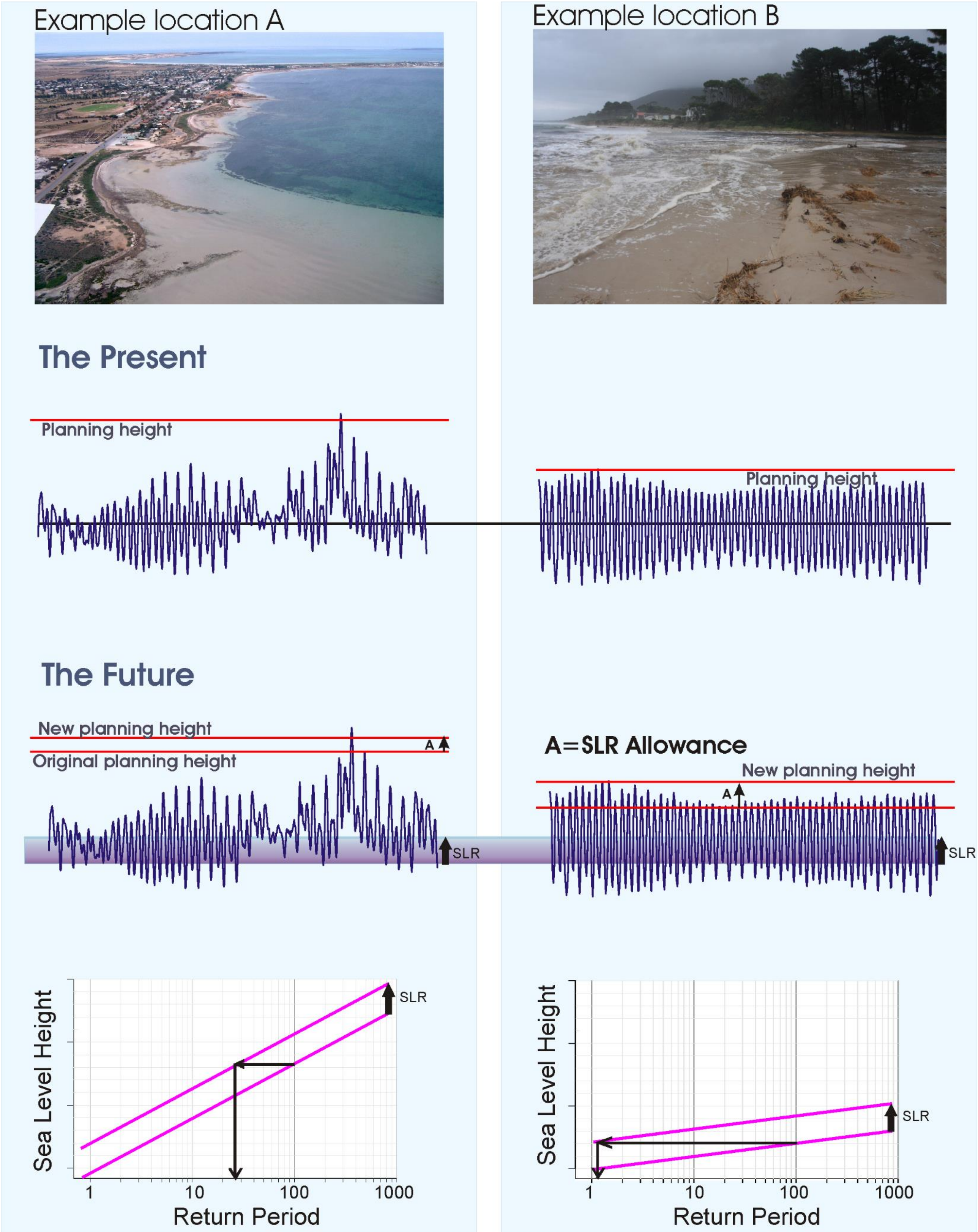

Figure 9. Two different coastal locations with different extreme sea-level variability. The causes of extreme sea levels varies from place to place and determines present planning heights. Under sea-level rise, the increase in threshold exceedance varies from place to place. (Photo A courtesy of Professor Nick Harvey and Photo B courtesy of Dr Penny Whetton).

