Sea Level Rise

Science and Synthesis for NSW

NSW Office of Environment and Heritage's Coastal Processes and Responses Node - Technical Report

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1. Introduction

This report provides an introduction to sea level changes over time. The report draws upon the most recent publications of the Intergovernmental Panel on Climate Change (IPCC), the Commonwealth's Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology (BOM) and other recent scholarly peer-reviewed publications to present the current science and future projections for sea levels on the NSW coast. The sea level rise projections presented in this report will be used as reference data within web based tools to be released by the NSW Office of Environment and Heritage (OEH)/Adapt NSW for coastal zone planning.

The report is structured to allow the reader to progress through background content on the causes, trends and projected values of sea levels in NSW. The report has been arranged as follows:

Section 2 provides an introductory background to the natural processes affecting regional sea levels over various time scales.

Section 3 summarises research regarding the observed changes to sea levels during the 20th century in a global, Australian and NSW context.

Section 4 provides an overview of the latest climate modelling undertaken by the Intergovernmental Panel on Climate Change (IPCC) and presents recent projections of sea levels for the 21st century along the NSW coast.

Section 5 provides a summary of the factors to consider when calculating sea levels for coastal zone management and planning. This includes the consideration of both the open coast and estuaries.

The following report has been prepared by scientist within NSW's Office of Environment and Heritage's Adaptation Research Hub (Coastal Processes and Responses Node). Various independent scientist and engineers have contributed including staff from the UNSW Australia Water Research Laboratory (within the School of Civil and Environmental Engineering), the Australian Climate Change Adaptation Research Network for Settlements and Infrastructure (ACCARNSI), CSIRO and the Sydney Institute of Marine Science (SIMS).

2. Processes Driving Sea Levels

2.1 Preamble

Sea levels are affected by regular and irregular processes associated with astronomic bodies, ocean waves, oceanic currents, meteorological factors, and geological phenomena. Extreme sea levels rarely occur due to a singular process, but, more commonly, result from a combination of several processes occurring over varying temporal and spatial scales as shown in Figure 1 (after McInnes *et al.*, 2016). As a result, when planning for sea level rise the combined effect of these factors requires detailed analysis to interpret observations and projections. The manifestation of these processes on the coast is shown in Figure 2.

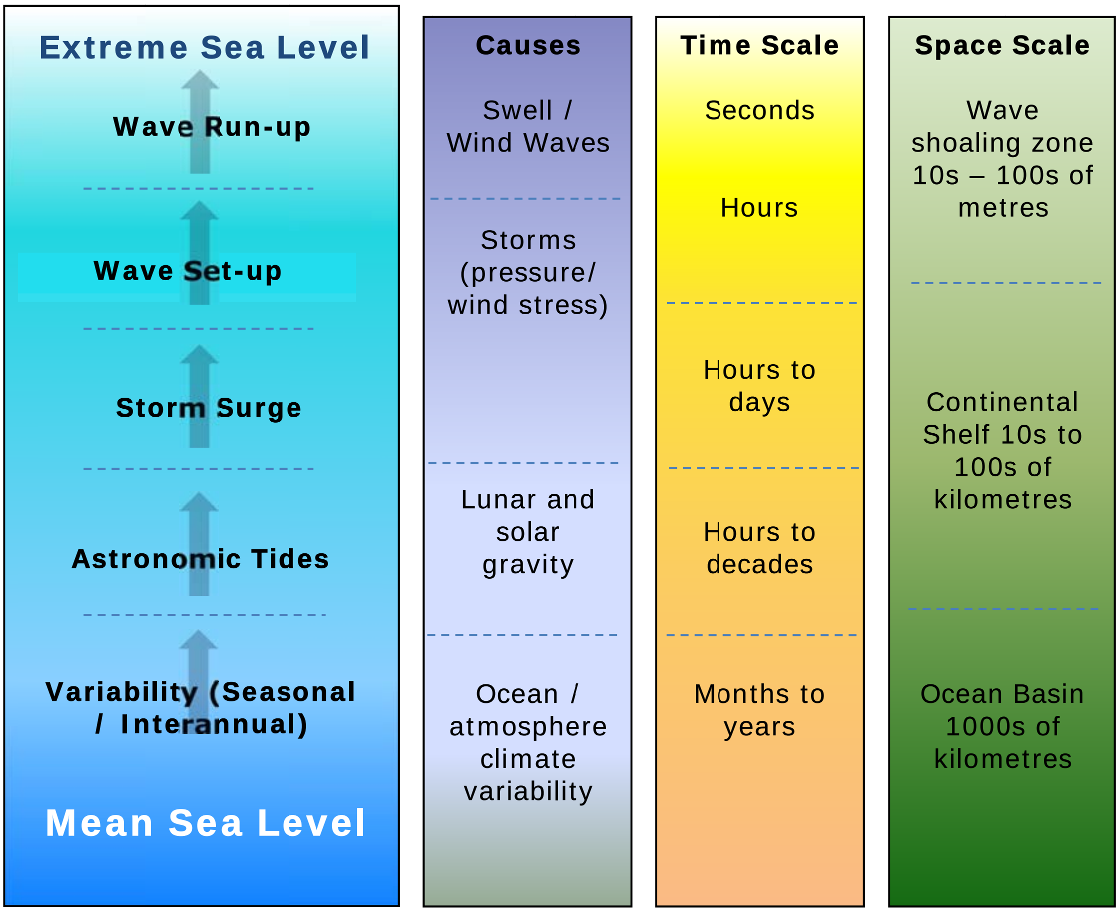

Figure 1: Contributions to the Total Water Levels at the Coast (after McInnes *et al.*, 2016)

Understanding the various components that affect sea levels requires an understanding of the variability that can be expected when assessing long-term sea level trends. Of particular interest to coastal zone managers and planners are the impacts of extreme sea levels on important coastal infrastructure or environmental resources. The following section provides a brief overview of the factors affecting sea levels and their relative influence along the NSW coast.

2.2 Astronomical Tides

Sea levels fluctuate daily with the tide. Tides are caused by the gravitational attraction between the sun, moon, and the rotating earth, which generates forces on the ocean. Along the NSW coast, tides are semi-diurnal, that is, there are two high and two low tides each day. Semi-diurnal tides are modulated (or varied) over a range of time scales, including systematic monthly, annual and inter-annual variations (MHL, 2013).

The most common modulation is known as the spring/neap tidal cycle, which occurs during a 28-day lunar phase (Masselink *et al.*, 2014). During a spring tide there is a larger (than average) increase in the gravitational force on the ocean, which causes an increase in the difference between the high and low tide levels (i.e. tidal range). During a neap tide cycle, a weaker gravitational force on the ocean results in a smaller tidal range. In addition to the spring/neap tidal cycles, the earth's tilt (of approximately 23.5 degrees) causes a shift in the tidal range which results in king tides during the annual summer/winter seasonal cycles. In the southern hemisphere, king tides occur in December/January (day-time) and in June/July (night-time) (Couriel *et al.*, 2014).

Additional inter-annual modulations include the 18.6 year lunar nodal cycle and the 8.85 year lunar perigee (which affects high tide levels as a quasi 4.4 year cycle) (Haigh *et al.*, 2011). These longer term cycles are difficult to identify within shorter tidal records (MHL, 2011). Haigh *et al.* (2011) suggests that the influence of the 18.6- year lunar cycle is not very significant along the NSW coast.

2.2.1 NSW Tidal Planes

Tidal ranges can vary along the NSW coast by up to ± 0.2 m (MHL, 2011). Smith and Davey (2013) highlighted the importance of considering site specific tidal planes when interpreting sea levels at a local scale. Table 1 provides an example of the tidal water level variability along the NSW coast.

Table 1: Tidal Planes for Three Select Locations on the NSW Coast (Australian Hydrographic Service, 2011) (after SMEC, 2013)

Tidal Plane	Water Level (m AHD)		
	Yamba (North Coast)	Sydney	Eden (South Coast)
Highest Astronomical Tide (HAT)	1.01	1.18	1.18
Mean High Water Springs (MHWS)	0.64	0.69	0.64
Mean High Water Neaps (MHWN)	0.38	0.44	0.44
Mean Sea Level (MSL)	-0.04	0.06	0.07
Mean Low Water Neaps (MLWN)	-0.30	-0.32	-0.30
Mean Low Water Springs (MLWS)	-0.63	-0.57	-0.51
Lowest Astronomical Tide (LAT)	-0.90	-0.92	-0.92

* AHD is the Australian Height Datum where 0 m AHD is approximately mean ocean level

2.3 Storm Surge

Storm surge (also referred to as storm tide, storm set-up, wind set-up, storm-induced rise, or storm rise) is the temporary rise in water levels along a coastline as a result of reduced atmospheric pressure (i.e. barometric set-up) and is often accompanied by strong onshore winds blowing across a large fetch of open water (i.e. wind set-up) (BOM, 2013) (Figure 2). In NSW, traditional definitions of storm surge exclude wave setup and wave runup, with storm surge comprising predominantly barometric and wind set-up, plus other components described below.

Reduced atmospheric pressure has a broad-scale influence on coastal water levels, while wind set-up is more severe in shallow coastal waters and semi-enclosed bays (NSW Government, 1990). Storm surge duration can vary from hours to days, depending on the severity of the event, with typical values along the NSW coast provided in Table 2. McInnes and Hubbert (2001) found that the most common weather system to contribute to storm surge levels in NSW are east coast low meteorological systems.

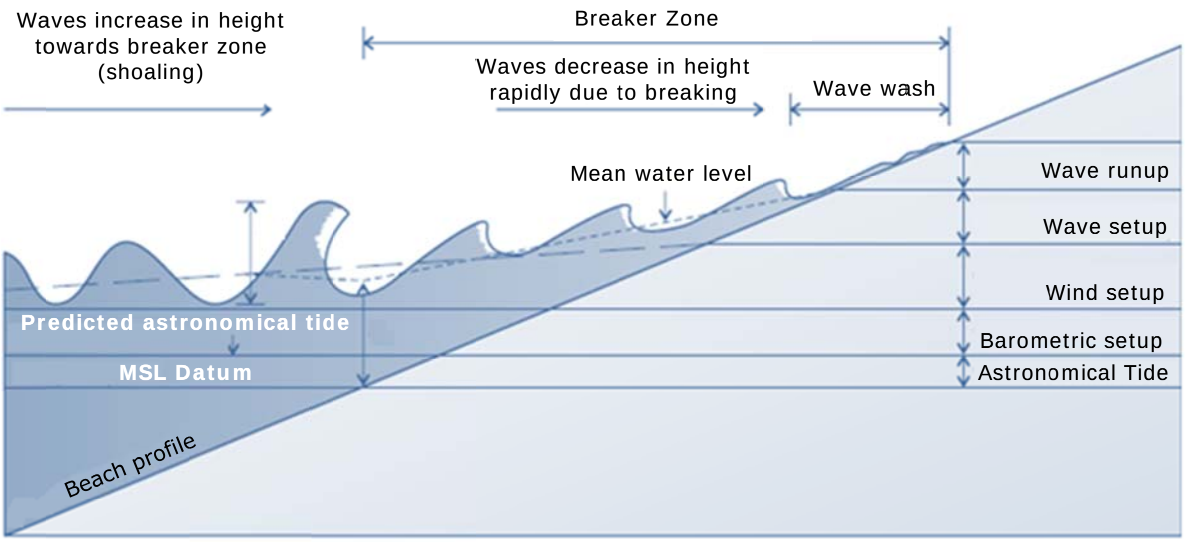

Figure 2: Components of Elevated Water Levels During a Storm Event (after NSW Government, 1990)

2.4 Waves

Waves also affect sea levels on the coast. Waves may be shorter period storm waves that are generated during strong wind conditions, or longer period swell waves generated by distant storm systems that propagate through the deep ocean (SCC & CSIRO, 2012).

