CLIMATE COMMISSION

THE CRITICAL DECADE: EXTREME WEATHER

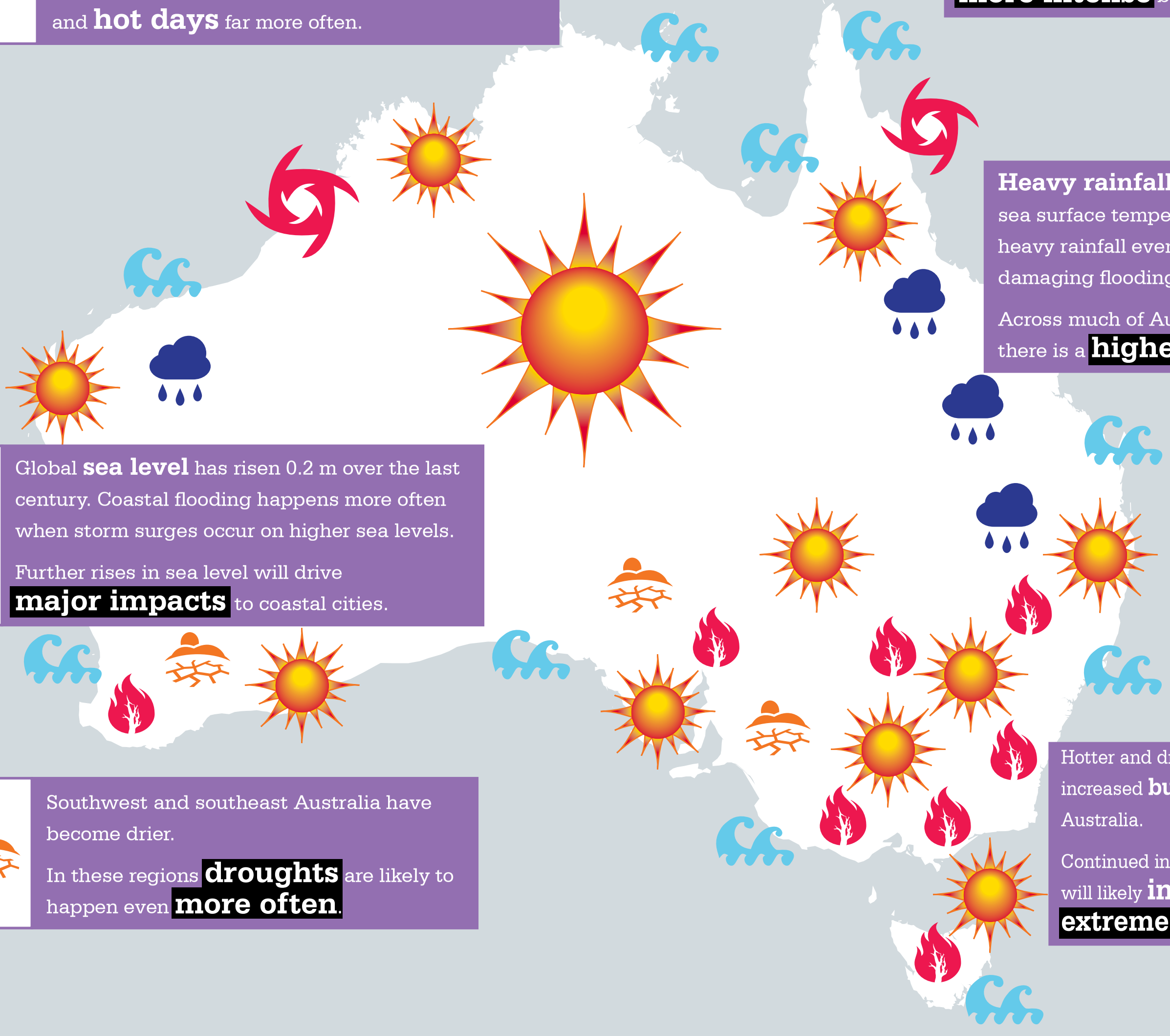
April 2013

Extreme weather has always occurred.

But due to additional **greenhouse gases** in the atmosphere, the **climate system** now contains significantly **more heat** compared to 50 years ago.

This means that **all extreme weather** events are **influenced** by **climate change.**

The **severity** and **frequency** of many **extreme weather** events are increasing due to **climate change.**



Heatwaves have become longer and hotter. The number of record hot days in Australia has doubled since the 1960s.

Australians will face **extreme heatwaves** and **hot days** far more often.

A hotter, moister global climate provides more energy for **tropical cyclones**.

Cyclones are likely to become **more intense** but less frequent.

Heavy rainfall events are increasing. Record sea surface temperatures fuelled recent very heavy rainfall events on the east coast, with damaging flooding.

Across much of Australia, when rain comes there is a **higher risk** of heavy rainfall.

Global **sea level** has risen 0.2 m over the last century. Coastal flooding happens more often when storm surges occur on higher sea levels.

Further rises in sea level will drive **major impacts** to coastal cities.

Southwest and southeast Australia have become drier.

In these regions **droughts** are likely to happen even **more often**.

Hotter and drier conditions have contributed to increased **bushfire** weather risk in southeast Australia.

Continued increases in hot and dry weather will likely **increase** the frequency of **extreme fire danger** days.

Extreme events have major impacts

- **environmental**
- **social**
- $ **economic**

How quickly and deeply we reduce greenhouse gas emissions will greatly influence the severity of extreme events our children and grandchildren experience.

Find out more: www.climatecommission.gov.au

CLIMATE COMMISSION

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PREFACE

The Climate Commission brings together internationally renowned climate scientists, as well as policy and business leaders, to provide an independent and reliable source of information about climate change to the Australian public.

This is the Climate Commission's 24th publication and follows a series of reports on the science and impacts of climate change, the opportunities in Australia associated with taking action to reduce greenhouse gas emissions and international action on climate change.

When extreme weather events occur the Climate Commission is consistently asked questions about the link to climate change. This report unpacks our current knowledge about different types of extreme weather events: extreme temperatures, rainfall, drought, bushfires, storm surges, cyclones and storms.

For each weather event the report considers:

- the definition of the extreme event
- their consequences for the things that matter to us
- observations of the event over the last several decades or longer
- the influence of climate change
- how the event is expected to change through the rest of this century.

The introductory section of the report and introductions to each extreme weather event are written in accessible language. However, the body of the report is somewhat more technical as it provides much more scientific detail on the nature of the event and how it is changing.

