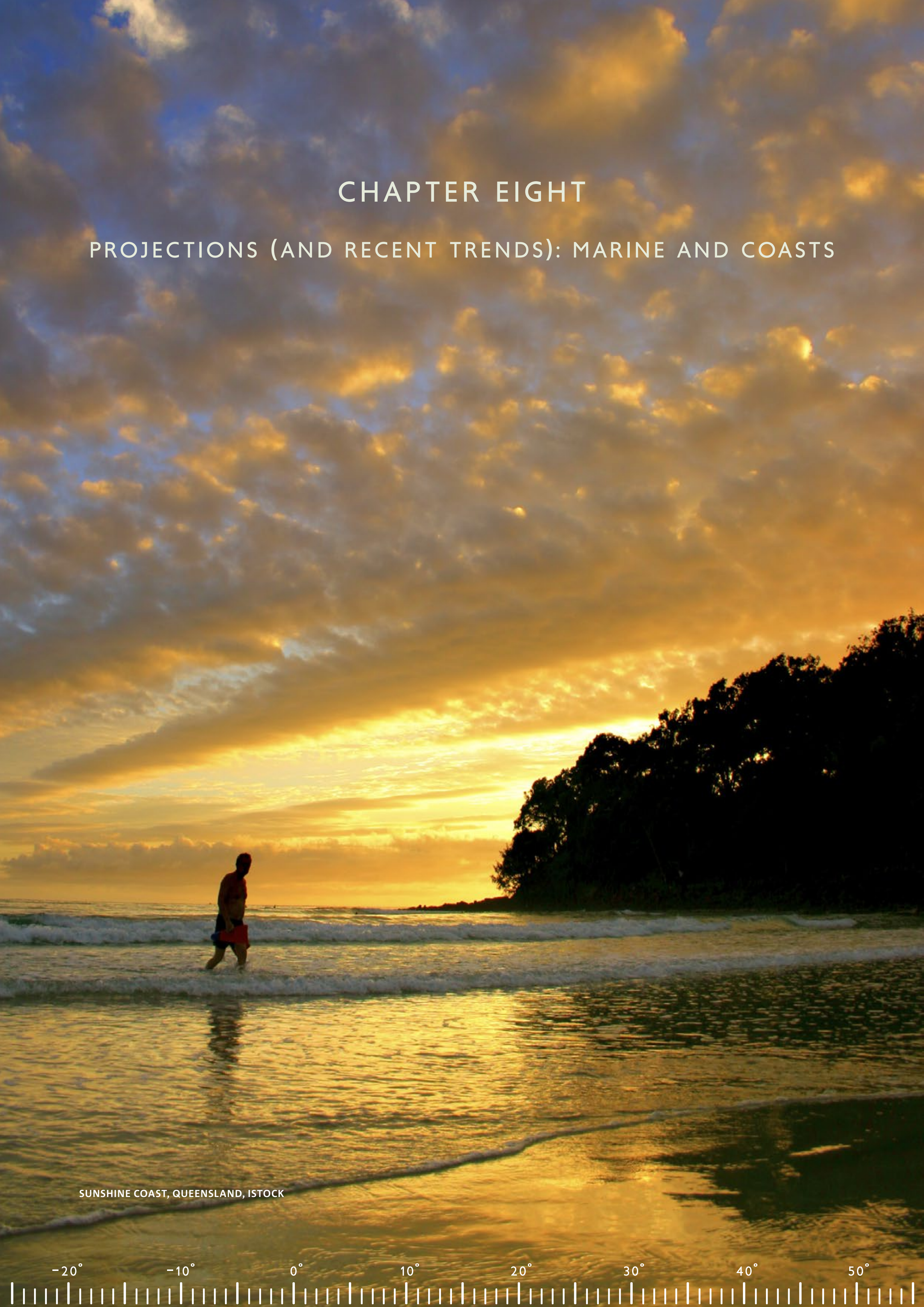
CHAPTER EIGHT

PROJECTIONS (AND RECENT TRENDS): MARINE AND COASTS



SUNSHINE COAST, QUEENSLAND, ISTOCK

CHAPTER 8 PROJECTIONS (AND RECENT TRENDS): MARINE AND COASTS

Changes in sea levels and their extremes, sea surface temperatures and ocean pH that have the potential to affect both the coastal terrestrial and marine environments are discussed in this Section. The impact of sea level rise and changes to the frequency of extreme sea levels will be felt through coastal flooding and erosion, and through resulting changes in coastal vegetation (*e.g.* salt marshes, mangroves and other coastal wetlands). For the adjacent marine environment, increases in ocean temperatures and decreases in pH have the potential to alter the distribution of marine vegetation (*e.g.* sea grass and kelp forests), increase coral bleaching and mortality, and affect coastal fisheries.

8.1 SEA LEVEL RISE

8.1.1 FACTORS CONTRIBUTING TO SEA LEVEL CHANGE

Global mean sea level (GMSL) changes as a result of changes in the density of the ocean (ocean thermal expansion or contraction) and/or 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.). In addition to the global averaged change, changes in relative sea level (i.e. the changes in sea level relative to the land) vary regionally as a result of changes in ocean dynamics (changes in ocean currents related to changes in surface winds, air-sea fluxes of heat and freshwater and internal variability), changes in the Earth's gravitational field as a result of changes in the distribution of water on the Earth, and vertical motion of the land (Church *et al*. 2013, Church *et al*. 2011a, Slangen *et al*. 2012, Church *et al*. 2014).

8.1.2 HISTORICAL GLOBAL MEAN SEA LEVEL CHANGE

Over time scales of hundreds of thousands of years, sea level has varied by over 100 m as the mass of ice sheets (particularly over north America and northern Europe and Asia) waxed and waned through glacial cycles (Foster and Rohling, 2013, Rohling *et al*. 2009). At the time of the last interglacial (129 to 116 thousand years ago), sea level was likely between 5 and 10 m higher than present (Kopp *et al*. 2009, Dutton and Lambeck, 2012, Kopp *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 (IPCC, 2013). Over the following 100,000 years sea level fell as major ice sheets formed over northern America, Europe and Asia.

Since the peak of the last ice age, sea level has risen by more than 120 m (Lambeck *et al*. 2002), mostly from about 20 to 6 thousand years ago, after which contributions from the decaying ice sheets reduced considerably. Over the last several thousand years, sea levels were comparatively steady with fluctuation in sea level not exceeding 0.25 m on time scales of a few hundred years (Woodroffe *et al*. 2012, Masson-Delmotte *et al*. 2014). Estimates of relative sea level from salt marshes (Gehrels and Woodworth, 2013) and the available long tide gauge records (Jevrejeva *et al*. 2008, Woodworth, 1999) indicate a transition from these low rates of sea level change (order tenths mm yr^{-1}) to 20th century rates (order mm yr^{-1}) in the late 19th to early 20th century.

Between 1900 and 2010, the available tide gauge estimates of GMSL (Church and White, 2006, Church and White, 2011, Jevrejeva *et al*. 2006, Jevrejeva *et al*. 2008, Ray and Douglas, 2011) indicate a rate of rise of 1.7 ± 0.2 mm/yr. All of these analyses indicate significant changes in the rate of rise during the 20th century with the largest rates since 1993 and also in the 1920 to 1950 period. The larger rate of rise since 1993 is also confirmed by the satellite altimeter data (Church *et al*. 2011b, Masters *et al*. 2012 and references therein). The Church *et al*. and the Jevrejeva *et al*. analyses indicate an acceleration (about 0.01 mm yr^{-2}) in the rate of sea level rise from the start of the analysis in the late 19th century. However, Ray and Douglas (2011) found no significant acceleration for the 20th century alone.

The 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, relative sea level has been falling in locations of former ice sheets, rising at faster than the global average rates in the immediately adjacent regions (for example New York) and rising slightly less than the global average in many locations distant from the locations of former ice sheets. For Australia, this means that sea level (compared to present day sea levels) was around a metre or more higher in some parts of Australia several thousand years ago and that the ongoing response of the Earth (Glacial Isostatic Adjustment, GIA) means that relative sea level around Australia is rising about 0.3 mm yr^{-1} less than it otherwise would (Lambeck, 2002).

8.1.3 THE AUSTRALIAN COASTLINE

A number of studies of the regional distribution of 20th century sea level rise have been completed over recent years, for example the North Sea (Wahl *et al*. 2013), British Isles (Woodworth *et al*. 2009), the English Channel (Haigh *et al*. 2009), the German Bight (Wahl *et al*. 2011), Norwegian and Russian coasts (Henry *et al*. 2012), the Mediterranean (Tsimplis *et al*. 2011, Calafat and Jorda, 2011), USA (Snay *et al*. 2007, Sallenger *et al*. 2012), and New Zealand (Hannah and Bell, 2012). The Australian region is perhaps the best instrumented southern hemisphere location for a comparable assessment (Burgette *et al*. 2013, White *et al*. 2014, whose results are quoted extensively here). However, to date, no coherent and robust global pattern in a regional distribution of sea level rise has been agreed for the 20th century or recent decades, other than that associated with GIA.

Sea level measurements began in Australia with the first sea level benchmark at Port Arthur (Tasmania) in about 1840 (Hunter *et al*. 2003), followed by the installation of tide gauges in Fort Denison (Sydney) and Fremantle (Western Australia). Indeed, Australia has the two longest sea level records in the southern hemisphere; Fort Denison from 1886 and Fremantle from 1897. The number of tide gauges around the Australian coast increased slowly until the mid 1960s. After 1966, there were 16 tide gauges along the Australian coastline (Figure 8.1.1), with at least one gauge in most sections of coast. Since 1993, high quality satellite altimeter data are also available for the surrounding oceans.

There is significant variability in sea level from year to year (Figure 8.1.2) and a single mode represents about 70 % of the total low-frequency variance (White *et al*. 2014). This variability is strongly correlated with the Southern Oscillation Index and propagates through the Indonesian Archipelago to north-western Australia and then propagates anticlockwise around Australia, decreasing in magnitude with distance from Darwin. Removing the signal associated with this mode of variability improves the agreement between long-term records (Figure 8.1.3). These results demonstrate the value of considering regional (spatial scales of order of 1000 km) signals and observations from several tide gauges (rather than just local measurements from a single gauge) when considering sea level variability and change (White *et al*. 2014). Over 1966 to 2009, the average of the relative tide gauge trends is

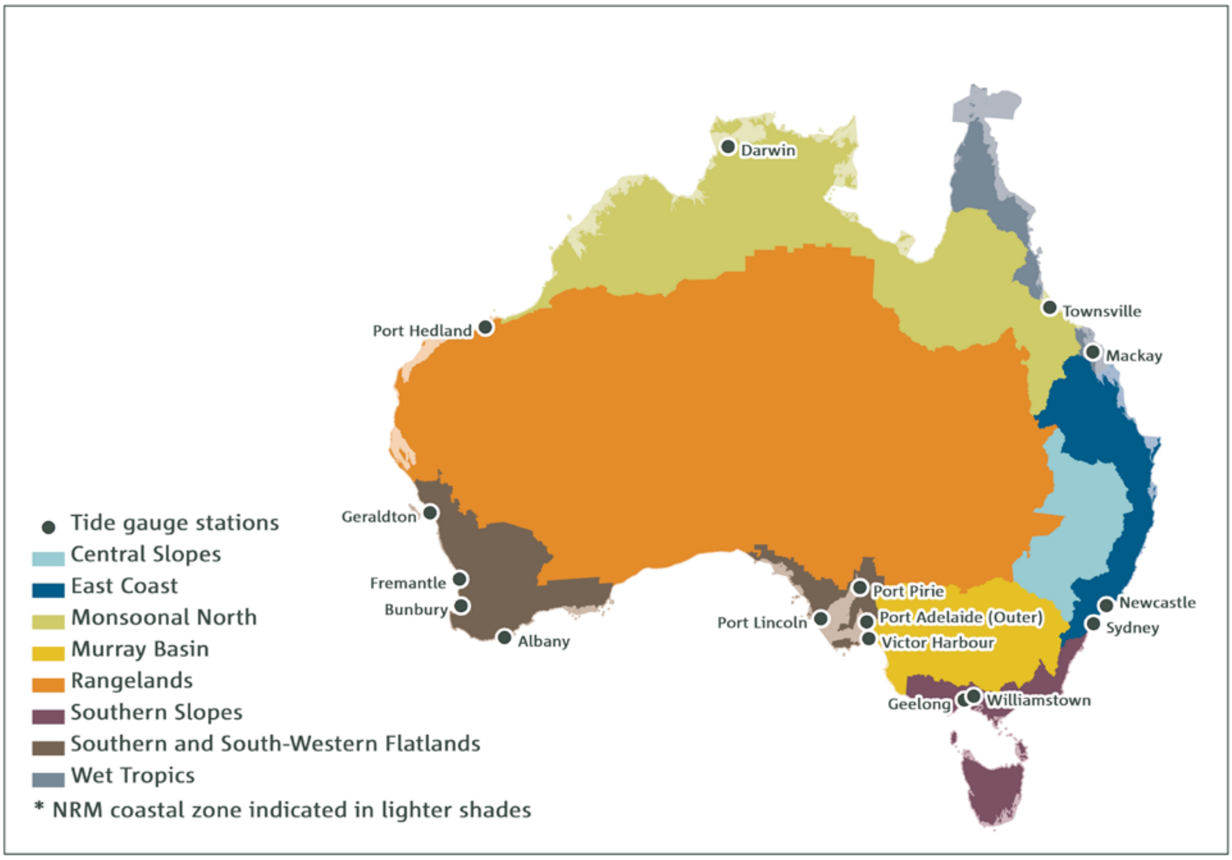


FIGURE 8.1.1: LOCATIONS ALONG THE AUSTRALIAN COASTLINE OF 16 STATIONS WITH NEAR CONTINUOUS TIDE GAUGE RECORDS AVAILABLE FOR THE PERIOD 1966 TO 2010 (SOURCE: WHITE *ET AL*. 2014).

1.4 ± 0.2 mm yr^{-1}, ranging from 0.8 mm yr^{-1} at Fort Denison and Victor Harbour 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 because the land is rising from GIA and atmospheric pressure is increasing at a number of locations in Australia (White *et al*. 2014). If it were not for these factors, the Australian average trend 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 (Figure 8.1.3).

