CRANKING UP THE INTENSITY: CLIMATE CHANGE AND EXTREME WEATHER EVENTS

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Cranking up the Intensity: Climate Change and Extreme Weather Events by Professor Will Steffen, Professor Lesley Hughes, Dr David Alexander and Dr Martin Rice.

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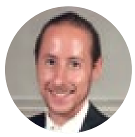

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Key Findings

1 Climate change is influencing all extreme weather events in Australia.

- All extreme weather events are now occurring in an atmosphere that is warmer and wetter than it was in the 1950s.
- Heatwaves are becoming hotter, lasting longer and occurring more often.
- Marine heatwaves that cause severe coral bleaching and mortality are becoming more intense and occurring more often.
- Extreme fire weather and the length of the fire season is increasing, leading to an increase in bushfire risk.
- Sea level has already risen and continues to rise, driving more devastating coastal flooding during storm surges.

2 Some of the most severe climate impacts the world has experienced have occurred in 2016.

- Arctic sea ice reached its lowest annual extent on record while record sea surface temperatures drove the worst coral bleaching event in the Great Barrier Reef's history.
- Tropical Cyclone Winston was the most intense cyclone to hit Fiji on record, while Hurricane Otto was the southernmost hurricane to hit Central America on record.
- Canada experienced its costliest wildfire in history in Fort McMurray, forcing the evacuation of almost 90,000 people.
- The US state of Louisiana experienced 1-in-500 year rains that brought severe flooding leading to 30,000 rescues and 13 deaths.

3 Across Australia, extreme weather events are projected to worsen as the climate warms further.

- Extreme heat is projected to increase across the entire continent, with significant increases in the length, intensity and frequency of heatwaves in many regions.
- The time spent in drought is projected to increase across Australia, especially in southern Australia. Extreme drought is expected to increase in both frequency and duration.
- Southern and eastern Australia are projected to experience harsher fire weather.
- The intensity of extreme rainfall events is projected to increase across most of Australia.
- The increase in coastal flooding from high sea level events will become more frequent and more severe as sea levels continue to rise.

4 The impacts of extreme weather events will likely become much worse unless global greenhouse gas emissions are reduced rapidly and deeply.

- Burning of coal, oil and gas is causing temperatures to rise at unprecedented rates and is making extreme weather events more intense, damaging and costly.
- Major emitters including China and the European Union are leading action on climate change, but Australia is lagging well behind and is on track to even miss its very weak target of a 26-28% reduction in emissions by 2030.
- Australia is expected to do its fair share to meet the global emissions reduction challenge by cutting its emissions rapidly and deeply.
- Phasing out ageing, polluting coal plants and replacing them with clean, efficient renewable energy sources such as wind and solar is imperative for stabilising the climate and reducing the risk of even worse extreme weather events.

Introduction

2016 was the hottest year on record globally, yet again. Global average temperature has risen by about 1.1°C above the pre-industrial baseline, with most of the warming occurring since the 1950s. The rapidly warming climate is driving a wide array of impacts, many of them associated with worsening extreme weather events.

Australia is one of the most vulnerable developed countries in the world to the impacts of climate change. Heatwaves in Australia are becoming longer, hotter and starting earlier in the year. In the populous south of the country, dangerous bushfire weather is increasing and cool season rainfall is dropping off, stretching firefighting resources, putting lives at risk and presenting challenges for the agriculture industry.

The nation has also been hit with a series of destructive storms in recent times. In September 2016, a vicious extra-tropical cyclone roared across South Australia, knocking down power lines and triggering a state-wide blackout, leaving 1.7 million people without power. Just a few months earlier, a deep east coast low sent record-high waves pounding onto the New South Wales coast, causing five deaths as well as significant loss of coastal property.

These extreme weather events are part of a disturbing global pattern (Figure 1). In the latter part of 2016, Santiago (Chile) experienced its hottest day on record, while dry and hot conditions led to the costliest wildfire in Canada earlier in the year. Some of the most intense, prolonged heatwaves ever recorded have been experienced in the Middle East and the Indian subcontinent. Extreme rainfall caused severe flooding and deaths in France and the United States. Some of the most intense tropical cyclones on record occurred in the Atlantic and Pacific basins.

The evidence for the link between climate change and extreme weather is already very strong for heatwaves and bushfire weather, and it is getting stronger for intense cyclones and heavy rainfall events. All extreme weather events are now occurring in an atmosphere that is warmer and wetter than it was in the 1950s. Generally, this means more intense extreme weather events and more devastation around the world, including Australia.

This report outlines the link between climate change and extreme weather events and outlines state-by-state projections. As global temperatures continue to rise, weather events will continue to become more extreme. To protect Australia from even more severe extreme weather, a global effort, with Australia contributing its fair share, to rapidly and deeply reduce greenhouse gas emissions is urgently required.

In December 2015, world leaders met in Paris and agreed to work together to do all they could to keep global temperature rise to well below 2°C. As of November 4 2016, the Paris Agreement entered into force. As one of the world's top 15 emitters, Australia is expected to do its part, and our current actions and pledges are far from meeting that challenge. Our Paris pledge is very weak, and under current policies we are unlikely to meet even that target.

All extreme weather events are now occurring in a warmer and wetter atmosphere compared to the 1950s, leading to more extreme weather events.

TIMELINE OF MAJOR 2016
EXTREME WEATHER EVENTS

JAN

HURRICANE PALI (CENTRAL PACIFIC)
Earliest hurricane on record in the central Pacific basin (The Weather Channel 2016a).

FEB

CYCLONE WINSTON (FIJI)
Tropical cyclone was the strongest storm to hit Fiji since records began (NASA 2016).

MAR

RECORD-BREAKING HEAT (MELBOURNE)
Hottest March night since records began (BoM 2016g).

MARINE HEATWAVE (QUEENSLAND)
Worst coral bleaching event in Great Barrier Reef's history begins (AIMS 2016).

APR

EXTREME RAINFALL (TEXAS)
Second wettest calendar day on record in Houston (The Weather Channel 2016b).

MAY

WILDFIRE (FORT MCMURRAY, CANADA)
Most costly fire in Canada's history (Financial Post 2016). Nearly 90,000 people were forced to evacuate the town.

JUN

RAINFALL (PARIS)
Highest levels of River Seine in thirty years causing severe flooding (Deutsche Welle 2016).

RAINFALL AND COASTAL FLOODING (SYDNEY)
Maximum wave height during east coast low storm was the highest ever recorded along the NSW coast (Louis et al. 2016).

JUL

EXTREME HEAT (KUWAIT)
Highest temperature ever recorded in the Eastern Hemisphere (54°C) observed in Mitribah[1] (WMO 2016).

AUG

HAILSTORM (SAMOA)
Second time since records began that hail fell in Samoa (The Guardian 2016c).

RAINFALL (LOUISIANA)
1-in-500 year rains bringing severe flooding (NOAA 2016), leading to 30,000 rescues and 13 deaths.

SEP

HURRICANE MATTHEW (CARIBBEAN)
Longest lived Category 4-5 cyclone in the East Caribbean on record (The Washington Post 2016).

STORMS (SOUTH AUSTRALIA)
Worst storm in over 50 years cut power to the entire state.

OCT

TYPHOON HAIMA AND SARIKA (PHILIPPINES)
Third time since 1950 that back-to-back storms with intensity of Category 4 or higher have hit the Philippines (CNN 2016).

NOV

HURRICANE OTTO (PACIFIC)
Southernmost hurricane on record to hit Central America (The Guardian 2016d).

WARMING CLIMATE (ARCTIC)
Arctic sea-ice extent at record low levels, as air temperatures soared up to 20°C above the mid-winter average (SMH 2016).

DEC

HEATWAVE (CHILE)
Santiago broke its maximum temperature record, which had stood for over 100 years (Al Jazeera 2016).

RECORD-BREAKING HEAT (SYDNEY)
Hottest December night since 1868 (ABC 2016b).

Figure 1: Timeline of major extreme weather events in 2016 across the world.

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[1] This record is currently under review by the World Meteorological Organization. See: http://public.wmo.int/en/media/news/wmo-examines-reported-record-temperature-of-54%C2%B0c-kuwait.

1. The Link Between Climate Change and Extreme Weather Events

All extreme weather events are being influenced by climate change as they are now occurring in a more energetic climate system (Trenberth 2012).

While extreme weather events are a natural feature of the climate system (Box 1), the atmosphere and surface ocean of today contain significantly more heat than in the 1950s. In fact, the rate of increase in global average temperature since 1970 is approximately 170 times the baseline rate over the past 7,000 years (Marcott et al. 2013; Steffen et al. 2016; NOAA 2017b). This extremely rapid, long-term rate of temperature increase is being driven by the additional greenhouse gases in the atmosphere that have accumulated primarily from the burning of coal, oil and gas.

Over the past decade climate scientists have made strong progress in identifying the links between climate change and extreme weather events, based on three main lines of evidence:

- The basic physics that govern the behaviour of the climate system shows that extreme weather events are now occurring in a significantly warmer and wetter atmosphere, which means the atmosphere contains more energy, facilitating more severe extreme weather.
- Where sufficient long-term data are available, observations show trends towards more intensity in many types of extreme weather events.
- More recently, 'attribution studies' based on detailed modelling experiments explore how climate change has already increased the probability that extreme weather events would have occurred (Figure 2).

All extreme weather events are being influenced by climate change.

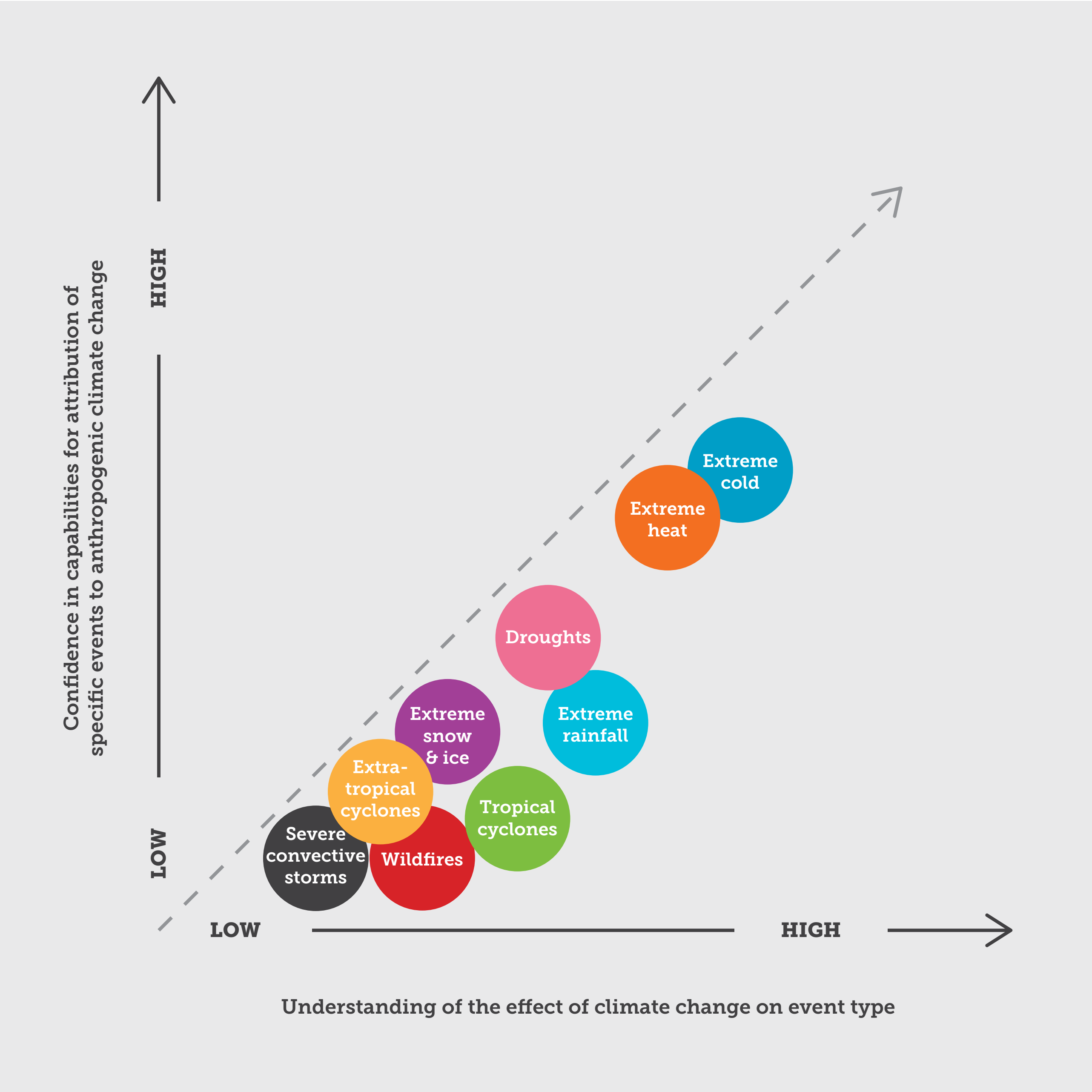

Figure 2: The level of confidence climate scientists have in attributing specific extreme weather events to climate change correlated with the understanding of the influence of climate change on each event (National Academies of Sciences 2016).

BOX 1: EXTREME WEATHER EVENT BASICS

The term extreme weather event refers to "an occurrence of a value of a weather or climate variable beyond a threshold that lies near the end of the range of observations for the variable" (IPCC 2012, p. 5). It is a weather event which is unusually intense or long, occasionally beyond what has been experienced before. Examples include very high (and low) temperatures, very heavy rainfall (and snowfall in cold climates), and very high wind speeds. By definition, extreme events occur only rarely; they are noticeable because they are so different from usual weather patterns; and they are often associated with adverse impacts on humans, infrastructure and ecosystems.

Extreme weather events are usually short-lived, abrupt events lasting only several hours up to several days; they are 'shocks' within the climate system. Examples include extremely hot days and heatwaves (three or more consecutive days of unusually high maximum and minimum temperatures), very heavy rainfall (Figure 3), hail storms, and tropical cyclones. These are 'acute' extreme events. A few extreme events can last for much longer periods of time and are usually termed extreme climate events. An example is drought, which is a significant lack of rainfall over a period of months to years.

Figure 3: A recent example of an extreme weather event. Widespread and devastating flooding in Louisiana as a result of a 1-in-500 year rainfall event in August 2016. Thirteen people died, and more than 30,000 people were rescued from the floodwaters that damaged or destroyed over 50,000 homes, 100,000 vehicles and 20,000 businesses. Estimated damages are $US 10 billion (NOAA 2017a).

Over the past few years, temperature records have been repeatedly shattered around the world, continuing a long-term trend from the mid-20th century of rising temperatures (Figure 4). 2016 saw global temperatures 0.94°C above the 20th century average (NOAA 2017b) - about 1.1°C above "pre-industrial" levels (UK Met Office 2017). 2016 was the hottest year on record globally, surpassing the record average temperature of 2015.

The long run of temperature anomalies includes strong warming from 1970 through the end of the century and into the 21st century (Figure 4). 2016 was the 40th consecutive year with an above-average global temperature (NOAA 2017b). You would now need to be greater than 40 years old – born in 1976 or earlier – to have lived in a year with temperatures at or below the global 20th century average.

2016 was the hottest year on record globally.

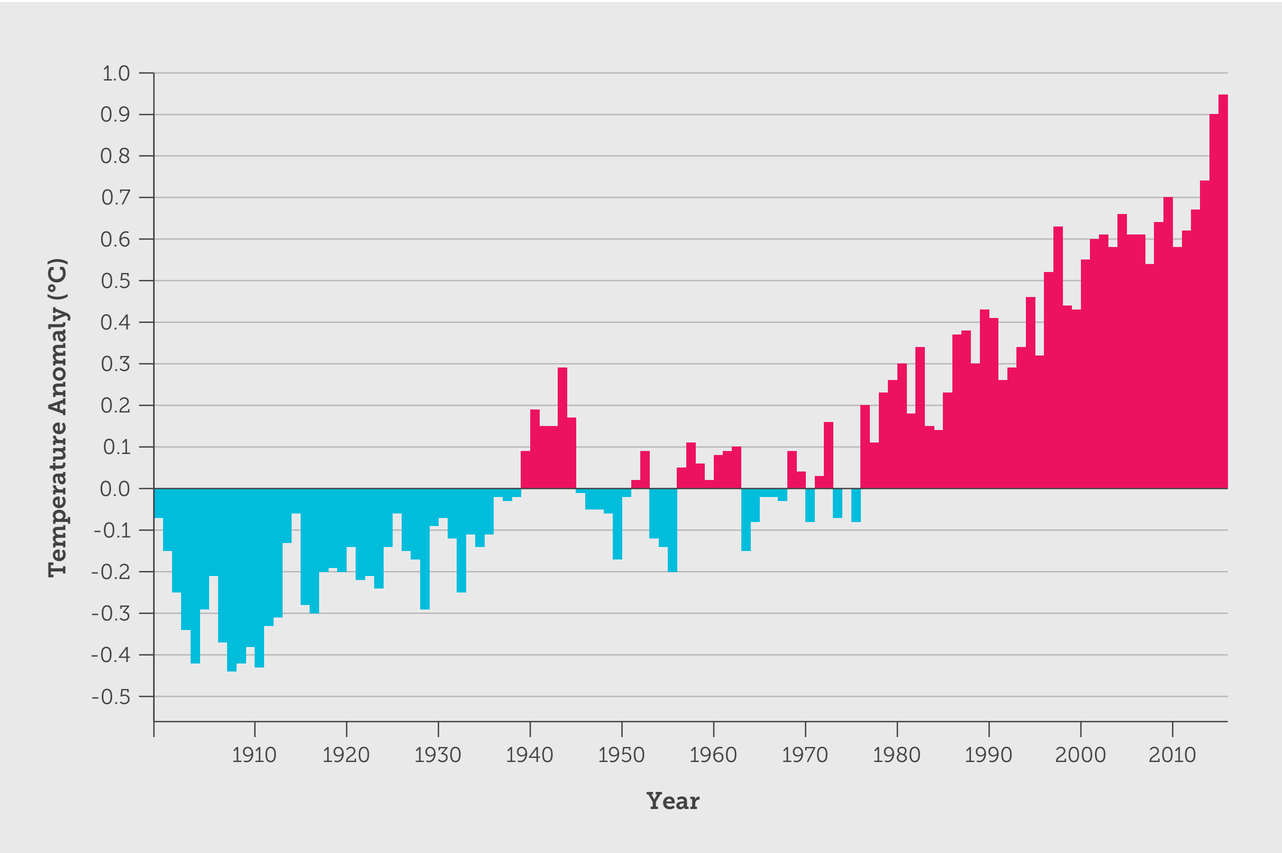

Figure 4: Annual global temperature anomalies to 2016, relative to global annual average temperature 1901-2000. Data from US National Oceanic and Atmospheric Administration (NOAA 2017).

In the last five years alone, a number of destructive storms, extreme heatwaves and bushfires have occurred around the world, including Australia (Figure 5). The influence of climate change on this increasingly severe and damaging extreme weather has been demonstrated more clearly through the development of climate attribution science, where models are used to examine how much more likely extreme weather events were as a result of climate change. Over the last five years, the Bulletin of the American Meteorological Society has released a special edition annually highlighting some of the extreme events in a calendar year and their relation to climate change (Accessible at: https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/). A selection of studies from their most recent publication that establish a clear link between specific 2015 extreme weather events and climate change include:

- Heatwaves: A heatwave in central Europe in the 2015 summer was influenced significantly by climate change (Dong et al. 2016). Deadly heatwaves in Pakistan and India in May and June 2015, causing thousands of deaths, were also exacerbated by human-induced climate change (Wehner et al. 2016).
- Extreme heat: Climate change tripled the risk of record-breaking heat over northwest China in July 2015, which culminated in 28 counties breaking maximum daily temperature records (Miao et al. 2016). Australia experienced its warmest October on record, which was significantly influenced by climate change (Black and Karoly 2016).
- Bushfires: Human-induced climate change may have increased the risk of the severe 2015 fire season in Alaska by 34-60% (Partain Jr et al. 2016). The fires burned the second largest number of hectares since records began in the 1940s.
- Drought: The extreme drought in western Canada in 2015 was likely to be a result of human-influenced warm spring conditions preceding dry May to July weather (Szeto et al. 2016).
- Extreme rainfall: In southeast China, extreme rainfall caused severe flooding in May 2015. Climate change increased the probability of intense, short-duration rainfall (Burke et al. 2016).
- Coastal flooding: The probability of a 0.57 m tidal flooding event in southeast Florida in September 2015 increased by more than 500% since 1994, due to a 10.9 cm sea level rise-related increase in monthly highest tides (Sweet et al. 2015).

Recent extreme weather events occurring across all parts of the globe are a clear warning of what lies ahead if greenhouse gas emissions are not reduced rapidly.

