Preface

This is the 14th report of the Climate Council. The Climate Council is an independent, non-profit organisation, funded by donations from the public. Our mission is to provide authoritative, expert information to the Australian public on climate change.

Many Australians live on or near the coast. The major population centres —Sydney, Melbourne, Brisbane, Perth, Adelaide, Hobart and Darwin—are all port cities and much of the nation's critical infrastructure—transport, commercial, residential, defence—is located along our coastlines. Virtually all of this infrastructure has been designed and built for a stable climate with known ranges of variability. But the climate system is no longer stable. Sea level is rising and so are the risks for our coastal infrastructure.

This report explores two of the most serious consequences of rising sea level—the large increase in the frequency of coastal inundation and the recession of 'soft' shorelines. Damage caused by increased coastal inundation and recession poses a massive financial burden due to damage and destruction of infrastructure. Coastal inundation and recession also have important implications for health and well-being, coastal ecosystems and communities. The report describes how scientific understanding of sea-level rise has improved significantly over the last decade, and we also explore the challenge of making better decisions about future coastal development. Finally, the report discusses the urgent need to stabilise the climate to reduce the level of risks from coastal flooding in the future.

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The authors retain sole responsibility for the content of the report.

Professor Will Steffen
Climate Councillor

Dr John Hunter

Professor Lesley Hughes
Climate Councillor

Introduction

Australia is largely a coastal country. Much of our population lives on or near the coast, and our six state capital cities —Sydney, Melbourne, Brisbane, Perth, Adelaide and Hobart, as well as Darwin in the Northern Territory—are all port cities. In addition to the many lifestyle amenities from living on the coast, much of the nation's critical infrastructure—transport, commercial, residential, defence—is located along our coastlines. Virtually all of this infrastructure has been designed and built for a stable climate with known ranges of variability. But the climate system is no longer stable. Sea levels are rising and so are the risks they pose for our coastal infrastructure.

The most immediate and serious consequence of rising sea level is the flooding of coastal areas through both inundation and recession (see Section 1). Coastal flooding creates many risks, including impacts on health and well-being, damage to coastal ecosystems and disruption of people's lives. In addition to these, the risks to coastal infrastructure – the major focus of this report - are potentially huge, particularly the economic losses due to damage and destruction and the flow-on effects to the economy more generally.

Scientific understanding of sea-level rise has improved significantly over the last decade. We now have more reliable and accurate information on the observed rates of sea-level rise, as well as a better understanding of regional variations around the Australian coast. We can assess the relative importance of various factors, such as the warming of ocean water and the loss of ice from the polar ice sheets, in driving sea-level rise. Our knowledge of the behaviour of the large polar ice sheets, such as those in Greenland and West Antarctica, has also improved, allowing better assessments of the risks from rapid and/or irreversible loss of ice from these regions.

Infrastructure that we are designing and building now should take climate change into account, but this is often not the case. In addition to a solid scientific knowledge base, perceptions, values, institutions, rules and other social factors are crucially important in developing appropriate responses to climate-related risks. An acceptance of the reality of climate change and its risks is essential, but much more is needed. The challenge is to build effective approaches for dealing with the risks to existing infrastructure as well as making better decisions about future infrastructure development.

Ultimately, stabilising the climate is necessary to reduce the level of risks from coastal flooding. Rapid and deep cuts in greenhouse gas emissions are critical here in Australia and around the world to stabilise the climate.

Contents

Key findings

1. **Sea levels have already risen and continue to rise due to climate change. Climate change exacerbates coastal flooding from a storm surge as the storm rides on higher sea levels.**

   › Climate change drives up sea level by warming the oceans and increasing the flow of ice from the land into the sea, for instance from melting glaciers.

   › Over half the Australian coastline is vulnerable to recession from rising sea level, with 80% of the Victorian coast and 62% of the Queensland coast at risk.

   › At both Fremantle and Sydney, flooding events became three times more frequent during the 20th century as a result of sea-level rise.

   › With just 10 cm of sea level rise the risks of coastal flooding roughly treble.

2. **Australia is highly vulnerable to increasing coastal flooding because our cities, towns and critical infrastructure are mainly located on the coast. Australia's infrastructure has been built for the climate of the 20th century and is unprepared for rising sea level.**

   › Sea level is likely to increase by 0.4 to 1.0 m through the 21st century. Strong action to reduce greenhouse gas emissions would constrain sea-level rise towards the lower end of that range, while a business-as-usual approach to burning fossil fuels would drive it towards the upper end.

   › A sea-level rise of only 0.5 m would, on average, mean that a 1-in-a-100 year flood—a very rare event today—would occur every few months. It could also involve a potential retreat of sandy shorelines by 25 to 50 m.

   › Sydney is particularly vulnerable. It is likely that the frequency of flooding would increase so today's 1-in-100 year flood would occur every month or more often

3. **Coastal flooding is a sleeping giant. If the threat of sea level rise is ignored, the projected increases in economic damage caused by coastal flooding are massive.**

   › More than $226 billion in commercial, industrial, road and rail, and residential assets around Australian coasts are potentially exposed to flooding and erosion hazards at a sea level rise of 1.1 m, a high end, but quite plausible, scenario for 2100.

   › In Southeast Queensland—without adaptation—a current 1-in-100 year coastal flooding event risks damage to residential buildings of around $1.1 billion. With a 0.2 m rise in sea level, a similar flooding event would increase the damages to around $2 billion, and a 0.5 m rise in sea level would raise projected damages to $3.9 billion.

- By 2050—without adaptation—the losses from coastal flooding globally are projected to rise to $US1 trillion per year, about the size of the entire Australian economy. By 2100 the losses from coastal flooding are projected to be 0.3–9.3% of global GDP per year. The high-end projection is a scenario for global economic collapse.

4. Rising sea levels pose risks for many of Australia's species and iconic natural places, such as Kakadu National Park and the Great Barrier Reef.

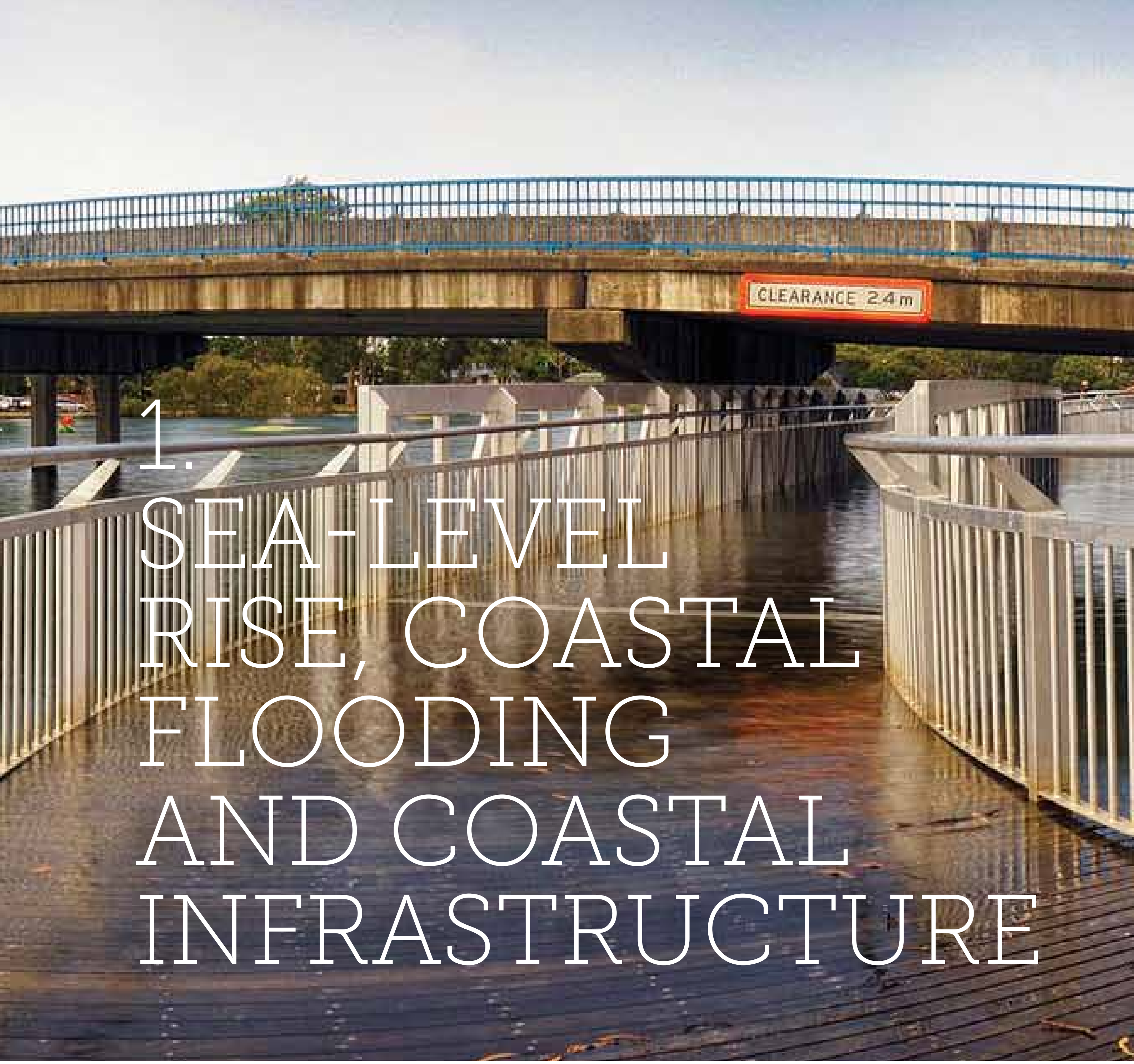
- Many ecosystems, like mangroves, saltmarshes and seagrass beds, may become trapped in a 'coastal squeeze' between rising sea levels and fixed landward barriers such as seawalls and urban development. Damaging these ecosystems has negative flow-on effects to water quality, carbon storage and fisheries.
- Sea-level rise is increasing the salinity of coastal groundwater and pushing salty water further upstream in estuaries, affecting salt-sensitive plants and animals. Salt-water intrusion from rising sea levels is contributing to the loss of freshwater habitats in coastal regions such as Kakadu National Park.
- Some corals may not be able to keep up with periods of rapid sea-level rise, leading to "drowning" of reefs.
- Australia's multi-billion dollar tourism industry relies on Australia's beautiful sandy beaches, from the Gold Coast to Fremantle to Wine Glass Bay. Sandy beaches are at risk from coastal erosion.

5. Rising sea level is eroding the viability of coastal communities on islands in the Torres Strait and the Pacific, and in low-lying areas of Asia, increasing the likelihood of migration and resettlement.

- Several Torres Strait Island communities are situated on extremely low-lying areas and already experience flooding during high tides. Building seawalls and raising houses can buy time, but in the long-term, some communities may face relocation.
- A sea-level rise of 0.5 to 2 m could displace 1.2 and 2.2 million people from the Caribbean region and the Indian and Pacific Ocean islands, assuming that no adaptation occurs.
- Globally, considerable displacement of people from the impacts of climate change, including increasing coastal flooding and erosion, is likely in coming decades. Projections range from tens of millions to 250 million people.

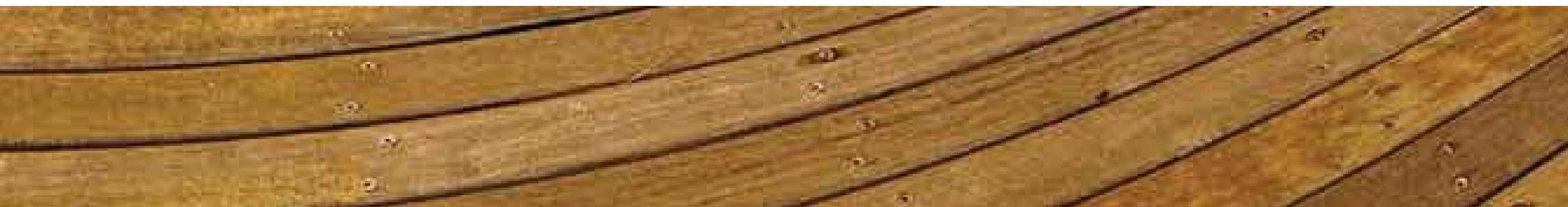
6. We need deep and urgent cuts in greenhouse gas emissions this decade and beyond if we are to avoid the most serious risks from rising sea levels and coastal flooding.

- Stabilising the climate system through deep and rapid reductions in greenhouse gas emissions today is the only way to significantly reduce the level of risk that we face from coastal flooding in the second half of the century and beyond.
- To prepare for the sea-level rise that we can't prevent is also essential to lower the risks of coastal flooding. This requires a coordinated national planning framework integrated across federal, state and local governments with clear allocation of responsibilities.



1. SEA-LEVEL RISE, COASTAL FLOODING AND COASTAL INFRASTRUCTURE

Australians are very familiar with the short-term, regular variations in the level of the sea that occur on a daily basis—the tides. We are also familiar with both longer-term variations in the size of the tides that are related to the phases of the moon and to short-term extreme flooding events that are caused by storm systems that drive a mass of seawater onto the coast. We are now experiencing another driver of change to our coasts—the global rise in sea levels caused by the warming of the climate system. This sea-level rise operates on much longer timescales than the phenomena that we are used to experiencing, and will be with us for centuries.



Sea-level rise affects the coast in two distinct ways: by *inundation*, and by *coastal recession*. Inundation is the process by which the rise in sea level floods the land, without causing any change of the actual land surface. On the other hand, coastal recession is the process by which "soft" (e.g. sandy or muddy) shorelines tend to be eroded landwards under a rising sea level (Table 1). The latter process is complicated by the fact that coastal recession (or the opposite effect, *progradation*, where the shoreline migrates seawards) is affected by several other processes such as waves, water currents and sediment supply and so is not determined solely by changes in sea level.

Over half the Australian coastline is vulnerable to erosion from rising sea level.

Figure 1: An example of coastal recession at Broadbeach Queensland

Table 1: Fraction of coastline susceptible to recession under sea-level rise, defined as shore composed of sand and mud, backed by soft sediment (so that recession is largely unconstrained), and shore composed of soft rock. Based on DCC (2009).

State	Total length of open coast, km	Total length of vulnerable coast, km	Proportion of vulnerable coast (%)
Vic	2395	1915	80
NSW	2109	839	40
Qld	12,276	7551	62
NT	11,147	6990	63
WA	20,513	8237	40
SA	5876	3046	52
Tas	4995	2336	47
Aus	59,311	30,914	52

This report focuses primarily on infrastructure, which is defined as the basic physical structures and facilities needed for the operation of a society. Australia's infrastructure is mostly concentrated in the coastal zone around centres of population (DCC 2009; Chen and McAneney 2006). In this report, infrastructure includes buildings (private, commercial, industrial and public buildings), community services (e.g. police, fire and ambulance stations, hospitals and schools), transport (e.g. roads, railways, ports and airports) and essential services (e.g. facilities for water, waste treatment and energy supply). Defence facilities (e.g. naval bases) are also built assets under threat from climate change and coastal flooding.

In addition to infrastructure, other features of coastal regions are vulnerable to coastal inundation and recession. The impact of shoreline recession on the land values along the coast is a prime example. Shorelines composed of sand, mud and soft rock may recede under changing environmental conditions such as sea-level rise. However, sandy shorelines are the only ones that have the potential to restore themselves after an erosion event—for example, after a large storm.

The average recession of sandy shorelines under sea-level rise can be roughly estimated through the Bruun rule (Zhang et al. 2004), which states that, on average for every metre of sea-level rise, sandy shorelines recede by 50–100 metres. The Bruun rule operates on the assumptions that without sea-level rise, the beach would be in steady state and that other physical conditions (e.g., waves or currents) are unchanged. No simple rule exists for the movement of shorelines of mud or soft rock, although sea-level rise still tends to make such shorelines recede. Table 1 above shows the total lengths of vulnerable coastline susceptible to recession under adverse conditions such as sea-level rise; these are defined as all those composed of sand and mud, which are backed by soft sediment (so that recession is largely unconstrained), and all those composed of soft rock. More than half of Australia's coastline, about 31,000 km, is potentially vulnerable to recession.

It is not only human infrastructure that is at risk from rising sea levels and coastal flooding. Large stretches of Australia's coasts that are vulnerable to sea-level rise include coastal wetlands, saltmarshes, mudflats, mangroves, seagrass beds, rocky shores and sandy beaches. These provide important habitats for many species, including commercially and recreationally important fish and shellfish. These ecosystems provide many additional services, including protection from erosion and storms, filtration of water and stabilisation of sediments (Spalding et al. 2014). The sediments within these habitats also play a very important role in carbon sequestration ("blue carbon"), contributing about half of the total carbon burial in the oceans (Duarte et al. 2005).

Many of these habitats are already in serious decline due to human impacts, and climate change is posing multiple new threats. As sea levels rise, low-lying habitats will become increasingly inundated. In some cases, species and habitats will be able to adjust by moving landwards but this will not be possible if the terrain is very steep, or if human development is a barrier—the "coastal squeeze".

Tourism, one of Australia's most important income earners, is also vulnerable. Our spectacular coastline and natural marine habitats are central attractions for domestic and international visitors. Rising sea levels and increased coastal flooding pose great risks to the maintenance of our beaches and the attractiveness and access of many of our prime natural tourist attractions.