The number of gauges increased further during the late 1980s to early 1990s. For 1993 to 2009, the corresponding average Australian trend in relative mean sea level change is 4.5 ± 1.3 mm yr^{-1}, but 2.7 mm yr^{-1} after the signal correlated with the Southern Oscillation Index is removed, and 3.1 mm yr^{-1} after allowance for GIA and atmospheric pressure changes are also included. The GMSL trend estimated from tide gauge records is 2.0 and 2.8 mm yr^{-1} over 1966 to 2009 and 1993 to 2009, respectively (White *et al*. 2014), and 3.4 mm yr^{-1} as estimated from satellite altimeters over 1993 to 2009 (and 3.2 mm yr^{-1} to December 2013). That is, after correcting for GIA and atmospheric pressure changes, the average of the Australian tide gauge trends are similar to and show a similar increase in rate as the trend in GMSL. At least part of the reason for the spatial and temporal variability in trends around Australia relates to decadal and natural variability.

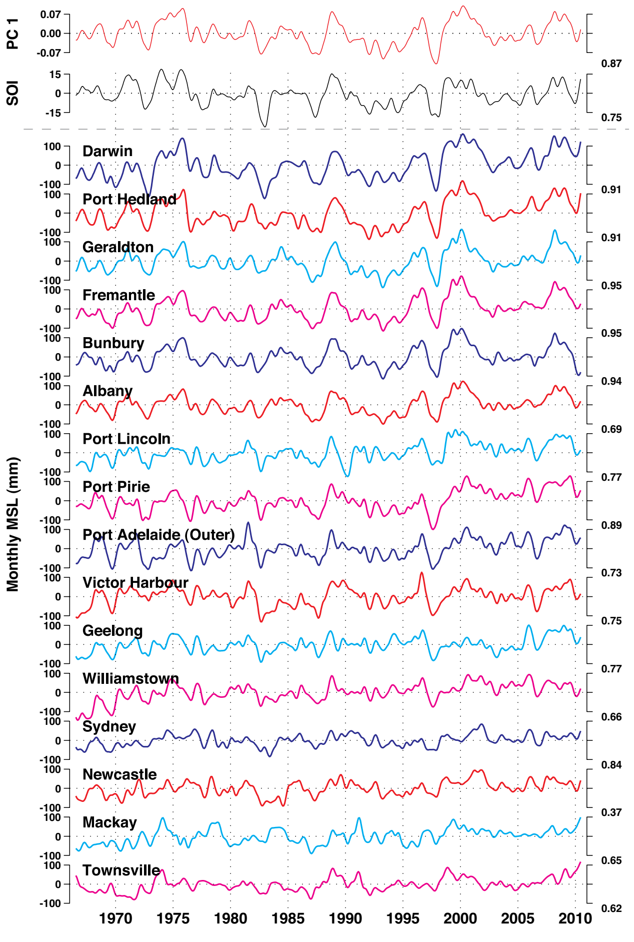


FIGURE 8.1.2: LOW-PASSED RELATIVE MEAN SEA LEVEL FOR THE 16 NEAR CONTINUOUS RECORDS AVAILABLE FOR THE PERIOD 1966 TO 2010, FROM DARWIN IN THE NORTH, ANTICLOCKWISE TO TOWNSVILLE IN THE NORTH-EAST. THE LOW-PASSED SOUTHERN OSCILLATION INDEX AND THE AMPLITUDE (PC1) OF THE SEA LEVEL VARIABILITY REPRESENTING 70 % OF THE TOTAL VARIANCE ARE ALSO SHOWN. NOTE THAT THE RECORDS AT PORT ADELAIDE AND NEWCASTLE ARE AFFECTED BY LOCAL LAND SUBSIDENCE (SOURCE: WHITE *ET AL*. 2014).

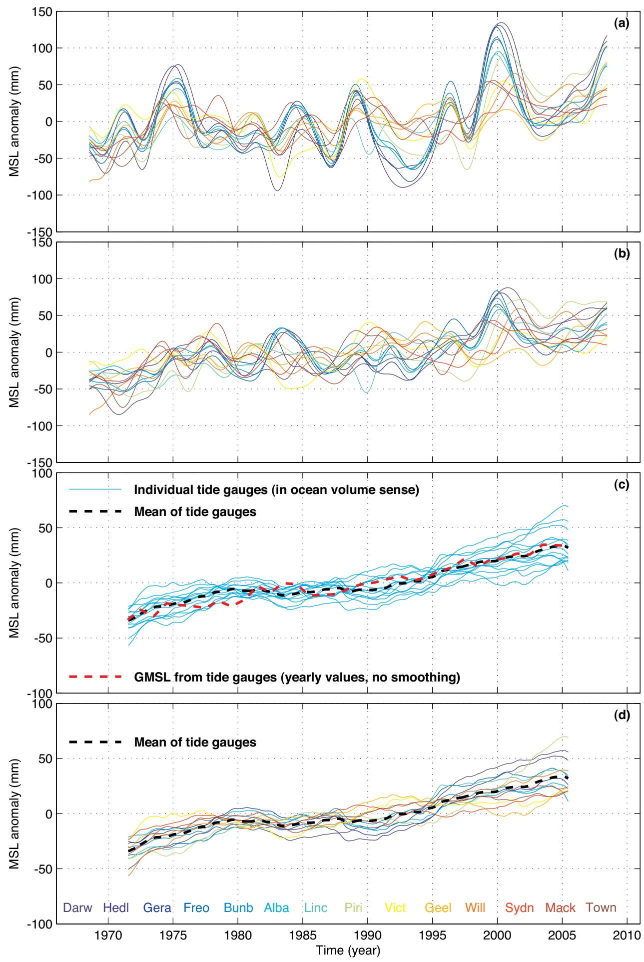


FIGURE 8.1.3: (A) LOW-PASSED RELATIVE MEAN SEA LEVELS FOR THE 14 RECORDS AVAILABLE FOR 1966 TO 2010 THAT ARE USEFUL FOR CALCULATING LONG-TERM TRENDS, AND (B) AFTER THE COMPONENT OF VARIABILITY RELATED TO ENSO HAS BEEN REMOVED. IN (C), THE DATA SMOOTHED WITH A TEN YEAR RUNNING AVERAGE AND CORRECTED FOR GIA ARE COMPARED WITH THE AVERAGE OF THE RECORDS AND THE GLOBAL MEAN SEA LEVEL FROM CHURCH AND WHITE (2011). (D) AS IN (C), BUT WITH 14 TIDE GAUGE RECORDS PLOTTED IN DIFFERENT COLOURS TO AID DISTINCTION (SOURCE: WHITE *ET AL*. 2014).

The rates of sea level rise are not uniform around Australia. Over the period from 1993 when satellite altimeter data are available, the sea level trends are larger than the GMSL trend in northern Australia and similar to the GMSL trend in southern Australia (Figure 8.1.4; White *et al*. 2014). The tide gauge and altimeter trends are generally similar, with several exceptions: the tide gauge rates at Hillary's (northern Perth) and Adelaide are larger because of downward land motion; at the Gold Coast Seaway there is an instrumental issue; and the gauges at Eden and Bunbury have trends that are anomalous compared with nearby locations to the north and south that may be related to unresolved datum or vertical land motion issues. Off south-eastern Australia, the altimeter shows a larger trend offshore than the tide gauge trends. This is thought to be associated with a strengthening of the ocean circulation in the South Pacific Ocean and southward extension of the East Australian Current (Hill *et al*. 2011, Deng *et al*. 2010), resulting in lower trends at the coast compared with offshore. The larger rates in northern Australia are largely associated with interannual variability and these larger rates are not representative of a longer term trend (Zhang and Church, 2012, White *et al*. 2014).

The two longest Australian sea level records from Fort Denison Sydney and Fremantle extend back to the late 19th century. The Sydney record appears to contain some anomalous data between 1910 and 1940, with falling sea level near the start of the period and rapidly rising sea level near the end of this period (White *et al*. 2014). Over the full record from 1886 to 2010, the relative sea level trend at Sydney is 0.65 ± 0.05 mm yr^{-1}, slightly less than the trend of 0.8 mm yr^{-1} over 1966 to 2010. When this latter period is corrected for GIA and atmospheric pressure changes, the trend is 1.3 mm yr^{-1}, less than the global average trend over 1966 to 2009 of 2.0 mm yr^{-1}. At Fremantle, the relative sea level trend over 1897 to 2010 is 1.6 ± 0.1 mm yr, with a trend of 2.2 mm yr^{-1} over 1920 to 1960, little trend from 1960 to 1990 and 4 mm yr^{-1} over the last two decades.

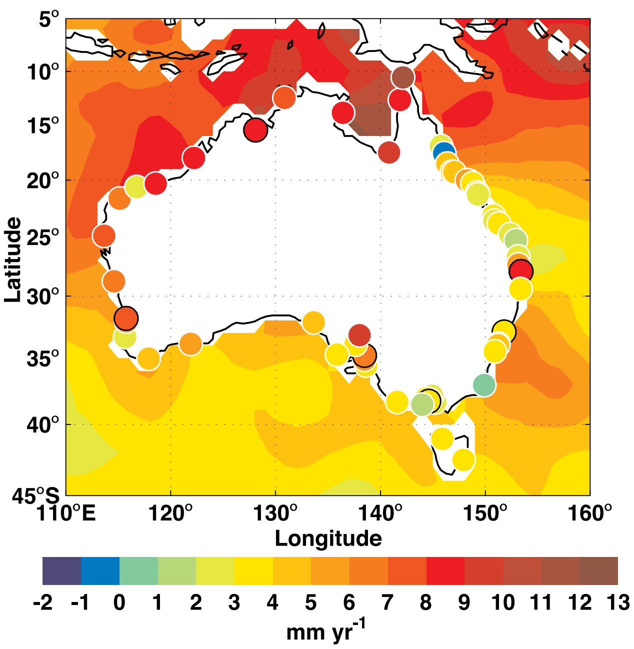


FIGURE 8.1.4: SEA LEVEL TRENDS FROM JANUARY 1993 TO DECEMBER 2010 FROM SATELLITE ALTIMETERS (COLOUR CONTOURS) AND TIDE GAUGES (COLOURED DOTS), BOTH AFTER CORRECTION FOR GLACIAL ISOSTATIC ADJUSTMENT (GIA). THE RED DOT ON THE EAST COAST AT 28 °S IS GOLD COAST SEAWAY.

8.1.4 GLOBAL PROJECTIONS

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

The methods of Church *et al*. (2014) are used to project future sea level changes by combining projected changes in sea level related to changes in ocean density and circulation (available directly from available CMIP5 GCMs) with contributions derived from purpose-built models designed to estimate additional sea level contributions. These additional contributions are the loss of mass from glaciers, the surface mass balance and the dynamic response of the Greenland and Antarctic ice sheets, changes in land water storage, the mass redistribution from glacier and ice sheet loss and its gravitational response on the ocean, and GIA.

Time series for individual contributions to global mean sea level projections are displayed in Figure 8.1.5. 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* and will not be repeated here.

As in Church *et al*. (2014), global mean sea level change for various contributions under four different RCPs is given in Table 8.1.1. Projected changes for 2090 (the average over 2080 to 2100) compared to 1986–2005 range from 26–55 cm for RCP2.6 (strong mitigation scenario) to 45–82 cm for RCP8.5 (high emissions scenario), where the range represents 90 percent of the model range. Ocean thermal expansion and melting glaciers and ice caps are the main contributors to global mean sea level change. The IPCC *Fifth Assessment Report* concluded that the global mean sea level change was likely to be in the 5-95th percentile range of model results. However, because of uncertainties in climate sensitivity and other parameters, this range is considered to be the likely range covering 66 % of possibilities. It is possible that a larger global mean sea level rise could occur prior to 2100 as a result of an instability of the marine based West Antarctic Ice Sheet, but there is currently insufficient scientific evidence to assign a specific likelihood to values larger than the above likely range. Any additional contribution from the potential collapse of the marine-based sector of the Antarctic Ice Sheet, if initiated, was assessed not to exceed several tenths of a metre of sea level rise by 2100 (Church *et al*. 2014).

Ocean thermal expansion, glaciers and ice caps are the main contributors to global mean sea level change (about 35 to 45 and 25 to 26 percent of the total, respectively) by 2090 across all RCPs. For RCP8.5 and 6.0, the rate of rise for both contributions increases throughout the 21st century, whereas for RCP2.6 and 4.5, the rate of rise decreases after about 2030 and 2070, respectively (Church *et al*. 2014).

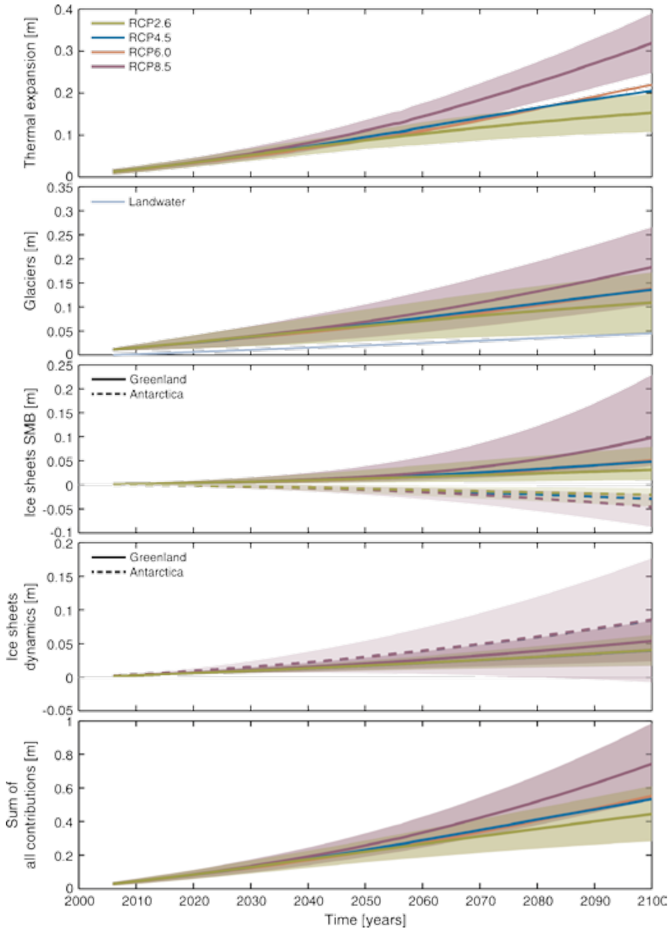


FIGURE 8.1.5: CONTRIBUTIONS (THICK COLOURED LINES) TO 21ST CENTURY SEA LEVEL RISE IN METRES CALCULATED USING THE RESULTS OF INDIVIDUAL GCMS FOR ALL RCPs. (A) GLOBAL AVERAGED OCEAN THERMAL EXPANSION. (B) GLACIER MASS LOSS. (C) CHANGES IN THE SURFACE MASS BALANCE OF THE GREENLAND AND ANTARCTIC ICE SHEETS,
(D) ICE SHEET DYNAMICAL CONTRIBUTIONS (E) THE SUM OF ALL CONTRIBUTIONS. FOR RCP8.5 AND RCP2.6 THE MULTI-MODEL MEAN VALUES WITH 5 TO 95 PERCENT UNCERTAINTY RANGES (SHADED AREAS) ARE SHOWN. FOR RCP6.0 AND RCP4.5, ONLY THE MULTI-MODEL MEAN VALUES ARE SHOWN. THE CONTRIBUTION FROM CHANGES IN TERRESTRIAL STORAGE IS NOT SHOWN. NOTE THAT THE RANGES OF SEA LEVEL RISE SHOULD CONSIDERED LIKELY (66TH PERCENTILE RANGE) AND THAT IF A COLLAPSE IN THE MARINE BASED SECTORS OF THE ANTARCTIC ICE SHEET WERE INITIATED, THESE PROJECTIONS COULD BE SEVERAL TENTHS OF A METRE HIGHER BY LATE IN THE CENTURY.