The information in this report is compiled from the most authoritative sources. A reference list is included at the end for those who would like further information on a particular subject.

We would like to thank our fellow Commissioners and acknowledge the reviewers who provided advice for this report, including the Science Advisory Panel, Dr Lisa Alexander (temperature-related extreme events and rainfall), Dr Seth Westra (heavy rainfall events), Professor Ross Bradstock (bushfires), Dr John Hunter (sea-level rise and coastal flooding) and Professor Kevin Walsh (tropical cyclones and storms).

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

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KEY FACTS:

1. **Climate change is already increasing the intensity and frequency of many extreme weather events, adversely affecting Australians. Extreme events occur naturally and weather records are broken from time to time. However, climate change is influencing these events and record-breaking weather is becoming more common around the world.**
   - Some Australian examples include:
     - **Heat:** Extreme heat is increasing across Australia. There will still be record cold events, but hot records are now happening three times more often than cold records.
     - **Bushfire weather:** Extreme fire weather has increased in many parts of Australia, including southern NSW, Victoria, Tasmania and parts of South Australia, over the last 30 years.
     - **Rainfall:** Heavy rainfall has increased globally. Over the last three years Australia's east coast has experienced several very heavy rainfall events, fuelled by record-high surface water temperatures in the adjacent seas.
     - **Drought:** A long-term drying trend is affecting the southwest corner of Western Australia, which has experienced a 15% drop in rainfall since the mid-1970s.
     - **Sea-level rise:** Sea level has already risen 20 cm. This means that storm surges ride on sea levels that are higher than they were a century ago, increasing the risk of flooding along Australia's socially, economically and environmentally important coastlines.
2. **Climate change is making many extreme events worse in terms of their impacts on people, property, communities and the environment. This highlights the need to take rapid, effective action on climate change.**
   - It is crucial that communities, emergency services, health and medical services and other authorities prepare for the increases that are already occurring in the severity and frequency of many types of extreme weather.
   - The southeast of Australia, including many of our largest population centres, stands out as being at increased risk from many extreme weather events - heatwaves, bushfires, heavy rainfall and sea-level rise.
   - Key food-growing regions across the southeast and the southwest are likely to experience more drought in the future.
   - Some of Australia's iconic ecosystems are threatened by climate change. Over the past three decades the Great Barrier Reef has suffered repeated bleaching events from underwater heatwaves. The freshwater wetlands of Kakadu National Park are at risk from saltwater intrusion due to rising sea level.

3. **The climate system has shifted, and is continuing to shift, changing the conditions for all weather, including extreme weather events.**
   - Levels of greenhouse gases from the combustion of fossil fuels have increased by around 40% since the beginning of the Industrial Revolution, causing the Earth's surface to warm significantly.
   - All weather events are now occurring in global climate system that is warmer and moister than it was 50 years ago. This has loaded the dice towards more frequent and more severe extreme weather events.
4. **There is a high risk that extreme weather events like heatwaves, heavy rainfall, bushfires and cyclones will become even more intense in Australia over the coming decades.**
   - There is little doubt that over the next few decades changes in these extreme events will increase the risks of adverse consequences to human health, agriculture, infrastructure and the environment.
   - Stabilising the climate is like turning around a battleship – it cannot be done immediately given its momentum. When danger is ahead you must start turning the wheel now. Any delay means that it is more and more difficult to avert the future danger.
   - The climate system has strong momentum for further warming over the next few decades because of the greenhouse gases that have already been emitted, and those that will be emitted in future. This means that it is highly likely that extreme weather events will become even more severe in Australia over that period.
5. **Only strong preventive action now and in the coming years can stabilise the climate and halt the trend of increasing extreme weather for our children and grandchildren.**
   - Averting danger requires strong preventative action. How quickly and deeply we reduce greenhouse gas emissions will greatly influence the severity of extreme events in the future.
   - The world is already moving to tackle climate change. Ninety countries, representing 90% of global emissions, are committed to reducing their emissions and have programs in place to achieve this. As the 15th largest emitter in the world, Australia has an important role to play.
   - Much more substantial action will be required if we are to stabilise the climate by the second half of the century. Globally emissions must be cut rapidly and deeply to nearly zero by 2050, with Australia playing its part.
   - The decisions we make this decade will largely determine the severity of climate change and its influence on extreme events that our grandchildren will experience. This is the critical decade to get on with the job.

1.

LIVING IN A LAND OF EXTREME WEATHER

Figure 1: Some of the many examples of extreme weather events in Australia. Pictured are: the township of Omen, Victoria, after the Black Friday bushfires (1939); Brisbane in flood (1974); Darwin after cyclone Tracy (1974); damage to Naringal Primary School, east of Warrnambool, Victoria after Ash Wednesday bushfires (1983); the Millennium Drought (1997-2009); fires approaching a home in Steels Creek, Victoria during the Black Saturday bushfires (2009); and Eagle Street Pier, Brisbane being flooded in January 2011.

Sources (in order): Museum Victoria MM002905; National Archives of Australia: A6135, K19/2/74/13; wikicommons/Billbeee; © State of Victoria, Department of Sustainability and Environment, 1983; Arthur Mostead; wikicommons/Daniel Cleaveley; and Peter Wallis in the Courier Mail, 13 January 2011.

The occurrence of extreme weather events is not unusual in the Australian landscape or to the Australian people.

Extreme weather events (*Box 1*) have been etched into Australian culture and history over 40,000 years or more. Indigenous peoples have depicted their experience of extreme weather events in paintings and stories, while colonial history is rich with descriptions of the impact of climate on settlers. For many Australians, this quintessential aspect of our continent is best expressed in Dorothea Mackellar's poem *My Country* - 'of droughts and flooding rains'.

Since federation, our experiences of extreme weather have been described through a more modern lens (*Figure 1*). Importantly, science has played a role in both recording and understanding events such as the Federation Drought (1895-1902), the Black Friday bushfires (1939), the Brisbane floods of 1974, cyclone Tracy (1974), the Ash Wednesday bushfires (1983), the Sydney hailstorm (1999), the Millennium Drought (1997-2009), the Black Saturday bushfires (2009), the Brisbane floods of 2011, and cyclone Yasi (2011).

Our knowledge of Australian weather and climate is now vastly greater than a century ago, and it is with this knowledge that we approach a new century, and new challenges.

