Sunshine Coast
COUNCIL

Additional Information

Item 8.2

Ordinary Meeting

Thursday, 27 May 2021

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ITEM **SUBJECT** **PAGE NO**

8.2 COASTAL HAZARD ADAPTATION STRATEGY

Sunshine Coast COUNCIL | Our region. Healthy. Smart. Creative.

Related Report / Additional Information Request

Meeting:	**May Ordinary Meeting**	**Date:**	**27 May 2021**
Requesting Councillor:	**Cr Rick Baberowski, Division 1**		
Item:	**8.2 Coastal Hazard Adaptation Strategy**		
Confidential			
Circulation			
Officer (title):	**Manager Environment and Sustainability Policy**	**Approving GE (title):**	**Group Executive Liveability and Natural Assets**

In response to a question raised by Councillor Rick Baberowski, please note the following additional information for your consideration.

Question:

What is our understanding of projected sea level rise for the Sunshine Coast as planned for in the Coastal hazard Adaptation Strategy?

Response:

- The Coastal Hazard Adaptation Strategy has been prepared based on a projected sea level rise of 0.8m by 2100, as mandated by the state government and a key element of the QCoast$_{2100}$ Program's Minimum Standards and Guideline.
- In addition to a 0.8m sea level rise, a 1.1m sea level rise scenario was also modelled to provide an appreciation of the potential impact of a higher sea level and was used to inform adaptation responses as identified in the Strategy.
- A CSIRO Report "Sea-level Rise: Current state of knowledge" was prepared to confirm the use of the 0.8m projected sea level rise was appropriate for the Coastal Hazard Adaptation Strategy.
- The Intergovernmental Panel on Climate Change prepares comprehensive Assessment Reports about knowledge on climate change, its causes, potential impacts and response options. Their next draft report is due in 2021 and it is likely that a higher projected sea level rise will be identified.

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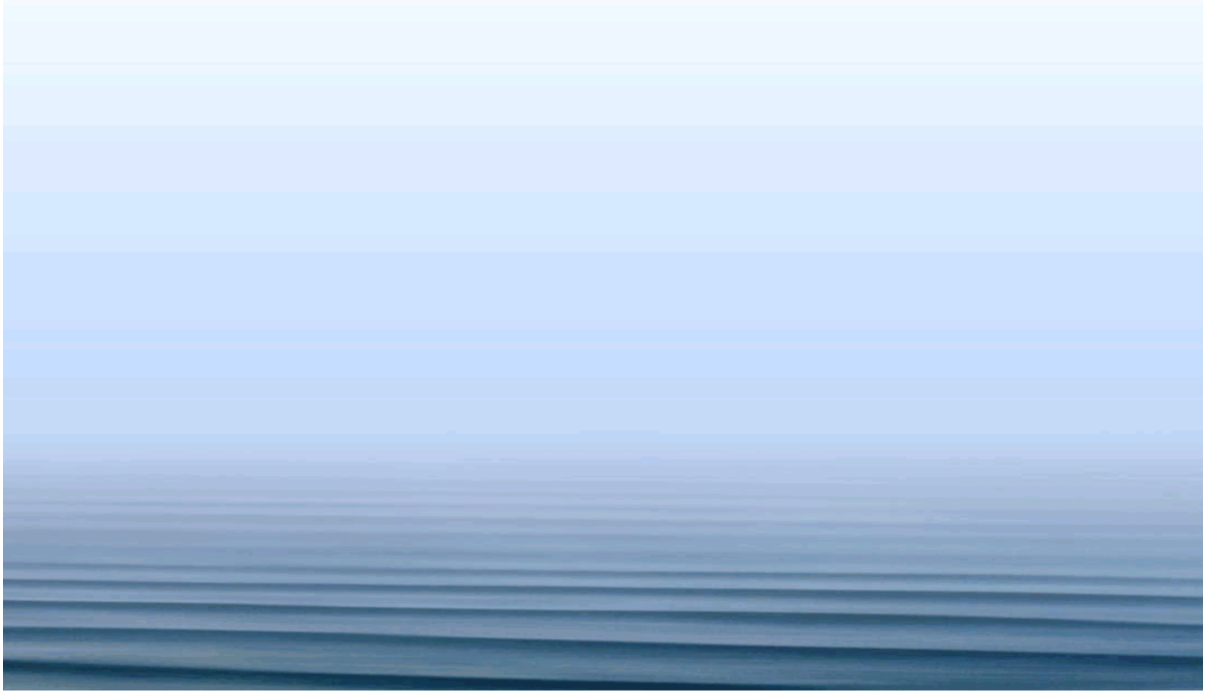
Sea-level Rise:
Current state of knowledge

Report prepared for the Sunshine Coast Council

Kathleen McInnes and Xuebin Zhang

CSIRO Climate Science Centre

July 2019



CSIRO Oceans and Atmosphere Business Unit

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Abbreviations and Glossary

CMIP	Coupled Model Intercomparison Project – An international collaboration of the global climate modelling community in which modelling groups design and undertake coupled atmospheric and ocean model simulations under specific parameters such as scenarios for future greenhouse gas emissions
ENSO	El Niño-Southern Oscillation
GCM	Global Climate Model
IPCC	Intergovernmental Panel on Climate Change - An intergovernmental body of the United Nations, dedicated to providing the world with an objective, scientific view of climate change, its natural, political and economic impacts and risks, and possible response options.
MICI	Marine Ice Cliff Instability
MISI	Marine Ice Sheet Instability
NDC	Nationally Determined Contributions – Pledges made by countries to the Paris Agreement to cut greenhouse gas emissions
PDO	Pacific Decadal Oscillation
RCP	Representative Concentration Pathway
RSLR	Relative Sea-level Rise
SMB	Surface Mass Balance – the contribution to sea level rise or fall that arises from the sum of ice sheet accumulation through precipitation and ablation (loss of ice and snow) through melting and evaporation
SRES	Special Report on Emission Scenarios
ToE	Time of Emergence
VLM	Vertical Land Movement

Executive Summary

To plan for the inevitable impact of higher sea levels on the Sunshine Coast, the Sunshine Coast Council has commissioned a report to synthesise the latest scientific understanding on the contributing factors driving sea-level rise (SLR), the timing and magnitude of sea level rise estimates, and the uncertainties inherent in these contributions. This information is required in order to understand how the Queensland Coastal Hazard Guidelines, which stipulates a SLR of 0.8 m by 2100, relate to recent IPCC and CSIRO projections. This, in turn will inform and increase community confidence that the mandated SLR projection is suitable for assessments of future shoreline response (Dept. of Environment and Heritage Projection, 2013).

The key factors contributing to SLR include changes in ocean volume due to warming and changes in ocean mass and volume due to melting of land ice and reductions in terrestrial water storage. Additional factors affect the spatial distribution of sea level and include atmospheric pressure and wind, ocean circulation, movement in the Earth's crust due to mass distribution changes and associated changes in the Earth's gravity field and rotation.

Current SLR projections for Australia have been produced by CSIRO using a methodology similar to that of the IPCC Fifth Assessment Report (AR5) (Church et al, 2013). These projections cover a range of scenarios including a low warming scenario of RCP2.6 that assumes global warming of 1.0 (0.3 – 1.7) by 2081-2100 relative to 1986-2005 and a high warming scenario of RCP 8.5 that assumes global warming of 3.7 (2.6 – 4.8) by 2081-2100 relative to 1986-2005. Note that SLR from 1900 up to the period 1986-2005 was around 0.15 m. The 2°C warming target of the Paris agreement, signed in 2015, is broadly consistent with achieving the mid-range temperature increase associated with the RCP 2.6 scenario (note that the upper warming estimate for RCP 2.6 is 1.7°C relative to 1986-2005 and 0.6°C warming occurred from pre-industrial to 1986-2005) but current greenhouse emissions are more aligned with RCP 8.5. CSIRO SLR projections for Sunshine Coast based on RCP 8.5 are 0.76 (0.53-1.03) m of SLR by 2100 relative to the average of the period 1986-2005. Known vertical land movement factors are incorporated within CSIRO

SLR projections[1] through Glacial Isostatic Adjustment, which is typically in the order of -0.1 to -0.4 mm yr^{-1} around Australia's coastline (i.e. land is slightly subsiding). However, as with the projections provided by the IPCC AR5, the CSIRO projections for Australia do not include a potentially larger contribution from Antarctica due to the collapse of marine-based sectors of the icesheet.

An IPCC Special Report on 1.5°C was released in 2018 to understand the impact of limiting long-term global temperature increase to 1.5°C above the pre-industrial level in view of the fact that RCPs that were used as inputs to the CMIP5 climate models did not consider a greenhouse gas concentration pathway that would lead to an average global warming by 2100 of 1.5°C or less. This report determined that achieving the greenhouse gas reductions necessary to reduce global warming 1.5°C above preindustrial global temperatures by 2100 would lead to about 0.1 m less SLR in 2100 than meeting a global warming target of 2.0°C. However, it also noted that the Nationally Determined Commitments that were pledged by the nations signed onto the Paris Agreement would not limit global warming to 1.5°C.

Changes in thermal expansion and glacier melting have been the dominant drivers of SLR during the 20th century but recent literature points to an increasing contribution to SLR from the Greenland and Antarctic ice sheets in the future. Concerns regarding considerably higher rates of sea level rise by 2100 have resulted from a study published following the IPCC AR5 that suggested that under a high-end greenhouse gas emissions and global warming scenario, the collapse of marine-based sectors of the Antarctic ice sheet alone could contribute around 1 m of SLR by 2100. While the processes in this modelling are physically plausible, the confidence that they will cause such a large contribution to sea level rise on this timescale is generally low because the widespread early surface melting of the ice shelves required to trigger this more rapid collapse has not been observed to date. Indeed, the most recent studies based on modelling and observations suggest that an additional contribution from Antarctica will not add more than several tenths of a meter of sea level rise during the 21st century. These new observations and modelling studies on the role of ice sheet dynamics that have emerged since the IPCC AR5 will be assessed in upcoming IPCC assessment reports such as the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (due for release in September 2019) and the IPCC Sixth Assessment Reports (due for release in 2021).