TABLE 8.1.1: MEDIAN VALUES AND LIKELY RANGES EXPRESSED IN METRES FOR PROJECTIONS OF GLOBAL AVERAGE SEA LEVEL RISE AND ITS COMPONENTS IN 2081 TO 2100 RELATIVE TO 1986 TO 2005 UNDER FOUR RCPs (BASED ON TABLE 13.5 OF THE IPCC *FIFTH ASSESSMENT REPORT*). THESE RANGES ARE BASED ON THE 5 TO 95 % RANGE OF MODEL RESULTS FOR SEA LEVEL RISE BUT SHOULD ONLY BE CONSIDERED LIKELY (GREATER THAN 66 % PROBABILITY). IF A COLLAPSE IN THE MARINE BASED SECTORS OF THE ANTARCTIC ICE SHEET WERE INITIATED, THESE PROJECTIONS COULD BE SEVERAL TENTHS OF A METRE HIGHER BY LATE IN THE CENTURY.

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
THERMAL EXPANSION	0.14 (0.10 to 0.18)	0.19 (0.14 to 0.23)	0.19 (0.15 to 0.24)	0.27 (0.21 to 0.33)
GLACIERS	0.10 (0.04 to 0.16)	0.12 (0.06 to 0.19)	0.12 (0.06 to 0.19)	0.16 (0.09 to 0.23)
GREENLAND ICE SHEET SMB	0.03 (0.01 to 0.07)	0.04 (0.01 to 0.09)	0.04 (0.01 to 0.09)	0.07 (0.03 to 0.16)
ANTARCTIC ICE SHEET SMB	-0.02 (-0.04 to 0.00)	-0.02 (-0.05 to -0.01)	-0.02 (-0.05 to -0.01)	-0.04 (-0.07 to -0.01)
GREENLAND ICE SHEET RAPID DYN	0.04 (0.01 to 0.06)	0.04 (0.01 to 0.06)	0.04 (0.01 to 0.06)	0.05 (0.02 to 0.07)
ANTARCTIC ICE SHEET RAPID DYN	0.07 (-0.01 to 0.16)	0.07 (-0.01 to 0.16)	0.07 (-0.01 to 0.16)	0.07 (-0.01 to 0.16)
LAND WATER STORAGE	0.04 (-0.01 to 0.08)	0.04 (-0.01 to 0.08)	0.04 (-0.01 to 0.08)	0.04 (-0.01 to 0.08)
SEA LEVEL RISE IN 2081-2100	0.40 (0.26 to 0.55)	0.47 (0.32 to 0.63)	0.47 (0.33 to 0.63)	0.62 (0.45 to 0.82)

8.1.5 REGIONAL PROJECTIONS FOR AUSTRALIA FOR THE 21ST CENTURY

SEA LEVELS WILL CONTINUE TO RISE THROUGHOUT THE 21ST CENTURY AND BEYOND.

In line with global mean sea level, Australian sea levels are projected to rise through the 21st century (very high confidence), and are very likely to rise at a faster rate during the 21st century than over the past four decades, or the 20th century as a whole, for the range of RCPs considered (*high confidence*). Sea level projections for the Australian coastline by 2090 (the average of 2080 to 2100) are comparable to, or slightly larger than (by up to about 6 cm) the global mean sea level projections of 26-55 cm for RCP2.6 and 45-82 cm in RCP8.5 (*medium confidence*). These ranges of sea level rise are considered likely (at least 66 % probability), and that if a collapse in the marine based sectors of the Antarctic ice sheet were initiated, the projections could be up to several tenths of a metre higher by late in the century. Regional projections for 2100 (a single year) are not given because of the effect of interannual to decadal variability on regional sea levels. However, for all scenarios, global averaged sea level in 2100 will be higher than in 2090 and sea level is projected to continue to rise beyond 2100.

To determine the regional changes in sea level around the Australian coastline, the approach of Church *et al*. (2011a) and Slangen *et al*. (2012) is used. This involved combining the dynamic ocean sea level distribution (changes in sea level from ocean circulation changes) with the regional changes associated with contemporary changes in mass of glaciers and ice sheets and its gravitational response in the ocean, and an ongoing GIA from the viscoelastic response of the Earth (movement in the mantle) to the redistribution of ice sheet mass since the last glacial maximum.

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). This analysis used the fingerprints calculated by Mitrovica *et al*. (2011). The glacier fingerprints were based on the loss of mass during the latter half of the 20th century, as estimated by Cogley (2009). 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 is insensitive to details of the exact location of mass loss on the Greenland Ice Sheet. Lacking more detailed information, for Antarctica, the mass gain from increased accumulation of snow is assumed 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.

For the GIA, the sea level projections presented here 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. The ice load history is based on the ICE-5G model of Peltier (2004).

The regional distribution in sea level change for projections for 2081 to 2100 compared to 1986 to 2005 for each of the four scenarios is shown in Figure 8.1.6. For all scenarios, the rate of rise is larger during the 21st century is faster than over the past four decades, or the 20th century as a whole, for the range of emissions scenarios considered (*high confidence*). The amount of regional sea level rise is largest for RCP8.5 and smallest for RCP2.6, with RCP4.5 and 6.0 being similar. On the larger scale, the CMIP3 climate model simulations assessed in the IPCC Fourth Assessment (Sen Gupta and England, 2006, Hall and Visbeck, 2002) 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. The East Australian Current (EAC) and associated sea level anomalies also show intensification likely due to a strengthening of the subtropical gyre circulation coupled to ACC changes as shown by Zhang *et al*. (2013) for CMIP3 simulations.

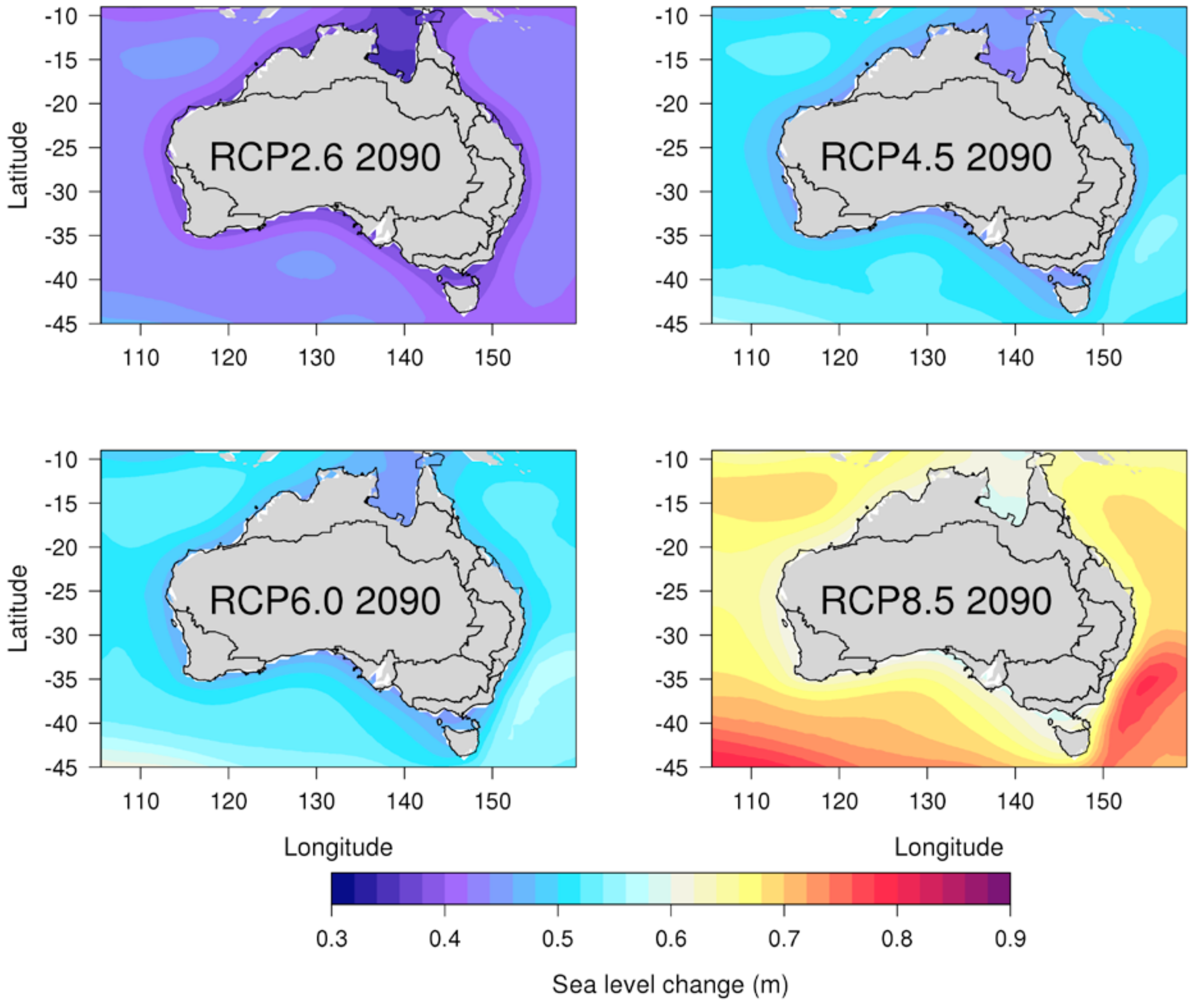


FIGURE 8.1.6: THE REGIONAL DISTRIBUTION IN SEA LEVEL CHANGE IN METRES FOR PROJECTIONS FOR 2090 (THE AVERAGE OF 2080 TO 2100) COMPARED TO 1986 TO 2005 MEAN LEVEL FOR EACH OF THE FOUR SCENARIOS. THE REGIONAL SEA LEVEL PROJECTIONS (SHADINGS) AND UNCERTAINTIES (SOLID LINES) COMBINE CONTRIBUTIONS FROM THE OCEAN DYNAMICAL RESPONSE WITH CHANGES IN MASS OF GLACIERS AND ICE SHEETS AND ITS GRAVITATIONAL RESPONSE ON THE OCEAN, AND AN ONGOING GLACIAL ISOSTATIC ADJUSTMENT (GIA). THE REGIONAL DISTRIBUTIONS IN SEA LEVEL RISE PROJECTIONS ARE CONSIDERED LIKELY. HOWEVER, IF A COLLAPSE IN THE MARINE BASED SECTORS OF THE ANTARCTIC ICE SHEET WERE INITIATED, THE PROJECTIONS COULD BE SEVERAL TENTHS OF A METRE HIGHER BY LATE IN THE CENTURY.

The projections indicate that around the Australian Coast, the rate of sea level rise during the 21st century will be larger than the average rate during the 20th century as radiative forcing from increasing greenhouse gas emissions continues (Figure 8.1.7). This result applies even for the lowest emission scenario, RCP2.6, which would require significant mitigation measures. For the first decades of the 21st century the projections are almost independent of the RCP chosen (Table 8.1.2), but they begin to separate significantly from about 2050. For higher emissions, particularly for RCP8.5, the rate of rise continues to increase through the 21st century and results in sea level rise about 30 percent higher than RCP4.5 and 6.0 levels by 2100. 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; however the current low resolution models may not adequately represent how these higher offshore sea levels are expressed at the coast. This pattern intensifies with higher emissions. Sea level projections for the Australian coastline (Table 8.1.2) are comparable to or slightly larger (by up to about 0.06 m) than the GMSL projections (*medium confidence*).

TABLE 8.1.2: MEDIAN VALUES AND LIKELY RANGES FOR PROJECTIONS OF REGIONAL SEA LEVEL RISE (IN METRES) RELATIVE TO 1986 TO 2005 UNDER ALL RCP EMISSION SCENARIOS FOR LOCATIONS ALONG THE AUSTRALIAN COASTLINE OF 16 STATIONS WITH NEAR CONTINUOUS TIDE GAUGE RECORD AVAILABLE FOR THE PERIOD 1966 TO 2010. HOWEVER, NOTE THAT THE CURRENT LOW RESOLUTION MODELS MAY NOT ADEQUATELY REPRESENT HOW OFFSHORE SEA LEVELS (PARTICULARLY THE HIGHER SEA LEVELS OFFSHORE FROM SOUTH-EASTERN AUSTRALIA) ARE EXPRESSED AT THE COAST. NOTE ALSO THAT THESE RANGES ARE BASED ON THE 5 TO 95 % RANGE OF MODEL RESULTS FOR SEA LEVEL RISE BUT SHOULD ONLY BE CONSIDERED LIKELY (GREATER THAN 66 % PROBABILITY). IF A COLLAPSE IN THE MARINE BASED SECTORS OF THE ANTARCTIC ICE SHEET WERE INITIATED, THESE PROJECTIONS COULD BE SEVERAL TENTHS OF A METRE HIGHER BY LATE IN THE CENTURY.