Extreme events adversely affect Australians through significant impacts on health, property, infrastructure and ecosystems. Extreme events take lives, cause injuries and can lead to psychological trauma and longer-term stress. Their economic costs can often be very high. For example, the cost of the 2009 Black Saturday bushfires to Victoria was estimated to be about $4.4 billion (PoV, 2010). Floods also cause significant economic damages, with the Queensland floods of 2010/2011 costing in excess of $5 billion (QFCI, 2012). The Sydney hailstorm of 14 April 1999 was Australia's most costly storm in terms of insured losses, which totalled $4.3 billion (normalised to 2011) (Insurance Council of Australia, 2013; Crompton, 2011; Crompton and McAneney, 2008).

The basic features of the global climate system have now shifted and are continuing to shift. The system is now warmer and moister than it was 50 years ago, and this is influencing all extreme weather events (Trenberth, 2012). Greenhouse gases in the atmosphere trap heat at the Earth's surface and in the lower atmosphere. Greenhouse gases have increased by around 40% since the industrial revolution, which causes substantially more heat to be trapped. There is vastly more heat in the ocean and in the atmosphere, ice is melting at the poles and on high mountain ranges, and the circulation of the air and seas is changing. This extra heat means that the climate is now more energetic. This is making many extreme weather events more frequent and more severe (*Box 2*).

Severe heat is increasing. The number of record hot days across Australia has doubled since the 1960s, and there has also been a significant increase in the frequency of days over 35ºC in the last 50 years (CSIRO and BoM, 2012). Bushfire weather conditions are being exacerbated by the increase in extreme heat. Sea-level rise is increasing the risk of coastal flooding and beach erosion. Shifting atmospheric circulation patterns are leading to increasing drought conditions in the southeast and the southwest of Australia, while northwest Australia has become wetter (see *Figure 22*). Warmer oceans around the continent contributed to the very heavy rainfall during the 2010-2011 period.

The changes observed in the nature of extreme events around Australia are part of a global pattern. During the past decade unusually severe heatwaves, which cost tens of thousands of lives, occurred in the central regions of Western Europe, Greece, Russia and the United States. On balance heavy rainfall is increasing around the world (IPCC, 2012). Global average sea level has risen by about 20 cm since the late 1800s and is currently rising at about 3 mm per year, increasing the risk of coastal flooding in many low-lying areas around the world.

Extreme events often have adverse consequences for health, survival, property, infrastructure and ecosystems. Awareness of the influence of climate change on extreme weather is critical to enable communities, emergency services, health services and other authorities to prepare for the future.

Just like turning around a battleship, we cannot turn around the increase in the severity and frequency of extreme events immediately. Extreme heat is virtually certain to increase over coming decades. Bushfire weather also generally increases as the atmosphere becomes hotter. Coastal flooding and beach erosion will happen more often as the sea level continues to rise. The southeast and southwest of the continent are likely to experience more droughts in the future. Tropical cyclones are likely to occur less often but bring stronger winds and heavier rainfall. There is little doubt that over the next several decades changes in these extreme events will increase the risks of adverse consequences.

To turn around the battleship you must start turning the wheel now. Any delay in turning the wheel just means that the battleship gets closer to danger and it becomes more and more difficult to avert the danger. Strong preventative action now and in the coming years can gradually slow and then halt the long-term trend toward more severe extreme events. How quickly and deeply we reduce global greenhouse gas emissions will greatly influence the severity of extreme events that our children, and especially our grandchildren, will experience. This is the critical decade to get on with the job.

STRONG PREVENTATIVE ACTION NOW AND IN THE COMING YEARS CAN GRADUALLY SLOW AND THEN HALT THE LONG-TERM TREND TOWARD MORE SEVERE EXTREME EVENTS ... THIS IS THE CRITICAL DECADE TO GET ON WITH THE JOB.

Box 1: Extreme weather events: basics

Many different terms are used to describe extreme weather events and it is important to clearly define the terms that are used in this report.

Extreme weather or climate events

The term *extreme weather or climate 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). It is a weather or climate 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, and they are noticeable because they are so different from the usual weather and climate, and because they are associated with adverse impacts on humans, infrastructure and ecosystems.

Extreme weather events are often short-lived, abrupt events lasting only several hours up to several days; they are 'shocks' within the climate system. Examples include extremely hot days, very heavy rainfall, 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. These are '*chronic*' extreme events. An example all Australians are familiar with is drought, which is a significant lack of rainfall over a period of months to years.

While there are obvious and immediate effects of extreme weather events, changes in average weather or climate conditions are also associated with impacts. Slow, ongoing changes in the average state of the climate system occur over decades, centuries or even millennia. In the context of human-driven climate change, the obvious example is the Earth's rising ocean and air average temperatures. Other examples are the increasing acidity of the ocean due to the increasing absorption of carbon dioxide from the atmosphere and the rise of sea level. Such slow changes have important longer-term consequences. In particular, shifts in the average climate state can increase vulnerability, or undermine the resilience, of communities and ecosystems to the shocks of extreme weather events. While these shifts are described as '*slow*', human-driven climate change is exceedingly fast on geological timescales, around 100 times faster than the periodic natural climate shifts between ice ages and warm periods. Such rapid change seriously threatens the resilience of natural ecosystems, and will increasingly challenge the ability of our society to cope.

Combinations of extreme events

In many cases the most severe impacts are felt when several extreme events occur together. Examples include: (i) the impacts on agriculture of a combination of drought and a heatwave; (ii) high bushfire danger weather, which can be a combination of high temperature, low humidity, high wind and drought.

Extreme weather and climate events can also combine with unrelated factors to drive impacts on society, infrastructure or ecosystems. Examples include: (i) inland flooding, which is associated with very heavy rainfall but also influenced by the condition of the catchment and flood mitigation infrastructure such as dams; and (ii) coastal flooding (sometimes called '*a high sea-level event*'), which is often driven by the combination of a high tide, a storm surge and rising sea level.

Consequences of extreme weather events

The consequences of an extreme weather event also depend on the exposure, vulnerability and adaptive capacity of the people, infrastructure or ecosystem affected by the event.

Exposure refers to the degree that people place themselves, their property and our infrastructure in places where they could be adversely affected by an extreme event. An example is where settlements have been placed on the flood plain of a river.

Vulnerability refers to the propensity to suffer negative impacts from an extreme event. For example, children and elderly people are more vulnerable to extreme heat events. Vulnerability is sometimes described as a lack of resilience.

Adaptive capacity refers to the ability to adjust to actual or expected extreme events (or climate in general) to reduce the adverse impacts and to take advantage of opportunities (adapted from IPCC, 2012). For example, people with chronic health conditions have less adaptive capacity than healthy people.