The most common waves impacting the NSW coast are wind-generated waves. The size and form of wind-generated waves are controlled by wind velocity, duration, fetch, and water depths. In NSW, waves along the open coast are measured using one of the longest running wave rider buoy networks in the world. Shand *et al.* (2011) reviewed the wave rider buoy records and reported significant wave heights (H_s) between 8.0 to 9.0 m at Eden, 8.5 to 9.5 m at Sydney, and 7.3 to 7.9 m at Byron Bay, for the 1% Annual Exceedance Probability (AEP), 1-hour duration storm event. It is important to note that as this data was recorded by wave rider buoys, the conditions reported are offshore, not observed at the coastline itself.

2.4.1 *Wave Set-up*

Shoaling occurs as waves enter shallower water. The shoaling process causes waves to decrease in speed and wave length with increasing wave height until ultimately they break. Inshore of the break point a local increase in water level, known as wave set-up, occurs (Figure 2). Wave set-up can result in the elevation of the sea above mean water levels, particularly near the beach face. Typical values for wave set-up in NSW are provided in Table 2.

2.4.2 *Wave Run-up*

Wave run-up occurs when breaking waves surge up the beach face (Figure 2). Wave run-up is a function of beach profile, surface roughness, and other shoreline features affecting breaking waves at a particular site. Wave run-up is a dynamic process and varies on a wave by wave basis. For steeper slopes, such as at rock shelves, cliffs, structures such as wharves, jetties, breakwaters and seawalls, waves may dissipate their energy more rapidly. The level of run-up and overtopping depends on the water depths fronting the structure, the slope, height and other geometric attributes of the structure as well as its permeability. Typical values for wave run-up in NSW are provided in Table 2.

Table 2: Elevated Water Level Components Due to Storm Events (after NSW Government, 1990 with updates)

<table>
<tr><th>Component</th><th>Typical Range (m)</th><th>Additional Comments</th></tr>
<tr><td>Barometric set-up</td><td>0.1 – 0.4</td><td rowspan="2">Barometric set-up can cause a 0.1 m increase in water level for every 10 hPa drop below 1013 hPa (i.e. average atmospheric pressure). Storm surge (the combination of barometric and wind set-up) can raise coastal water levels in NSW by up to 0.5 m (Couriel et al., 2014).</td></tr>
<tr><td>Wind set-up</td><td>0.1 - 0.2</td></tr>
<tr><td>Wave set-up</td><td>0.7 - 1.5</td><td>Measurements taken on open coast beaches in NSW suggest that a wave set-up of up to 1.5 m can be expected at the shoreline during serve storm events (Nielsen, 2010).</td></tr>
<tr><td>Wave run-up</td><td>3.0 - 6.0</td><td>Design levels for wave run-up on open coast beaches in NSW exposed to waves may be up to 10 m AHD (Coghlan et al., 2012).</td></tr>
</table>

2.5 Other Sea Level Anomalies

Sea level anomalies (often referred to as tidal anomalies) describe the differences between the actual water level and the predicted tidal water level(s). Anomalies can include a combination of short-term factors, such as variations in seasonal temperature, air pressure, wind stress, and coastal-trapped waves and longer term effects caused by variations in global atmospheric and oceanic patterns. A comprehensive summary of sea level anomalies along the NSW coastline is discussed in Modra and Hesse (2011). MHL (2015) showed that sea level anomalies of up to 0.5 m can occur during the course of an event. Details of the most common sea level anomalies in NSW are discussed below.

2.5.1 Ocean Density Changes

Heat and freshwater exchange between the ocean surface and the atmosphere can change the density of the ocean and result in sea level variations. Changes in ocean density leading to changes in sea level is known as the Steric Effect. Steric variability occurs over regional scales (1,000 km or larger) (Siedler *et al*., 2001) and results in seasonal to inter-decadal sea level variations. Steric Effects also occur on smaller spatial scales. For example, the warm waters of the Eastern Australia Current (EAC) have been shown to raise local sea levels from 0.3 to 0.5 m for sustained periods at Lord Howe Island and Norfolk Island (Couriel *et al*., 2014). On the NSW coast, temperature variations from the East Australian Current can lead to sea level variations of up to 0.4 m (SCC & CSIRO, 2012).

2.5.2 Coastal Trapped Waves

Coastal trapped waves are caused by meteorological disturbances and can travel along continental shelves freely in the absence of wind effects (SCC & CSIRO, 2012). Coastal trapped waves are episodic events with a typical period of one to two weeks with the wave travelling clockwise around land masses in the southern hemisphere. The magnitude of coastal trapped waves is closely correlated with the strength of the alongshore winds and the width of the continental shelf and is largest along the south coast of Australia with amplitudes up to 0.70 m (Woodham *et al.*, 2013).

The NSW coast has been the site of major international studies of coastal trapped waves (Church *et al.*, 1986; Freeland *et al.*, 1986; Church and Freeland, 1987). In NSW, these waves may originate in the Bass Strait but more commonly propagate from the Great Australian Bight, through Bass Strait, and northwards along the NSW coast. Early research suggested coastal trapped waves were responsible for sea level anomalies of up to 0.2 m along the east coast (Freeland *et al.*, 1986; Couriel *et al.*, 2014). Larger coastal trapped waves are thought to be associated with the reinforcement by strong wind forcing on the southern part of the east coast and/or Bass Strait (Maiwa *et al.*, 2010; Woodham *et al.*, 2013). Recent research suggests that coastal trapped waves reinforced by these winds may have magnitudes as high as 0.5 m on the NSW coast (MHL, 2015). However, further research work is needed to characterise coastal trapped waves in NSW and develop annual recurrence intervals.

2.5.3 El Niño - Southern Oscillation

The El Niño – Southern Oscillation (ENSO) refers to the periodic change in atmospheric and oceanic patterns (on time scales typically between two to seven years) in the tropical Pacific Ocean (BOM, 2007). During El Niño events, there is an eastward shift of the warmest waters in the tropical Pacific Ocean, resulting in higher than normal sea levels and warmer than normal sea surface temperatures in the central and eastern Pacific and lower sea levels in the west. The opposite phase of El Niño, called La Niña, is characterised by colder ocean temperatures and lower sea levels in the eastern tropical Pacific Ocean and higher sea levels in the west. Sea level anomalies around Australia are strongly correlated with ENSO, decreasing in magnitude with distance (anticlockwise around the coast) from Darwin (White *et al.*, 2014). ENSO may affect coastal water levels through a range of mechanisms including the pressure difference across the Pacific, trade wind strength, frequency and severity of storms, sea surface temperatures and the East Australian Current (MHL, 2011). The associated water level changes along the NSW coastline due to ENSO have been estimated at around ± 0.1 m (NSW Government, 1990).

2.5.4 Inter-decadal Pacific Oscillation (IPO)

The Inter-decadal Pacific Oscillation (IPO) is based on water temperatures in the mid-latitude Pacific basin and is associated with long-period variations in atmospheric pressure and sea surface temperature, with time scales of 20 to 50 years. During the positive phase of the IPO, El Niño-like conditions are commonly observed and sea levels in Eastern Australia are lower than average. However, during the negative phase of the IPO, La Nina-like conditions prevail and sea levels are higher than average. During the 20^{th} century, the IPO was in a positive phase from 1922 to 1946 and 1978 to 1998, and in a negative phase between 1947 to 1976. As a result, it is difficult to assess the impact of the IPO on sea level predictions from observations alone since the analysis would require long-term observations of water level data over several IPO cycles.

2.6 Long-Term Contributors to Sea Level Change

The Earth's climate is complex and influenced by both natural and anthropogenic (human induced) processes. Regardless of the cause, changes in climate, in particular changes to global temperatures, have significant consequences for long-term mean sea levels. CSIRO & BOM (2015) summarise the main long-term contributors to sea level change, including:

1. Changes in the density of the ocean from thermal effects;
2. Changes in the mass of the ocean from glacial mass loss; and
3. Changes to the freshwater storage in the terrestrial environment.

The dominant cause of sea level change in the 20^{th} Century has been due to the thermal expansion of oceans and glacial mass loss with smaller contributions from the ice sheets in Greenland and Antarctica (Church *et al.*, 2013). Sea level rise from loss of mass from glaciers or ice sheets is non-uniform due to changes in the Earth's gravitational field, Earth's rotation and vertical land motion.

2.6.1 Glacial Isostatic Adjustment

The Glacial Isostatic Adjustment (GIA) refers to the ongoing vertical movement of the land surface and changes in the earth's rotation following relief from extreme overburden pressures caused by thick ice sheets from the last ice age (approximately 20,000 years ago) (Peltier, 2001). As a result of GIA, regional sea levels are falling in locations of former ice sheets, as the land mass rebounds upwards relative to the sea (Figure 3). It is worth noting that GIA occurs in addition to tectonic movements or local land subsidence. GIA is not uniform across the globe. Sea level relative to the land mass immediately adjacent to the former ice sheets, which was subject to more pressure, is rising faster than the global average, whereas sea level relative to the land distant from the former ice sheets (such as Australia) is rising less rapidly than the global average (Church *et al.*, 2013).

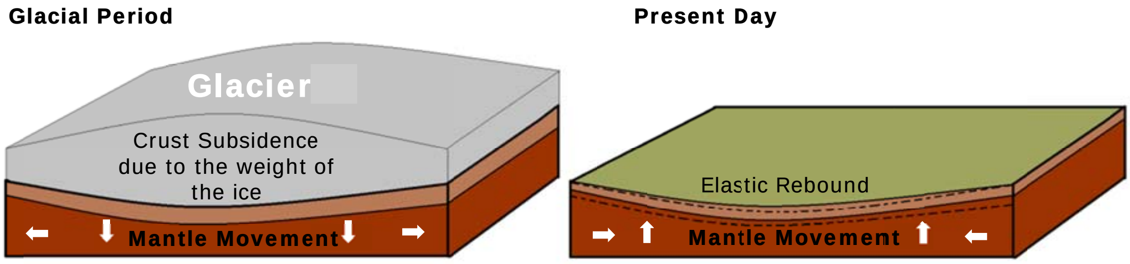

Figure 3: Glacial Isostatic Adjustment (GIA)

Spatial variations in GIA along the Australian coastline are minor (Figure 4), with slightly more positive values in Tasmania and South West Australia, as shown in Figure 4. In NSW, GIA (alone) is estimated to cause a slight fall (of about 20 -40 mm over a century) in sea level relative to the land. A GIA adjustment of 0.4 mm per year has been used in the projections within this report (CSIRO & BOM, 2015).