STATIONS	SCENARIOS	2030	2050	2070	2090
DARWIN	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.28)	0.30(0.18-0.42)	0.38(0.22-0.55)
	RCP4.5	0.12(0.08-0.16)	0.22(0.14-0.30)	0.34(0.22-0.46)	0.46(0.29-0.65)
	RCP6.0	0.11(0.07-0.15)	0.21(0.14-0.28)	0.33(0.21-0.45)	0.47(0.30-0.65)
	RCP8.5	0.13(0.08-0.17)	0.25(0.17-0.33)	0.41(0.28-0.56)	0.62(0.41-0.85)
PORT HEDLAND	RCP2.6	0.11(0.07-0.16)	0.20(0.13-0.28)	0.29(0.18-0.42)	0.38(0.22-0.55)
	RCP4.5	0.12(0.07-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.46(0.28-0.64)
	RCP6.0	0.11(0.07-0.15)	0.21(0.13-0.28)	0.32(0.21-0.45)	0.47(0.29-0.65)
	RCP8.5	0.12(0.08-0.17)	0.24(0.16-0.33)	0.41(0.27-0.55)	0.61(0.40-0.84)
GERALDTON	RCP2.6	0.12(0.07-0.17)	0.21(0.13-0.29)	0.30(0.18-0.42)	0.39(0.22-0.56)
	RCP4.5	0.12(0.07-0.16)	0.22(0.14-0.30)	0.34(0.21-0.47)	0.46(0.28-0.65)
	RCP6.0	0.11(0.06-0.16)	0.21(0.13-0.29)	0.33(0.20-0.45)	0.47(0.29-0.65)
	RCP8.5	0.13(0.08-0.17)	0.24(0.16-0.33)	0.41(0.27-0.56)	0.61(0.40-0.85)
FREMANTLE	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.29)	0.30(0.18-0.42)	0.39(0.22-0.56)
	RCP4.5	0.12(0.07-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.46(0.28-0.65)
	RCP6.0	0.11(0.06-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.47(0.29-0.65)
	RCP8.5	0.12(0.08-0.17)	0.24(0.16-0.33)	0.41(0.26-0.56)	0.61(0.39-0.84)
BUNBURY	RCP2.6	0.12(0.07-0.17)	0.21(0.13-0.29)	0.30(0.18-0.43)	0.40(0.23-0.57)
	RCP4.5	0.12(0.07-0.17)	0.22(0.14-0.30)	0.34(0.21-0.47)	0.47(0.29-0.65)
	RCP6.0	0.11(0.07-0.16)	0.21(0.13-0.29)	0.33(0.21-0.46)	0.47(0.30-0.66)
	RCP8.5	0.13(0.08-0.18)	0.25(0.16-0.34)	0.41(0.27-0.56)	0.62(0.40-0.85)
ALBANY	RCP2.6	0.12(0.08-0.17)	0.22(0.14-0.30)	0.31(0.20-0.44)	0.41(0.24-0.58)
	RCP4.5	0.13(0.08-0.17)	0.23(0.15-0.31)	0.35(0.23-0.48)	0.48(0.31-0.66)
	RCP6.0	0.12(0.07-0.17)	0.22(0.14-0.30)	0.34(0.22-0.47)	0.49(0.31-0.67)
	RCP8.5	0.13(0.09-0.18)	0.26(0.17-0.34)	0.43(0.29-0.57)	0.64(0.43-0.87)
PORT LINCOLN	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.28)	0.30(0.18-0.42)	0.38(0.23-0.55)
	RCP4.5	0.12(0.08-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.45(0.28-0.63)
	RCP6.0	0.11(0.07-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.46(0.29-0.64)
	RCP8.5	0.13(0.08-0.17)	0.24(0.16-0.33)	0.40(0.27-0.55)	0.60(0.39-0.83)
PORT PIRIE	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.28)	0.30(0.18-0.42)	0.38(0.23-0.55)
	RCP4.5	0.12(0.08-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.45(0.28-0.63)
	RCP6.0	0.11(0.07-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.46(0.29-0.64)
	RCP8.5	0.13(0.08-0.17)	0.24(0.16-0.33)	0.40(0.27-0.55)	0.60(0.39-0.83)
PORT ADELAIDE (OUTER)	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.29)	0.30(0.19-0.42)	0.39(0.23-0.55)
	RCP4.5	0.12(0.08-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.46(0.29-0.63)
	RCP6.0	0.11(0.07-0.16)	0.21(0.13-0.29)	0.33(0.20-0.45)	0.46(0.29-0.65)
	RCP8.5	0.13(0.08-0.17)	0.25(0.16-0.33)	0.41(0.27-0.56)	0.61(0.40-0.84)

STATIONS	SCENARIOS	2030	2050	2070	2090
VICTOR HARBOUR	RCP2.6	0.12(0.07-0.16)	0.21(0.13-0.28)	0.30(0.18-0.42)	0.38(0.23-0.55)
	RCP4.5	0.12(0.08-0.16)	0.22(0.14-0.30)	0.33(0.21-0.46)	0.45(0.28-0.63)
	RCP6.0	0.11(0.07-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.46(0.28-0.64)
	RCP8.5	0.13(0.08-0.17)	0.24(0.16-0.33)	0.40(0.26-0.55)	0.60(0.39-0.83)
GEELONG	RCP2.6	0.11(0.07-0.16)	0.20(0.12-0.28)	0.29(0.18-0.41)	0.37(0.22-0.53)
	RCP4.5	0.12(0.07-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.44(0.27-0.62)
	RCP6.0	0.11(0.06-0.16)	0.20(0.12-0.28)	0.31(0.19-0.44)	0.45(0.27-0.63)
	RCP8.5	0.12(0.08-0.17)	0.24(0.15-0.33)	0.40(0.26-0.54)	0.59(0.38-0.82)
WILLIAMSTOWN	RCP2.6	0.11(0.07-0.16)	0.20(0.12-0.28)	0.29(0.17-0.40)	0.37(0.22-0.53)
	RCP4.5	0.11(0.07-0.16)	0.21(0.13-0.29)	0.32(0.20-0.45)	0.44(0.27-0.62)
	RCP6.0	0.11(0.06-0.16)	0.20(0.12-0.28)	0.31(0.19-0.44)	0.45(0.27-0.63)
	RCP8.5	0.12(0.08-0.17)	0.24(0.15-0.32)	0.39(0.25-0.54)	0.59(0.38-0.81)
SYDNEY	RCP2.6	0.13(0.09-0.18)	0.22(0.14-0.29)	0.30(0.19-0.42)	0.38(0.22-0.54)
	RCP4.5	0.13(0.09-0.18)	0.24(0.16-0.31)	0.35(0.24-0.48)	0.47(0.30-0.65)
	RCP6.0	0.13(0.08-0.17)	0.22(0.15-0.30)	0.34(0.23-0.46)	0.48(0.32-0.65)
	RCP8.5	0.14(0.10-0.19)	0.27(0.19-0.36)	0.44(0.31-0.59)	0.66(0.45-0.88)
NEWCASTLE	RCP2.6	0.13(0.09-0.18)	0.22(0.14-0.30)	0.30(0.19-0.42)	0.38(0.22-0.54)
	RCP4.5	0.14(0.09-0.18)	0.24(0.16-0.32)	0.36(0.24-0.48)	0.47(0.31-0.65)
	RCP6.0	0.13(0.08-0.17)	0.22(0.15-0.30)	0.34(0.23-0.46)	0.48(0.32-0.66)
	RCP8.5	0.14(0.10-0.19)	0.27(0.19-0.36)	0.45(0.31-0.59)	0.66(0.46-0.88)
MACKAY	RCP2.6	0.13(0.08-0.17)	0.21(0.14-0.29)	0.30(0.19-0.42)	0.38(0.22-0.55)
	RCP4.5	0.13(0.09-0.17)	0.23(0.16-0.31)	0.35(0.23-0.47)	0.47(0.30-0.64)
	RCP6.0	0.12(0.08-0.17)	0.22(0.15-0.29)	0.34(0.23-0.45)	0.48(0.31-0.65)
	RCP8.5	0.14(0.09-0.18)	0.26(0.18-0.35)	0.43(0.30-0.57)	0.64(0.44-0.87)
TOWNSVILLE	RCP2.6	0.13(0.08-0.17)	0.21(0.14-0.29)	0.30(0.19-0.42)	0.38(0.23-0.54)
	RCP4.5	0.13(0.09-0.17)	0.23(0.16-0.31)	0.35(0.23-0.47)	0.47(0.30-0.64)
	RCP6.0	0.12(0.08-0.16)	0.22(0.15-0.29)	0.34(0.22-0.45)	0.47(0.31-0.65)
	RCP8.5	0.13(0.09-0.18)	0.26(0.18-0.34)	0.43(0.30-0.57)	0.64(0.44-0.86)

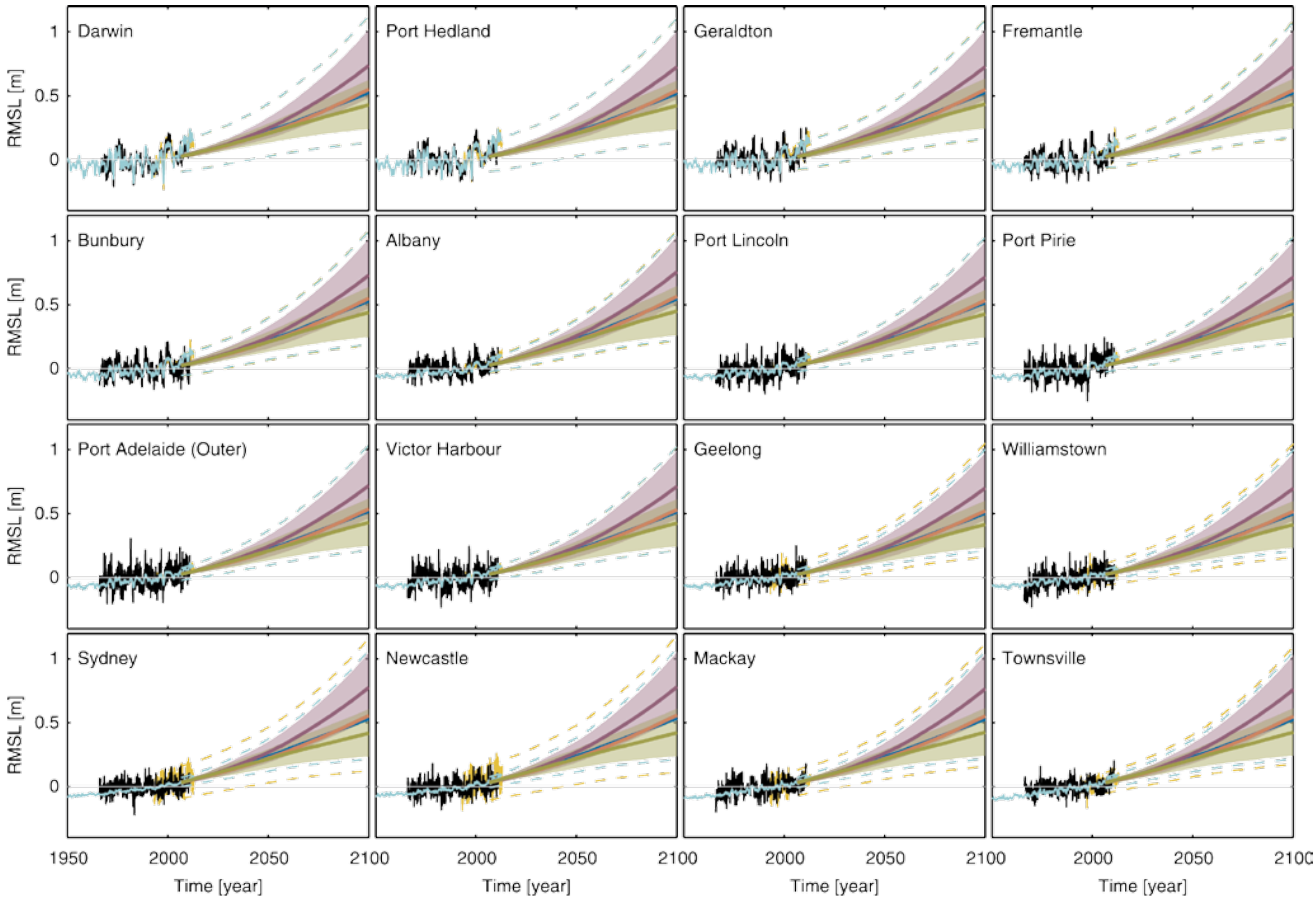


FIGURE 8.1.7: OBSERVED AND PROJECTED RELATIVE SEA LEVEL CHANGE IN METRES FOR THE 16 NEAR CONTINUOUS RECORDS AVAILABLE FOR THE PERIOD 1966 TO 2010, FROM DARWIN IN THE NORTH, ANTICLOCKWISE TO TOWNSVILLE IN THE NORTH-EAST. THE OBSERVED TIDE GAUGE RELATIVE SEA LEVEL RECORDS ARE INDICATED IN BLACK, WITH THE SATELLITE RECORD (SINCE 1993) IN MUSTARD AND TIDE GAUGE RECONSTRUCTION (WHICH HAS LOWER VARIABILITY) IN CYAN. MULTI-MODEL MEAN PROJECTIONS SHOWN AS THICK LINES (RCP8.5 PURPLE, RCP6.0 ORANGE, RCP4.5 BLUE AND RCP2.6 OLIVE) WITH LIKELY UNCERTAINTY RANGE FOR THE RCP8.5 AND RCP2.6 EMISSIONS SCENARIOS SHOWN BY THE PURPLE AND OLIVE SHADED REGIONS FROM 2006 TO 2100. THE MUSTARD AND CYAN DASHED LINES ARE AN ESTIMATE OF INTERANNUAL VARIABILITY IN SEA LEVEL DERIVED FROM OBSERVED ALTIMETER AND TIDE GAUGE RECONSTRUCTION RECORDS (LIKELY UNCERTAINTY RANGE ABOUT THE PROJECTIONS) AND INDICATE THAT INDIVIDUAL MONTHLY AVERAGES OF SEA LEVEL CAN BE ABOVE OR BELOW LONGER TERM AVERAGES. NOTE THAT THESE RANGES ARE BASED ON THE 5 TO 95 % RANGE OF MODEL RESULTS FOR SEA LEVEL RISE BUT SHOULD ONLY BE CONSIDERED LIKELY (GREATER THAN 66 % PROBABILITY). IF A COLLAPSE IN THE MARINE BASED SECTORS OF THE ANTARCTIC ICE SHEET WERE INITIATED, THESE PROJECTIONS COULD BE SEVERAL TENTHS OF A METRE HIGHER BY LATE IN THE CENTURY.