Box 2: Extreme weather and climate change: the science

Much of the discussion of extreme weather events and climate change is based on the wrong question. The question is not whether climate change has '*caused*' an extreme weather event or whether such an event can be '*attributed*' to climate change. Extreme weather events are a natural feature of the climate system and occur with or without human-driven climate change.

The real question is how climate change is ***influencing*** *extreme weather events. All extreme weather events are now influenced by climate change* (Trenberth, 2012). Compared to 50 years ago the climate system of today contains significantly more heat because of the additional greenhouse gases in the atmosphere, and all extreme weather events are happening in this more energetic climate.

The critical issue is the extent to which this more energetic climate is influencing extreme weather events.

What is important is how extreme weather is changing:

1) in frequency

2) in intensity or severity

3) in geographical extent (for instance, whether drought-prone areas are increasing).

Ultimately, the most important question is how human-driven climate change is making extreme weather events worse in terms of their adverse impacts on people, infrastructure and ecosystems.

How do we know if an extreme weather event has been influenced by climate change?

Scientists use multiple lines of evidence to explore how climate change might influence extreme weather events now and into the future.

- Understanding the basic physical processes of the climate system – for example, that a warmer atmosphere can hold more water vapour – provides important insights. Much of what we understand about climate, and climate change, stems from fundamental physics and chemistry.
- Observations of what has already happened, especially since the mid-20th century, provide additional evidence, although the observational record is often constrained by the time span and geographical coverage of the data. For data records of two decades or less, an underlying trend may be masked by natural climate variability.
- Climate model simulations of past and future climate behaviour also contribute important information, and provide our best understanding of how extreme weather events might change through the rest of this century.

When all of these lines of evidence point in the same direction, we have more confidence in understanding the influence of climate change on extreme weather events.

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 large number 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, 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. 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.

ALL EXTREME WEATHER EVENTS ARE NOW INFLUENCED BY CLIMATE CHANGE.

2.

TEMPERATURE-RELATED EXTREME EVENTS

SUMMARY

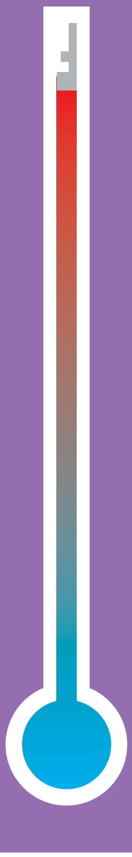
The duration and frequency of heatwaves in Australia have increased, and the hottest days during a heatwave have become even hotter. This section outlines how human-driven climate change has influenced this increase in hot weather and heatwaves. Extreme hot weather has many adverse impacts on Australian society and our environment, affecting human health, infrastructure, agriculture and ecosystems. It is virtually certain that extreme hot weather will continue to become even more frequent and severe around the globe, including Australia, over the coming decades (IPCC, 2012). In summary, climate change is making hot days and heatwaves more frequent and more severe.

2.1 Heatwaves and hot weather

What are heatwaves and very hot days?

A heatwave in Australia is described as a period of at least three days where the combined effect of high temperatures and excess heat is unusual within the local climate (BoM, 2012a). Excess heat often occurs when unusually high overnight temperatures prevent daytime heat from being released (BoM, 2012a). Other descriptors of temperature extremes are given in *Box 3*.

Box 3: Descriptors of Australian extreme temperature



Very hot days: Maximum temperature greater than 40°C

Hot days: Maximum temperature greater than 35°C

Cold days: Maximum temperature is less than 15°C

Very cold days: Maximum temperature is less than 5°C

Source: BoM 2013a

What are the consequences of heatwaves and very hot days?

Very hot days and heatwaves have a significant impact on human health, infrastructure, agriculture and natural ecosystems.

Human health. Research at the Natural Hazards Research Centre (NRHC) has shown that heatwaves are the most significant natural hazard in Australia in terms of loss of life. There have been 4287 fatalities directly attributable to heatwaves during the period 1803-1992 (Coates, 1996).

Humans can survive only when core body temperature remains in a narrow range around 37°C (Hanna et al., 2011). If the body produces or absorbs more heat (for example, from physical activity or high air temperatures) than it can remove through direct transfer to the surrounding air or through sweating, core body temperature will rise. If core body temperature exceeds 38°C for several hours, the body can suffer heat exhaustion and reduced mental and physical capacity (Parsons, 2003; Berry et al., 2010). Serious heatstroke and even death can occur after a relatively short time if core body temperature goes above 42°C (Parsons, 2003). Children, the elderly, people with existing health issues and workers with heat-exposed jobs are the most vulnerable to extreme heat.

Over the last decade, severe heatwaves around Australia have resulted in deaths and in increased hospital admissions for heart attacks, strokes, kidney disease and acute renal failure. During the 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; *Figure 2*). During the Brisbane heatwave of 7-26 February 2004 the temperature ranged from 26° to 42°C.