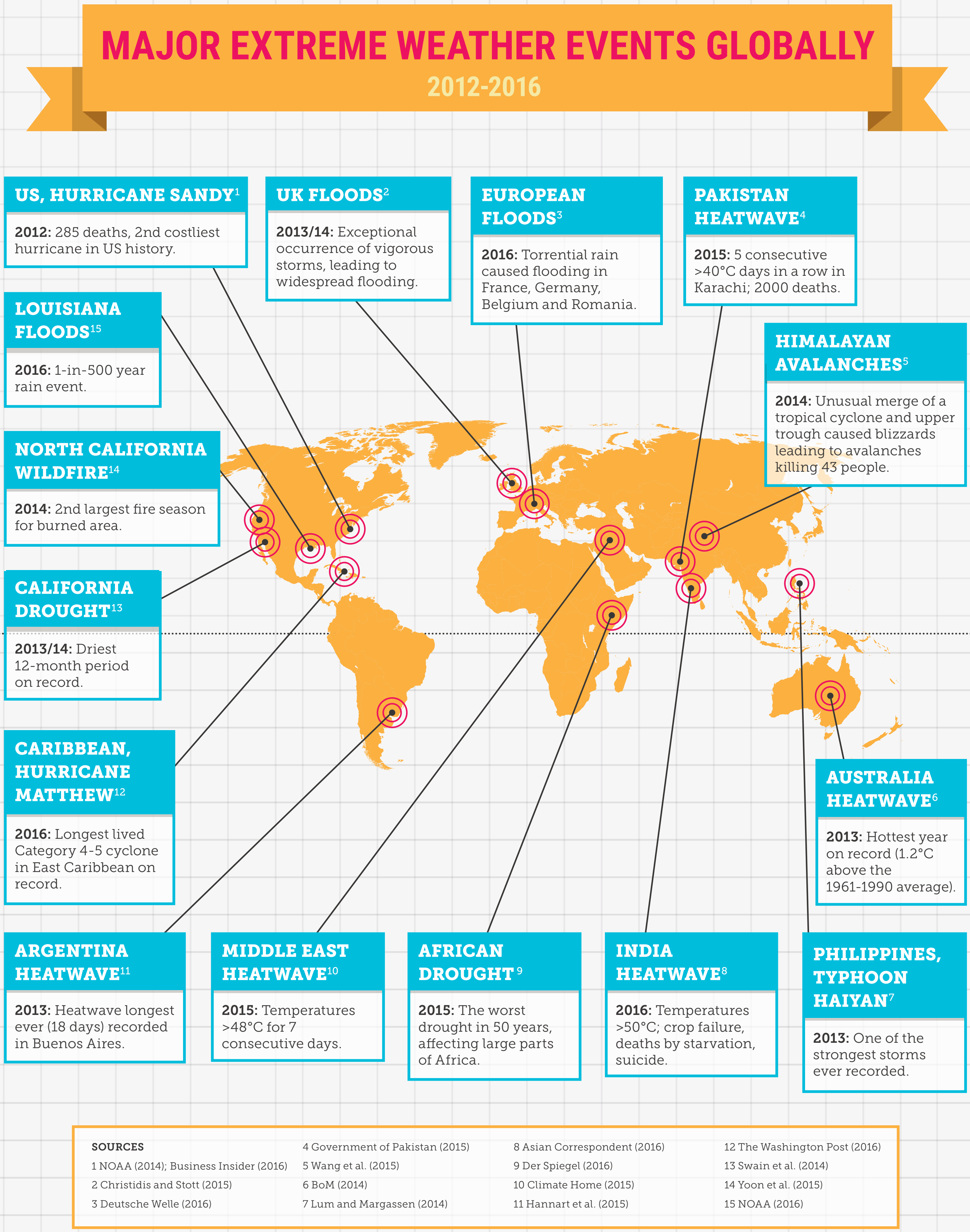

Figure 5: Major extreme weather events that have occurred during the past five years. These events have caused a significant number of deaths; damage to housing, transport and other infrastructure; as well as damage to natural ecosystems.

The long-term implications of worsening extreme weather are worrying. Even modest increases in temperature beyond the current 1.1°C rise above the pre-industrial baseline can have a significant effect on the risk profile for extreme events. Figure 6 shows that the risk profile has entered the "high" range when the global average temperature rise has reached just 1.5°C, let alone 2°C Paris target – the so-called "guardrail" temperature to keep the Earth's climate stable and avoid the worst impacts of climate change. Even more worrying, the various national pledges and commitments for emission reductions that were made in Paris, when aggregated, would likely lead to 2.9-3.4°C warming by 2100 (UNEP 2016). If the rest of the world adopted a level of ambition equivalent to Australian targets and policies, we would be on track for an even greater rise – 3-4°C rise or more by the end of the century (Climate Action Tracker 2016). Those scenarios would push the risks of worsening extreme weather towards the "very high" level.

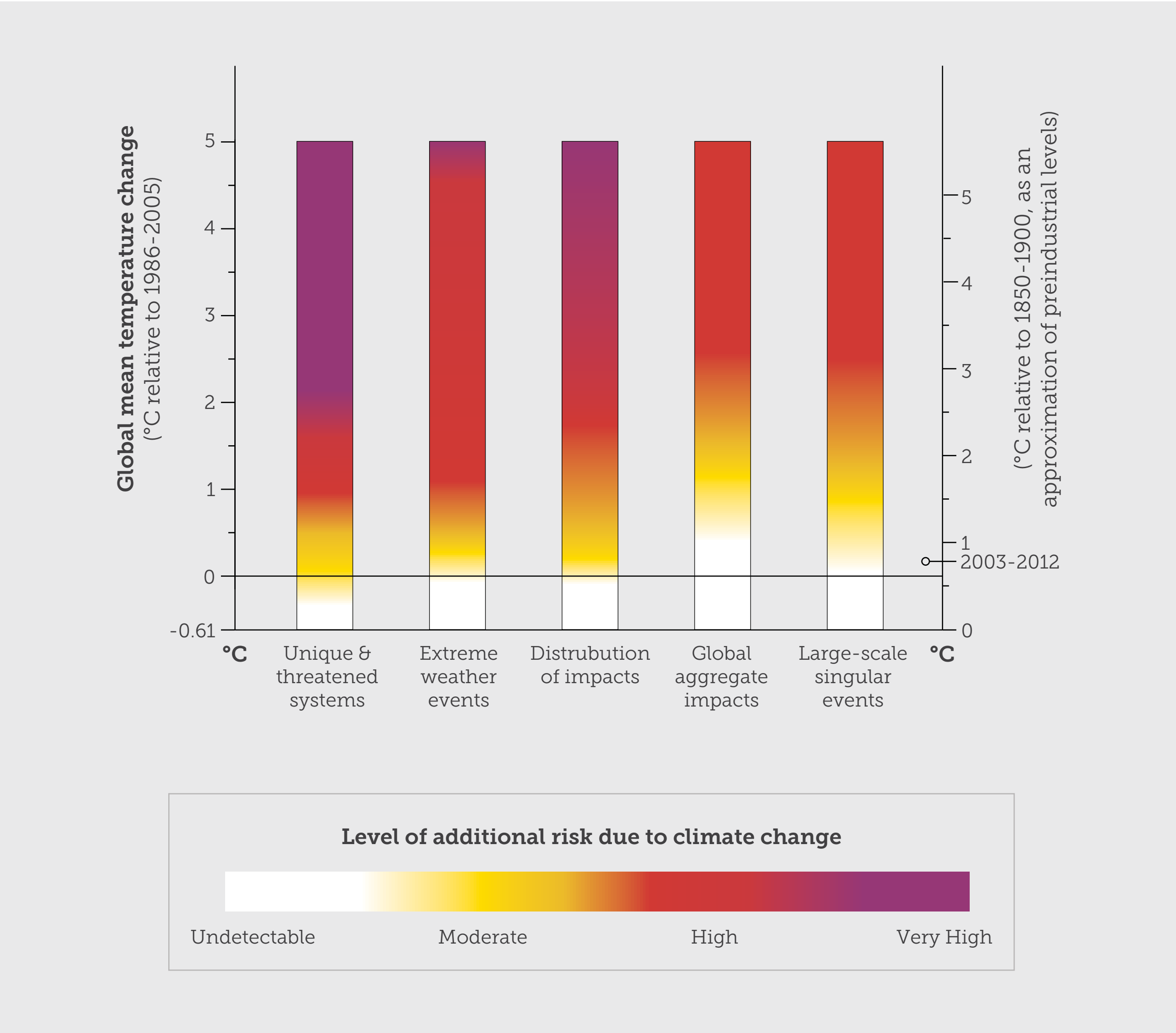

Figure 6: Risks from climate change by reason for concern (RFC) compared with global temperature rise (IPCC 2014b). Each column corresponds to a specific RFC and represents additional outcomes associated with increasing global mean temperatures. The colour scheme represents progressively increasing levels of risk.

2. Increasing Severity and Intensity of Extreme Weather in Australia

The severity and intensity of extreme weather events are increasing. This section presents an overview of the long-term trends in Australian extreme events and their connections with climate change: (i) heatwaves, (ii) bushfires, (iii) drought, (iv) extreme rainfall, (v) storms, and (vi) coastal flooding and sea-level rise. We also highlight recent attribution studies that link specific extreme weather events to climate change in both Australian and global settings.

2.1 Extreme Heat and Heatwaves

2.1.1 Land

Climate change is making hot days and heatwaves more frequent and more severe (Climate Council 2014a). Australia's climate has warmed by about 1°C from 1910, with most warming occurring since 1950 (CSIRO and BoM 2016). As a result, the number of hot days, defined as days with maximum temperatures greater than 35°C, has increased in the last 50 years (CSIRO and BoM 2016; Figure 7).

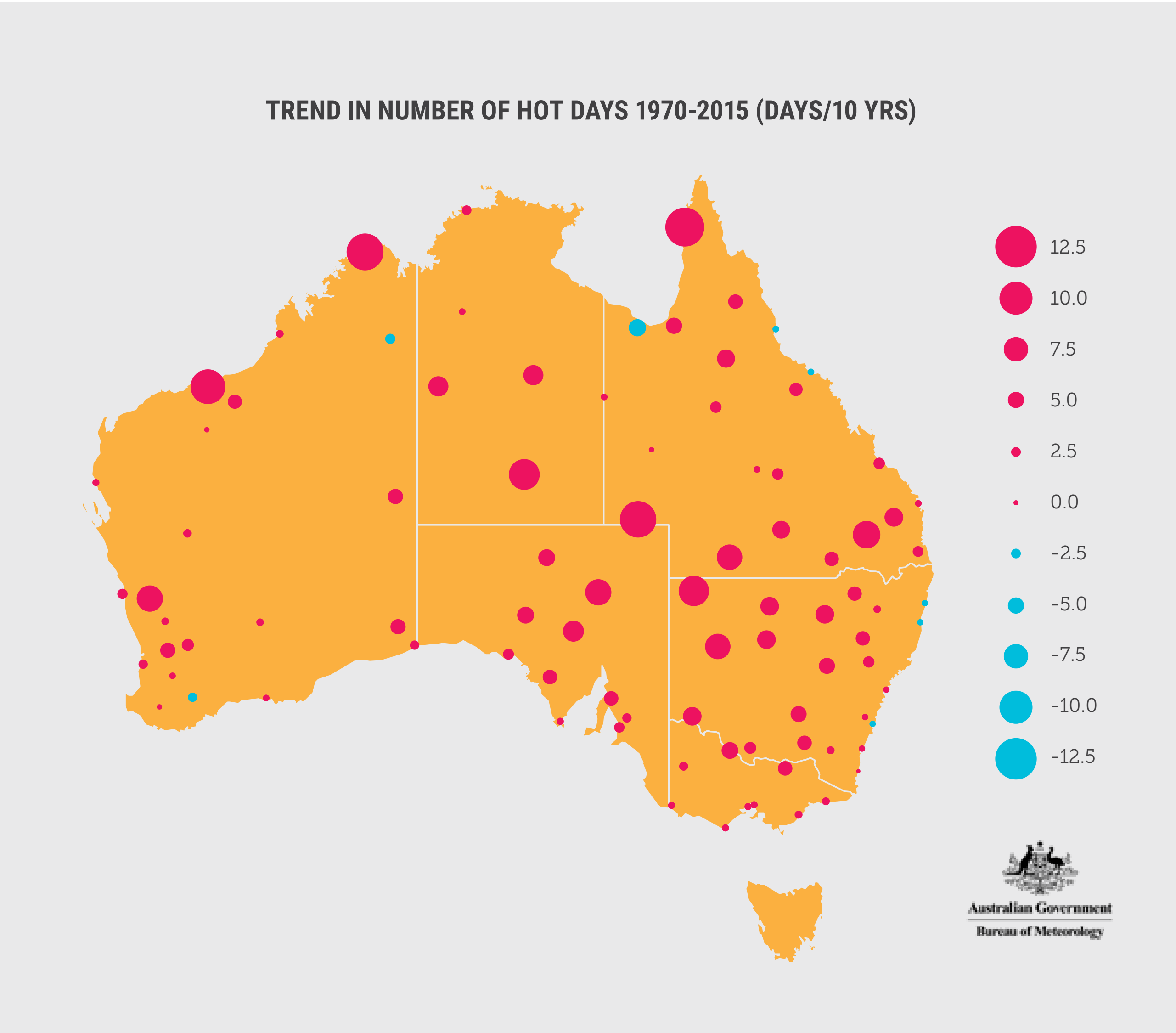

Figure 7: Trend in the number of hot days experienced during the 1970-2015 period. Almost all of Australia has seen an increase in the number of hot days (>35°C) since the 1970s (BoM 2016a).

Hot days in mid-December 2016 across the southeast of the country resulted in maximum daily temperatures of 38°C in Sydney (Observatory Hill), 37°C in Adelaide (Kent Town) and 36°C in Melbourne (Olympic Park) (BoM 2016b). Sydney broke a record that had stood for almost 150 years for the warmest minimum temperature, reaching a minimum overnight temperature of 27.1°C (ABC 2016b). Lewis and King (2015) showed that for the period 2000-2014, the ratio of observed hot to cold temperature records is 12 to 1. Australia's hottest year on record, the 'Angry Summer' of 2012/13, broke 123 temperature and rainfall records (Box 2).

The duration and frequency of heatwaves in Australia have increased in the past decades, and the hottest days during a heatwave have become even hotter over the south of the continent (Figure 8). A heatwave in Australia is described as a period of at least three days where the combined effects of high temperatures and excess heat are unusual within the local climate (BoM 2012). Over the period 1971–2008, both the duration and frequency of heatwaves increased, and the hottest days during heatwaves became even hotter (Perkins and Alexander 2013). Australian capital cities, where the majority of Australians live, are at risk from the increasing severity and intensity of extreme weather (Figure 10).

Figure 8: Climate change has been making hot days and heatwaves more frequent and more severe in Australia. For example, in Sydney heatwaves now start earlier (Perkins and Alexander 2013).

BOX 2: THE ANGRY SUMMER OF 2012/2013

Over the summer of 2012/2013, Australia was hit with a series of flood, heatwave, drought and bushfire events. Australia endured extreme heat and rainfall, breaking 123 records, some of which spanned decades (Climate Commission 2013). Nicknamed 'The Angry Summer', it was the hottest summer since records began.

During the Angry Summer, over 70% of the nation experienced an unusually long and intense heatwave (BoM 2013a). Over the previous 102 years, there had only been 21 days where the national average temperature exceeded 39°C; eight of these days occurred during the Angry Summer (BoM 2013a). The heatwave brought temperatures that broke regional records from Perth all the way through to Sydney. New high temperature records were set in every state and territory.

Fires raged alongside the heatwave, with Tasmania, Victoria and New South Wales fighting catastrophic fires on multiple fronts. In just one day, up to 40 fires were ignited in Tasmania alone (BoM 2013b). Properties, homes, businesses and entire towns were engulfed in the fires, leading to widespread evacuations. Fire outbreaks are very sensitive to changing weather conditions, and the Angry Summer brought conditions ideal for rapid fire spread.

Extreme weather continued into February. Extreme low pressure systems battered Queensland and northern New South Wales, which led to flooding and wind damage within 200 km of the coast. This was brought about by Cyclone Oswald, which travelled from the Gulf of Carpentaria down the east coast to Sydney. The Pilbara region in northwest Western Australia was also hit with a Category 4 storm, Cyclone Rusty.

Although the increase in global average temperature of about 1.1°C above pre-industrial levels (UK Met Office 2017) might not appear to be very significant, a small increase in the average temperature creates a much greater likelihood of very hot weather and a much lower likelihood of very cold weather as shown in Figure 9. The records of the Angry Summer bear this out, lying at the extreme right tail of the temperature distribution shown in the figure.

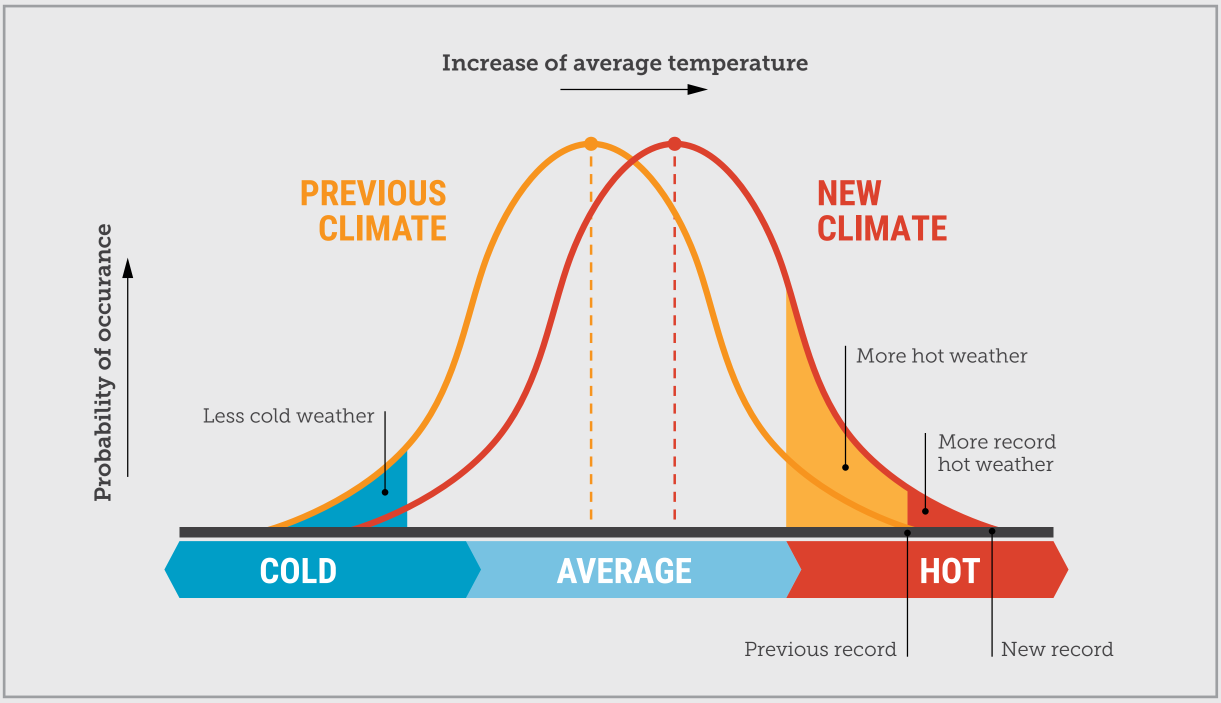

Figure 9: Relationship between average and extreme weather, showing how a small increase in average temperature has a large impact on the prevalence of extreme heat (adapted from IPCC 2007).