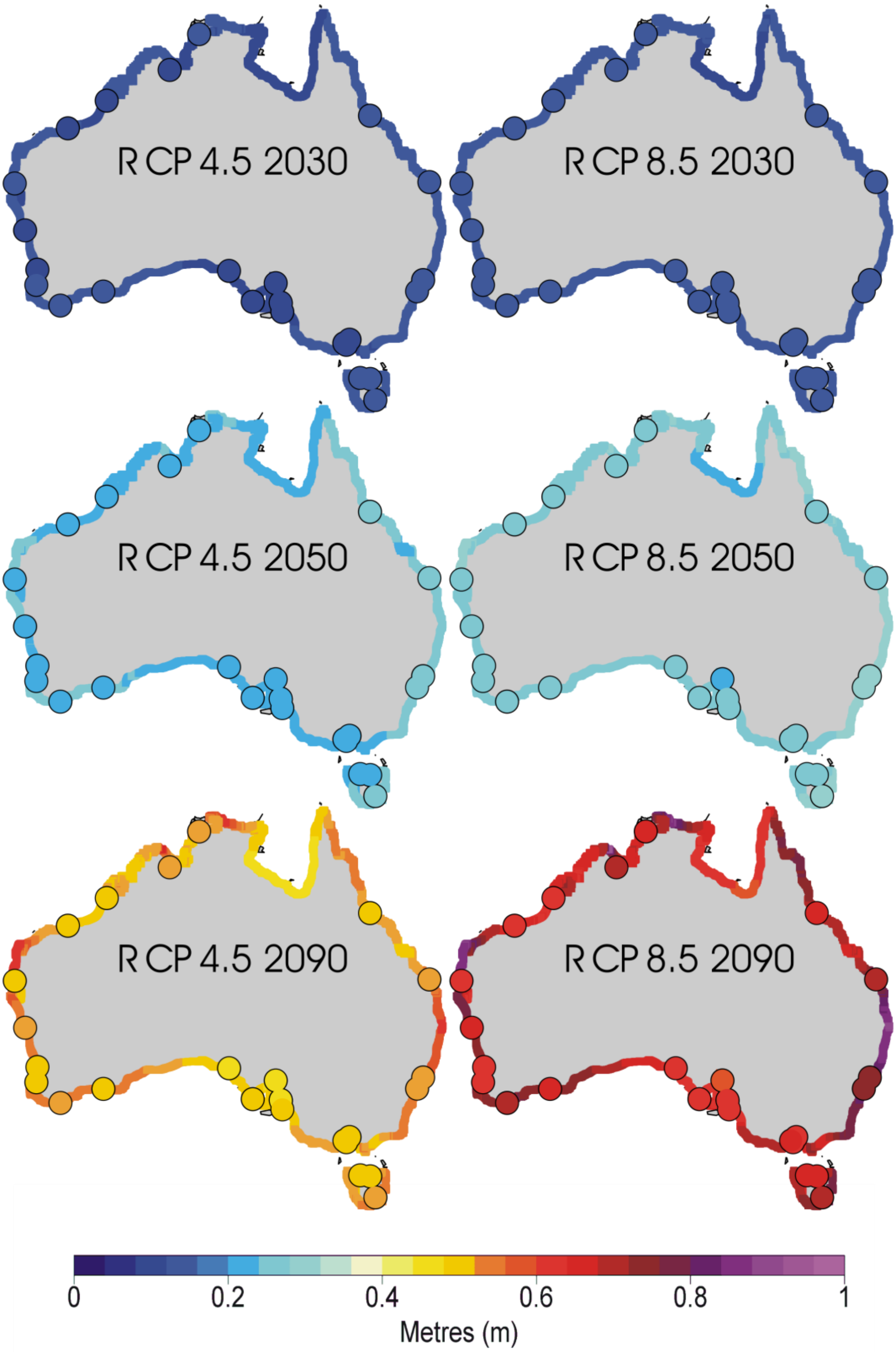

Figure 10: Allowances representing the vertical distance that an asset needs to be raised under a rising sea level so that the present likelihood of flooding does not increase. Allowances are calculated using sea-level rise projections. Small circles following the coastline use the scale parameter from the modelled results of Haigh et al., (2014) while the large circles use scale parameters from tide gauge data reported in Hunter (2012). The allowances are shown for RCPs 4.5 and 8.5 assuming the projected sea-level increase and associated uncertainty for 2030, 2050 and 2090.