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[1] For the Sunshine Coast the known value of Vertical Land Movement is a subsidence of 0.4 mm yr^{-1}

The planning policy for Queensland requires consideration of 0.8 m of SLR from “present day” to 2100 (Dept of Environment and Heritage Projection, 2013). CSIRO projections for the Sunshine Coast are relative to a baseline average period of 1986-2005 with a central value of 1995. Moving the baseline of the CSIRO projections to an average period of 2008-2018 with a central value of 2013 reduces the projections by approximately 0.05 m, i.e. a high-end projection for the Sunshine Coast becomes 0.71 (0.48-0.98). The Queensland planning policy guideline of 0.8 m by 2100 therefore still resides within the upper half of the RCP 8.5 uncertainty range for 2100 and so is considered an appropriate guideline given the most currently available projections for SLR. However as noted previously, new IPCC assessment reports will reassess future sea level rise in view of new information on Antarctic ice sheet instability, and will update the AR5 projections that did not include this component quantitatively.

In relation to the development of a Coastal Hazard Adaptation Strategy (CHAS) for the Sunshine Coast Local Government Area, it is prudent to initiate the development of such a strategy, however, it is recommended that this be done in such a way that the strategy and associated supporting material readily revised to consider the guidance of future IPCC assessment reports.

1 Introduction

As greenhouse gases continue to accumulate in the atmosphere and cause warming of the climate system, sea levels will continue to rise at a global scale as the oceans expand from warming and the ongoing addition of meltwater from the world's glaciers and ice sheets. To plan for the inevitable impact of higher sea levels on the Sunshine Coast, the Sunshine Coast Council requires information on the latest scientific thinking in relation to the contributing factors driving sea level rise, the timing and magnitude of sea level rise estimates, and the uncertainties inherent in these contributions. This information is provided in order to understand the context of the Queensland Coastal Hazard Guidelines that stipulate a sea-level rise (SLR) of 0.8 m by 2100 with regard to current IPCC and CSIRO projections and, therefore, to inform and increase community confidence that the mandated sea level rise projection is suitable for assessments of future shoreline response (Dept. of Environment and Heritage Projection, 2013). The Sunshine Coast Council seeks to understand the suitability of this SLR planning benchmark in view of more recent IPCC assessments and new scientific developments in relation to future sea level rise and so the present report has been commissioned to provide this information.

The Planning Policy for Queensland states: "The estimated sea level rise is based on the best information currently available, with the current projected rise adopted for calculating the erosion prone area being 0.8 m by the year 2100. This value was based on the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) sea level rise projections to 2100 relative to the 1990 level, however the preference is to adopt a 100 year planning period. Therefore a sea level rise value of 0.8m from present day to 2100 was adopted rather than the strict scientific value of 0.84m from 1990 to 2100 to simplify determinations and prevent inaccuracies from using older (1990) tidal plane estimates. As the sea level rise value is updated in line with future IPCC projections, errors from a diminishing time period with a fixed sea level rise will be minimised" (Dept. of Environment and Heritage Projection, 2013).

The specific information to be addressed by this report includes the following topics:

- the contributing factors in SLR including potential contributions to relative SLR
- the state of knowledge regarding these contributions in previous IPCC reports (in particular the IPCC fifth assessment report) including historic trends, future emission scenarios, sea level rise projections and their uncertainties
- the planned topics that will be addressed by the IPCC in the sixth assessment cycle including the '1.5 degree report' and the 'Special Report on Oceans and Cryosphere under Climate Change'

- New peer-reviewed studies on sea level contributions that have emerged since the IPCC Fifth Assessment report including studies of the Antarctic ice-sheet, and 'time of emergence' studies
- State planning benchmarks and sea level rise projections for 2100
- An indication of the extent to which vertical land movement through Glacial Isostatic Adjustment is contributing to relative sea level rise along the Queensland coast
- A recommendation with regard to the suitability of using a high-end sea level rise projection to inform the development of the Coastal Hazard Adaptation Strategy (CHAS)
- An indication of a time-based (or other) trigger that could be incorporated into the CHAS in order to prompt a re-evaluation of coastal hazard mapping when it is likely that there will be a high level of scientific certainty with regard to identifying an upper limit for SLR for 2100.

2 Sea-level Rise: Contributing Factors

Changes in sea level are caused by a number of factors. These include changes in ocean mass due, for example, to changes in the distribution of water between land and oceans (e.g. land-based ice sheets and glaciers, dams, groundwater, floods), changes in ocean volume associated with ocean density changes, and changes in the spatial distribution of height of the ocean surface due to factors such as atmospheric pressure, ocean currents, movements in the Earth's crust due to mass distribution changes and associated changes in the Earth's gravity field and rotation vector. These various factors must be considered in interpreting measurements of past sea level change and projections of future sea levels. Since the beginning of the Industrial era, the burning of fossil fuels has been elevating concentrations of carbon dioxide and other greenhouse gases in the atmosphere and this is causing temperatures of the atmosphere and ocean to rise, which in turn is causing sea levels to rise. The various factors contributing to SLR are described in Table 1 and discussed in more detail in the following subsections. Figure 1 illustrates the various processes.

2.1 Sea Level Measurements and Frames of Reference

Sea levels are typically observed by coastal tide gauges, which measure sea levels along coastlines of continents or islands or by satellite altimeters, which provide near-global measurements of sea surface height (White et al, 2014). Digital records of many tide gauges in Australia commence around 1966 although longer digital records are available for some locations (e.g. McInnes et al, 2016). Satellite altimeter measurements, on the other hand, commence in 1993 providing a much shorter record of near-global sea level change. While the two datasets are complementary in their respective length and spatial coverage, the reference frames of the two data sources differ and must undergo conversions to be directly comparable to each other.

Tide gauge data are measured in relation to a fixed benchmark on the land on which it is located and is therefore referred to as Relative Sea Level (RSL). On the other hand, sea level measured by altimeters, often referred to as geocentric sea level (or absolute sea level), uses an Earth-fixed geocentric reference frame (White et al., 2014). Information on the vertical movement of the Earth's crust is required to convert tide gauge data to the same reference frame as satellite data (see subsequent sections). This can be achieved by using vertical land movements (VLM) measurements from co-located Global Positioning System (GPS) station, which facilitate the conversion between two sea level reference frames.

Table 1: Factors contributing to sea level change

Components of sea- level change	Contributing factors
Thermal expansion /contraction	Warming/cooling of sea water leads to expansion/contraction of the ocean's volume
Change in mass of ice sheets (Antarctica and Greenland)	The Antarctic and Greenland ice sheets have the greatest potential to contribute to sea level rise, contain enough water to raise sea levels by 50 and 7 m respectively if they were completely melted. Atmospheric processes such as precipitation and temperature rise cause accumulation and melting respectively. The combination of effects is referred to as Surface Mass Balance (SMB) Warming oceans melt and thin the ice shelves from below, reducing the buttressing effect of the ice sheet and increasing the mechanical breakdown at the ocean terminus. Other dynamical/mechanical mechanisms include cliff collapse as a result of meltwater refreezing in crevasses at the seaward edges contributing to destabilisation of the ice cliffs
Change in mass of glaciers	Glaciers (excluding those of Antarctica and Greenland) contain enough mass to raise global sea levels by 0.3-0.5 m. Glacier mass gain occurs through precipitation and loss occurs through melting or calving of ice at the glacier outflows at lakes or oceans
Changes in terrestrial storage	The main anthropogenic factors are the retention of water on land through dams and reservoirs that reduces net sea level and extraction of groundwater which eventually drains to the ocean providing a positive contribution to sea level. Other factors such as rainfall extremes, often associated with climate variabilities especially ENSO, can temporarily alter global mean sea level for periods of one to two years
Vertical land movement	On geological time scales, the Earth's mantle has been readjusting to the melting of ice sheets that covered land masses during the last ice age and this Glacial Isostatic Adjustment (GIA) can lead to relative sea level change. On shorter time scales, removal of groundwater or oil or gas or sediment compaction can lead to land subsidence and increase in RSL Rise (RSLR). Tectonic activity such as earthquakes can also lead to land movement with consequent changes in relative sea level.
Ocean density, atmospheric and ocean circulation	Ocean density relates to both temperature of the ocean (the thermosteric component) and the salinity (the halosteric component). Rainfall/evaporation patterns contribute to regional differences in density and this in turn contributes to ocean circulation as the denser water sinks. Momentum flux (i.e., wind stress) also affects ocean density and ocean circulation.
Spatial redistribution of sea level through changes in gravity and rotation (Fingerprints)	The gravitational attraction of ocean to large masses such as ice sheets diminishes as the ice sheets melt causing the water to migrate to distant parts of the ocean. Earth's rotation also changes with above mass changes, which further induce regional sea level patterns. Solid-earth deformation (in particular the fast elastic response) can also cause upward or downward vertical land movement. The spatial patterns of this redistribution, considering rotational-gravitational-elastic impacts, are referred to as Fingerprints

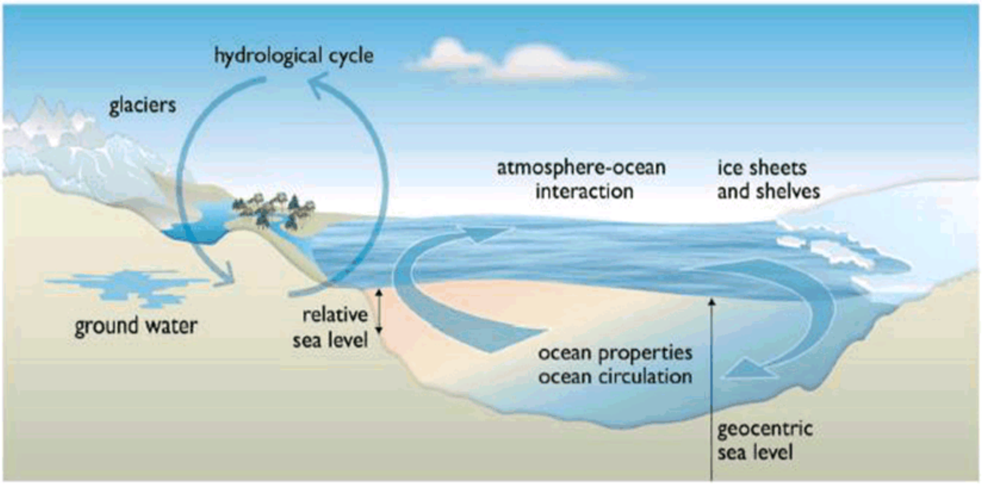

Figure 1. Climate-sensitive processes and components that can influence global and regional sea level. The term 'ocean properties' refers to ocean temperature, salinity and density, which influence and are dependent on ocean circulation (source: Church et al., 2013).