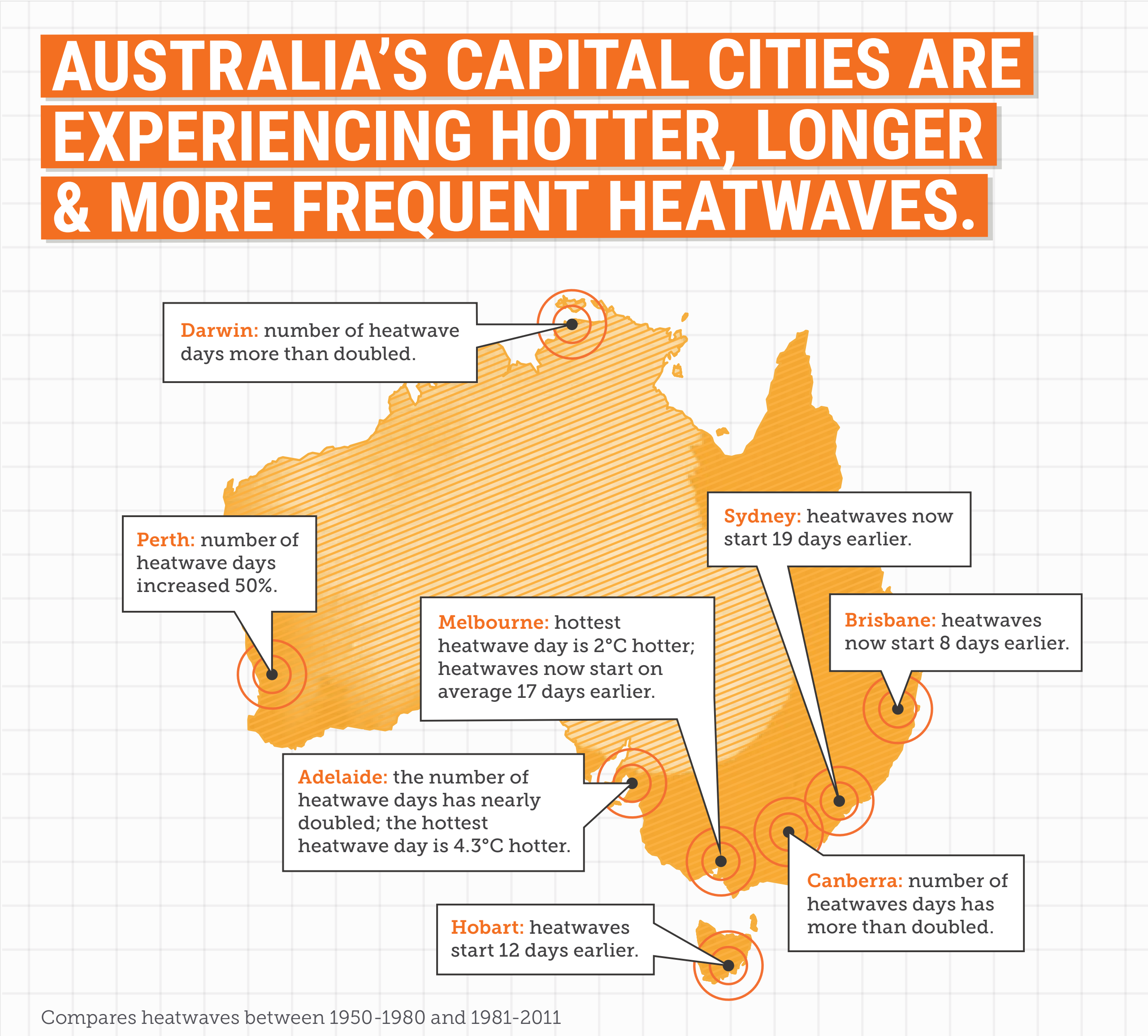

Figure 10: Australia's capital cities are experiencing hotter, longer or more frequent heatwaves, based on a comparison by Perkins and Alexander (2013) of heatwaves during the 1950-1980 period with those during the 1980-2011 period.

While it has been clear for many years that climate change is a major factor in intensifying heat, recent scientific advances now allow us to understand the extent of its impact on individual extreme events. For example, the record hot year of 2013 in Australia, where mean temperatures were 1.2°C above the 1961-1990 average (BoM 2016a), was virtually impossible without human-induced climate change. That is, without climate change, the record temperature would occur only once every 12,300 years (Knutson et al. 2014; Lewis and Karoly 2014). The risk of experiencing severe heatwaves in summer, in terms of their frequency and intensity, has increased two- and three-fold, respectively, due to climate change (Perkins et al. 2014). In 2015, Australia experienced its warmest October on record (BoM 2015a), driven by an early season heatwave over the south of the continent. Black and Karoly (2016) found that anthropogenic climate change had a substantial influence on the extreme heat, while Hope et al. (2016) showed that 50% of the record heat anomaly in October can be attributed to increasing carbon dioxide levels.

The impact of climate change on extreme heat-related events is also evident at a global level. Lewis et al. (2016) showed that the global record hot year of 2015 will likely be the 'new normal' climate of 2040. The influence of climate change on some specific extreme events can also be quantified. For example, the extreme heatwave that affected the greater Buenos Aires region in Argentina in December 2013 was the longest ever recorded (18 days). This event was made five times more likely due to climate change (Hannart et al. 2015). Climate change also increased the probability of record-breaking heat over western China in the summer of 2015, which was the hottest on record, by at least three times and 42 times for the highest daily maximum and minimum temperatures, respectively (Sun et al. 2016). Meanwhile, the Middle East experienced a scorching heatwave in August 2015. This was particularly severe in Iran and resulted in temperatures exceeding 48°C for seven consecutive days. Heatwaves in this region are likely to make the Persian Gulf uninhabitable if the global average temperature increases by only 3°C from its current level (Pal and Eltahir 2016).

Australia's record warmth in October 2015 was significantly influenced by climate change.

2.1.2 Marine

Just as for the land surface, upper ocean temperatures have been steadily increasing globally and around Australia (CSIRO and BoM 2016). This warming, particularly since 1950, has led to a greater prevalence of 'marine heatwaves' (CSIRO and BoM 2016), which are extreme ocean warming events. For example, a marine heatwave off the west coast of Australia in February to March 2011 saw temperatures of 2-4°C above average persisting for more than ten weeks along more than 2,000 km of coastline (Wernberg et al. 2013). This exceptional event was driven by a strong La Niña, in addition to the longer-term trend of increasing temperatures in the region (Pearce and Feng 2013). In 2016, a marine heatwave struck the Great Barrier Reef and resulted in average water temperatures around 1-1.5°C above the recent long term average (2002-2011) for the February to April period (BoM 2016c; Climate Council 2016a; Figure 11). This heatwave was a result of record-breaking ocean temperatures driven by climate change and El Niño, and caused the longest global coral bleaching event on record (Hoegh-Guldberg 2016). The extreme ocean temperatures that caused the bleaching event on the Great Barrier Reef were made at least 175 times more likely by climate change (CoECSS 2016).

Ocean warming since the 1950s has led to a greater prevalence of marine heatwaves off the coasts of Australia.

Figure 11: Bleached coral on the Great Barrier Reef 50 km offshore from Port Douglas, caused by a marine heatwave in early 2016.

2.2 Bushfires

Australia has a long history of bushfires and routinely faces the risk of serious and extreme fire danger conditions. Climate change is affecting bushfire conditions by increasing the probability of dangerous bushfire weather. Many parts of Australia, including southern New South Wales, Victoria, Tasmania and parts of South Australia and southwest Western Australia have all experienced an increase in extreme fire weather since the 1970s (CSIRO and BoM 2016; Figure 12).

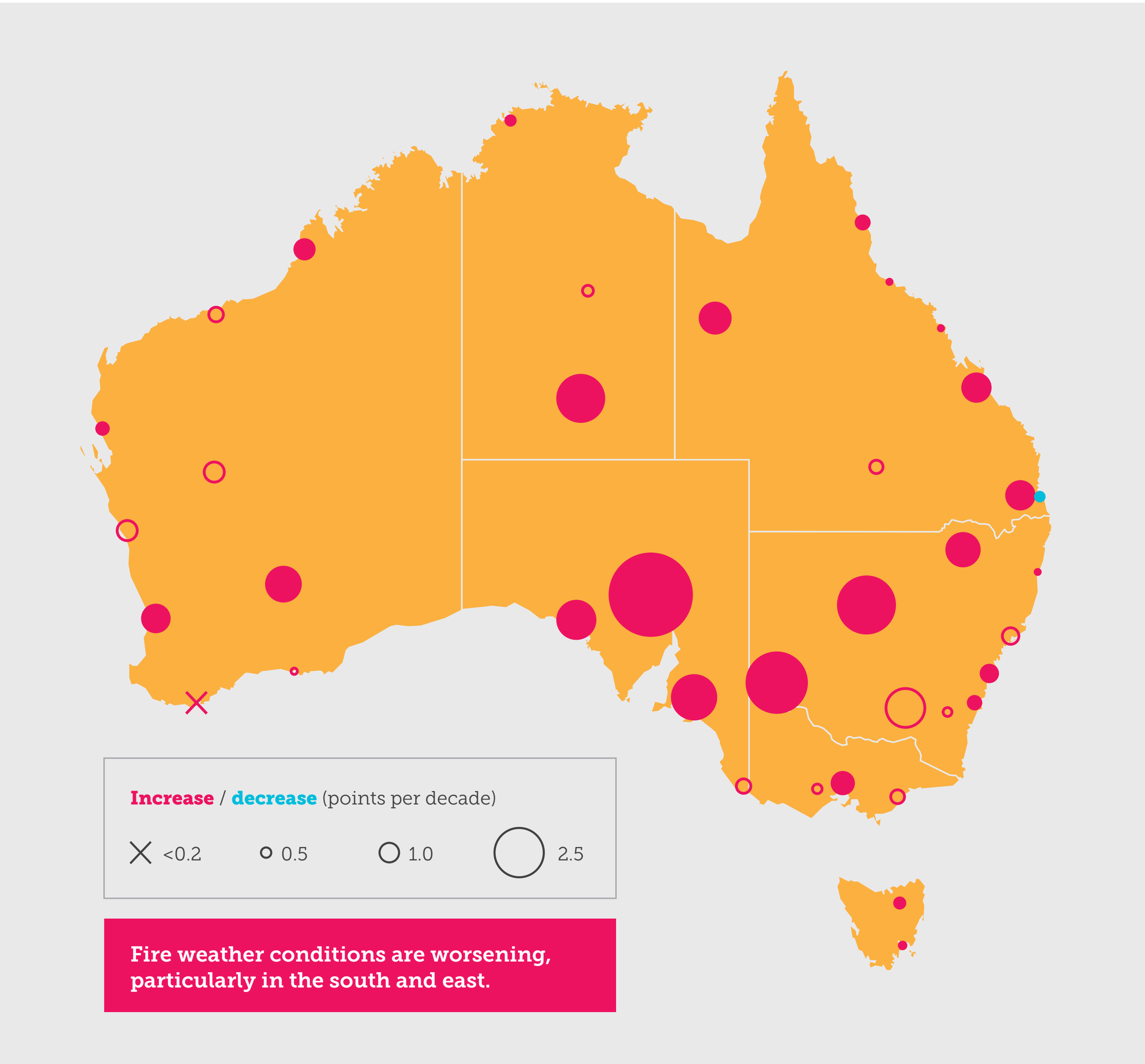

Figure 12: Trends in fire weather conditions from 1974 to 2015 (CSIRO and BoM 2015). Fire weather conditions, measured by the Forest Fire Danger Index (FFDI), are worsening in Australia, particularly in the south and east (Clarke et al. 2013).

During the period 1973-2009, the area burned in southeast Australia has increased in seven out of eight forest biomes (Bradstock et al. 2014). Since the start of the 21st century, large and uncontrollable fires destroyed 500 houses in Canberra in 2003, bushfires in Victoria in 2009 claimed 173 lives and destroyed over 2,000 houses, and in 2013 large fires in Tasmania destroyed nearly 200 properties and forced the evacuation of hundreds of people from the Tasman Peninsula.

The West Australia town of Yarloop, located on the coast south of Perth, experienced one of Australia's worst bushfires in 2016. With minimal warning, the fires reached Yarloop and destroyed the entire town centre (ABC 2016a). 121 homes were destroyed and approximately 67,000 hectares of land were burned (ABC 2016a). The fire was so intense that it created its own weather system, causing rainfall and triggering extensive lightning. The bushfire occurred during a strong El Niño event, bringing warmer and drier weather to western Australia (BoM 2016d), in addition to the long-term trend of a warming climate.

The impacts of a changing climate on bushfire regimes are complex. A fire needs to be started (ignition), it needs something to burn (fuel), and it needs conditions that are conducive to its spread (weather) (Bradstock et al. 2014; Figure 13). While a fire must be ignited (by humans or lightning), the main determinants of whether a fire will take hold are the condition of the fuel and the weather, which are linked. The influence of climate change on the amount and condition of the fuel is complex. For example, increases in rainfall may dampen the bushfire risk in one year by keeping the fuel load wetter, but increase the risk in subsequent years by enhancing vegetation growth and thus increasing the fuel load in the longer term. It is clear, however, that climate change is driving up the likelihood of dangerous fire weather. At higher temperatures, fuel is 'desiccated' and is more likely to ignite and to continue to burn (Geoscience Australia 2015). In addition, fires are more likely to break out on days that are very hot, with low humidity and high winds – that, is high fire danger weather (Clarke et al. 2013).

As discussed in Section 2.1, heatwaves are becoming hotter, longer and more frequent, which is contributing to an increase in dangerous bushfire weather. Also, over the past several decades in the southeast and southwest of Australia, there has been a drying trend characterised by declining rainfall and soil moisture (CSIRO and BoM 2014). Contributing to this drying trend is a southward shift of fronts that bring rain to southern Australia in the cooler months of the year (CSIRO and BoM 2015). In very dry conditions, with relative humidity less than around 20%, fuel dries out and becomes more flammable (BoM 2009). Jolly et al. (2015) and Williamson et al. (2016) highlighted that the combination of droughts and heatwaves contribute significantly to particularly bad fire seasons in Australia's southeast. A study into forested regions of Australia found that, in the majority of cases, years with drought conditions resulted in a greater area of burned land (Bradstock et al. 2014).

Climate change is driving up the likelihood of dangerous fire weather.

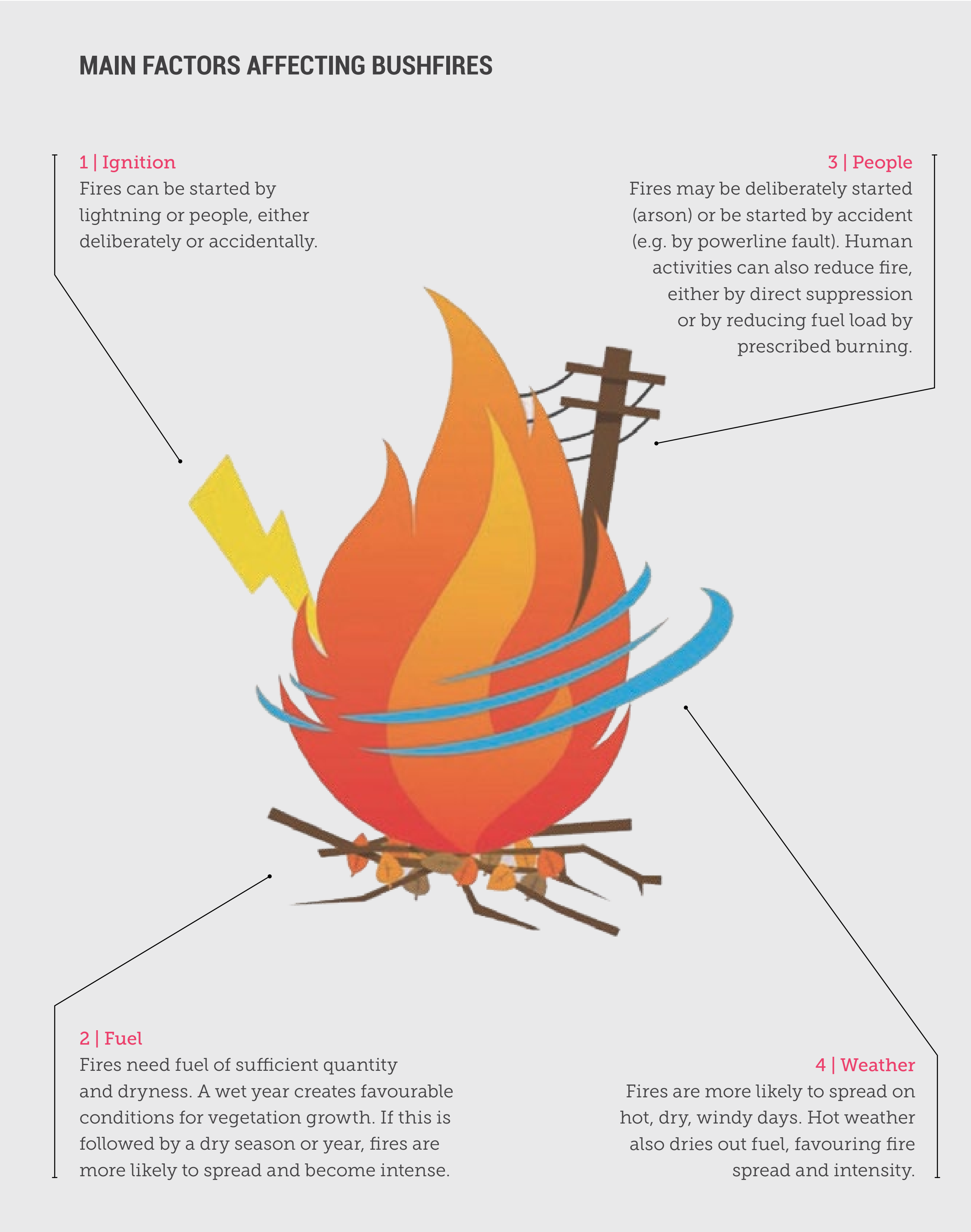

Figure 13: The main factors affecting bushfires: (1) ignition, (2) fuel, (3) people and (4) weather (Bradstock 2010; Climate Council 2015).

While there have been relatively few attribution studies for bushfires, those that have been undertaken show that the risk in North America is increasing as a result of climate change. Northern California experienced its second largest fire season in 2014 in terms of area burned. Yoon et al. (2015) showed that the risk of bushfires has increased due to human-induced climate change. Further north, climate change increased the risk of the severe 2015 fire season in Alaska by 34-60%, and burned the second largest area since records began in the 1940s (Partain Jr et al. 2016). Attribution of bushfires in Australia to climate change is harder because of our highly erratic climate and short length of historical records (Williamson et al. 2016). However, severe ecological impacts of 21st century fires in the Victorian Alps and Tasmania (Figure 14), unprecedented in recent history, is consistent with climate change (Bowman and Prior 2016).

Figure 14: Bushfire rages through Lake Repulse/Meadowbank area in Tasmania in January, 2013.

2.3 Drought

Australia is the driest inhabited continent on Earth, with some of the world's most variable rainfall and stream flow (DFAT 2014). Drought has deeply affected Australia throughout its history. The Millennium Drought from 1996-2010 serves as a recent reminder of the wide-reaching impacts that drought can have on Australia's people and environment (Kiem et al. 2016; Figure 15).

Drought can be termed an extreme climate event, because it can last for much longer time periods than extreme weather events, in the order of years to decades. Drought is defined as a period of abnormally long dry weather compared to the normal pattern of rainfall over at least three months (BoM 2013c).

Figure 15: Lake Eppalock only 7% full in 2007 during the Millennium Drought.

Whilst some parts of Australia are getting wetter, particularly the northwest of the continent, it is likely that climate change is making drought worse in the southeast and southwest, some of the most populous and agriculturally productive regions (Climate Council 2015b; CSIRO and BoM 2016). There has been a decline of around 11% since the mid-1990s in the April–October growing season rainfall in southeast of Australia (Figure 16). This period encompasses the Millennium Drought, with low annual rainfall totals across the region from 1996 to 2010. The drying trend is particularly strong between May and July over southwest Western Australia, with rainfall since 1970 around 19% less than the long-term average. The recent drying trend across southern Australia marks a record-breaking large-scale change in rainfall since national records began in 1900 (CSIRO and BoM 2016).

Evidence for the influence of climate change on observed drought patterns is strongest for southwest Western Australia and the far southeast of the continent, including Victoria and southern parts of South Australia (CSIRO 2012). The link is related to the southward shift of the fronts from the Southern Ocean that bring rain across southern Australia during the cool months of the year (winter and spring) (CSIRO and BoM 2015). This shift, which is consistent with the changes in patterns of atmospheric circulation expected in a warming climate system, has led to the observed declines in rainfall in the southwest and southeast of the continent and the resulting drought conditions (Timbal and Drowdowsky 2012).

It is likely that climate change is making drought worse in the southeast and southwest of Australia, some of the most agriculturally productive regions in the country.