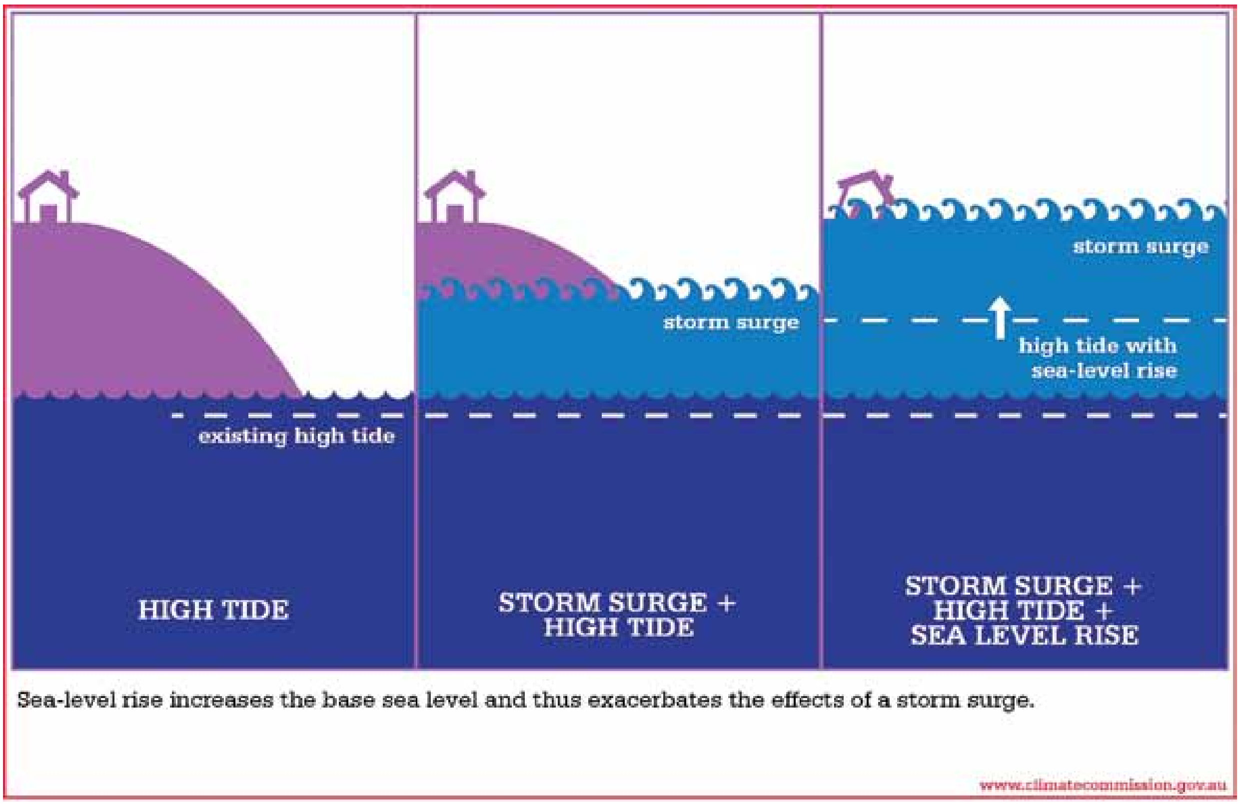
One of the most common misconceptions about sea-level rise is that its rate – currently about 3 mm per year—is so slow that it is not important in terms of impacts. By contrast, the impacts of extreme weather events, such as heatwaves, extreme rainfall, bushfires, are immediate and often very serious. Similarly, sea-level rise is often experienced via extreme inundation or recession events.

The immediate trigger of a high sea-level event is often a combination of a high tide and storm surge (a "storm tide" is the sum of a storm surge and tide). The latter is a short-term rise in sea level driven by strong winds and/or reduced atmospheric pressure. Around northern Australia, storm surges are often driven by tropical cyclones while intense low pressure systems can also lead to storm surges along our non-tropical coasts. For example, Cyclone Yasi caused a large storm surge that contributed to extensive coastal flooding in north Queensland. Storm surges can extend for hundreds of kilometres along a coast and the area of flooding can extend several kilometres inland in particularly low-lying areas. Other factors, such as human modification of the coastline, also influence the severity of the impacts of a storm surge.

As illustrated in Figure 2, the most direct link between coastal flooding and climate change is based on the fact that storm surges are now occurring on base sea levels that have already risen and are continuing to rise. Storm surges are thus becoming more damaging as they are able to penetrate further inland.

When the weather system that drives the storm surge—a tropical cyclone, large

Figure 2: Climate change exacerbates the effects of a storm surge increasing the base sea level (Climate Commission 2013a).



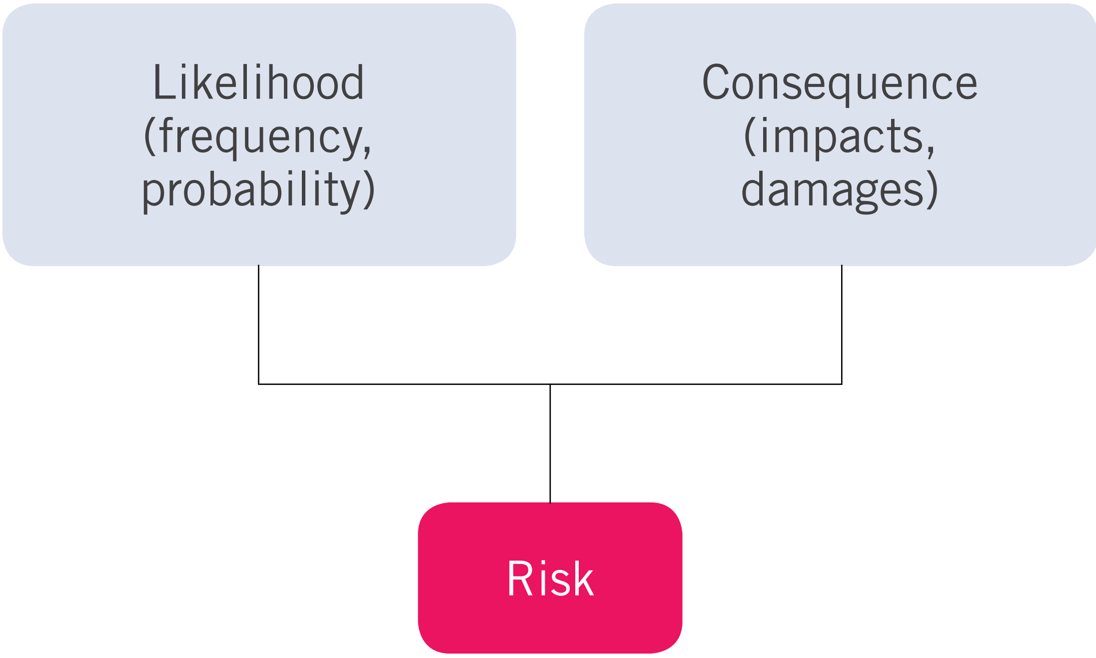
storm or intense low pressure system—also brings heavy rainfall to the coastal area, a "double whammy" flooding event may occur as water comes from both the ocean (as described above) and from the land. These events may become more common in future as the sea level rises and the probability of heavy rainfall events increases (IPCC 2013).

In this report we take a risk-based approach to assessing the link between climate change and coastal flooding and adopt the simple relationship shown in Figure 3 (an interpretation of the ISO standard definition) to assess changes in risk.

Risk is defined as the combination of the likelihood that (or frequency with which) an extreme flooding event will occur and the consequences that result. Both contributing factors are important. For example, an increase in the frequency of flooding events will obviously increase the risk of damage, but as more infrastructure is built in vulnerable locations and its value increases, the consequences of a flooding event of the same magnitude that occurred previously will become more costly, thus also raising the risk.

The next section of this report examines the changes that are occurring in the physical part of the equation—the observed rate of sea-level rise globally, the regional variations in sea-level rise around Australia, the factors that are driving the observed rise in sea level, and the projected further rises in sea level to

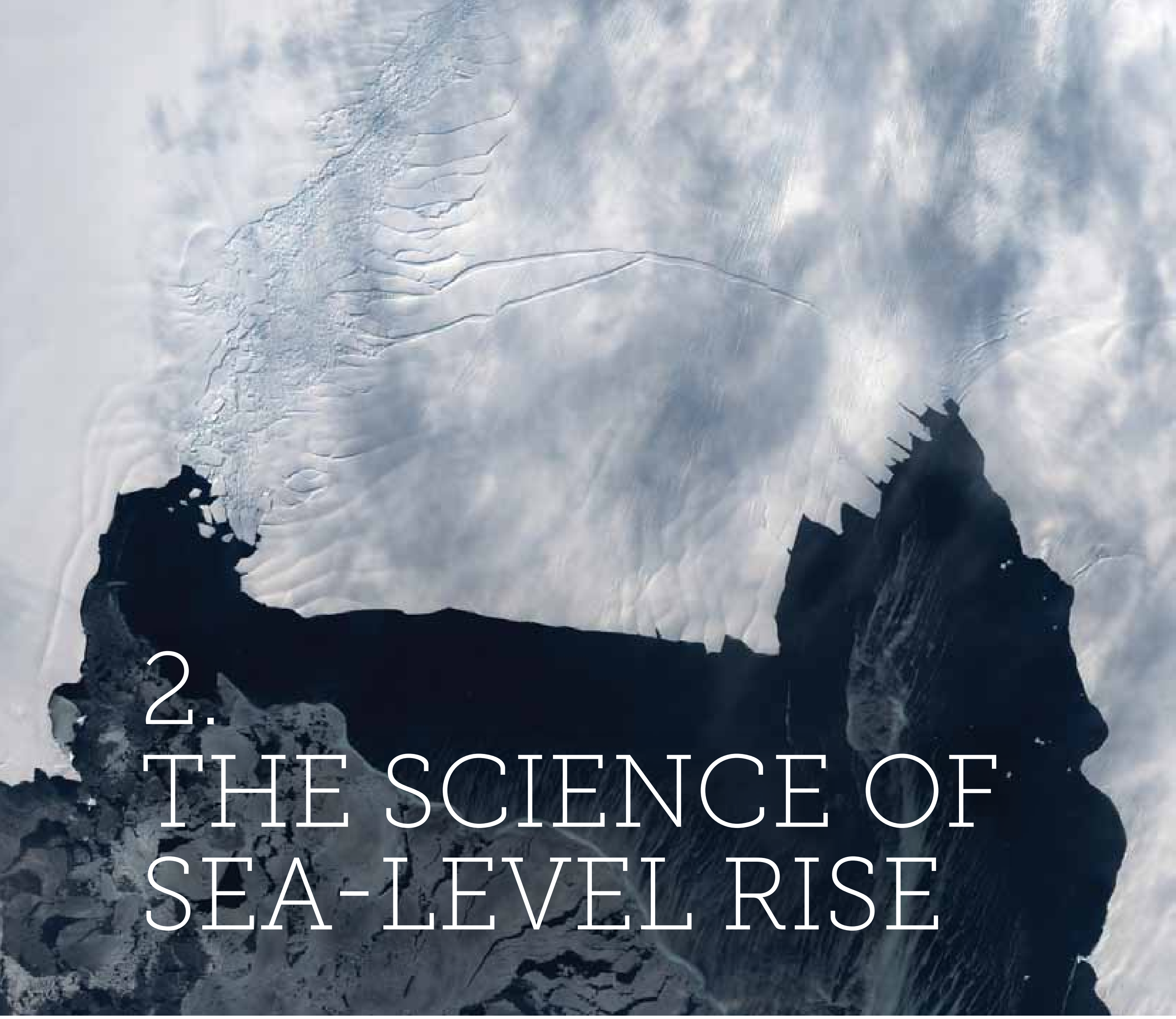
Figure 3: A diagram based on an interpretation of the ISO standard definition of risk used in Australia and New Zealand (AS/NZS ISO 31000:2009).



the end of the century. Importantly, this section also examines the changes in the frequency with which high sea-level events are likely to occur as the base sea level rises.

Section 3 explores the other side of the risk equation—the consequences of high sea-level events when they occur. This section focuses strongly on the economic costs associated with flooding and erosion, especially in urban areas. We also consider the coastline itself ("soft" coasts) and the loss of property, as well as the consequences of coastal flooding and erosion for tourism and natural ecosystems.

Section 4 puts the two components of the risk equation together and examines the approaches we can take to deal with the changing risk profile. Because sea level is already rising as a result of climate change and will continue to rise through this century and beyond, denying climate change and ignoring its consequences, or understanding the risks but failing to act, are not wise options. Adaptation is essential to minimise the risk of high sea-level events, where the IPCC defines "adaptation" as "...the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC 2012). Stabilising the climate system through deep and rapid emission reductions is also essential, as it will influence the rate at which sea level rises this century and the ultimate level at which it is stabilised.



2. THE SCIENCE OF SEA-LEVEL RISE

There is strong evidence that the primary cause of the sea-level rise observed during the past half-century was the warming of the atmosphere and oceans due to an increase in the concentration of greenhouse gases in the atmosphere (IPCC 2013). Sea level is certain to rise further through the rest of this century and beyond, leading to large increases in frequency of coastal flooding.

The effect of changes in sea level that we experience at the coast is actually the result of two processes. They are the vertical motion (rise or fall) of the sea surface itself and the vertical motion (rise or subsidence) of the land surface adjacent to the sea. This is called *relative* sea-level change and is the change that is measured by a tide gauge. On the other hand, a satellite measures the motion of the sea surface relative to the centre of the Earth (called a *geocentric* measurement).

Relative sea-level change is the more important measurement in terms of assessing impacts on infrastructure, property and ecosystems. In many parts of the world today, especially around some large cities located on deltas, impacts are increased by local subsidence of the land, which causes relative sea-level rise to be greater than geocentric sea-level rise.

2.1 Observations of sea-level rise

Sea level is most commonly observed by instruments, such as tide-gauges located on the coastline (generally in ports), or satellites that measure the height of the sea surface over most of the world's ocean, using a form of radar. In addition, methods called *proxy* techniques are sometimes used, primarily in cases where instrumental records are not available. Coring in salt marshes is a popular proxy technique for the estimation of sea-levels over the past few centuries.

Long-term tide-gauge measurements started around 1700 in Amsterdam (Pugh and Woodworth 2014) and around the middle of the 19th century in Australia (Hunter et al. 2003; Matthäus 1972). The longest near-continuous Australian records are from Fremantle (from 1897) and Fort Denison (Sydney; from 1886) (NOC 2014). There are now around 300 Australian locations where tide gauges have been, or are being, operated. The primary purpose of these gauges has been to aid port and survey operations, rather than for scientific studies of sea level. From 1990 to the present, however, the Australian Baseline Sea Level Monitoring Project (BoM 2014d) has provided scientific-quality sea level data at 15 locations around Australia (see Figure 5 for locations).

Global-average sea level has risen by 17 cm over the 20th century.

The most widely used continuous satellite observations of sea level started in 1992 and provide coverage of the world's oceans, except near the poles, approximately every 10 days. The broad spatial coverage of satellite observations has been combined with the long duration of tide-gauge measurements to provide long-term regional records of sea-level change commonly called *sea-level reconstructions*. Examples of the global-average sea level derived from these reconstructions are shown in Figure 4 (Rhein et al. 2013), which indicates an average rise of about 17 cm (1.7 mm/yr) over the 20th century. Over the past two decades, satellite observations indicate a global-average rate of about 3.2 mm/yr (Pugh and Woodworth 2014). It is not clear at present whether this apparent increase represents a long-term acceleration or simply a manifestation of natural variability. However, using model results, Church et al. (2013a) concluded that 'the increased rate of rise since 1990 is not part of a natural cycle but a direct response to increased radiative forcing (both anthropogenic and natural), which will continue to grow with ongoing greenhouse gas emissions'.

Long-term tide-gauge records and cores from salt marshes indicate that a significant acceleration in sea-level rise occurred towards the end of the nineteenth century (Church et al. 2013b).

Figure 5 shows the observed rate of *relative* sea-level rise around Australia from 1990–1993 (the period of installation of the ABSLMP tide gauges) to June 2014 (BoM 2014d). The average rate is 5.6 $\pm$ 2.3 (sd) mm/yr; the lowest rate is 3.5 mm/yr at Stony Point (Vic) and the largest is 10.0 mm/yr at Hillarys (WA). These rates are all higher than the global-average rate since 1992 of about 3.2 mm/yr measured by satellite, although southeastern Australia is closest to the global average. There are a number of reasons for the differences between the global rate and those measured around Australia. Firstly, regional variations in sea level cover a range of scales in time and space. Over long time scales, if one region of the oceans warms faster than elsewhere, the rate of rise will tend to be larger in that region. Such changes in ocean temperature are inextricably linked with long-term changes in wind, pressure and/or ocean currents. At shorter time scales, ocean-wide phenomena such as the El Niño-Southern Oscillation (ENSO) cause sea level at many (especially western and northwestern) locations around Australia to fall during an El Niño event (Church et al. 2006). Douglas (2001) showed that individual tide-gauge records need to be at least 50–80 years long to average out such temporal variability and yield robust estimates of long-term local sea-level change (the records used to derive the trends shown in Figure 5 are only about 20 years long). Secondly, the rates of rise shown in Figure 5 are *relative* rates and so may be significantly affected by land movement. The high rate of sea-level rise observed at Hillarys is related to subsidence of the surrounding land, believed to be due to groundwater extraction for the city of Perth (Burgette et al. 2013).

Average sea-level rise around Australia has been close to the global average.

If adjustments are made to Australian tide-gauge observations to account for ENSO, glacial isostatic adjustment (GIA; the effect on relative sea level of changes in the Earth's loading and gravitational field caused by past changes in land ice) and atmospheric pressure, the mean sea-level rise over the periods 1966–2009 and 1993–2009 was 2.1 and 3.1 mm/yr, respectively, which compares well with the global-average sea-level rise over the same periods of 2.0 mm/yr (from tide gauges) and 3.4 mm/yr (from satellites) (White et al. 2014). Over these periods, the mean sea-level rise around Australia was therefore close to the global-average.

The above analysis shows that unadjusted observations of present regional sea-level rise around Australia should be treated with caution when considering the likely future sea-level rise. The most useful estimates of future sea-level rise (i.e. the rise several decades or more hence) come from climate projections provided by computer models (see Section 2.3) rather than from simple extrapolation of recent observations.

Figure 4: Yearly average global mean sea level reconstructed from tide gauges (1880–2010) by three different approaches (Jevrejeva et al., 2008; Church and White, 2011; Ray and Douglas, 2011). All uncertainty bars are one standard error as reported by the authors. Adapted from IPCC AR5 WGI, Chapter 3, Figure 3.13(a) (Rhein et al. 2013).