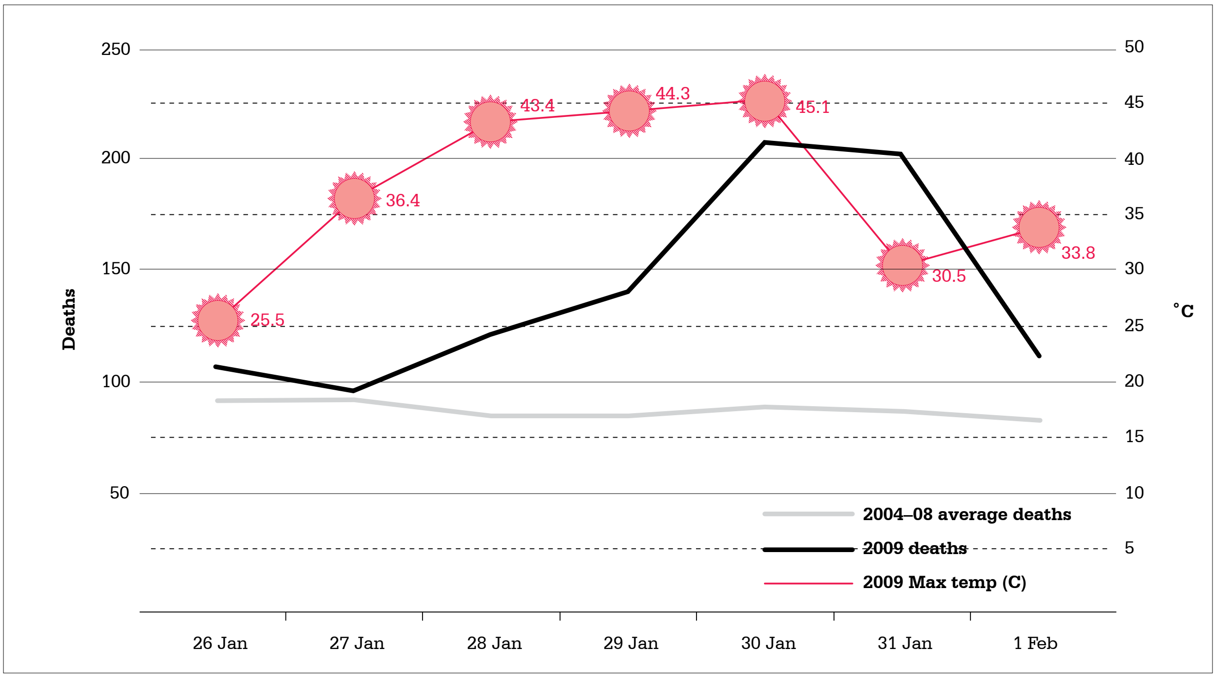


Figure 2: Mortality and temperature during the 2009 Melbourne heatwave. This graph shows the relationship between prolonged periods of higher temperatures and death rates over the same period.

Source: DHS, 2009

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).

Longer-term trends in the impacts of extreme heat have also been observed. In Adelaide, from 1993 to 2006 an increase in total hospital admissions of 7% was recorded during heatwave periods compared with non-heatwave periods, and the number of people requiring ambulance transport during heatwaves increased by 4% (Nitschke et al., 2007).

Hot weather is becoming a more serious risk for health than cold weather in Australia. The upward trend in recent decades in average annual temperatures and in the annual frequency of very hot days, along with the decreased frequency of very cold periods, has been accompanied by a shift in the seasonal distribution of deaths in Australia, in both men and women. An increasing proportion of annual deaths are now occurring in the summer months (Bennett et al., in press). Within-decade analyses indicate that this is primarily an effect of temperature, not background trends in other seasonally-associated health risk factors.

Other species. Humans aren't the only species to suffer from extreme heat. Many other species of animals are vulnerable to ill health and death when temperatures rise too high and they can't move to cooler environments fast enough (*Box 4*). Marine organisms, even though they live in water, are also affected by the impacts of severe heat. Just as for air, heatwaves can occur in the surface waters of the ocean, sometimes leading to dramatic impacts on marine ecosystems (*Box 5*).

Box 4 – Impacts of extreme heat on terrestrial ecosystems

Plants and animals, like humans, are susceptible to extreme heat events. 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 Hopetoun, Western Australia (Saunders et al., 2011).

Flying foxes are also particularly susceptible to extreme heat events (*Figure 3*). 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, for example, 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). In January and February 2009, nearly 5,000 flying fox deaths were recorded at a single site – Yarra Bend Park in Victoria (DSE, 2009).

Some of Australia's most iconic marsupials could also be at risk during extended periods of hot weather. The green ringtail possum (*Figure 4*), for example, 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 5 hours per day, over 4-6 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), and to 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).

Figure 3: Flying foxes are particularly susceptible to extreme heat events. In warm temperatures flying foxes urinate on themselves and flap their wings to cool down.

Source: Daniel Vianna/Wikicommons

Figure 4: The green ringtail possum is unable to control its body temperature when exposed to temperatures above 30oC for long periods of time, making it at risk during extended periods of hot weather.

Source: Flickr/Algaedoc

Box 5 – Impacts of extreme heat on marine ecosystems

Heatwaves also affect marine ecosystems. When coral reefs are subject to sea surface temperatures more than 1-2°C above average summer maximum temperatures, the corals can bleach and die (*Figure 5*). Bleaching events on the Great Barrier Reef have occurred repeatedly since the late 1970s, contributing to the decline in coral cover observed from 1985 to 2002 (De'ath et al., 2012). The 2011 marine heat wave in Western Australia (*Figure 6*) caused the first-ever reported bleaching at Ningaloo Reef (Wernberg et al., 2013).The ability to recover from bleaching events varies among coral species and among 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).

Corals are not the only marine systems to be affected by extreme heat. Mortality and reduced reproduction have also been observed in intertidal and estuarine species during heatwaves (e.g., Cardoso et al., 2008; Garrabou et al., 2009). In some ecosystems, the species composition can be so dramatically affected by a single event, such as occurred in the 2003 European heatwave, that these ecosystems appear to never fully return to their former state.

Figure 5: Coral bleaching in the Great Barrier Reef.

Source: GBRMPA

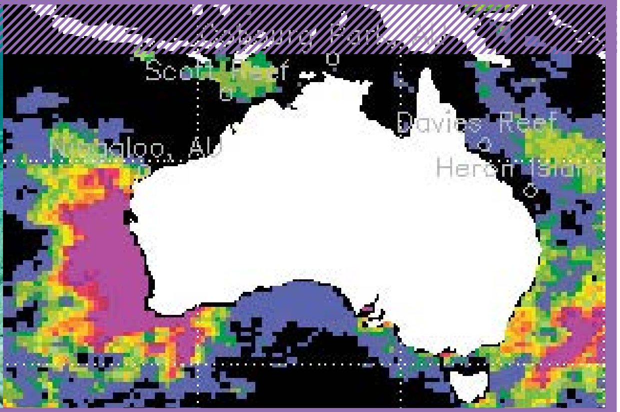


Figure 6: Satellite image of an underwater heatwave. The hottest areas are shown in pink.

Source: NOAA

*Infrastructure***.** The prolonged extreme heat in Melbourne in January 2009 caused substantial damage to critical infrastructure including energy transmission and rail transportation. Increased demand for electricity during the heatwave broke previous records for Victoria by approximately 7% (QUT, 2010). In addition faults to the transmission systems made the entire grid vulnerable to collapse (QUT, 2010). During the heatwave the Basslink electricity cable between Tasmania and Victoria reached maximum operating temperature and was automatically shut down for safety reasons (QUT, 2010). The shutdown of this transmission source combined with faults at a number of transformers caused widespread blackouts across Melbourne (QUT, 2010). On the evening of 30 January 2009 an estimated 500,000 residents were without power (QUT, 2010).

Melbourne's train and tram networks also suffered widespread failures during the 2009 heatwave, caused by faults to air conditioning systems and tracks buckling in the extreme heat (QUT, 2010; *Figure 7*). On 30 January, approximately one quarter of train services did not run (QUT, 2010). Financial losses from the heatwave, estimated at $800 million, were mainly caused by the power outages and disruptions to the transport system (Chhetri et al., 2010).