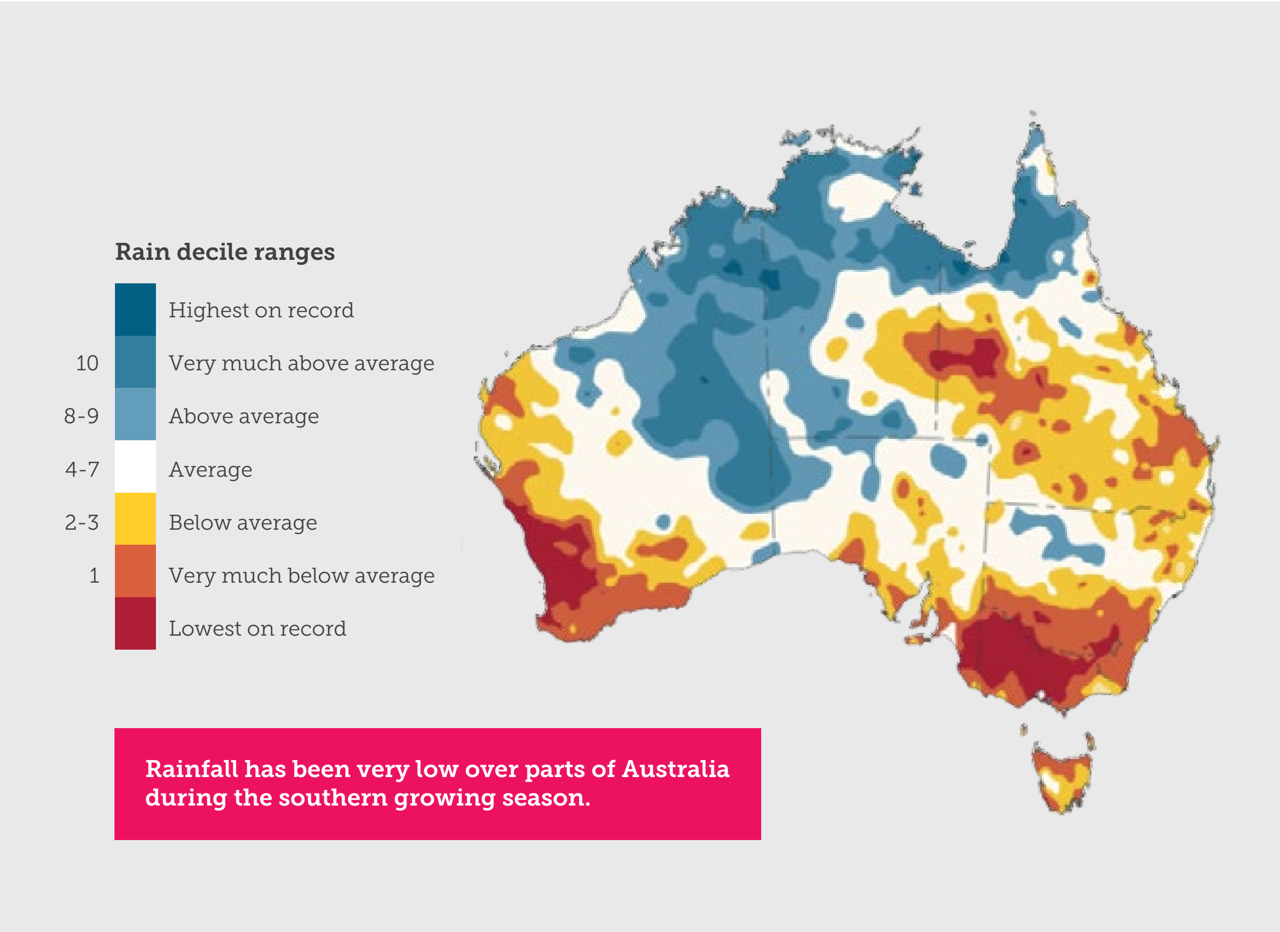

Figure 16: Southern growing season (April–October) rainfall deciles for the last 20 years (1996–2015) (CSIRO and BoM 2016). Note this map does not include the heavy 2016 rains in northern Queensland. The decile map shows the extent that rainfall is above average, average, or below average from the specified time period, in comparison with the entire national rainfall record from 1900.

2.4 Extreme Rainfall

As greenhouse gases increase in the atmosphere, primarily carbon dioxide from the combustion of fossil fuels, the climate system is warming because these gases are trapping more heat. The oceans are also warming, especially at the surface, and this is driving higher evaporation rates that, in turn, increases the amount of water vapour in the atmosphere (Figure 17). In addition, a warmer atmosphere can hold more water vapour, leading in turn to more intense rainfall. The 1°C temperature rise that has already occurred, together with increasing evaporation, has led to an increase of about 7% in the amount of water vapour in the atmosphere (Hartmann et al. 2013).

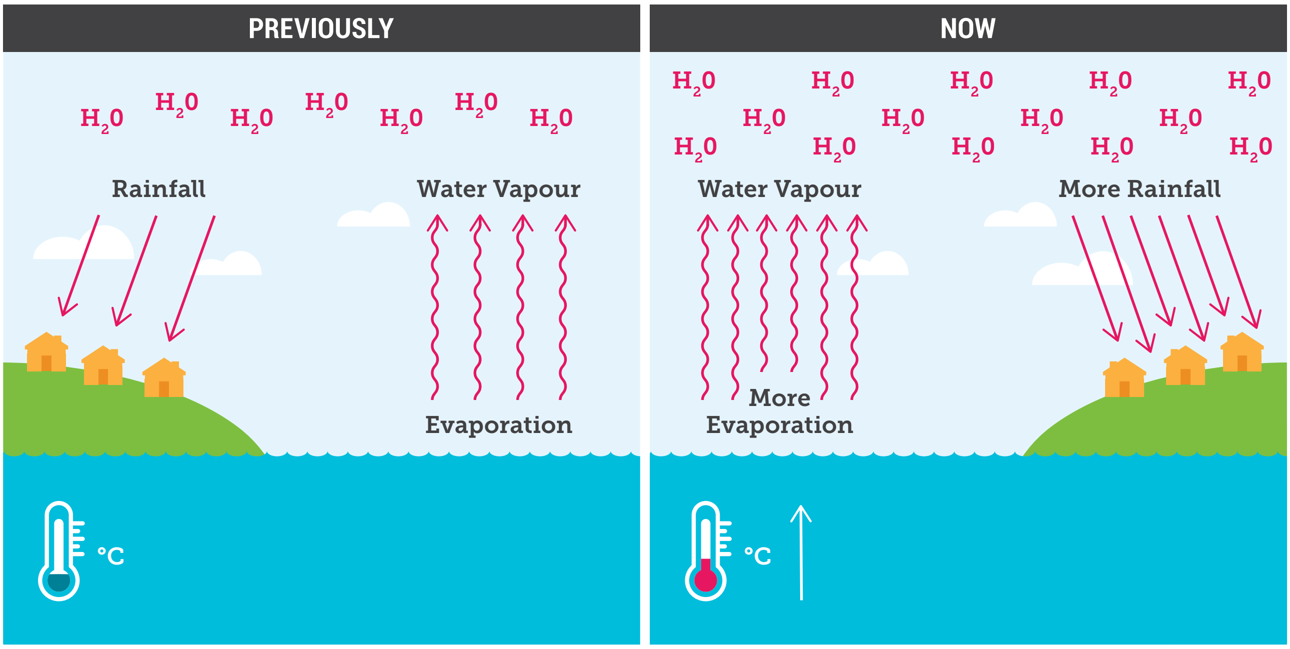

Figure 17: The influence of climate change on the water cycle. Left: The pre-climate change water cycle. Right: The water cycle operating under higher surface and ocean air temperatures, leading to more water vapour (H_2O) in the atmosphere, and in turn, more rainfall (Climate Commission 2013).

Greenhouse gas emissions are warming the climate system, increasing evaporation and the amount of water vapour in the atmosphere, in turn leading to more intense rainfall.

A global analysis has shown that during the 1951-2010 period there are more areas around the globe with significant increases in heavy precipitation events than with decreases (Donat et al. 2013a). The incidence of heavy rainfall events is also changing in different regions of Australia. There is a long-term trend (1910-2015) of increases in extreme one-day rainfall in northwest Australia and declines in southern Australia, most notably in the southwest (BoM 2016e; Donat et al. 2013b; Figure 18). These findings are consistent with the changing pattern of annual average rainfall across Australia, where southeast and southwest Australia are experiencing a decrease and the northwest is experiencing an increase (BoM 2013c). An increasing trend in short duration (less than a day/hourly) rainfall extremes in Australia is stronger than for longer duration events (Westra and Sisson 2011; Jakob et al. 2011).

While extreme rainfall trends are less clear in Tasmania than in other parts of Australia (Figure 18), heavy rainfall in the northern part of the state in late January 2016 resulted in the highest two-day rainfall in Launceston on record, with rain totalling 140 mm in the city (BoM 2016f). A daily rainfall record was also set with a total of 85.8 mm (BoM 2016f). The downpours resulted in flash flooding, causing road closures and damage to homes (The Examiner 2016). This extreme rainfall was influenced by exceptionally high local sea surface temperatures of more than 2°C above average off the eastern and southern coasts of Tasmania (BoM 2016f), which resulted in a marine heatwave (see Section 3.1). Marine heatwaves are becoming more common as ocean waters warm over the long-term (CSIRO and BoM 2016). Unusually warm waters were likely to have increased local rainfall due to increased evaporation (BoM 2016f).

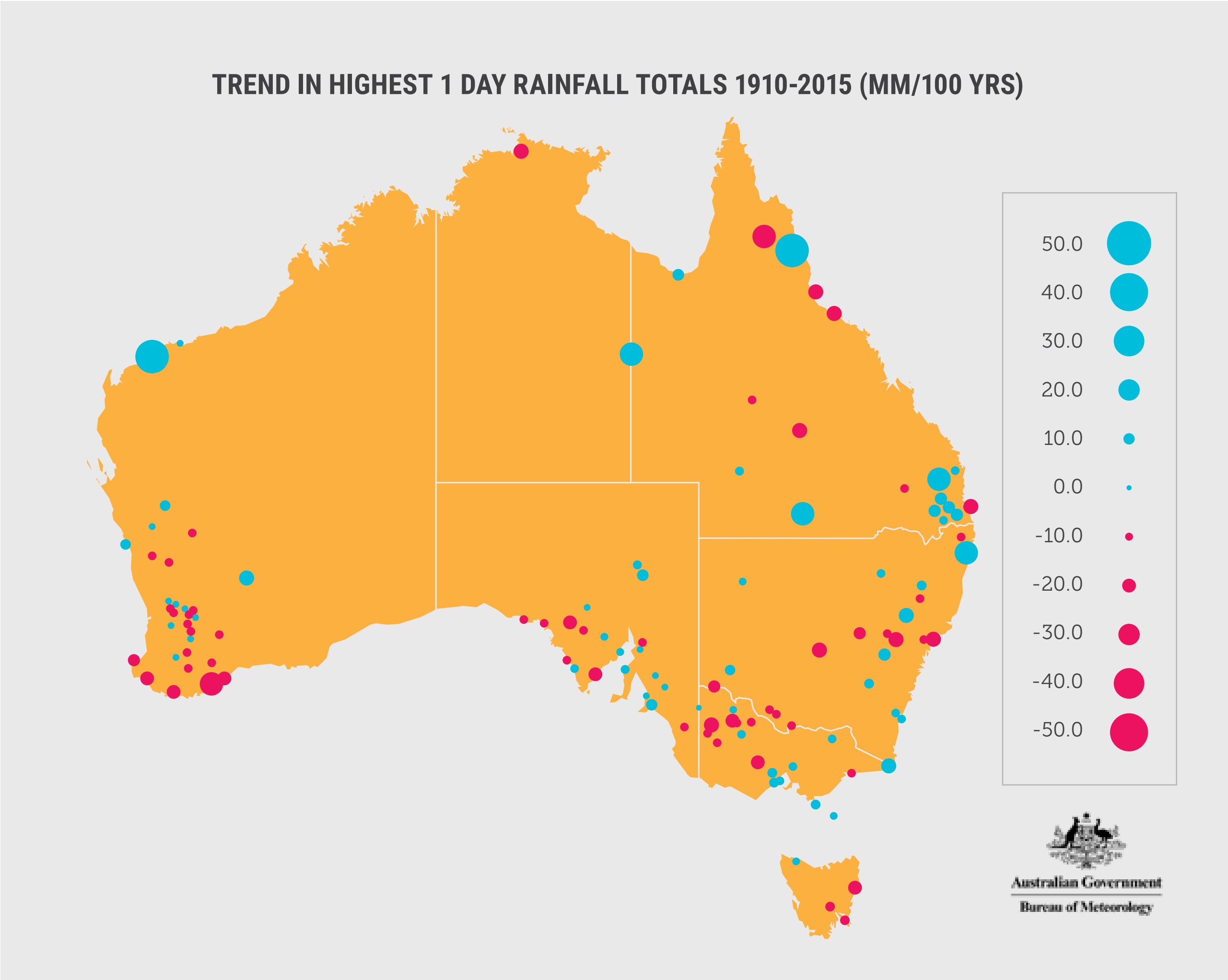

Figure 18: Trends in extreme one-day rainfall patterns in Australia, 1910-2015 (BoM 2016e).

Recent attribution studies have drawn links between extreme rainfall in Australia and climate change. The warming trend in sea surface temperatures to the north of Australia may have contributed, by up to 20%, to the magnitude of the heavy rainfall of 2010-11 in eastern Australia (Hendon et al. 2014). Another study found that the high sea surface temperatures increased the probability of above average rainfall in eastern Australia in March 2012 by 5-15% (Christidis et al. 2013). However, the results of different attribution studies differ between different regions and for different extreme rainfall definitions (Lewis and Karoly 2014). From a global perspective, it has been recently shown that in southeast China, climate change increased the probability of intense, short-duration rainfall, which caused severe flooding in May 2015 (Burke et al. 2016).

2.5 Storms

In this section, we classify storms into the following: (i) hail and thunderstorms, (ii) tropical cyclones (low pressure systems that form over warm, tropical waters and have gale force winds), and (iii) extra-tropical cyclones (known as "east coast lows" along Australia's east coast) (Climate Council 2016c).

At present, observational records are not long enough to discern trends in either the frequency or intensity of thunderstorms and hail. However, climate change is very likely increasing the intensity of these storms because, as noted earlier, they are now occurring in a more energetic, moisture-laden atmosphere. A recent example is the Melbourne 'thunderstorm asthma' episode in mid-November 2016; Figure 19). During such an event, pollen grains can rupture and release allergen-carrying granules that can be inhaled into the lower airways causing asthmatic reactions (D'Amato et al. 2007). The rare phenomenon of 'thunderstorm asthma' was responsible for nine deaths and over 8,500 patients were hospitalised. Paramedics who responded to the event described it as severe as a bushfire or terrorist attack (The Guardian 2016a).

Figure 19: Thunderstorms in Melbourne in November brought a rare health phenomenon known as thunderstorm asthma, which resulted in nine deaths and thousands of hospitilisations.

Trends in tropical cyclone frequency and intensity are difficult to discern for the Australian region due to the short observational records, as well as high year-to-year variability. While some trends have been identified in tropical cyclone data in the past few decades, such as a statistically significant increase in intense cyclone activity in the North Atlantic region since the 1970s (Kossin et al. 2007; IPCC 2013; Figure 20), in other regions the identification of statistically significant trends is limited by the lack of long-term, consistent observational data. This is the case in Australia, where for the 1981 to 2007 period, no significant trends in the number of cyclones or their intensity were found (Kuleshov et al. 2010), although a comparison between tropical cyclone numbers in 1981-82 to 2012-13 shows a decreasing trend (Dowdy 2014).

Climate change is likely to affect tropical cyclone behaviour in two ways. First, the formation of tropical cyclones most readily occurs when there are very warm conditions at the ocean surface and when the vertical gradient is strong. As the climate continues to warm, the difference between the temperature near the surface of the Earth and the temperature higher up in the atmosphere, is likely to decrease as the atmosphere continues to warm. As this vertical gradient weakens, it is likely that fewer tropical cyclones will form (DeMaria et al. 2001; IPCC 2012). Second, the increasing temperature of the surface ocean affects the intensity of cyclones (along with changes in upper atmosphere conditions), both in terms of maximum wind speeds and in the intensity of rainfall that occurs in association

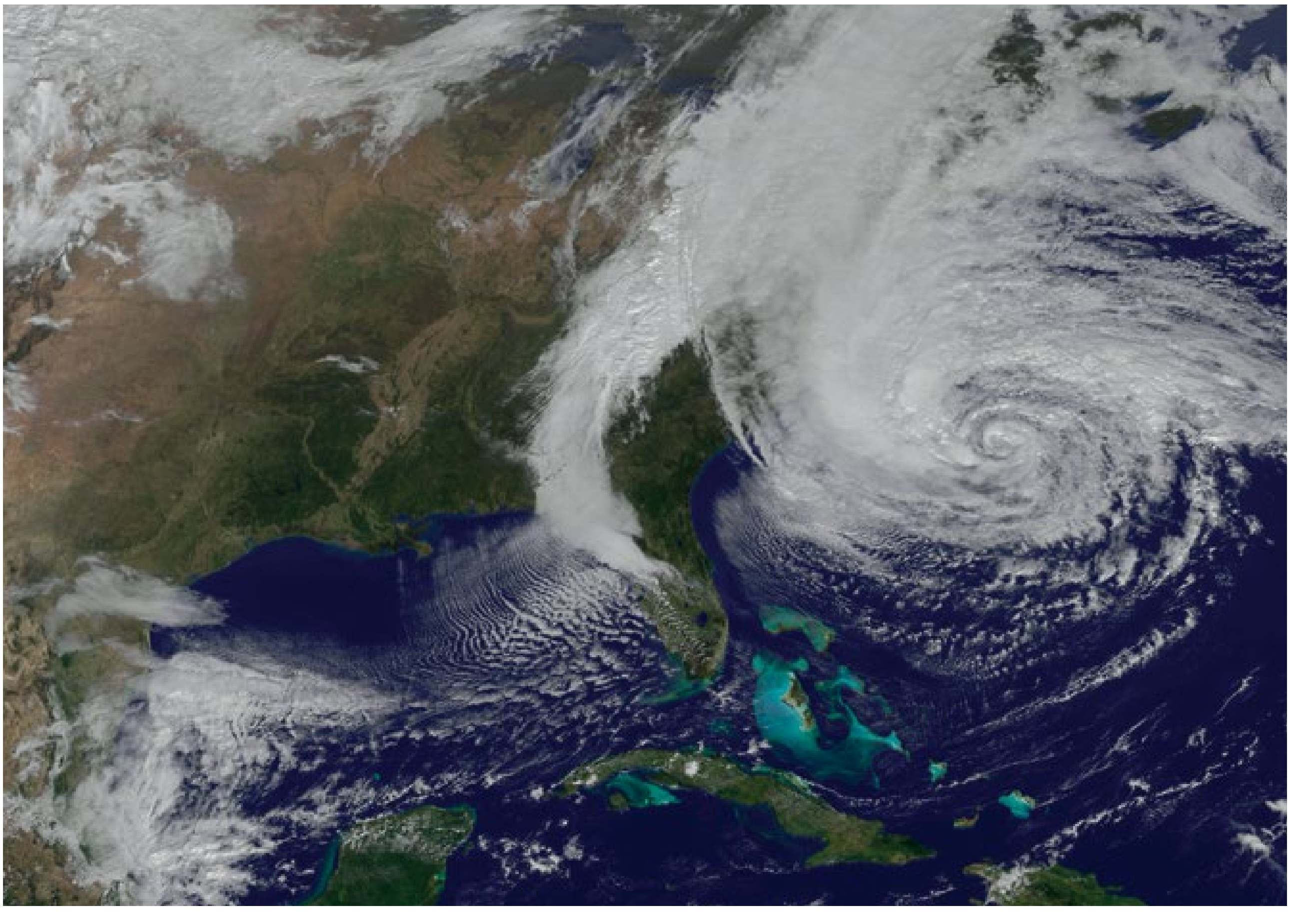

Figure 20: Hurricane Sandy developing in the Atlantic before it struck the United States east coast. Increases in tropical cyclone intensity have been observed in the North Atlantic region. Note that the American term 'hurricane' refers to the same meteorological phenomenon as the standard term 'tropical cyclone' (also called 'typhoons' in the northeast Pacific basin).

with the cyclone. This is because the storms draw energy from the surface waters of the ocean, and as more heat (energy) is stored in these upper waters, the cyclones have a larger source of energy on which to draw (Emanuel 2000; Wing et al. 2007).

Deep low-pressure systems with high winds and heavy rainfall can also develop outside of the tropics, where they are known as extra-tropical cyclones. When such storms occur along the east coast of Australia, they are commonly known as east coast lows.

Observations show a slight decreasing trend in the number of east coast lows over the past several decades (Dowdy et al. 2013). Extra-tropical cyclones can also occur as deep low pressure systems from the Southern Ocean that can batter South Australia and Victoria, such as the storm that knocked out the electricity distribution system across South Australia in late September 2016 (Figure 21). This 1-in-50 year storm triggered 80,000 lightning strikes, carried wind gusts of up to 260 km/h and spawned tornadoes across the state.

Storms are now occurring in a more energetic, moisture-laden atmosphere – a recipe for more destructive storms.

Figure 21: A severe extra-tropical cyclone crossed South Australia in late September 2016, with 80,000 lightning strikes, golf-ball sized hailstones and damaging winds gusting up to 260 km/h. The storm knocked out the electricity distribution system, causing the entire state (1.7 million people) to lose power.

2.6 Sea-level Rise and Coastal Flooding

A high sea-level, coastal flooding or inundation event is caused by wind-driven waves or a storm surge, generally exacerbated by a high tide. A storm surge is a rise above the normal sea level resulting from strong, mainly onshore winds and/or reduced atmospheric pressure. Storm surges accompany tropical cyclones as they make landfall but can also be formed by intense low pressure systems in non-tropical areas, such as east coast lows in the Tasman Sea.