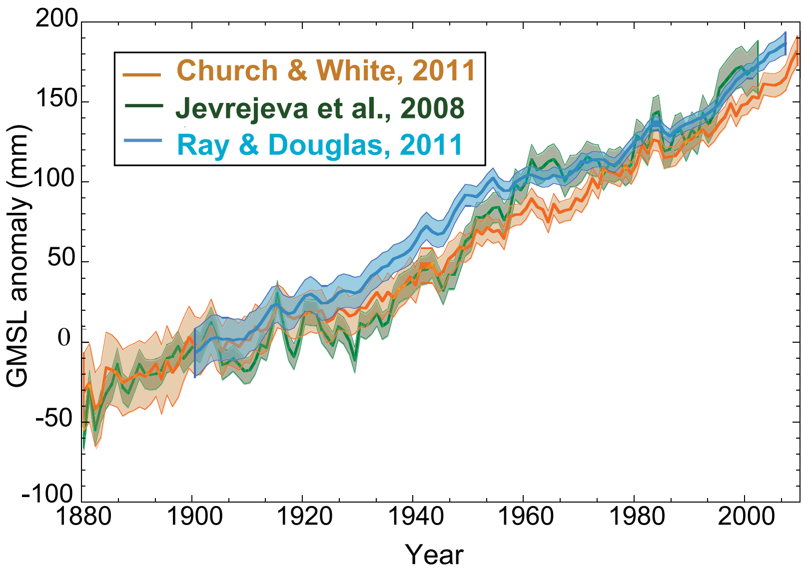
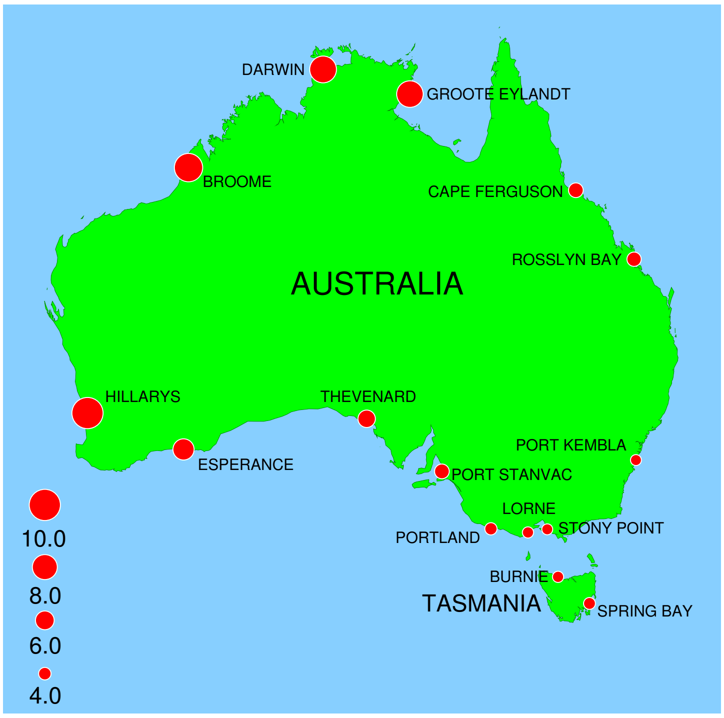


Figure 5: Observed rate of relative sea-level rise at 15 sites around Australia for the period 1990–1993 to June 2014 in mm/yr (BoM 2014d).



BOX 1: SEA-LEVEL RISE BUDGET

It is important to understand the processes that cause sea-level change if we are to predict future changes. One way in which scientists gain this understanding is to construct a budget of sea-level change, which entails comparing the observed change in sea level with our best estimates of the individual contributions to that change. For the current rise in sea level, these contributions are:

(i) Thermal expansion of the ocean water—warm water is less dense than cooler water, and therefore takes up more space

(ii) Flow of ice from the land into the sea, which adds to the total amount of water in the ocean. This additional water comes from:

  (a) glaciers and ice caps (more recently referred to as "glaciers" only)

  (b) the Greenland Ice Sheet

  (c) the Antarctic Ice Sheet

(iii) Flow of liquid water between the land and the sea. This water may be stored above ground or as groundwater. For example, increased storage of water in dams lowers the rate of sea-level rise.

Thermal expansion of the oceans is estimated from measurements of temperature and salinity (saltiness) in the oceans. Flow of ice from the land into the sea is estimated by conventional glaciological and remote-sensing (i.e. satellite and aerial) techniques. The amount of water on land and in groundwater is derived by estimating the total volumes of natural and artificial freshwater bodies, and aquifers.

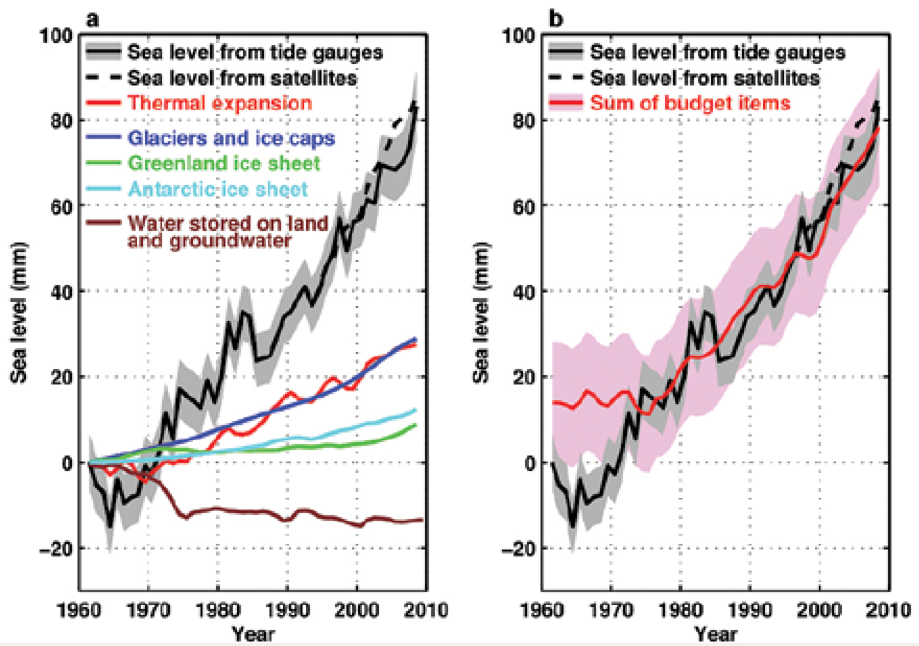
A major advance reported in the IPCC Fifth Assessment Report (AR5) (Church et al. 2013b) is that scientists now have a better understanding of the relative importance of the main factors that cause sea-level rise, and can track how these factors have changed over time.

Figure 6(a) shows the individual contributions to sea-level rise (coloured lines) and the observed sea-level rise from tide gauges (black). The dashed black line shows the observed satellite record. Figure 6(b) shows the same observations in black, and the sum of the budget terms in red, so that a direct comparison can be made between global observations of sea-level rise and the sum of the individual components that contribute to sea-level rise (Church et al. 2011).

Since about 1970, the observations accord with the sum of the individual budget terms, indicating that we have a good understanding of the relative importance of the contributing factors to sea-level rise and how their importance is changing through time. Since 1972, thermal expansion has contributed about 45% to total sea-level rise, glaciers and ice caps about 40% with the remainder being made up from Greenland and Antarctica, which are partially offset by water stored on land and groundwater. There has been a significant acceleration in the contribution from Greenland since 2000.

BOX 1: SEA-LEVEL RISE BUDGET (continued)

Figure 6: The global sea-level budget from 1961 to 2008. (a): The individual terms of the budget (coloured) lines and observations of sea-level rise (black solid and dashed lines); (b) The sum of the budget terms (red line) and observed sea-level rise (solid and dashed black lines). Shading around the solid black lines and around the red line in part (b) show the ±one standard deviation uncertainty range. After Church et al. (2011).



Since 1972 thermal expansion has contributed about 45% to total sea-level rise and the loss of ice from glaciers and ice caps about 40%.

2.2 Projections of future sea-level rise

The amount that sea level rises in the future will depend on the amount of greenhouse gases emitted into the atmosphere. The most commonly used projections of likely regional and global sea-level rise cover the 21st century, which corresponds to the period of most interest to coastal planners (see Section 4.2). The projections are based on certain assumed trajectories of atmospheric greenhouse gas concentrations; in the IPCC AR5, these are called *Representative Concentration Pathways* or *RCPs* (van Vuuren 2011; Box 2).

BOX 2: PATHWAYS OF FUTURE GREENHOUSE GAS CONCENTRATIONS IN THE ATMOSPHERE

Projections of future changes in the climate system, such as global-average air temperature or sea-level rise, require assumptions about the changes in the concentration of greenhouse gases in the atmosphere through time. Throughout its Fifth Assessment Report, the IPCC (2013) has used the concept of *Representative Concentration Pathways*, or RCPs, to provide trajectories of changes in the concentration of greenhouse gases in the atmosphere.

RCPs are related to the rate at which human activities are emitting greenhouse gases to the atmosphere, but are rather different from the emission scenarios that have been used previously. The RCPs also incorporate the rate at which greenhouse gases are absorbed by the oceans and by the land, the so-called *carbon sinks*. Currently these carbon sinks absorb slightly more than half of human emissions of carbon dioxide. Unless there are significant changes in the strength of these sinks, the concentration pathways, or RCPs, will generally reflect the rate of emission of greenhouse gases to the atmosphere.

Two RCPs are considered in this report:

(a) RCP4.5: this is a mitigation pathway that stabilises greenhouse gases in the atmosphere by 2100. However, the temperature at the end of the 21st century is more likely than not to exceed 2°C relative to the latter half of the nineteenth century.

(b) RCP8.5: this is a "business as usual" trajectory in which atmospheric greenhouse gas concentrations continue to rise through the century. This trajectory will result in global temperatures around 4°C at the end of the 21st century relative to the latter half of the nineteenth century.

Through the rest of this report, we use the term "weak mitigation pathway" for RCP4.5 and the term "business as usual pathway", or "BAU pathway", for RCP8.5.

The IPCC also used a stronger mitigation pathway, RCP2.6, in its Fifth Assessment. Of the four pathways that the IPCC used, RCP2.6 most closely resembles the budget approach, described in Section 4.3, which requires rapid and deep cuts in greenhouse gas emissions to stabilise the climate at a temperature rise of no more than 2°C above pre-industrial. We focus on RCP4.5 and RCP8.5 in this report to highlight the very serious risks from coastal flooding that we face if we do not take decisive and rapid action to reduce greenhouse gas emissions.

Figure 7 shows the projected global-average sea level rise for the weak mitigation pathway (blue) and for the BAU pathway (orange), relative to 1986–2005, as reported in the IPCC AR5 (Church et al. 2013b). For each projection, the central black line is the median, and the coloured band represents the "likely range". This range represents the 5- to 95-percentile range of the model projections, and was further interpreted in the AR5 as being the range within which future sea level has a 66% likelihood of occurring.

The amount that sea level rises in the future will depend on the amount of greenhouse gases emitted into the atmosphere.

Based on Figure 7, the sea-level rise over the 21st century is in the approximate range 0.4–0.7 m for the weak mitigation pathway and 0.5–1.0 m for the BAU pathway. These ranges are relatively large—about the same magnitude as the lower limit of the estimate. However, as will be shown in Section 2.4, this uncertainty increases the amount that we need to allow for sea-level rise; it is certainly not an excuse for inaction.

Sea level could rise between 0.4–1.0 m over the rest of this century depending on how rapidly we reduce emissions of greenhouse gases.

One potentially large future contributor to sea level that that cannot yet be well modelled is the West Antarctic Ice Sheet, the destabilisation of which could add a few tens of centimetres to the 2100 projections in a worst-case scenario (Church et al. 2013b). Recent observations of changes in the West Antarctic Ice Sheet (Joughin and Alley 2011; Joughin et al. 2014; Rignot et al. 2014) suggest that there are legitimate concerns about its long-term stability through the rest of this century.

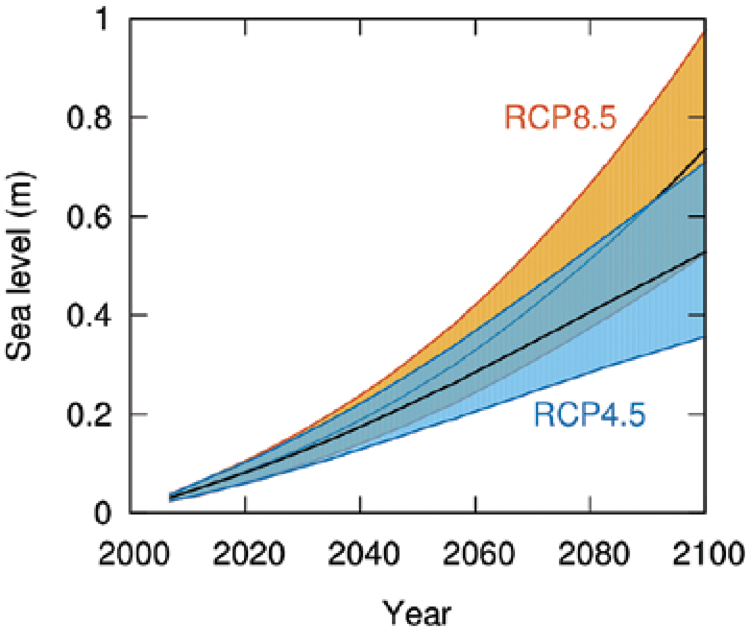
Two important analyses of risks to Australia's coast (DCC (2009) and DCCEE (2011), which are referred to in Section 3, assumed a 'high end' sea-level rise at 2100 of 1.1 metre, based on projections from the IPCC's 2007 Fourth Assessment Report (AR4) and other research suggesting that the AR4's projections may have been underestimated. Although higher than the upper 95-percentile limits shown in Figure 7, this 'high end' projection is still highly plausible.

If the West Antarctic Ice Sheet is destabilised, sea-level could rise higher than currently expected.

A major advance in the IPCC AR5 was the development of regional projections of *relative* sea level, including the effects of thermal expansion of the oceans, addition of water to the oceans through the flow of ice from the land into the sea, changes in ocean dynamics, and past and future changes in the Earth's gravitational field and in the vertical movement of the Earth's crust due to the melting of land ice. These projections are therefore the most appropriate ones for determining the effect of sea-level rise on the coast. It should be noted, however, that these projections do not include tectonic effects or local land motion due to processes such as subsidence caused by groundwater withdrawal, as occurs at Hillarys, WA (see Section 2.1).

Best estimates (central values) of sea-level projections for Australia from the IPCC AR5, over the period 2010–2100, for the weak mitigation and the BAU pathways, are shown in Figures 8a and 9a, respectively. The locations shown in these figures are the sites of long (greater than about 30 years) Australian tide-gauge records. These sites are representative of the major population centres. In addition, these tide-gauge records provide the basis for the estimation of the increased probability of coastal flooding described in Section 2.3. The ranges of projected sea-level

Figure 7: Projected global-average sea-level rise for the weak mitigation (RCP4.5: blue) and BAU (RCP8.5: orange) pathways, relative to the average for the 1986–2005 period.



rise at the tide-gauge locations shown are 0.45–0.53 m and 0.65–0.76 m for the weak mitigation and BAU pathways, respectively. The rise is slightly larger on the southeast, east and northwest coasts of Australia.

Without significant reduction of emissions, sea-level rise will likely be measured in metres in coming centuries.

Sea-level rise after 2100 becomes progressively less certain, both due to uncertainties inherent in the models and to a lack of knowledge of future emissions. However, Church et al. (2013b) reported the spread of model projections of global-average sea-level rise (over only a few models) for a “medium scenario” (which is similar to the weak mitigation pathway) of 0.26–1.09 m and 0.27–1.51 m for 2200 and 2300, respectively (both relative to 1986–2005). They also considered a “high scenario” (which is similar to the BAU pathway), which gave model spreads of 0.58–2.03 m and 0.92–3.59 m, for 2200 and 2300, respectively. We could possibly see a rise of 2 m by 2450 under the “medium scenario” and by 2200 under the “high scenario”. Without significant mitigation of emissions, sea-level rise will likely be measured in metres in coming centuries.

Over longer time periods, sea-level rise could be significantly higher. During the Last Interglacial Period, about 120,000 years ago, when global temperature was 1° to 2° C warmer than pre-industrial (which will more likely than not be exceeded even under the weak mitigation pathway) the sea level reached at least 5 m higher than present (Church et al. 2013b).

2.3 Increased probability of coastal flooding

The surface of the sea is never still. Apart from the increases we are measuring as a result of increasing greenhouse gas emissions, the surface is continually affected by tides, storm surges and variations over seasonal, annual and decadal cycles. A piece of infrastructure, if located near the coast, may experience the occasional flooding event as result of these variations in sea level.

The frequency of coastal flooding events trebles for every 0.1 m of sea-level rise.

Such flooding events generally occur when a storm surge coincides with a high tide (Figure 2), but other processes may come into play that make the flooding event higher or lower. Under a long-term trend of rising sea level, the frequency of flooding events (at a given infrastructure height) increases. Church et al. (2006) showed that, at both Fremantle and Sydney, flooding events of a given height increased their frequency of occurrence by a factor of about three during the 20th century as a result of sea-level rise.

A rough "rule of thumb" is that the frequency of flooding events trebles for every 0.1 m of sea-level rise (Hunter 2012). Therefore, for a 0.2 m rise, the frequency of flooding events increases by a factor of about 3x3 = 9; for a 0.3 m rise, the frequency of flooding events increases by a factor of about 3x3x3 = 27, and so on. Therefore, a 0.5 m rise (for the 21st century this would represent a mid-range projection for the weak mitigation pathway and a projection at the lower end of the range for the BAU pathway) would increase the frequency of flooding events by about 250. This means that, if a piece of infrastructure was designed for a 1-in-100-year flooding event (a common design criteria), it would experience the same flood every few months after the sea level had risen 0.5 m.

For a sea-level rise of only 0.5 m, flood events that today might be expected once every hundred years could occur every few months in the future.

As noted in Section 2.2, projections of sea-level rise entail significant uncertainty. The multiplying factor by which the average frequency of flooding events increases with sea-level rise depends both on the best estimate of that rise and on its uncertainty (Hunter 2012). Taking both these contributions into account, Figs. 8b and 9b show this multiplying factor over the period 2010–2100. There are wide ranges of multiplying factors over the locations shown: 13 to >10,000 and 45 to >10,000 for the weak mitigation and BAU pathways, respectively. In cases where the multiplying factor is 10,000, what is now a 1-in-100-year flooding event is projected to occur every few days by 2100.