Table 1 Median values and likely ranges (66% range) for projections of regional sea-level rise relative to 1986 to 2005 under all RCP emission scenarios for locations along the Australian coastline for selected tide gauge locations with record available for the period 1966 to 2010 together. Also given is the allowance, which is the vertical distance that an asset would need to be raised by the given future time so that the frequency of exceedances of present planning heights would not be changed. Note, as discussed above, higher sea levels could occur in response to an increased contribution from the Antarctic Ice Sheet.

Scenarios	2030		2050		2070		2090	
	SLR	A	SLR	A	SLR	A	SLR	A
Darwin								
RCP2.6	0.12(0.07-0.16)	0.10	0.21(0.13-0.28)	0.21	0.30(0.18-0.42)	0.32	0.38(0.22-0.55)	0.43
RCP4.5	0.12(0.08-0.16)	0.12	0.22(0.14-0.30)	0.23	0.34(0.22-0.46)	0.36	0.46(0.29-0.65)	0.52
RCP6.0	0.11(0.07-0.15)	0.12	0.21(0.14-0.28)	0.22	0.33(0.21-0.45)	0.35	0.47(0.30-0.65)	0.53
RCP8.5	0.13(0.08-0.17)	0.13	0.25(0.17-0.33)	0.26	0.41(0.28-0.56)	0.45	0.62(0.41-0.85)	0.71
Port Hedland								
RCP2.6	0.11(0.07-0.16)	0.12	0.20(0.13-0.28)	0.21	0.29(0.18-0.42)	0.32	0.38(0.22-0.55)	0.43
RCP4.5	0.12(0.07-0.16)	0.12	0.22(0.14-0.30)	0.23	0.33(0.21-0.46)	0.36	0.46(0.28-0.64)	0.52
RCP6.0	0.11(0.07-0.15)	0.11	0.21(0.13-0.28)	0.22	0.32(0.21-0.45)	0.35	0.47(0.29-0.65)	0.52
RCP8.5	0.12(0.08-0.17)	0.13	0.24(0.16-0.33)	0.26	0.41(0.27-0.55)	0.44	0.61(0.40-0.84)	0.70
Geraldton								
RCP2.6	0.12(0.07-0.17)	0.12	0.21(0.13-0.29)	0.22	0.30(0.18-0.42)	0.35	0.39(0.22-0.56)	0.49
RCP4.5	0.12(0.07-0.16)	0.12	0.22(0.14-0.30)	0.24	0.34(0.21-0.47)	0.39	0.46(0.28-0.65)	0.57
RCP6.0	0.11(0.06-0.16)	0.12	0.21(0.13-0.29)	0.23	0.33(0.20-0.45)	0.38	0.47(0.29-0.65)	0.58
RCP8.5	0.13(0.08-0.17)	0.13	0.24(0.16-0.33)	0.27	0.41(0.27-0.56)	0.48	0.61(0.40-0.85)	0.78
Fremantle								