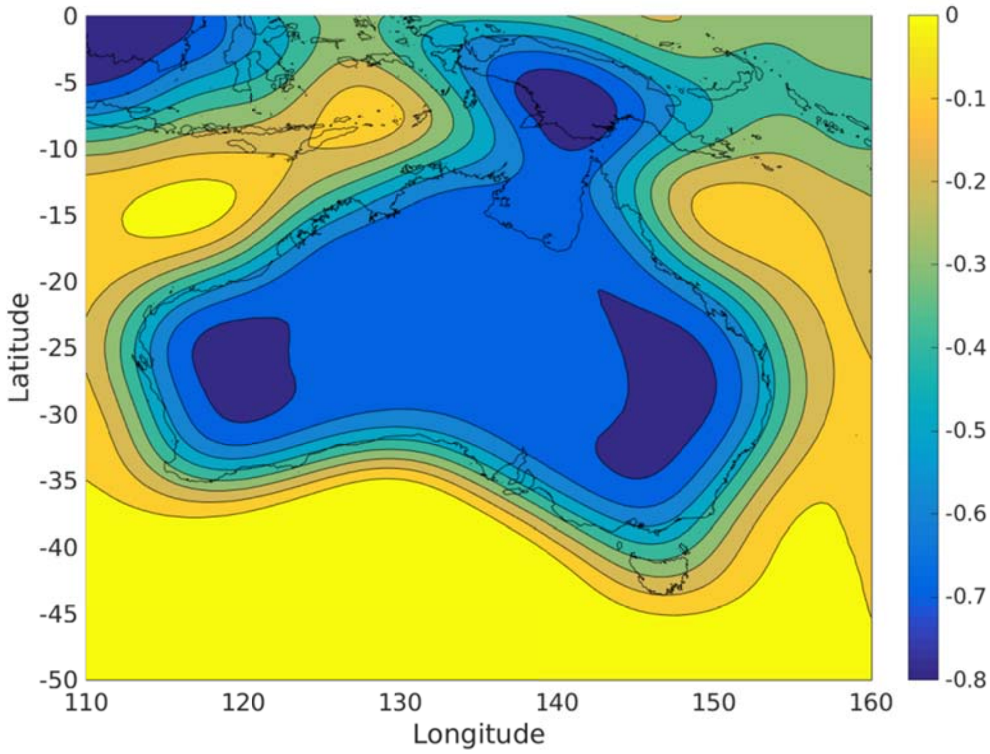

Figure 4: Indicative GIA Magnitudes across Australia (in mm/year) (after Kendall *et al.*, 2005)

3. Summary of Observed Sea Level Rise

3.1 Preamble

Observed sea level trends have been the topic of extensive research. It is now broadly accepted that global sea levels have risen over the past two centuries (Church *et al.*, 2013). Following a relatively stable period (several thousand years in the case of Australia), global sea levels began to rise during the 19th century and have continued to rise throughout the 20th century (CSIRO & BOM, 2015). The rate of rise over the 20th century was an order of magnitude larger than the rate of rise over the two millennia prior to the 18th century (Masson-Delmotte *et al.*, 2013).

Current literature reviewed below includes the research of Couriel *et al.* (2014), White *et al.* (2014), Burgette *et al.* (2013), Rhein *et al.* (2013), and Church and White (2011) to summarise observed sea level rise trends in NSW.

3.2 Global and Regional Distribution of Sea Level Rise

Sea levels can vary significantly on global and regional scales due to the relative influence and superposition of the various processes identified in Section 2. The combination of these processes produces a complex pattern of total sea level change that varies through time. As such, it is important to recognise that while global mean values of sea levels can be a useful indicator of sea level rise trends, regional factors can contribute to sea level rise and significantly influence observations and projections on a local scale. This may result in local trends that differ from global mean values (IPCC, 2014a).

3.2.1 Global Sea Level Trends

Rhein *et al.* (2013), in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), reports that global mean sea levels have risen by between 0.17 to 0.21 m over the period of 1901 to 2010. The IPCC AR5 assessment was based on multiple studies (with high agreement), independent observations, and analysis of long-term tide gauge records from around the world. A summary of global mean sea level trends over different inter-decadal time periods from IPCC AR5 is provided in Table 3. The mean rate of sea level rise during 1901 to 2010 was between 1.5 to 1.9 mm per year, and has since increased to between 2.3 to 3.3 mm per year for the period 1993 and 2010 (Rhein *et al.*, 2013). Global mean sea levels between 1950 and 2010 , as reported by the IPCC, are provided in Figure 5. A recent analysis has suggested an annual sea level rise rate from 1993 to mid-2014 of 2.6 ± 0.4 to 2.9 ± 0.4 mm per year, which is marginally lower than the IPCC estimate (Watson *et al.*, 2015). These results signify that the rate of global mean sea level rise is spatially variable and reliable estimates of future sea level rise trends cannot be made by extrapolating historical observations (Church and White, 2011).

Table 3: Trends in Global Mean Sea Level (after Table 3.1 Rhein *et al.*, 2013)

Period	Sea Level Trend (mm per year)
1901-2010	1.7 [1.5 - 1.9]
1901-1990	1.5 [1.3 - 1.7]
1971-2010	2.0 [1.7 - 2.3]
1993-2010	2.8 [2.3 - 3.3]

Note: Uncertainty range provided represents the 90% confidence interval.

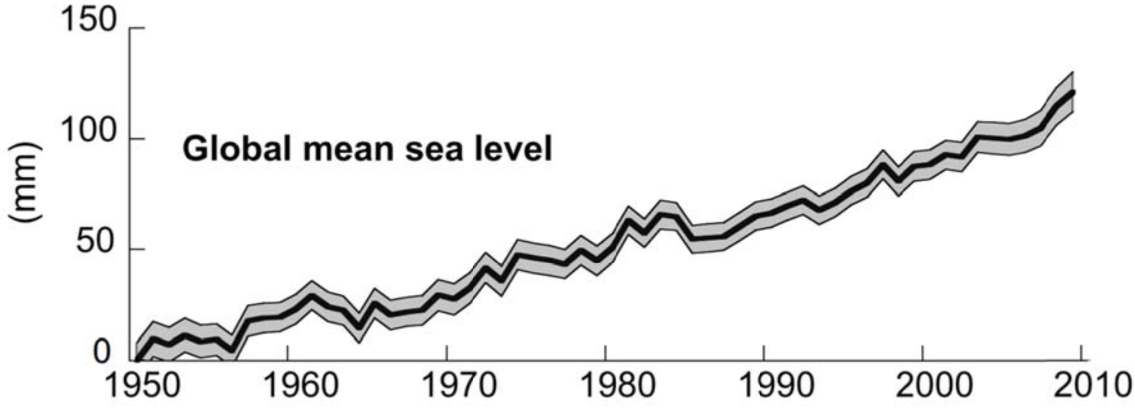

Figure 5: Global Mean Sea Level (after Figure 3.21 (b) Rhein *et al.*, 2013)

Since the publication of the most recent IPCC report (AR5), more research relating to sea level rise over the 19th and 20th century has emerged (Clark *et al.*, 2015). This research has also highlighted new observations of changes in sea levels (Becker *et al.*, 2014; Jevrejeva *et al.*, 2014b; Wenzel and Schroter, 2014; Dangendorf *et al.*, 2015; Hamlington and Thompson, 2015; Hay *et al.*, 2015); contributions to that change (Balmaseda *et al.*, 2013; Chen and Tung, 2014; Roemmich *et al.*, 2015), studies on understanding the reasons for sea level change and improved projections of future global averages and regional change (Burgette *et al.*, 2013; White *et al.*, 2014). Other studies have covered specific topics relating to sea level trends, including the La Niña event of 2010 (Yi *et al.*, 2015), ocean thermal expansion (Cazenave *et al.*, 2014), storage of water on land (Fasullo *et al.*, 2013) and improved interpretation of altimeter records (Ablain *et al.*, 2015). A comprehensive review of these publications completed by Clark *et al.* (2015) revealed that the new publications mostly support and strengthen the AR5 conclusions.

Since the release of AR5, longer tide-gauge records have become available. Research by Wenzel and Schroter (2014) and Jevrejeva *et al.* (2014b) presented global mean sea level rise estimates in the upper range of the values reported in AR5. Three recent studies (Lyu *et al.*, 2014; Richter and Marzeion, 2014; Bilbao *et al.*, 2015) have investigated the time period (termed time of emergence), which is required to distinguish changes in the rates of sea level rise from the natural variability in the data. There have been various studies attempting to quantify evidence of acceleration in the rate of sea level rise, in the presence of natural variability (Olivieri and Spada, 2013; Haigh *et al.*, 2014; Hogarth, 2014; Jevrejeva *et al.*, 2014b; Wenzel and Schroter, 2014; Hay *et al.*, 2015; Spada *et al.*, 2015). These studies reveal increasing evidence for an acceleration in historical estimates of global mean sea level. However, an acceleration in individual local sea level records is difficult to isolate from the natural variability and it will be several years before additional sea level accelerations become detectible in individual tide gauge records (Haigh *et al.*, 2014). It is expected that sea level increases above the values recorded during the mid-1990s will become more apparent in the coming decades.

3.2.2 Sea Level Trends in Australia

Australia is one of the most instrumented locations for assessing sea level observations in the southern hemisphere. Sea level measurements in Australia began with the first sea level benchmark at Port Arthur in Tasmania (1840), followed by the installation of tide gauges in Fort

Denison in Sydney (1886) and Fremantle in Western Australia (1897) (CSIRO & BOM, 2015). There have been two comprehensive assessments (Burgette *et al*., 2013; White *et al*., 2014) of 20th century sea level change around the Australian coastline, from which the following section has been summarised.

The two longest tide gauge records (Fremantle and Sydney) reveal rising sea levels prior to 1960, relatively stable sea level rise rates between 1960 and 1990, followed by an increased rate of rise from the early 1990s (White *et al.*, 2014). White *et al*. (2014) analysed tide data for a 45 year period between 1966 to 2010. This was the longest period for which data is available around the whole country. White *et al*. (2014) demonstrated that there is significant variability in sea levels from year to year and there is a strong impact of interannual to decadal variability on Australian sea levels (much of which is related to the Southern Oscillation Index and the Pacific Decadal Oscillation).

