



# Sea-level rise and climate change

## Information Manual 2

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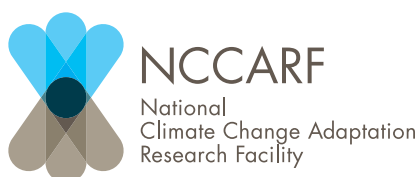
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# Understanding sea-level rise and climate change, and associated impacts on the coastal zone

## Information Manual 2

**Mark Siebentritt**  
Seed Consulting Services



**Australian Government**

**Department of the Environment and Energy**



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# Preface

In 2014, the National Climate Change Adaptation Research Facility (NCCARF) was commissioned by the Australian Government to produce a coastal climate risk management tool in support of coastal managers adapting to climate change and sea-level rise. This online tool, known as CoastAdapt, provides information on all aspects of coastal adaptation as well as a decision support framework. It can be accessed at [www.coastadapt.com.au](http://www.coastadapt.com.au).

Coastal adaptation encompasses many disciplines ranging from engineering through to economics and the law. Necessarily, therefore, CoastAdapt provides information and guidance at a level that is readily accessible to non-specialists. In order to provide further detail and greater insights, the decision was made to produce a set of Information Manuals, which would provide the scientific and technical underpinning and authoritativeness of CoastAdapt. The topics for these Manuals were identified in consultation with potential users of CoastAdapt.

**There are ten Information Manuals, covering all aspects of coastal adaptation, as follows:**

1. Building the knowledge base for adaptation action
2. Understanding sea-level rise and climate change, and associated impacts on the coastal zone
3. Available data, datasets and derived information to support coastal hazard assessment and adaptation planning
4. Assessing the costs and benefits of coastal climate adaptation
5. Adapting to long term coastal climate risks through planning approaches and instruments
6. Legal Risk. A guide to legal decision making in the face of climate change for coastal decision makers
7. Engineering solutions for coastal infrastructure
8. Coastal sediments, beaches and other soft shores
9. Community engagement
10. Climate change adaptation planning for protection of coastal ecosystems

The Information Manuals have been written and reviewed by experts in their field from around Australia and overseas. They are extensively referenced from within CoastAdapt to provide users with further information and evidence.

NCCARF would like to express its gratitude to all who contributed to the production of these Information Manuals for their support in ensuring that CoastAdapt has a foundation in robust, comprehensive and up-to-date information.

# Acronyms and abbreviations

<b>AHD</b>	Australian height datum
<b>BoM</b>	Bureau of Meteorology
<b>CSIRO</b>	Commonwealth Scientific and Industrial Research Organisation
<b>DEM</b>	Digital elevation models
<b>GCM</b>	Global climate model
<b>HAT</b>	Highest astronomical tide
<b>IIASA</b>	International Institute for Applied Systems Analysis
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>LAT</b>	lowest astronomical tide
<b>LiDAR</b>	Light Detection and Ranging
<b>MSL</b>	Mean sea level
<b>NCCARF</b>	National Climate Change Adaptation Research Facility
<b>NOAA</b>	National Oceanic and Atmospheric Administration
<b>RCPs</b>	Representative Concentration Pathways
<b>VisTool</b>	Coastal Flooding Visualisation Tool



## Executive summary

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The vast majority of Australians live, recreate and work close to the coast. As a result, sea-level rise caused by climate change has the potential to change the Australian way of life.

### A coastal nation

Over 80% of Australians live within 50 km of the coast. The trend of people moving to the coast is set to continue, with a further one million people forecast to take up residence in coastal areas near our capital cities or in large regional centres over the coming one to two decades.

With large populations living on the coast, much of our social and economic infrastructure is also on the coast, including residential housing, infrastructure and essential services. In developed areas, these are in close proximity to environmental features such as beaches, estuaries, mangroves and seagrass beds, which sustain many of the values we hold for the coast but are also at risk from the human activities.

### Climate change has and will continue to occur

Climate change is being driven by human activities that increase the concentration of greenhouse gases in the atmosphere. The concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide are currently at levels unprecedented in at least the last 800,000 years.

The evidence of human impact on the climate system is clear, based on the increasing greenhouse gas concentrations in the atmosphere, positive amount of energy being trapped in the atmosphere, observed warming, observed impacts and our understanding of the climate system. Part of this evidence base is the observation that average temperatures in Australia have increased by nearly 1 °C since 1910.

### Sea levels have risen and will continue to rise

Global sea levels have risen by approximately 21 cm since 1880. Thermal expansion and melting glaciers explain about 75% of the observed rise in sea levels over the past four decades. This has been driven by increasing temperatures in the atmosphere and absorption of heat by the oceans. The observed rates of rise for Australia are consistent with global average values.

There is very high confidence that sea levels will continue to rise over the coming century. Compared to the period 1986–2005, global mean sea levels are projected to increase by the end of the century by:

- 0.26–0.55 m under a low emissions scenario
- 0.32–0.63 m under an intermediate scenario, where emissions stabilise mid-century
- 0.33–0.63 m under an intermediate scenario, where emissions stabilise late-century
- 0.45–0.82 m under a high emissions scenario.

It is virtually certain that sea levels will continue to rise after 2100, with sea-level rise due to thermal expansion to continue for many centuries due to the slow response of the oceans to the accumulating greenhouse gases in the atmosphere.

Regional sea-level rise projections have been prepared for Australia and show that the extent of rise is likely to be similar around the nation, with only small differences existing between locations for different time frames and emissions scenarios.

Extreme sea levels are expected to change in the future because of increases in regional sea level and changes in climate events. This means that when planning for climate change, consideration needs to be given to the combined effects of tides, storm surges and wind waves.

## Rising sea levels will affect coastal environments, settlements, infrastructure and services

Rising sea levels, combined with the effects of wind, waves and currents, will lead to increasing permanent inundation, periodic inundation and erosion of the shoreline. It is estimated that nearly half of Australia's open coast is vulnerable to the impacts of sea-level rise because of the presence of sand or mud shorelines or soft rock.

Sea-level rise will affect many of the features that people value in the coastal zone. The coastal systems at greatest risk are estuaries and associated wetlands, coral reefs, constrained tidal flat communities and beaches where there is a lack of sediment replenishment. Not only do these systems have intrinsic environmental value, they provide a range of ecosystem services such as acting as nursery grounds for commercially and recreationally important fish and crustaceans and protecting vulnerable parts of the coastline.

The economic impacts on settlements and infrastructure will include property damage, increased maintenance, repair and replacement of buildings and reduced access to essential services and transport.

## Information to assist with planning and managing responses to sea-level rise is readily available

Planning and managing the impacts of sea-level rise require access to data. Historical sea-level data are readily available from the Bureau of Meteorology's National Tidal Unit, and there are various sources of sea-level rise projection data. The most up-to-date set of projections for Australia comes from the Marine Explorer site that can be accessed from the CSIRO and Bureau of Meteorology's Climate Change in Australia website.

Sea-level inundation mapping is also available, but the type of mapping that is needed will depend on its end use. Mapping from a simple bathtub modelling approach will be enough for awareness raising and capacity building, whereas more detailed wave and hydrodynamic modelling will be required for detailed impact and risk assessments. Freely available sea-level rise mapping products using the bathtub modelling approach include the OzCoasts sea-level rise maps and the Coastal Risk Australia tool.

# 1 Introduction

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## 1.1 Coastal living

Despite the large expanses of land away from the coast, over 80% of Australians live within 50 km of the sea (Hugo et al. 2013). Our preference for coastal living shows no sign of slowing, with another 6.8 million people likely to move to the coast over the next 40 years (National Sea Change Taskforce Inc. 2010). This growth is focused on high-amenity coastal regions and large regional centres.

The prominent coastal lifestyles enjoyed by many Australians means that much of our social and economic infrastructure also occurs in coastal areas, including along coastal waterways. Important infrastructure includes:

- local government and community assets such as surf lifesaving clubs, beach pathways, amenities, car parks and recreational open space
- coastal residential property, including beachfront and waterway properties that are highly valued within the property market
- hospitals and water, electricity and telecommunication networks
- transport infrastructure, such as roads, bridges, airports, ports and harbours.

(Kirkpatrick 2012)

This infrastructure has significant economic value associated with it, as well as the value of the social benefits it provides to the community.

People also enjoy living along the coast and coastal waterways because of the environmental values offered by onshore and near-offshore coastal ecosystems, such as coastal forests, woodlands and heathlands, sandy beaches, coastal lakes, mangrove forests, coral reefs and seagrass beds. These environmental values have social and economic benefits. For example, more people use sandy beaches than any other type of coastal habitat, so beaches underpin the economy in many coastal regions.

However, the Earth's oceans are changing in response to climate change, leading to higher sea levels, high sea surface temperatures and lower pH levels (i.e. increased acidity). This trend will continue until at least the end of the century. As these changes occur, the way we live, work and play along the coast will be impacted.

## 1.2 Role of this Information Manual within the Coastal Tool

The purpose of this Information Manual is to provide information that can improve the understanding of coastal planners and managers about sea-level rise and climate change and their associated impacts on the coastal zone. The primary focus is on sea-level rise, but other changes in the oceans – such as sea surface temperature and pH (a measure of the concentration of hydrogen ions in water and hence acidity) – are also considered briefly, particularly in the context of coastal impacts. The manual is targeted at planners and managers who require an introduction to the key concepts about management of the coastal zone. It has been informed by interactions with coastal managers and policymakers across state and local governments.

In using this manual, it is important to note that many of the key conclusions are synthesised from more detailed analyses. Readers interested in developing a more extensive understanding of sea-level rise and climate change and their associated impacts on the coastal zone are encouraged to read technical reports such as the Intergovernmental Panel on Climate Change's Summary for Policymakers (IPCC 2013a) or the CSIRO and Bureau of Meteorology's Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report (2015a).

## 2 Why is the climate changing?

### 2.1 How does the Earth's climate system work?

Our climate is influenced by the five 'spheres' that comprise the Earth: atmosphere (layer of gases and water vapour surrounding the planet), hydrosphere (all gaseous and liquid forms of water on the planet), cryosphere (all frozen water on the planet), lithosphere (Earth's crust and mantle), and biosphere (all living organisms on Earth). Warming by the sun near the equator provides the energy for global-scale air movements, which influence seasonal temperature, rainfall and other climate variable fluctuations across the globe. The climate changes away from normal fluctuations when there are significant and/or long-term disruptions in the spheres, such as volcanic eruptions, changes in the amount of energy received from the sun (e.g. through impacts on the atmosphere), or human-driven changes to the atmosphere and land (IPCC 2013a).