RCP2.6	0.12(0.07-0.16)	0.12	0.21(0.13-0.29)	0.22	0.30(0.18-0.42)	0.34	0.39(0.22-0.56)	0.47
RCP4.5	0.12(0.07-0.16)	0.12	0.22(0.14-0.30)	0.24	0.33(0.21-0.46)	0.38	0.46(0.28-0.65)	0.56
RCP6.0	0.11(0.06-0.16)	0.12	0.21(0.13-0.29)	0.22	0.32(0.20-0.45)	0.37	0.47(0.29-0.65)	0.56
RCP8.5	0.12(0.08-0.17)	0.13	0.24(0.16-0.33)	0.26	0.41(0.26-0.56)	0.47	0.61(0.39-0.84)	0.76
Bunbury								
RCP2.6	0.12(0.07-0.17)	0.12	0.21(0.13-0.29)	0.22	0.30(0.18-0.43)	0.34	0.40(0.23-0.57)	0.47
RCP4.5	0.12(0.07-0.17)	0.12	0.22(0.14-0.30)	0.24	0.34(0.21-0.47)	0.38	0.47(0.29-0.65)	0.55
RCP6.0	0.11(0.07-0.16)	0.12	0.21(0.13-0.29)	0.23	0.33(0.21-0.46)	0.37	0.47(0.30-0.66)	0.56
RCP8.5	0.13(0.08-0.18)	0.13	0.25(0.16-0.34)	0.27	0.41(0.27-0.56)	0.47	0.62(0.40-0.85)	0.75
Albany								
RCP2.6	0.12(0.08-0.17)	0.13	0.22(0.14-0.30)	0.24	0.31(0.20-0.44)	0.36	0.41(0.24-0.58)	0.50
RCP4.5	0.13(0.08-0.17)	0.13	0.23(0.15-0.31)	0.25	0.35(0.23-0.48)	0.40	0.48(0.31-0.66)	0.59
RCP6.0	0.12(0.07-0.17)	0.13	0.22(0.14-0.30)	0.24	0.34(0.22-0.47)	0.39	0.49(0.31-0.67)	0.60
RCP8.5	0.13(0.09-0.18)	0.14	0.26(0.17-0.34)	0.28	0.43(0.29-0.57)	0.50	0.64(0.43-0.87)	0.81
Port Adelaide								
RCP2.6	0.12(0.07-0.16)	0.13	0.21(0.13-0.29)	0.24	0.30(0.19-0.42)	0.36	0.39(0.23-0.55)	0.50
RCP4.5	0.12(0.08-0.16)	0.13	0.22(0.14-0.30)	0.25	0.33(0.21-0.46)	0.40	0.46(0.29-0.63)	0.59
RCP6.0	0.11(0.07-0.16)	0.13	0.21(0.13-0.29)	0.24	0.33(0.20-0.45)	0.39	0.46(0.29-0.65)	0.60
RCP8.5	0.13(0.08-0.17)	0.14	0.25(0.16-0.33)	0.28	0.41(0.27-0.56)	0.50	0.61(0.40-0.84)	0.81
Victor Harbour								
RCP2.6	0.12(0.07-0.16)	0.12	0.21(0.13-0.28)	0.21	0.30(0.18-0.42)	0.32	0.38(0.23-0.55)	0.43
RCP4.5	0.12(0.08-0.16)	0.12	0.22(0.14-0.30)	0.22	0.33(0.21-0.46)	0.35	0.45(0.28-0.63)	0.50
RCP6.0	0.11(0.07-0.16)	0.12	0.21(0.13-0.29)	0.21	0.32(0.20-0.45)	0.34	0.46(0.28-0.64)	0.51
RCP8.5	0.13(0.08-0.17)	0.13	0.24(0.16-0.33)	0.25	0.40(0.26-0.55)	0.44	0.60(0.39-0.83)	0.69
Sydney								