2.2 Contributing Factors to Sea-level Change

A number of factors contribute to sea level change. These factors typically relate to changes in the density of water due to temperature or salinity changes and the movement of water between land and ocean. These are discussed in the following subsections. To provide context, the distribution of water across the planet is first summarised in Table 2. By far, the most significant source of planetary water is found in oceans, seas and bays, with smaller amounts frozen on land in ice sheets and glaciers and groundwater systems. By comparison, the atmosphere stores a negligible amount of water. Furthermore, even with increased evaporation and moisture holding capacity of the atmosphere under climate change -- the atmospheric moisture holding capacity of the atmosphere increases around 7% for every degree of global warming, (State of the Climate, 2018), this tends to lead to more extreme rainfall events, and the overland rainfall tends to make its way back to the oceans eventually as run-off, meaning that increased evaporation has only a small and transitory effect on global sea levels.

Table 2: Estimate of the distribution of water across the globe (Source: Shiklomanov, (1993) and accessed via http://ga.water.usgs.gov/edu/earthwherewater.html). Note that percentages have been rounded and so will not sum to 100.

Water Source	Percent of Total Water
Oceans, seas and bays	96.5
Ice sheets, Glaciers, & Permanent Snow	1.74
Ground water	1.69
Soil moisture	0.001
Ground ice & permafrost	0.022
Lakes, swamps & rivers	0.014
Atmosphere	0.001
Biological water	0.0001

2.2.1 Thermal Expansion

Approximately 93% of the excess energy in the climate system has been absorbed by the oceans where it has contributed to ocean warming (Rhein et al, 2013; Church et al, 2013). Over the 20th Century thermal expansion contributed to approximately one third of the measured sea level rise. About 60% of the heat is absorbed in the upper 700 m of the ocean but the deep ocean is also warming although measurements of warming in the deep ocean are fewer and so the magnitudes are less certain (Purkey and Johnson, 2010).

2.2.2 Antarctica and Greenland Ice sheets

Atmospheric processes such as precipitation and temperature rise cause accumulation and melting respectively over the ice sheets. The combination of these effects is referred to as the Surface Mass Balance (SMB). In addition, warming ocean temperatures can melt and thin the ice from below the ocean surface, reducing the buttressing effect of the ice sheet and increasing the mechanical breakdown at the ocean terminus. A particularly unstable configuration arises when the grounding line of the icesheet is situated on reverse-sloped bedrock. In this situation advection of warm water underneath the icesheet accelerates ice sheet loss in a process referred to as Marine Ice Sheet Instability (MISI) (De Conto and Pollard, (2016). Other dynamical/mechanical mechanisms include hydrofracturing of ice shelves where successive melting and freezing of meltwater in crevasses at the seaward edges of ice cliffs cause cliff collapse into the ocean (Marine Ice Cliff Instability – MICI), De Conto and Pollard (2016) (see Figure 2). Recent contributions of Greenland to sea level rise have been mostly due to SMB and glacial retreat across the grounding line (van den Broeke et al, 2016). Contributions from west Antarctica in recent years have been due mainly to ocean-driven melting in west Antarctic and increased ice-shelf collapse in the Antarctic Peninsula region (Shepherd et al, 2017).

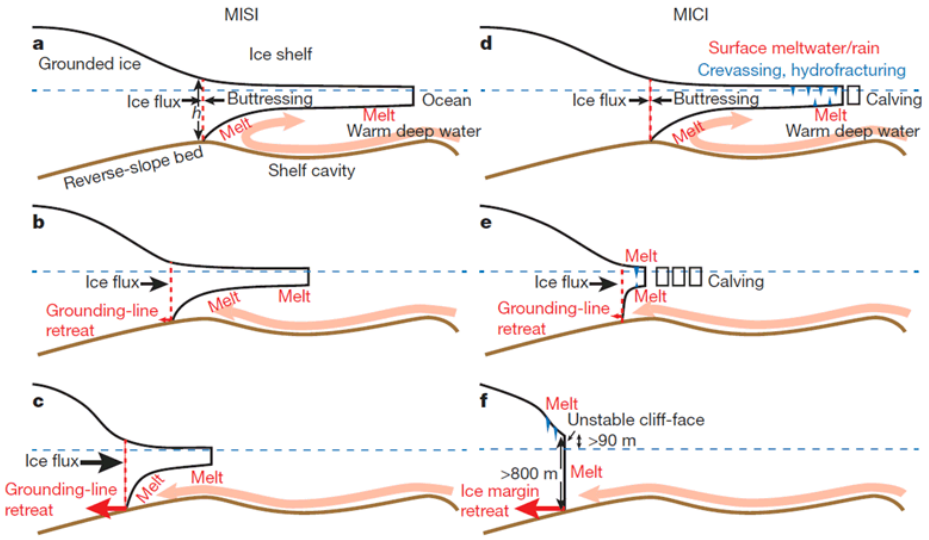

Figure 2: Schematic representation of the processes of Marine Ice Sheet Instability and Marine Ice Cliff Instability. From De Conto and Pollard (2016).

2.2.3 Glaciers

The world's glaciers, excluding those located on Antarctica and Greenland, contain enough mass to raise global sea levels by 0.3-0.5 m (Vaughan et al, 2013). Over the past century, the majority of glaciers have been retreating across the globe and the rate of retreat has increased (Zemp et al, 2015).

2.2.4 Terrestrial Storage

Terrestrial water storage refers to dams and underground aquifers. Over much of the Twentieth Century, this term was small and slightly negative (i.e. contributing to sea level fall rather than rise) because dam building projects across the globe were impounding water that otherwise would have flowed to the sea. However, as dam building has slowed globally in recent decades and groundwater extraction for domestic, agricultural and industrial applications has increased, the terrestrial storage term is now contributing positively to sea level rise, although the term is small (Church and White, 2011). It is noteworthy that major flood events can contribute to temporary sea level variations. For example, excess rainfall over the Australian Continent during 2010/2011 La Niña event led to so much water temporarily located on the land surface that average global sea levels fell by 7 mm in this period (Fasullo et al. 2013; Ummenhofer et al, 2015).

2.2.5 Vertical Land Movement

On geological time scales, the Earth's mantle has been readjusting to the melting of ice sheets that covered land masses during the glacial maximum that occurred about 20 thousand years ago. This Glacial Isostatic Adjustment (GIA) can lead to relative sea level change. On shorter time scales, removal of groundwater or oil or gas can lead to land subsidence and an increase in RSLR. In seismically active areas, tectonic activity can lead to ongoing land movement changes or abrupt changes in land level due to events such as earthquakes. In Australia, VLM based on GPS measurements indicates subtle subsidence at many locations, although the VLM rates are usually not significant (i.e., within one stand error). GIA-induced VLM is also relatively small, mostly negative ranging from −0.2 mm yr^{-1} to 0.0 mm yr^{-1} (White et al. 2014; see Fig. A1 in Appendix). GIA models can also provide a solution about the contribution of GIA to relative sea levels, which are small around much of the Australian coast ranging from -0.1 to -0.4 mm yr^{-1} depending on GIA model (Peltier, 2004; Kendall et al, 2006; White et al. 2014; see Appendix A).

2.2.6 Ocean Density, Atmospheric and Ocean Circulation

Ocean density relates to both temperature of the ocean (the thermosteric component) and the salinity (the halosteric component). Rainfall/evaporation patterns contribute to regional differences in density and this in turn contributes to ocean circulation as the denser water sinks. Atmospheric wind and pressure changes influence local sea levels with climatological high and low pressure centres causing regional depression or elevation of sea levels. Warm and cool currents also influence sea levels. In Australia, the East Australian Current transports warm tropical water southwards along the east coast. This leads to sea levels that are relatively higher along the southern half of the east coast compared to elsewhere along Australia's coast.

2.2.7 Gravity and Rotation Changes (Fingerprints)

Sea level is also influenced by the mutual attraction of the ice-sheets and ocean, which diminishes as the volume of land based sea ice falls, and this is compensated by a sea level rise in the far field on the opposite side of the earth. The Earth's rotation also changes with mass changes, which further induce regional sea level patterns. Solid-earth deformation (in particular the fast elastic response) can also cause upward or downward vertical land movement. The spatial patterns of this redistribution, considering rotational-gravitational-elastic impacts, are referred to as Fingerprints (Mitrovica et al. 2011).

3 Projecting Sea-Level Rise

This chapter describes the different methods that are used to develop sea level projections as well as the different ways in which sea level projection information may be presented. A brief summary of the sea level information contained in recent and upcoming Intergovernmental Panel on Climate Change (IPCC) assessment reports is also provided.