The Earth's climate also depends on energy exchanges between the ocean, atmosphere, land and biosphere. As such, the oceans play a vital role in transferring heat around the globe, with regional currents affecting local climate.

It is important to note that the 'weather' is not the same as the 'climate'. 'Weather' describes short-term changes in variables such as temperature and rainfall. In comparison, 'climate' relates to the average weather over a period of months to thousands or millions of years. The classical definition, as used by the World Meteorological Organization, describes climate as the average weather over a 30-year period (World Meteorological Organization 2016).

### 2.2 What is causing global climate change?

Climate change is a change in the climate over periods of decades or longer, affecting both the average climate and its variability. Climate change is caused by substances and processes that alter the Earth's energy budget, including the activity of the sun, natural factors (e.g. volcanic eruptions) and the influence of humans (CSIRO and Bureau of Meteorology 2015b).

Greenhouse gases trap energy from the sun in the Earth's atmosphere. In contrast, airborne solid or liquid particles called aerosols can reflect energy back into space. Combined, they affect what is called radiative forcing, or the net amount of energy that enters the Earth's atmosphere.

The most common greenhouse gases are water vapour (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>) and ozone (O<sub>3</sub>). The concentrations of carbon dioxide, methane, and nitrous oxide have all increased since the start of the industrial era (circa. 1750) due to human activities. They are currently at concentrations unprecedented in at least the last 800,000 years. Greenhouse gases are released into the atmosphere through activities such as combustion of fossil fuels, agriculture and land-use change. (IPCC 2013a)

**Current concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide are unprecedented in at least the last 800,000 years.**

More of the sun's energy is being trapped now in the atmosphere compared to 1750 in response to increasing levels of greenhouse gases. For example, concentrations of carbon dioxide have increased by 40% since 1750 as a consequence of emissions from fossil fuel use and land-use change. (IPCC 2013a)

Around half of the carbon dioxide released into the atmosphere since 1750 is currently being stored by the oceans and by living organisms on the land, such as trees (Ciais et al. 2013), with the rest leading to increased atmospheric carbon dioxide concentrations.

Data on current carbon dioxide levels are readily accessible through the internet, such as for carbon dioxide measured at Mauna Loa Observatory, Hawaii. The most recent monthly average, for March 2016, was 404.83 ppm (NOAA 2016). These data can be accessed for use in presentations or discussions about how the Earth's atmosphere is changing.

### 2.3 What is the evidence that the climate is changing?

The latest report from the Intergovernmental Panel on Climate Change (IPCC), the world's leading scientific body on climate change, explicitly stated that the 'human influence on the climate system is clear' (IPCC 2013a). Evidence from temperature records provides the clearest signal. For example, the 10 warmest years on record, with the exception of 1998, have occurred since 2000. Furthermore, 2015 and 2014 rank as the first and second warmest years on Earth since 1880 (NOAA 2015; World Meteorological Organization 2016). Data from 2015 show that the global average temperature for the year was around 0.8 °C above the 1961–1990 average and approximately 1 °C above the 1850–1899 period.

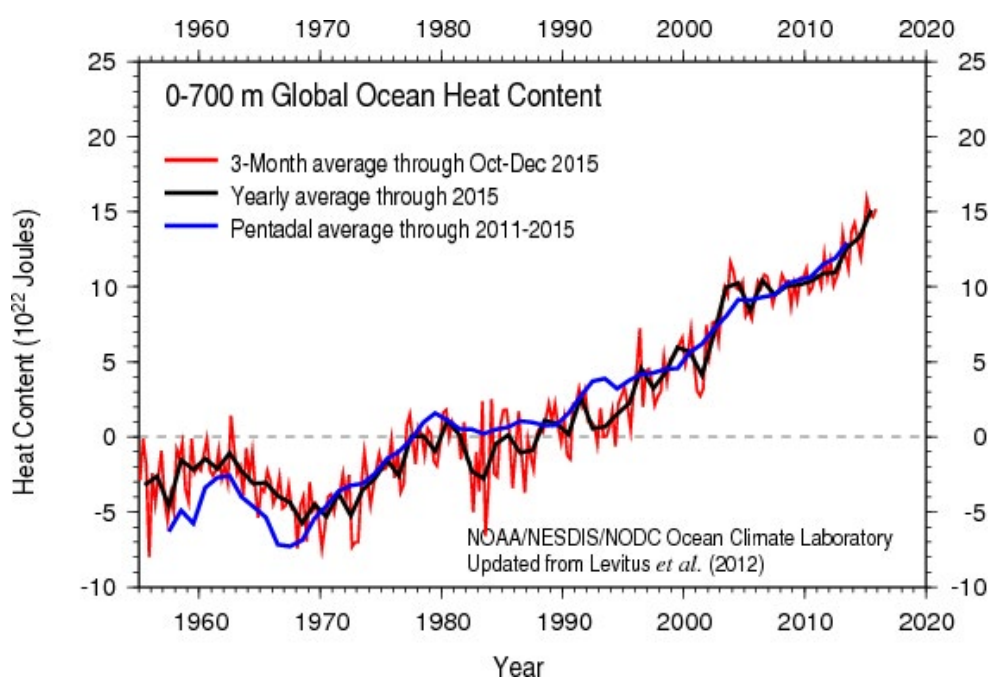
The world's oceans also show a strong warming signal as illustrated in Figure 1. This indicates that the ocean heat content from the surface down to a depth of 700 m has been increasing since the 1950s and is currently at the highest levels experienced for the last half century. A similar trend also exists for the amount of heat stored in the ocean to a depth of 2 km.

There is also strong evidence that Australia's climate has changed and continues to change. At a national scale, average temperatures have increased by 0.9 °C since 1910. Warming has occurred in all states and territories, with the majority of areas experiencing a 0.5–1.5 °C increase in temperatures (Figure 2). Many aspects of the warming across Australia can be attributed to global climate change.

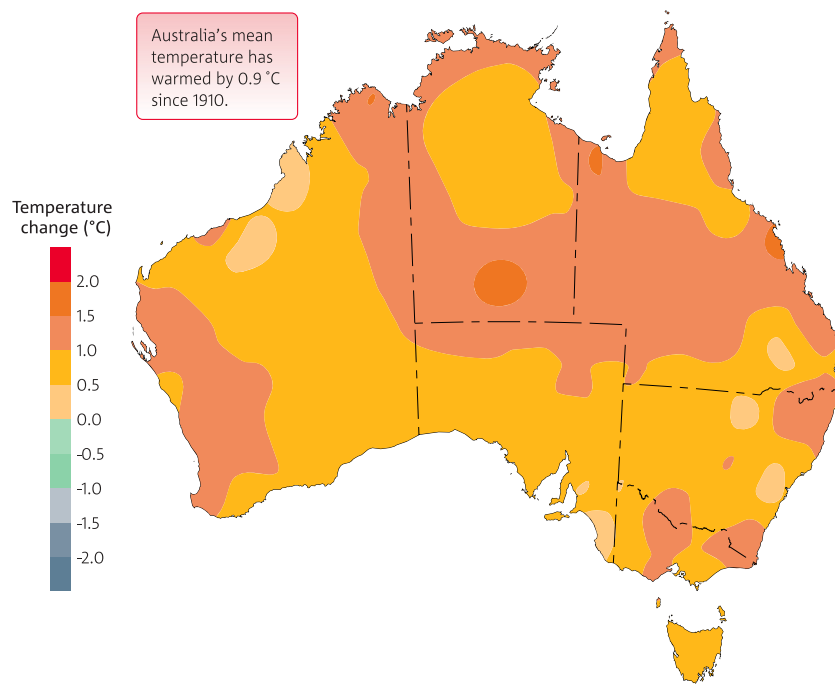
There are several other indicators of a change in Australia's climate. For example, since 2001, there have been three times more extreme heat records than extreme cool records; very warm months have increased five-fold in the past 15 years; and the frequency of very cool months declined by around a third (Trewin and Vermont 2010; Trewin and Smalley 2013).

Rainfall averaged across Australia has slightly increased since 1900, with the largest increases in the north-west since 1970. However, rainfall has declined since 1970 in the south-west, dominated by reduced winter rainfall. Autumn and early winter rainfall has mostly been below average in the south-east since 1990 (Bureau of Meteorology 2014).

**Average temperatures in Australia have increased by nearly 1 °C since 1910, and rainfall has declined across the south-west over recent decades.**



**Figure 1:** Ocean heat content down to a depth of 700 m: 3-month averages (red), 5-year averages (blue), and annual averages (black). Source: NOAA 2015.



**Figure 2:** Annual mean temperature changes across Australia since 1910. Source: Bureau of Meteorology 2014, State of the Climate 2014, published by CSIRO and BoM.

## 2.4 Projecting climate change and sea-level rise

Climate models are used to develop multiple projections of the Earth's future climate. 'Projections' are not the same as 'predictions'. They are based on a range of assumptions about future social, economic and technological drivers that may or may not occur and which will alter the impact on the future release of greenhouse gas and aerosol emissions into the atmosphere (IPCC 2013b). Climate models use many of the same atmospheric physics principles as weather forecast models and are more commonly referred to as global climate models (GCMs). However, state-of-the-art GCMs differ from weather forecast models in that they are coupled to a fully dynamic ocean model. The IPCC provides updated climate projections every 5–6 years using an agreed set of climate models, with updates being based on additional weather and climate data collected over the years, as well as refinements in future scenarios based on actions being taken globally to mitigate climate change.

Future sea-level changes are projected by combining the outputs of climate models with purpose-built models designed to estimate other contributors to sea level. The combined models consider factors such as ocean density, global circulation patterns, the changing size of glaciers and the response of the Greenland and Antarctic ice sheets to changing temperature.