RCP2.6	0.13(0.09-0.18)	0.14	0.22(0.14-0.29)	0.24	0.30(0.19-0.42)	0.35	0.38(0.22-0.54)	0.48
RCP4.5	0.13(0.09-0.18)	0.14	0.24(0.16-0.31)	0.26	0.35(0.24-0.48)	0.41	0.47(0.30-0.65)	0.59
RCP6.0	0.13(0.08-0.17)	0.13	0.22(0.15-0.30)	0.24	0.34(0.23-0.46)	0.40	0.48(0.32-0.65)	0.60
RCP8.5	0.14(0.10-0.19)	0.15	0.27(0.19-0.36)	0.30	0.44(0.31-0.59)	0.52	0.66(0.45-0.88)	0.84
Newcastle								
RCP2.6	0.13(0.09-0.18)	0.14	0.22(0.14-0.30)	0.24	0.30(0.19-0.42)	0.36	0.38(0.22-0.54)	0.49
RCP4.5	0.14(0.09-0.18)	0.14	0.24(0.16-0.32)	0.26	0.36(0.24-0.48)	0.42	0.47(0.31-0.65)	0.60
RCP6.0	0.13(0.08-0.17)	0.13	0.22(0.15-0.30)	0.25	0.34(0.23-0.46)	0.40	0.48(0.32-0.66)	0.61
RCP8.5	0.14(0.10-0.19)	0.15	0.27(0.19-0.36)	0.30	0.45(0.31-0.59)	0.53	0.66(0.46-0.88)	0.86
Mackay								
RCP2.6	0.13(0.08-0.17)	0.13	0.21(0.14-0.29)	0.22	0.30(0.19-0.42)	0.33	0.38(0.22-0.55)	0.43
RCP4.5	0.13(0.09-0.17)	0.14	0.23(0.16-0.31)	0.24	0.35(0.23-0.47)	0.38	0.47(0.30-0.64)	0.53
RCP6.0	0.12(0.08-0.17)	0.13	0.22(0.15-0.29)	0.23	0.34(0.23-0.45)	0.36	0.48(0.31-0.65)	0.53
RCP8.5	0.14(0.09-0.18)	0.14	0.26(0.18-0.35)	0.28	0.43(0.30-0.57)	0.47	0.64(0.44-0.87)	0.73
Townsville								
RCP2.6	0.13(0.08-0.17)	0.13	0.21(0.14-0.29)	0.23	0.30(0.19-0.42)	0.33	0.38(0.23-0.54)	0.44
RCP4.5	0.13(0.09-0.17)	0.13	0.23(0.16-0.31)	0.24	0.35(0.23-0.47)	0.38	0.47(0.30-0.64)	0.53
RCP6.0	0.12(0.08-0.16)	0.13	0.22(0.15-0.29)	0.23	0.34(0.22-0.45)	0.37	0.47(0.31-0.65)	0.54
RCP8.5	0.13(0.09-0.18)	0.14	0.26(0.18-0.34)	0.28	0.43(0.30-0.57)	0.47	0.64(0.44-0.86)	0.74

Extreme sea levels may also change in the future due to changes in meteorological forcing. McInnes et al. (2015) discusses the findings of several studies that examine the future changes to extreme sea levels and waves due to future changes in weather and circulation patterns. They conclude that studies undertaken to date 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 may be neglected to first order. However, they note that changes to coastal currents and waves may also affect littoral transport and shoreline response and that coastal hotspots may exist where the change in extreme sea levels may be larger due to a combination of local geomorphology and changes in weather patterns. However, few studies to date have investigated these aspects.

6 How to Use Projections of Sea-level Rise and Allowances

The sea-level rise scenarios and allowances provided in this manual may be used to support council activities around planning and adaptation to ongoing sea-level rise. Examples of the use of these data are discussed under the following topic headings.

6.1 Flood mapping

Flood mapping is commonly undertaken to identify low-lying areas potentially vulnerable to flooding from the combination of extreme sea levels and projected sea-level rise. The sea-level rise projections and allowances discussed in this report can provide a basis for such investigations. Essentially, by adding the allowance to an extreme sea level whose present day ARI is known will yield a new level at the future time that will have the same ARI. Examples of extreme sea levels for which ARI's can be calculated under present conditions can include tides (e.g. Highest Astronomical Tide) or storm tides. Spatial analysis is then carried out, either using GIS software or hydrodynamic modelling to identify areas and infrastructure potentially vulnerable to flooding from the combination of sea-level rise and extreme water levels. The projected sea-level rise over different time horizons and RCPs enables the exploration of a range of options so that the prioritisation and staging of adaptation interventions can be investigated (e.g. McInnes et al., 2013). Also provided for each greenhouse gas history is an uncertainty range. For some applications the median projected sea-level rise may provide the appropriate value for exploration. However, to maintain the same risk to infrastructure or the environment the "allowance" is the appropriate value to use. For assessing potential exposure to critical infrastructure, it may be appropriate to investigate a higher projection such as the upper end of the *likely* range or an even higher value given the possibility that sea-level rise could exceed the *likely* range given in the IPCC AR5 Assessment by more than several tenths of a metre by 2100 if the marine sectors of the ice sheet were to disintegrate more rapidly than previously assessed (see discussion in section 4.1). Similar reasoning may apply to the choice of RCP as to whether to explore exposure to sea-level rise associated with a business-as-usual scenario such as RCP 8.5 or a strong mitigation scenario such as RCP 2.6 or the mid-range scenarios RCP 4.5 and RCP 6.0.