3.1 Methods of Projecting Sea-level Rise

3.1.1 Projections based on physical models of sea-level rise

Projections based on process models involve combining the contributions of the various processes identified as contributing to sea level rise. Global climate models (GCMs) run as part of the Coupled Model Intercomparison Project (CMIP) in support of the IPCC process provide the underlying projections of sea level change due to thermal expansion and the SMB of glaciers and ice sheets. However, other components of sea level change such as the terrestrial storage changes, GIA, spatial redistribution sea level due to changes in gravity and rotation arising from ice sheet loss (fingerprints) and the contribution to sea level rise from dynamical processes contributing to icesheet and glacier reduction and the exchange of water between the terrestrial environment and the ocean are obtained from separate off-line models. Process-based projections are also categorised more generally as a type of ‘bottom-up’ projection by Horton et al, (2018). Outputs from these models are often represented in the form of probabilistic scenarios, which are probability distributions over possible values of sea level at given points in time conditional on an emission, concentration or radiative forcing scenario (IPCC, 2013, Hinkel et al, 2019). They may be presented as a central estimate and an upper and lower bound that represents a quantile range (e.g. the 5-95 percentile range of the spread of climate model simulations) as an estimate of uncertainty.

3.1.2 Semi-empirical models

Semi-empirical methods for sea-level projection involve by-passing the individual factors that contribute to sea level change and instead building statistical relationships between past surface temperature and sea level. These relationships can then be used to estimate future sea level rise for different projections of future surface temperature change. The data on which the statistical relationships are calibrated include paleo records of sea level and temperature change that span millennia and include studies such as

Rahmstorf et al, 2012 and Kopp et al, 2014. Semi-empirical approaches were assessed by the AR5 where it was concluded that the projections of some semi-empirical approaches overlapped the projections produced by process-based models whereas others were higher by a factor of two (Church et al, 2013). Because of the large spread in results and the inability to explain the reasons for the differences in results arising from semi-empirical models, the AR5 assessed that "there is no consensus in the scientific community about their reliability, and consequently *low confidence* in projections based on them" (Church et al, 2013).

3.1.3 Expert elicitation

In scientific applications expert elicitation is the process of synthesising the opinions of authorities of a subject to generate consensus. Such approaches may be used in situations where there is insufficient data or data cannot be obtained due to lack of resources. Recent examples of expert elicitation include Bamber and Aspinall, (2013), Kopp et al., (2014); Le Bars et al., (2017). These studies use expert input to provide guidance on SLR beyond the central or likely ranges by including information about potential contributions to SLR from sources that have not formally been assessed (e.g. marine ice sheet instability; De Conto and Pollard, 2016). They generally aim to evaluate the tails of probability distributions for mean SLR (Hinkel et al, 2019).

3.2 IPCC Assessments

The Intergovernmental Panel on Climate Change undertakes comprehensive assessments on the state of understanding of the climate system including SLR on approximate six to seven year cycles. The Assessment reports are delivered by three working groups; Working Group 1 assesses current understanding of the science of climate change, Working Group 2 assesses impacts and adaption needs while Working Group 3 assesses mitigation options. Here, a brief summary is given of sea level projections from the relevant chapters of the Working Group 1 report over the past two assessment cycles culminating in the fourth assessment report released in 2007 (AR4) and the fifth assessment report released in 2013 (AR5). During assessment cycles, the IPCC may also commission special reports on specific topics as proposed by the member countries of the IPCC. A brief summary of the sixth assessment cycle is also given in terms of both AR6 and the commissioned reports.

3.2.1 Emission Scenarios and Representative Concentration Pathways

The starting point for projecting future climates using climate models is a set of assumptions about future anthropogenic greenhouse gas and aerosol emissions. These are linked to socio-economic pathways because factors such as population growth, future energy generation and globalisation ultimately determine the amount of greenhouse gases and aerosols will be emitted. Prior to the AR5, the development of emission scenarios commenced with the socio-economic scenarios, which provided the basis for assumptions about greenhouse gas and aerosol emissions into the atmosphere. From the emissions, concentrations of greenhouse gas and aerosols in the atmosphere were estimated using simple climate models that accounted for some of the emissions being absorbed by the oceans and biosphere and these were subsequently applied to climate model simulations to simulate climate change. In the AR4, the emission scenarios based on the Special Report on Emission Scenarios (SRES) were used (Nakicenovic and Swart, 2000). To shorten the development of new scenarios for the AR5, the process commenced with greenhouse gas Representative Concentration Pathways (RCPs) that could be simultaneously used in climate models to explore future changes in the climate system while at the same time being used in Integrated Assessment Models (IAMs) to explore the different socio-economic conditions that would lead to such future atmospheric composition changes. Figure 3 compares the key SRES and RCPs in terms of atmospheric concentrations of CO_2 while Table 3 summarises the warming ranges projected by climate models under the different scenarios.

Table 3: The range of atmospheric temperature change predicted by climate models in response to the listed scenario as reported in the AR4 and AR5 assessment reports. Note that the atmosphere has already warmed approximately 1°C since pre-industrial times. (Note that CO_2 equivalent concentrations include CO_2 concentrations together with the warming potential of other greenhouse gases that have been converted into a CO_2 equivalent concentration).

Scenario	Atmospheric CO_2 equivalent in 2100 (ppm)	Temperature Increase (°C by 2090-2099 relative to 1980-1999)	Scenario	Atmospheric CO_2 equivalent in 2100 (ppm)	Temperature Increase (°C by 2081-2100 relative to 1986-2005)
A1FI	1550	4.0 (2.4 – 6.4)	RCP 8.5	>1370	3.7 (2.6 – 4.8)
A2	1250	3.4 (2.0 – 5.4)	RCP 6.0	850	2.2 (1.4 – 3.1)
A1B	850	2.8 (1.7 – 4.4)	RCP 4.5	650	1.8 (1.1 – 2.6)
B1	600	1.8 (1.1 – 2.9)	RCP 2.6	490	1.0 (0.3 – 1.7)

3.2.2 IPCC Fourth Assessment Report

The AR4 employed climate models and other process-based models to develop projections of SLR. Climate model simulations were based on the Climate Model Intercomparison Project Cycle 3 (CMIP3) suite of Global Climate Models. A global-averaged SLR of 0.18 to 0.59 m was projected for 2090-2099 relative to 1980-1999 (Meehl et al., 2007) including the processes of ocean thermal expansion, glaciers and ice caps, and ice sheet contributions (i.e. SMB). The range encompassed 90% of the uncertainty across all scenarios considered. The dynamic ice-sheet processes were poorly understood at the time of the AR4, therefore preventing a formal estimation of their contribution. However, an additional contribution to the sea level rise projections of 0.1 to 0.2 m was calculated using a simple linear relationship with projected temperature to account for a possible rapid dynamic response of the Greenland and West Antarctic ice sheets. Because of the insufficient understanding of the dynamic response of ice sheets, Meehl et al. (2007) also noted that a larger contribution could not be ruled out. In reporting on the SLR projections, the upper value of the potential dynamic ice sheet contribution was often added to the upper value of the sea level range to yield a high-end projection of 0.79 m of SLR by 2090-2099.

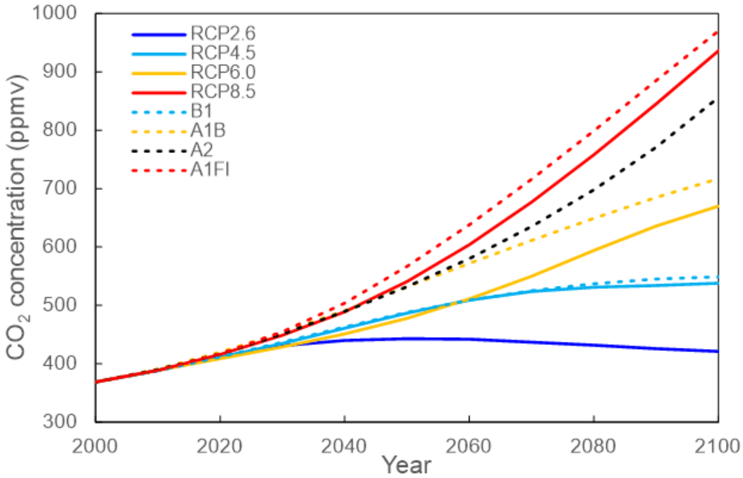

Figure 3: A comparison of RCPs and SRES CO2 concentrations. Note that these are CO2-only and do not include the 'CO$_2$-equivalent' concentrations. (Data is available at http://www.pik-potsdam.de/~mmalte/rcps/). (Note that these curves are for CO$_2$ concentrations not CO$_2$-equivalent concentrations, so will be smaller than the values indicated in columns 2 and 5 of Table 2)

3.2.3 IPCC Fifth Assessment Report

The most recent IPCC assessment report released in 2013 contained a chapter on ocean observations (Rhein et al, 2013) and on sea level change including future projections (Church et al, 2013). A number of key advancements in sea level science reported in Church et al, (2013) are summarised in Table 4.

Table 4: Key advancements in understanding of SLR from the AR5 (selected).