The four main emissions scenarios used by the IPCC in its most recent report, and described as Representative Concentration Pathways (RCPs), are as follows (IIASA 2015):

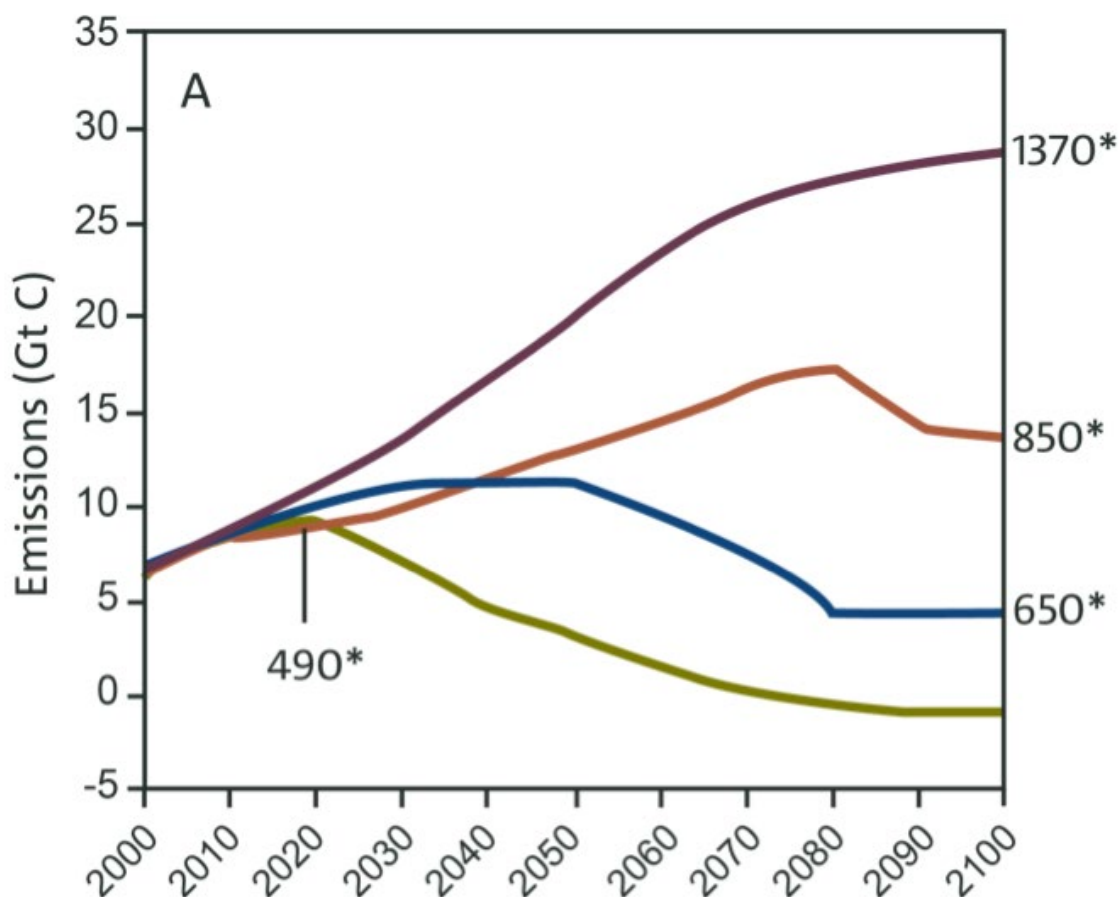
- **RCP2.6** Peak and decline scenario – an emissions pathway leading to very low greenhouse gas concentration levels (radiative forcing<sup>1</sup> peaks at approximately 3 W m<sup>-2</sup> before 2100 and then declines)
- **RCP4.5** Intermediate stabilisation scenario – an emissions pathway where the impact of climate change on the atmosphere is stabilised before 2100 by using a range of technologies and strategies for reducing greenhouse gas emissions (radiative forcing stabilises at approximately 4.5 W m<sup>-2</sup> after 2100)

<sup>1</sup> Measure of the net energy trapped in the Earth's atmosphere

- **RCP6.0** Intermediate stabilisation scenario – an emissions pathway where the impact of climate change on the atmosphere is stabilised after 2100 by using a range of technologies and strategies for reducing greenhouse gas emissions (radiative forcing is stabilised at approximately  $6.0 \text{ W m}^{-2}$  after 2100)
- **RCP8.5** High emissions scenario – an emissions pathway characterised by increasing greenhouse gas emissions over time leading to high greenhouse gas concentration levels (radiative forcing reaches  $8.5 \text{ W m}^{-2}$  by 2100, but continues to rise beyond this date).

Projections are generated primarily for four different timeframes: 2030, 2050, 2070 and 2090, which represent the median of a 20-year average (e.g. 2090 refers to the average for the period 2081–2100). Changes in climate variables are described in relation to an averaged reference baseline period, which for the current RCPs is 1986–2005.

The (estimated) carbon emissions and the corresponding CO<sub>2</sub> equivalent levels in parts per million for the four emissions scenarios are illustrated in Figure 3. Continued emissions, which may increase and/or decrease through time depending on the scenario, will result in an increase in the cumulative concentration of greenhouse gases in the atmosphere.



**Figure 3:** Emissions of carbon in gigatonnes for the different emissions (RCP) scenarios used by the IPCC for climate modelling. Notes: Green = RCP2.6, blue = RCP4.5, orange = RCP6.0 and purple = RCP8.5. Asterisks show the CO<sub>2</sub> equivalent levels in parts per million (ppm). Source: CSIRO and Bureau of Meteorology 2015b.

## 3 How are the oceans changing?

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### 3.1 Sea-level rise: a global phenomenon

#### 3.1.1 What causes sea levels to change?

At a global scale, sea levels can rise or fall because of changes in the density of the ocean (thermal expansion) and changes in the amount of water in the ocean because of the melting or formation of glaciers and ice sheets and interactions with the land (CSIRO and Bureau of Meteorology 2015a).

Changes in sea level relative to land can be due to ocean dynamics (currents, air–sea fluxes of heat and freshwater and internal variability), the Earth’s gravitational field as a result of changes in the distribution of water on the Earth, and vertical motion of the land up (uplift) or down (subsidence). (CSIRO and Bureau of Meteorology 2015a).

Over the past hundreds of thousands of years, sea levels have varied by over 100 m as major ice sheets have formed or melted. For example, during the last interglacial period (i.e. between glacial periods) about 130,000–115,000 years ago, sea level is estimated to have been 5–10 m higher than it is now. It is estimated that global average temperatures at that time were up to 2 °C warmer than pre-industrial (1750) values (CSIRO and Bureau of Meteorology 2015a).

Sea levels were considered to have stabilised over the last few thousand years before beginning to rise again in the nineteenth century (CSIRO and Bureau of Meteorology 2015a).

Key terms and concepts relating to sea-level rise are described in Box 1.

#### 3.1.2 How has sea level changed globally and in Australia?

Global sea levels show a rise of approximately 21 cm from 1880 to 2009. Thermal expansion and melting glaciers (excluding Antarctic glaciers next to the ice sheet) explain 75% of the observed rise in sea levels over the past four decades, with thermal expansion the lead contributor (Church et al. 2013). While this amount of sea-level rise is relatively small compared to historical levels, the impacts of it are significant given that many coastal assets are built in low-lying areas close to the coast.

From 1966 to 2009, sea levels have risen around the Australian coastline at an average rate of 1.6 mm/yr, which is about 7 cm over the past half century (CSIRO and Bureau of Meteorology 2015a). These observed rates of rise for Australia are consistent with global average values.

**Sea levels have risen in Australia at an average rate of 1.6 mm/yr over the past half century**



**Box 1:** Key terms and concepts related to sea-level rise.

Sea level is often described in relation to the tide or storm-surge events. The tide causes sea levels to vary each day as a result of the gravitational pull of the moon and sun. In relation to the tide, we might observe daily low and high tide levels, but for planning it is important to understand the:

- **highest astronomical tide (HAT)**, which is the highest level of water that can be predicted to occur under any combination of astronomical conditions (ICSM 2011); and
- **lowest astronomical tide (LAT)**, which is the lowest tide level that can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions (ICSM 2011).

The **mean sea level** is the surface level of the ocean at a particular point averaged over an extended period of time such as a month or year (IPCC 2013b). In Australia, mean sea level approximates to 0 m Australian Height Datum (AHD).<sup>2</sup> At any given gauging station, sea level is often relative to a local mark, such as the low water mark.

**Extreme sea levels** are a combination of tides, storm surges and wind waves.

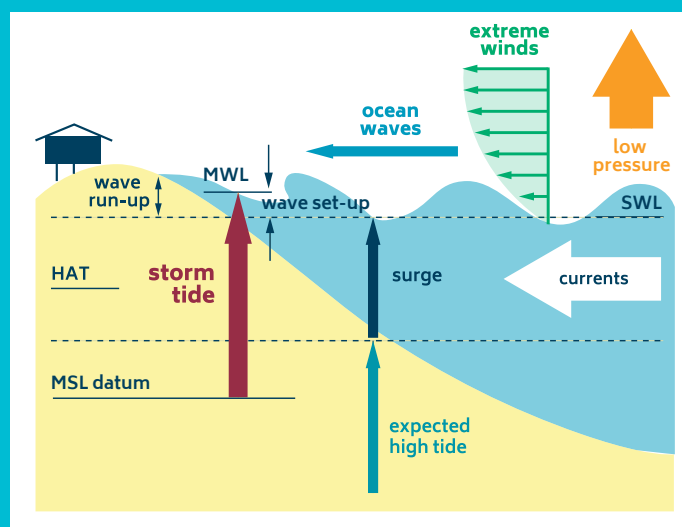
**Storm surges** can be caused by local weather systems and associated falling atmospheric pressure and strong surface winds, which increase the water level against the coast. A **storm tide** is the combination of storm surge and tides.

During storm events, the local prevailing wind moving across the sea can create **wind waves** that result in higher sea levels as these arrive at the coast. These are in addition to swell waves generated by distant weather systems.

Wave breaking can further increase coastal sea levels. This is a result of the **wave set-up**, which is the temporary increase in sea levels due to effect of wave breaking, and wave run-up which is the maximum elevation up the shore that is reached by an individual wave breaking.