The work of White *et al*. (2014) indicates that the spatial scale of the variability in regional mean sea level is in the order of thousands of kilometres. White *et al*. (2014) reported that for the period between 1966 to 2009, (when there are observations of most sections of the Australian coastline), the average rate of relative sea level rise around Australia was 1.4 ± 0.2 mm per year, which is slightly less than the global averaged rise for the same period (CSIRO & BOM (2015). This slightly smaller rate is partly due to the ongoing vertical adjustment of landmass (GIA) and partly due to the increase in atmospheric surface pressures (which had a depressing impact on sea level) at various locations around Australia. If it were not for these factors, the average trend would be 2.1 ± 0.2 mm per year (ranging from 1.3 mm per year at Sydney to 3.0 mm per year at Darwin), which is almost equivalent to the global averaged value of 2.0 ± 0 .3 mm per year (over the same period) (White *et al.*, 2014).

White *et al.* (2014) also highlighted that whilst there is an extensive network of tide gauges across Australia, most individual tide gauge records are too short and contain too much variability for detection of statistically significant accelerations of sea level rise. Ideally, tide gauge records need to be long enough to capture significant instances of long period climatic and astronomic cycles (such as ENSO, IPO, 18.6 year Lunar cycle etc.) if they are to be used as the sole indicator of local sea level rise (Haigh *et al.*, 2014). As such, it is important to consider both regional spatial scales (of the order of 100 km and larger) and observations from several tide gauges (of adequate time length) instead of single measurements from a local gauge to assess sea level rise trends.

In general, the rates of sea level rise measured offshore by satellites is similar to the rate measured by coastal tide gauges around the Australian coastline. The major exception to this finding was off the southern NSW coast where the offshore rate of rise is larger than that at the coast. This difference is attributed to a strengthening of the East Australian Current in this region (Hill *et al.*, 2008; Deng *et al.*, 2011). For the period of high-quality satellite-altimeter data (since 1993), sea levels around Australia have been rising at close to the global average rate in the south and south-east (the NSW coast) and above the global average in the north and north-west (Deng *et al.*, 2011; Haigh *et al.*, 2011).

3.2.3 Sea Level Trends in NSW

Couriel *et al.* (2014) summarised yearly average relative sea levels for various gauged locations along NSW (presented to a common datum relative to Fort Denison) as shown in Figure 6. This data shows that sea levels rise and fall over a multitude of time scales, which masks longer term trends, especially for shorter tidal records. Over longer periods, these trends become more apparent as the influence of ENSO and IPO average out over several observation cycles. For the period where tide data is available for the entire coast of NSW, the records show common trends. Couriel *et al.* (2014) highlighted that Fort Denison is the only station to have sufficient data to account for medium term ENSO and IPO cycles, and can be used as a good reference indicator of longer-term historical sea level trends for NSW. Couriel *et al.* (2014) suggested that there is a general consistency between Fort Denison and published global rates of sea level rise for the 20th century, especially after allowance for the regional impacts of GIA and atmospheric pressure changes as discussed above.

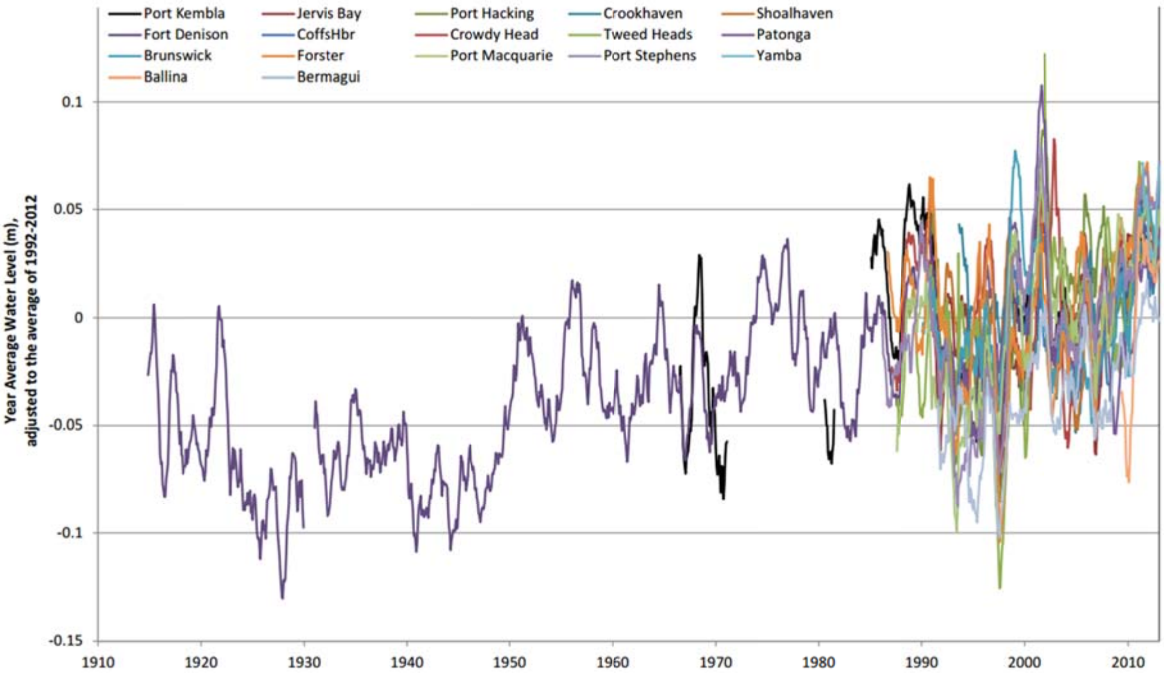

Figure 6: Superimposed Average Sea Level along the NSW Coast (1914-2013) Couriel *et al.* (2014)

4. Projected Sea Level Rise

4.1 Preamble

The IPCC is the international body for assessing the science related to climate change. The IPCC was set up in 1988 (by the World Meteorological Organisation and United Nations Environment Programme) to provide policymakers with regular assessments of the scientific basis of the Earth's climate (IPCC, 2014a). Due to the immense spatial and temporal scales over which the different climatic factors take effect, the future climate system cannot be studied using physical or experimental methods alone. As such, researchers have also used numerical simulations, which include mathematical representations of processes important in the Earth's climate system, to explore the earth's climate changes with time.

The following sections draw upon the background material of the IPCC Fifth Assessment Report (AR5) (Stocker *et al.*, 2013) and selected publications since AR5, to provide a summary of the most recent literature relating to sea level rise trends expected in the 21st Century. The sea level rise magnitudes quoted in this section are based upon the most recent analysis of the general circulation models (GCMs) developed by modelling experts from around the world through the "Coupled Model Intercomparison Project phase 5" (CMIP5). These results have been summarised by CSIRO and the Australian Bureau of Meteorology (BOM) as part of a larger package of products for assessing risks of regional climate change due to global warming (CSIRO & BOM, 2015). The NSW Government has also assessed regional climate change through the "NSW and ACT Regional Climate Model" (NARCliM) project, with results available via the Adapt NSW web portal.

4.2 Climate Models

The future rise in the magnitude of global mean sea level is one of the most certain consequences of climate change (Haigh *et al.*, 2014). That being said, the interactions of physical processes that drive the changes are highly complex. This means that to gain an understanding of possible effects into the future, climate models need to be developed and tested for their ability to replicate current observations of climate variables (NSW CS&E, 2012).

In general, global climate models are used for three main purposes. They are used to understand the present climate, they are used to project climatic conditions into the future, and finally, they are a tool to assess the potential impacts of human activities on a future climate (OCCRI, 2010). Even though climate modelling has existed since the 1950's, the understanding of physical climate processes (and modelling of those processes) to predict sea levels is an evolving research field (McGuffie and Henderson-Sellers, 2001). The complexity and resolution of global climate models have increased over time as the understanding of climate processes and computing power has improved. To date, there exists an immense volume of literature to describe the physical mechanisms and progression of climate models (Flato *et al.*, 2013).

With particular reference to modelling global sea levels, the AR5 climate models focus on processes within the ocean, atmosphere, land ice, and hydrological cycle that are climate sensitive and expected to contribute to sea level change, at regional to global scales in the coming decades to centuries (Church *et al.*, 2013). These processes are represented in Figure 7.

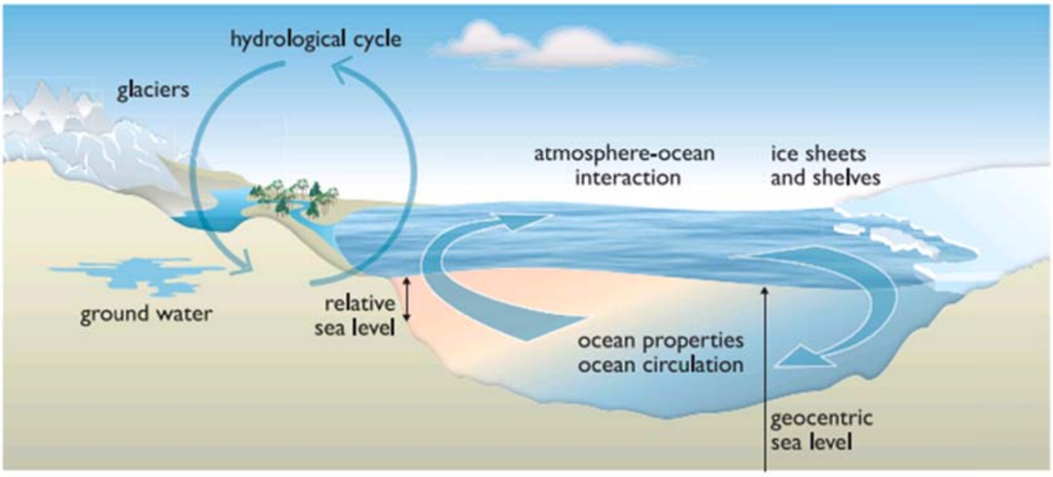

Figure 7: Climate Sensitive Processes and Components that Influence Sea Level Trends (Figure 13.1 IPCC, 2014a)

There are two main types of climate models that are considered by the IPCC in projecting sea level change. The first is process-based models that consider the different physical processes which cause sea levels to rise, and the second is semi-empirical models, which use the information contained in measurements of past sea level change.

Process based models aim to describe quantitatively the different physical processes that contribute to sea level rise. These models characterise global sea level rise in three fundamentally different ways; changes to the volume of the existing ocean mass by warming (thermal expansion); addition of mass primarily from loss of land ice (i.e. from glaciers and ice sheets on Greenland and Antarctica); and the changing in depths of the global ocean basins (by movements of the Earth's crust). Semi-empirical models try to link observed sea level rise and observed global temperature changes from the past to predict the future, based on the physical principals that sea levels rise faster as the temperature increases (Rahmstorf, 2012). IPCC (Church *et al.*, 2013) found there was no consensus in the scientific community on the reliability of semi-empirical models and low confidence in projections based on them. For further background details on climate modelling, refer to chapter 9 of the AR5 report entitled the "Evolution of Climate Models" (Flato *et al.*, 2013).