Significant interannual variability of monthly sea level records (Figure 8.1.2) has been effectively removed in forming the ensemble average projections. However, the interannual variability will continue through the 21st century and beyond. An indication of its magnitude is given by the dotted lines plotted above the top and below the bottom of the projections in Figure 8.1.7, indicating the 5 to 95 precent uncertainty range of the detrended historical records.

8.1.6 CAVEATS

Changes in local winds, ocean currents and changes in seawater density on the continental shelves contribute to the variability and trends of sea level along the coast. However, due to their coarse resolution (spatial resolution of order 1° of lat/lon), GCMs do not accurately represent the details of ocean currents such as the East Australian Current, are not eddy resolving and do not completely represent deep ocean and continental shelf interactions or local coastal processes resulting in changes of coastlines. As a result, the coastal response of sea level to climate change contains additional uncertainties to those represented in GCMs. These additional uncertainties are not expected to change the large-scale results qualitatively but may result in slightly higher or lower sea levels than reported here. Also, GCMs do not represent processes such as fluvial and wave erosion, sediment transport or land subsidence. Local geological effects could lead to significant departure from the modelled local sea level changes. Compaction of sediments in deltaic regions and reclaimed land from the sea for infrastructure developments, subsidence exacerbated by ground water extraction, and changes in sediment supply to the coast as rivers become more managed, may quantitatively increase sea level change projections at some locations.

Note the regional projections included here are slightly different to those in Church *et al*. (2013). Here, the projections only include any changes in mean sea level averaged over 20 years. The interannual variability in sea level is assumed approximately constant and is indicated by the dashed lines in Figure 8.1.7. In contrast, in Church *et al*. (2013), the regional projections include the year to year variability in sea level. Other minor differences in the way regional sea levels are computed result in only trivial differences in the projections.

8.1.7 BEYOND 2100

At the end of the 21st century, sea level is continuing to rise in all scenarios, with the rate in the high emission scenario equivalent to the average rate experienced during the deglaciation of the Earth following the last glacial maximum. Global mean and Australian sea levels will continue to increase beyond 2100, with thermal expansion contributions continuing to rise for many centuries proportional to the degree of warming. In contrast, mountain glacier contributions per degree of warming show a tendency to slow as the amount of glacier ice available to melt decreases. Surface melting of the Greenland ice sheet is projected to continue. 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 ocean and atmosphere future warming. Longer term sea level rise will depend on future emissions.

8.2 EXTREME SEA LEVELS

EXTREME SEA LEVELS WILL RISE

Taking into account uncertainty in sea level rise projections and nature of extreme sea levels along the Australian coastline, an indicative extreme sea level ‘allowance’ is calculated. This allowance is the minimum distance required to raise an asset to maintain current frequency of breaches under projected sea level rise. Along the Australian coast, these allowances are comparable to the upper end of the range of the respective sea level projections (*medium confidence*). The main contribution to increasing extreme sea levels is from the rise in mean sea level (*medium confidence*). Contributions to extreme sea levels from changes in weather events are projected to be small or negative (*low confidence*).

Extreme coastal sea levels arise from the combination of factors including astronomical tides, storm surges and wind waves. Storm surges can arise from the passage of weather systems and their associated strong surface winds and falling atmospheric pressure. Sea levels increase at a rate of approximately 1 cm per hPa fall in local air pressure (the so-called inverse barometer effect) and wind stress directed onshore increases the water level against the coast (wind setup), while offshore winds reduce coastal sea levels (referred to as wind setdown). Along mid-latitude coastlines, sustained longshore wind stress can also alter coastal sea levels. In the Southern Hemisphere, anticlockwise/clockwise flow around a coastline leads to elevated/lowered coastal sea levels through Earth rotation effects that deflect the induced longshore current to the left of the direction of flow (often referred to as current setup/setdown). For example, along the south coast of Australia, the majority of storm surges have been found to occur in response to westerly to south-westerly winds that accompany strong cold fronts, which are most common during the colder months of the year from about April to October (McInnes and Hubbert, 2003).

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 and wave runup, the first of which is the temporary elevation in sea levels due to the cumulative effect of wave breaking, and the second of which is the maximum elevation up the shore that is reached by an individual wave breaking. In general, storm surges tend to be higher in coastal regions with relatively wide and shallow continental shelves compared to narrow shelf regions. In Australia, such regions include the tropical regions, Bass Strait and the Great Australian Bight. On the other hand, higher wave energy can reach the coast in regions where the continental shelf is narrower such as the coastlines of the Southern and South-Western flatlands west, Murray Basin and the East Coast South.

Other factors such as ocean currents and climate variability can also contribute to variations in coastal sea levels on different timescales. For example, on the south-west Western Australia 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 (Pattiaratchi 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 similar magnitudes.

Haigh *et al*. (2014) simulated the extreme sea levels arising from weather and tides over the period 1949 to 2009 using 6-hourly meteorological forcing obtained from the NCEP reanalyses. Extreme sea level data were found to be well represented by a particular extreme value distribution (the Gumbel distribution). Fitting the 61 years of modelled data to this distribution enabled return periods of storm tides to be estimated. The 1-in-100 year storm tide level is shown in Figure 8.2.1. This is the height that has a 1 per cent chance of occurring in any given year. The heights vary around the coastline according to both the tidal range and the magnitude of storm surges that can occur along a section of coast due to the coastline features and the prevailing meteorology of the region. The highest storm tides occur on the north-west shelf due to the large tidal range and the fact that large storm surges can occur over the wide shelf region. Lower storm tides occur on the coastlines of the southern and SW flatlands west, Murray Basin and East Coast South due to the narrower continental shelf and smaller tidal range.

Under future climate conditions, extreme sea levels are expected to change due to increases in regional sea level (Section 8.1) and changes in climate and meteorological events (Section 7.3). To account for the projected increase in mean sea levels and associated uncertainties, Hunter (2012) developed an allowance, based on the range of sea level rise projections and the behaviour of extreme sea levels, which provides guidance on the amount of sea level rise that should be considered for future planning and adaptation activities. The method estimates the minimum height that structures would need to be raised in a future period so that the expected number of exceedences of that height would remain the same as those expected under present sea level conditions (see also Hunter *et al*. 2013).

The allowance accounts not only for the uncertainty in the sea level rise projections but also the characteristics of extreme sea level events in the coastal location of interest. In this method it is assumed that extreme sea level return periods follow a simple Gumbel distribution and that the uncertainty in future sea level rise can be approximated using a normal distribution.

The allowance is given by $A = \Delta z+(\sigma 2/2\lambda)$ where Δz is the mid-range sea level rise scenario, σ is the standard deviation of the sea level rise projection uncertainty, and λ is the Gumbel scale parameter. This scale parameter describes the degree of stretching of the extreme sea level distribution where a larger scale parameter describes a distribution with a heavier tail and hence a greater probability of extreme events occurring.

The allowances were calculated using the regional sea level rise projections presented in Section 8.1 and the scale parameters generated by Haigh *et al*. (2014). Values for 2030 and 2090 (relative to 1986 to 2005) under RCP4.5 and 8.5 are shown in Figure 8.2.2. Selected allowance values around Australia are also provided in Table 8.2.1. 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 sea level rise scenario. For example, for both Townsville and Albany the allowances for RCP4.5 are calculated to be 0.13 m, the same as the median sea level rise scenarios in these locations (Table 8.1.2). However as the uncertainty becomes larger, as is the case for 2090,

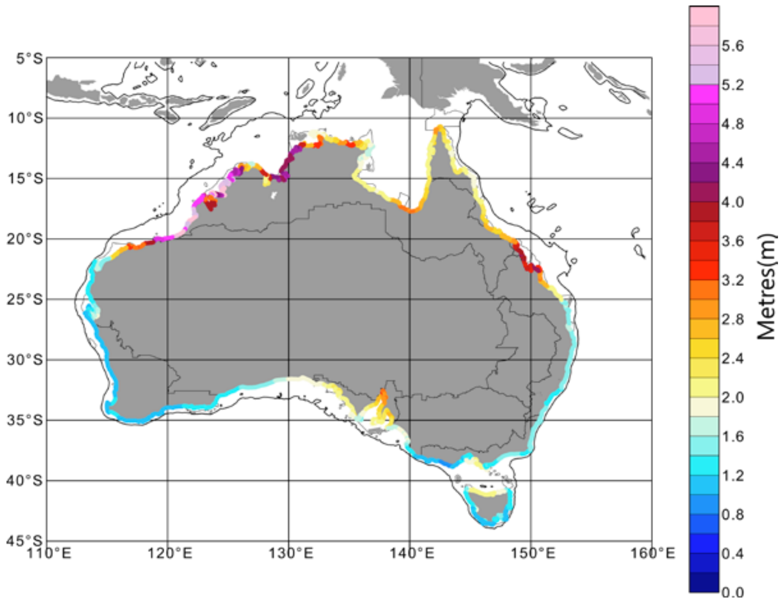


FIGURE 8.2.1: THE 1-IN-100 YEAR STORM TIDE HEIGHT IN METRES (COLOURED DOTS) RELATIVE TO MEAN SEA LEVEL CALCULATED FROM A HYDRODYNAMICAL MODEL OF STORM TIDES FROM 1949 TO 2009 USING 6-HOURLY METEOROLOGICAL FORCING FROM THE NCEP REANALYSES AND TIDAL FORCING FROM THE TPXO7.2 TIDAL MODEL. ALSO SHOWN IS THE 150 M ISOBATH. RETURN PERIODS OF STORM TIDES WERE ESTIMATED BY FITTING A GUMBEL DISTRIBUTION TO THE MODELLED ANNUAL MAXIMUM SEA LEVELS OVER THE 61-YEAR PERIOD.

the allowances become larger and tend to lie between the median and 95th percentile sea level rise projection. For example, for Townsville and Albany under RCP8.5, the allowances become 0.74 and 0.81 m respectively, which lie between the median and 95th percentile projections of both locations i.e. 0.64 [0.44-0.86] and 0.64 [0.43-0.87] respectively.

The relatively higher allowance at Albany compared to Townsville is because the allowances are also dependent on the current nature of extreme sea levels, which are characterised by the steepness of the extreme sea level return period curves. In areas that do not experience large sea level extremes, 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. For example, in Albany, extreme sea levels tend to be less extreme leading to a less steep return period curve compared to Townsville. Consequently the sea level allowance for Albany is higher than that for Townsville.

Extreme sea levels may also change in the future due to changes in weather systems. Colberg and McInnes (2012) examined the changes to annual maximum sea levels along the coastline of southern Australia and Tasmania over the period 2080 to 2099 compared to 1980 to 1999 in four climate model simulations under the SRES A2 emission scenario (Nakicenovic and Swart, 2000). Changes were found to be small, amounting to at most a few centimetres (typically at least an order of magnitude smaller than the projected sea level rise for that scenario). They were also mostly negative (i.e. leading to a reduction in extreme sea levels) 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 bringing weaker winds to the south coast but stronger winds and higher variability over Tasmania. 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

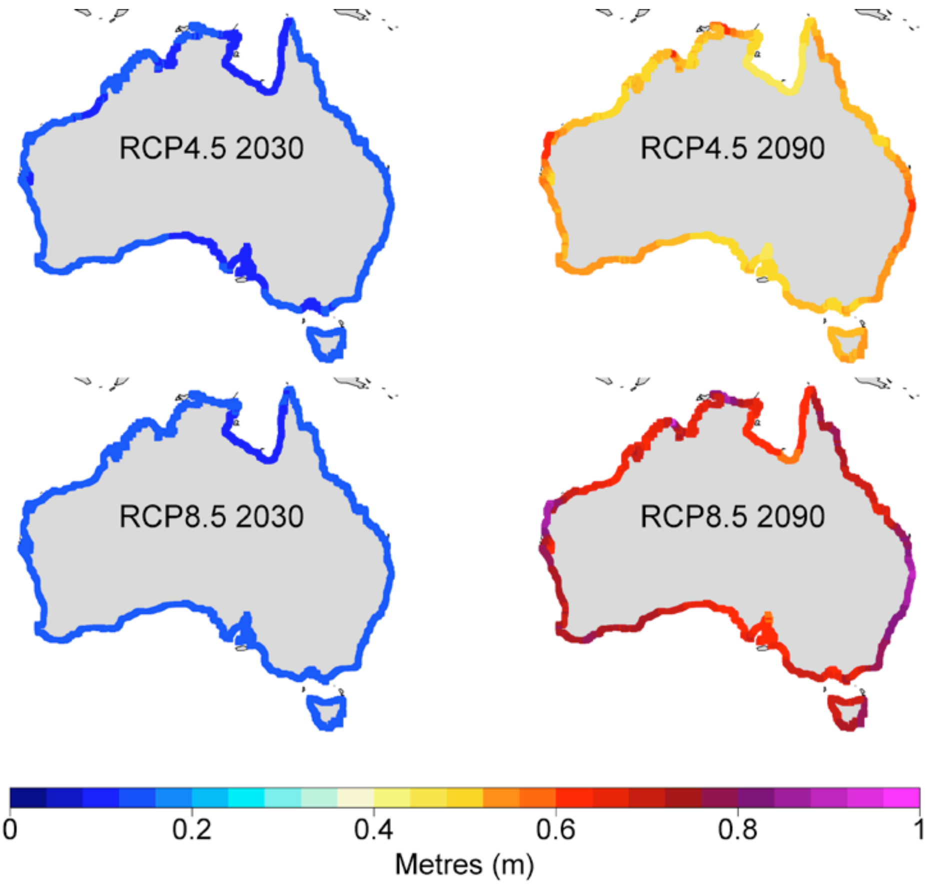


FIGURE 8.2.2: THE ALLOWANCE OR THE VERTICAL DISTANCE THAT AN ASSET NEEDS TO BE RAISED UNDER A RISING SEA LEVEL SO THAT THE PRESENT LIKELIHOOD OF FLOODING DOES NOT INCREASE. VALUES ARE SHOWN FOR RCP4.5 AND RCP8.5 ASSUMING THE PROJECTED SEA LEVEL INCREASE FOR 2030 AND 2090, THE UNCERTAINTY IN THOSE PROJECTIONS AND AN ESTIMATE OF EXTREME SEA LEVEL FREQUENCY AND HEIGHTS BASED ON SEA LEVELS OVER THE PERIOD 1949–2009.