The 1-in-100-year storm tide level is the height that has a 1% chance of occurring in any given year. This height varies around the coastline according to the tidal range and the magnitude of storm surges that can occur along a section of coast due to the coastline features and the prevailing meteorology of the region.

(Bureau of Meteorology 2015; CSIRO Marine and Atmospheric Research 2008).



**Figure 4:** Contributions to coastal sea level from tides, storm surge and wave processes. Source: After Harper 2001.

<sup>2</sup> Australian Height Datum (AHD) is a coordinate system used for altitude measurement in Australia. This mark was set in the late 1970s, since which time several centimetres of sea-level rise have occurred.

### 3.1.3 Future sea-level rise

The most up-to-date climate projections generated by the IPCC suggest that the rate of global mean sea-level rise in the coming century will be greater than over the past four decades for all emissions scenarios (RCPs).

#### Sea levels will continue to rise throughout the twenty-first century and beyond.

Compared to the period 1986–2005, global mean sea levels are projected to rise by 2090 by the following amounts:

- 0.26–0.55 m under a low emissions scenario (RCP2.6)
- 0.32–0.63 m under an intermediate (mid-century) stabilisation scenario (RCP4.5)
- 0.33–0.63 m under an intermediate (late-century) stabilisation scenario (RCP6.0)
- 0.45–0.82 m for the high emissions scenario (RCP8.5).

For the high emissions scenario, the rise by 2100 is projected to be 0.52–0.98 m. Sea-level rise of greater than this would require additional melting of the Antarctic ice sheet (Church et al. 2013), which is unlikely to exceed several tens of centimetres this century.

By the end of the century, the main contributors to global mean sea-level change will be ocean thermal expansion, accounting for about 35–45% of the total, and the melting of glaciers and ice caps, accounting for 25–26% of the total. Under the high emissions scenario and upper-end intermediate scenario, the rate of rise for both contributions increases throughout the twenty-first century, whereas for the low and lower-end intermediate scenarios, the rate of rise decreases after about 2030 and 2070, respectively (Church et al. 2013).

Sea-level rise models suggest that it is virtually certain that sea levels will continue to rise after 2100, with sea-level rise due to thermal expansion to continue for many centuries. The extent of longer term sea-level rise depends on future emissions. For example, if emissions were to continue along the high emissions scenario, the projected rise could be 1 m to more than 3 m over a period of 100–200 years (Church et al. 2013).

Work by the IPCC has concluded that it is very likely that there will be a significant increase in the frequency of sea-level extremes in some regions by 2100, with a likely increase in the early twenty-first century. This will mainly occur because of an increase in tropical storm activity and a rise in mean sea level, with the frequency of a particular sea-level extreme increasing by an order of magnitude or more in some regions by the end of the twenty-first century (Church et al. 2013). Region-specific projections will be influenced by local weather patterns and associated storm surges.

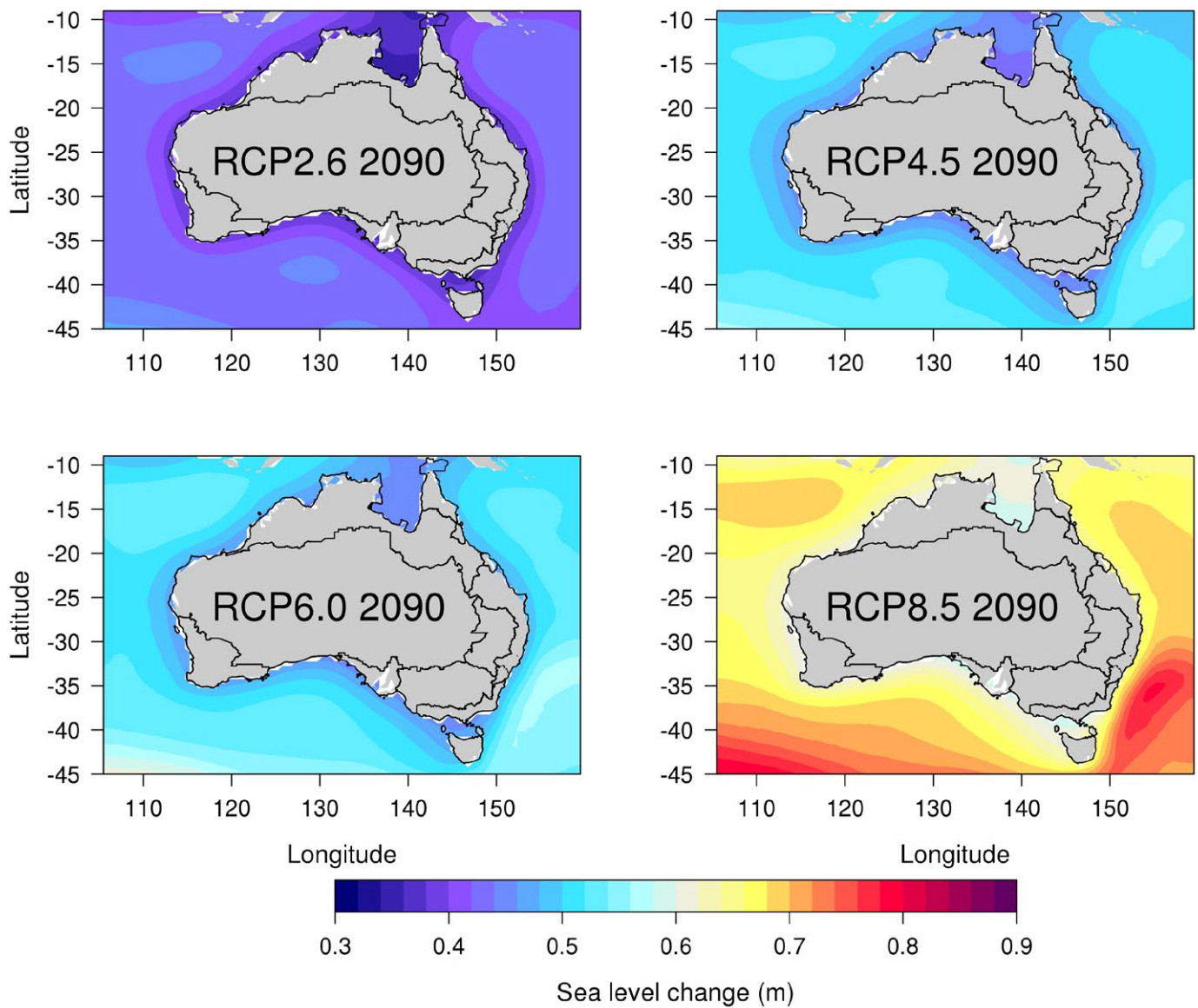
### 3.2 Future sea-level rise in Australia

Sea-level rise projections for Australia are illustrated in Figure 5 for all four emission scenarios.

For all scenarios, there is high confidence that the rate of rise will be larger during the twenty-first century than over the past four decades. The amount of regional sea-level rise is largest for the high emissions scenario and smallest for the low emissions scenario, with the intermediate emissions scenarios being similar (CSIRO and Bureau of Meteorology 2015a).

Numeric values for sea-level rise projections are provided in Table 1 for major Australian coastal cities. This shows a similar trend across the nation with respect to the direction and extent of sea-level rise, with small differences between locations. In general, coastal capital cities like Brisbane, Darwin, Perth, Adelaide and Sydney need to be planning for 40 cm (under RCP2.6) to at least 60 cm (under RCP8.5) of sea-level rise towards the end of the century, assuming current rates of emissions continue.

Extreme sea levels are expected to change in the future because of increases in regional sea level and changes in climate events. This means that, when planning for climate change, consideration needs to be given to the combined effects of tides, storm surges and wind waves. Tools that can be used for local-scale planning for sea-level rise and the associated risk of extreme sea levels are discussed further in Section 5.



**Figure 5:** The regional distribution in sea-level change in metres for projections for 2090 (the average of 2080–2100) compared to 1986–2005 mean level for each of the four scenarios. Source: CSIRO and Bureau of Meteorology 2015a.

**Table 1:** Median, low-end (10th percentile) and upper-end (90th percentile) sea-level projections for 2030 and 2090 using the intermediate (RCP4.5) and high (RCP8.5) emissions scenarios. Source: CSIRO and Bureau of Meteorology (2015a).

Station	2030 RCP4.5	2030 RCP8.5	2090 RCP4.5	2090 RCP8.5
Brisbane	0.13 (0.09–0.18)	0.14 (0.09–0.18)	0.47 (0.31–0.65)	0.65 (0.45–0.87)
Burnie	0.12 (0.08–0.16)	0.13 (0.08–0.18)	0.46 (0.29–0.63)	0.61 (0.41–0.83)
Cairns	0.13 (0.09–0.17)	0.14 (0.09–0.18)	0.48 (0.31–0.65)	0.65 (0.44–0.87)
Darwin	0.12 (0.08–0.16)	0.13 (0.08–0.17)	0.46 (0.29–0.65)	0.62 (0.41–0.85)
Fremantle	0.12 (0.07–0.16)	0.12 (0.08–0.17)	0.46 (0.28–0.65)	0.61 (0.39–0.84)
Port Adelaide	0.12 (0.08–0.16)	0.13 (0.08–0.17)	0.45 (0.28–0.63)	0.60 (0.39–0.83)
Stony Point	0.11 (0.07–0.16)	0.12 (0.08–0.17)	0.44 (0.27–0.62)	0.59 (0.38–0.81)
Sydney	0.13 (0.09–0.18)	0.14 (0.10–0.19)	0.47 (0.30–0.65)	0.66 (0.45–0.88)

### 3.3 Ocean acidification and sea surface temperature

Combined with sea-level rise, the key stressors for the coastal zone, shallow marine waters and estuaries are ocean acidification and increasing sea surface temperatures.

The exchange of carbon dioxide between the atmosphere and the ocean is a natural process. As carbon dioxide enters the ocean it reacts with sea water to create carbonic acid, which affects pH. Increased carbon dioxide in the atmosphere results in more carbon dioxide entering the ocean, which causes a decrease in pH and carbonate concentration, collectively known as ocean acidification. Carbonate and calcium are used by marine organisms such as corals, oysters, clams and some plankton to form hard skeletons or shells. These in turn break down to form many of our valued sandy beaches, which are calcareous in nature (i.e. composed of calcium carbonate).