Description/significance	Statement
Historical context. Paleo evidence demonstrates a precedent for future SLR	"Paleo sea level records from warm periods during the last 3 million years indicate that global mean sea level has exceeded 5 m above present (*very high confidence*) when global mean temperature was up to 2°C warmer than pre-industrial (*medium confidence*)."
Closing the observed sea level budget. By showing that the sum of the individual contributing factors to sea level rise amounts to the values measured directly by tide gauges or	"The sum of thermal expansion simulated by Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs), glacier mass loss computed by global glacier models using CMIP5 climate change simulations, and estimates of land water storage explain 65% of the observed global mean sea

satellite altimeters builds confidence in the ability to use models to project future sea level rise	level rise for 1901–1990 and 90% for 1971–2010 and 1993–2010 (*high confidence*).”
Sources of recent SLR	“Ocean thermal expansion and glacier melting have been the dominant contributors to 20th century global mean sea level rise. Observations since 1971 indicate that thermal expansion and glaciers (excluding Antarctic glaciers peripheral to the ice sheet) explain 75% of the observed rise (*high confidence*). The contribution of the Greenland and Antarctic ice sheets has increased since the early 1990s, partly from increased outflow induced by warming of the immediately adjacent ocean.”
Rate of future SLR	“It is very *likely* 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 due to increases in ocean warming and loss of mass from glaciers and ice sheets.”
Sea-level Projections “Projections of sea level rise are larger than in the AR4, primarily because of improved modelling of land-ice contributions.”	“For the period 2081–2100, compared to 1986–2005, global mean sea level rise is likely (*medium confidence*) to be in the 5 to 95% range of projections from process-based models, which give 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5. For RCP8.5, the rise by 2100 is 0.52 to 0.98 m with a rate during 2081–2100 of 8 to 16 mm yr^{-1}.”
Potential for higher projections	“We have considered the evidence for higher projections and have concluded that there is currently insufficient evidence to evaluate the probability of specific levels above the assessed *likely* range. 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. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century.”
Regional variations in SLR “It is very likely that in the 21st century and beyond, sea level change will have a strong regional pattern, with some places experiencing significant deviations of local and regional sea level change from the global mean change.”	“Over decadal periods, the rates of regional sea level change as a result of climate variability can differ from the global average rate by more than 100% of the global average rate. By the end of the 21st century, it is *very likely* that over about 95% of the world ocean, regional sea level rise will be positive, and most regions that will experience a sea level fall are located near current and former glaciers and ice sheets. About 70% of the global coastlines are projected to experience a relative sea level change within 20% of the global mean sea level change.” Figure 4 shows spatially the sea level projections around Australia (McInnes et al, 2015).
Assessment of extreme sea levels and waves	“It is very likely that there will be a significant increase in the occurrence of future sea level extremes in some regions by 2100, with a likely increase in the early 21st century. It is likely (*medium confidence*) that annual mean significant wave heights will increase in the Southern Ocean as a result of enhanced wind speeds”

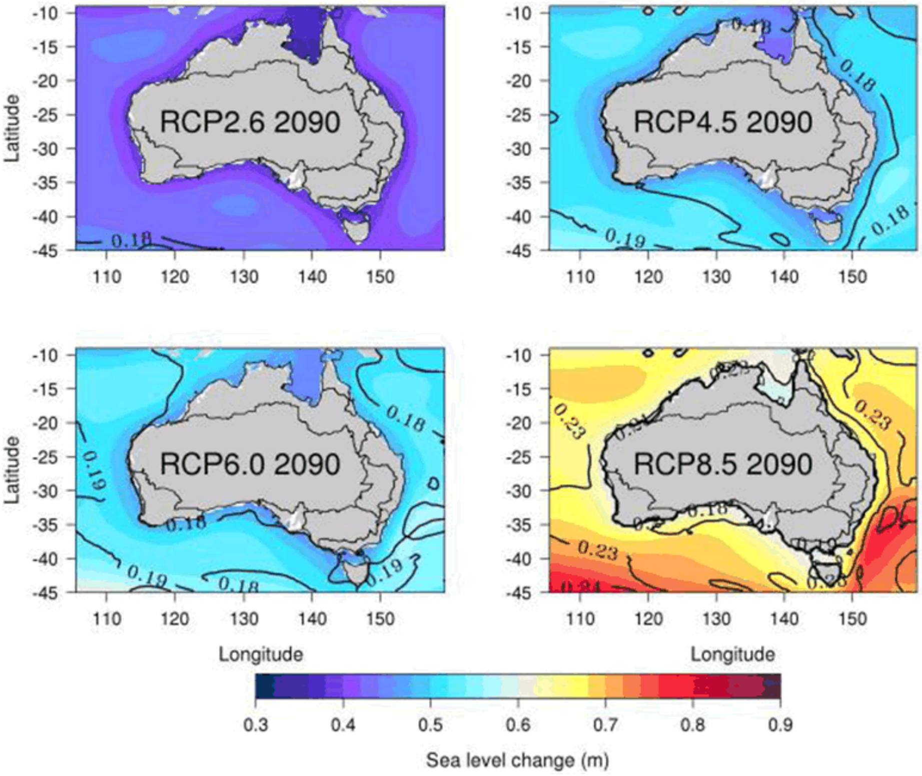

Figure 4: Ensemble mean regional relative sea level change (meters) evaluated from 21 CMIP5 models for the RCP scenarios as indicated between 1986-2005 and 2081-2100. The projections (shadings) and uncertainties (solid lines) represent the contributions from the changes in terrestrial ice, the gravitational response of the ocean to these changes, and an ongoing GIA (Source: McInnes et al, 2015).

3.2.4 IPCC Sixth Assessment Cycle

The sixth assessment cycle is underway. In addition to the preparation of new assessment reports from Working Groups 1 to 3, the IPCC will also release three special reports. The IPCC 1.5 degree report was proposed by the UNFCCC after the Paris Agreement was adopted and was released in October 2018. The goal of the report was to investigate how humanity could prevent a global temperature rise of more than 1.5°C above pre-industrial levels. This was partly to address the issue that the RCPs used in the AR5 did not cover a 1.5°C warming scenario by 2100. The lowest investigated, RCP 2.6, would still lead to an average global warming of around 2°C above preindustrial levels. Selected key findings of the 1.5 degree report are summarised in Table 5.

A second special report currently under preparation is the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (SROCC). The agreed outline for the special report is given below:

Chapter 1: Framing and Context of the Report
Chapter 2: High Mountain Areas
Chapter 3: Polar Regions
Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities
Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities
Chapter 6: Extremes, Abrupt Changes and Managing Risks

The report will assess literature published since the AR5 including that related to the Antarctic ice sheet response and its effect on sea-level projections and will be finalised in September 2019. A third special report on Climate Change and Land will address climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Table 5: Key findings from the IPCC 1.5°C report (selected).

Statement
"By 2100, sea level rise would be around 0.1m lower with 1.5°C global warming compared to 2°C (*medium confidence*) "
Limiting global warming to 1.5°C would require rapid and far-reaching systems transitions occurring during the coming one to two decades, in energy, land, urban, and industrial systems
Fulfilling the current pledges under the Paris Agreement (known as Nationally-Determined Contributions or NDCs) will still result in global warming of more than 1.5°C, with associated risks and adaptation challenges.
Policy implementation to successfully limit warming to 1.5°C and to adapt to global warming of 1.5°C implies international cooperation and strengthening institutional capacity of national and sub-national authorities from civil society, the private sector, cities, local communities and Indigenous peoples

The AR6 assessment reports from the three working groups are due to be released in 2021, with the Synthesis report of all three working groups to be released in 2022. It is anticipated that new SLR projections will be developed that are based on a new suite of improved climate model simulations (CMIP6) as well as improved models of other sea level processes.

4 Summary of Sea Level Information for Australia

This section provides an update of sea level observations. It also summarises the state of sea level knowledge at the time of the last IPCC release in 2013 together with Australia-specific sea level projections.

4.1 Observed Sea-Level Rise

Sea level is continuing to rise. Figure 5 shows the global-averaged sea level rise as measured by the various altimeters that have been in operation since 1993, which indicates a linear trend of 3.2 mm yr^{-1} to June 2018. Sea level rise varies from year to year and from place to place. This is partly due to the natural variability of the climate system from influences such as ENSO and the Pacific Decadal Oscillation (e.g., Fasullo et al. 2013).

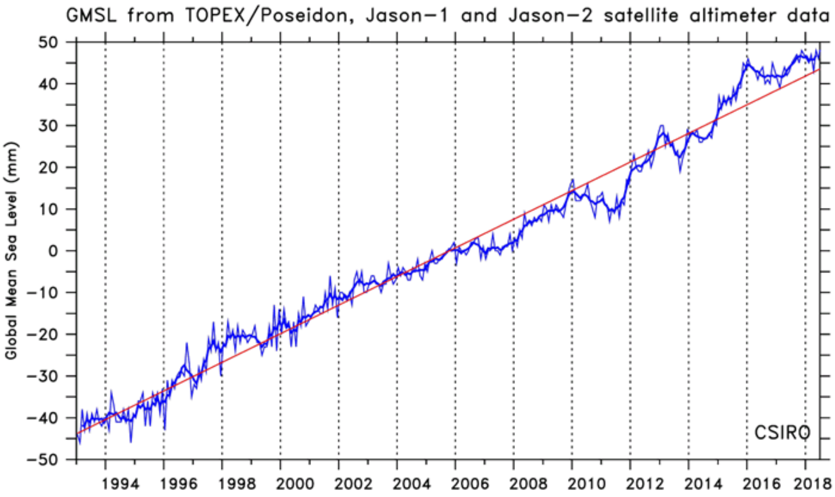

Figure 5. Satellite altimeter data showing a linear trend of 3.2 mm yr^{-1}.

Figure 6 shows the spatial pattern of sea level rise around Australia as measured by satellite altimeters. The rates of rise to the northwest, north and southeast of Australia have been higher than the global average. In the case of the northwest and north, the contributing factor to the higher rate of rise is the influences of El Niño, La Niña and the Pacific Decadal Oscillation (White et al, 2014). In the southeast, the high rate of sea level rise is related to the stronger southward transport of warm water within the East Australian current in recent years. Also shown are the trends in sea level over the same time period as determined from coastal tide gauges. While most gauges are broadly similar to the adjacent satellite measurements (noting that tide gauge data is measuring relative SLR and altimeters are measuring geocentric SLR as discussed in Section 2.1.1), some large differences at some gauges are apparent. For example, the Gold Coast Seaway (red dot on the east coast) is likely to be anomalous due to a previous datum shift in about 1999/2000 (White et al, 2014; Burgette et al, 2013).