TABLE 8.2.1: THE ALLOWANCE, OR MINIMUM HEIGHT (IN METRES) THAT STRUCTURES WOULD NEED TO BE RAISED FOR THE FUTURE PERIOD SO THAT THE EXPECTED NUMBER OF EXCEEDENCES OF THAT HEIGHT WOULD REMAIN THE SAME AS FOR THE 1986-2005 AVERAGE SEA LEVEL CONDITIONS. EXAMPLES ARE SELECTED FOR A SUBSET OF LOCATIONS GIVEN IN TABLE 8.1.2.

STATIONS	SCENARIOS	2030	2050	2070	2090
DARWIN	RCP2.6	0.12	0.21	0.32	0.43
	RCP4.5	0.12	0.23	0.36	0.52
	RCP6.0	0.12	0.22	0.35	0.53
	RCP8.5	0.13	0.26	0.45	0.71
PORT HEDLAND	RCP2.6	0.12	0.21	0.32	0.43
	RCP4.5	0.12	0.23	0.36	0.52
	RCP6.0	0.11	0.22	0.35	0.52
	RCP8.5	0.13	0.26	0.44	0.70
GERALDTON	RCP2.6	0.12	0.22	0.35	0.49
	RCP4.5	0.12	0.24	0.39	0.57
	RCP6.0	0.12	0.23	0.38	0.58
	RCP8.5	0.13	0.27	0.48	0.78
FREMANTLE	RCP2.6	0.12	0.22	0.34	0.47
	RCP4.5	0.12	0.24	0.38	0.56
	RCP6.0	0.12	0.22	0.37	0.56
	RCP8.5	0.13	0.26	0.47	0.76
BUNBURY	RCP2.6	0.12	0.22	0.34	0.47
	RCP4.5	0.12	0.24	0.38	0.55
	RCP6.0	0.12	0.23	0.37	0.56
	RCP8.5	0.13	0.27	0.47	0.75
ALBANY	RCP2.6	0.13	0.24	0.36	0.50
	RCP4.5	0.13	0.25	0.40	0.59
	RCP6.0	0.13	0.24	0.39	0.60
	RCP8.5	0.14	0.28	0.50	0.81
PORT ADELAIDE (INNER)	rcp25	0.13	0.24	0.36	0.50
	RCP4.5	0.13	0.25	0.40	0.59
	RCP6.0	0.13	0.24	0.39	0.60
	RCP8.5	0.14	0.28	0.50	0.81
VICTOR HARBOUR	rcp25	0.12	0.21	0.32	0.43
	RCP4.5	0.12	0.22	0.35	0.50
	RCP6.0	0.11	0.21	0.34	0.51
	RCP8.5	0.13	0.25	0.44	0.69
SYDNEY	RCP2.6	0.14	0.24	0.35	0.48
	RCP4.5	0.14	0.26	0.41	0.59
	RCP6.0	0.13	0.24	0.40	0.60
	RCP8.5	0.15	0.30	0.52	0.84

STATIONS	SCENARIOS	2030	2050	2070	2090
NEWCASTLE	RCP2.6	0.14	0.24	0.36	0.49
	RCP4.5	0.14	0.26	0.42	0.60
	RCP6.0	0.13	0.25	0.40	0.61
	RCP8.5	0.15	0.30	0.53	0.86
MACKAY	RCP2.6	0.13	0.22	0.33	0.43
	RCP4.5	0.14	0.24	0.38	0.53
	RCP6.0	0.13	0.23	0.36	0.53
	RCP8.5	0.14	0.28	0.47	0.73
TOWNSVILLE	RCP2.6	0.13	0.23	0.33	0.44
	RCP4.5	0.13	0.24	0.38	0.53
	RCP6.0	0.13	0.23	0.37	0.54
	RCP8.5	0.14	0.28	0.47	0.74

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, although larger increases were apparent for longer return periods (*e.g.* 1-in-1000 year storm tides). Such changes have not been incorporated in the allowances presented using the method of Hunter (2012).

In summary, the projected sea level allowances provide guidance on the amount of sea level rise that should be considered for future planning and adaptation activities to ensure that the frequency of extreme sea level exceedences in the future will remain unchanged from present conditions. For 2030, the current rate of sea level exceedences can be preserved by adopting a median sea level rise scenario, but by 2090 a value higher than the median sea level rise projection will be necessary (*high confidence*). However, only *medium confidence* is given to the actual allowance values provided since their calculation has utilised modelled extreme sea level data, which contains uncertainties, and because the allowances have not taken into account possible changes in the behaviour of extreme sea levels in the future. Although future changes in weather conditions may also contribute to changes in future extreme sea levels, the hydrodynamic downscaling studies that investigate such changes are few and of limited regional extent, which leads to *low confidence* in their projected changes at this time. However, the studies that have been undertaken suggest that the influence of such changes on the 1-in-100 year storm tide may be small for parts of Australia's coastline.

8.3 SEA SURFACE TEMPERATURE

OCEANS AROUND AUSTRALIA WILL WARM

There is very *high confidence* that sea surface temperatures around Australia will rise, with the magnitude of the warming dependent on the RCP. Near-coastal sea surface temperature rise around Australia is typically around 0.4-1.0 °C by 2030 and around 2-4 °C by 2090 under RCP8.5 compared to current (1986–2005).

Sea surface temperature (SST), the temperature measured in the upper ocean (from the surface down to 20 m), has significantly warmed globally over the last five decades (*e.g.* Levitus *et al*. 2000). SST is key variable in controlling the temperature of the land surface as well as the productivity of the marine environment. SSTs vary spatially around Australia, between 9 °C in the far south and 29 °C in the north (Locarnini *et al*. 2010), but these can be higher close to land. SST varies on interannual, seasonally and diurnal timescales. Analysis of the last 30 years shows warming along more than 70 % of the world's coastlines, with an earlier onset of the warm season although the rates of change are highly heterogeneous (Lima and Wethey, 2012). An example of this is the unprecedented ocean temperatures that were recorded along the Western Australian coast during the austral summer of 2010/2011, with near shore temperatures peaking at about 5 °C above average (Pearce and Feng, 2013, also see Section 4.2). This event is associated a long-term SST increase off the Western Australian Coast (Leeuwin Current) that has intensified post 1980 (Zinke *et al*. 2014). There has also been a warming of western boundary currents, such as off the east of Australia and Tasmania (Holbrook and Bindoff, 1997) where the

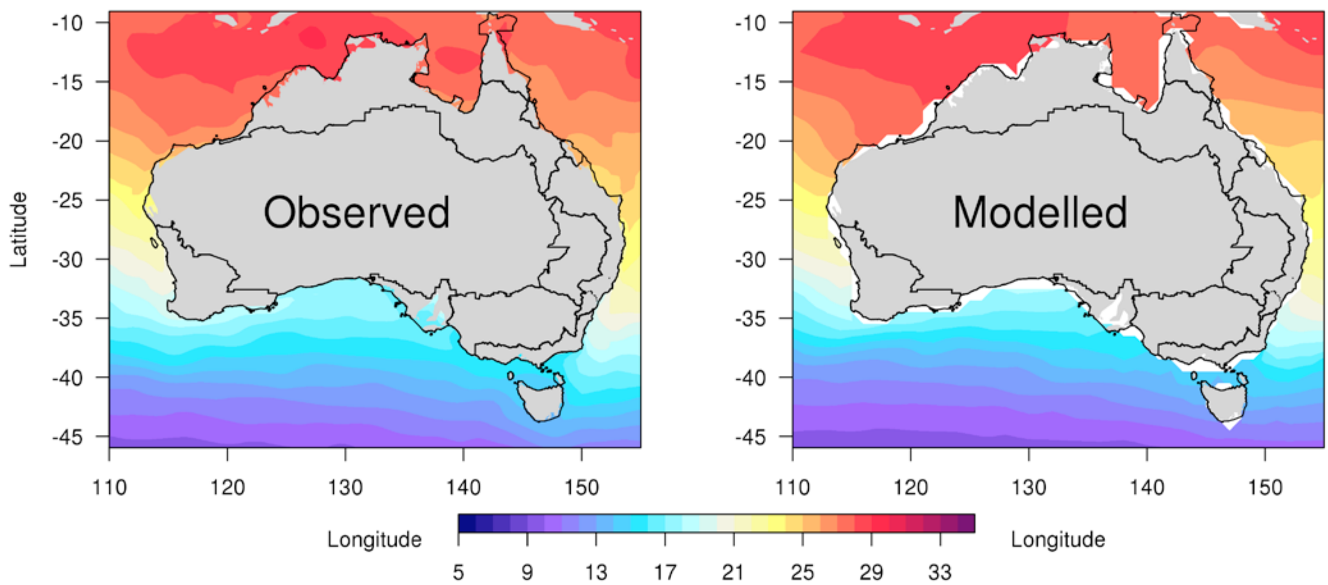


FIGURE 8.3.1: (A) OBSERVED SEA SURFACE TEMPERATURE (CARS; RIDGWAY *ET AL*. 2002) AND (B) SIMULATED SEA SURFACE TEMPERATURE 1986–2005 (°C); THE SIMULATION REPRESENTS THE MEDIAN OF 14 CMIP5 MODELS.

warming has been 2 to 3 times faster than the global mean (Wu *et al*. 2012). In the future, sea surface temperatures are projected to continue to increase (*e.g.* Knutti and Sedláček, 2013) although the impacts on the coastal ocean, where local processes and hydrodynamics can play a key role are not resolved in climate models.

Figure 8.3.1 compares observed *in situ* SSTs with those of the simulated mean over the 1986 to 2005 period. Overall the spatial pattern of SST is well represented, with the north to south gradient captured well in the simulations. However the SST is slightly warmer in the simulations with the isotherms shifted southwards and this is more evident along the southern coastline of Australia.

Under all emissions scenarios, a sea surface temperature increase around Australia is projected (Figure 8.3.2). All emissions scenarios show that the smallest increases in SST occur in southern Australia, while the largest warming occurs along the north-west coast of Australia, southern Western Australia, and along the east coast of Tasmania. The magnitude of this warming depends on the emissions scenario, with the largest increases in SST under RCP8.5. Generally warming is around (0.4-1.0 °C) in 2030 (under RCP 4.5), but is typically around 2-4 °C under RCP8.5 in 2090. Along the east coast of Tasmania in particular, very large changes are seen, with median changes as large as 4 °C projected under RCP8.5, and greater than 6 °C in the 90th percentile. The 10th and 90th percentiles of RCP8.5 show the same spatial pattern as the 50th percentile but with different magnitudes, which indicates a robust spatial warming pattern. The magnitude of the large-scale increases in SST may be much larger along the coast (*e.g.* Lima and Wethey, 2012) and modulated by processes such as local hydrodynamics and processes that are not well resolved in climate models (Matear *et al*. 2013). Nevertheless, this large-scale warming projected under RCP4.5 and RCP8.5 indicates that around Australia marine biodiversity is likely to impacted through southward shifts in some marine species (to cooler regions) and local extinction for others (Wernberg *et al*. 2011), as well as threatening the long-term viability of key habitats such as coral reefs *e.g.* Frieler *et al*. (2012) and Hoegh-Guldberg *et al*. (2007). There is *very high confidence* that the oceans around Australia will warm in the future, and the magnitude of this warming will dependent on the RCP, but only *medium confidence* in the coastal projections of this warming.

-20° -10° 0° 10° 20° 30° 40° 50°

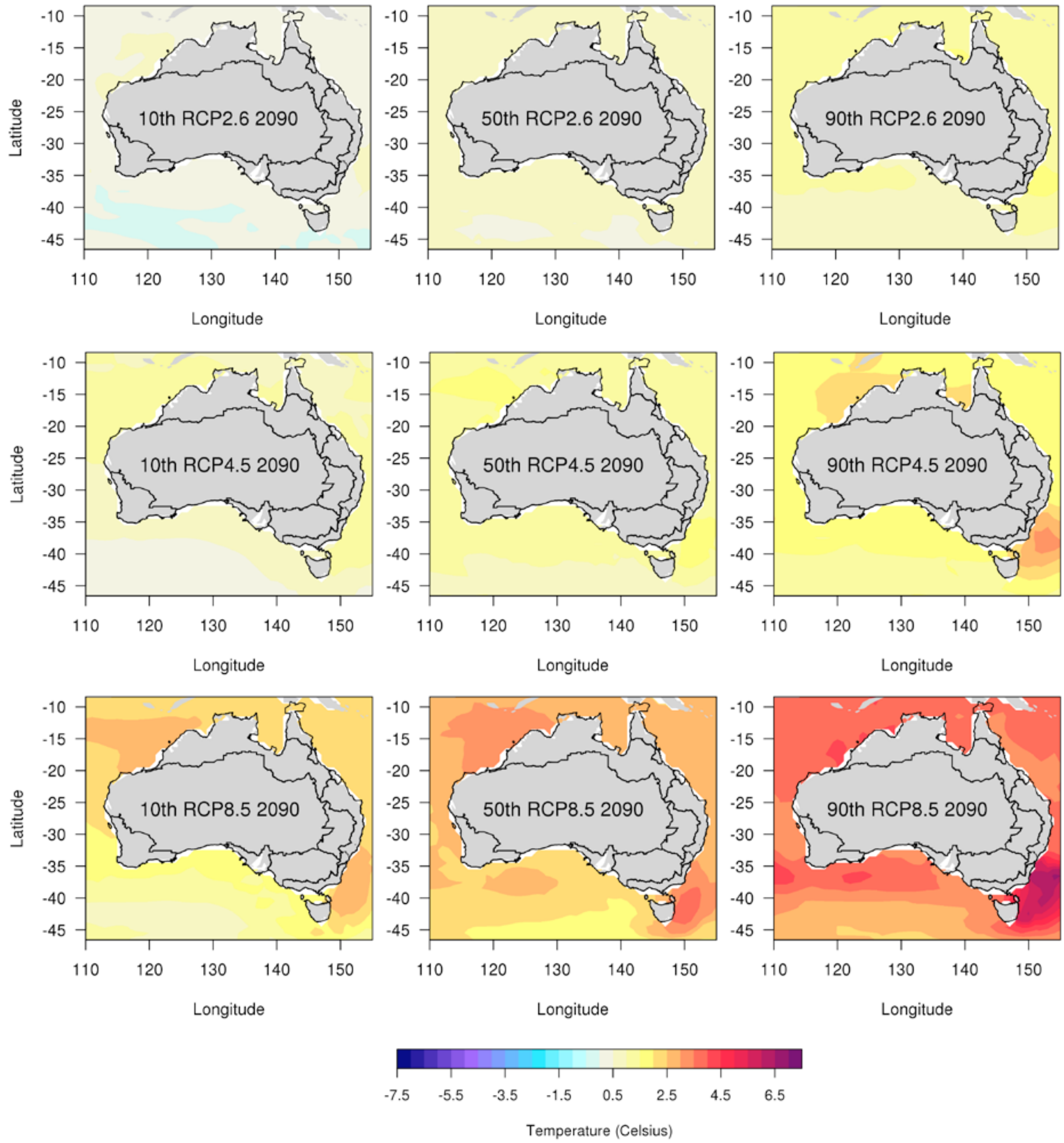


FIGURE 8.3.2: THE PERCENTILE CHANGES IN SEA SURFACE TEMPERATURE (°C) FOR 2080–2099 RELATIVE TO THE PERIOD 1986–2005 FOR RCP2.6 (TOP), RCP4.5 (MIDDLE) AND RCP8.5 (LOWER). SHOWN IN EACH ROW ARE THE (LEFT) 10TH PERCENTILE, (MIDDLE) 50TH PERCENTILE AND (RIGHT) 90TH PERCENTILE OF 14 CMIP5 MODELS.