It is estimated that about 30% of the carbon dioxide released by human activities into the atmosphere over the past 200 years has already been absorbed by the oceans. This has led to a 0.1 unit change in the ocean's surface water pH. This may appear small, but as pH is measured on a logarithmic scale it represents a 26% increase in the concentration of hydrogen ions in seawater (CSIRO and Bureau of Meteorology 2015a).

Models project a global increase in ocean acidification for all emissions scenarios (IPCC 2013a). Projected changes in pH around Australia are relatively uniform, of about 0.06–0.08 units decline in pH relative to 1986–2005 by 2030 for all emissions scenarios. By 2090, projections become much more regionally different and the impact of emissions scenarios leads to larger differences, with greater decline in pH under the high emissions scenario. For example, by 2090 the decline in pH under the low emissions scenario is in the range 0.16–0.2, and under the high emissions scenarios the decline is of at least 0.3 pH units (CSIRO and Bureau of Meteorology 2015a).

Warming of the ocean accounts for the vast majority of the increase in energy in the climate system, with about 60% of the increase stored in the upper ocean (top 700 m) (IPCC 2013a). High rates of warming along the world's coastline have been recorded over recent decades (Locarnini et al. 2010). In Australia, warming has been observed off the Western Australian Coast (Leeuwin Current) (Zinke et al. 2014), and off the east of Australia and Tasmania (Holbrook and Bindoff 1997).

A net increase in sea surface temperature (measured in the top few metres of the ocean) is projected under all emissions scenarios around Australia (Lenton et al. 2015). Sea surface temperature rises close to the Australian coast could be around 2–4 °C by the end of the century under a high emissions scenario compared to current conditions (1986–2005) (CSIRO and Bureau of Meteorology 2015a). The smallest increases are projected for southern Australia, while the largest warming is likely to occur along the north-west coast of Australia, to the south of Western Australia and along the east coast of Tasmania (Lenton et al. 2015).

**There is very high confidence that the pH of the oceans around Australia will decline and sea surface temperature will rise.**

Ocean acidification will affect the health, longer term sustainability and biodiversity of reef ecosystems and sandy shore ecosystems (Fabricius et al. 2011; Silverman et al. 2009), while warming will affect the productivity of the ocean as a whole (e.g. Hofmann et al. 2011). The interaction between variables is also important; for example, ocean acidification lowers the temperature at which corals bleach, reducing resilience to natural variability, and can also affect fin and shellfish fisheries, aquaculture, tourism and coastal protection (Cooley et al. 2009). The IPCC concluded that there is medium confidence that long-term viability of corals will be impacted under high and intermediate emissions, and that there will be harm to marine ecosystems from the large reduction in pH under high emissions.

## 4 What are the impacts of sea-level rise on the coastal zone?

### 4.1 Direct consequences of sea-level rise

Sea-level rise affects coastal areas through inundation and coastal erosion. Inundation occurs when high sea levels cause sea water to move across the land. This can lead to permanent inundation of land and assets or, if as a consequence of extreme sea levels and storm surges, periodic flooding.

Coastal erosion leads to the recession of shorelines and destabilisation of dune systems. It generally occurs when 'soft' shorelines, typically made from sand or mud, erode landwards. For sandy beaches, the Bruun Rule is often used to provide a general indication as to the extent of shoreline recession that occurs for every unit increase in sea level (Box 2).

The extent of coastal erosion that will occur in the coming century due to rising sea levels will depend on a range of factors such as the erodibility of different coastal landforms like rocky cliffs,

**Box 2:** How much coastal recession will occur as sea levels rise?

The Bruun Rule (Bruun 1962) is commonly used to explain the rate of shoreline recession under sea-level rise for sandy (unconsolidated) shores. As an approximate rule of thumb, a 1 cm rise in sea level will lead to a 1 m retreat of the coastline. When localised factors such as longshore interactions and the wave climate are taken into consideration, the range can be greater or smaller. For purposes of precise estimation of the rates of shoreward recession at a single beach (the scale at which coastal managers often work), use of the Bruun Rule is not always appropriate. For further information on the Bruun Rule refer to [CoastAdapt: Rules of thumb](#).

estuaries and rocky beaches; regional differences in the processes driving erosion; and local factors such as topography and sediment budgets (Department of Climate Change 2009).

Further information on the direct consequences of sea-level rise on soft shores and beaches is presented in [Information Manual 8: Coastal sediments and beaches](#).

### 4.2 Impacts of climate change on the coastal environment

Climate change will affect the coastal environment through changes to sea level, ocean pH and sea surface temperatures. The major impacts of climate change will be shoreline recession and increased saline inundation of wetlands due to sea-level rise, sediment accumulation following permanent or periodic inundation, and the modification and southward (poleward) shift of marine habitats.

The natural coastal systems at greatest risk are estuaries and associated wetlands, coral reefs, constrained tidal flat communities and beaches where there is a lack of sediment replenishment.

One of the impacts of most concern in the vicinity of developed coastal areas is coastal squeeze. This occurs where constructed obstacles such as roads, seawalls or settlements prevent the landward retreat of coastal ecosystems such as saltmarshes, mangroves and beaches. To prevent the loss of these ecosystems – which have social, economic and environmental benefits – or to limit the damage, allowances should be made to enable natural or assisted migration.

**Coastal squeeze could lead to the loss of beaches and coastal ecosystems, such as mangroves, that are important nursery grounds for commercially valuable fish and crustaceans.**

The mitigation of non-climate-related pressures on coastal ecosystems, such as urban development and nutrient run-off from agricultural lands, can play an important role in increasing the resilience of coastal zones to the impacts of climate change.

A summary of the potential impacts of climate change on coastal ecosystems is provided in Table 2.

**Table 2:** Summary of impacts on the coastal environment. Based on Department of Climate Change (2009).

Ecosystem type	Description of impacts
Coral reefs	Australian coral reefs provide habitat for diverse fauna and flora, including resources and habitat for commercially important fish and crustaceans. They protect the coast by moderating the impacts of waves and underpin up to \$6.1 billion in tourism revenue each year. Climate change will lead to changes in reefs rather than their disappearance.
Seaweeds (macroalgae)	There are 3,000–7,000 species of seaweed in Australian waters, from species growing on coral reefs to the giant kelp forests in southern waters. Their sensitivity to climate change is likely to be significant and related to stresses in their current location, such as coastal pollution. Increasing sea surface temperatures will most likely affect southern seaweed species the most, changing the composition of habitats and species richness.
Mangroves	Mangroves act as an important buffer between the land and sea, filtering water flowing off surrounding land, decreasing the amount of sediment entering coastal waters and protecting coastlines from erosion. Mangroves also act as nursery and breeding grounds for fish and crustaceans, including many commercial species. The major climate change threats to mangroves are rising sea levels and changing rainfall patterns. Rising sea levels will force the landward migration of mangroves.
Saltmarsh	Coastal saltmarsh ecosystems occur worldwide on low-energy coasts, usually in the shelter of estuaries and open lagoons where waves do not scour away plant growth. Saltmarshes provide extensive ecosystem services, including biofiltration, carbon and nutrient retention and physical protection of coastlines. Many changes in climate variables will influence saltmarshes; however, the dominant impact is likely to be sea-level rise. This is because saltmarshes are trapped between impacts of urban development on the land side and impacts of climate change from the sea.
Seagrasses	Australia has the world's highest diversity of seagrasses and most extensive seagrass beds, most of which occur in shallow water (<30 m). Seagrass beds process nutrients and carbon, act as a buffer between the land and the sea and provide important habitat for many fish and crustaceans, including commercially valuable species. As the climate warms, tropical species are expected to move southwards, and temperate species will retreat. A higher proportion of dissolved CO <sub>2</sub> in ocean waters may favour seagrass productivity.
Beaches	Nearly half of the Australian mainland coastline is composed of sandy beaches. Together with their offshore sandbanks and coastal dunes, beaches buffer coastal habitats and coastal developments through erosion control and storm protection. Sea-level rise driven by climate change will affect beach communities through habitat loss and fragmentation, but these impacts will be restricted largely to areas suffering from coastal squeeze. Where habitats are lost, the unique fauna of the beach will be replaced by the fauna of sea walls and surf zones.

### 4.3 What are the impacts of climate change for settlements, industry and services?

The high number of Australians living close to the coast means that many of our settlements, industries and services are located in at-risk areas. Climate change-induced sea-level rise will cause greater periods of inundation of settlements and infrastructure and greater exposure to the effects of intense storm events, including heavy precipitation, high wind velocity, increased wave action and higher storm surges. Assets in low-lying areas in the coastal zone will be especially at risk of inundation in the coming century.

The economic impacts for residential settlements and the tourism sector will include increased residential, community and commercial property damage; and increased maintenance, repair and replacement of residential and commercial buildings. The delivery of essential services such as electricity generation, water and wastewater management will increasingly be affected by inundation, erosion, the effects of salt water intrusion into coastal freshwater systems and drainage systems and increased corrosion. Key transport infrastructure, such as ports and airports, will also be affected. The need to consider the impacts of sea-level rise on the future design of major infrastructure such as airports is already occurring, as was demonstrated during the design of the new runway at Brisbane Airport (Box 3).

The impacts of climate change on settlements and infrastructure will be exacerbated by interactions between several factors during extreme events. For example, where storm surges coincide with heavy local rainfall, stormwater systems may become ineffective, further exacerbating flooding as sea water pushes back up stormwater drains, preventing run-off from being discharged to the sea.

A summary of the potential impact of climate change on key infrastructure and services is provided in Table 3.

**Box 3:** Brisbane Airport: Factoring climate change impacts into runway design. National Climate Change Adaptation Research Facility (2013).

To cope with the rapidly growing number of flights and to accommodate future growth, a new parallel runway on a low-lying coastal area, parallel to Brisbane Airport's existing runway, was proposed. Given the strong role weather plays in the successful and sustainable operation of an airport, the Brisbane Airport Corporation recognised that climate change could potentially affect the proposed runway, so its design considered both historical and future predictions of weather and climate. Key climate change-related risks were identified as sea-level rise, storm surge, local/regional flood events and increasing average temperatures. The cost during the preliminary design to incorporate consideration of climate change impacts was negligible. The Brisbane Airport Corporation took into consideration all future climate change impacts in the design of the new runway, so that it will not need to be upgraded for some time.