Storm surges can cause extensive flooding of coastal areas (Climate Council 2014b). The area of sea water flooding may extend along the coast for hundreds of kilometres, with water pushing several kilometres inland if the land is low-lying. As the sea level continues to rise, these storm surges are becoming more damaging as they are able to penetrate further inland. The worst impacts of a storm surge occur when it coincides with a particularly high tide.

It is likely that climate change is contributing to the increasing number of inundation events through an increase in sea level (IPCC 2012; Figure 22), which is exacerbating the impact of flooding on coastlines around the world, including Australia.

Climate change is increasing the sea level through both the thermal expansion of a warming ocean and the flow of water into the ocean from melting of continental glaciers and polar ice sheets. Sea levels have risen about 20 cm since the mid-19th century (IPCC 2013). The rate of sea-level rise over the 20th century is considered extremely likely to be faster than during any other period in the last 2,700 years (Kopp et al. 2016).

Climate change is increasing sea levels, which is exacerbating the impact of coastal flooding on coastlines around the world, including Australia.

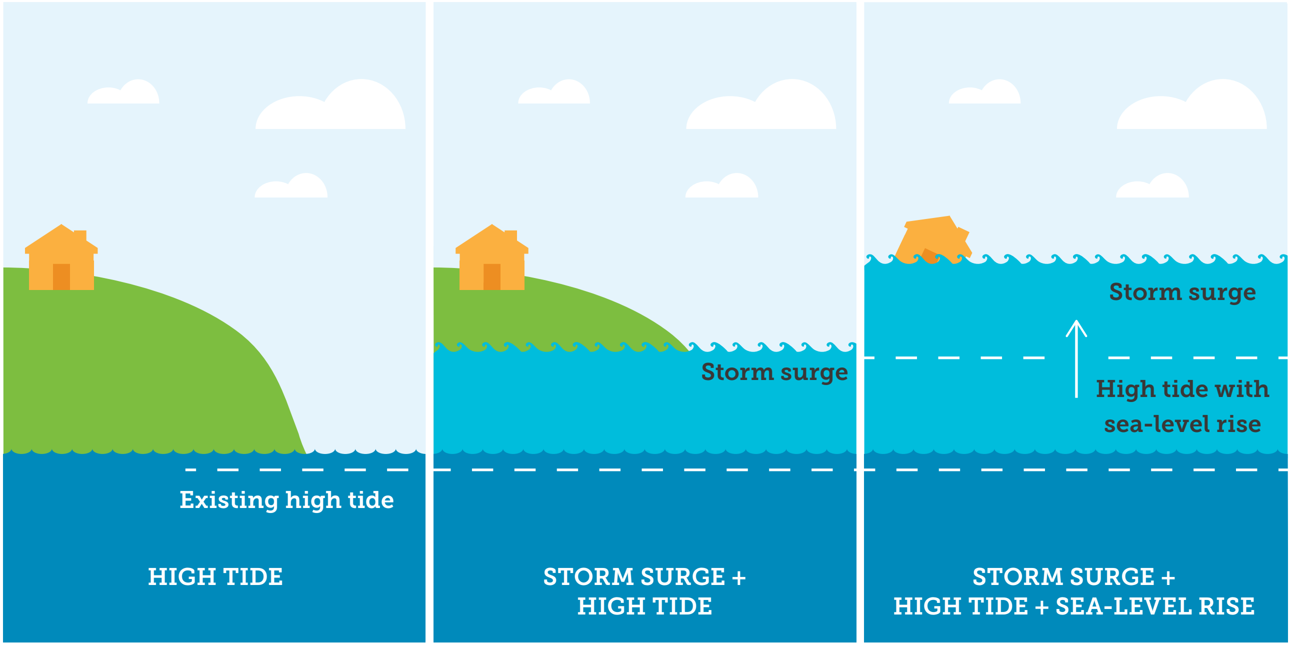

Figure 22: Climate change increases the base sea-level and thus exacerbates the effects of a storm surge on coastal flooding (Climate Commission 2013).

The effect of sea-level rise as a result of climate change, in combination with a king tide that caused the sea level to be well above its usual height, was evident when a strong east coast low struck the New South Wales coast in June 2016. Significant erosion of beaches occurred, most notably around Sydney, and loss of property culminated in an insurance bill of at least $235 million (ICA 2016b). Climate change likely made this east coast low particularly damaging to the New South Wales coastline not only because of higher sea levels but also because of more intense rainfall.

Several studies have investigated the links between sea-level rise and coastal flooding. In the United States, Strauss et al. (2016) demonstrated that 40-84% of the 8,700 total flood days since 1950 exceeded local 'nuisance[2]' flood thresholds as a result of human-induced climate change. Their research shows an increasing trend in the number of flood days due to sea-level rise. During the 1955–1964 period, 45% of flood days occurred as a result of sea-level rise, and this increased to 76% during the 2005–2014 period (Strauss et al. 2016). This trend is consistent with global trends identified by Slangen et al. (2016), who found that before 1950, anthropogenic emissions of greenhouse gases accounted for 15% of sea-level rise, while by 2000 the warming caused by greenhouse gases contributed 72% of the observed sea-level rise. The probability of specific high sea-level events occurring, such as the 0.57 cm tidal flood in the Miami region in 2015 (Figure 23), has increased by more than 500% since 1994, due to a 10.9 cm sea level rise-related increase in monthly highest tides (Sweet et al. 2015).

[2] 'nuisance' flooding causes public inconveniences such as frequent road closures, overflowing storm drains, and other impacts on infrastructure (NOAA 2014b).

Climate change increases the base sea-level and thus exacerbates the effects of a storm surge on coastal flooding.

Figure 23: Miami Beach tidal flooding. Portable pumps are being used to protect coastal property and homes from flooding. These events are becoming more common as sea levels rise.

3. Impacts of Extreme Weather Events

As extreme weather events become more frequent and/or more intense, so do their impacts. This section discusses some of the main impacts associated with extreme weather events. In particular, health, environmental and economic impacts are outlined here, although the impacts discussed are by no means exhaustive.

3.1 Extreme Heat and Heatwaves

3.1.1 Land

Health Impacts

Heatwaves are a silent killer (Figure 24). Major heatwaves have caused an estimated 2,900 deaths in Australia in the 1890-2013 period – more deaths than bushfires, tropical cyclones, earthquakes, floods and severe storms combined (DIT 2013). Children, the elderly, people with existing health issues, and workers with heat-exposed jobs are the most vulnerable to extreme heat.

Figure 24: Warming temperatures have wide-reaching impacts, especially on human health.

Major heatwaves in Australia have caused more deaths than storms, bushfires, flooding and earthquakes combined.

Over the last decade, severe heatwaves around Australia have resulted in deaths and an increased number of hospital admissions for heart attacks, strokes, kidney disease and acute renal failure. Table 1 provides examples of the nature of heat impacts on health. During severe heatwaves in southeastern Australia in 2009, Melbourne experienced three consecutive days at or above 43°C in late January. There were 980 heat-related deaths during this period, 374 more than would have occurred on average for that time of year (DHS 2009). During the Brisbane heatwave of 7-26 February 2004, the temperature ranged from 26°C to 42°C. Overall deaths increased by 23% (excluding injury and suicide) compared with the death rate during the same period in 2001-2003, when the temperature ranged from 22°C to 34°C (Tong et al. 2010).

Table 1: Illustrative examples of the impacts of recent Australian heatwaves on health services and mortality (Climate Council 2015). Note that 'excess deaths' refers to the number of deaths estimated to be additional to those which would have been expected during this period without an extreme heat event. Data sourced from DHS (2009), Nitshke et al. (2011), Schaffer et al. (2012) and Wang et al. (2013).

City	Month	Ambulance callouts	Emergency department presentations	Excess deaths
Melbourne	January 2009	46% increase in ambulance callouts	12% increase in emergency department presentations	374 excess deaths were recorded, a 62% increase on the previous year
Sydney	February 2011	14% increase in ambulance callouts, with 116 callouts specifically related to heat	104 people in emergency departments for heat effects and 236 for dehydration	The number of deaths increased by 13%
Adelaide	January 2009	16% increase in ambulance callouts	13% increase in emergency department presentations	32 excess deaths recorded, with a 37% increase in total mortality in the 15-64 age group
Brisbane	February 2004		More than a 30% increase in emergency department presentations	64 excess deaths recorded within the heatwave period

Environmental Impacts

In periods of extreme heat, birds may lose up to 5% of their body mass per hour and rapidly reach their limit of dehydration tolerance (McKechnie and Wolf 2010). In January 2009, a heatwave where air temperatures were above 45°C for several consecutive days caused the deaths of thousands of birds in Western Australia, mostly zebra finches and budgerigars (McKechnie et al. 2012). Another event in January 2010, where temperatures up to 48°C were combined with very low humidity and a hot northerly wind, had similar impacts, with the deaths of over 200 of the endangered Carnaby's Black Cockatoo recorded near Hopetown, Western Australia (Saunders et al. 2011).

Flying foxes are also particularly susceptible to extreme heat events (Figure 25). Exposure to air temperatures over 40°C can lead to heat stress and death from dehydration, especially when very hot conditions are accompanied by dry weather. Lactating females and their young are the most at risk. Since 1994, more than 30,000 flying foxes have died in heatwaves at sites along the east coast of Australia. On 12 January 2002, in a single heatwave event, over 3,500 flying foxes were killed in nine colonies along the New South Wales coast when temperatures exceeded 42°C (Welbergen et al. 2007). During the heat of January and February 2009, nearly 5,000 flying fox deaths were recorded at a single site – Yarra Bend Park in Victoria (DSE 2009). On January, 2014, an estimated 45,000 flying foxes died in a single day southeast QLD when temperatures reached over 44°C (Welbergen et al. 2014).

Figure 25: Grey-headed flying foxes. Flying foxes are particularly susceptible to extreme heat events.

Some of Australia's most iconic marsupials could also be at risk during extended periods of hot weather. For example, the green ringtail possum, which is restricted to rainforests above 300 m in Queensland's Wet Tropics, is unable to control its body temperature if subjected to air temperatures greater than 30°C for five hours per day, over four to six days (Krockenberger et al. 2012). Hotter, drier conditions in the future are predicted to put this and many other rainforest marsupials at increased risk of population decline and eventual extinction (Williams et al. 2003). Heatwaves, combined with extended droughts, have also been observed to cause mass mortality in koalas (Gordon et al. 1988), affect forest productivity (Ciais et al. 2005), frog reproduction (Neveu 2009), cyanobacterial blooms in lakes (Huber et al. 2012) and increase the success of invasive species (Daufresne et al. 2007).

Economic Impacts

Heatwaves in Australia during 2013-2014 cost approximately $8 billion through absenteeism and a reduction in work productivity (Zander et al. 2015). This is the equivalent to 0.33 to 0.47% of Australia's gross domestic product (GDP). Zander et al. (2015) found that 70% of about 1,700 survey respondents were less productive because of heat stress. Impacts of hot weather include higher work accident frequency because of concentration lapses, and poor decision-making ability due to time perception change and higher levels of fatigue (Morabito et al. 2006; Tawatsupa et al. 2013; Tamm et al. 2014).

During heatwaves critical infrastructure can also be severely affected. For example, during the January 2009 heatwave in Melbourne, financial losses were estimated to be $800 million, mainly caused by power outages and disruptions to the transport network (Chhetri et al. 2012). During this time, Victoria broke previous electricity demand records by approximately 7% (QUT 2010).

3.1.2 Marine

Environmental Impacts

The environmental impacts of marine heatwaves in 2016 have been devastating. Australia's iconic reefs, namely the northern part of the Great Barrier Reef in Queensland and the Kimberley region in Western Australia, experienced severe coral bleaching. On the Great Barrier Reef, 93% of individual reefs experienced some degree of bleaching (Coral CoE 2016), with two-thirds of the coral subsequently dying in the most pristine northern sector (ARC Coral Reef Studies 2016) just north of Port Douglas; fortunately on this occasion, the area south of Cairns escaped significant mortality (GBRPMA 2016).

Coral reefs in northwestern Australia, including those in the Kimberley, Christmas Island, Scott and Seringapatam regions, were also bleached by record-breaking ocean temperatures in early 2016. The most severe bleaching occurred in the Kimberley, where in general reefs suffered about 50% bleaching, with up to 60 to 90% in shallow lagoon waters (Schoepf 2016). While the iconic Ningaloo Reef escaped severe bleaching during this event, it was severely affected in 2011 by another marine heatwave (Figure 26). The impacts of the 2011 event were unprecedented and included widespread fish and invertebrate mortality, habitat range changes of seaweeds, whale sharks and mantra rays, as well as tropical fish occupying more southern waters (Pearce and Feng 2013).

Figure 26: Coral bleaching on the Ningaloo Reef in 2011. The unprecedented marine heatwave in Western Australia caused the first-ever reported bleaching of Ningaloo reef.

Economic Impacts

Marine heatwaves can have a significant impact on the economy. For example, a marine heatwave persisting into March 2016 off the east coast of Tasmania devastated the oyster industry from a new disease thought to be linked to unusually warm water temperatures (Figure 27). It is estimated that this extreme event caused the loss of oyster beds, at least 80 jobs and $12 million to the industry (Hobday et al. 2016). While the impact on the tourism industry of the recent coral bleaching on the Great Barrier Reef is yet to be quantified, a recent survey indicates that two-thirds of tourists 'want to see it before it's gone'. This survey of over 200 respondents was carried out before the bleaching event began (Piggott-McKellar and McNamara 2016). This 'last chance' tourism, while in the short-term may continue to contribute to the local economy, over the long-term may not be sustainable. Given that the Great Barrier Reef employs about 69,000 people (Deloitte Access Economics 2013) and contributes around $7 billion to the national economy (Jacobs 2016), the loss in tourism as a result of marine heatwaves could be dire both for the region and the country in general.

Marine heatwaves are increasing the risk of diseases to local fisheries industries, job losses, and loss of tourism revenue.

Figure 27: Oyster beds in Tasmania. A marine heatwave off the east coast of Tasmania in 2016 resulted in the loss of oyster beds, 80 jobs and $12 million to the industry.

3.2 Bushfires

Environmental Impacts

More than two million people live in high bushfire risk areas in Australia (IAG 2016). This means that a considerable proportion of the Australian population are at risk from the health impacts of bushfires, including effects on both physical and mental health, in addition to deaths (Johnston 2009). Tragically, bushfires have accounted for 825 civilian and firefighter deaths in Australia since 1901, with more than two-thirds of all civilian fatalities (454 out of a total of 674) occurring in Victoria (Blanchi et al. 2014).

In addition to fatalities from the fires themselves, bushfire smoke can seriously affect human health (Figure 28). Smoke contains not only respiratory irritants, but also inflammatory and cancer-causing chemicals (Bernstein and Rice 2013).

Smoke can be transported in the atmosphere for hundreds or even thousands of kilometres from the fire front, exposing large populations to its impacts (Dennekamp and Abramson 2011; Bernstein and Rice 2013; Figure 29). The annual health costs of bushfire smoke in Sydney have been estimated at $8.2 million per annum (adjusted to 2011 values) (Deloitte Access Economics 2014). In Melbourne, cardiac arrests increase by almost 50% on bushfire smoke-affected days (Dennekamp et al. 2011), while an extreme smoke event in the Sydney Basin in May 2016 from fires designed to reduce fire hazard, is thought to have caused the premature death of 14 people (Broome et al. 2016). The impacts of bushfire smoke in the community are also uneven, with the elderly, infants and those with chronic heart or lung diseases at higher risk (Morgan et al. 2010).

Figure 28: Bushfire smoke from the Blue Mountains blankets Sydney in 2013.

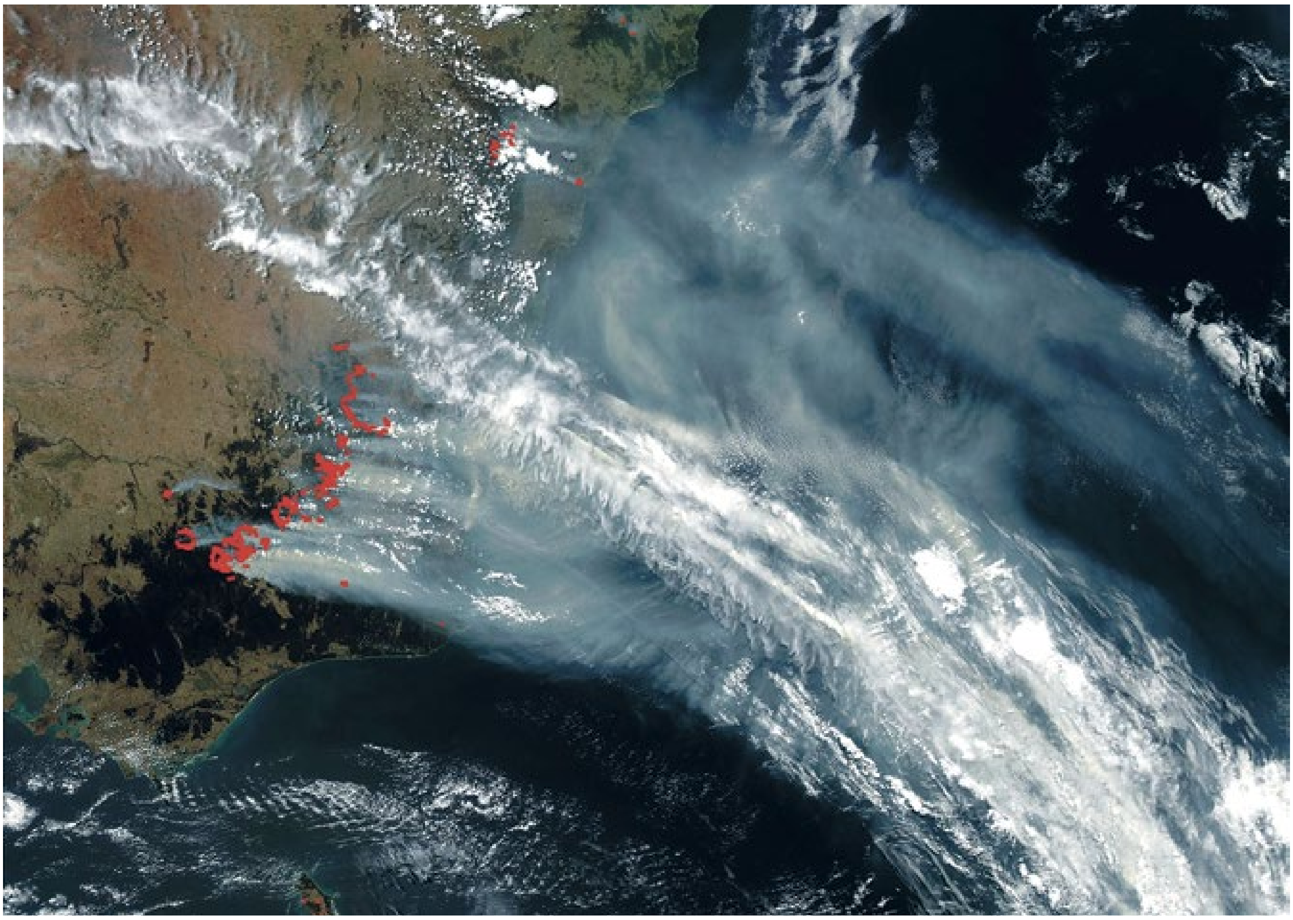

Figure 29: A satellite image of southeastern Australia on 19 January 2003 showing active fires (highlighted in red) of the Canberra-alpine bushfire event and smoke plumes streaming southeastward across the Tasman Sea (Steffen et al. 2004).

The trauma and stress of experiencing a bushfire can increase depression, anxiety and other mental health issues, both in the immediate aftermath of the trauma and for months or years afterwards (McFarlane and Raphael 1984; Sim 2002; Johnston 2009; Whittaker et al. 2012). A study conducted three-four years after the Black Saturday bushfires in Victoria found that some members of the affected community developed Post Traumatic Stress Disorder (PTSD), major depressive episodes and increased alcohol use (Bryant et al. 2014). A study of over 1,500 people who experienced losses in the 1983 Ash Wednesday bushfires found that after 12 months, 42% were suffering a decline in mental health ('psychiatric morbidity') (McFarlane et al. 1997). Post-traumatic stress, major depression, anxiety and suicide can also manifest among firefighters, sometimes only becoming evident many months after an extreme event (McFarlane 1988; Cook and Mitchell 2013).