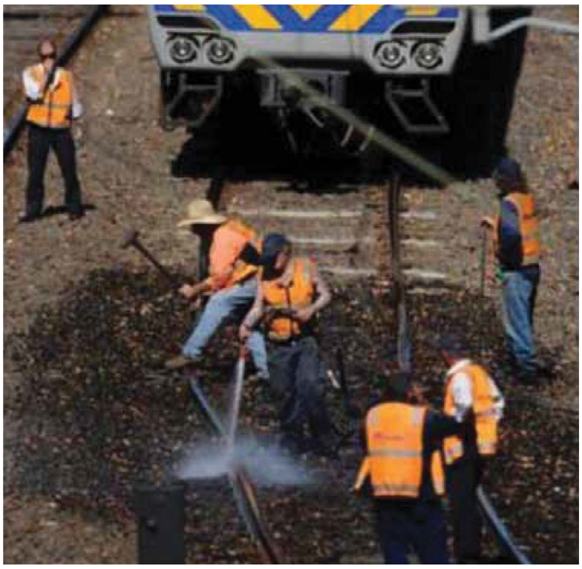


Figure 7: Rail tracks in Melbourne buckled during the 2009 heatwave.

Source: Herald Sun

Agricultural production. Agricultural productivity, which is already sensitive to extremes of natural climate variability, is expected to suffer net decreases with increasing temperatures. For example, dairy cattle are likely to suffer heat stress more frequently, which can reduce appetite and thus milk production, as well as decreasing milk quality (QFF, 2008; DEEDI, 2010). Rising temperatures will affect yield, quality and the length of the growing season for crops such as tomatoes and lettuces, although the development of more heat-tolerant cultivars may offset some of these impacts (Deuter et al., 2011; Deuter et al., 2012).

What changes have been observed in heatwaves and very hot days?

Since 1950, it is very likely that there has been an overall increase in the number of warm days and nights on the global scale (IPCC, 2012), as well as an increase in the frequency, intensity and duration of heatwaves and warm spells at the global level (Perkins et al., 2012). In the last decade, a large number of extreme heatwaves have occurred around the world, each causing major societal impacts. Recent events include the European heatwave of 2003 (Stott et al., 2004); a major heatwave in Greece in 2007 (Founda and Giannaopoulos, 2009); the Russian heat wave of 2010 (Barriopedro et al., 2011); a heatwave in Texas (USA) in 2011 (NOAA, 2011); and a more widespread heatwave in the USA in 2012 (NOAA, 2012).

The annual number of record hot days across Australia has doubled since 1960 and the number of record cold days has decreased (CSIRO and BoM, 2012; *Figure 8*). In fact, the frequency of record hot days has been more than three times the frequency of record cold days during the past ten years (Trewin and Smalley, 2012). The number of very hot days is also increasing in many places. For example, in Canberra the long-term average (1961-1990) number of days per year above 35°C was 5.2, but during the decade 2000-2009 the average number of such days nearly doubled to 9.4 days (BoM, 2013b; Table 1).

The nature of heatwaves has already changed in many parts of Australia. Over the period 1971-2008, the duration and frequency of heatwaves has increased, and the hottest days during a heatwave have become even hotter. This change has been likely driven by the increase in the frequency of hot days alone (Perkins and Alexander, 2013).

The Australian heatwave of the summer of 2012/2013 was exceptional for its extent and for its intensity (*Box 6*).

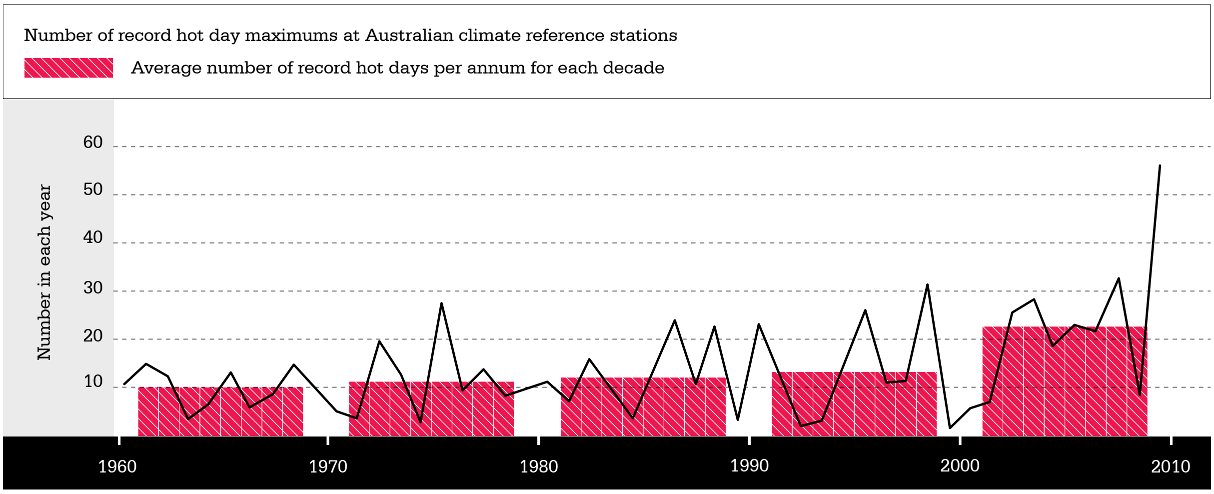


Figure 8: Number of record hot day maximums at Australian climate reference stations.

Source: CSIRO and BoM, 2011

Box 6: Extreme heat over the summer of 2012/2013

A severe heatwave, unusual in length, extent and severity, affected 70% of Australia in late December 2012 and early January 2013 (*Figure 9*). Temperature records were set in every state and territory and the national average daily temperature reached levels never previously observed.

The summer of 2012/2013 was Australia's hottest summer since records began in 1910. New records that were set included:

- The hottest ever area-averaged Australian maximum temperature, which occurred on 7 January reaching 40.30°C (BoM, 2013c);
- The hottest month on record for Australia – January 2013 (BoM, 2013c);
- All-time high maximum temperatures at 44 weather stations, including Sydney (45.8°C), Hobart (41.8°C) and Newcastle (42.5°C) (BoM, 2013c);
- The average daily maximum temperature for the whole of Australia was over 39°C for seven consecutive days (2-8 January 2013), easily breaking the previous record of four consecutive days over 39°C (BoM, 2013c); and
- The hottest sea-surface temperatures on record for the Australian region for January and February 2013, and the entire summer period. The average temperature of the waters around Australia during February was 23.9°C, 0.6°C above the long-term average and 0.13°C above the previous record (BoM, 2013d).