4.2.1 Representative Concentration Pathways (RCPs)

The magnitude of climate change (and sea level rise) is dependent on the magnitude of future greenhouse gas emissions. Since extensive uncertainties exist in future climate interactions, the use of "emissions scenarios" are required to predict social, technological and demographic changes into the future (Moss *et al.*, 2010). Over the last two decades, the IPCC has encouraged the development of several scenarios for use in climate research. These scenarios have been developed to reflect the advances in research over the relevant period and have supported the increasing sophistication of the climate models (Van Vuuren *et al.*, 2011). Previously climate scenario development involved the assessment of socio-economic factors, the prediction of total greenhouse gas and aerosol emissions (that arise from the scenario) and the evaluation of the climate systems (which results from modelling the changed atmospheric conditions) (Jubb *et al.*, 2013).

The most recent modelling (as used in the AR5) project adopts a different approach where the scenarios are represented as greenhouse gas and aerosol concentrations resulting from different emission rates (rather than socio-economic scenarios that give rise to different emission concentrations, as assumed in AR4). These new scenarios are referred to as Representative Concentration Pathways (RCP) and are named according to their "radiative forcing" target level for 2100 (IPCC, 2014b). The radiative forcing estimates are based on greenhouse gases and other forcing agents (such as solar radiation, aerosols and albedo), which alter the energy balance in the earth-atmosphere system. Four main RCP scenarios are represented by IPCC and include; a mitigation scenario leading to a low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6) and one high baseline emission scenarios (RCP8.5). The RCP scenarios quantify the total radiative forcing level by 2100 and is expressed in Watts per square meter (i.e. the RCP8.5 scenario refers to a forcing pathway leading to 8.5 W/m^2 in 2100). The four RCP scenarios reported by the IPCC were chosen to represent a broad range of climate outcomes, based on a literature review. These scenarios are neither forecasts nor policy recommendations. Van Vuuren *et al.* (2011) presents a useful summary of the RCPs, some elements of which been summarised in Table 4.

Table 4: Summary of RCPs (after Van Vuuren *et al.*, 2011)

Scenario	Model Description	Climate Change Pathway	Temperature Anomaly
RCP2.6	A "peak-and-decline" scenario, where gas emissions are reduced substantially and urgently over time in order to reach target radiative forcing levels.	Peak and Decline	1.5^{o}C
RCP4.5	A stabilisation scenario in which total radiative forcing is stabilised shortly after 2100, without overshooting the long-run radiative forcing target level.	Stabilisation without Overshoot	2.4^{o}C
RCP6	A stabilisation scenario in which total radiative forcing is stabilised shortly after 2100, without any overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions.	Stabilisation without Overshoot	3.0^{o}C
RCP8.5	Characterised by scenarios in the literature that lead to high greenhouse gas concentration levels over time.	Rising throughout the 21st century	4.9^{o}C

The new RCP scenarios have two notable advantages. First, it gives researchers the opportunity to assess the climate implication of emission pathways (in parallel) without needing to classify them with an underlying socio-economic baseline, and second, as the state of the socio-economic response to climate changes over time, there is always an opportunity to relate the projected emission with an RCP pathway. The aim of the new RCP scenarios *"is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures"* (IPCC, 2014b). This effectively means that under the new RCP model, subjectivity relating to future "socio-economic scenarios" are removed and additional confidence can be placed on future climate pathways as the scientific community produces more empirical evidence to validate which pathway is more likely from ongoing physical observations (Jubb *et al.*, 2013).

It is important to recognise that this new approach offers an opportunity to investigate management options that will reduce future impacts and vulnerabilities from sea level rise. As with any risk assessment, planners need to consider a combination of consequence and likelihood to determine the overall risk. In the context of sea level rise planning, RCP scenarios represent the likelihood side of this equation. Therefore, it is prudent to consider the potential impacts and adopt a risk based approach to decipher which RCP scenario is applicable.

It is worth noting that current emission trends are following the highest emission pathway (RCP8.5) (Raupach *et al.*, 2015) and current mitigation “pledges” are insufficient to maintain global warming to below 2^0C increase. Limiting emission to the RCP2.6 scenario will require very significant mitigation efforts and global efforts are currently not on track to follow this scenario or limit warming to 2^0C.

4.2.2 Model Performance

There is considerable confidence that AR5 climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above (Flato *et al.*, 2013). AR5 models are able to better reproduce the observed sea level trends during the 20th century than in the previous (AR4) and earlier assessments (IPCC, 2014a).

As with any modelling exercise, model performance is determined by the ability of a model to simulate historic data and observations. Figure 8 compares the observed and modelled sea levels and rates of sea level rise. In both instances, there is general agreement between the modelled and historic observations of sea level and rates of rise (Church *et al.*, 2013).

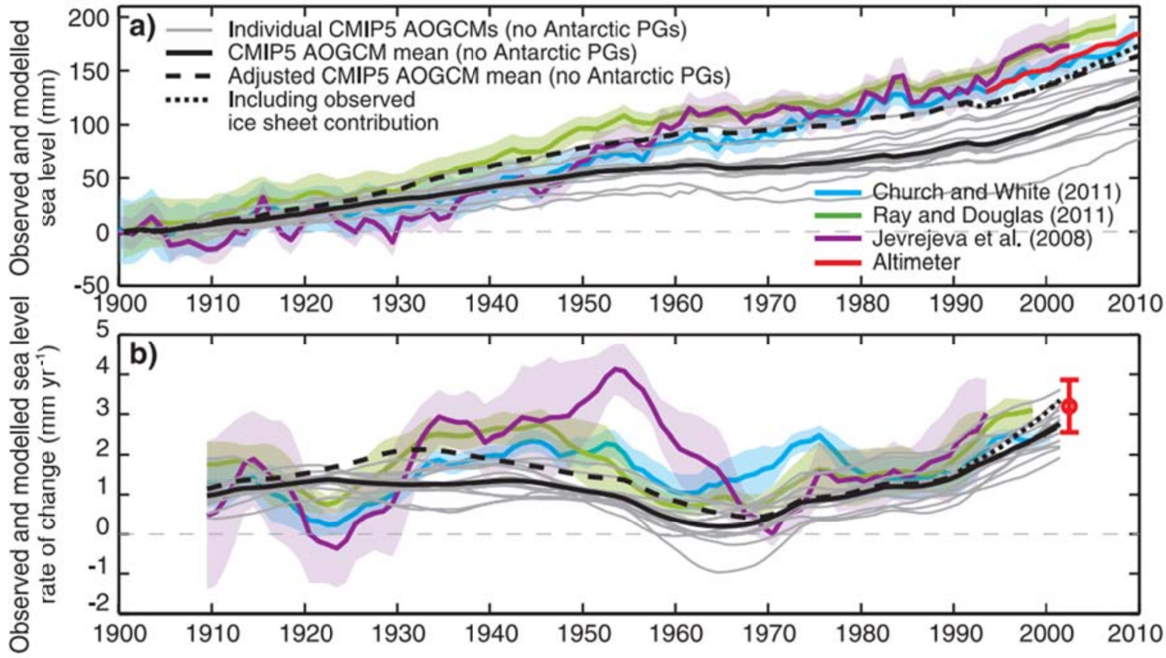

Figure 8: Modelled Versus Observed Global Sea Level Rise: (a) Sea level relative to 1900 AD and (b) The Rate of Rise (After Figure 13.7 Church *et al.*, 2013 - WG1 report for IPCC AR5)[1]

4.3 Global Sea Level Projections

Improved understanding of the major polar ice sheets (Greenland and Antarctica) has led to greater confidence in projections of sea level rise since the previous AR4 IPCC assessment (Stocker *et al.*, 2013). Global mean sea level rise is projected to continue during the 21st century, very likely at a faster rate than observed from 1971 to 2010 (Stocker *et al.*, 2013). The IPCC AR5 report states that sea level rise from thermal expansion of the ocean, melt of glaciers and small ice caps, and from Greenland and Antarctica, would be in the range 0.28 to 0.61 m for RCP2.6 and 0.52 to 0.98 for RCP8.5 by 2100. Projections of global average sea level change over the 21st century relative to 1986-2005, are shown in Figure 9.

It is important to note that IPCC AR5 reported the magnitudes of the "*likely* range" (66% confidence range) of projected sea-level rise. This was based on the assessed likely range of climate sensitivities and model projections of surface temperatures and other properties. A "*very likely*" range (90% confidence limit) was not given because there were no "*very likely*" surface temperature projections and because there was insufficient knowledge to assess the values in the tails of the probability distributions, particularly for the ice sheet dynamic contributions. However, the AR5 assessments (Church *et al.*, 2013) concluded that:

- *"It is very likely[2] (90 -100% likelihood) that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971– 2010 for all Representative Concentration Pathway (RCP) scenarios"*;

[1] PGs: Refers to "peripheral glaciers" which are not connected to the Greenland ice sheets.
[2] The following terms have been used by the IPCC to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%,

- *"It is virtually certain (99-100% likelihood) that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions"*; and
- *"Based on current understanding, only the collapse of marine based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. However, there is medium confidence that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century"*.

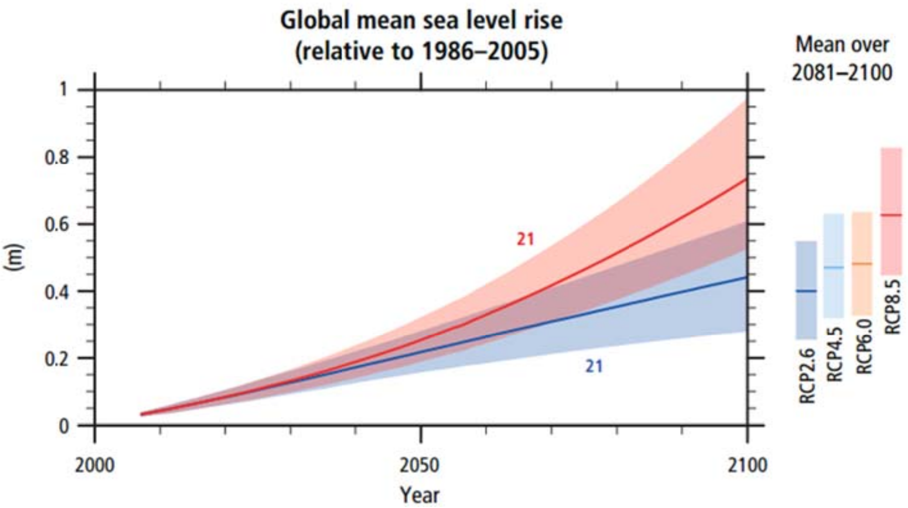

Figure 9: Global Mean Sea Level Rise as Determined by Multi-Model Simulations (relative to 1986–2005) (after Figure SPM.6 IPCC, 2014a)

Since the publication of the AR5 report a number of regional projections building on and consistent with the AR5 projections have been completed (CSIRO, 2014; Han *et al.*, 2014; Kopp *et al.*, 2014; Simpson *et al.*, 2014; Slangen *et al.*, 2014; Carson *et al.*, 2015; Little *et al.*, 2015; McInnes *et al.*, 2015) and the regional response to anthropogenic forcing has been estimated (Bilbao *et al.*, 2015). Post AR5 projections have also included consideration of expert opinion (Horton *et al.*, 2014) and probabilistic projections (Jevrejeva *et al.*, 2014a; Kopp *et al.*, 2014). Most recently, Clark *et al.* (2015) assessed that recent progress in observations and modelling of ice sheets largely confirmed the AR5 projections to 2100, but also pointed to ongoing ice sheet contributions.