Environmental Impacts

Ecosystems in which the natural fire intervals are very long (greater than 100 years) can undergo substantial change if fire frequency increases. For example, after successive fires in 2003 and 2006–07 in Victoria, Acacia shrublands have replaced some mountain and alpine ash forests because there was insufficient time between fires for the ash trees to become reproductively mature (Lindenmayer et al. 2013; Bowman et al. 2013). This change in vegetation has important flow-on effects for other species, especially the approximately 40 vertebrate species that rely on the hollows of 120–150 year old mountain ash trees for habitat, such as the endangered Leadbeater's possum (Figure 30). An estimated 42% of the possum's habitat was burned in the 2009 bushfires (Lindenmayer et al. 2013). Deliberate fuel reduction burning can also destroy habitats if not managed properly. For example, in the Shoalhaven region of New South Wales, the habitats of the threatened eastern bristlebird and the glossy black cockatoo have been considered at risk from hazard reduction burning (Whelan et al. 2009).

In 2016 over 20 separate fires in Tasmania caused considerable damage to fire-sensitive areas in the Central Highlands, West Coast and South West regions. Trees such as king billy and pencil pines, some estimated to be over 1,500 years old, were killed in the World Heritage Area wilderness, described by one ecologist as being like 'losing the thylacine' (SMH 2016).

Figure 30: The Black Saturday 2009 bushfires affected much of the habitat of the already endangered Leadbeater's possum.

Economic Impacts

Bushfires have also had a major impact in recent times in terms of lives lost and damage to property, forestry and livestock (Table 2). The 2009 Black Saturday fires in Victoria claimed 173 lives, killed 8,000-11,800 stock (Teague et al. 2010; Stephenson et al. 2013) and caused $1.3 billion of insured losses (ICA 2013; Box 3). This value is significantly less than the total economic cost of the fires, estimated to be at least $4 billion (Teague et al. 2010). Recent major bushfires near the Great Ocean Road at Christmas 2016 resulted in the destruction of 116 homes and caused $86 million in insured losses (EMV 2016; ICA 2016a). Projections by Deloitte Access Economics (2014) reveal that Australian bushfires cost approximately $380 million per annum, a figure incorporating insured losses and broader social costs. Even though Victoria comprises only 3% of the country's landmass, it has sustained around 50% of the economic damage from bushfires (Buxton et al. 2011). This is not surprising given that 17.5% of Victoria's population live in high to extreme bushfire risk local government areas (IAG 2016). Firefighting costs are also considerable. For instance, the 2016 wilderness fires in Tasmania cost approximately $55 million for the 60-day campaign (Tasmania Government 2016).

Large-scale, high intensity fires that remove vegetation expose top soils to erosion and increased runoff after subsequent rainfall (Shakesby et al. 2007). This can increase sediment and nutrient concentrations in nearby waterways, potentially making water supplies unfit for human consumption (Smith et al. 2011; IPCC 2014a). During the Black Saturday fires in 2009, 10 billion litres of Melbourne's drinking water were pumped to safer storage locations because of fears it would be contaminated (Johnston 2009). These bushfires affected about 30% of the catchments that supply Melbourne's drinking water. Melbourne Water estimated the post-fire recovery costs, including water-monitoring programs, to be more than $2 billion (WRF 2013). The 2016 Tasmanian wilderness fire caused more than $130 million in damages to roads, hydro-electric infrastructure and bridges (The Mercury 2016).

Bushfires in Australia cost approximately $380 million a year.

Table 2: The ten costliest bushfires in Australia for the 2001-2016 period, in chronological order.

Year	State	Name of event and location	Economic cost	Damages
2001	ACT	ACT Black Christmas bushfires	$131 million (2011$) (Deloitte Access Economic 2014)	750,000 ha land burnt
2001-02	NSW	44 LGAs in Greater Sydney, Hunter, North Coast, Mid North Coast, Northern and Central Tablelands	$131 million (NSW PRS 2014)	744,000 ha land burnt, 109 houses destroyed, 40 houses damaged, 6,000 stock lost (NSW PRS 2014)
2003	ACT/VIC	Canberra and Alpine bushfires	$660 million (2011$) (ICA 2013)*	5 deaths, more than 500 properties destroyed, 13,000 sheep and almost 4,000 cattle killed (Stephenson et al. 2013)
2009	VIC	Black Saturday bushfires: Churchill, Kilmore and Murrundindi, Vectis (Horsham), Coleraine, Weerite, Redesdale, Harkaway, Upper Ferntree Gully, Maiden Gully / Eaglehawk, Lynbrook / Narre Warren, Beechworth	$1.3 billion* (ICA 2013)	173 deaths (Teague et al. 2010; Stephenson et al. 2013), more than 2,000 houses destroyed (CFA 2012; Stephenson et al. 2013), 8,000-11,800 stock killed (Teague et al 2010; Stephenson et al. 2013)
2013	NSW	Blue Mountains, Port Stephens, Lake Munmorah, Hunter, Hawkesbury, Central Coast and Southern Highlands	$193 million* (ICA 2016c)	2 deaths, 118,000 ha burnt, 222 houses destroyed, 168 houses damaged (NSW PRS 2014)
2013	TAS	Tasmania Peninsula fires	$88 million* (ICA 2016c)	232 residential properties destroyed (ICA 2016c)
2014	WA	Perth Hills Bushfire, semi-rural suburbs	$87 million* (ICA 2016c)	55 homes destroyed in the Mundaring Shire (ICA 2016c)
2015	SA	Pinery Bushfires, areas to the north of Adelaide	$172 million* (ICA 2016c)	2 deaths, 90 structures lost, thousands of stock deaths and crops impacted (ABC 2015a; ICA 2016c)
2015	VIC	Wye River and Separation Creek	$110 million* (ICA 2016c)	116 homes destroyed (ICA 2016c)
2016	WA	Yarloop Bushfires	$71 million* (ICA 2016)	181 buildings destroyed in Yarloop town (ICA 2016)

* Note that these refer to insured losses only.

BOX 3: BLACK SATURDAY BUSHFIRES

The bushfires of Black Saturday, 7 February 2009, caused the deaths of 173 people, injured 414 people and destroyed 2,029 homes (PoV 2010; Figure 31). The Black Saturday fires also resulted in the deaths of 8,000-11,800 stock (Teague et al. 2010; Stephenson et al. 2013) and $1.3 billion of insured losses (ICA 2013). The extreme heat of early 2009 and the prolonged dry spell in the months preceding the fires provided the tinderbox conditions for Black Saturday. Victoria endured one of its most severe and prolonged heatwaves during the final week of January 2009. The temperature in Melbourne was above 43°C for three consecutive days for the first time since records began. Furthermore, little to no rain had fallen in the previous two months (PoV 2010).

On February 7 temperatures across Victoria reached at least 40°C (and over 46°C in Melbourne) and were accompanied by strong winds, creating extreme and unprecedented bushfire conditions (PoV 2010). The Forest Fire Danger Index (FFDI), a measure of bushfire threat, ranged from 120 to 190 at a number of sites (compared to a previously assumed maximum of 100). These ratings were much higher than the fire weather conditions on Black Friday 1939 or Ash Wednesday 1983 (Williams 2009). The weather conditions of Black Saturday were so extreme that they changed the way in which dangerous bushfire conditions are now rated, with the introduction of the Code Red (termed ‘catastrophic’ in some Australian states) Fire Danger Rating level.

Figure 31: An example from Kinglake in Victoria of the disturbing impacts of bushfires in Australia. The unprecedented ferocity of the Black Saturday bushfires in Victoria claimed 173 lives.

3.3 Drought

Health Impacts

Droughts can have wide ranging implications for health, with impacts on nutrition, an increased risk of infectious diseases and air pollution from bushfires (Haines et al. 2006). Declines in physical health are particularly prevalent amongst the elderly in drought-affected rural communities in Australia (Horton et al. 2010). Furthermore, drought can exacerbate mental health problems and increase suicide rates in drought-affected rural populations, especially amongst male farmers (Alston 2012). A recent study in New South Wales found that the relative risk of suicide can increase by up to 15% for rural males aged 30-49 as the severity of drought increases (Hanigan et al. 2012).

Environmental Impacts

Drought has significant impacts on Australia's natural environment. For example, decreased water supplies to aquatic ecosystems reduce the availability of suitable habitat and reduce populations of fish and invertebrate species, in some cases, contributing to local extinctions (Bond et al. 2008). During the Millennium Drought, there was a marked decline in water bird, fish and aquatic plant populations in the Murray-Darling Basin (LeBlanc et al. 2012).

Many terrestrial ecosystems are also affected by drought, with iconic species such as the river red gum dying over extensive areas in the Murray-Darling Basin between April 2002 and January 2003 (Murray-Darling Basin Commission 2003; Bond et al. 2008). Severe heatwaves and drought are one of the greatest threats to native eucalyptus species (Butt et al. 2013). Drought also poses risks to planted forests. During the Millennium Drought, for example, 57,000 ha of planted forest in Australia were lost (van Dijk et al. 2013).

Economic Impacts

The socio-economic impacts of droughts in Australia are severe, largely because agricultural, water storage and supply systems were originally designed by European settlers who did not understand the significant variability in Australia's climate (Kiem et al. 2016). Between 2002 and 2003 decreases in agricultural production due to drought resulted in a 1% reduction in the Gross Domestic Product (GDP) and a 28.5% fall in the gross value added for the agricultural industry, compared to the preceding year (ABS 2004). This is a significant hit to the economy, considering that the global financial crisis caused a reduction of 2% in Australia's annual GDP from 2008 to 2009 (World Bank 2015). Drought assistance has significant economic consequences for Australian taxpayers. From 2002-2008 the government provided $1 billion in drought assistance to farmers (Productivity Commission 2009). From 1991 to mid-2010 the government had paid a total of $4.4 billion in drought assistance (ABARES 2012).

Figure 32: Drought stricken Upper Stony Creek reservoir in 2010. This reservoir provides some of Geelong's water supply.

Water scarcity in major cities, particularly Melbourne, Sydney and Perth, has been exacerbated by drought and remains an ongoing challenge. Reduced rainfall typically lessens stream flow disproportionately more than the reduction in rainfall. For example, the rainfall decline in southwest Western Australia of 19% since the mid-1970s has reduced the annual average stream flow into Perth's dams by nearly 80% (WC 2012; BoM 2015b). In Melbourne, stage 3 water restrictions were implemented from 2007 to 2010, and by 2009 the city's water storage levels fell to a record minimum of 25.6% (Melbourne Water 2013; Figure 32).

Water scarcity in major cities, particularly Melbourne, Sydney and Perth, has been exacerbated by drought.

3.4 Extreme Rainfall

Health Impacts

Periods of heavy rainfall can threaten human health and wellbeing. While intermediate levels of rainfall can cause damage to property, heavy rainfall can claim lives. For example, in 2011 intense downpours of 40-50 mm in only 30 minutes falling in already saturated catchments in Toowoomba and the Lockyer Valley led to burst creeks and caused flash flooding of up to 11 m through the Toowoomba city centre (Coates 2012); 23 people drowned in these floods (van den Honert and McAneney 2011). 78% of the state (an area larger than France and Germany combined) was declared a disaster zone. The floods created major health risks, including contamination of drinking water and food, as well as difficulties in accessing health services and treatments. Health impacts of extreme rainfall can also persist days and weeks after the rainfall event has occurred. Large quantities of standing water can lead to the explosion of mosquito populations, which are known to transmit diseases such as dengue fever (Jacups et al. 2015).

Environmental Impacts

Extreme rainfall events can cause significant environmental damage, usually as a result of flooding. Large scale erosion due to heavy rainfall can destabilise river banks, resulting in clogged rivers and reduced flow (Saynor and Erskine 2016). In central Australia, where water is sparse, an extreme rainfall event can replenish water supplies for towns and invigorate ephemeral rivers. Often, though, these extreme rainfall events will usually be followed by rat plagues, which can cause widespread environmental and agricultural destruction (Greenville et al. 2013). A recent example of this is from Paris, where severe flooding in mid-2016 has caused serious infestations of rats (The Guardian 2016b).

Economic Impacts

The economic impacts of heavy rainfall can be devastating. One of the worst flooding events in recent times in Australia as a result of heavy rainfall was the Queensland 2010/2011 floods (Figure 33). Extreme and extended rainfall over large areas of Queensland from a strong La Niña event in the latter part of 2010 led to record-breaking and very damaging flooding in Queensland in December 2010 and January 2011. December 2010 was Queensland's wettest December on record (BoM 2011). Approximately 2.5 million people were affected and 29,000 homes and businesses experienced some form of flooding. The economic cost of the flooding was estimated to be in excess of $5 billion (QFCI 2012), with 18,000 homes inundated, damage to 28% of the Queensland rail network and damage to 19,000 km of roads and 3 ports (van den Honert and McAneney 2012). Around 300,000 homes and businesses lost power in Brisbane and Ipswich at some stage during the floods (QFCI 2012).

Figure 33: Onlookers survey the levels of the flood waters in inner city Brisbane. Flooding as a result of an exceptionally wet December and January caused economic damages of at least $5 billion.

The economic cost of the Queensland 2010/2011 floods was at least $5 billion.

3.5 Storms

Health Impacts

Storms can cause damage to property, infrastructure and claim human lives. A recent example of this was the 'thunderstorm asthma' episode from a severe storm in Melbourne, which affected thousands of people and claimed at least six lives in November 2016. A severe storm in the Hunter Valley in 2007 resulted in the deaths of ten people (Cretikos et al. 2007). The spread of infectious disease was a strong focus of recovery efforts, as sewage contaminated flood waters.

While storms can cause immense physical damage, including destruction to housing, property and infrastructure, Martin (2015) showed that in the aftermath of severe storms, survivors demonstrated a 25% increase in the onset of depression after the storm event. Emotional stress can undermine the resilience of individuals and communities, placing further physical, emotional and financial burdens onto recovery efforts (Martin 2015).

Environmental Impacts

Natural ecosystems can suffer serious impacts from the high winds of tropical cyclones. For example, the Great Barrier Reef suffered extensive physical damage to the coral in 2011 when tropical cyclone Yasi passed over large areas of the reef. Coral damage was reported across an area of approximately 89,000 km^2 of the Great Barrier Reef Marine Park. In total 15% of the park sustained some damage and 6% was severely damaged (GBRMPA 2011). The ecological impact of this severe tropical cyclone is likely to be evident for several decades (GBRMPA 2011).

Economic Impacts

The damages from major flooding, tropical cyclones and severe storms for the 1967-1999 period were estimated to be $28.6 billion, based on 2008 residential pricing (DCC 2009). Australia has experienced a stormy last five years, with some of the most damaging storm events in recent times occurring within this period. Detailed below are some of the most damaging storms (from an insured loss perspective) for each category of storm: (i) hailstorms, (ii) tropical cyclones and (iii) east coast lows.

Brisbane Hailstorm (2014): An intense hailstorm with strong wind gusts up to 140 km/h caused widespread damage to homes, cars, windows and roofs in Brisbane, November 2014 (ABC 2015b). This culminated in insured losses of almost $1.4 billion (Understand Insurance 2016). The total economic costs of extreme natural events (that cost more than $10 million in damages) is likely to be two to five times greater than insured losses alone (BTE 2001), so this estimate is likely to be conservative.

Cyclone Yasi (2011): Severe tropical cyclone Yasi was one of the most powerful cyclones to have affected Queensland since records began, and was one of Australia's costliest natural disasters. Cyclone Yasi first hit the North Queensland coast on 2 February 2011, creating widespread damage and contributing to flooding across Queensland. The cyclone brought extreme winds of up to 285 km/h, heavy rain of up to 200-300 mm in 24 hours and storm surges, including a 5 m tidal surge at Cardwell (QRA and World Bank 2011). The costs to the agricultural and tourism industries were estimated at $1.6 billion and $600 million respectively (QRA and World Bank 2011).

NSW East Coast Low (2015): An east coast low brought intense rainfall to the NSW coast and Hunter Valley, causing widespread flooding in April 2015. The 1-in-100 year rainfall event dropped more than 400 mm of rain in 48 hours, with wind gusts of 135 km/h in Newcastle (Naumann 2015). Damage from the storm resulted in $950 million in insured losses (Understand Insurance 2016) and caused additional losses of $110 million to the tourism industry (Naumann 2015).

The total economic costs of extreme natural events (that cost more than $10 million in damages) is likely to be two to five times greater than insured losses alone.

3.6 Sea-level Rise and Coastal Flooding

Sea-level rise is increasing the risk of flooding along Australia's economically, socially and environmentally important coastlines, and other coastlines across the world. Impacts can include loss of life; disruption of health and social services; inundation of property and coastal infrastructure, such as houses, businesses, ports, airports, railways and roads; and damage to coastal, estuarine, and freshwater ecosystems.

Health Impacts

Coastal flooding presents a significant threat to human health and well-being. For example, Hurricane Sandy caused 147 deaths in the Caribbean and continental United States (NOAA 2013). A third of these deaths were in New York City (Tollefson 2013). In Australia, the low-lying Torres Strait Island communities are vulnerable to sea-level rise and coastal inundation (Box 4). 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 inadequate prevention measures are not taken (Preston-Thomas et al. 2012). Extreme weather and coastal flooding can also cause increased rates of post-traumatic stress disorder in the low-lying Torres Strait Island communities (AIHW 2012; Green and Minchin 2014).

Some of the most severe health impacts of climate change on Australian society, particularly those due to sea-level rise and coastal flooding, may be felt indirectly

Figure 34: Millennium Island in the South Pacific. This island is part of the Island nation of Kiribati, and is highly vulnerable to sea-level rise, which is likely to force inhabitants from small atolls like these to other islands and countries.

via impacts in other countries. The IPCC has 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 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 many as 250 million (Myers 2002; McMichael et al. 2012).

Most of the critical infrastructure, agricultural production and human settlements on small islands in the western Pacific and in Australia's Torres Strait Islands are on the coast (Figure 34), exposed to extreme tides, storm surge events and inundation exacerbated by sea-level rise (Hoeke et al. 2013; see also Box 4 on Torres Strait Islands). These impacts raise the prospect of the need for relocation of some Torres Strait and Pacific Island communities in the future. The decision to migrate is a complex one, whether at the level of individuals or a community (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 4: FLOODING IN THE TORRES STRAIT ISLANDS

Many Torres Strait Islands are already vulnerable to flooding, but rising sea levels are increasing this vulnerability (Figure 35). Around 7,000 people live on 16 of the over 100 small islands between northern Cape York and the coast of Papua New Guinea (AHREOC 2008). Torres Strait communities are particularly vulnerable because the remoteness and small size of the islands can make recovery from storms and flooding events difficult, and because of the social and economic disadvantages faced by many islanders (DCC 2009; TSRA 2010).

Many of the islands are already very low-lying and exposed to the impacts of flooding from king tides and storm surges. The islands of Boigu and Saibai are especially vulnerable because the average height of the communities on these islands is already below the highest astronomical tide (the highest tide under average meteorological conditions; TSRA 2010).

Major flooding events in 2005, 2006, 2009 and 2010 affected roads, residential buildings, cultural sites, community gardens and the functioning of waste treatment facilities (Green 2006; Green et al. 2008; Climate Commission 2013). These flooding events were very likely exacerbated by the increases in sea level that the Torres Strait Islands have already experienced. Sea level in the Torres Strait region has been rising at approximately 6 mm per year over the 1993-2010 period (Suppiah et al. 2011), nearly twice the global average (Church et al. 2013).

Continuing increases in sea level will result in increased frequency and severity of such flooding events (Green et al. 2008). Large sea-level rises could completely inundate some Torres Strait Islands (TSRA 2010), forcing communities to relocate to islands with higher ground or to mainland Australia (AHREOC 2008). Forced relocation would cause a variety of social, cultural and economic difficulties because the Torres Strait Islanders' culture relies heavily on connection with country (Green 2006).

Figure 35: Seawater overflowing a protective wall, Saibai, Torres Strait Islands.

Environmental Impacts

Australia has some of the most extensive and diverse seagrass communities in the world. Seagrasses are marine flowering plants that grow in shallow, sheltered sandy areas around coasts where they provide food, shelter and nursery grounds for fish, invertebrates, turtles and dugongs. They also help stabilise marine sediments, protect shorelines, and filter and oxygenate the water column (Saunders et al. 2013). Rising sea levels pose a 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.

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 36; Barbier et al. 2011; McLeod et al. 2011; Saintilan and Rogers 2013). The coastal squeeze is 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 in Australia. 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 Queensland coast (Manson et al. 2005). Likewise, estuaries provide breeding grounds for many commercially important fish and shellfish species, as well as crocodiles in northern regions (Fuentes et al. 2012).

Figure 36: Mangroves are particularly vulnerable to climate change, and their loss has significant impacts on important habitat for many marine species.

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 on the 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; Figure 37); coupled with the impacts of storms, this threat is substantially increased with up to 75% of nesting areas affected.

Figure 37: Marine life in the coastal environment is vulnerable to sea-level rise and coastal flooding. For example, many green turtle nesting areas are likely to be inundated from rising sea levels and storms.

Economic Impacts

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). Nationally 62% of international visitors visit beaches at some time in their stay (Amelung and Nicholls 2014). However, many of Australia's beaches are vulnerable to erosion from rising sea levels. Table 3 shows the proportion of coast which is vulnerable to recession under sea-level rise; the total is more than 50% of Australia's coastline. Most noteworthy is that Victoria's coastline is most vulnerable of any Australian state to sea-level rise.