A "planning allowance" may be derived by calculating how much a piece of infrastructure would need to be raised to keep the average frequency of flooding events the same in the future as it is now. Figures 8c and 9c show this planning allowance over the period 2010–2100 for the weak mitigation and BAU pathways, respectively. The ranges of allowances over the locations shown are 0.48–0.66 m and 0.72–0.95 m for the weak mitigation and BAU pathways, respectively, which are 0.1–0.2 m above the central values of the projections (Section 2.2 and Figures 8a and 9a); this increase results from uncertainties in the projections. The allowances are larger on the southeast and east coasts of Australia.

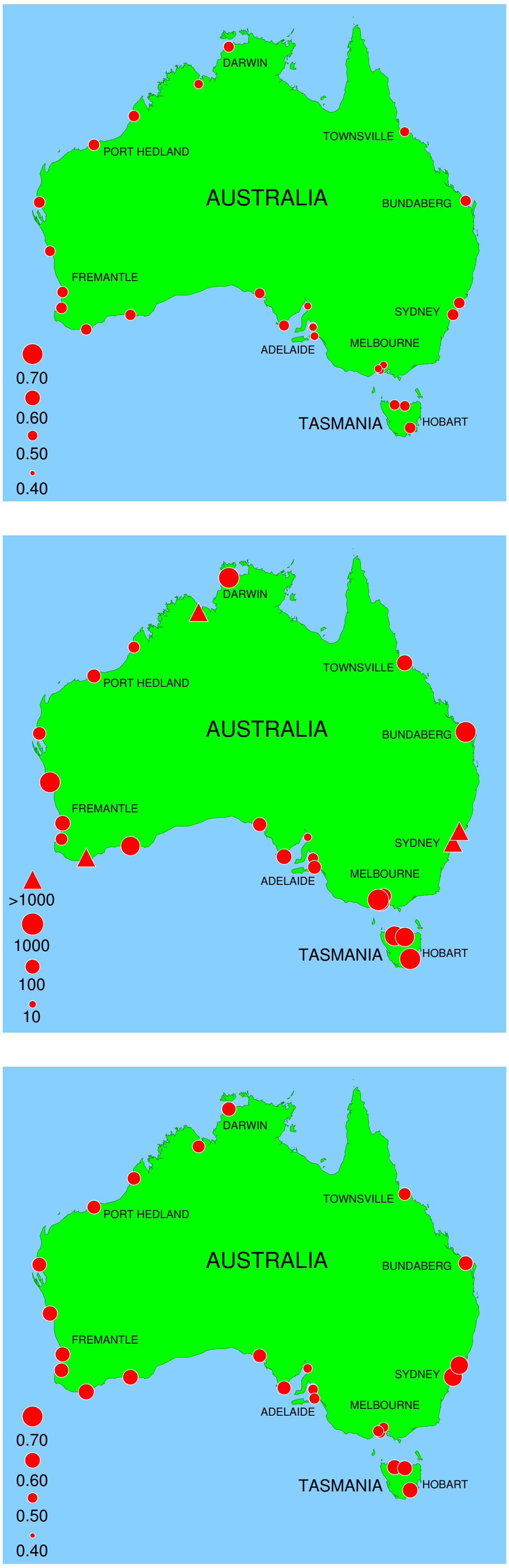


Figure 8: (a) best estimate (top, metres), (b) multiplying factor (middle), and (c) allowance (lower, metres) for 2100 relative to 2010 for the sea-level rise projections for the weak mitigation pathway (RCP4.5).

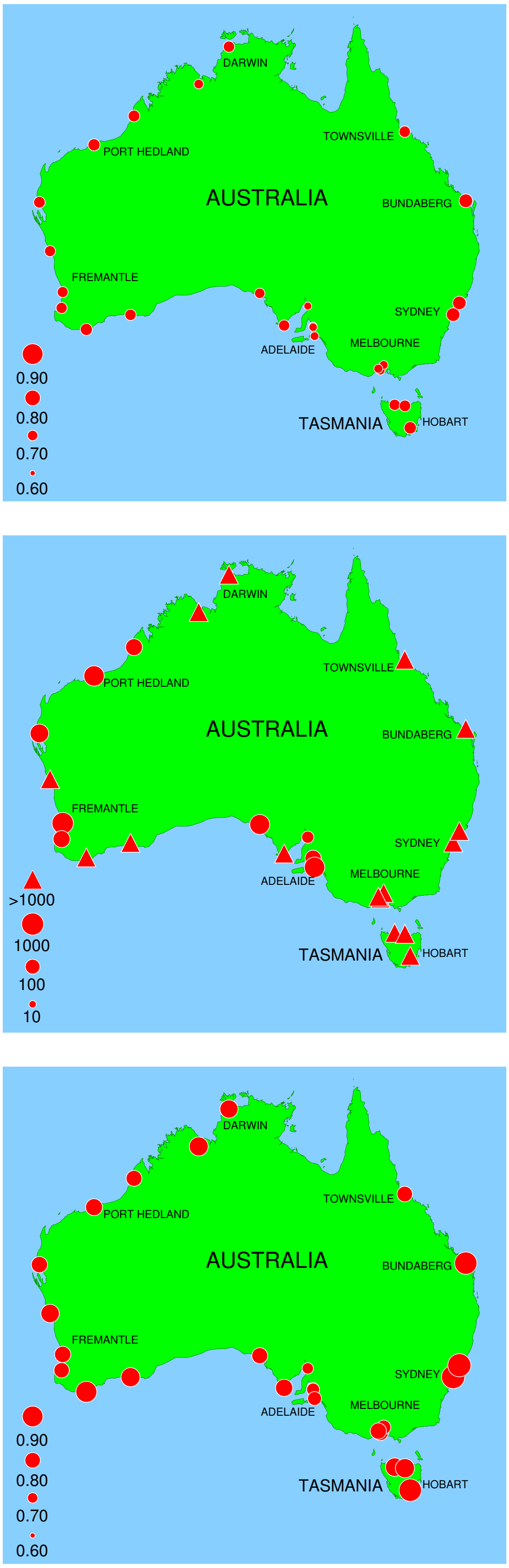


Figure 9: (a) best estimate (top, metres), (b) multiplying factor (middle), and (c) allowance (lower, metres) for 2100 relative to 2010 for the sea-level rise projections for the BAU pathway (RCP8.5).

2.4 Other contributing factors to risks of sea-level rise

Coasts are always at risk, even in the absence of climate change and sea-level rise. Coasts are exposed to storm surges and waves, which can cause inundation of low-lying land and modifications to soft shorelines (i.e. those composed of sand, mud or soft rock). Of the soft shorelines, sandy shorelines are probably the least vulnerable because, even though they can suffer significant recession after a large storm (which brings high waves and often a higher mean water level), they generally "repair" during quieter times. However, as indicated in Section 1, sea-level rise may lead to an overall recession, which often manifests itself as an inadequate "repair" process after a major storm. Muddy and soft-rock shorelines cannot repair themselves in this way once they are eroded as there is no corresponding post-storm "repair" process.

Coastal engineers and planners design infrastructure to cope with events of a certain probability of occurrence. For example much of our infrastructure has been designed to cope with a "one-in-one-hundred-year" extreme event, which relates to a water level or wave height that is exceeded, on average, once in 100 years. This is approximately the same as the water level or wave height that has a likelihood of 1% (or 1 in 100) of occurring in any one year. There is much debate about whether this is a sufficient safety margin. For example, infrastructure is often designed to last 100 years and also to just withstand the "one-in-one-hundred-year" extreme event. However (paradoxical as it may seem), simple statistics tells us that such infrastructure is more likely than not to experience something at least as severe as the one-in-one-hundred-year event during its 100-year lifetime—therefore it is more likely than not to get flooded at least once. In the Netherlands, where flooding could be widespread and disastrous, coastal design and planning is based on the 1-in-10,000-year extreme event, such that the likelihood of flooding in any 100-year period would only be about 1% (or 1 in 100) (Kabat et al. 2009).

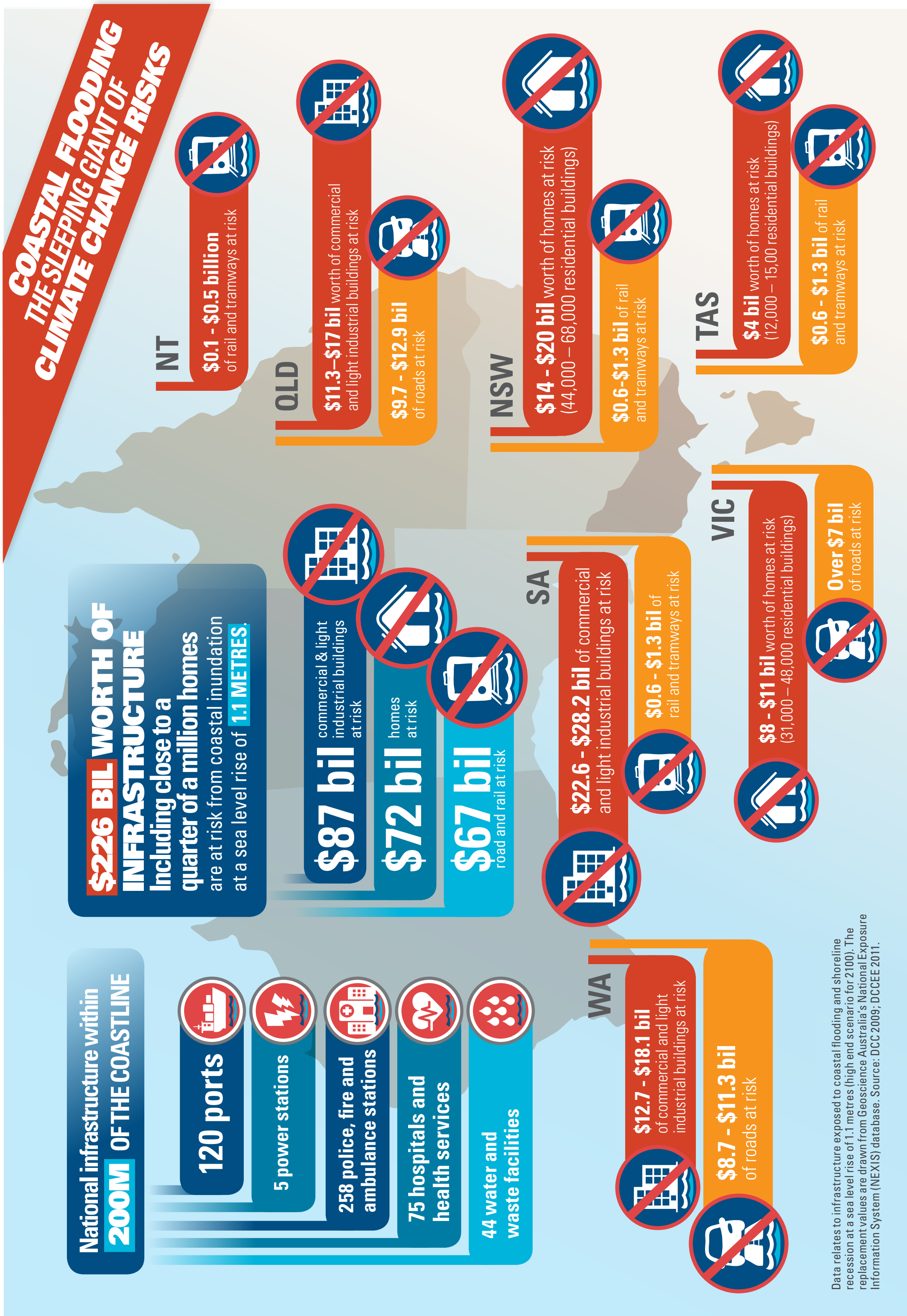
As noted in Section 2.1, local subsidence of land increases the rate of relative sea-level rise, thereby increasing the vulnerability of the shoreline to flooding. This effect is evident at several locations around Australia and is generally due to the extraction of groundwater (e.g. Hillarys, see Section 2.1; Adelaide, see Belperio, 1993) or the extraction of oil and gas (e.g., Gippsland, see Freij-Ayou et al. 2007).

3. COUNTING THE COSTS

The potential costs of coastal flooding can be estimated in a number of ways, including (i) the value of infrastructure that is exposed to coastal flooding, both at current sea level and at levels projected for the future; (ii) observed damages of coastal flooding events that have already occurred; and (iii) estimated damages of future coastal flooding events at a projected amount of sea-level rise.

Various methods are used to assess present and future damages to infrastructure. Some studies focus specifically on direct infrastructure damage and the resulting insurance claims, whilst others incorporate indirect costs, such as the economic disruption from flooded businesses or cut roads, the losses of state's tax income, or long-term declines in property value. Projected costs can also vary depending on the factors considered in different studies, such as the presumed extent of sea level rise or the local adaptive capacity of the area at risk. The discount rate employed in the study can also have a large bearing on projected future costs of coastal flooding.

Figure 10: Counting the costs of coastal flooding



In this section we briefly examine the amount of infrastructure currently exposed to coastal flooding, followed by a description of the observed economic costs of coastal flooding events that have already occurred. We then explore potential future economic damage to infrastructure from the increase in coastal flooding from sea-level rise, noting the differences in methods and approaches used to make the estimates. Although the focus is primarily on Australia, global examples are also given.

We conclude with a discussion of the risks of a rising sea level for sectors other than human infrastructure—natural ecosystems, coastal tourism, and the potential cultural and social issues associated with environmentally induced migration.

3.1 Infrastructure exposed to coastal flooding

The exposure of coastal assets to sea level rise associated with climate change is widespread and this hazard will increase into the future. More than $226 billion (2008$) in commercial, industrial, road and rail, and residential assets are potentially exposed to flooding and erosion hazards at a sea level rise of 1.1 m (a high end scenario for 2100). Coastal assets at risk from the combined impact of inundation and shoreline recession include: between 5,800 and 8,600 commercial buildings, with a value ranging from $58 to $81 billion (2008 replacement value); between 3,700 and 6,200 light industrial buildings, with a value of between $4.2 and $6.7 billion (2008 replacement value); and between 27,000 and 35,000 km of roads and rail, with a value of between $51 and $67 billion (2008 replacement value) (DCCEE 2011) (Figures 10, 11). Replacement values quoted above were drawn from the Geoscience Australia's National Exposure Information System (NEXIS) database.

Because of its location close to the shoreline, the Gold Coast is particularly exposed to sea-level rise, storms surges, flooding, beach erosion and the potential damage to infrastructure. A 2009 study by the Department of Climate Change, (DCC) study estimated that there are 2,300 residential buildings located within 50 m of sandy coast and 4,750 within 110 m. This exposes between 4,000 and 8,000 private dwellings to the impacts of coastal flooding, if sea levels were to rise by 1.1 m, whilst a 5 m rise, would flood most of the developed area (DCC 2009).

At a sea level rise of 1.1 m, more than $226 billion in commercial, industrial, road and rail, and residential assets are at risk from flooding.

Exposure will likely increase as the population grows (DCCEE 2011). The Intergenerational Report 2010 projects that Australia's population will grow by 65% to more than 35 million people in 2049 (Commonwealth of Australia 2010), and a large share of this growth would be absorbed by coastal settlements and cities (DCCEE 2011). How many of these new coastal settlements and dwellings will be built in areas vulnerable to coastal flooding will depend, at least in part, on the effectiveness of urban and regional planning to account for the increasing risk of coastal flooding in future development (see Section 4).

Figure 11: The combine estimated replacement value of infrastructure flooded by a 1.1 m sea-level rise (DCCEE 2011).

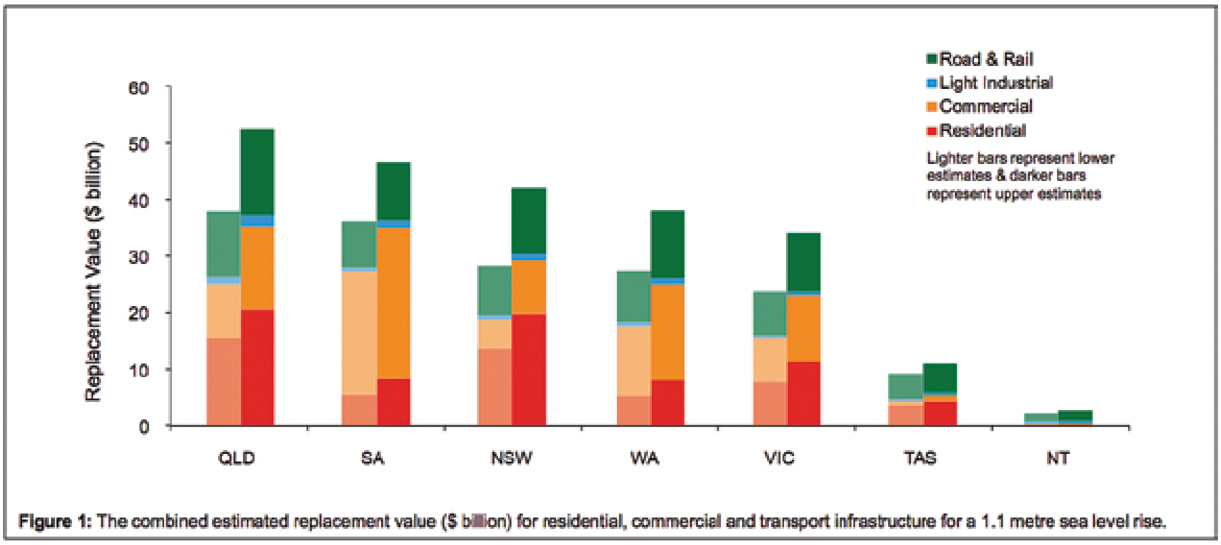


Figure 12: An example of damage to a road from coastal flooding.

3.2 Observed economic costs of coastal flooding

3.2.1 Costs of coastal flooding in Australia

The costs incurred from extreme climate events have been significant in the past; the damages from major flooding, tropical cyclones and severe storms for the 1967–1999 period, based on 2008 residential building pricing, were estimated at $28.6 billion (DCC 2009). Particular examples of the extreme events in which coastal flooding was an important component are given below.