There have only been 21 days in 102 years of records where the average maximum temperature across Australia has exceeded 39°C; eight of these days happened in the summer of 2012/2013 (2-8 January and 11 January 2013) (BoM, 2013c).

Based on the network of long-term, climate monitoring stations, no previous event has resulted in so many temperature records (BoM, 2013c). The impacts of the heatwave are yet to be fully determined; nonetheless, the number of records set clearly demonstrates the extreme nature of this event.

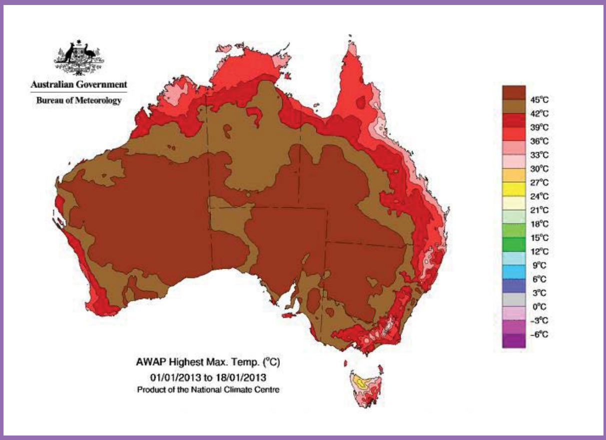


Figure 9: Highest maximum temperature between 1 and 18 January 2013.

Source: BoM, 2013c

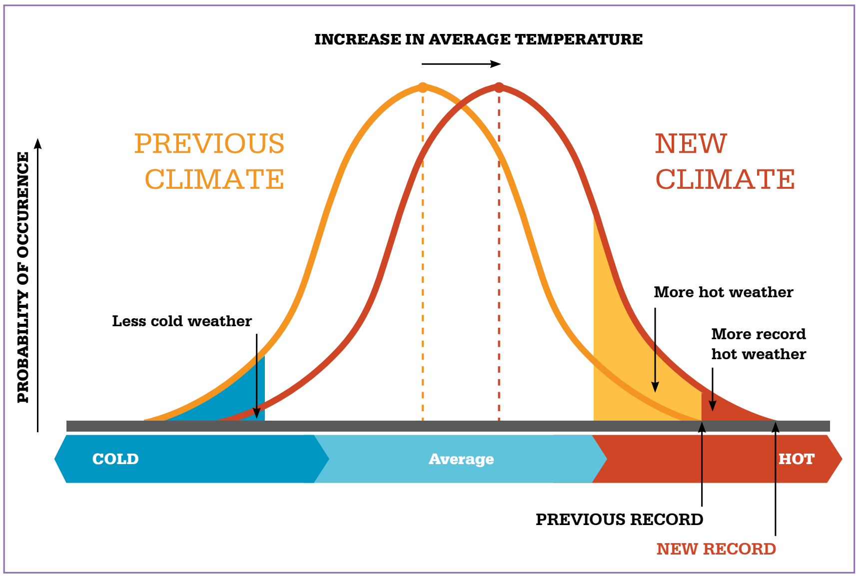


Figure 10: Relationship between average and extremes, showing the connection between a shifting average and the proportion of extreme events.

Source: Modified from IPCC, 2007

ALTHOUGH RECORDS HAVE ALWAYS BEEN BROKEN FROM TIME TO TIME, RECORDS ARE NOW BEING BROKEN MUCH MORE FREQUENTLY.

How does climate change influence heatwaves and very hot days?

While hot weather has always been common in Australia, it has become more common and severe over the past few decades. Australia's average air temperature has risen by 0.9°C since 1910, with most of that rise occurring in the post-1950 period (CSIRO and BoM, 2012). This means that there is much more heat in the atmosphere and so hot weather becomes more likely. This is consistent with the global trend of increasing average temperature and the increase in hot weather globally.

A small increase of 0.9°C in average temperature can have a disproportionately large effect on the number of hot days and record hot days. When the average temperature increases, the temperatures at the hot and cold ends (tails) of the temperature range shift to create a much greater likelihood of very hot weather and a much lower likelihood of very cold weather (*Figure 10*). The heavy shaded area at the extreme right shows the record hot weather that occurs only after the shift to the warmer background climate. This means that we are beginning to see weather events that have never been observed since instrumental records were begun, and events that were extremely rare in the previous climate are becoming more common. Although records have always been broken from time to time, records are now being broken much more frequently.

It is likely that human influences have already led to warming of extreme daily minimum and maximum temperatures at the global scale (IPCC, 2012). Although Australia has always had heatwaves and hot days, climate change has increased the risk of more intense heatwaves and hot days (*Figure 10*). In summary, climate change is making hot days and heatwaves more frequent and more severe.

What are the projections for heatwaves and hot days in a changing climate?

It is virtually certain that 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, 2012). As climate change continues, it is virtually certain that Australians will face extreme hot weather much more often (see Table 1) and the impacts will become more severe. It is highly likely that there will be an increased frequency of hot days, hot nights and heatwaves at the global level (IPCC, 2012). The number of heatwaves across Australia is also projected to increase significantly by the end of the century (Alexander and Arblaster, 2009).

If climate change continues on its current path, extreme heat will become a much more common occurrence in most of Australia's capital cities (Table 1). The annual number of hot days (over 35°C) averaged over the 2000-2009 decade has already risen compared to the 1961-1990 baseline in most capital cities. In fact, for Adelaide, Melbourne and Canberra the observed annual number of hot days is increasing more quickly than the climate models projected. In these cities the annual number of hot days occurring now is at the level projected for around 2030, although the increase in this decade may in part be due to natural variability. If rapid and deep cuts in greenhouse gas emissions are not achieved, the number of hot days will very likely rise even further in all major cities by the end of the century (CSIRO and BoM, 2007). However, with lower emissions the projected increases in hot days for 2070 are much less (Table 1).

2.2 Extreme cold weather events

The definition of a cold spell is a prolonged period of time with cold temperatures relative to local conditions. In Australia, a cold spell is defined as at least four nights where minimum temperatures fall within the coldest 10% of recorded temperatures for a local climate (BoM, 2013a).