Surveys on the Gold Coast, home of Australia's most well-known beach, found that 74% of visitors identified beach-going as the top activity (Tourism Research Australia 2013). The beach is central to the Gold Coast's appeal as a tourism destination and maintenance of the beach resource is central to the city's future (Figure 38). However, the beach, like many around Australia, is vulnerable to recession from rising sea levels. As sea levels continue to rise, there is no opportunity for the beach to move landwards due to the adjacent high-rise development. 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 rise scenario used (Cooper and Lemckert 2012).

Table 3: Fraction of coastline susceptible to recession under sea-level rise, defined as shores composed of sand and mud, backed by soft sediment (so that recession is largely unconstrained), and shores composed of soft rock. Based on data from DCC (2009).

State	Total length of open coast, km	Total length of vulnerable coast, km	Proportion of vulnerable coast (%)
Victoria	2,395	1,915	80
New South Wales	2,109	839	40
Queensland	12,276	7,551	62
Northern Territory	11,147	6,990	63
Western Australia	20,513	8,237	40
South Australia	5,876	3,046	52
Tasmania	4,995	2,336	47
Australia	59,311	30,914	52

Saltwater intrusion from rising sea levels, in combination with other human impacts, is already having significant impacts on coastal freshwater ecosystems in some regions. For example, the extensive freshwater wetlands along the northern coast of Australia, such as those in the iconic Kakadu National Park, are under threat from saltwater intrusion as the sea level rises (Hennessy et al. 2007). Much of the Kakadu floodplain has very low relief – falling to only 0.5 m above sea level for more than 70 km (Finlayson et al. 2009). The low level of these areas means that even small rises in sea level could result in relatively large areas being affected by saltwater intrusion, with the expansion of the estuarine wetland system at the expense of present-day freshwater wetlands. This national park is the most important natural, cultural, recreational and tourist resource in the coastal region of the Northern Territory (Finlayson et al. 2009; Figure 39). 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).

More than 50% of Australia's coastline is vulnerable to recession as a result of sea-level rise.

Figure 38: Tourism on the Gold Coast, in southern Queensland, is centred around its pristine beaches. However, the Australian coastline is vulnerable to recession in the 21st century as sea level continues to rise, including along the Gold Coast (DCC 2009; DCCEE 2011).

Figure 39: Kakadu National Park, Northern Territory. The extensive freshwater wetlands are under threat from saltwater intrusion as sea levels continue to rise.

4. How Much Worse Will Extreme Weather Events Become in Australia?

Extreme weather events are very likely to become more intense and destructive over the next couple of decades because of the climate change that is already locked in from past greenhouse gas emissions. But the severity of extreme weather events that our children and grandchildren will face later this century depends on how fast and how deeply greenhouse gas emissions can be reduced now, next year and over the next couple of decades (Box 5). If the world can meet the Paris 2°C target, the trend towards more severe extreme weather can be slowed and then halted in the second half of the century.

Australia is on the frontline of climate change. Our nation has already experienced many extreme events that have been influenced by climate change. All Australian states and territories are currently and will continue to be affected by climate change in different ways (Figure 40).

The severity of future extreme weather events in Australia depends on how fast and deeply greenhouse gas emissions can be reduced.

Figure 40: Impacts of climate change on extreme weather events across the Australian continent. Nowhere in Australia is immune to the impacts of climate change.

BOX 5: HOW DO WE KNOW WHAT EXTREME WEATHER WILL DO IN THE FUTURE?

Projections of future changes to extreme events are based on climate model simulations. Climate models are mathematical representations of the climate system, based on the laws of physics. They are driven by a number of Representative Concentration Pathways (RCPs) that represent future pathways of greenhouse gas concentrations in the atmosphere. The RCPs are broadly consistent with the wide range of scenarios of future human emissions of greenhouse gases. These range from worst-case 'business-as-usual' scenarios, in which emissions continue to rise strongly through the rest of the century (RCP8.5), to scenarios in which effective climate policy leads to rapid and deep emission cuts over the next few decades with very low or no emissions towards the end of the century (RCP2.6; Figure 41).

Because of momentum in the climate system, the climate projections for the next two decades are largely independent of the particular emissions scenario chosen, and thus the influence of climate change on extreme events is likely to increase over that time period regardless of emission pathways. However, over the longer term the level of emission reductions now and in the coming decades will have a major influence on the degree of climate change that occurs and its influence on extreme events. More pronounced changes in extremes are predicted for the higher concentration pathways.

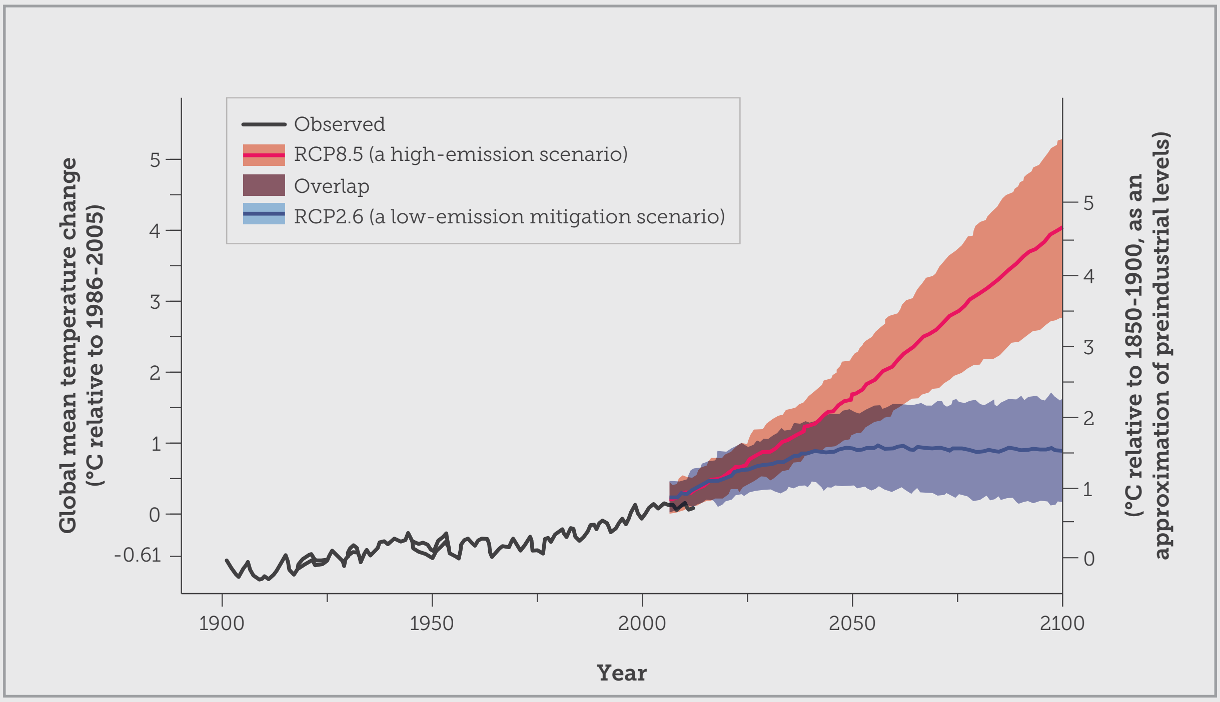

Figure 41: Projected global mean temperature change for two Representative Concentration Pathways (RCPs) (IPCC 2014b). The upper projection (red, RCP8.5) is based on a 'business as usual' CO_2 emissions pathway, while the lower trajectory (blue, RCP2.6) is based on a very rapid reduction in CO_2 emissions, equivalent to a 1.5°C increase in temperature from pre-industrial levels. We are locked in to temperature rises until about 2050, but these paths begin to diverge significantly around 2030 or 2040, depending on the level of climate action we take from now onwards. Larger rises in global mean temperature are projected for the higher concentration CO_2 pathways (e.g., RCP8.5) and hence more pronounced extreme weather, including storms, are likely if high levels of emissions continue.

4.1 General Projections

4.1.1 Heatwaves

Land

It is virtually certain that ongoing increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur at the global scale in the 21st century (IPCC 2013). Consistent with the global trend, Australia will continue to warm substantially during the 21st century (CSIRO and BoM 2015). Extreme heat and heatwaves will continue to become even more frequent and severe around the globe, including Australia, over the coming decades (IPCC 2012; Cowan et al. 2014), and the impacts will also become more severe. Cowan et al. (2014) project that the largest increase in summer heatwave frequency and duration will occur in the northern tropical regions, while there is an expected increase of approximately 3°C in the maximum temperature of the hottest heatwaves in southern Australia.

CSIRO and BoM (2015) project with very high confidence that mean, daily minimum and daily maximum temperatures will continue to increase for all regions in Australia. By 2030, the annual average temperature in Australia is projected to increase by 0.6-1.3°C above the climate of 1986-2005. A high-end emissions scenario (RCP8.5), equivalent to 'business as usual' greenhouse gas emissions, would result in a temperature increase from present of 2.8-5.1°C by 2090. A low-emissions scenario (RCP2.6) would result in a 0.6-1.7°C increase in temperatures by 2090. Spatially, inland Australia is likely to experience the highest increases in average temperatures, including popular tourist destinations such as Uluru National Park (Figure 42). The increase in temperature will be significant, but relatively lower, for coastal areas, especially in southern coastal areas in winter (CSIRO and BoM 2015).

Figure 42: Inland Australia is likely to observe the greatest temperature increases in the 21st century. This will make extreme heat and associated health risks even greater in places like Uluru National Park.

Marine

Marine heatwaves are likely to occur more frequently as oceans continue to warm (Feng et al. 2013), although there are not yet sufficient modelling studies to project how marine environments may be affected by these short-lived (weeks to months) extreme ocean warming events. For a high emissions scenario, projected net warming in sea surface temperatures off the Australian coastline of 2-4°C by 2090, relative to present climate (1986-2005), will significantly increase the probability of marine heatwaves (Perkins-Kirkpatrick et al. 2016). The ability to recover from bleaching events, one of the main impacts of marine heatwaves (Figure 43), varies among coral species and across regions, but there is only limited evidence so far that corals can adapt to rising temperatures and to ocean acidification (Hoegh-Guldberg et al. 2007). Extreme coral bleaching will be the new normal by the 2030s unless significant reductions in greenhouse gas emissions are achieved (CoECSS 2016).

Extreme coral bleaching will be the new normal by the 2030s unless significant reductions in greenhouse gas emissions are achieved.

Figure 43: Coral bleaching on the Great Barrier Reef. Marine heatwaves that cause devastating coral bleaching, similar to the 2016 event, will occur once every two years in just over a decade or so if significant reductions to greenhouse gas emissions are not achieved.

4.1.2 Bushfires

It is very difficult to project the future behaviour of bushfires themselves, as many non-climate and non-weather factors also influence the nature of fires and their consequences (Harris et al. 2016). Perhaps the most important of these non-climate factors is the role of human management and decision-making, such as fire suppression activities (Figure 44) and land-use planning. However, as dangerous fire weather is sensitive to extremes in climatic and weather conditions, such as air temperatures, duration of heat events, and wind speed, changes in these factors as the climate continues to shift can be aggregated to estimate the potential changes in dangerous fire weather in the future (e.g. Lucas et al. 2007; Clarke et al. 2011).

While the detailed results of future fire activity studies vary due to the use of different global circulation models (GCMs) and different emission scenarios, their collective conclusion is clear – weather conditions conducive to fire in the southeast of the continent are becoming increasingly frequent. The projected increases in hot days across the country, and in consecutive dry days and droughts in these regions, will very likely lead to increased frequencies of days with extreme fire danger (Clarke et al. 2011). Model simulations by CSIRO and BoM (2015) confirm that southern and eastern Australia are projected to experience harsher fire weather.

Figure 44: A hazard reduction burn being conducted by the New South Wales Rural Fire Service in Belrose, 2011. The increasing length of the fire season will reduce the window of opportunity for hazard reduction at the same time as the need for hazard reduction becomes greater. Hazard reduction burning can result in extensive smoke pollution as authorities attempt to meet burning schedules in the few safe days for burning.

As warming and drying continues in these regions, fuel will become drier and more 'ready-to-burn', with associated increases in the average FFDI and a greater number of dangerous fire weather days (CSIRO and BoM 2015). However, the higher risk of uncontrollable bushfires due to a drier, warmer climate may eventually be counter-balanced by lower fuel loads as biomass is burned more often (Matthews et al. 2012), although the dynamics of fuel loads in future bushfire weather projections are yet to be resolved (Sharples et al. 2016). In the tropical and monsoonal north of Australia, little change in fire frequency is projected, while in arid inland areas future projections are challenging because fire risk is dependent on fuel availability, which is driven by episodic rainfall (CSIRO and BoM 2015).

Future changes in the El Niño-Southern Oscillation (ENSO) phenomenon are also likely to have an influence on fire activity, as well as on drought (see next section). El Niño events worsen fire weather conditions and increase fire activity in southeast and central Australia (Verdon et al. 2004; Lucas 2005; Harris et al. 2013; Figure 45).

Weather conditions conducive to fire in the southeast of Australia are becoming increasingly frequent.

Figure 45: Elvis – the Erickson Air-Crane fire bomber – dumping about 9,000 litres of water to assist firefighters battling a blaze in Australia's southeast. Specialised firefighting aircraft like this are shared each year between the Northern and Southern hemispheres for their respective bushfire seasons, but as bushfire seasons lengthen in both hemispheres and begin to overlap, the sharing of costly firefighting equipment is becoming more difficult.

4.1.3 Drought

The time spent in drought is projected to increase across Australia, especially in the south (CSIRO and BoM 2015; Figure 46). This is consistent with an ongoing drying trend and projected decline in rainfall in this region. While moderate to severe droughts are expected to become less frequent, extreme drought is expected to increase in both frequency and duration (CSIRO and BoM 2015). More extreme droughts could lead to decreases in production in Australia's most important agricultural regions, including the largest catchment and most productive agricultural areas in the country, the Murray-Darling Basin, and the southwest wheat belt (IPCC 2014a). The projected drying trend across southern Australia could also threaten urban water supplies, as nearly 13 million Australians live in the southern cities of Perth, Adelaide, Melbourne, Canberra and Sydney (ABS 2014).

The El Niño phase of the ENSO phenomenon plays a strong role in the occurrence and intensity of drought in Australia. Significant changes have occurred in the nature of ENSO since the 1970s, with the phenomenon being more active and intense during the 1979–2009 period than at any other time in the past 600 years (Aiken et al. 2013). It is likely that climate change is and will continue to influence ENSO behaviour, although the nature of this influence is still uncertain. There is some suggestion that El Niño-driven drying in the western Pacific Ocean will increase by the mid-to-late 21st century (Power et al. 2013; Cai et al. 2014). One study further suggests that particularly extreme El-Niño events (e.g. 1982/83, 1997/98, 2015/16) could double in frequency due to anthropogenic warming (Cai et al. 2014). If these projected changes in El Niño behavior eventuate, the incidence of heat and drought, as well as fire activity, could increase in eastern and southern Australia.

Figure 46: Failed wheat crops in Victoria, 2006. The ongoing drying trend and projected increase in severe droughts could lead to decreases in production in Australia's most important agricultural regions, including the largest catchment and most productive agricultural area in the country, the Murray-Darling Basin, and the southwest wheat belt.

4.1.4 Extreme Rainfall

A 2°C rise in average global temperatures could result in a 10-30% increase in extreme downpours (Bao et al. 2017). In Australia, extreme rainfall events are projected, with high confidence, to increase in intensity, where extreme events are defined as the wettest day of the year and the wettest day in 20 years (CSIRO and BoM 2015; Bao et al. 2017; Figure 47). The tendency for an increase in intensity may be stronger for the larger, rarer events (current 1-in-20 year events) (Rafter and Abbs 2009) particularly at the sub-daily timescale (Westra et al. 2013).

Regionally, increases in heavy rainfall are expected to be less evident in regions where mean rainfall is projected to decline, such as southern Australia (CSIRO and BoM 2007; Pitman and Perkins 2008; Moise and Hudson 2008). Indeed, this projected trend may be less prominent in southwest Western Australia, where large reductions in mean rainfall are projected. However, England et al. (2006) note that an increase in sea surface temperatures will drive more extreme anomalies in the Indian Ocean Dipole (temperature difference between the western and eastern Indian Ocean). This could result in more extreme and periodic rainfall events in southwest Western Australia.

Extreme rainfall events are projected to increase in intensity across most of Australia.

Figure 47: Extreme rainfall and hailstorm in March 2010, Melbourne, causing flash flooding in the city. Extreme rainfall events are very likely to increase in intensity as the climate system continues to warm.

4.1.5 Storms

Hail and Thunderstorms

Climate models do not yet simulate the dynamics of the climate system well enough at small scales to predict changes in hail, thunderstorms and tornadoes. Thus, projections of changes in these types of storms are not yet feasible, although analysis of the larger-scale environments conducive to severe thunderstorms in Australia indicates significant increases in southern and eastern areas in the frequency of conditions conducive to thunderstorm development (Allen et al. 2014).

Tropical Cyclones

An increase is likely in the proportion of the most intense tropical cyclones, those with stronger winds and heavier rainfall such as Yasi (Figure 48), while the total number of tropical cyclones will likely decrease. A greater proportion of tropical cyclones may reach further south along Australia's east and west coastlines (CSIRO and BoM 2015).

Extra-Tropical Cyclones

These systems and their associated cold fronts are projected to shift south in the winter, consistent with the observed expansion of the tropics (intensification of the subtropical ridge and expansion of the Hadley Cell circulation). In addition to a southward shift, the westerly wind flow is projected to strengthen (CSIRO and BoM 2015). These projections imply a decrease in the number of deep lows affecting southwest Western Australia and in the number of fronts affecting southern Australia in the cooler months of the year, that is, a decrease in storminess and rainfall (CSIRO and BoM 2015). Projections for the warmer months are less clear, with one projection finding that towards the end of the century, southeast Australia will experience a significant increase in intense frontal systems that bring extreme winds and dangerous fire conditions (Hasson et al. 2009).

Figure 48: The impacts of Tropical Cyclone Yasi, which struck the north Queensland coast in 2011, included felled trees, beach erosion and damaged roads.

4.1.6 Sea-level Rise and Coastal Flooding

Sea level is projected to rise by 26-55 cm for a low emissions scenario and 45-82 cm for a 'business as usual' scenario by 2080-2100, relative to 1986-2005 levels (CSIRO and BoM 2015). Larger rises cannot be ruled out because of uncertainties around the stability of the large ice sheets on Greenland and Antarctica as the climate continues to warm. If the current increase in the rate of mass loss from the polar ice sheets continues, it alone could contribute up to 0.5 m to sea-level rise by 2100 compared to 1990 (Rignot et al. 2011; Box 6).

Australian sea levels are very likely to rise at a faster rate during the 21st century than the past four decades (CSIRO and BoM 2015). Projections indicate that the increase in coastal flooding from high sea-level events will become more frequent and more severe as sea levels continue to rise. Figure 49 shows the results of an analysis exploring the implication of sea-level rise for such events around the Australian coastline (Church et al. 2008; Hunter 2012). A sea-level rise of 0.5 m, which lies near the lower end of the estimates for 2100 compared to 1990, was assumed in the analysis shown in Figure 49, and leads to surprisingly large impacts. For coastal areas around Australia's largest cities, a sea-level rise of 0.5 m would lead to very large increases in the incidence of extreme events, typically by a factor of several hundred and in some places by as much as one thousand. A multiplying factor of 100 means that an extreme event with a current probability of occurrence of 1-in-100 – the so-called one-in-a-hundred-year event – would occur on average every year. A multiplying factor of 1,000 implies that the one-in-a-hundred-year inundation event would occur almost every month.

A sea-level rise of only 0.5 m would lead to very large increases in the incidence of extreme coastal flooding events around the Australian coastline, typically by a factor of several hundred.