Cyclone Yasi (2011): One of the most powerful cyclones to have affected Queensland since records began was Tropical Cyclone Yasi in February 2011. Queensland had already been devastated by a series of severe floods that occurred throughout December 2010 and January 2011, with record flood peaks at over 100 Queensland river height locations (Queensland Floods Commission 2011). The cost of the 2010–11 floods, combined with the costs from Cyclone Yasi, reduced the Queensland Gross State Product (GSP) by $6 billion in 2010–11, with consequences for coal exports and tourism as well as rural production (Queensland Government 2011).

The Pasha Bulker Storm (2007): In June 2007, the 'Pasha Bulker Storm' hit Australia's east coast between the llawarra and the Hunter regions, causing substantial damage and erosion as a result of coastal flooding. The storm was comprised of a total of five east coast lows (ECLs), with the first ECL causing the most significant damage, including widespread flooding and wind damage, coastal erosion, the grounding of the Pasha Bulker—a 40,000 tonne bulk carrier ship—and the loss of nine lives. The Pasha Bulker Storm was one of the most severe meteorological events in Australia's history, with substantial economic losses and social disruption due to the loss of critical infrastructure. Approximately 300,000 people were without mains electricity for four days, the coal export chain was frozen for two weeks and telecommunications were cut off (Verdon-Kidd 2010). It is estimated that the value of work-related property loss and damage from the storm and flood was around $458 million, 22% ($123 million) of which was not covered by insurance (McDonald and Redford 2008; Verdon-Kidd 2010).

Cyclone Larry (2006): Severe Tropical Cyclone Larry hit the coast of north Queensland, near Innisfail, on 20 March 2006 (BoM 2014a). Accompanying the cyclone was a powerful storm surge, with coastal areas devastated by flooding. About 10,000 homes were affected and the cost of the damage to both infrastructure and crops around Innisfail was estimated to be over $500 million. Transport infrastructure was also damaged, with flooding disrupting road and rail access for several days (BoM 2014a).

Cyclone Ingrid (2005): In early March 2005 Severe Tropical Cyclone Ingrid caused significant damage along the coastlines of Queensland, the Northern Territory, Western Australia and Papua New Guinea. The cyclone was accompanied by a significant storm surge that damaged ocean vessels and coastal infrastructure. In

Western Australia the accompanying storm tide stranded boats 100 m inland (BoM 2005). The swell was so large that a vessel was capsized in Papua New Guinea with a loss of five lives (BoM 2005). In Queensland, Cyclone Ingrid caused approximately $2 million worth of damages (Queensland Government 2005). In the Northern Territory the coastal regions of Croker Island, Melville Island, Nhulunbuy, Bathurst Island and the Coburg Peninsula were all severely affected by the cyclone and accompanying flooding, with damages reaching an estimated $10 million (Northern Territory Government 2005). Croker Island was particularly affected, with the island's school, local store, fishing lodge and pearl farms all damaged, with the cost of rebuilding infrastructure estimated to be over $5 million (ABC 2005).

Cyclone Vance (1999): Severe Tropical Cyclone Vance passed across Exmouth Gulf in Western Australia on 22 March 1999. The storm surge that accompanied the cyclone was coupled with a high tide, illustrating the significant damage that can be triggered when the two occur simultaneously (for example, the storm surge and high tide in Figure 2). The combination of high seas and high tides caused severe erosion of the beachfront at Exmouth, damaged barges, left vessels stranded and caused severe structural damage to 10% of buildings in Exmouth (BoM 1999; BoM 2014b). Water and power supplies were also disrupted and the main rail and road links to the south were cut. The Insurance Council of Australia estimated the 1999 damage at $35 million, putting the 2011 estimated normalised cost at $108 million (AEM 2014).

3.2.2 Costs of coastal flooding globally

Severe coastal flooding caused by storm surges and exacerbated by rising sea level has occurred in many places around the world, with significant damages. Average global flood losses in 2005 for the world's coastal cities were estimated to be about $US6 billion (Hallegatte et al. 2013). Severe coastal flooding caused by storm surges and exacerbated by rising sea level has occurred in many places around the world, with significant damages. In the United States, the most costly natural disaster in its history was Hurricane Katrina, which hit the Gulf Coast and the city of New Orleans in 2005. In addition to damage from high wind speeds, the storm surge that accompanied the cyclone caused significant damage to infrastructure and loss of life. The coastal flood heights, which reached 8.5 m above ordinary tide levels (www.nhc.noaa.gov/outreach/history), were the highest ever recorded in the USA, with an estimated $US100 billion in losses and approximately 2,000 fatalities (Lin et al. 2012).

Seven years later the Atlantic Coast of the USA was battered by Hurricane Sandy, an unusual storm in terms of its size and its northerly track. Again, the combination of storm surges and higher sea level combined to wreak havoc on some of the country's most populous and economically important areas (Box 3).

BOX 3: HURRICANE SANDY (22–29 OCTOBER 2012)

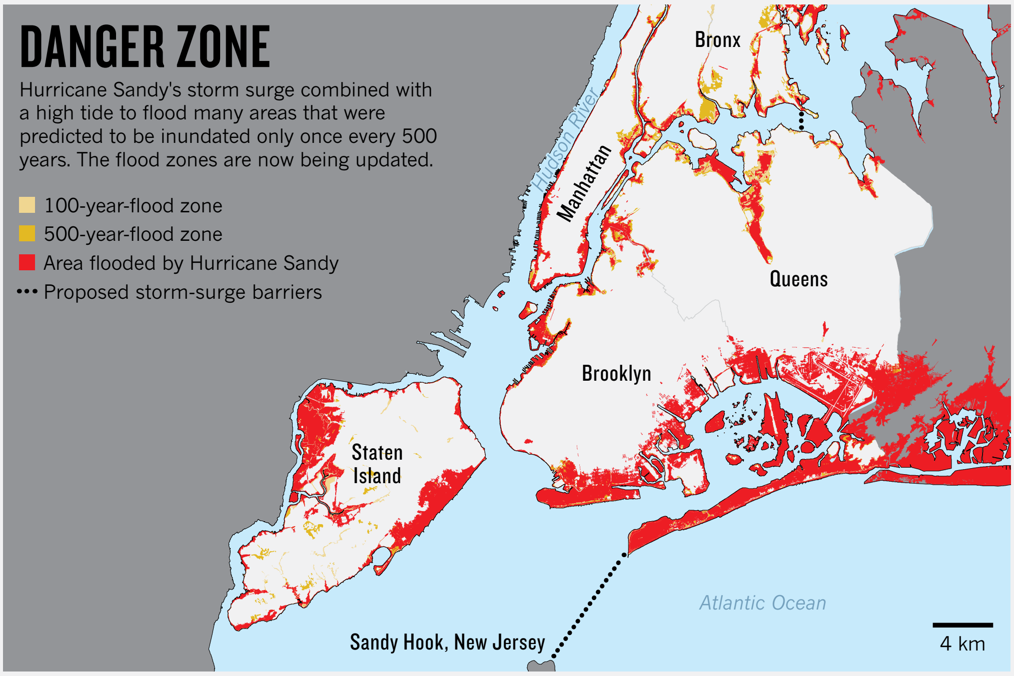
Hurricane Sandy had a profound impact on life and property in the Caribbean and continental United States with 24 states experiencing direct impacts from the storm. The superstorm caused 147 deaths, damaged or destroyed at least 650,000 houses and left approximately 8.5 million people without power (NOAA 2013). Other impacts included the cancellation of 20,000 airline flights from 27 October to 1 November 2012, 8.6 million power outages in 17 states (some lasting for weeks), and unparalleled disruption of rail networks across the Northeast (Halverson and Rabenhorst 2013).

The tropical storm force winds stretched over 1,600 km, making Hurricane Sandy one of the largest Atlantic tropical storms ever recorded, covering over 4.6 million square kilometres. The high winds drove large storm surges; the tide gauges at the Battery in Manhattan and at Bergen Point West Reach on Staten Island recorded values of 2.7 m and 2.9 m above ordinary tide levels, respectively. The worst flooding occurred over Staten Island and to the south along the New Jersey shore ((Middlesex, Monmouth, and Ocean Counties; Figure 13). In coastal Monmouth and Ocean Counties, entire communities were flooded, with houses swept off foundations, and cars and boats carried inland by the surge (NOAA 2013).

Hurricane Sandy killed 43 people in New York City, left thousands homeless, caused an estimated $US19 billion in public and private losses and crippled the financial district. The New York Stock Exchange closed for the first time since 1888 and the storm surge flooded New York City's subway tunnels and inundated the runways at La Guardia and Kennedy airports. The damage to the New Jersey Transit System was estimated at $US400 million (Tollefson 2013).

An assessment by the New York City Panel on Climate Change in 2010 suggested that local relative sea level could rise by 0.3–1.4 m by 2080. Recent studies by Lin et al (2012) found that floods that occur once every 100 years in the current climate could happen every 3–20 years by the end of this century if sea level rises by 1 m. What is considered a '500-year' event today could occur every 25–240 years (Tollefson 2013).

Figure 13: Areas of New York City vulnerable to coastal flooding and areas flooded in 2012 by the storm surge from Hurricane Sandy.



3.3 Projected costs of coastal flooding in future

While the costs of damage to infrastructure from coastal flooding events that have already occurred can be assessed or estimated based on the current value of the infrastructure, the insured losses, or the current replacement value of the infrastructure, it is not as easy to estimate the costs of a coastal flooding event at some point in the future, especially in the distant future. Economists use discount rates to compare the cost of some future event with current costs of a similar event. Use of discount rates in estimating impacts of climate change is the topic of lively debate, with no consensus on the rate that should be used for impacts decades into the future (Box 4).

BOX 4: DISCOUNTING FUTURE BENEFITS AND COSTS

Frank Jotzo

Crawford School of Public Policy, The Australian National University

Economic assessment of investments for climate change mitigation or adaptation requires comparing costs and benefits that occur at different points in the future. In economic benefit-cost analysis the intertemporal dimension is captured by "discounting" future benefits and costs relative to today's, reducing the present-day value of future events by some percentage rate per year.

The longer the time frames involved, the more important the discount rate. In evaluating the expected benefits of reducing greenhouse gas emissions to limit future climate change impacts, very long timeframes are involved. Thus the choice of the discount rate can be crucial in the evaluation. Benefit-cost analysis of adaptation decisions may also be strongly affected by discount rates, especially for long-lived capital investments like port facilities, roads and rail lines.

A benefit-cost analysis of an investment to reduce emissions or invest in adaptation measures will show a lower net present value (the discounted stream of benefits and costs over time) the higher the discount rate. In many cases, the discount rate will determine whether an investment is seen as economically beneficial (with a positive net present value) or not.

A high discount rate means that events in the far future are given almost no weight compared to the present. For example, a benefit of $1 million occurring in 50 years has a present value of $364,000 if the discount rate is 2%, but only $27,000 if the discount rate is 7%.

The choice of discount rate may be viewed from a normative or prescriptive perspective, and from a positive or descriptive perspective. The descriptive approach involves observing how individuals and markets make intertemporal decisions, as revealed by market interest rates. Market rates for example as charged for financing of commercial investment projects do not reflect the preferences of future generations, and there are no risk-free financial assets of similarly long maturity as the time horizons involved in most decisions about climate change responses. Inflation-adjusted interest rates for long-term government bonds for a number of developed countries have been in the range of -1% to 2% (Blanco et al. 2014).

Determining a discount rate normatively involves ethical judgments. It requires judgment about whether and how much future benefits and costs should be discounted simply because they occur later in time, and about the fair distribution of benefits and costs between different generations that are likely to differ in their wealth.

The first of these parameters is sometimes termed the "pure rate of time preference". The recent literature on the economics of climate change suggests a rate of zero or near-zero, on the basis that there is no valid ethical argument to place less emphasis on the future than the present purely because of the impatience or desires of the present generation. This was the approach taken in the Stern Review on the economics of climate change and the Garnaut Climate Change Review (see Stern 2007 and Garnaut 2008).

The second parameter involves making a judgment about societies' aversion to inequality between generations, and an estimation about whether and by how much future generations will be richer than today's population.

The recent IPCC report (Working Group III, Technical Summary) finds that the parameter used for intergenerational inequality aversion "[...] should be consistent with attitudes towards inequality between people of different income today. Although this is ultimately a normative decision, the recent literature favors a risk-free discount rate between one and three times the anticipated growth rate of consumption per capita, which in turn can differ greatly between countries. Because the long term growth rate is uncertain, there is a precautionary argument to use a smaller discount rate" (Kolstad et al. 2014).

For Australia, projections by the Treasury (Commonwealth of Australia 2010) assume real per capita GDP growth of 1.5% per year toward the middle of the century. On the basis of the IPCC findings, this implies a discount rate of between 1.5% and 4.5%, minus an adjustment for precaution. Views will diverge about the long-term rate of per capita income growth, with some arguing that lower rates are possible or likely; about the adequate parameter for inter-generational inequality aversion; and about reductions in the discount rate to adjust for risk.

Ultimately, societies and policymakers need to base their decisions on ethical positions and value judgments, informed by analysis from natural science and social science including economics. Economic assessment of expected benefits and costs cannot adequately deal with the uncertainties involved in climate change, in particular the risk of catastrophic climate change impacts. Benefit-cost analysis also struggles to put a monetary value on non-market impacts such as the loss of human health and life, species and iconic natural environments.

Where possible in the discussion below, we note the discount rate that has been used in the cost estimates.

3.3.1 Projected costs in Australia

The economic costs of natural disasters, currently estimated at $6.3 billion per year, are projected to double by 2030 and reach $23 billion by 2050—these estimates do not account for climate change. These projected future costs incorporated ABS data on predicted growth rates for the value of housing in each state (Deloitte Access Economics 2013).

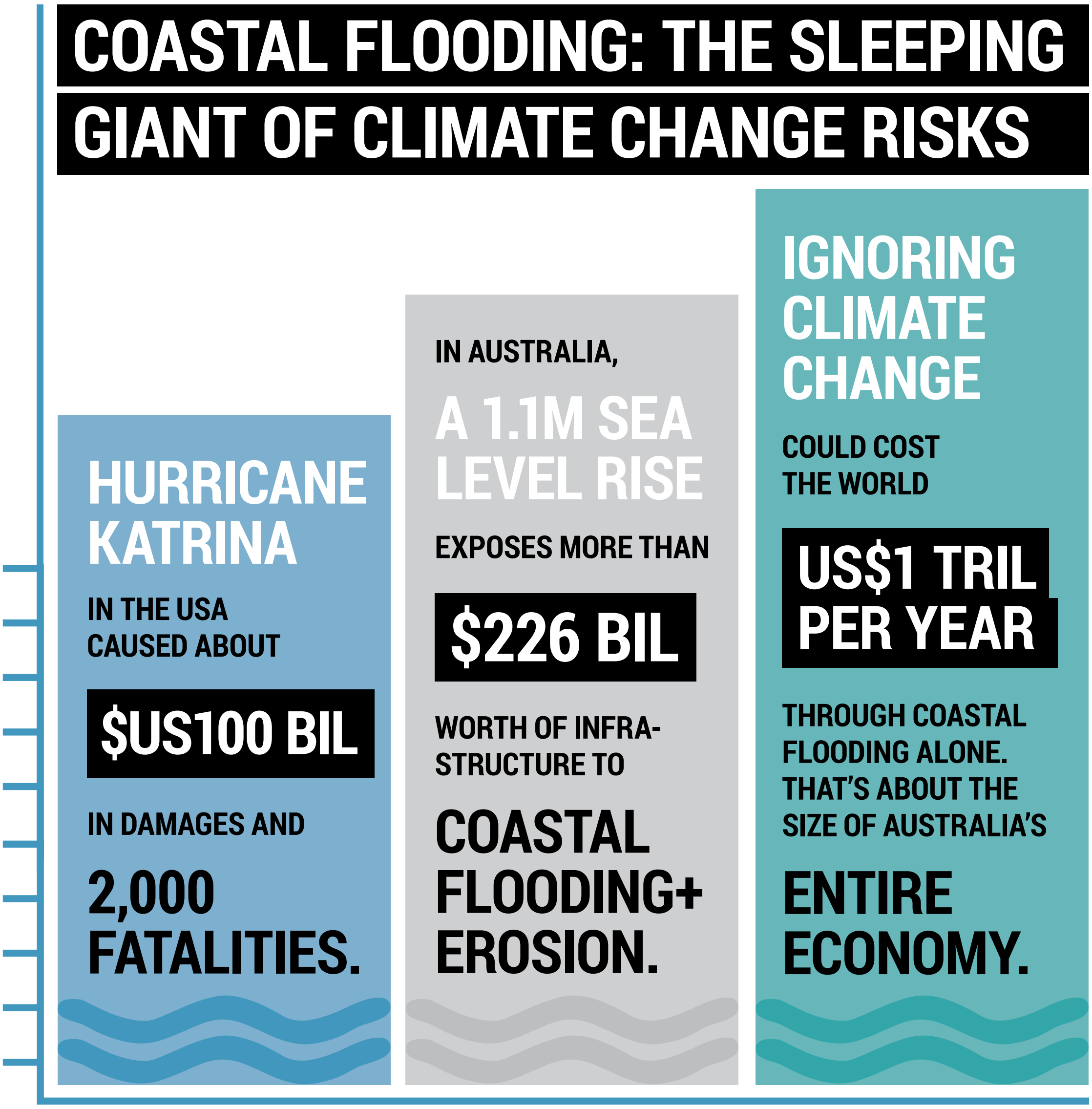
CSIRO (2014) assessed the future impacts of four hazards, including coastal inundation, on residential housing across Australia. Total damage from coastal inundation under what was termed "a medium climate outlook" over the period to 2100 in the absence of adaptation is expected to amount to a net present value of almost $6 billion, based on 2006$ using a 5.6% nominal discount rate.

Gosford NSW. A study focusing on future coastal flooding in Gosford shows the sharp increase in costs that can be expected from even modest increases in sea-level rise (Lin et al 2014). The study was based on projected infrastructure damages caused by seawater flooding to residential buildings and to sections of vulnerable roadways. As a baseline for the study, Lin et al. (2014) simulated a coastal flooding event in 2011 that would cause approximately $3 million in damages and affect about 200 dwellings. With an increase in sea level of 0.4 m, which is certainly possible this century (see Section 2), coastal flooding would damage about 680 dwellings at an anticipated cost of $13.5 million (adjusted to 2010$ values) (Lin et al. 2014).