6.2 Providing planning allowances and adaptation guidelines

The CoastAdapt web portal also provides sea-level allowances. As discussed in section 4, these provide guidance on appropriate vertical distances that infrastructure or coastal protection works may need to be elevated to ensure that the expected frequency of exceedance events in the future under sea-level rise will not be changed from those expected under present day conditions. When clear guidelines are to be provided to the community for infrastructure planning and design, the allowance is useful in that it has been framed in terms of maintaining the present day effectiveness of flood defences. An example of its usage is in the revision of the Victorian planning allowance for sea-level rise. The Victorian Coastal Strategy (2008) stipulated that planning applications account for a sea-level rise increase of 'not less than' 0.8m by 2100. Hunter (2014) applied his allowance method (as used here) to the sea-level rise scenarios of Church et al. (2013a) to assess the ongoing suitability of the Victorian sea-level planning allowances and concluded that these levels remained appropriate for planning activities. Therefore the planning allowances have been retained in the revised Victorian Coastal Strategy (2014).

In relation to the use of allowances, Hunter et al (2013, 2014) noted that "These allowances represent a practical solution to planning for sea-level rise while preserving an acceptable level of flooding likelihood, in cases where 'getting the allowance wrong' is manageable. However, in cases where the consequence of flooding would be 'dire' (in the sense that the consequence of flooding would be unbearable, no matter how low the likelihood, as in the case of the Netherlands), a precautionary approach is to choose an allowance based on the best estimate of the *maximum* possible rise".

This point is important in the context of the allowances provided here, which are based on the 5-95% range of the model projections. McInnes et al, (2015) notes that the 5-95% range of the model projections, as reported in Church et al., (2013b) is assessed as being *'likely'* in IPCC terminology. In other words it is assessed that there is a 66.7% probability that future sea-level rise will lie within the range. The '*likely*' assessment of confidence is because of the incomplete knowledge about the future contribution of some components of sea-level rise, particularly relating to the contribution from the ice sheets and implies a broader range of uncertainty is associated with the sea-level rise projections. A higher range of uncertainty would lead to higher associated allowances.

In considering an appropriate value for the ‘maximum possible’ rise, one could consider the upper (i.e. 95th percentile value) associated with the sea-level projections for RCP 8.5 presented here. However, if the consequences of sea levels exceeding the maximum projected range are to be avoided at all costs, coastal managers may wish to consider an even higher value of sea-level rise. This may include contributions from sources whose scientific understanding remains uncertain such as the possible more rapid disintegration of the marine sectors of the Antarctic ice sheets as discussed in section 3.1.

Improving our understanding of how ice-sheets may contribute to SLR is an active area of research. A number of recent studies generally support the range of SLR reported in Church et al., (2013a) (section 3.1). However, some studies that include additional processes such as the collapse of Antarctic ice shelves, due to surface melting and hydro-fracturing (DeConto and Pollard, 2016), indicate that rises of more than several tenths of a meter by 2100 could occur. This highlights the need to continue to assess and revise if necessary the sea-level projections and guidance material provided here.