4.4 Sea Level Projections for Australia

Regional projections of sea level rise around Australia have been completed as part of the National Climate Change Projections[3] with selected regional sea level projections available through the "Climate Change in Australia" web tool developed by the CSIRO[4] (CSIRO & BOM, 2015). The methodology used in these projections is essentially the same as the ones used in AR5 (McInnes *et al.*, 2015). McInnes *et al.* (2015) and Church *et al.* (2013) provide further details on the methodology used to derive these numbers.

more likely than not >50–100%, more unlikely than likely 0– <50% and extremely unlikely 0-5%) are also used where appropriate.

[3] http://www.climatechangeinaustralia.gov.au/en/

[4] http://www.climatechangeinaustralia.gov.au/en/climate-projections/coastal-marine/marine-explorer/

As with the global mean sea level projections, there is a very high statistical confidence that Australian sea levels will continue to rise during the 21st century. Further, Australian sea levels are very likely to rise at a faster rate during the 21st century than over the previous four decades for the range of RCP scenarios considered (CSIRO & BOM, 2015). The regional distribution in sea level change for projections for 2090 (compared to the 1986 to 2005 mean level) for each of the RCP scenarios is shown in Figure 10. Note that the regional sea level projections in Figure 10 combines contributions from the dynamic ocean response with changes in the mass of glaciers and ice sheets and its gravitational response on the ocean, and an ongoing glacial isostatic adjustment (GIA) (CSIRO & BOM, 2015).

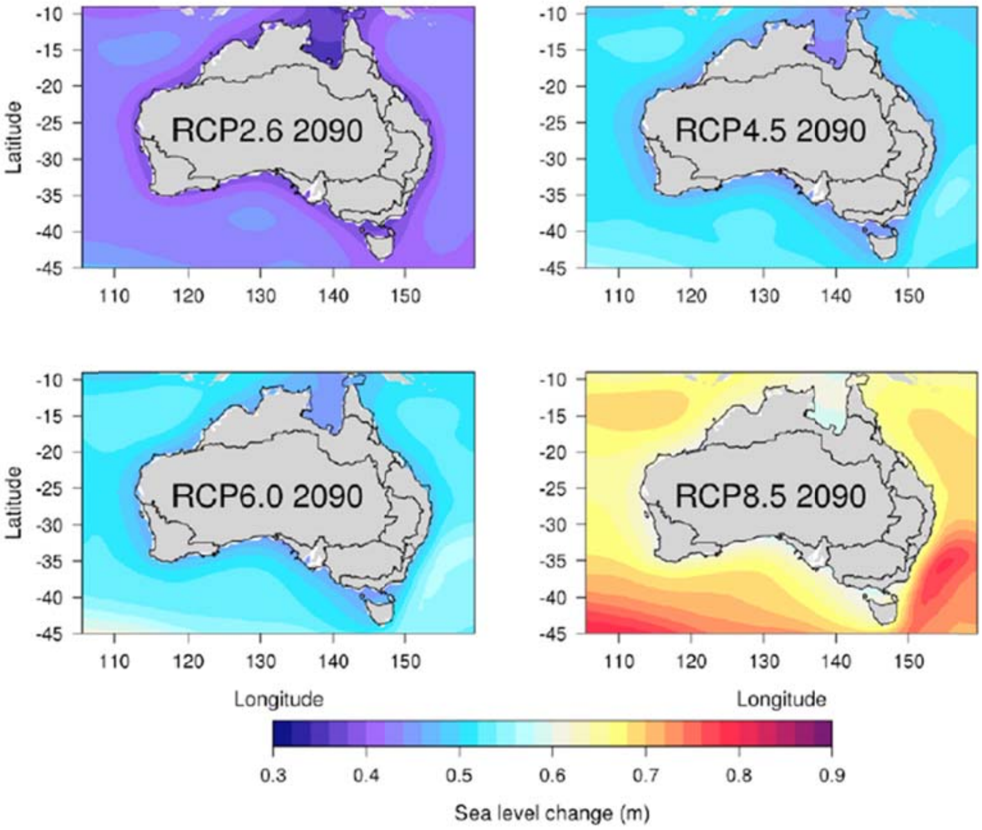

Figure 10: Regional Distribution in Sea Level Change (m) for Projections for 2090 (relative to 1986-2005 mean) for each RCP Scenario (after Figure 8.1.6 CSIRO & BOM, 2015)

4.5 Sea Level Projections for NSW

Sea level rise projections averaged along the NSW coastline, provided for each RCP scenario, are shown in Figure 11 (following McInnes *et al.*, 2015). This data demonstrates that sea levels are projected to increase under all scenarios. Note that sea level projections presented here are relative to the 1986-2005 mean and are expressed as the rise in sea level relative to the land. This method of reporting is consistent with CSIRO & BOM (2015) and IPCC (AR5) (Church *et al.*, 2013).

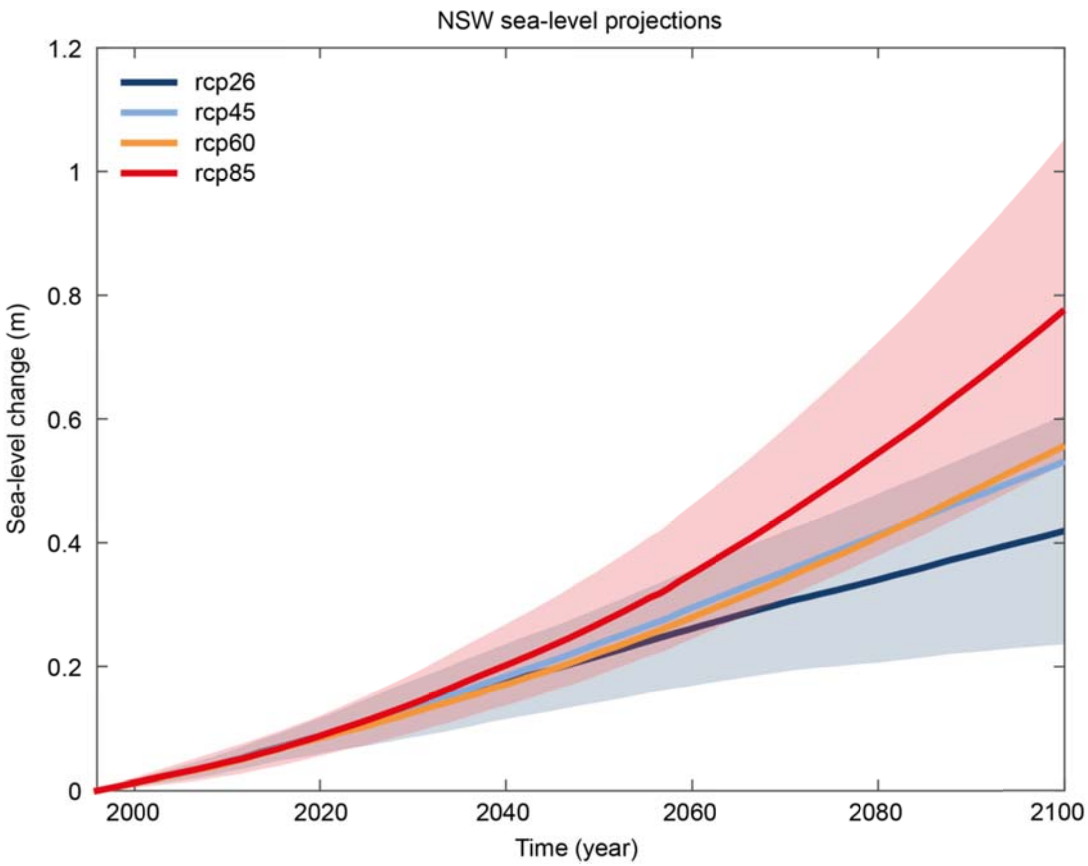

Figure 11: Sea Level Rise Projections Relative to the Coast, Averaged Along the New South Wales Coast, from 1996 to 2100 (Relative to 1986-2005 Mean) for each RCP Scenario

Note: The central values are given for each scenario and the *likely* range (66% confidence limits) given for the unmitigated greenhouse gas emission scenario (RCP8.5) and the strong mitigation scenario (RCP2.6). For the two intermediate scenarios (RCP4.5 and RCP6.0) only the central values are shown (for clarity).

Projections of sea level rise magnitudes under each RCP scenario (averaged along the NSW coast) have been presented in Table 5 (based on McInnes *et al.*, 2015). The results indicate sea level rise will continue through the 21st century and beyond (particularly for the unmitigated RCP8.5 scenario). The intermediate scenarios (RCP4.5 and RCP6.0), which still require substantial mitigation of greenhouse gas emissions, have intermediate values of rise and rates of rise by 2100. For the strong mitigation scenario (RCP2.6), the rise along the NSW coast is slightly lower than the global average, whereas for unmitigated (RCP8.5) emissions it is slightly higher than the global average. It should be noted that these differences to the global average are largely a result of the ongoing land motion (GIA) leading to slightly reduced rates of sea level rise around the Australian coastline, versus a larger than global average rise as a result of elastic deformation of the Earth and changes in the Earth's gravitational field from the loss of mass for glaciers and ice sheets. For RCP2.6, the former effect is larger and for RCP8.5 the latter affect is larger. For the lowest greenhouse gas scenario (RCP2.6), the rate of rise stabilises in the first half of the 20th century then decreases slightly to about 4 mm per year by 2100, with a total sea level rise by 2100 of 0.42 m (and *likely* range between 0.24m and 0.61 m). For unmitigated emissions (RCP8.5), the rate of rise increases throughout the 21st century and reaches 11.7 mm per year (equivalent to over 1.17 m per century, with a likely range of 7.6 to 16.6 mm per year) for 2081 to 2100, with a total sea level rise by 2100 of 0.78 m (and a *likely* range of 0.54 to 1.06 m).