Whilst the Gosford study focused on direct infrastructure damages, it also noted the significant impacts that more frequent and more severe flooding events could have on Gosford's ecological assets, such as it wetlands. Rising sea level is increasing the risk to the wetlands by contributing to the salinisation and destruction of key habitats on the Gosford peninsula (Lin at al. 2014). The Gosford area is representative of numerous low-lying coastal areas across Australia that are becoming increasingly urbanised and are thus at risk from rising sea levels (Lin et al. 2014).

Southeast Queensland. There are an estimated 35,200 residential buildings in Southeast Queensland (SEQ) currently exposed to a 1-in-100-year coastal flooding event; these buildings would will suffer damages of about $1.1 billion (2009 prices) from such an event (Wang et al. 2010). By 2030, with an additional 0.2 m rise in sea level (Figure 7)—and with the same planning and building regulations as today—the number of residential buildings at risk from a similar event is estimated to increase to about 61,500 and the costs to about $2 billion (based on 2009 value). By 2070, with a 0.5 m rise in sea level compared to 2000, a similar event will affect approximately 121,000 residential buildings with potential damages of about $3.9 billion (2009$) (Wang et al. 2010).

Figure 14: Coastal flooding: the sleeping giant of climate change risks



In Southeast Queensland the cost of coastal flooding could double by 2030 and quadruple by 2070.

Brisbane. A study in the inner city Brisbane area found that a significant property-price discounting of 5.5% occurs for each metre that the property lies below the defined flood level. After the 2011 floods, individual land valuations fell by as much as 20 percent. A 0.5 m rise in sea levels could affect the value of 5.1% of inner city properties, up from 3.6% of properties affected at today's sea level (Rambaldi et al. 2013). It should be noted that the discount/height relationship found in this paper is specific to the flood characteristics of the Brisbane floodplain, which is dominated by floods from the Brisbane River. Different relationships would apply in open coast situations.

At a national level, land value forms a substantial part of overall property value in coastal regions and whilst the buildings themselves may be insured, the land itself is not (SCCCWEA 2009). The Insurance Council of Australia has emphasized that damage caused by storm surge, landslip and sea-level rise is not insured and coastal inundation and erosion can leave landowners with significant losses (Sullivan 2009; SCCCWEA 2009).

3.3.2 Projected costs globally

The average global losses for the world's coastal cities due to floods is expected to rise to $US52 billion per year by 2050 from projected socio-economic change alone, that is, an increase in exposure (e.g., more infrastructure placed in vulnerable locations). But the more important factors are environmental. When land subsidence—a serious problem for some coastal cities—and sea-level rise are taken into account —and assuming that no adaptation measures are taken—the projected flood losses rise to a staggering $US1 trillion or more per year, about the size of the entire Australian economy (Hallegatte et al. 2013). These estimates are for direct costs only. The indirect costs may be even more substantial; these include economic impacts down supply chains, competition for capital in rebuilding after the flood, and the social costs of environmentally induced migration (see Section 3.4.3).

Without adaptation, global losses from coastal flooding could increase to $US1 trillion per year by 2050.

Hurricanes Katrina and Sandy are harbingers of things to come. In just over a decade, a double whammy of higher sea levels coupled with storm surges is likely to increase the average annual cost of coastal storms along the USA Eastern Seaboard and the Gulf of Mexico by $US2 billion to $US3.5 billion (Risky Business Project 2014). When potential increases in North Atlantic hurricane intensity are added to the mix (IPCC 2013), the likely increase in average annual losses increases to up to $US7.3 billion, bringing the total annual cost of hurricane and other coastal storm damage to $US35 billion (Risky Business Project 2014). With a 'business as usual' scenario, by 2050 between $US66 billion and $US106 billion of existing coastal property in the USA will likely be below mean sea level, with $US238 billion to $US507 billion worth of property below mean sea level by 2100 (Risky Business Project 2014).

Hurricanes Katrina and Sandy are harbingers of things to come.

The observed and projected damages from coastal flooding in the USA are large in absolute terms due to the very large amount of valuable infrastructure located in vulnerable areas. Although projected damages from coastal flooding in smaller countries are much smaller in absolute terms, they are nonetheless important in terms of proportional effects on the economies of these countries (Box 5).

At the global level damage from coastal flooding is expected to grow considerably throughout this century as sea levels rise and socioeconomic development increases the number of people and value of the built environment in areas vulnerable to flooding. Applying national population and GDP growth rates, and without including adaptation, 0.2–4.6% of the global population (1,400,000–32,200,000 people) is expected to be flooded annually in 2100 with a rise in global-average sea level of 0.25–1.2 m, with expected annual losses of 0.3–9.3% of global GDP (Hinkel et al. 2014). The upper limit of this range—over 9% loss GDP annually—is much larger than the annual average growth rate in global GDP. In effect, this is a scenario for a climate change-driven global economic collapse.

3.4 Other impacts of coastal flooding

3.4.1 Species and natural ecosystems

Coastal ecosystems in many parts of Australia are already under serious pressure from development. Rising sea levels and the resultant increase in flooding frequency are exacerbating these pressures. Many ecosystems are trapped in a 'coastal squeeze' between rising sea levels and fixed landward barriers such as seawalls, and urban development. This squeeze will continue to threaten the range of benefits that these ecosystems provide, and the species they support.

BOX 5: INTERNATIONAL ASSESSMENTS OF THE ECONOMIC RISKS OF COASTAL FLOODING

Cost estimates are difficult to compare across studies because of a diverse range of scenarios employed, impacts and adaptation options considered, methodologies applied and baseline conditions assumed. Despite the large diversity across studies, there is strong agreement that it makes economic sense to protect large parts of the world's coastline during the 21st century against increased coastal flood damage and land loss (see, for example, Nicholls and Tol 2006; Anthoff et al. 2010; Hinkel et al. 2013).

Some developing countries and Small Island States are especially vulnerable economically. The cost of a 1 m rise in global-average sea level is estimated to be more than 1% of national GDP for Micronesia, Palau, the Bahamas and Mozambique (Anthoff et al. 2010). For coastal flooding, annual damage and protection costs are projected to amount to several percentages of the national GDP for countries such as Kiribati, the Solomon Islands, Vanuatu and Tuvalu under sea-level rise projections of 0.6–1.3 m by 2100 (Hinkel et al. 2013). In some countries, particularly developing countries, coastal defences are not fully effective for the current flooding risk, resulting in an 'adaptation deficit'. The costs of eliminating this deficit could be very high. For example, the capital cost of building dykes to adapt to the current flooding regime in Africa was estimated in 2011 to cost $US300 billion per year with $US3 billion per year required for maintenance (Hinkel et al. 2011).

Ironically some types of adaptation (see next section) could actually increase vulnerability to very large coastal flooding events, with dramatic increases in damages when these floods occur. For example, in the IPCC Fifth Assessment Report (AR5) Wong et al. (2014) described how increasing coastal flooding protection could attract even more people and development to the flood-prone areas on the assumption that the protection measures have decreased vulnerability. However, if coastal defences were breached, the consequences would be catastrophic for coastal communities (Gibbs 2013). The risk of failure of defence structures and consequent catastrophic flooding increases with rising sea level (Hinkel et al. 2013). London, Tokyo, Shanghai, Hamburg and Rotterdam are good examples of this phenomenon (Nicholls et al. 2007).

3.4.1.1 Coral reefs

Coral reefs are under multiple threats from climate change, especially from rising sea temperatures that cause bleaching, from increased ocean acidification, and from increased intensity of tropical cyclones. But rising sea levels also have profound implications for the structure and composition of coral reef communities – favouring some faster growing species over those that grow more slowly. There is evidence that corals have had difficulty keeping up with some periods of rapid sea level rise in the past, leading to "drowning" of reefs (Hoegh-Guldberg, 2011; Woodroffe and Webster, 2014).

3.4.1.2 Estuaries

Estuaries provide the critical link between freshwater and saltwater habitats, and are among the most degraded habitats on Earth (Koehn et al. 2011). These habitats are highly productive and provide breeding grounds for many commercially important fish and shellfish species, as well as crocodiles in northern regions (Fuentes et al. 2012). Sea-level rise is increasing the salinity of groundwater and pushing salty water further upstream, affecting species of salt-sensitive plants and animals both in the estuaries themselves, and in adjacent aquifers (Werner and Lockington, 2006).

3.4.1.3 Seagrass meadows

Seagrasses are marine flowering plants that grow in shallow, sheltered sandy areas around coasts and provide food, shelter and nursery grounds for many species of fish, invertebrates, turtles and dugongs (Figure 15) and help stabilise marine sediments, protect shorelines, and filter and oxygenate the water column (Saunders et al. 2013). Globally, the role of seagrasses in nutrient cycling has been estimated to be worth US$1.9 trillion per year (Waycott et al. 2009). The sediments beneath seagrasses also store more carbon ("blue carbon") than any other ecosystem on Earth (McLeod et al. 2011).

Australia has some of the most extensive and diverse seagrass communities in the world. On the Great Barrier Reef, for example, seagrasses cover more than twice the area of corals (Dennison 2009). Sea grass beds in southeastern Australia contain more than a third of all seagrass species known worldwide (Carruthers et al. 2007).

Figure 15: Seagrasses, threatened by rising sea levels, are relied upon by dugongs for food, shelter and nursery grounds.

Seagrass habitats are threatened worldwide from coastal development, dredging, nutrient input and sedimentation (Hughes et al. 2009; Sheaves et al. 2014). Indeed it has been estimated that seagrass globally is being lost at a rate of 7% per year since the 1990s, compared to 0.9% before 1940 (Waycott et al. 2009). In Australia, the total area of seagrass beds is estimated to have declined by 450 km^2 just in the single decade from 1986–1996, mostly in tropical regions as a result of cyclone damage (Kirkman 1997). Following Cyclone Yasi in November 2011, all three species of seagrasses in Cairns Harbour completely disappeared, having been at stable levels for at least six decades (Pollard and Greenway 2013).

Rising sea levels pose a new threat because, as water depths increase, light availability for seagrass photosynthesis will decline in current locations. In some areas, seagrasses will be able to adapt by colonising new, landward, habitats. In other locations, increased sedimentation (accretion) may be sufficient to maintain plants at an appropriate depth (Waycott et al. 2009). If neither of these processes occur at a sufficient rate, continued loss of seagrass habitats is inevitable. For example, seagrass extent in Moreton Bay, QLD, has been projected to decline by 17% by 2100 with a sea level rise of 1.1 m, if no concurrent improvements to water quality occur (Saunders et al. 2013). Seagrass decline will have significant impacts on fisheries. The economic contribution of seagrass to the fisheries in the gulf waters of South Australia, for example, has been estimated to contribute around $114 million per annum (McArthur and Boland 2006).

3.4.1.4 Mangroves and saltmarshes

Like seagrasses, *mangroves and saltmarshes* provide extremely important habitat for many marine species, as well as other ecosystem services such as coastal protection, sediment trapping and carbon storage (Figure 16; Barbier et al. 2011; McLeod et al. 2011), (Saintilan and Rogers 2013). Mangroves and saltmarshes intercept nitrogen-rich runoff from the land, protecting coastal habitats from excessive nutrient input that can lead to stimulation of harmful algal blooms (Valiela et al. 2009). In some regions, saltwater inundation due to rising sea levels is leading to landward encroachment of mangroves, sometimes at the expense of freshwater habitats (e.g. Mulrennan and Woodroffe 1998; Williamson et al. 2011) or saltmarsh (Rogers et al. 2013; Saintilan and Rogers 2013). In some areas, this encroachment is being enhanced by the sediment from land-clearing washing into waterways. Increasing atmospheric CO_2 may also lead to greater productivity in these habitats (Lovelock et al. 2012). However, the coastal squeeze is also affecting mangroves in many parts of the Australian coastline, inhibiting the ability of mangroves to adapt as sea levels rise.

Any overall loss of mangrove extent will have significant impacts on the viability of commercially important fisheries. Catches of barramundi, banana prawns and mud crabs, all of which use mangroves as nursery habitat, are significantly correlated with the local extent of mangroves along the QLD coast (Manson et al. 2005).

Figure 16: Mangroves in some regions may be subject to "coastal squeeze"—caught between rising sea levels and coastal development. In other regions, mangroves are moving landward at the expense of saltmarsh and freshwater wetlands.

3.4.1.5 Sandy beaches

Sandy beaches, which provide nesting habitat for species such as seabirds and turtles are threatened directly by sea level rise as well as increased damage from storm surges (Fuentes et al. 2010; Chambers et al. 2012).

Marine turtles face multiple threats from climate change, especially from the impacts of rising temperatures on the ratio between males and females, and development of hatchlings. Inundation of beaches from rising sea levels and flooding where turtles nest will also reduce breeding success (Fuentes et al. 2010); many nesting beaches will eventually be lost entirely. Up to 38% of key green turtle nesting areas in the northern Great Barrier Reef are projected to be inundated with a sea level rise of ~80 cm by 2100 (Fuentes et al., 2010); under storm events this threat is substantially increased with up to 75% of nesting areas affected.

Up to 38% of key green turtle nesting areas in the northern Great Barrier Reef could be inundated by 2100.

Turtles and their nest sites are also vulnerable to increases in either the intensity or frequency of extreme events such as storm surges and tropical cyclones (Fuentes and Abbs 2010). A dramatic increase in the number of dead green turtles on northern Queensland beaches was reported in late 2011 following Cyclone Yasi, one of the most powerful tropical cyclones to have crossed the Great Barrier Reef and the coast of Queensland—1275 deaths reported at this time compared to 754 for the same period in the previous year (GBRMPA 2012). Many of the turtles appeared malnourished, likely due to the destruction of coastal seagrass by the extreme weather.

3.4.1.6 Coastal freshwater wetlands

Saltwater intrusion from rising sea levels, in combination with other human impacts, is already having significant impacts on coastal freshwater ecosystems in some regions. Kakadu National Park, a UNESCO World Heritage Area, was identified in the IPCC's Fourth Assessment Report as being particularly vulnerable to this impact (Hennessy et al. 2007). The coastal wetlands of Kakadu have high conservation significance and are used by traditional Aboriginal owners, as well as for tourism (see Section 3.4.2) and recreational boating and fishing. Much of the Kakadu floodplain has very low relief—falling only 0.5 m over more than 70 km (Finlayson et al. 2009). This means that only small increases in sea level can potentially have very large impacts. Indeed, in the East Alligator River region, intrusion of salt water several kilometers along tidal creeks has occurred over the past few decades, resulting in a nine-fold increase in the area of saline mudflats and more than 60% loss of *Melaleuca*-dominated freshwater swamp vegetation (Winn et al. 2006). These impacts have likely occurred due to a complex of interacting factors, including sea-level rise and past damage by feral buffalo (Bowman et al. 2010). Similar losses of freshwater habitats have been documented in other rivers in the region, including the Wildman, South Alligator and Mary Rivers (Catford et al. 2013, Mulrennan and Woodroffe 1998).

Loss of freshwater habitats in locations such as Kakadu can have serious flow-on impacts to the animals that use the swamps as habitat. Magpie geese, with an estimated population of 2–3 million in the Northern Territory, rely on these swamps for nesting and feeding. A 5% loss of wetland area could reduce the population of these birds to just a few thousand (Catford et al. 2013, Traill et al. 2010). Transformation of the Kakadu floodplains to saline habitats will also have dramatic negative effects on other waterbirds, crocodiles, mammals that use the areas in the dry season, and fish species such as barramundi that use the habitats during part of their life cycles (BMT WBM 2011; Catford et al. 2013).

Saline flooding is not only a risk for northern Australia. Modelling of sea-level rise in the Hunter region of NSW, for example, indicates that by 2100, saline flooding in the Hunter River estuary could wipe out virtually all of the Hunter Wetlands National Park, an important habitat for migratory birds (Rogers et al. 2014).

3.4.2 Coastal tourism

Tourism is one of Australia's most important industries, contributing $42.3 billion to GDP in 2013 and employing over 900,000 people, directly or indirectly (8% of total employment) (Tourism Research Australia 2014). A substantial proportion of tourism revenue can be attributed directly to marine biodiversity and resources ($5.1 billion annually and 54,000 jobs in the Great Barrier Reef catchment alone) (Mapstone et al. 2010). Sixty-two percent of international visitors visit beaches at some time in their stay (Amelung and Nicholls, 2014) and surveys on the Gold Coast found that 74% of visitors identified beach-going as the top activity (Tourism Research Australia 2013).

Marine tourism is extremely vulnerable to the impacts of climate change because of its strong dependence on environmental aesthetics and favourable weather (Pham et al. 2010; Ruhanen and Shakeela 2013). Changes in the quality of marine and coastal ecosystems, especially coral reefs and beaches, will have important flow-on impacts not only to the local region, but also to the Australian economy in general. Increases in extreme weather will also affect the access, cost, and/or both real and perceived safety of some tourist activities and destinations (Mapstone et al. 2010). Any climate change-associated decline in recreational fishing will also have impacts in some coastal regions.

Cities such as the Gold Coast may be particularly vulnerable (Figure 17). The city hosts over 11 million visitors per year (Business Gold Coast 2011). The beach is central to the city's appeal as a tourism destination and maintenance of the beach resource is central to the city's future. As sea levels rise, there is no opportunity for the beach to move landwards due to the adjacent high-rise development. This means that maintenance of the beach in the future will require sand to be brought from external sources. At current prices, this equates to an expenditure (of sand alone, without any additional infrastructure) of $11–54 million per year over the next century, depending on sea level scenario used (Cooper and Lemckert, 2012). Beaches in the region are also vulnerable to increased damage from extreme events (Castelle et al. 2008).

Sea-level rise and associated coastal flooding (as outlined in section 3.4.1.6) also has serious implications for habitats in Kakadu National Park, the most important natural, cultural, recreational and tourist resource in the coastal region of the Northern Territory (Finlayson et al. 2009). Kakadu attracts more than 160,000 visitors per year, and was conservatively estimated in 2007 to bring in more than $15 million per year to the Top End economy (Tremblay 2007). Visitor surveys consistently rate "wildlife viewing" as the main reason for visiting the region.