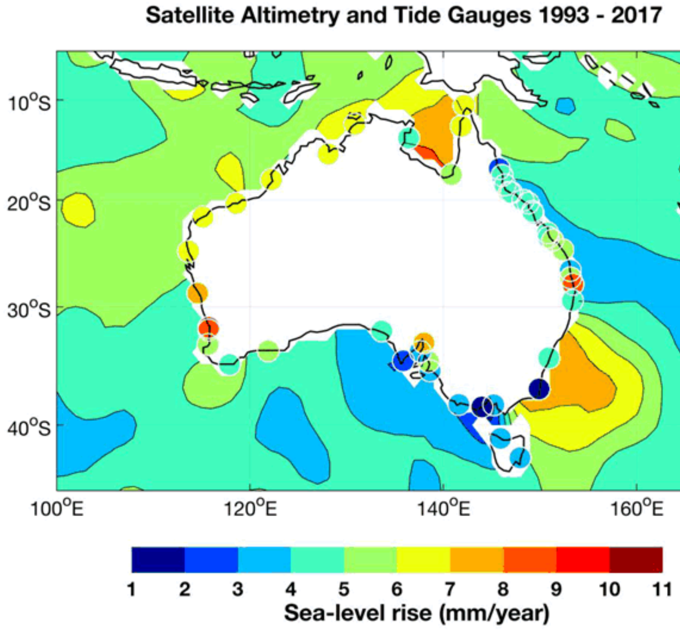

Figure 6. The spatial pattern of sea level rise as determined from satellite altimeter records. These measurements apply to trends that are at least 25 km off the coast. Also shown are trends measured at tide gauges at the coast, some of which exhibit large departures from adjacent gauges and altimeter data due to coastal processes, vertical land motion or changes to the surveyed reference level of the tide records that can be caused by (for example) a site change.

4.2 Sea Level Projections

Dedicated climate projections for Australia were released in 2015 (BoM and CSIRO, 2015). The projections were developed using the same overall method as that used in Church et al, (2013) with specific details of the method described in McInnes et al, (2015). These results were disseminated through the Climate

Change in Australia web portal (https://www.climatechangeinaustralia.gov.au/en/) and the Marine Explorer portal within it (https://www.climatechangeinaustralia.gov.au/en/climate-projections/coastal-marine/marine-explorer/). In addition to this, sea level projection information based on these projections can also be downloaded from the National Climate Change and Adaptation Facility web portal 'CoastAdapt' (https://coastadapt.com.au/sea-level-rise-information-all-australian-coastal-councils) where the sea level projections have been provided for all coastal councils in Australia. The values for the Sunshine Coast are presented in Table 5. The uncertainty range represents the 5-95% probability range of some twenty to thirty CMIP5 climate model simulations (the number of available models varies between the different RCPs). IPCC (Church et al, 2013) assessed this to be the 'likely' range meaning that there is a 66% chance sea-rise will lie within this range and approximately 33% chance it will lie outside this range.

Table 6: Sea-level rise projections for the Sunshine Coast for the specified year relative to an average calculated between 1986 and 2005.

Date (unit)	Very low (RCP2.6)	Low (RCP4.5)	High (RCP6.0)	Very high (RCP8.5)
2030 (m)	0.13 (0.09-0.17)	0.13 (0.09-0.17)	0.13 (0.08-0.17)	0.13 (0.09-0.18)
2050 (m)	0.22 (0.15-0.29)	0.24 (0.16-0.31)	0.22 (0.15-0.29)	0.27 (0.19-0.35)
2070 (m)	0.30 (0.19-0.42)	0.35 (0.23-0.47)	0.34 (0.23-0.45)	0.44 (0.31-0.58)
2090 (m)	0.38 (0.23-0.55)	0.47 (0.30-0.65)	0.48 (0.32-0.65)	0.65 (0.45-0.87)
2100 (m)	0.42 (0.24-0.61)	0.53 (0.33-0.73)	0.56 (0.37-0.76)	0.76 (0.53-1.03)
Rate of change at 2100 (mm yr^{-1})	4.1 (1.6-6.6)	5.9 (3.2-8.6)	7.5 (4.7-10.5)	11.4 (7.5-16.0)

5 Scientific Developments on Key Uncertainties

This chapter provides examples of key new developments in sea level science that have emerged since the last IPCC assessment report. It is not anticipated to be exhaustive or comprehensive. A full assessment of such studies will occur in upcoming IPCC reports. The purpose here is to provide a broad overview of emerging scientific developments.

5.1 Observed Changes in Sea Level

Church et al, 2013 estimated the sea level trend and acceleration over the period 1900–2010. They concluded that it is very likely that the long-term trend in GMSL from tide gauge records is 1.7 (1.5 to 1.9) mm yr^{-1} between 1900 and 2010 with a likely average acceleration over the 20th century between –0.002 to 0.019 mm yr^{-2}. The derivation of sea level acceleration is very sensitive to the study period, datasets and empirical models used (e.g., whether multi-decadal oscillation is considered) (Church et al. 2013). It's hard to verify whether acceleration of sea level rise exists in the short altimetry era over 20 years, mainly constrained by the short period and influences of interannual-to-decadal climate variabilities.

By comparing tide gauge and satellite altimeter sea-level observations, Watson et al. (2015) identified a possible systematic drift within the altimeter record, particularly affecting the first six years (1993-1999). After removing these biases, the estimated rate of GMSL rise from 1993 to mid-2014 was between 2.6 ± 0.4 and 2.9 ± 0.4 mm yr^{-1}, which leads to a positive but not statistically significant acceleration of 0.041 ± 0.058 mm yr^{-2}, compared with a not statistically significant deceleration of -0.057 ± 0.058 mm yr^{-2} for unadjusted data. By adopting a novel data analysis method (Empirical Mode Decomposition) to derive yearly GMSL rising rate without being affected by internal climate variabilities, Chen et al. (2017) further identified the increasing GMSL rate (i.e. acceleration), over the altimetry era, which was mainly due to the increased contribution from the melting of Greenland Ice Sheet. This finding is consistent with Dieng et al. (2017), who identified an increase of the GMSL rate of 0.8 mm yr^{-1} during the second half of the altimetry era (2004–2015) compared to the first half span (1993–2004), mostly due to added mass from Greenland. Watson et al, (2016) utilises more sophisticated trend analysis methods and also finds that sea levels are accelerating.

5.2 Attribution and Time of Emergence Studies

Attribution studies focus on determining the extent to which observed trends in sea level can be attributed to anthropogenic warming as opposed to other naturally occurring sources of internal variability in the climate system (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation) and external factors such as volcanic eruptions and solar variability. They analyse climate model simulations over the observational period that include all forcing factors (natural and anthropogenic) and compare them to simulations that include only natural or only anthropogenic factors. New studies since the AR5 have attributed anthropogenic emissions as the principal cause of increased thermal expansion (Slangen et al, 2014; Marcos and Amores, 2014) and glacier mass loss (Marzeion et al, 2015; Dangendorf et al, 2016) and in total sea level rise (Slangen et al, 2016; Dangendorf et al, 2016). For example, Slangen et al (2016) find that the role of anthropogenic contributions in observed sea level rise has increased in time explaining only 15±55% before 1950, but explaining 69±55% after 1970 and reaching 72±39% in 2000. On the other hand they find that radiative forcing makes almost no contribution over the period 1900-2005. Similarly for glacier loss, Marzeion et al, find that only 25±35% of global glacier mass loss during the period 1851 to 2010 is attributable to anthropogenic causes whereas over the period 1991 to 2010 the fraction increases to 69±55%. Kopp et al, 2016 use semi-empirical models to assess that a significant sea level acceleration began in the 19th century and yielded a 20th century rise that is extremely likely faster than during any of the previous 27 centuries and that without anthropogenic climate change, 20th century sea level rise would have been less than 51% of the observed.

Related studies address how far into the future it will be before the anthropogenic sea level trend will emerge from the background sea level variability. For example, for coastlines with low sea level interannual variability the climate change signal is expected to emerge from the noise by 2020 in 50% of the ocean (Lyu et al, 2014; Richter and Marzeion, 2014). Furthermore, Lyu et al. (2014) concluded that the anthropogenic signal in sea level change will be detectable in 50% of the ocean area by 2020. For the Australian region, the time-of-emergence (ToE) of SLR varies between Australia's east and west coasts. Under RCP8.5, SLR is likely to emerge on the south and southeast coasts before 2030, and the west and northwest coasts before 2040. The later ToE off the west and northwest coasts is due to larger natural variability, associated with ENSO and PDO, consistent with the variance ratio analysis by Lyu et al. (2014).

5.3 Response of Ice Sheets

Since the release of the AR5 (Church et al, 2013) many studies have emerged that aim to better understand the sea level response of Antarctica during past interglacial periods and during the 21st Century through monitoring and modelling. Satellite observations and model studies suggest that MISI is occurring in West Antarctica caused by warm circumpolar deep water breaching the continental shelf and contributing to basal melting of the icesheet (Rignot et al, 2014; Favier et al, 2014; Joughin et al 2014) (see Figure 2). De Conto and Pollard (2016) developed a model to account for the dynamically-driven ice sheet decay due to MISI and MICI (see Figure 2) to understand its potential role in future SLR and found that by 2100 SLR of more than 1 m could occur. These findings were subsequently incorporated in several SLR projection studies (e.g. Nauels et al, 2017; Le Bars et al, 2017) projecting total sea level increases by 2100 of between 0.8-1.9 m relative to 1986-2005. However, more recent studies have shed doubt on whether widespread MICI would occur on the timescale of this century since observations of this process are limited (e.g. Edwards et al, 2019; Golledge et al, 2019). Bronselaer et al, (2018) also note that ocean circulation feedbacks that are not currently included in climate models would slightly offset some of the sea level rise during the 21st century thereby avoiding some of the high projections of SLR due to Antarctic ice sheet loss . Edwards et al, (2019) show that meltwater from Antarctica will trap warm water below the sea surface, creating a positive feedback that increases Antarctic ice loss. They account for an important feedback in which ice-sheet meltwater reduces ocean mixing and find that this can increase sea ice extent and delay 21st century warming. The improved ice sheet models applied in Golledge et al (2019) and Edwards et al (2019) point to higher contributions from the Greenland and Antarctica than used in the AR5. The delayed atmospheric warming reduces the likelihood that MICI would make a large contribution during the 21st Century. Golledge et al (2019) estimates future ice-sheet melt up to 25 centimetres to sea level by 2100, in line with the *medium confidence* that collapse of marine-based sectors of the Antarctic ice sheet 'would not exceed several tenths of a meter of sea level rise during the 21st century (Church et al, 2013).