Table 5: Projection of Sea Level Rise Relative to the Coast, Averaged Along the New South Wales Coast, from 1996 to 2100

Scenario	RCP2.6	RCP4.5	RCP6.0	RCP8.5
	Sea Level rise relative to the coast (m)			
2030	0.13 [0.09-0.18]	0.13 [0.09-0.18]	0.13 [0.08-0.17]	0.14 [0.10-0.19]
2050	0.22 [0.14-0.29]	0.24 [0.16-0.31]	0.22 [0.15-0.30]	0.27 [0.19-0.36]
2070	0.30 [0.19-0.42]	0.35 [0.24-0.48]	0.34 [0.23-0.46]	0.45 [0.31-0.59]
2090	0.38 [0.22-0.54]	0.47 [0.30-0.65]	0.48 [0.32-0.66]	0.66 [0.45-0.88]
2100	0.42 [0.24-0.61]	0.53 [0.34-0.74]	0.56 [0.37-0.77]	0.78 [0.54-1.06]
	Rate of Rise (mm yr^{-1})			
2081-2100	3.9 [1.5-6.4]	5.9 [3.1-8.8]	7.4 [4.5-10.5]	11.7 [7.6-16.6]

Note: The central values are given for each greenhouse gas scenario with the *likely* range (66% confidence limits) in brackets. The last row gives the rate of rise over the last two decades of the 21st century. The central values provides an estimate of the *likely* range (66% confidence limits). The values for 2030, 2050, 2070 and 2090 are twenty year averages.

4.6 Sea Level Projections Beyond 2100

AR5 projections indicate that it is *"virtually certain that global mean sea level rise will continue beyond 2100*" (IPCC, 2014a). The magnitude of sea level rise beyond 2100, however, is less certain and will depend on future greenhouse gas emissions and complex scientific interactions. For instance, "*on multi-centennial to millennial time scales, feedbacks between regional climate and the ice sheet become increasingly relevant, especially under strong climate change scenarios*" and therefore require coupled climate-ice sheet models to capture potential feedbacks (Church *et al.*, 2013). Continued high emissions of greenhouse gasses could result in sea level rise of meters over centuries.

Projections beyond 2100 are uncertain because of several factors, including:

- Scenario Projections: The RCPs are defined from the integrated assessment models up to the year 2100. Beyond 2100, Extended Concentration Pathways (ECPs) describe extensions of the RCPs *"that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios"* (IPCC, 2013).*;*
- Uncertainty: Sea level contributions *"only represent the model spread and cannot be interpreted as uncertainty ranges. An uncertainty assessment cannot be provided beyond the year 2100 because of the small number of available simulations.*" (Church *et al.*, 2013);
- Spatial Resolution: These models *"apply a reduced spatial resolution in order to be computationally efficient enough to evaluate longer time scales and to combine the different climatic components.*" (Church *et al.*, 2013);
- Model Complexity: The few available models used for projections beyond 2100 are "less complex" than those used to project sea levels for the 21st century. The models that beyond 2100 incorporate at a basic level the coupling of the processes of thermal expansion of oceans, which increases with global warming, and the sea level rise due to melting ice sheets. There is however *low confidence in the ability of the coarse-resolution models to capture the dynamic ice discharge from Greenland and Antarctica"* as they require parameterisation of sub-grid processes that can greatly impact the simulation results (Church *et al.*, 2013).

As such, any sea level rise projection beyond 2100 has inherent *uncert*ainties. The available evidence from *AR5 indicates that sustained global warming from continued, unmitigated greenhouse gas emissions would lead to "near-complete loss of the Greenland Ice Sheet over the next millennia*" (Church *et al.*, 2013). However, "*current evidence and understanding is insufficient to make accurate quantitative assessments*" (Church *et al.*, 2013).

5. Sea Level Rise Considerations for Coasts and Estuaries

5.1 Preamble

Sea level rise is anticipated to impact low-lying coastal areas as a result of increasing inundation over the next century. In general, mean sea level rise will amplify factors that contribute to coastal flooding and have disproportionate impacts on coastal regions. This has prompted considerable focus by all levels of government to better understand these impacts to coastal regions (SCC & CSIRO, 2012). Since NSW coastal catchments can flood as a result of either catchment runoff, coastal inundation or a combination of both factors, additional knowledge of the direct implications of sea level rise is required to interpret these changes for engineering applications and coastal management.

The following section presents a brief discussion on the different considerations required when undertaking coastal risk assessments for open coasts and estuaries.

5.2 Open Coast Considerations

Coastal inundation occurs due to a combination of oceanic and atmospheric processes. The various components of sea level rise have been discussed previously in Section 2. Additional considerations by coastal engineers can include the storm characteristics (such as size and vicinity), wave direction and local bathymetry of the coastline. Determination of extreme ocean water levels for the open coast is complex as it includes both commonly predictable phenomena such as tides, and event driven phenomena, such as storm surges, which are related to short term weather patterns (e.g. wind, waves, and atmospheric pressure).

To date, coastal inundation studies have commonly used static "bathtub" approaches where sea level rise projections are added to existing estimates of coastal extreme sea levels to formulate an inundation extent (McInnes *et al.*, 2016). Whilst these approaches provide useful guidance for areas most vulnerable to coastal inundation from sea level rise, they do not completely capture the processes that influence inundation during extreme events To better assess these impacts, the various components that contribute to the overall expected extreme water level should be considered. A schematic of these considerations is illustrated in Figure 12.

Figure 12: Water Level Drivers for the Open Coast

In addition to the above factors, geomorphic factors such as land subsidence, anthropogenic dredging, biological sediment deposition, sand mining, beach erosion and nourishment should be considered as they may have a local impact to set-up and run-up dynamics at a local scale.

5.3 Estuarine Considerations

Assessment of extreme water levels in estuaries is even more complex and consists of additional components of uncertainty related to catchment runoff, as illustrated by Figure 13. Additional uncertainties can arise from bathymetry, catchment rainfall variations (total rainfall intensity and volume), catchment infiltration and runoff properties, land use distribution, and the conveyance of the catchment runoff through drainage systems. These differences could lead to individual estuaries along the NSW coast (within close proximity to one another) experiencing different impacts from sea level rise.

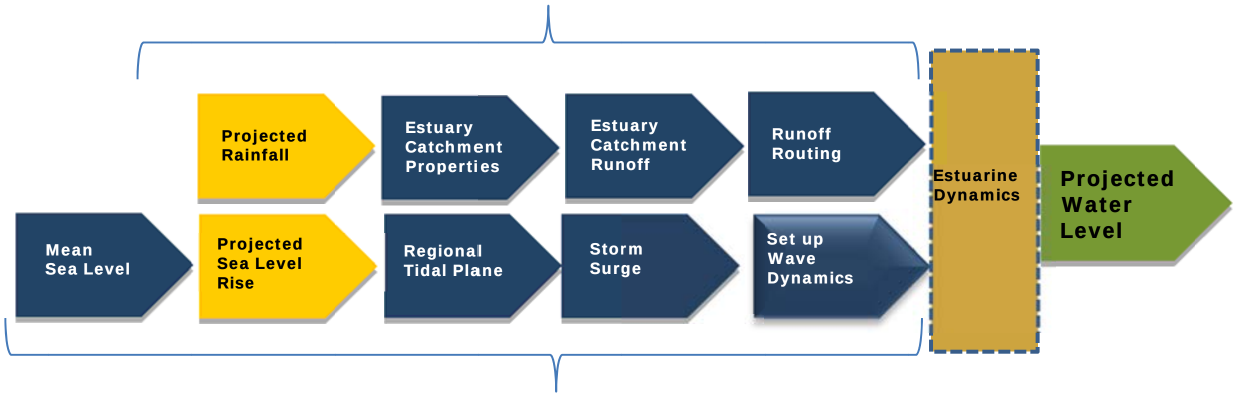

Figure 13: Water Level Drivers in Estuaries

Importantly, the tidal propagations inland through estuaries can differ greatly. The length, width and depth of an estuary affects the propagation of tides along the water body (Smith and Davey, 2013). Roy *et al.* (2001) denotes three main estuarine geomorphic types and their influence on tidal behaviour including drowned river valley estuaries tidal rivers and tidal lakes. These types and their tidal characteristics upstream are depicted in Figure 14.

Estuarine floods are affected by a combination of catchment runoff volumes and the sea level boundary conditions. Sea level boundaries comprise the various factors discussed in Section 2. Catchment runoff can be estimated using numerous methods with different degrees of complexity, the most reliable of which are those that can account for total volume and replicate the timing of the peak flood (Smith and Davey, 2013).

In NSW, there are not many coincident instances of both large catchment flooding and elevated ocean levels. This may be because the NSW coastal database contains approximately 20 years of continuous water level data, which is not adequate to capture a statistically significant number of major floods. Smith and Davey (2013) state that it would be unwise to dismiss the possibility of elevated water levels and catchment runoff events coinciding. Smith and Davey (2013) propose that uncertainty in this “joint occurrence” can be addressed through sensitivity analysis, which involves simulating a range of model scenarios to examine upper and lower outcomes. Joint probability is discussed further in Section 5.4.

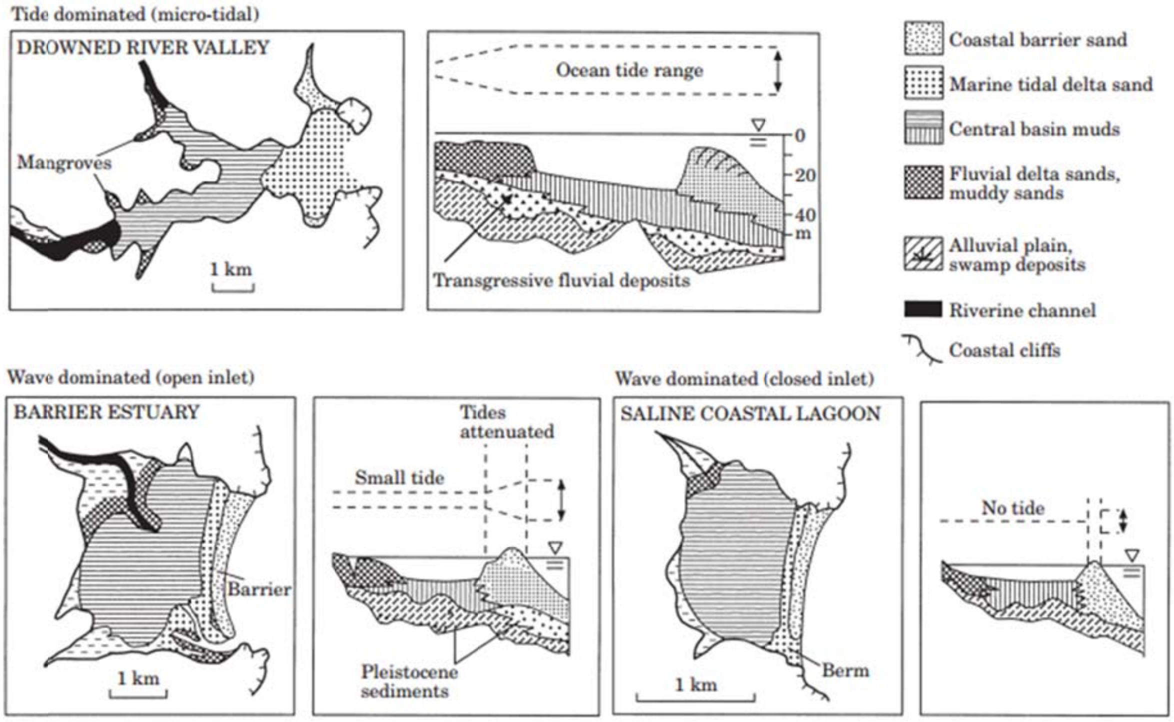

Figure 14: Tidal Behaviour of Three Main Estuary Types in New South Wales (Roy *et al.*, 2001)

5.4 Joint Probability

Joint probability is a measure of two events happening at the same time. In the context of coastal flooding, joint probability describes the probability that two extreme events (e.g. extreme runoff and extreme ocean water level) will coincide. Examples of coincident catchment and coastal flooding events in NSW are limited and may be due to the relatively short continuous dataset that exists for the NSW coastline.