8.4 SEA SURFACE SALINITY

OCEAN SALINITY MAY CHANGE

Changes in sea surface salinity reflect changes in rainfall and may affect ocean circulation and mixing. A net reduction in the salinity of Australian coastal waters is projected, but this projection is of *low confidence*. For some southern regions, models indicate an increase in sea surface salinity, particularly under higher emissions.

Salinity is an important gauge to help understand how the water cycle is changing due to climate change and changes in salinity are likely to have local impacts on estuaries and riverine environments. Over the last 50 years the sea surface salinity around Australia has changed, becoming more saline in southern and south-eastern Australia and less saline in northern Australia (Ridgway, 2007, Durack and Wijffels, 2010). These changes are associated with changes in the hydrological cycle and strengthening of the East Australian Current (EAC); the increase in salinity in Southern Australia can be attributed to a decrease in precipitation. These changes in precipitation and the EAC have been attributed to a strengthening the Southern Annular Mode (SAM) over this period (*e.g.* Hendon *et al*. 2007, and see Section 4.2). In northern Australia there has been an increase in precipitation (*e.g.* Josey *et al*. 1998) leading to a decrease in salinity. In the future the hydrological cycle is expected to continue to undergo significant changes (Held and Soden, 2006, Knutti and Sedláček, 2013). In projecting changes in sea surface salinity it is important to note that in the coastal ocean local processes such as river input and hydrodynamics can play a key role, but these processes are not well resolved (or even necessarily represented) in current GCMs.

Figure 8.4.1 compares the observed sea surface salinity (CARS: Ridgway *et al*. 2002) with the median of 14 CMIP5 models. Overall there are large biases; the models show significantly less salinity than observed. These biases are most pronounced in north-western Australia where the changes are up to 2 units lower, in the Coral Sea, and on the boundary of the Southern Ocean. The differences in northern Australia are likely associated with errors in simulating tropical precipitation, *e.g.* Lee and Wang (2014) while in southern Australia the explanation of the model biases is not well known.

All emissions scenarios show that in the 10th percentile and median case there is a net reduction in sea surface salinity around Australia. However in some areas, particularly under RCPs 8.5 and 4.5, there is an increase in sea surface salinity *e.g.* Tasmania and south-west Western Australia. The 90th percentile suggests an increase in surface salinity around all of Australia, and some large changes in Torres Strait and along the east coast of Australia. The large-scale pattern is consistent across all emission scenarios (Figure 8.4.2) with the strength of the change proportional to the emission scenario. The pattern of sea surface salinity changes is related to both changes in precipitation (see Section 7.2) and evaporation, the latter of which is expected to increase as the ocean warms. These changes will impact ocean circulation and mixing around Australia.

A net reduction in the salinity of Australian coastal waters is projected with *low confidence*, as some regions may show an increase in sea surface salinity, particularly under higher emissions.

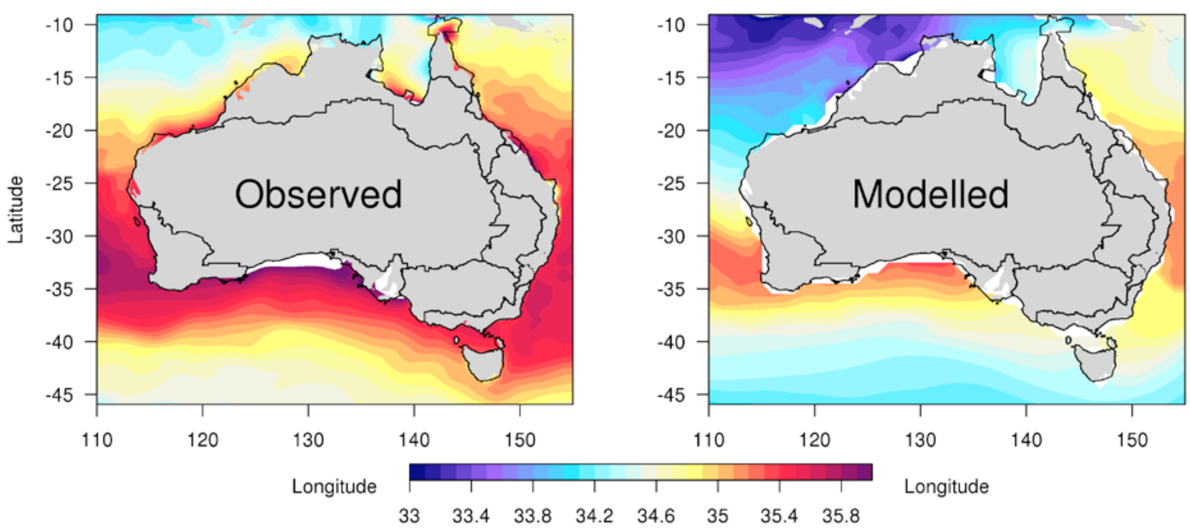


FIGURE 8.4.1: (A) OBSERVED SEA SURFACE SALINITY (CARS; RIDGWAY *ET AL*. 2002) AND (B) SIMULATED SEA SURFACE SALINITY 1986–2005; THE SIMULATION REPRESENTS THE MEDIAN OF 14 CMIP5 MODELS.

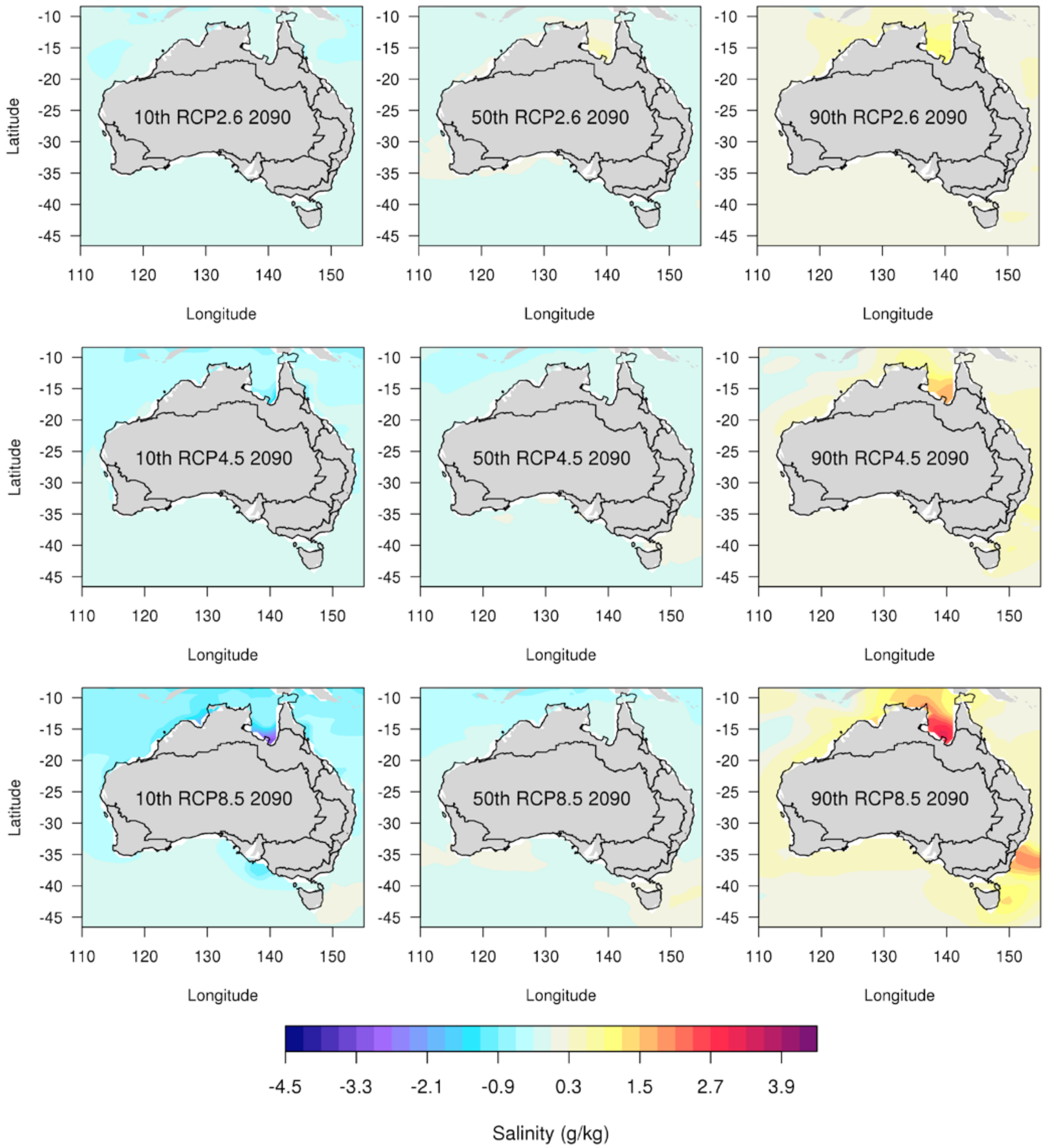


FIGURE 8.4.2: THE PERCENTILE CHANGES IN SEA SURFACE SALINITY FOR 2080–2099 RELATIVE TO THE PERIOD 1986–2005 FOR RCP2.6 (TOP), RCP4.5 (MIDDLE) AND RCP8.5 (LOWER). IN EACH ROW SHOWN IS THE 10TH (LEFT), 50TH (CENTRE) AND 90TH (RIGHT) OF 14 CMIP5 MODELS.

8.5 OCEAN ACIDIFICATION

OCEANS AROUND AUSTRALIA WILL BECOME MORE ACIDIC

There is *very high confidence* that around Australia the ocean will become more acidic, with a net reduction in pH. There is also *high confidence* that the rate of ocean acidification will be proportional to the carbon dioxide emissions. There is *medium confidence* that long-term viability of corals will be impacted under RCP8.5 and RCP4.5, and that there will be harm to marine ecosystems from the large reduction in pH under RCP8.5.

The oceans play a key role in reducing the rate of global climate change as they have absorbed nearly 30 % of the anthropogenic CO_2 emitted over the last 200 years (Ciais *et al*. 2013 and references therein), and at present take up more than 25 % of current annual CO_2 emissions (Le Quéré *et al*. 2013). When CO_2 is dissolved at the sea surface it reacts with the seawater to form carbonate, bicarbonate and hydrogen ions (a small proportion remains as dissolved CO_2). As CO_2 enters the ocean it changes the equilibrium between these ions, leading to a net reduction in carbonate concentration and a reduction in the seawater pH. These two changes are collectively known as ocean acidification. Ocean acidification is a predictable and measurable consequence of rising atmospheric CO_2 and therefore the rate of future ocean acidification will be determined mainly by its future concentration.