5.4 Models and Projections

The state-of-the-art global coupled climate models, with a relatively coarse spatial resolution (typical 1° resolution in the ocean), are primarily designed to study large-scale climate change and variability globally over decades to centuries. However, for local applications including climate adaption and mitigation planning, practitioners require much finer resolution at the coast—at least tens rather than 100 km [Intergovernmental Panel for Climate Change (IPCC), 2014]. Moreover, coarse-resolution models may have some limitations in representing ocean dynamics, since many processes cannot be resolved directly but have to be parameterized instead. To address this limitation of most GCMs, Zhang et al. (2016, 2017) used a near-global eddy-resolving (1/10°) ocean general circulation model (OGCM) to downscale ocean states for both the historical period and the 21st century projections of the ensemble average of 17 CMIP5 models under RCP8.5. High-resolution (1/10°) sea level projection is produced by combining downscaled dynamic sea level with other sea level contributions such as ocean thermal expansion, mass loss of glaciers, changes in Greenland and Antarctic ice sheets and land water storage, and glacial isostatic adjustment. Off the southeast coast, dynamic downscaling provides better representation of high sea level projections associated with subtropical ocean gyre circulation and western boundary current changes.

5.5 Risk-based Approaches to Sea-level Rise Projections

The sea-level projections discussed in chapter 4 relate to the 'likely range' of future SLR. In other words, IPCC scientists have estimated that future sea level has a 66% probability of lying within this range. For certain applications, high-end scenarios or scenarios that consider higher probability percentiles such as the 99th percentile of the estimated future distribution of SLR are preferred for decision making, especially when the consequences of failure are extremely dire. An example includes the case of the Netherlands Delta Commission in its ongoing planning and management of the Netherlands extensive dyke system and storm surge barriers into the future (https://www.deingenieur.nl/artikel/accelerated-sea-level-rise-poses-a-major-challenge-to-the-dutch-delta). Another example is the Thames Estuary 2100 project where planners considered a plausible worst-case SLR scenario in the technical analysis to support planning of new flood-control infrastructure to protect the city of London from tidal flooding from the Thames River basin over the 21st century (Ranger et al., 2013).

For the US, NOAA (Sweet et al, 2017) established risk-based sea level rise scenarios that included high-end scenarios of ice sheet loss such as the upper limit established by Pfeffer et al. (2008), on the maximum plausible loss rate from Greenland leading to sea level rise scenarios of 2 m by 2100 and the potential for continued acceleration of mass loss from Antarctica based on DeConto and Pollard, (2016). In addition, a number of contributing sea level terms reported in Church et al (2013) were increased on the basis of various studies. By combining these high-end estimates of the various sea level contributions, Sweet et al (2017) recommended a revised worst-case (extreme) GMSL rise scenario of 2.5 m by 2100. This assessment does not take into account more recent studies that suggest the DeConto and Pollard (2016) assessments may be unrealistically high on the time frame of 2100.

In Australia, various state and territory governments have established SLR planning guidelines, (see for example Good, (2011)). For the most part, these have been based on the upper end of the likely range of recent IPCC SLR projections. These estimates are reviewed from time-to-time, usually following the release of a new IPCC assessment, which contains a synthesis of new scientific studies and understanding on the contributing factors to SLR. For example, in 2008, Victoria's coastal policy stipulated that planning authorities must plan for SLR of 'not less than 0.8 m by 2100', based on the IPCC AR4 assessment report. This benchmark was reviewed following the IPCC AR5 release by Hunter (2014), who recommended its continued suitability as a state planning guideline.

In relation to the development of a Coastal Hazard Adaptation Strategy (CHAS) for Queensland, the comprehensive assessment of new science relating to SLR in the upcoming IPCC Special Report on Oceans and Cryosphere in a Changing Climate, due for release in September 2019, and the release of the IPCC AR6 assessment report in 2021 will provide opportunities to reassess the suitability of current state-based SLR planning guidelines.

6 Discussion and Recommendations

The key factors contributing to SLR have been reviewed. They include changes in ocean volume due to warming and changes in ocean mass due to melting of land ice and terrestrial water storage. In addition there are several factors that affect the spatial distribution of sea level that include atmospheric pressure and wind, ocean currents, movement in the Earth's crust due to mass distribution changes and associated changes in the Earth's gravity field and rotation vector.

Sea-level rise projections for Australia have been produced by CSIRO (McInnes et al, 2015) using a methodology similar to that of the IPCC Fifth Assessment Report (AR5) (Church et al, 2013). These projections cover a range of future scenarios including a low warming scenario of RCP2.6 that assumes global warming of 1.0 (0.3 – 1.7) by 2081-2100 relative to 1986-2005 and a high warming scenario of RCP 8.5 that assumes global warming of 3.7 (2.6 – 4.8) by 2081-2100 relative to 1986-2005. The 2°C warming target of the Paris agreement, signed in 2015, is broadly consistent with achieving RCP 2.6, but current greenhouse emissions are more aligned with RCP 8.5. CSIRO sea-level rise projections for Sunshine Coast based on RCP 8.5 indicate 0.76 (0.53-1.03) m of sea-level rise by 2100 relative to the average of the period 1986-2005. Known Vertical Land Movement factors are incorporated in CSIRO SLR projections. For the Sunshine Coast the known value of Vertical Land Movement is a subsidence of 0.4 mm yr^{-1}. However, as with the AR5, these projections do not include a larger potential contribution from Antarctica due to collapse of marine-based sectors.

An IPCC Special Report on 1.5°C was released in 2018 to understand the impact of achieving a temperature increase of 1.5°C above the pre-industrial level in view of the fact that RCPs that were used as inputs to the CMIP5 climate models did not include a greenhouse gas concentration pathway that would achieve the 1.5°C warming target. This report determined that by reducing global greenhouse gas emissions to limit warming to 1.5°C global-average warming by 2100 would lead to 0.1 m less SLR than meeting a global warming target of 2.0°C. However, it also noted that the NDCs pledged by the nations signed onto the Paris Agreement would not achieve a 1.5°C warming. The IPCC AR6 assessment report will consider a new suite of climate model simulations (CMIP6) and is due for release in 2022.

Changes in thermal expansion and glacier melting have been the dominant drivers of SLR during the 20th century but recent literature points to an increasing contribution to SLR from the Greenland and Antarctic ice sheets in the future. Concerns regarding considerably higher rates of sea level rise by 2100 have resulted from a study published following the IPCC AR5 that suggested that under a high-end greenhouse gas emissions and global warming scenario, the collapse of marine-based sectors of the Antarctic ice sheet alone could contribute around 1 m of SLR by 2100. While the processes in this modelling are physically plausible, the confidence that they will cause such a large contribution to SLR on this timescale is generally low because the widespread early surface melting of the ice shelves required to trigger the process of hydrofracturing and icesheet collapse has not been observed to date. Indeed, the most recent studies based on modelling and observations suggest that an additional contribution from Antarctica will not add more than several tenths of a meter of SLR during the 21st century. These new observations and modelling studies of the contribution of ice sheet dynamics to future SLR will be assessed in upcoming IPCC assessment reports such as the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (due for release in September 2019) and the IPCC Sixth Assessment Report (due for release in 2022). These assessments will provide an opportunity to reassess the suitability of existing state-based SLR planning guidelines.

SLR projections in Australia have followed the IPCC approach of assessing the likely range (McInnes et al, 2015) and state-based planning guidelines (including those in Queensland) have typically adopted a high-end value of the likely range. Elsewhere and for certain applications where the consequences of failure of defences protecting against SLR are extremely dire, high-end SLR scenarios are often used to guide planning. Examples where high-end SLR scenarios have been developed include the Dutch Delta Commission, the Thames Estuary 2100 project and the NOAA SLR scenarios for the United States (Sweet et al, 2017). These projections predate the most recent science reviewed in this report that suggest that the more dire projections of Antarctic ice sheet loss are unlikely to be realised by 2100.

The planning policy for Queensland requires consideration of 0.8 m of SLR from “present day” to 2100 (Dept of Environment and Heritage Projection, 2013). CSIRO projections for the Sunshine Coast are relative to a baseline average period of 1986-2005 with a central value of 1995. Moving the baseline of the CSIRO projections to an average period of 2008-2018 with a central value of 2013 reduces the projections by approximately 5 cm, i.e. a high end projection for the Sunshine Coast becomes 0.71 (0.48-0.98), (see appendix B). The Queensland planning policy guideline of 0.8 m by 2100 therefore still resides within the upper half of the uncertainty range of the most recent projections for RCP 8.5 for 2100 and is considered an appropriate guideline given the most currently available projections for SLR. However as noted previously, new IPCC assessment reports will reassess future SLR in view of new information on Antarctic ice sheet instability, thereby updating the AR5 projections that did not assess this component quantitatively. In view of the rapidly evolving understanding of the ice sheet contribution to SLR, and in relation to the development of a Coastal Hazard Adaptation Strategy (CHAS) for Queensland, the comprehensive assessment of new science relating to SLR in the upcoming IPCC Special Report on Oceans and Cryosphere in a Changing Climate, which is due for release in September 2019, will provide an opportunity to reassess the suitability of current state-based SLR planning guidelines.