3.4.3 Environmentally Induced Migration

Some of the impacts of climate change on Australian society may be felt indirectly, via impacts in other countries. The IPCC has recently concluded that, given evidence of major extreme weather events leading to significant population displacement in the past, and projected changes in the incidence of extreme events in the future, climate

Figure 17: Coastal erosion on the Gold Coast

change seems likely to amplify the risks of population displacement, and that "models, scenarios, and observations suggest that coastal inundation can lead to migration and resettlement" (Adger et al. 2014).

Projections of global, climate change-induced movement of people in coming decades vary from tens of millions to as much as 250 million (Myers 2002; McMichael et al. 2012). A world that has warmed 4°C above pre-industrial levels (by 2100 or later), producing a 0.5–2 m sea level rise, has the estimated potential to displace 1.2 and 2.2 million people from the Caribbean, Indian Ocean and Pacific Ocean, assuming no adaptation (Nicholls et al. 2011). While the empirical basis of such estimates has been questioned (Barnett and O'Neill 2012), considerable displacement of people as a result of future environmental changes and extreme climate events seems likely.

In some parts of the tropical western Pacific rates of sea-level rise of up to four times the global average (approximately 12 mm yr -1) have been reported between 1993 and 2009 (Cazenave and Remy 2011). These are generally thought to be associated with natural cyclic climate phenomena such as ENSO (El Niño-Southern Oscillation), which may cause changes in sea level of about ±20–30 cm (White et al. 2014). Most of the critical infrastructure, agricultural production, and human settlements on small islands in the western Pacific is on the coast and so is exposed to extreme tides, storm surge events, inundation due to swell waves (Hoeke et al, 2013) and sea-level rise (see also Box 6 on Torres Strait Islands). These impacts raise the prospect of the need for relocation of some Pacific Island communities in the future. Thus far, however, there appear to be no formal government policies that allow for climate 'refugees' from islands to be accepted into another country (Bedford and Bedford, 2010) and there are considerable financial and legal barriers expected to inhibit such policies (Barnett and Chamberlain 2010).

The decision to migrate is a complex one, whether at the level of individuals or a community and there is rarely a single cause (Nurse et al. 2014). Some social science researchers warn of the dangers of forced relocation, and of social, economic and health problems associated with resettlement away from traditional homelands, cautioning that such strategies should be an option of last resort (Barnett and O'Neill 2012).

BOX 6: VULNERABILITY OF TORRES STRAIT ISLAND COMMUNITIES

The Torres Strait is a broad stretch of shallow water between the tip of Cape York and the southwestern coast of Papua New Guinea. The region includes over 100 islands, cays, coral reefs and sand banks and is home to 18 communities with a total population of around 8,700. More than 80% of inhabitants are Torres Strait Islander and Aboriginal people.

The Torres Strait communities have very strong cultural, economic, social and spiritual connections with their country, and are governed by their distinct Ailan Kastom (Island custom). The region is also known for the diversity of its marine ecosystems, providing habitats for many endangered species such as turtles and dugongs.

Many of the Torres Strait Island communities are extremely low-lying and are thus among the most vulnerable in Australia to the impacts of climate change. The shallowness of the Strait exacerbates storm surges and when such surges coincide with very high tides, extreme sea levels result. Sea level data collected by satellite from one location in the Torres Strait for the period 1993–2010 shows a rise of 6 mm p.a., more than twice the global average—although it should be acknowledged that this is a single, relatively short dataset and that the signal is strongly influenced by the ENSO cycle (see Section 2.1; White et al. 2014).

Even modest sea level rises in the future will threaten the Torres Strait communities because many are situated very close to high tide level and some are already experiencing inundation during annual high tides. Inundation affects houses, roads, water supply, power stations, sewage and stormwater systems, cultural sites, cemeteries, gardens, community facilities and ecosystems, and are often accompanied by severe erosion. By affecting the infrastructure of the communities and surrounding environment, climate change threatens the lives, livelihoods, and unique culture of the islanders.

The islands of Boigu and Saibai are especially at risk, as well as the central coral cay islands and several other communities located on low coastal flats. Dengue fever and malaria are already concerns on many of the islands, and the mosquito vectors of these diseases breed in brackish pools on islands such as Saibai. Increases in extreme weather, in combination with the prevalence of water tanks near houses, could increase the risks of infection if adequate preventative measures are not taken.

Adaptation options for the communities include seawalls and levees, relocating and raising houses and other facilities, managing dunes and associated vegetation, building desalination plants, and beach nourishment. However, there are limits to adaptation in these islands because of limited land area, or by the lack of high land, such as on Saibai and Boigu. In the long-term, the worst-case scenario is that several communities will face relocation, which would be associated with significant cultural, spiritual and economic costs.

Figure 18: Seawater overflowing a protective wall on Sabai, Torres Strait Islands.

Source: David Hanslow, TSRA

Main sources: TSRA 2008; Green et al 2010; Suppiah et al 2010; TSRA 2010; McNamara et al 2012; Preston-Thomas et al 2012.

4.
HOW CAN WE DEAL WITH THE RISKS?

4.1 The nature of the challenge

Some of the projected increases in economic damage caused by coastal flooding—for example, losses of $US1 trillion per year by 2050 (Hallegatte et al. 2013) or a loss of over 9% in global annual GDP by 2100 (Hinkel et al. 2014) are extremely large. Yet, even though these projections are based on rates of sea-level rise that are entirely plausible—even likely—for the remainder of this century (the lifetime of infrastructure being designed and built now), action on climate change is too little and too slow compared to the risks that climate change poses for our future well-being. So why is there not more concern over the risks of sea-level rise?

One problem is the mismatch between the time horizons of much present-day economic analyses and planning, and those of the climate system. There are two fundamental aspects of this mismatch. The first is the perception that the present rate of sea-level rise, about 3 mm yr-1, is too slow to matter. This is a very short-term view. The huge thermal inertia of the oceans and the increasing loss of ice from the polar ice sheets means that not only are we committed to significant sea-level rise this century, sea levels will continue rising for many centuries (Figure 7; Section 2.2). Although we can slow the rate of sea-level rise through rapid and deep cuts in greenhouse gas emissions, we have absolutely no choice but to deal with the risks of rising seas for generations into the future.

Second, many people conceive of sea-level rise like a very slow filling of a bathtub, in which the impact is one of an imperceptibly slow intrusion of water across low-lying land, so slow that we can readily adapt at the time. However, like many aspects of climate change, the far more important impacts are felt through extreme events. As described in Section 2.3, one of the most damaging impacts will be from extreme coastal flooding events; with a sea-level rise of 0.5 m, coastal flooding events are likely to occur *hundreds of times* more frequently.

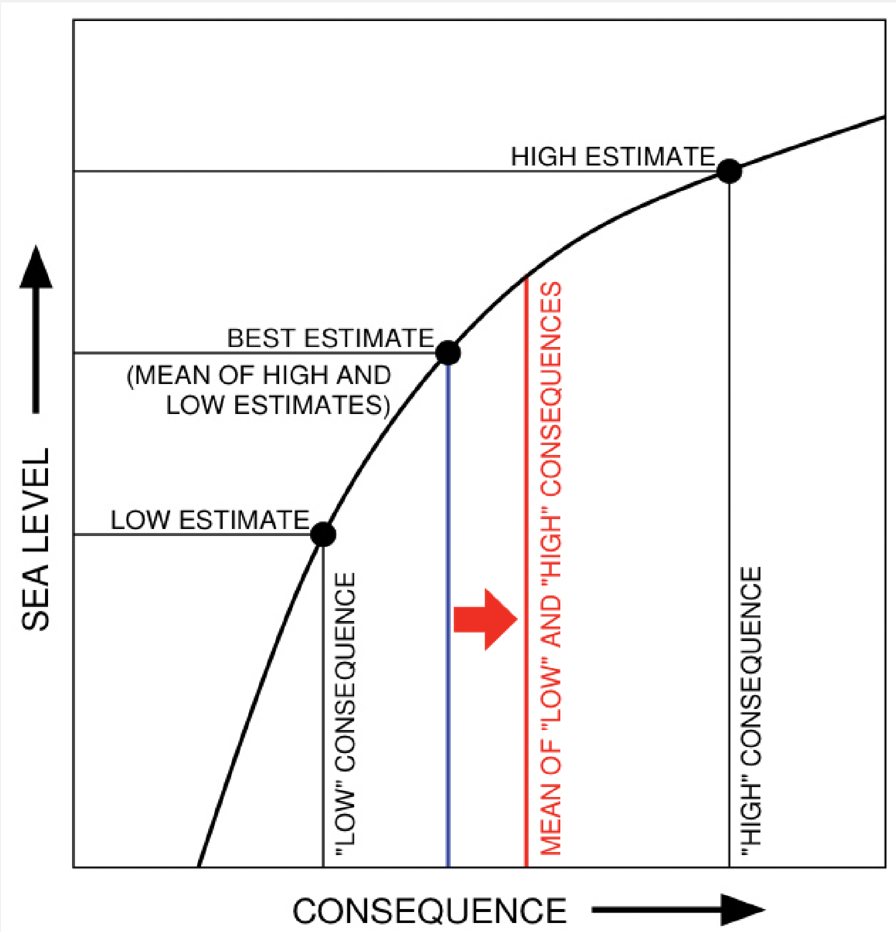
With a sea-level rise of 0.5 m, coastal flooding events are likely to occur *hundreds of times* more frequently

Studies in a number of states across Australia, despite variations in methodologies, all indicate that the projected increase in coastal flooding will come at great economic cost (Section 3). Furthermore, the economic costs will rise more sharply than the change in sea-level itself (Lewandowsky et al. 2014; Box 7).

BOX 7: THE RAPIDLY RISING CONSEQUENCES OF SEA-LEVEL RISE

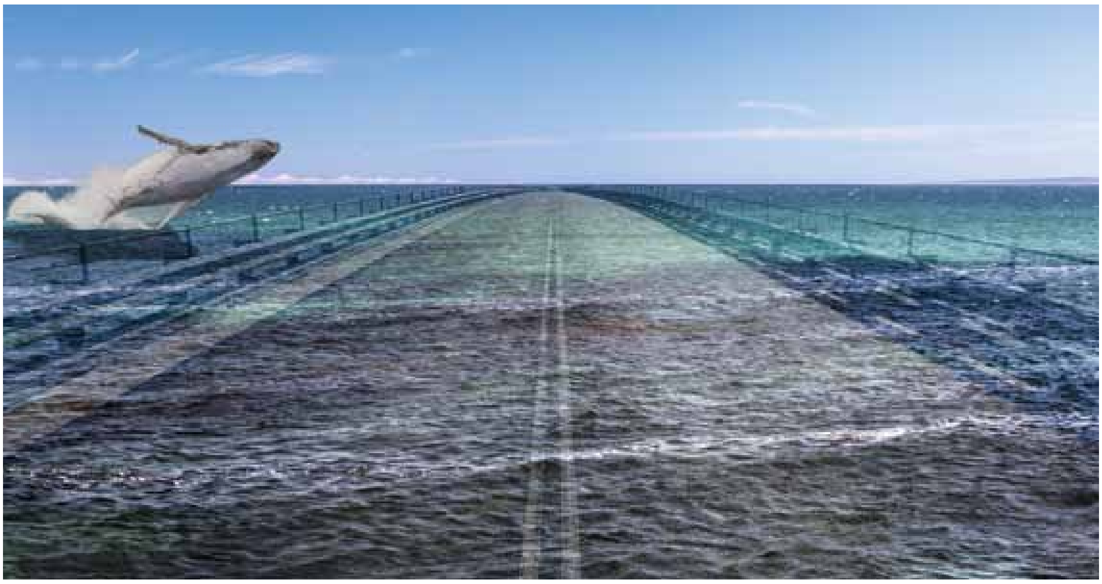
There is not a simple, proportional relationship between the amount of sea-level rise and the consequences associated with it (Lewandowsky et al. 2014). That is, every 10 cm rise in sea level does not increase the consequences of coastal flooding by the same amount, as shown in Figure 19. For example, the increase in consequences for a future 70 cm sea-level rise compared to 50 cm is much larger than the decrease in consequences for a 30 cm sea-level rise compared to 50 cm. Therefore, taking a best estimate or average projected sea-level rise is not a wise way to assess the economic risks from higher sea levels. A more appropriate way would be to take the average of the consequences for the high and low estimates of sea-level rise, which would give a value higher than the consequence for the average value of sea-level rise.

Figure 19: Curvature in the shape of the potential consequence associated with rising sea level.



Finally, it is very difficult for people to imagine what the future might hold for their children and grandchildren as the sea level slowly but inexorably rises as a result of the warming of the planet. Visual artists can bring possible futures to life in a way that the models, projections, facts and figures of natural scientists can't. Figure 20 shows two examples of photographic artworks from an exhibition shown at southeast Australian coastal communities as part of a research project aimed at helping the communities to understand the implications of rising sea levels and to deal effectively with them (Norman et al. 2014).

Figure 20: Visual artists depict the impact of rising sea levels.



John Boyd MacDonald *Humpback flight.* 2013.

Heike Qualitz *Contemplating adaptation.* 2013.

This section focuses on (i) why ignoring the problem of sea-level rise is not an appropriate approach; (ii) the urgent need to stabilise the climate system to prevent unacceptable—and unmanageable—risks of coastal flooding in the future, and (iii) what we can do to cope with the sea-level rise that we can't avoid.

4.2 Do nothing: The head-in-the-sand approach

The risks of sea-level rise highlight the dangers inherent in the denial of the science of climate change, in taking a wait-and-see attitude, or in responding in an uncoordinated or ineffectual way. In fact, doing nothing is itself a conscious choice. By doing nothing, we are in effect becoming increasingly ill-prepared for the coastal flooding that is already happening, and we will continue to make poor planning and investment decisions for the infrastructure of the future. Doing nothing has serious implications for emergency management authorities, who have to deal with the increasing occurrence of coastal flooding, and for the economic well-being of communities, states and the country. We'll be increasingly left with damaged, stranded and unusable infrastructure as it is abandoned before the end of its useful economic life.

Responsibility for coastal management in Australia is shared between federal, state and local governments, and this means that a coordinated approach to the risks of sea-level rise, built on a sound base of scientific understanding, will be the most effective way forward. Lack of agreement across governmental levels on the scientific knowledge base, on the seriousness of the risks, or on the need for a common approach can lead to inaction, conflict or maladaptation, leaving coastal communities at higher risk from the inevitable increase in coastal flooding events. Lack of a common approach can also lead to significant decreases in business efficiency, given the difficulty of assessing the risk of investment in different local government areas if they all use different risk assessment criteria and methods.

The most effective way to deal with sea-level rise is a coordinated approach from all levels of government based on science.

All of Australia's states have, at one time, acknowledged the reality of a rising sea level and the need to plan for it. As a result, all have instituted planning allowances for sea-level rise until around the end of this century (e.g., a high end scenario for 2100, see Figure 7), with allowances in the range 0.8–1.0 m. Such allowances provide guidance to communities, local governments, businesses and industries as they plan their infrastructure for the future. At present mandatory state planning allowances for 2100 are in place in Victoria, South Australia and Western Australia, with local governments having responsibility as to how the allowances should be implemented.

In NSW and Queensland the allowances have been revoked or suspended, with local authorities now having broad discretion for coastal planning (Reisinger et al 2014). Tasmania has developed recommended, but not mandated, planning allowances for 2050 and 2100 (Tasmanian Climate Change Office 2012).

Failing to deal effectively with sea-level rise means greater risks for communities.

Approaches to coastal planning across the country remain highly variable and inconsistent (Good 2011; Gibbs and Hill 2012). Some policies focus on managing climate change risks to new development but provide little guidance on how to manage risks to existing settlements (Gibbs and Hill 2012). Planning for emergency management requirements in light of climate change risks is generally focused on responding to storms, floods and other events rather than on the longer term planning impacts of climate change (Gibbs and Hill 2012).

Many local governments lack the resources for detailed coastal mapping and hazard assessment, and coastal policies in many regions are highly contested (Gorddard et al. 2012). Some councils have applied coastal set backs to limit development in high risk areas and some have attempted to implement specific policies of coastal retreat. These policies have the potential for litigation (see Box 8), to conflict with different policies at state government level, and to lead to ad hoc, individual measures that are likely to be maladaptive. Results of litigation have varied and, in the absence of clearer legislative guidance, more litigation is expected as rising sea levels affect existing properties and adaptation responses constrain development on coastal land (Verschuuren and McDonald 2012).

Local governments have often called for clear policy direction from state/territory governments and for financial resources to assess risks and implement coastal adaptation initiatives. Many have argued for a coordinated national approach with clear allocation of responsibilities, agreed allowances across jurisdictions (Figure 9(c) provides an illustration of a consistent set of Australian allowances), and policy integration across sectors and scales to reduce (i) the risks of conflict between different levels of government, (ii) litigation where private and public interests collide, and (iii) the possibility of maladaptation (Barnett and O'Neill 2010; Good 2011; Gibbs and Hill 2012; Serrao-Neumann et al. 2013).

At present, however, there are no standardised national guidelines for planning for the impacts of climate change in coastal areas across Australia, with most state and the Northern Territory governments operating independently and, as a result, inconsistently (NCCOE 2012a). The National Committee on Coastal and Ocean Engineering have sought to address this, with the development of three guidelines designed to assist coastal engineers, managers and planners in developing adaptation responses at the local and state government level (NCCOE 2012a; 2012b; 2012c).

BOX 8: GRAPPLING WITH THE CONSEQUENCES OF COASTAL EROSION: THE CASE OF OLD BAR NSW

Jan McDonald, University of Tasmania

The town of Old Bar on the NSW mid-coast has a long history of coastal erosion and associated concern about the impacts on coastal properties. One-in-50-year and 1-in-100-year coastal impact lines were introduced in the 1980s and 1990s to restrict new development. Development intensified landward of the 1-in-100-year line, but many of these properties are now at risk because of a significant increase in erosion intensity. A major tourist resort, 35 homes, the surf club and significant public infrastructure were identified as being within the 1-in-5-year impact line.