Climate change impacts in the coastal zone will affect settlements, industry and services that underpin the functioning of our community and economy.



**Table 3:** Examples of the potential impact of climate change on coastal infrastructure and associated services.

Infrastructure and services	Description of impacts
Ports	Ports and shipping carry 99% of Australia's merchandise trade and 75% of its value. Climate change will bring more intense storm events, including chaotic, heavy precipitation; high wind velocity; increased wave action; and higher storm surges. This will lead to increased run-off and siltation, requiring increased dredging; increased high wind stoppages under Occupational Health and Safety requirements; delays to berthing and cargo handling; coastal flooding; and required engineering upgrades to wharfs, piers, gantries and other cargo-handling equipment.
Airports	There are a number of airports in low-lying areas in the coastal zone and at risk of inundation in the coming century as a result of climate change. Significant disruption can be expected to regional economies if a major capital city airport closed even for a short period of time. While there has been no comprehensive assessment of climate change risks to Australian airports, in the medium term it is possible that consideration will need to be given to protective works for a number of key airports.
Water and wastewater	Significant water and wastewater infrastructure has been built close to the coast to accommodate coastal cities and communities. Rising sea levels can raise coastal water tables, which can affect infrastructure, including through leakage to septic tanks, sewer systems and basements and instability of tanks and pipes. Stormwater pipes and drainage assets will also be exposed to the impacts of rising sea levels and may not be adequate to accommodate future changes in extreme rainfall and storm surge.
Waste – landfill	While the construction of most new landfills is restricted within 100 m of a watercourse, there is a large legacy of landfill sites located in areas vulnerable to the future impacts of climate change and sea-level rise. Existing clay capping and vegetative cover is unlikely to be able to withstand the erosive power of waves. Permanent inundation of the base of the landfill could create significant leachate problems.
Energy supply	Many power plants are located in coastal areas for ease of access to sea water cooling, to obtain fuel supplies delivered by sea and to be close to population centres. At least 11 power plants/substations are located within 500 m of the coastline in Australia. For power stations located very close to the coast, storm surge and resultant flooding could pose a great risk. Damage may also occur to powerlines from winds associated with storms or cyclones. Generation facilities may cease operation in preparation for a flood; if infrastructure is flooded, delays in restarting generation will occur.

## 5 Data and information available to inform decision-making

### 5.1 Where to access historical sea-level data

Sea levels are monitored around Australia in real time by the Bureau of Meteorology's National Tidal Unit, which also manages the national data archive for sea levels and tides.

State and territory tide gauge metadata and observed monthly sea levels and statistics can be used to generate local historical sea levels. This information is available from Bureau of Meteorology (2016). Monthly sea-level statistics and plots are available for download, and statistics for shorter time periods are available on request.

While historical sea-level rise data are available for gauging stations around the country, it should be noted that explaining underlying sea-level rise trends requires detailed analysis and understanding of the implications of land movement and the impact of climate patterns such as the Southern Oscillation Index (White et al. 2014).

### 5.2 Where to access sea-level rise projection data

There are a variety of sources of information on projected sea levels for regions around Australia. The sources differ in terms of regional specificity, emissions scenarios and time frames.

The IPCC reports (e.g. Church et al. 2013) provide information on the general trends of sea-level rise at a global level. More specific to Australia is the information contained in the Climate Change in Australia reports and website (CSIRO and Bureau of Meteorology 2015a, 2015b). The reports provide summary-level information on projected sea-level rise, which can also be accessed through the interactive Marine Explorer tool on the Climate Change in Australia website (CSIRO and Bureau of Meteorology 2015b). The Marine Explorer tool provides access to data for the low (RCP2.6), intermediate (RCP4.5) and high (RCP8.5) emissions scenarios for 2030, 2050, 2070 and 2090 for variables including sea surface temperature, sea surface salinity, ocean pH and sea-level rise.

### 5.3 Where to access sea-level rise mapping

#### 5.3.1 Approaches to sea-level rise mapping

Sea-level rise and coastal zone inundation can be mapped in various levels of detail. A common and basic approach to mapping sea-level rise is the 'bathtub' method. As the name suggests, this approach models the effect of filling a bathtub: to a given elevation of land, water is added (representing sea-level rise), which rises uniformly. This approach can be applied in multiple ways. For example, projected sea-level rise heights can be overlain on the elevation of land surface (NOAA 2010; Lacey and Mount 2012) or, as was done for *Australia's National Coastal Risk Assessment* (see Department of Climate Change 2009), a sea-level rise scenario can be added to either a tidal maximum, such as highest astronomical tide, or added to a 1-in-100-year storm tide height.

The degree of sea-level rise is based on projections specific to a nominated time period and emissions scenario. For example, sea-level rise maps generated by the OzCoasts online database use three emission scenarios representing 0.5 m, 0.8 m and 1.1 m of sea-level rise for the period 2100.

**Tip:** The type of sea-level rise mapping needed depends on how the information will be used. Mapping from a simple bathtub modelling approach will be enough for awareness raising and capacity building, but more detailed wave and hydrodynamic modelling will be required for detailed impact and risk assessments.

Determining the elevation of the land surface for sea-level rise mapping can be done by using high-resolution digital elevation models (DEMs) that are often generated using airborne Light Detection and Ranging (LiDAR). The output from LiDAR is three-dimensional information on the topography of the land surface.

When adding sea-level rise scenarios to an extreme sea level, practitioners can use 1-in-100-year storm tide data, and, where this is not available, tidal maximum can be used. Inundation maps can also take into account wave set-up, such as was done for the Sydney Coastal Councils Group (see: [www.sydneycoastalcouncils.com.au/Project/Mapping\\_and\\_Responding\\_to\\_Coastal\\_Inundation](http://www.sydneycoastalcouncils.com.au/Project/Mapping_and_Responding_to_Coastal_Inundation) - accessed 18 April 2016).

Sea-level rise maps using the bathtub approach are generally only used as a communication tool to assist in illustrating the general risks of sea-level rise and should not be relied on solely for decision-making purposes. This is because the maps are simple and do not consider many of the complex processes of coastal inundation.

For example, the bathtub approach does not consider existing seawalls, storm surge, erosion or other local factors, which can all influence the extent of erosion from sea-level rise (Geoscience Australia 2015).

As the bathtub model bases inundation on sea-level rise and land elevation or high-water level alone, areas that are not hydraulically connected to the coast because of natural or built barriers to sea-level rise can still show as being affected by inundation (Department of Sustainability and Environment 2012). This methodology also does not consider i) the time associated with coastal inundation events, because it assumes that inundation occurs instantaneously, or ii) connectivity between the sea and inland areas that may occur due to underground drain systems. The effect of this assumption can result in an overestimation of inundation as the potential buffering effects of formations and structures such as estuaries, shallow flowpaths, channels, culverts and bridges are not taken into account in the model outputs (Department of Sustainability and Environment 2012). Due to the limitations of simple bathtub model approaches, modified bathtub approaches have been developed that do account for the hydraulic connectivity of inundated areas.

Increasingly more complex models are available that provide a better prediction of the potential impacts of coastal inundation. Such approaches involve use of wave models and hydrodynamic models. Outputs of this type of modelling are not freely available and will typically be the output of a specific coastal modelling project. It is common that such modelling projects will require the use of proprietary software.

## 5.4 Sources of sea-level rise inundation maps

There are two main sources of freely available sea-level rise mapping information for Australia:

### OzCoasts

One of the most readily accessible sets of coastal inundation maps is available from OzCoasts, which was developed by the Australian Government to illustrate the potential impacts of climate change for urban areas in Perth–Mandurah, Adelaide, Melbourne, Sydney, Hunter and Central Coast, and South East Queensland. The maps were prepared by combining a sea-level rise value with a high tide value. They illustrate an event that could be expected to occur at least once a year, but possibly more frequently, up to the year 2100. Maps are available for sea-level increases of 0.5 m, 0.8 m, and 1.1 m. The maps are based on the bathtub modelling approach and do not take account of existing seawalls, storm surge, erosion or other local factors.

### Coastal Risk Australia

The Coastal Risk Australia tool has been developed by the Cooperative Research Centre for Spatial Information. Compared to other free sea-level rise tools, Coastal Risk Australia allows users to investigate the extent of coastal flooding under different climate change scenarios using high-resolution DEMs derived from airborne LiDAR, combined with a bathtub inundation modelling approach. Users can investigate the risks and potential impacts of sea-level rise, tidal heights and seasonal storm surge up to a combined height of 10 m wherever high-resolution elevation data are available.

## 5.5 Sea-level allowance

For planning purposes, coastal managers may also want to consider changes in potential extreme sea levels. This can be informed by the sea level 'allowance', which is the amount of sea-level rise that should be considered for future planning and adaptation activities to ensure that the frequency of extreme sea-level exceedances remain unchanged from present conditions (CSIRO and Bureau of Meteorology 2015a).

Using sea-level allowance information, coastal managers can estimate the minimum height that structures would need to be raised compared with allowing for sea-level rise alone. For example, while the median sea-level rise projected for Darwin under RCP4.5 by 2090 is 0.46 m, the sea-level allowance is slightly higher at 0.52 m (CSIRO and Bureau of Meteorology 2015a). Further information on sea-level allowances for coastal locations in Australia can be accessed through the Marine Explorer tool (CSIRO and Bureau of Meteorology 2015b).

## 5.6 Looking for other information?

There are other Information Manuals in this series that provide further, more detailed information that can assist in understanding the potential impacts of sea-level rise along the coast. Additional information is also available from the following sources:

### **National Committee on Coastal and Ocean Engineering Climate change adaptation guidelines in coastal management and planning**

The National Committee on Coastal and Ocean Engineering has prepared three documents to provide guidance to coastal engineers, coastal managers and planners in responding to the challenges of our changing climate. The manuals are available from the Engineers Australia website. The guideline Climate change adaptation guidelines in coastal management and planning in particular is directed at local government engineers and managers whose area of responsibility includes a section of the Australian coastline (Engineers Australia 2012).