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Appendix A: GIA models

There are ongoing changes in relative sea level associated with changes in surface loading over the last glacial cycle, i.e., the GIA (e.g., Davis and Mitrovica, 1996). A GIA model provides solution of three fields: a) vertical velocity of the crust relative to the geocentre, b) vertical velocity of the sea surface relative to the geocentre, c) relative sea-level change rate (the difference between a and b).

Fig. A1 shows the GIA-induced relative sea level rate and rate of vertical crust motion from the GIA model provided by Peltier (2004). Fig. A2 compares the GIA-induced relative sea level rate between two GIA models: Peltier (2004) and Kendall, Mitrovica and Milne (2005). There are some differences between two of them, in particular, the latter product tends to give a slightly stronger lowering relative sea level rates (about -0.2 mm yr-1) along the Australian coastline.

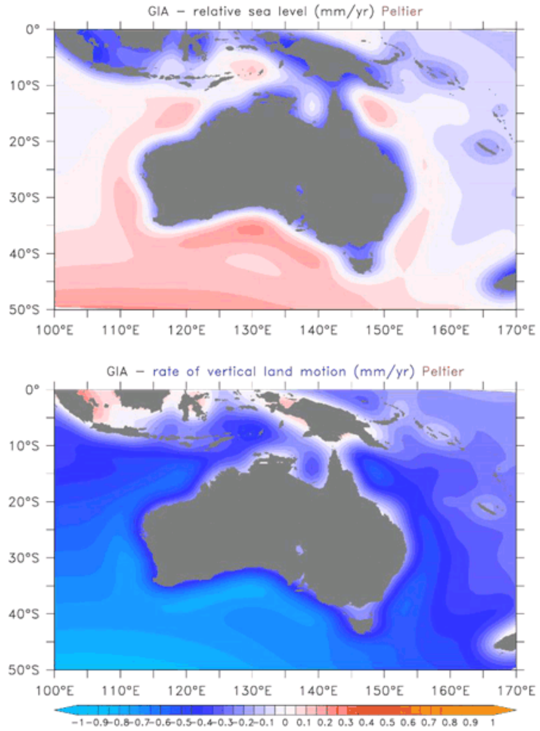

Figure A1. (a) Relative sea level rate (mm yr^{-1}) and (b) rate of vertical land motion (mm yr^{-1}) from the GIA model by Peltier (2004).

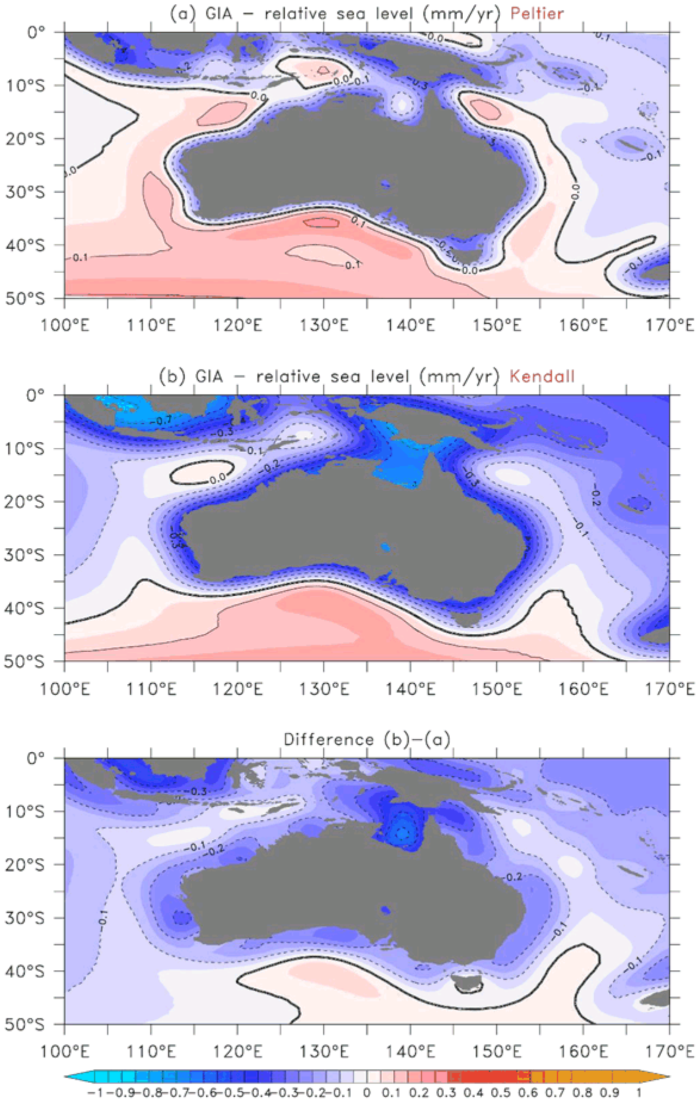

Figure A2. Comparison of relative sea level rate (mm yr^{-1}) from two GIA models: (a) Peltier (2004) and (b) Kendall, Mitrovica and Milne (2005), and (c) their difference.

Appendix B: Baseline Adjustments to SLR projections

The planning policy for Queensland requires consideration of 0.8 m of SLR from "present day" to 2100 (Dept of Environment and Heritage Projection, 2013). CSIRO projections for the Sunshine Coast are relative to a baseline average period of 1986-2005 with a central value of 1995. Here, an assessment is made of the impact on the SLR projections for the Sunshine Coast of shifting the baseline from a central reference year of 1995 to 2013 (Figure B1). Moving the baseline of the CSIRO projections to an average period of 2008-2018 with a central value of 2013 reduces the projections by approximately 5 cm, i.e. a high emission scenario (RCP8.5) projection for the Sunshine Coast becomes 0.71 (0.48-0.98), (see appendix B). The Queensland planning policy guideline of 0.8 m by 2100 therefore still resides within the upper half of the present projections uncertainty range under RCP8.5 for 2100. It is therefore considered appropriate given the most currently available guidance.

Also shown is the emission scenario difference between RCP8.5 and RCP2.6 (i.e. RCP8.5 minus RCP2.6) for sea level projection in 2013 relative to 1995, which indicates that the difference between the two scenarios over this time period is negligible. These calculations show that adjusting the baselines for sea level projections from a central year of 1995 to a central year of 2013 has a very small impact on the projections.

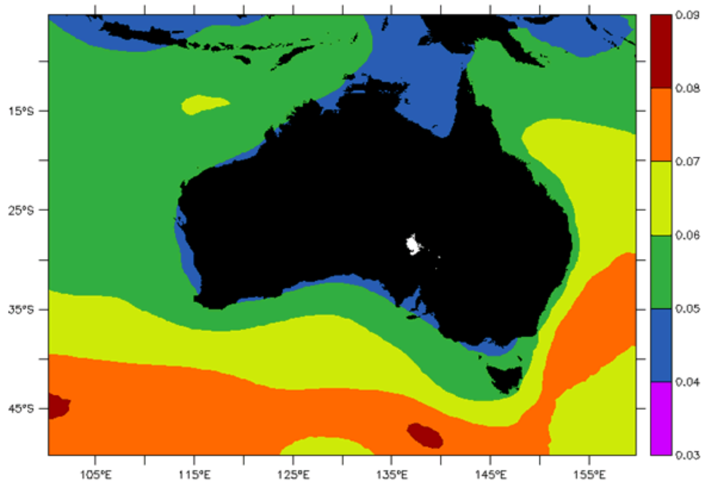

Figure B1. The CSIRO sea level projection under RCP8.5 in year 2013 with reference to 1996-2005. (Units are m).

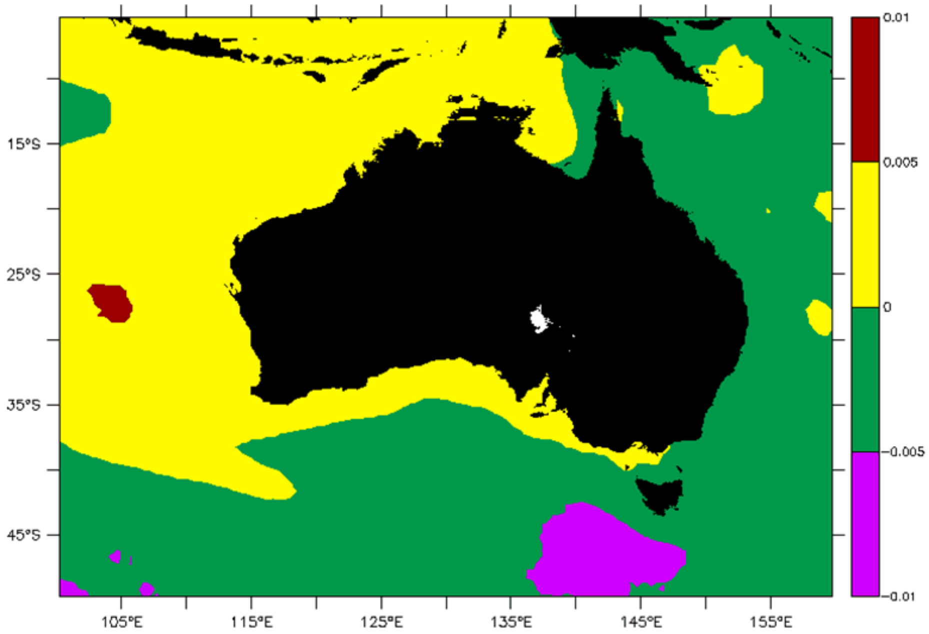

Figure B2. The difference between RCP8.5 and RCP2.6 (i.e. RCP8.5-RCP2.6) of sea-level projections in 2013 relative to 1995 showing negligible divergence of the projections over this time period (units are m).

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