A local coastal hazard study for Old Bar Beach prepared in 2008 concluded that the earlier hazard lines had underestimated erosion risks and a coastline management study identified a range of management options. These included planned (staged) and immediate retreat, as well as a range of hard protections in combination with soft protective works such as beach nourishment. The high cost of defensive structures and concern about impacts on beach access caused Greater Taree Council to adopt a 'planned retreat' policy for vulnerable coastal areas in 2010.

This policy required at-risk properties to be removed or demolished and only permitted new development on condition that it be removed when the erosion line reached a prescribed point. The owners of threatened properties at Old Bar continued to exert considerable pressure on Council to construct a permanent defensive structure. The tourist resort constructed a temporary geotextile wall in front of its property, but the NSW Coastal Panel rejected its application to build a more permanent structure citing its potential impacts on public access and amenity.

The Coastal Panel's decision and on-going beach erosion led to declines in property values and intensified outcry from property owners. Meanwhile, a change in state government in 2011 led to shifts in coastal policy that allowed for greater protection of private properties against coastal hazards. In response to growing property-owner opposition and the change in state policy, GTCC reversed its planned retreat policy and has now included plans for a permanent rock revetment for Old Bar in its Draft Coastal Zone Management Plan. This outcome highlights the inevitability of tradeoffs between private property vs public interests and that conflicts over coastal planning can lead to sub-optimal outcomes when considered long-term. It emphasizes the urgent need for clear guidance from state and federal government about the prioritisation and valuing of short- and long-term public interest values.

Main source: Foerster A, Macintosh A and McDonald J (2014)

4.3 Stabilise the climate system: Reducing greenhouse gas emissions

Doing nothing, or taking piece-meal, uncoordinated actions, are not appropriate options to deal with the risks of sea-level rise and coastal flooding. To lower the risks in the longer term, there is no alternative but to stabilise the climate system as soon as possible. Although there is a large degree of inertia in several of the factors that drive sea-level rise, the actions we take now can significantly reduce the level of risk that we face from coastal flooding in the second half of the century and beyond.

As Figure 7 shows, by 2100 the central estimate of sea-level rise for the BAU pathway on which we are currently tracking is approximately 20 cm higher than that for the weak mitigation pathway. A difference of 20 cm will have a significant influence on the frequency of coastal flooding, as described in Section 2.3.

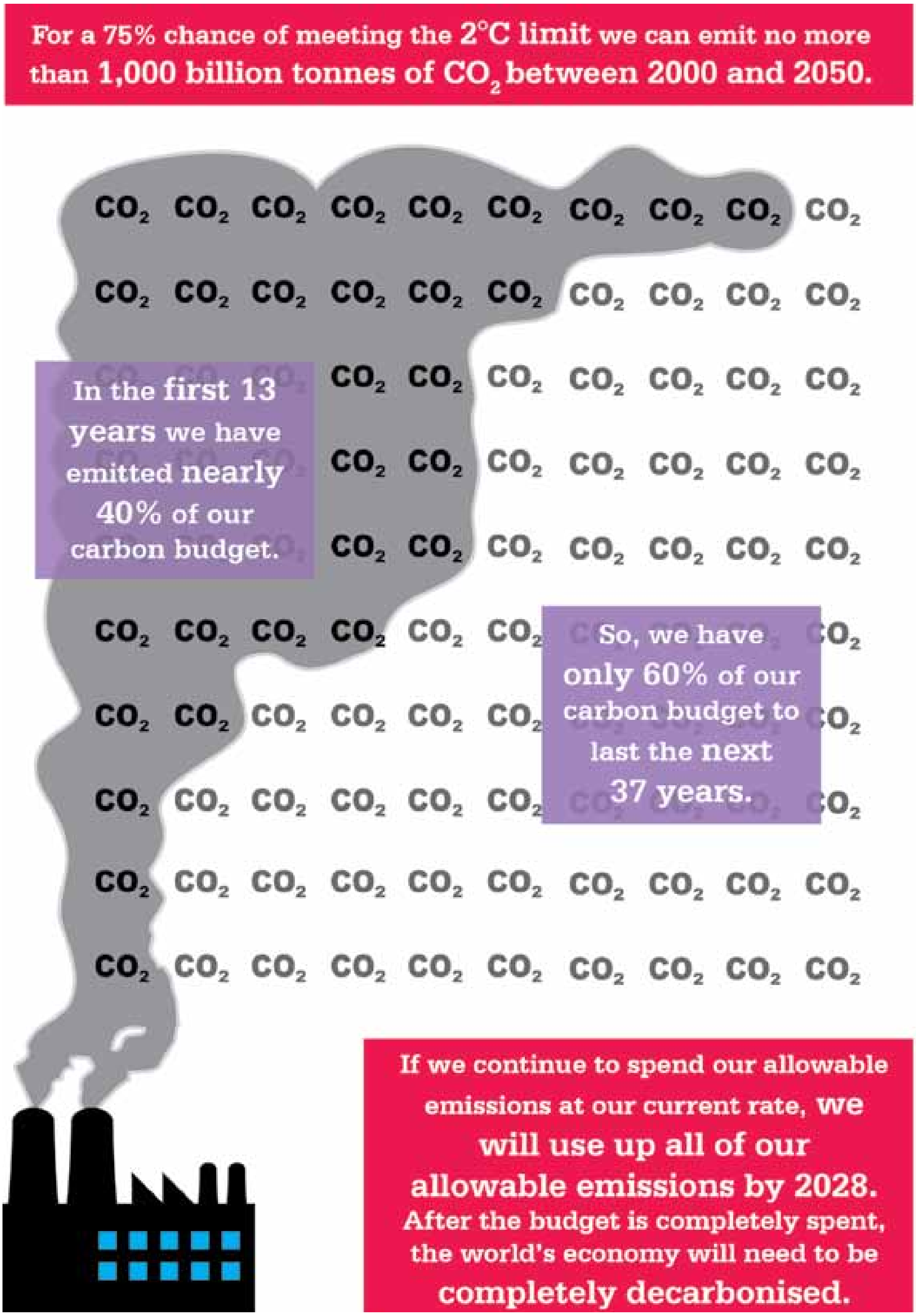
The gap between scenarios widens further after 2100, which means that the actions that we take (or don't take) now will have a very large effect on the severity of the sea-level rise challenge that future generations will face. It could make the difference between a level of coastal flooding they might be able to cope with and one that could overwhelm them.

To stabilise the climate system this century at a temperature rise of no more than 2°C above the pre-industrial level, which would put the sea-level rise trajectory at the lower end of the ranges shown in Figure 7, requires urgent, rapid and deep cuts in greenhouse gas emissions, particularly CO_2 emissions. The carbon budget approach provides the clearest framework for understanding the nature and magnitude of this challenge (Meinshausen et al. 2009; IPCC 2013).

The carbon budget is the maximum amount of CO_2 that can be emitted to the atmosphere by human activities to meet the 2°C target. The budget approach accommodates a risk management framework. The more stringent the budget, the greater the chance we'll meet the 2°C target, and *vice versa*.

To have a good chance—two-thirds or greater—of stabilising the climate at the 2°C target, we have a total budget of 1000 billion tonnes of carbon emissions from all human sources since the beginning of the Industrial Revolution in the late 1700s. By 2011, we had consumed half of the budget and the rate of emissions is rising, meaning that we are consuming the remaining budget at an ever-increasing rate (Figure 21).

Figure 21: Overspend in the carbon budget. Each CO_2 symbol represents 10 billion tonnes of CO_2 (Climate Commission 2013b).



The implication of the budget approach is clear. The recent flurry of activity in finding and developing non-conventional fossil fuel energy sources is a futile exercise if we want to stabilise the climate system (Carbon Tracker and Grantham Institute 2013). About 80% of the fossil fuel reserves will have to stay in the ground and cannot be burnt.

If we are to have any chance at all of meeting the carbon budget, stabilising the climate system, and reducing the risk to future generations of coastal flooding, this is the critical decade for action. Not only will Australia's and global carbon emissions need to be headed strongly downward by 2020, but the investment decisions we make over the coming years will have a profound impact on our capability to drive global emissions down to very low levels by mid-century.

4.4 Be prepared: Adapting to the sea-level rise we can't avoid

Adaptation responses to rising sea levels include a number of options, such as 'protection' which can involve the development of infrastructure such as sea walls or flood gates, 'accommodation' which includes actions such as developing pumps and raising footpaths, and 'retreat' which involves the relocation of residents from areas that are likely to become inundated (Fletcher et al. 2013). However, deciding which approach to take and when to implement it, as well as gaining community support for any actions, can be a challenging process. Furthermore, adaptation responses may only provide protection for a limited amount of time. Ultimately, as the impacts of climate change intensify, areas of land may eventually have to be abandoned (NCCOE 2012a).

A complex array of social factors influence how communities decide on which actions to take in response to an increase in coastal flooding (Gorddard et al. 2012; Abel et al. 2011; Barnett et al. 2013). Integrating these factors and the scientific knowledge base is perhaps most effectively achieved via an adaptation pathway framework focused on decision-making (Box 9). The question of whether an additional runway should be built at Brisbane Airport to relieve air traffic congestion is an excellent case study of the way a decision-centred framework can be used to deal with the risks of coastal flooding (Box 10).

BOX 9: A DECISION-CENTRED APPROACH TO CLIMATE ADAPTATION

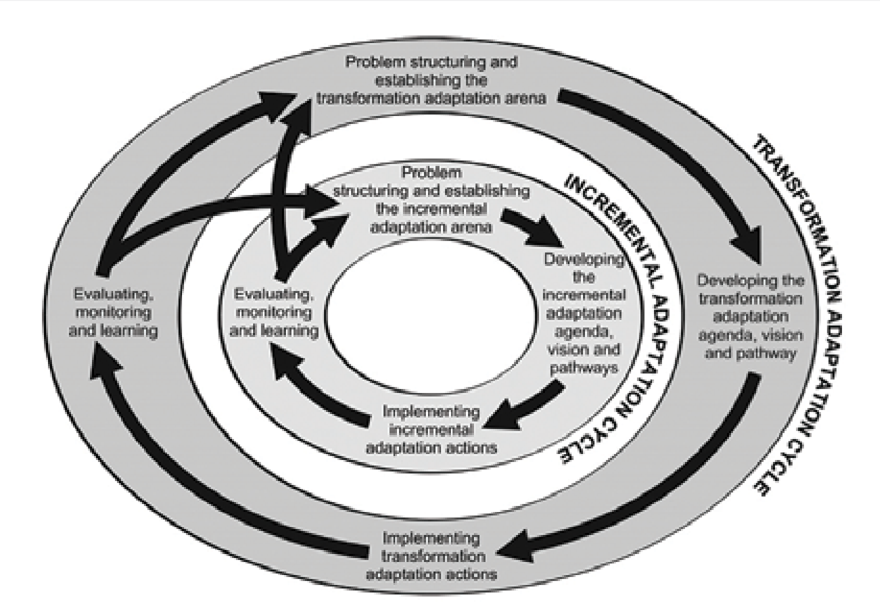
One of the most effective ways of approaching adaptation to the risks of coastal flooding is to embed the process in a decision-centred framework (Wise et al. 2014). This approach aims to develop adaptation decision pathways that manage risks through time as conditions change, rather than taking a one-off action that may prove to be ineffective or even maladaptive in the longer term

Ideally, a decision-centred approach can accommodate many approaches to managing the risks of coastal flooding, can deal with uncertainties in the science or in the projected impacts, can explicitly consider values and rules, and can evaluate adaptation decisions in a variety of different social contexts.

Two aspects of the decision-centred approach are especially important. First, many adaptation actions can be *incremental* modifications of existing management approaches to account for the increasing risk of coastal flooding. An example of this might be increasing the pumping capacity of a tidal pond that is prone to flooding the surrounding area at high tide. However, at some point in the decision making process, it might be more appropriate to undertake a more *transformative* approach to adaptation. An example of this might be the abandonment of a planned development close to the coastline and its relocation to a less vulnerable location.

Second, an adaptation pathway approach allows for evaluation, monitoring and learning at regular intervals. This is especially appropriate for incremental adaptation actions. Insights gained from evaluation and monitoring – and from the consideration of new or improved scientific knowledge as it develops—then allows for modification of the pathway or, if appropriate, the switch to a more transformative adaptation pathway (Figure 22).

Figure 22: Cycles of incremental and transformative adaptation (Park et al. 2012).



Different approaches to adapting to the risks of coastal flooding can have very large economic implications. For example, adaptation could occur through tightening planning regulations so that the risk to the existing stock of properties is held to today's levels, despite sea-level rise. If planning regulations in southeast Queensland did not allow further developments in high-risk areas—but with no action to protect existing housing stock—the impact of 2.5 m storm tides with an additional 0.2 m sea level rise in 2030 could be limited to approximately 40,300 residential buildings, and a cost of about $1.3 billion (compared to 61,500 buildings and about $2 billion without adaptation). This same adaptation could limit the impact of these storm tides in 2070 to approximately 48,000 residential buildings and a cost of about $1.5 billion, compared to 121,000 buildings and about $3.9 billion without adaptation (Wang et al. 2010).

A recent study by CSIRO (2014) found that some proactive adaptation measures nationally could provide net present benefits (damage avoided minus prevention cost) of up to $4 billion ($2006, nominal discount rate 5.6%, medium climate outlook) when compared to implementing current standards based on historic climate information. Note that that these estimates are for residential housing only, and do not include commercial, industrial, road and rail infrastructure, or the power and water infrastructure needed to service the residences.

Adaptation measures can come at a variety of costs, subject to region and method of estimation, but these costs were consistently lower than the damages that these measures help to prevent (CSIRO 2014). However, this study assessed that, even after appropriate adaption measures, there would still be a present value of costs of nearly $2 billion in residual damages as well as the costs of adaptation. Furthermore, there are a variety of barriers in Australia, in addition to cost, that may prevent the adoption of essential adaptation measures. These can include difficulties with governance, lack of policy certainty, and lack of local resources (Barnett et al. 2013).

BOX 10: ADAPTING TO CLIMATE CHANGE AT BRISBANE AIRPORT.

The development of the new parallel runway at Brisbane Airport is an excellent case study in the incorporation of climate change considerations in the decision-making process for long-lived infrastructure.

The owners of Brisbane Airport, Australia's third busiest airport, decided to build a new runway to deal with rapidly increasing capacity constraints that are beginning to generate air traffic congestion and flight delays. The new runway is a nationally important piece of infrastructure, and is expected to accrue economic benefits (net present value) by 2035 of $8.2 billion to the Brisbane –Moreton region, $1.1 billion to the rest of Queensland, and $0.6 billion to the rest of Australia.

Figure 23: A cross runway at Brisbane Airport, located on a low-lying site near Moreton Bay, with a new runway under construction (top left of photo).

The project faces considerable environmental challenges given the airport's location on a low-lying coastal site prone to flooding events (Figure 23). With the long lifetime required of a new runway, the projected increase in coastal flooding due to sea-level rise has become an important consideration in the planning.

The decision process already had a number of important considerations to deal with, including:

- Interests of stakeholders, which include federal, state and local government agencies, airlines, nearby residents and passengers from the broader area.
- Cost, an important consideration for owners and investors; the airport is majority owned (81%) by superannuation funds.
- Safety considerations, which require the airport to meet regulatory requirements to ensure a very high standard of aviation safety.
- Operational and noise restrictions, which place limitations on the possible location of the new runway.

Added into this mix were the implications of climate change, and the need to ensure that the runway would remain viable during its lifetime in the face of a rising sea level. The trade-off between viability and cost was an interesting one, as the cost of increasing the height of a 3,300 m long runway, even by a few centimetres, is very large.

The decision-making process was supported by the most up-to-date, authoritative scientific advice and modelling tools on the increasing risks of coastal flooding, information supplied by the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC). The advice apparently was valuable, as the airport opted for a height of 4.1 m above current sea level (see Colonial First State Global Asset Management 2012, fig 7), a decision that the ACE CRC described as "strongly precautionary".

The decision on the new parallel runway at Brisbane Airport demonstrates that taking a decision-oriented approach to climate adaptation, in the context of many other factors that need to be considered, can deliver an outcome that meets the needs of the various stakeholders whilst providing long-term resilience against the risks of coastal flooding.

5. THE BOTTOM LINE

The risks associated with rising sea level are largely under the radar despite the enormous implications they have for our economy and our way of life. In terms of the potential for significant economic damage and major social disruption, coastal flooding is the sleeping giant.

- While the costs of transforming to a low carbon economy are frequently estimated and widely debated, the costs of NOT making this transformation are much less known.
- Assessing the costs of coastal flooding begins to redress this critical imbalance. Globally, one estimate puts these costs at $US 1 trillion by 2050, while others estimate that costs could rise to over 9% of global GDP annually. This is a scenario for economic collapse.
- Reducing these costs through proactive adaptation is clearly essential, but there will usually still be significant residual risks and damages even after appropriate adaptation.
- When the estimated economic costs of increases in other extreme weather events in addition to coastal flooding (e.g., heatwaves, bushfires, storms and wind damage) are also considered, the costs of NOT reducing greenhouse emissions becomes even greater.

Climate change is ultimately an ethical, moral, equity and intergenerational issue. Nevertheless, the economic risks from climate impacts are also important and often neglected in the public discourse. Much more reliable information on the rising economic costs of climate change impacts and risks, and a better understanding of how to adaptively plan for the future under uncertainty, are essential for informed decision-making.

The bottom line is clear. The enormous risks of sea-level rise, both in the short and long terms, can be ultimately managed only by stabilising the climate system. This requires that greenhouse gas emissions are reduced deeply and quickly, and that the transition to a carbon-free global economy is achieved this century, the sooner the better. This is the critical decade for action. Now is the time to get on with the job.

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2. Global-average IPCC AR5 sea-level projections:

   www.met.rdg.ac.uk/~jonathan/data/ar5_sealevel

3. Tide-gauge data:

   "Sea-level data were supplied by the National Tidal Centre (Bureau of Meteorology, Australia)".

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Page 43: Figure 18 “Seawater overflowing a protective sea wall on Sabai, Torres Strait Islands” David Hanslow TSRA.

Page 47: Figure 20 “Visual artists depict the impact of rising sea levels” John Boyd MacDonald (Humpback fight. 2013) and Heike Qualitz (Contemplating adaptation. 2013).

Page 56: Figure 23 “Brisbane airport runway” by Brisbane Airport Corporation.