### **Generic design coastal erosion volumes and setbacks for Australia**

This report presents numerical model predictions of coastal erosion volumes and setbacks at selected representative open coast, sandy beaches along the Australian coastline. Also, for a range of extreme storm events, the predictions allow the assessment of storm erosion vulnerability on a regional level and provision of a range of storm erosion volumes along the Australian coastline and recession due to sea-level rise (Mariani et al. 2012).

### **Coastal compartments project**

The Coastal Compartments Project aims to help users undertake or commission best practice risk and erosion assessments using a consistent approach based on the physical characteristics of the coastal environment. As part of this project, Australia's coastline has been mapped as compartments based on landforms and patterns of sediment (sand and other beach material) movement (Geoscience Australia n.d.).



## Case Study: Port Adelaide seawater and stormwater flood risk treatment

Based on City of Port Adelaide  
Enfield n.d.; King and Jacobi n.d.

An example of a more detailed site-specific study is the Port Adelaide seawater and stormwater flood risk treatment study. The study was undertaken due to the region's susceptibility to flooding as a consequence of low elevation combined with land subsidence in some of the Council areas. The study assessed the flood risks from a range of combined influences, including stormwater run-off, land subsidence and the impacts of future sea-level rise due to climate change. To achieve this, a detailed 2D hydrodynamic model was used to analyse the propagation of storm tides into the Port River estuary. From this, data and animations illustrating the inundation of low-lying areas were produced.

To assess future climate change impacts, floodplain mapping was undertaken for sea-level rise scenarios of 0.1 m, 0.3 m, 0.5 m and 0.88 m. From this research, the damage costs of future inundation events were estimated under 100-year average return interval tide events. The results of the study were used to inform future mitigation actions to respond to the threats identified, including engineering, planning and community preparedness solutions.

In several low-lying catchments, gravity stormwater drains were found to no longer be feasible under the sea-level rise scenarios considered, and a number of stormwater pump stations were proposed. Indicative construction cost estimates for these works were \$11–18 million.

## 6 Tips and traps

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The following section provides responses to frequently asked questions that might arise when considering how to respond to sea-level rise.

### Why do we need to manage the risks of climate change?

Climate change is already occurring and has been experienced in Australia through increases to average temperatures and sea level and changes to rainfall patterns. Climate change will have deleterious effects on communities, the economy and the environment.

### Why do we need to manage the risks of sea-level rise?

Over 80% of Australians live within 50 km of the coast, meaning that much of the infrastructure that underpins our community and economy is within the coastal zone.

Sea levels have already risen around the Australian coastline, and there is high confidence that they will continue to rise over the coming century.

Managing the risk of sea-level rise will help reduce future damage and associated costs to settlements and infrastructure.

### Can we act when there is uncertainty about how much sea levels will rise?

Climate change has already occurred and will continue well into the coming century under a range of emission scenarios. There is high confidence that sea levels will rise across the full range of emission scenarios.

There are no scenarios under which a decline in sea levels is predicted. Likely ranges for projections of regional sea-level rise along the Australian coastline for the end of the century compared to 1986–2005 are 0.3–0.9 m.

### What scenario of future change should be used?

Decision-makers need to understand the full range of emissions scenarios and their implications for planning and management. Decision-makers may choose scenarios to work with based on their appetite for risk, or choose adaptation options that are robust or effective across multiple scenarios.

### How much do we need to know about future climate change and sea-level rise before we can decide how to respond?

The amount of information and understanding required depends on the purpose for which it will be used or the decisions that will be made. In most instances, broad trends of change in temperature, rainfall and sea levels will be sufficient for awareness-raising, education and capacity-building activities. Where decisions have significant investment implications or will affect the health and wellbeing of members of the community, more detailed impact assessments will be required.

### What is the difference between sea-level rise and extreme sea levels?

Sea-level rise refers to the rise in the ocean's surface, which will lead to an increase in the mean sea level. Extreme sea levels are a combination of tides, storm surges and wind waves. Future modelling and planning in the coastal zone needs to account for the combined effects of sea-level rise and extreme sea levels.

### How much does the sea level need to rise before we act?

The extent of sea-level rise required before action is needed will vary from location to location. It will be influenced by the height of existing built and natural assets above the mean sea level and by factors including the erodibility of coastal landforms in the region, such as beaches, rocky shores and estuaries. Some actions will be identified that need to be implemented in the short term over coming decades, whereas others will be implemented in the long term, towards the end of the century. Sequencing implementation of responses will assist in spreading the investment required.

### How do we manage the concerns of our coastal communities likely to be affected by sea-level rise?

While discussing the impacts of sea-level rise on coastal communities may be confronting, awareness raising of the range of possible impacts is essential because information is already in the public domain about potential areas of inundation through freely available mapping tools. When holding such discussions, it is important to explain the rate of change, which will be slow in many cases, and identify potential adaptation options, including when they need to be implemented.

## 7 Glossary

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Unless indicated otherwise, this glossary is based primarily on key terms described in Department of Climate Change (2009):

**Carbon dioxide:** A colourless, odourless gas that occurs naturally and is also emitted by fossil fuel combustion and land clearing. The atmospheric concentration of carbon dioxide has increased by 40% since the Industrial Revolution. It is the main anthropogenic greenhouse gas affecting climate change.

**Climate model:** A numerical representation (typically a set of equations programmed into a computer) of the climate system. The most complex and complete climate models are known as interchangeably as General Circulation Models or Global Climate Models.

**Climate projection:** A projection of future climate based on simulations by climate models.

**Climate scenario:** A plausible and often simplified representation of the future climate, based on an internally consistent set of climatologically relationships.

**Coastal geomorphology:** The physical structures, processes and patterns associated with the coast, including landforms, soils, geology and the factors that influence them.

**El Niño Southern Oscillation (ENSO):** Refers to widespread two- to seven-year oscillations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia, La Niña brings above-average rain, and El Niño brings drought. A common measure of ENSO is the Southern Oscillation Index (SOI), which is the normalised mean sea level pressure difference between Tahiti and Darwin. The SOI is positive during La Niña events and negative during El Niño events.

**Greenhouse gases:** Gases in the Earth's atmosphere that absorb and re-emit infrared (heat) radiation.

**Ice sheet:** A mass of land ice that is sufficiently deep to cover most of the underlying bedrock, so that its shape is mainly determined by the flow of the ice as it deforms internally and/or slides at its base.

**Interglacial period:** The warm periods between ice age glaciations. The last interglacial (before the current one) occurred approximately 130,000–115,000 years ago.

**Relative sea level:** Sea level as measured by a tide gauge with respect to the land upon which it is situated.

**Sea-level rise:** An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean. Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land-level subsidence. In areas subject to rapid land-level uplift, relative sea level can fall.

**Storm surge:** Elevated sea level at the coast caused by the combined influence of low pressure and high winds associated with a severe storm such as a tropical cyclone; includes wave run-up and wave set-up.

**Storm tide:** The total elevated sea height at the coast combining storm surge and the predicted tide height.

**Thermal expansion:** Refers to the increase in volume that results from warming water.

**Wave run-up:** The ultimate height reached by waves (storm or tsunami) after running up the beach and coastal barrier.

**Wave set-up:** The super-elevation in water level across the surf zone caused by energy expended by breaking waves.

## 8 References

- ABC Science News, 2015: Climate change may increase risk of erosion, flooding along Pacific coasts. Accessed 18 April 2016. [Available from [http://www.abc.net.au/news/2015-09-22/pacific-beach-erosion-set-to-worsen-with-climate-change-storms/6783480?WT.mc\\_id=newsmail](http://www.abc.net.au/news/2015-09-22/pacific-beach-erosion-set-to-worsen-with-climate-change-storms/6783480?WT.mc_id=newsmail).]
- Bruun, P., 1962: Sea-level rise as a cause of shore erosion. *Journal of Waterways and Harbors Division, ASCE*, **88**, 117–130.
- Bureau of Meteorology, 2014: State of climate 2014: Bureau of Meteorology and CSIRO. Accessed 22 March 2016. [Available online at <http://www.bom.gov.au/state-of-the-climate/>.]
- Bureau of Meteorology, 2015: Storm surge preparedness and safety. Accessed 18 April 2016. [Available online at <http://www.bom.gov.au/cyclone/about/stormsurge.shtml>.]
- Bureau of Meteorology, 2016: Tide gauge metadata and observed monthly sea levels and statistics. Accessed 17 May 2016. [Available from <http://www.bom.gov.au/oceanography/projects/ntc/monthly/>.]
- Church, J. A., and Coauthors, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds, Cambridge University Press. Accessed 18 April 2016. [Available online at [http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5\\_Chapter13\\_FINAL.pdf](http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter13_FINAL.pdf).]
- Ciais, P., and Coauthors, 2013: Carbon and other biogeochemical cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds, Cambridge University Press. Accessed 18 April 2016. [Available online at [https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5\\_Chapter06\\_FINAL.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter06_FINAL.pdf).]
- City of Port Adelaide Enfield, n.d: Climate change and local government: Port Adelaide seawater and stormwater flood risk assessment. Accessed 18 April 2016. [Available online at [https://www.lga.sa.gov.au/webdata/resources/files/Session\\_C\\_-\\_Pt\\_Adelaide\\_Enfield.pdf](https://www.lga.sa.gov.au/webdata/resources/files/Session_C_-_Pt_Adelaide_Enfield.pdf).]
- Cooley, S. R., H. L. Kite-Powell, and S. C. Doney, 2009: Ocean acidification's potential to alter global marine ecosystem services. *Oceanography*, **22**, 4. Accessed 17 May 2016. [Available online at [http://tos.org/oceanography/assets/docs/22-4\\_cooley.pdf](http://tos.org/oceanography/assets/docs/22-4_cooley.pdf).]
- CSIRO and Bureau of Meteorology, 2015a: Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia. Accessed 18 April 2016. [Available online at <http://www.climatechangeinaustralia.gov.au/en/publications-library/technical-report/>.]
- CSIRO and Bureau of Meteorology, 2015b: Climate Change in Australia website. Accessed 18 April 2016. [Available online at <http://www.climatechangeinaustralia.gov.au/en/>.]
- CSIRO Marine and Atmospheric Research, 2008: Why does sea level change? Accessed 18 April 2016. [Available online at [http://www.cmar.csiro.au/sealevel/sl\\_drives\\_short.html](http://www.cmar.csiro.au/sealevel/sl_drives_short.html).]
- Department of Climate Change, 2009: Climate change risks to Australia's coasts: A first-pass national assessment. Accessed 18 April 2016. [Available online at <http://www.environment.gov.au/system/files/resources/fa553e97-2ead-47bb-ac80-c12adffea944/files/cc-risks-full-report.pdf>.]
- Department of Sustainability and Environment, 2012: Victorian coastal inundation dataset. State Government of Victoria. Accessed 18 April 2016. [Available online at <https://www.data.vic.gov.au/data/dataset/victorian-coastal-inundation>.]
- Engineers Australia, 2012: Climate change adaptation guidelines in coastal management and planning, 113pp. Accessed 18 April 2006. [Available online at [https://www.engineersaustralia.org.au/sites/default/files/shado/Learned%20Groups/National%20Committees%20and%20Panels/Coastal%20and%20Ocean%20Engineering/climate\\_change\\_adaptation\\_guidelines.pdf](https://www.engineersaustralia.org.au/sites/default/files/shado/Learned%20Groups/National%20Committees%20and%20Panels/Coastal%20and%20Ocean%20Engineering/climate_change_adaptation_guidelines.pdf).]