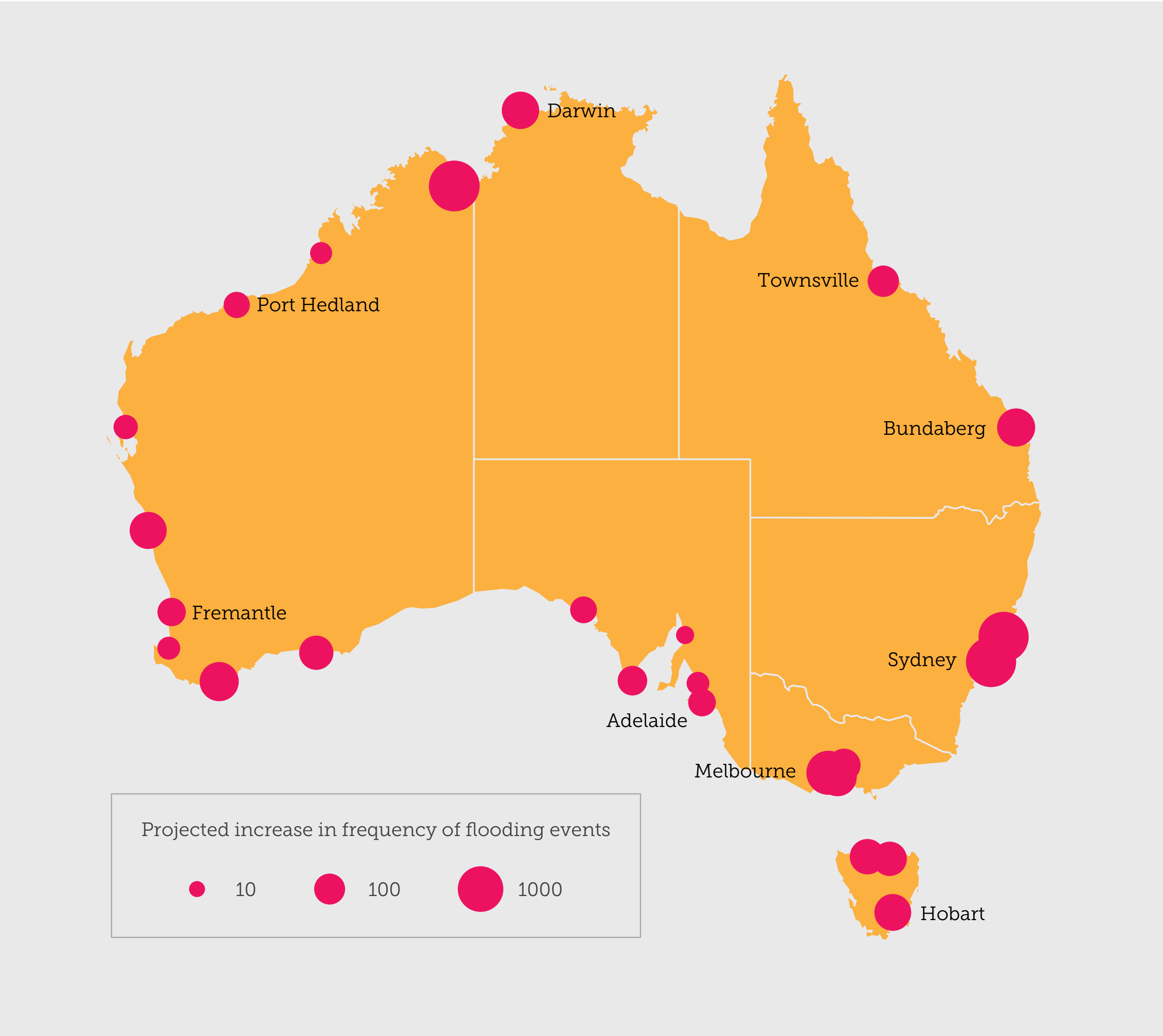

Figure 49: Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m (Hunter 2012).

Many coastal flooding events are associated with simultaneous high sea level events and heavy rainfall events in the catchments inland of coastal settlements. This means that coastal settlements can be inundated by water from both seaward and landward directions – that is, from (i) the combination of storm surge, a high tide and a higher sea level, and (ii) flooding rivers from the catchments behind the settlements. Little research has yet been done to connect these two phenomena and produce an overall change in risk factor for this type of 'double whammy' coastal flooding event. However, the rises in sea level over the 21st century, which are virtually certain, coupled with the projections of an increase in the intensity of heavy rainfall events for most regions of Australia (CSIRO and BoM 2015) suggest that the risk of these 'double whammy' flooding events will increase (Climate Commission 2013).

BOX 6: THE ROLE OF ICE-SHEETS IN FUTURE SEA-LEVEL RISE

The largest uncertainty in the projections of sea-level rise to 2100 and beyond is the melting of large masses of ice on Greenland and Antarctica (known as polar ice-sheets; Figure 50). Observed contributions to global mean sea-level rise over the 20th and 21st century show an increasing trend in contributions to sea level from Greenland in particular. For example, the IPCC (2007) estimated that from 1961 to 2003, the Greenland ice-sheet contributed global sea-level rise of 0.05±0.12 mm per year, while from 1993 to 2003 the ice-sheet contributed 0.21±0.07 mm per year to global sea-level rise. Van den Broeke (2016) estimated the average sea-level rise from Greenland ice-sheet to be 0.47±0.23 mm per year for the 1991-2015 period, with a maximum contribution in 2012 of 1.2 mm during an unusually warm melt season.

Greenland predominantly loses mass by melting at the surface, and the elevation at which ice now melts is reaching unprecedented levels. This meltwater runs off the surface and enters the ice-sheet via crevasses and moulins (cracks and vertical pipe-like structures) that feed water to the base of the glacier, potentially speeding up the flow of outlet glaciers, in turn causing more land-based ice to enter the ocean and raise sea levels.

In Antarctica, the most important process contributing to sea-level rise is the erosion by warming ocean waters of ice sheets that are grounded below sea level. As the bottom of the ice sheet is eroded and detached from the sea floor, the ice floats on the ocean water and thus raises the sea level. Just as the water level in a glass rises if a cube of ice is added, sea level rises immediately when the ice starts to float on the sea. The subsequent melting does not raise sea level further.

Recent projections indicate that by 2100 Greenland melting could contribute 0.1-0.17 m to global sea levels (Fürst et al. 2015), while Antarctica could contribute 0.09-0.19 m (Mengel et al. 2016). Some research suggests that this contribution to sea-level rise may exceed 1 m by 2100 (de Conto and Pollard 2016). The estimated sea-level rise contributions from Antarctica do not include potential instability and collapse of glaciers, such as the Totten Glacier, which could add 2 m to sea-level rise if temperatures rise 3-6°C above present values and activate this process (Aitken et al. 2016).

Figure 50: Aerial view of outlet glaciers entering the ocean (foreground) carrying ice from the Greenland ice-sheet (background). Melting ice and the dynamic flow of ice from Greenland contribute significantly to sea-level rise.

4.2 State-by-State Projections

4.2.1 Queensland

- Extreme heat: In Brisbane, the number of hot days (>35°C) per year is projected to increase from 12 to 18 per year by 2030 (relative to 1981-2010 climate), increasing to 55 per year by 2090 under a high emissions scenario (CSIRO and BoM 2015).
- Extreme rainfall: Maximum one-day rainfall is expected to increase by up to 18% for Queensland by the end of the century for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).
- Thunderstorms: An analysis of the larger-scale environments conducive to severe thunderstorms in Australia indicates that the annual frequency of potential severe thunderstorm days may rise by 14% for Brisbane by the end of the century, based on a high warming scenario (Allen et al. 2014).
- Tropical cyclones: It is likely that the proportion of the most severe tropical cyclones will increase, while the total number of tropical cyclones will likely decrease. A higher proportion of tropical cyclones may reach their observed southern-most extent, approximately a latitude of 25 degrees south (CSIRO and BoM 2015), equivalent to the Bundaberg/ Fraser Island region.
- Sea-level rise: Townsville and Mackay are expected to have a mean sea-level rise of up to 0.26 m by 2050 relative to 1986-2005 levels, increasing to up to 0.64 m by 2090 for a high emissions scenario (McInnes et al. 2015). A present-day 1-in-100 year flooding event would likely occur every month or so by 2100 for Bundaberg (Hunter 2012). Brisbane suburbs that could be partially submerged by 2050 from sea-level rise include Brighton, Nudgee Beach, Sandgate, Manly, as well as the Brisbane Airport (Coastal Adapt 2016).
- Marine heatwaves: For a high emissions scenario, projected net warming in sea surface temperatures off the Australian coastline of 2-4°C by 2090, relative to present climate (1986-2005), will significantly increase the probability of marine heatwaves (Perkins-Kirkpatrick et al. 2016).

Figure 51: Strong winds blowing sand during Tropical Cyclone Yasi on the Townsville coastline, North Queensland in 2011. In the future, the most severe tropical cyclones are likely to become more intense.

4.2.2 New South Wales

- **Extreme heat:** In Sydney, the number of hot days (>35°C) per year are projected to increase from 3 to 4 per year by 2030 (relative to 1981-2010 climate), increasing to 11 per year by 2090, under a high emissions scenario (CSIRO and BoM 2015).
- **Bushfires:** Increases in annual FFDI of up to 30% by 2050 over historical levels are projected in southeast Australia, including New South Wales (Lucas et al. 2007). The largest changes are projected to occur in the arid and semi-arid interior of NSW (Lucas et al. 2007). Modelling by Clarke et al. (2011) reveals that the fire season is projected to start earlier, leading to longer fire seasons (Clarke 2015) and more severe fire weather days in summer and spring (NSW Government 2014).

Figure 52: Thunderstorms over Sydney. Model simulations show that the number of potential thunderstorm days will increase in Sydney.

- **Drought:** The ongoing drying trend and projected increase in extreme droughts could lead to decreases in production in Australia's most important agricultural regions, including the largest catchment, the Murray-Darling Basin (IPCC 2014a).
- **Extreme rainfall:** Maximum one-day rainfall is expected to increase by up to 17% for the state of New South Wales by the end of the century for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).
- **Thunderstorms:** The annual frequency of potential severe thunderstorm days may rise by 30% for Sydney by the end of the century, based on a high warming scenario (Allen et al. 2014).
- **East Coast Lows:** Projections for east coast lows that affect the New South Wales coast suggest a reduction in the number of them by up to 30% towards the end of the century (Dowdy 2014), but there is some indication that the intensity of the most severe east coast lows could increase (Grose et al. 2012).
- **Sea-level rise:** Sydney and Newcastle are expected to have a mean sea-level rise of up to 0.27 m by 2050 relative to 1986-2005 levels, increasing to up to 0.66 m by 2090 for a high emissions scenario (McInnes et al. 2015). For the higher sea-level rise a 1-in-100 year flooding event would likely occur every month or so by 2100 in Sydney (Hunter 2012).

4.2.3 Australian Capital Territory

- **Extreme heat:** In Canberra, the number of hot days per year is projected to increase from 7 to 12 per year by 2030 (relative to 1981-2010 climate), increasing to 29 per year by 2090 under a high emissions scenario (CSIRO and BoM 2015). Earlier projections using data from BoM (2013d) and CSIRO and BoM (2007) show that for the 2000-2009 period, the number of hot days in Canberra has already exceeded the earlier 2030 projections.
- **Bushfires:** There is expected to be an increase in annual FFDI of up to 30% by 2050 over historical levels in southeast Australia, including the Australian Capital Territory (Lucas et al. 2007).
- **Drought:** The time spent in drought over Southern Australia, including the ACT is projected to increase, with a greater frequency of severe droughts (CSIRO and BoM 2015).

Figure 53: Hot days in Canberra are likely to become more prevalent as the climate continues to warm, and may contribute to more dangerous bushfire conditions in the ACT.

4.2.4 Victoria

- **Extreme heat:** In Melbourne, the number of hot days per year is projected to increase from 11 to 13 per year by 2030 (relative to 1981-2010 climate), increasing to 24 by 2090 under a high emissions scenario (CSIRO and BoM 2015). Earlier projections using data from BoM 2013d and CSIRO and BoM (2007) showed that for the 2000-2009 period, the number of hot days in Melbourne has already exceeded the earlier 2030 projections.

- **Bushfires:** There is expected to be an increase in annual FFDI of up to 30% by 2050 over historical levels in southeast Australia, including Victoria, with the largest changes projected to occur in northern Victoria (Lucas et al. 2007.

Figure 54: The severity of bushfires in Victoria is expected to increase. This is particularly worrying for the state because it is already the most vulnerable in Australia to bushfires.

- **Drought:** The ongoing drying trend and projected increase in extreme droughts could lead to decreases in production in the Murray-Darling Basin (IPCC 2014a). The time spent in drought for southern Australia, which includes Victoria, is likely to increase to nearly 50% by 2030 relative to 1986-2005 climate, increasing to 60% by 2090 under a high emissions scenario.

- **Thunderstorms:** The annual frequency of potential severe thunderstorm days may rise by 22% for Melbourne by the end of the century, based on a high warming scenario (Allen et al. 2014).

- **Extreme rainfall:** Maximum one-day rainfall is expected to increase by up to 17% over southern Australia, including Victoria, by the end of the century for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).

- **Sea-level rise:** Melbourne (based on Stony Point observations, close to Melbourne) is expected to experience a mean sea-level rise of up to 0.24 m by 2050 relative to 1986-2005 levels, increasing up to 0.59 m by 2090 for a high emissions scenario (McInnes et al. 2015). For this scenario a 1-in-100 year flooding event would likely occur every month or so by 2100 (Hunter 2012).

4.2.5 South Australia

- **Extreme heat:** In Adelaide, the number of hot days per year is projected to increase from 20 to 26 per year by 2030 (relative to 1981-2010 climate), increasing to 47 per year by 2090 under a high emissions scenario (CSIRO and BoM 2015). Earlier projections using data from BoM 2013d and CSIRO and BoM (2007) showed that for the 2000-2009 period, the number of hot days in Adelaide has already exceeded the earlier 2030 projections.

- **Bushfires:** The FFDI may increase across southern Australia, including coastal parts of South Australia, by 7% and 30% in 2030 and 2090, respectively, under a high emissions scenario (CSIRO and BoM 2015).

- **Extreme rainfall:** Maximum one-day rainfall is expected to increase by up to 17% for the southern areas of South Australia by the end of the century for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).

- **Sea-level rise:** Adelaide is expected to experience a mean sea-level rise of up to 0.25 m by 2050 relative to 1986-2005 levels, increasing up to 0.61 m by 2090 under a high emissions scenario (McInnes et al. 2015). Adelaide suburbs that are most at risk of being partially submerged by 2050 include Tennyson, West Lakes and Port Adelaide (Coastal Adapt 2016).

Figure 55: Adelaide Hills bushfire in 2015. The severity of bushfires across southern Australia, including the state of South Australia, is expected to increase.

4.2.6 Western Australia

- **Extreme heat:** In Perth, the number of hot days per year is projected to increase from 28 to 36 per year by 2030 (relative to 1981-2010 climate), increasing to 63 per year by 2090 under a high emissions scenario (CSIRO and BoM 2015).
- **Marine heatwaves:** Southwestern Australia is an identified 'hot-spot' for ocean warming (Foster et al. 2014). The projected ocean sea surface warming around coastal Australia of 0.4-1.0°C by 2030 relative to 1986-2005, and 2-4°C by 2090 under a high emissions scenario (CSIRO and BoM 2015), is a significant driver of marine heatwaves as the probability of large heat anomalies becomes greater as the average temperature rises (Perkins-Kirkpatrick et al. 2016).

Figure 56: Cracked and dry soil in Midland, Western Australia, in 2006. Future drying trends are likely to affect southwest Western Australia more than the rest of Australia. Projected increases in the frequency and intensity of extreme drought will have severe implications for Perth's water supply.

- **Bushfires:** The FFDI may increase across southern Australia, including southwestern parts of Western Australia, by 7% over historical levels by 2030, and by 30% by 2090 under a high emissions scenario.
- **Drought:** Future drying trends in Australia are projected to be most pronounced over southwest Western Australia, with total reductions in autumn and winter precipitation potentially as high as 50% by the late 21st century (Delworth and Zeng 2014; CSIRO and BoM 2015). Such drying could have significant implications for Perth, which has already experienced a reduction of nearly 80% in total annual inflow into its dams since the mid-1970s. Additionally, the projected increase in severe droughts could lead to decreases in production in the southwest wheat belt (IPCC 2014a).
- **Tropical cyclones:** It is likely that the proportion of the most severe tropical cyclones will increase, while the total number of tropical cyclones will likely decrease. A higher proportion of tropical cyclones may reach their observed southern-most extent, approximately a latitude of 25 degrees south (CSIRO and BoM 2015), equivalent to Dorre Island.
- **Sea-level rise:** Freemantle and Perth are expected to experience a mean sea-level rise of up to 0.24 m by 2050 relative to 1986-2005 levels, increasing up to 0.61 m by 2090 under a high emissions scenario (McInnes et al. 2015).

4.2.7 Northern Territory

- **Extreme heat:** In Darwin, the number of hot days per year is projected to increase from 11 to 43 per year by 2030 (relative to 1981-2010 climate), increasing to 265 per year by 2090 under a high emissions scenario (CSIRO and BoM 2015). In Alice Springs, the number of hot days per year is projected to increase, relative to the 1981-2010 climate, from 94 to 113 by 2030, increasing to 168 by 2090 under a high emissions scenario (CSIRO and BoM 2015).

- **Extreme rainfall:** Maximum one-day rainfall is expected to increase by up to 18% for the Northern Territory by the end of the century for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).

- **Tropical cyclones:** It is likely that the proportion of the most severe tropical cyclones will increase, while the total number of tropical cyclones will likely decrease.

- **Sea- level rise:** Darwin is expected to experience a mean sea-level rise of up to 0.25 m by 2050 relative to 1986-2005 levels, increasing to up to 0.62 m by 2090 under a high emissions scenario (McInnes et al. 2015). A present-day 1-in-100 year flooding event would likely occur every day or so by 2100 for a high emissions scenario (Hunter 2012). Darwin suburbs that could be partially submerged by 2050 from sea-level rise include Rapid Creek, Shoal Bay and East Point (Coastal Adapt 2016).

Figure 57: Flooding after torrential rain in Darwin. Extreme rainfall events are likely to become more intense across the Northern Territory.

4.2.8 Tasmania

- **Marine heatwaves:** Southeastern Australia is a 'hot-spot' for ocean warming, including along the east coast of Tasmania (Foster et al. 2014). The projected ocean sea surface warming around coastal Australia of 0.4-1.0°C by 2030 relative to 1986-2005, and by 2-4°C by 2090 under a high emissions scenario (CSIRO and BoM 2015), is a significant driver of marine heatwaves because the probability of large heat anomalies becomes greater as the average temperature rises (Perkins-Kirkpatrick et al. 2016).

- **Bushfires:** The FFDI may increase across southern Australia, including Tasmania 7% over historical levels by 2030, and 30% by 2090 under a high emissions scenario (CSIRO and BoM 2015).

- **Extreme rainfall:** Maximum one-day rainfall is expected to increase by up to 17% by the end of the century for southern Australia, including Tasmania, for a high emissions scenario, relative to 1986-2005 climate (CSIRO and BoM 2015).

- **Sea-level rise:** For a high emissions scenario, a 1-in-100 year flooding event would likely occur every day or so by 2100 in Hobart (Hunter 2012).

Figure 58: Oyster Farm in Tasmania. The recent marine heatwave caused significant economic losses to the oyster industry. These extreme events are likely to become more common.

5. Tackling Climate Change is Critical for Protecting Australians

To stabilise the global climate system, the long-term trend of increasing global emissions must be slowed and halted in the next few years. Emissions must be trending sharply downwards by 2020 at the latest if we are to slow the escalating risks from extreme weather events and meet the Paris goal of limiting global temperature rise to less than 2°C above pre-industrial levels.

Investments in and installations of renewable energy such as wind turbines and solar must therefore increase rapidly, replacing ageing, highly polluting coal-fired power stations. To meet the Paris target, the global economy must be completely decarbonized by 2050 at the very latest, and preferably earlier.

There are some encouraging signs. For the third year in a row, global greenhouse gas emissions have flat-lined at around 10 billion tonnes of carbon per year (Le Quéré et al. 2016). China is now taking the lead in stopping the increase in emissions by a rapid reduction in coal usage, with the European Union also making significant contributions to emission reductions.

The only approach to halting the escalating risks from extreme weather events is to reduce global emissions of greenhouse gases deeply and rapidly.

While the emissions of our closest allies and trading partners are flat-lining or even declining, Australia's emissions are still rising. Given its position as one of the top 15 greenhouse gas emitters out of nearly 200 countries, Australia is expected to do its fair share of meeting the global emissions reduction challenge. We are on track to miss even our very weak target of a 26-28% reduction in emissions by 2030 compared to 2005 levels. This leaves Australia lagging well behind other OECD (Organisation for Economic Co-Operation and Development) countries. Australia is ranked the worst of all G20 nations on climate change action and is the only country to receive a rating of 'very poor' in a majority of categories (Climate Transparency 2016).

Australia already has the means to tackle climate change, such as clean, technologically advanced and economically competitive renewable energy sources, including wind (Figure 59) and solar. Modelling by EY and the Climate Council (see Climate Council 2016b) shows that increasing renewable electricity sources would also have major benefits to employment. For example, a realistic increase to 50% renewable electricity by 2030 would create 28,000 new jobs, with the largest net growth in New South Wales (11,000 new jobs) and Queensland (6,000 new jobs).

The challenge is urgent. Australia has signed the Paris Agreement. Now is the time to deliver on our commitment.

Figure 59: Wind turbines at Brown Hill Range, South Australia.

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