7 Discussion and Conclusions

The projections provided here build on progress in understanding and developing projections of sea-level change over the last decade as summarised in the IPCC AR5 (Church et al., 2013a) and recent studies attributing ocean thermal expansion (Slangen et al., 2014b), glacier mass loss (Marzeion et al., 2014) and total sea-level rise (Slangen et al. 2016) to anthropogenic factors. Despite this progress, the largest uncertainty remains in the contribution of the Antarctic Ice Sheet to future sea-level rise with recent observations (Rignot et al., 2014) indicating increased loss of ice from West Antarctica. Recent modelling (Favier et al., 2014; Joughin et al., 2014; Cornford et al. 2015; Ritz et al. 2015) has been able to simulate the increased flow of individual glaciers and the 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) are still incomplete and the possibility of higher rates of sea-level rise cannot be excluded (Church et al., 2013a, DeConto and Pollard, 2016).

Regional projections of sea-level rise depend on many factors. During the 20th century, Australian rates of relative sea-level rise 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 leading to a larger than global-averaged rise in the Australian region for larger ice sheet contributions.

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 evaluation of regional climate change projections. However, estimates are that the local 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 the sea-level rise 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 sea-level rise around Australia will continue beyond 2100 in all of the scenarios considered. For the RCP8.5 scenario, the rates of sea-level rise by the end of the 21st century, will be well above 20th century rate and approaching average rates (1 m/century for many millennia) experienced during the last deglaciation of the Earth from 22 thousand to 6 thousand years ago.

The expected frequency of exceedances of heights associated with particular ARIs provides relevant context for planning for and adapting to future sea-level rise. Based on this, allowances have been calculated that provide estimates of how much these present planning heights would need to be raised under uncertain sea-level rise to ensure that the expected frequency of future exceedances remains the same as in the present climate. Values vary around the Australian coast depending on the regional variations in sea-level rise, its uncertainty and characteristics of tides and storm surges. The allowances show that for 2030, the present-day frequency of sea-level exceedances can be preserved by adopting a median sea-level rise scenario. However, by 2090, a value higher than the median sea-level rise projection will be necessary. It should be noted that the allowances are based on present climate extreme sea-level behaviour and do not take into account future changes in weather conditions that could change future extreme sea levels. To date there are few studies of future changes in extreme sea levels around the Australian coast, but those completed suggest that the influence of climate change on the 1-in-100 year storm tide may be much smaller than the projected MSL change and therefore neglected to first order for most locations (see McInnes et al; 2015, 2016 for more discussion). In addition to this, only moderate confidence is given to the allowance values provided since their calculation has utilised modelled extreme sea-level data, which contains uncertainties and also that the uncertainty associated with future sea-level rise may be larger than expressed by the 5 to 95% model range.

The greater uncertainty in sea-level projections towards the end of the 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 the delay of decisions to maximise future options for adaptation. It also allows the adaptation strategies to be assessed and revised if necessary as understanding of the processes contributing to SLR improve, particularly those processes related to uncertainties in the future contribution of the Antarctic ice sheet.

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Appendix: Sea-Level Projections and Allowances at the Coastal Council Scale

The sea level and allowance data provided in the NCCARF CoastAdapt web portal is based on the Climate Change in Australia data sets described in McInnes et al. (2015) and references therein. These data have been interpolated to approximately 250 locations around the Australian coastline corresponding with coastal council boundaries and relevant islands. Spatial information on the extent of council boundaries was sourced from the https://data.gov.au website in the form of shape polygons.

For the calculation of allowances, a list of scale parameters (λ), with corresponding latitudes and longitudes were sourced from the hydrodynamic modelling study of Haigh et al. (2014). These scale parameters were available at approximately every 8 km along the coast. Scale parameters were also sourced for the set of tide gauge locations as discussed in Hunter et al., (2013). For each point of a coastal council boundary polygon, the location of the closest scale parameter was identified. For all scale parameters identified within 5.5 km of the coastal boundary points, the minimum, maximum and median scale parameters and their associated locations were identified. When no scale parameters resided within 0.05° of the council's coastal points, the search area was extended to 1° (~111 km). Examples included King and Flinders islands in Bass Strait.

Sea-level data were sourced from the gridded historical regional sea-level dataset of Church and White (2011) and gridded regional projections of Church et al. (2013). Both of these data sets were on a 1° by 1° grid. The sea level data were extracted from the nearest grid point in these data sets to the coastal council boundary points. The annual projection values were first smoothed with a 21-year average to remove much of the interannual variability.

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