- Fabricius, K. E., and Coauthors, 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1**, 165–169.
- Geoscience Australia, 2015: Sea-level rise maps. Accessed 18 April 2016. [Available online at [http://www.ozcoasts.gov.au/climate/sd\\_visual.jsp](http://www.ozcoasts.gov.au/climate/sd_visual.jsp).]
- Geoscience Australia, n.d.: Primary and secondary coastal sediment compartment maps. Accessed 18 April 2016. [Available online at [http://www.ga.gov.au/metadata-gateway/metadata/record/gcat\\_76502](http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_76502).]
- Harper B.A. (Ed.), 2001: Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - stage 1. Report prepared by Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, Queensland Government. Accessed 17 May 2016. [Available online at <https://www.longpaddock.qld.gov.au/about/publications/vulnerabilitytocyclones/index.html>].
- Hofmann, M., B. Worm, S. Rahmstorf, and H. J. Schellnhuber, 2011: Declining ocean chlorophyll under unabated anthropogenic CO<sub>2</sub> emissions. *Environmental Research Letters*, **6**. Accessed 17 May 2016. [Available online at <http://iopscience.iop.org/article/10.1088/1748-9326/6/3/034035/pdf;jsessionid=1D95B15515B2991270FB79C16CCE19DE.c1>.]
- Holbrook, N. J., and N. L. Bindoff, 1997: Interannual and decadal temperature variability in the southwest Pacific Ocean between 1955 and 1988. *Journal of Climate*, **10**. Accessed 17 May 2016. [Available online at <http://journals.ametsoc.org/doi/full/10.1175/1520-0442%281997%29010%3C1035%3AIADTVI%3E2.0.CO%3B2>.]
- Hugo, G., Feist, H., and G. Tan, 2013: Population Change in Regional Australia, 2006–11. Australian Population & Migration Research Centre Policy Brief, Vol. 1, No. 3. The University of Adelaide. [Available online at [https://www.adelaide.edu.au/apmrc/pubs/policy-briefs/APMRC\\_Policy\\_Brief\\_Vol\\_1\\_3\\_2013.pdf](https://www.adelaide.edu.au/apmrc/pubs/policy-briefs/APMRC_Policy_Brief_Vol_1_3_2013.pdf).]
- ICSM, 2016: Australian Tides Manual Special Publication No. 9. Version 4.1. Commonwealth of Australia.
- IIASA, 2015: RCP Database (version 2.0). Accessed 18 April 2016. [Available online at <http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome#descript>.]
- IPCC, 2013a: Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, and Coauthors, Eds., Cambridge University Press. Accessed 18 April 2016. [Available online at [https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5\\_SPM\\_FINAL.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf).]
- IPCC, 2013b: Annex III: Glossary. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, and Coauthors, Eds., Cambridge University Press. Accessed 18 April 2016. [Available online at [https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5\\_AnnexIII\\_FINAL.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_AnnexIII_FINAL.pdf).]
- King, R., and D. Jacobi, n.d.: Port Adelaide seawater and stormwater flood risk treatment. Accessed 18 April 2016. [Available online at: [http://coastaladaptationresources.org/PDF-files/1185-KingJacobi\\_PortAdelaideSeawaterAndStormwaterFloodRisk-1.pdf](http://coastaladaptationresources.org/PDF-files/1185-KingJacobi_PortAdelaideSeawaterAndStormwaterFloodRisk-1.pdf).]
- Kirkpatrick, S., 2012: The economic value of natural and built coastal assets – Part 2: Built coastal assets. Australian Climate Change Adaptation Research Network for Settlements and Infrastructure Discussion Paper – Node 1 Coastal Settlements, Gold Coast: National Climate Change Adaptation Research Facility, 36pp. Accessed 18 April 2016. [Available online at <https://www.nccarf.edu.au/settlements-infrastructure/sites/www.nccarf.edu.au/settlements-infrastructure/files/ACCARNSI%20Node%201%20Discussion%20Paper%20-%20Part%202%20Economic%20Value%20of%20Built%20Coastal%20Assets%20Final.pdf>.]
- Lacey, M. J., and R. E. Mount, 2012: Victorian coastal LiDAR inundation modelling and mapping, revised Version 2. Report to the Department of Sustainability and Environment, Victoria by the School of Geography and Environmental Studies, University of Tasmania.
- Lenton, A., K. L. McInnes, and J. G. O’Grady, 2015: Marine projections of warming and ocean acidification in the Australasian region. *Australian Meteorological and Oceanographic Journal*, **65**, S1–S28.

- Levitus, S., and Colleagues, 2012: World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophysical Research Letters*, **39**(10).
- Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, H. E. Garcia, O. K. Baranova, M. M. Zweng, and D. R. Johnson, 2010: World ocean atlas 2009, Volume 1: Temperature. *NOAA Atlas NESDIS*, S. Levitus, Ed., U.S. Government Printing Office, 184pp.
- Mariani, A., T. D. Shand, J. T. Carley, I. D. Goodwin, K. Splinter, E. K. Davey, F. Flocard, and I. L. Turner, 2012: Generic design coastal erosion volumes and setbacks for Australia, 152pp. Antarctic Climate & Ecosystems Cooperative Research Centre. Accessed 18 April 2016. [Available online at <http://acecrc.org.au/wp-content/uploads/2015/03/TR-Generic-design-coastal-erosion-volumes-and-setbacks-for-Australia.pdf>.]
- National Climate Change Adaptation Research Facility, 2013: Brisbane Airport – New parallel runway project. Climate Change Adaptation Good Practice – Case Study. Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education. Gold Coast. Accessed 18 April 2016. [Available online at <https://www.nccarf.edu.au/localgov/case-study/brisbane-airport-new-parallel-runway-project>.]
- National Sea Change Taskforce Inc., 2010: A 10-point plan for coastal Australia: Towards a sustainable future for our coast, National Sea Change Taskforce Inc. Accessed 18 April 2016. [Available online at <http://www.gtcc.nsw.gov.au/assets/Main-Site/Files/Attachments/BusinessPapers/2010/October20/G4-Paper.pdf>.]
- NOAA, 2015: State of the climate: Global analysis –Annual 2014. Accessed 18 April 2016. [Available online at <https://www.ncdc.noaa.gov/sotc/global/201413>.]
- NOAA, 2010: Mapping inundation uncertainty. Accessed 18 April 2016. [Available online at [https://coast.noaa.gov/slr/assets/pdfs/Elevation\\_Mapping\\_Confidence\\_Methods.pdf](https://coast.noaa.gov/slr/assets/pdfs/Elevation_Mapping_Confidence_Methods.pdf).]
- NOAA, 2016: Recent monthly average Mauna Loa CO<sub>2</sub>. Accessed 6 April 2016. [Available online at <http://www.esrl.noaa.gov/gmd/ccgg/trends/>.]
- OzCoasts, 2015: Frequently asked questions. Accessed 18 April 2016. [Available online at [http://www.ozcoasts.gov.au/climate/sd\\_fqa.jsp#HAT](http://www.ozcoasts.gov.au/climate/sd_fqa.jsp#HAT).]
- Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez, 2009: Coral reefs may start dissolving when atmospheric CO<sub>2</sub> doubles. *Geophysical Research Letters*, Issue 36. Accessed 17 May 2016. [Available online at <http://dx.doi.org/10.1029/2008GL036282>.]
- Trewin, B., and R. Smalley, 2013: Changes in extreme temperatures in Australia, 1910 to 2011. *In proceedings of the Australian Meteorological and Oceanographic Society Annual Conference, Melbourne, 2013*, pp. 11–13.
- Trewin, B., and H. Vermont, 2010: Changes in the frequency of record temperatures in Australia, 1957–2009. *Australian Meteorological and Oceanographic Journal*, **60**, 113–119.
- White, N. J., and Coauthors, 2014: Australian sea levels – trends, regional variability and influencing factors. *Earth-Science Reviews*, **136**, 155–174.
- World Meteorological Organization, 2016: WMO statement on the status of the global climate in 2015, Geneva, Switzerland: World Meteorological Organization. Accessed 18 April 2016. [Available online at [http://library.wmo.int/pmb\\_ged/wmo\\_1167\\_en.pdf](http://library.wmo.int/pmb_ged/wmo_1167_en.pdf).]
- World Meteorological Organization, 2016: Climate. Accessed 1 May 2016. [Available online at <http://public.wmo.int/en/our-mandate/climate>.]
- Zinke, J., A. Rountrey, M. Feng, S. P. Xie, D. Dissard, K. Rankenburg, J. M. Lough, and M. McCulloch, 2014: Corals record long-term Leeuwin current variability including Ningaloo Niño/Niña since 1795. *Nature Communications*, **5**. Accessed 17 May 2016. [Available online at <http://www.nature.com/ncomms/2014/140401/ncomms4607/full/ncomms4607.html>.]





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