Two key joint probability analysis have been conducted for the NSW Coast. Shand *et al*. (2012) completed an investigation of the joint occurrence of large waves and elevated ocean water levels along the NSW coast. Westra (2012) investigated the joint probability of extreme rainfall and elevated ocean levels as part of the Australian Rainfall and Runoff Revision Project 18. The outcomes of these studies are presented in Section 5.4.1 and Section 5.4.2.

5.4.1 Coincidence of Extremes Waves and Elevated Water Levels

Shand *et al.* (2012) assessed the dependence between variables contributing to elevated coastal water levels. In this study the authors undertook a joint probability analysis of significant wave height and tidal residual for Sydney, as shown in Figure 15. This analysis demonstrated that design sea levels can result from different combinations of tidal residual and significant wave height.

Shand *et al.* (2012) concluded that there was a relatively high dependence for wave height and tidal residual in NSW. For designs where both tidal residual (anomaly) and wave height are of interest, their occurrence cannot be assumed to be independent (and therefore joint probability of extreme events should be considered).

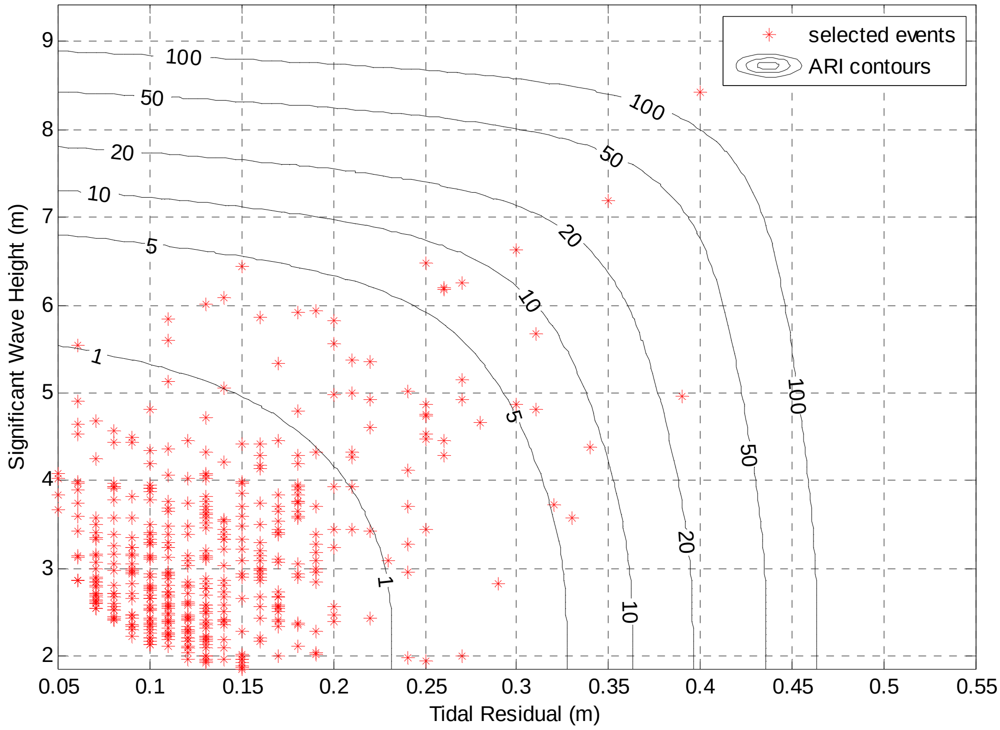

Figure 15: Estimated Joint ARI (Years) for Significant Wave Height and Tidal Residual at Sydney

5.4.2 Coincidence of Catchment Run-off with Elevated Coastal Water Levels

Westra (2012) applied statistical joint probability methods to identify the extent to which extreme rainfall and storm surge are dependent, with a view to providing guidance on the degree of interaction between these two physical process. The study examined three locations along the East Australian coastline (Sydney, Brisbane and Mackay) and found that:

- There is statistically significant dependence between extreme rainfall and storm surge;
- Dependence could be observed over distances of at least several hundred kilometres at each of the three tide gauge locations, although it weakens with distance; and
- The dependence between rainfall and storm tide is heavily influenced by storm burst duration, with relatively small levels of dependence for short durations (particularly sub-hourly durations) which increases gradually for longer durations.

Although more research is needed before the same conclusions can be drawn for catchment runoff, given the close association of both oceanic inundation and catchment flooding, a precautionary approach is recommended to account for the potential joint occurrence of these drivers for design flood analysis (Toniato *et al.*, 2014).

The above work highlights that while much is known about sea levels and the propagation of ocean tides into estuaries, the response of estuaries to extreme events is less well understood. In particular, the physical process of wave set-up in estuaries and catchment driven mechanisms during extreme events remains largely unquantified. Smith and Davey (2013) consolidated all relevant available information on flooding in NSW estuaries. Although this study did not account for impacts due to climate change directly, the authors presented a pragmatic approach for the combination of ocean driven and catchment driven flooding mechanisms. Smith and Davey (2013) highlighted that wave set-up can be an important consideration for estuaries and should be factored into ocean boundary water levels for flood studies in NSW. Smith and Davey (2013) presented a structured approach to joint catchment and ocean flooding, and proposed a selection criterion for setting ocean boundaries based upon the different NSW estuary classifications of Roy *et al.* (2001). This approach (updated to include considerations of sea level rise) is shown in Figure 16.

The interaction of catchment flooding and coastal processes is an important consideration in determining flood risk in coastal waterways. Presently, there is limited guidance for estimating flood risk along the Australian coastline for dependant events. The NSW Office of Environment and Heritage (OEH) has developed formal guidance for assessing the coincidence of coastal and catchment flooding in NSW under the Floodplain Management Program (Toniato *et al.*, 2014). This information is available on the OEH website.

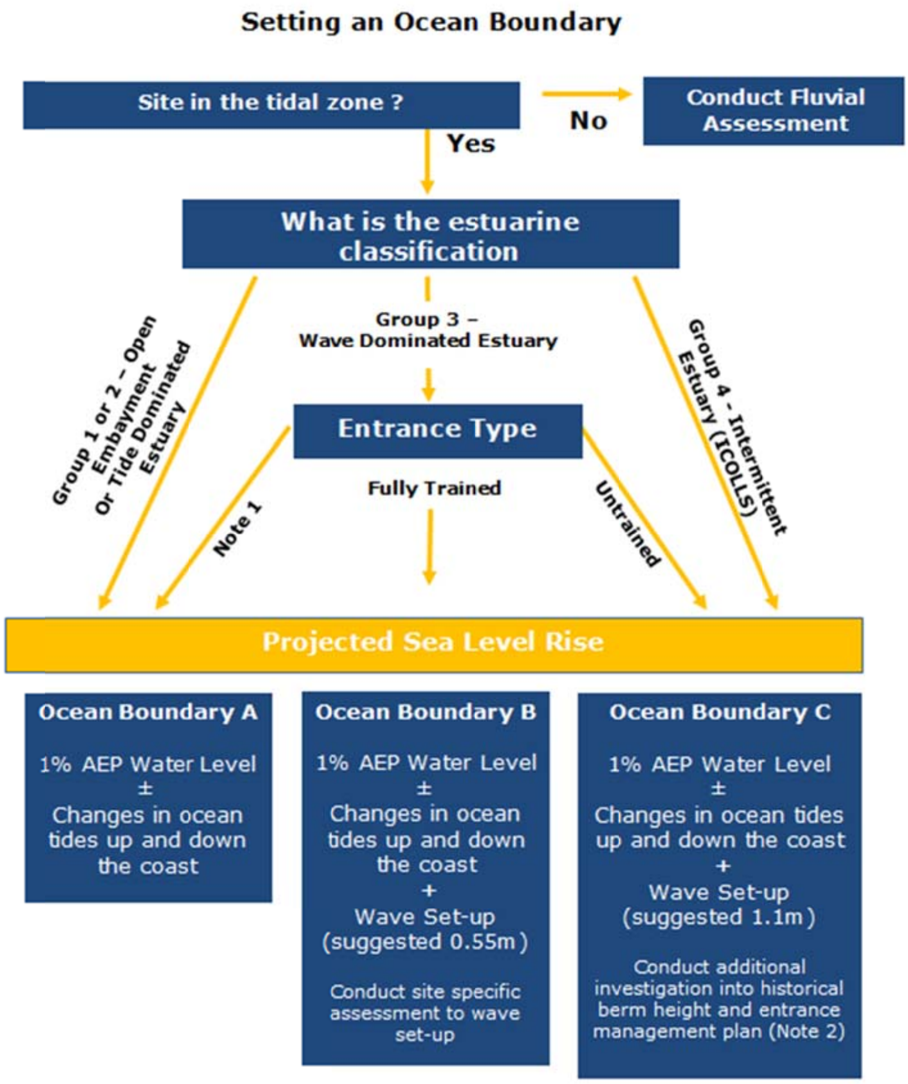

Figure 16: Setting an Ocean Boundary for Assessing Estuary Flooding (after Smith and Davey, 2013 with updates)

Note: 1. Wave dominated estuaries that are ports and harbours or drain into bays.

2. Berm Height will control the water level when the entrance is closed.

6. Conclusion

This report has been prepared through the Coastal Processes and Responses Node of the NSW Climate Adaptation Research Hub to synthesise technical advice on sea level rise in NSW. The report provides a scientific literature review of published data to highlight the various components influencing sea levels and the processes associated with global mean sea level rise projected over the 21st century. It is intended that the findings of this report will inform future considerations for engineering applications, resource management and coastal zone planning.

This report highlights that in addition to sea level rise there is considerable natural variability of sea levels along the NSW coastline, operating over different time scales. This variability should be considered when deriving local sea level projections across NSW. Updates to the science within this report may be required as new information is made available.

7. References

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