Over the past 200 years, there has been a 0.1 unit change in the ocean's surface water pH, representing a 26 % increase in the concentration of hydrogen ions in seawater (Raven *et al*. 2005). These changes in ocean pH in the global ocean have been extensively observed (Feely *et al*. 2009). Ocean acidification is likely to impact the entire marine ecosystem from plankton at the base to fish at the top. Factors that can be impacted include reproductive health, organism growth and physiology, species composition and distributions, food web structure and nutrient availability (Fabry *et al*. 2008, Iglesias-Rodriguez, *et al*. 2008, Munday *et al*. 2009, 2010). Carbonate is used (together with calcium) in the form of aragonite by corals to form hard reef structures and by other invertebrate organisms such as oysters, clams, lobsters, crabs and starfish and some plankton (*e.g.* pteropods, coccolithophores, foraminifera) to make their

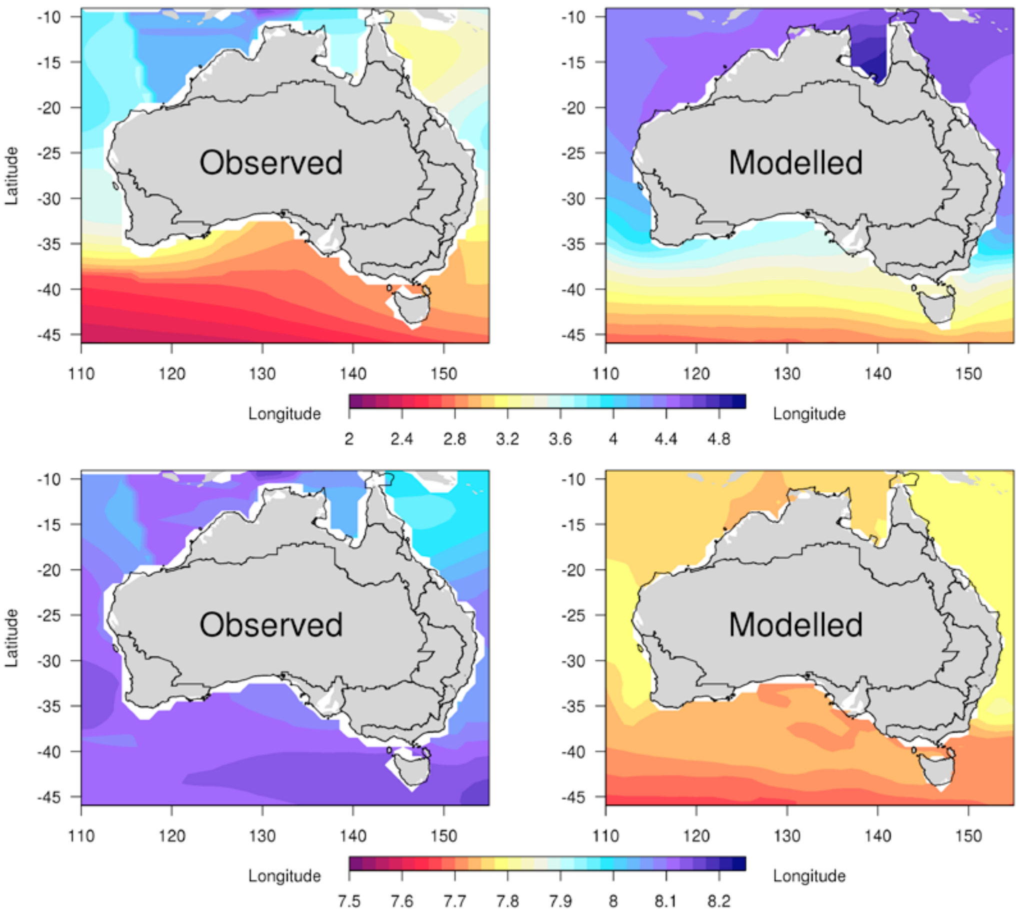


FIGURE 8.5.1: (TOP) ARAGONITE SATURATION STATE AND (BOTTOM) PH FOR THE YEAR 1995, WITH (LEFT) OBSERVED AND (RIGHT) SIMULATED. THE SIMULATION REPRESENTS THE MEDIAN OF SIX CMIP5 MODELS.

hard shells. The reduction of aragonite saturation state (ΩA) in the ocean means that it will be harder for these creatures to make their shells and for corals to build and repair reef structures (*e.g.* Doney *et al*. 2009). Such changes are already detectable in foraminifera and pteropods in the Southern Ocean (Moy *et al*. 2009, Bednaršek *et al*. 2012). The combined impacts of ocean acidification and other stresses, such as ocean warming, have implications for the health, longer term sustainability and biodiversity of reef ecosystems (Fabricius *et al*. 2011, Silverman *et al*. 2009). For example, ocean acidification has been shown to lower the temperatures at which corals bleach (Anthony *et al*. 2008), potentially reducing the resilience of these environments to natural variability. Ocean acidification has the potential to impact fin and shellfish fisheries, aquaculture, tourism and coastal protection (Cooley *et al*. 2009).

Figure 8.5.1 compares the observed pH and Aragonite saturations state (ΩA) (GLODAP; Key *et al*. 2004) with the median of all the models for the year 1995. Overall the north to south gradient in ΩA is well captured, equally the response of ΩA and pH at mid-latitudes are also well reproduced. The major differences between observed and simulated ΩA and pH are seen in the Coral Sea where

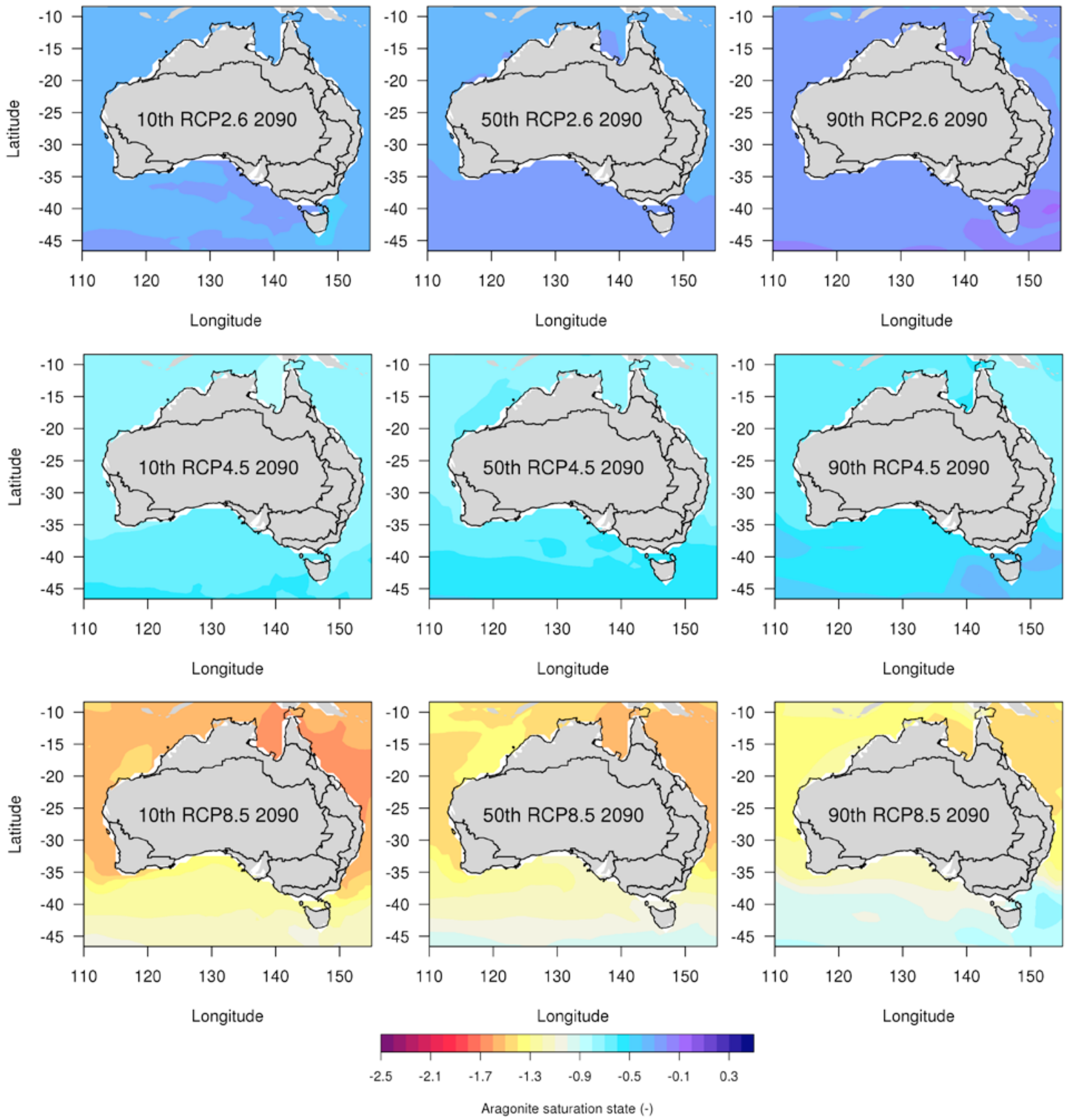


FIGURE 8.5.2: THE SIMULATED CHANGE IN ARAGONITE SATURATION STATE FOR 2080–2099 WITH REFERENCE TO THE PERIOD 1986–2005 FOR RCP2.6 (TOP), RCP4.5 (MIDDLE) AND RCP8.5 (LOWER). IN ROW IS SHOWN THE (LEFT) 10TH PERCENTILE, (MIDDLE) 50TH PERCENTILE OR MEDIAN AND (RIGHT) THE 90TH PERCENTILE FROM AN ENSEMBLE OF SIX CMIP5 MODELS.

models suggest that the values of ΩA and pH are higher than observed. Conversely along the north-West coastline, the values of ΩA and pH are lower than observed. However in these two regions the observations are very sparse. The other major difference occurs along the northern edge of the Southern Ocean where the models suggest that the values ΩA and pH are higher than observed. These differences are potentially due to both limited observations and model biases (Bopp *et al*. 2013). It is important to note that many of the impacts of ocean acidification will be felt along the coastlines, which are not well resolved in the relatively coarse climate models.

Under all emission scenarios a net decrease in pH and ΩA occurs, with the largest changes associated with the highest atmospheric CO_2 levels (Figures 8.5.2 and 8.5.3. Around Australia the largest decreases occur along the mid-latitude and northern Australia coast with the largest median drop

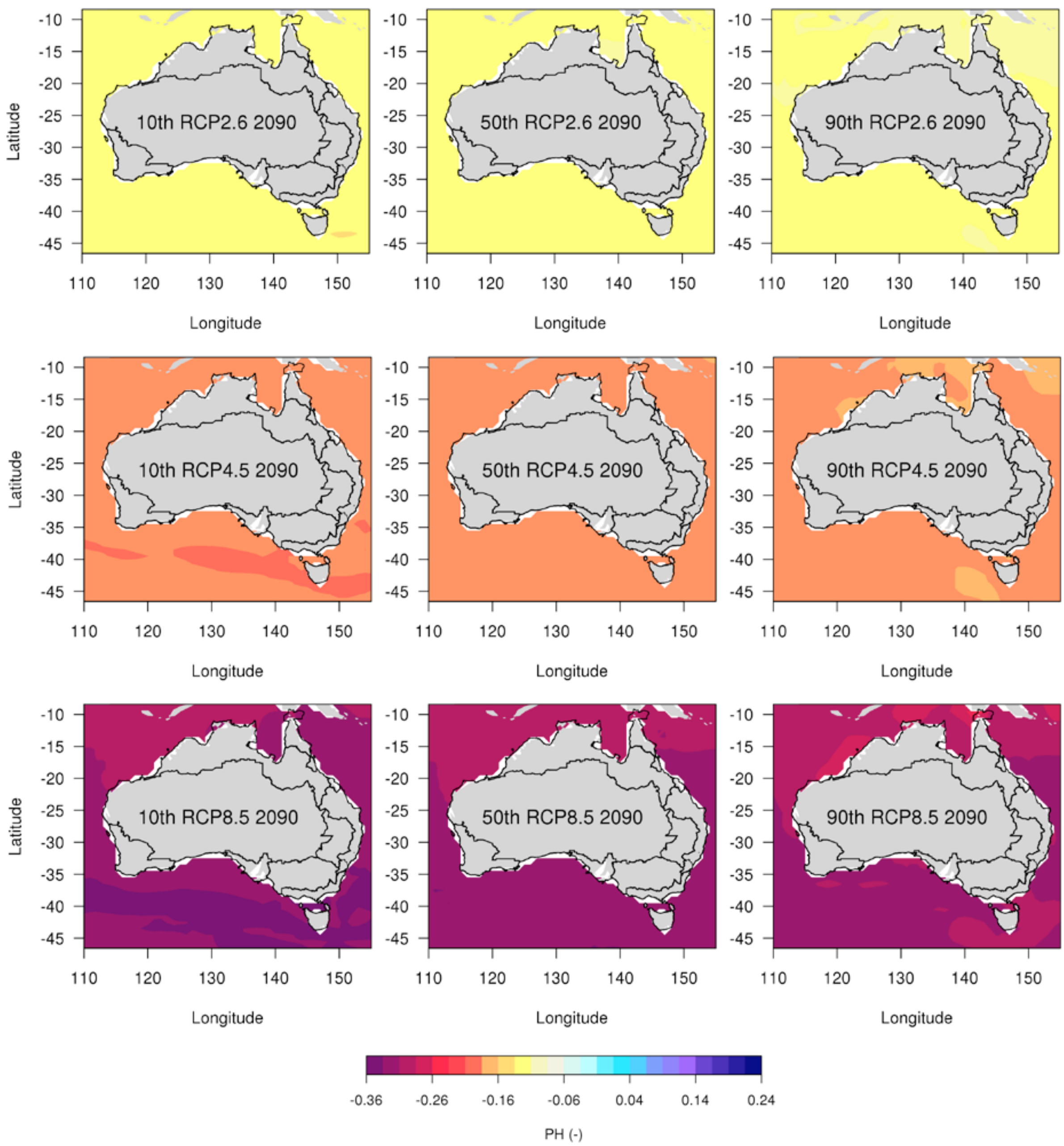


FIGURE 8.5.3: THE SIMULATED CHANGE IN PH FOR 2080–2099 WITH REFERENCE TO THE PERIOD 1986–2005 FOR RCP2.6 (TOP), RCP4.5 (MIDDLE) AND RCP8.5 (LOWER). IN EACH ROW IS SHOWN THE (LEFT) 10TH PERCENTILE, (MIDDLE) 50TH PERCENTILE (MEDIAN), AND (RIGHT) THE 90TH PERCENTILE FROM AN ENSEMBLE OF SIX CMIP5 MODELS.

in ΩA of 1.5 under RCP8.5. Such a decrease would mean that values of ΩA are lower than those at which corals are historically found. These changes are expected to have significant negative impacts on the long-term health, diversity and viability of corals (Fabricius *et al*. 2011) and aquaculture. In southern Australia, the changes in pH and ΩA are smaller than at mid-latitudes and northern Australia, but these changes are significant because their values in the present day are lower. This means impacts of ocean acidification are expected sooner. For example the values of ΩA under RCP8.5 by 2090 are close to or less than 1, meaning that the waters will no longer be super-saturated with respect to ΩA and dissolution of calcium carbonate will begin to occur. Such changes will have serious impacts on key marine species, *e.g.* pteropods at the base of the food web (*e.g.* Orr *et al*. 2005), as well as on aquaculture (*e.g.* Feely *et al*. 2008) and other industries.

There is *very high confidence* that around Australia as atmospheric CO_2 levels continue to rise the oceans will become more acidic, showing a net reduction in aragonite saturation state and pH. There is also *high confidence* that the rate and magnitude of ocean acidification will be dependent on RCP followed. Under high and medium emissions (RCP8.5 and RCP4.5) there is *medium confidence* that long-term viability of corals will be impacted. There is also *medium confidence* under high emissions (RCP8.5) that there will be negative impacts on the marine ecosystem from the large projected reduction in pH.