Extreme cold events can have serious consequences for human health. However, they are relatively rare in Australia compared to many other parts of the world. Heat-related health impacts will increasingly be of more concern than cold-related ones as the climate continues to warm. Cold weather also affects agriculture, as frost nights can damage newly planted crops. On the other hand, many species of stone fruit have a chilling requirement to set the fruit, and so a decrease in cold weather can negatively affect production of fruit (Hennessy and Clayton-Greene, 1995).

On a global scale it is very likely that there has been an overall decrease in the number of cold days and nights since 1950 (IPCC, 2012).

	LONG-TERM AVERAGE (1961-1990)	**2000 - 2009 AVERAGE**	**2030 PROJECTED**	**2070 PROJECTED (low emissions scenario)**	**2070 PROJECTED (high emissions scenario)**
MELBOURNE	**9.9**	**12.6**	**12** (11-13)	**14** (12-17)	**20** (15-26)
SYDNEY	**3.4**	**3.3**	**4.4** (4.1-5.1)	**5.3** (4.5-6.6)	**8** (6-12)
ADELAIDE	**17.5**	**25.1**	**23** (21-26)	**26** (24-31)	**36** (29-47)
CANBERRA	**5.2**	**9.4**	**8** (7-10)	**10** (8-14)	**18** (12-26)
DARWIN	**8.5**	**15.7**	**44** (28-69)	**89** (49-153)	**227** (141-308)
HOBART	**1.2**	**1.4**	**1.7** (1.6-1.8)	**1.8** (1.7-2.0)	**2.4** (2.0-3.4)

Table 1: The long-term average number of hot days (above 35°C) compared to the 2000 – 2009 average and the projected number for 2030 and 2070 for some Australian capital cities. Both 2030 and 2070 projections show the median and, in brackets, the range of projections for the number of hot days. The lowest number in the range is the 10th percentile and the highest number is the 90th percentile of the various model projections. The median is the 50th percentile. The 2070 projections are divided into low and high emissions scenarios. Brisbane and Perth are not included because the locations of observations for these cities differ from the locations on which projections are based.

Source: BoM, 2013b; CSIRO and BoM, 2007

A decrease in cold days and cold nights has also been observed in Australia (Nicholls and Collins, 2006; Alexander et al., 2007). The number of frost nights has also generally decreased across the country since 1970, although there are some significant regional variations (*Box 7*).

Climate change is decreasing the likelihood of very cold weather events. It is virtually certain that the frequency and magnitude of cold extremes will decrease over the coming decades at a global scale, and across Australia (IPCC, 2012).

Box 7: Frost nights in Australia

Frost occurs frequently in southern parts of the country when the temperature falls below freezing. Frost formation is affected by a number of variables, including cloud cover, humidity, wind and the aspect of the location. Frost is more likely to form under a clear sky, with low humidity and light winds (BoM, 2013e).

There has been a decrease in the number of frost nights in many areas across Australia, such as Canberra, which has experienced a reduction of 5 days per decade in frost nights between 1970 and 2011 (*Figure 11*). However, there have also been increases in frost nights in some areas. This is most likely due to reduced cloud cover associated with a decrease in rainfall, leading to clear night time skies and lower temperatures.

In the future, it is likely that Australia will continue to experience less frost events, depending on the magnitude of warming and the location (Tebaldi et al., 2006).

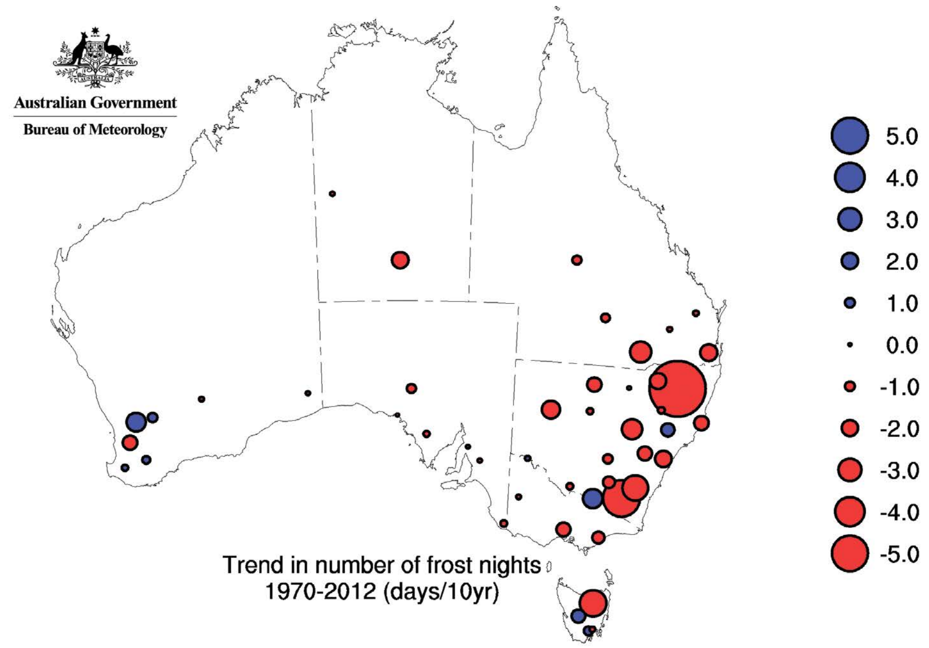


Figure 11: Trend in the number of frost nights in Australia between 1970 and 2012.

Source: Prepared by the Bureau of Meteorology for the report

3.

RAINFALL AND DROUGHT

SUMMARY

Australia has long had a highly variable climate of droughts and heavy rains, and this pattern is likely to continue into the future. However, climate change is likely to increase the severity of these extreme weather events. Over the last three years Australia's east coast has experienced several very heavy rainfall events, fuelled by record-high sea surface temperatures. These events led to very damaging flooding in Queensland and parts of New South Wales and Victoria. In the future the changes in rainfall patterns for much of the continent are difficult to predict, but we can expect a higher risk of heavy rainfall events in general.

Since the 1970s the southwest of Australia has become drier and since the mid-1990s the southeast has become drier, especially in the cooler months of the year. The Millennium Drought of 1997-2009 was one of Australia's most severe droughts, with far-reaching impacts on agricultural production, urban water supplies and natural ecosystems. A return to the earlier, wetter climate is unlikely, and such dry conditions and droughts are likely in the southwest and southeast to become more common and intense.

3.1 Heavy rainfall events

What is a heavy rainfall event?

A heavy rainfall event is a deluge of rain that is much longer and/or more intense than the average conditions experienced at a particular location. The Bureau of Meteorology uses a number of extreme precipitation (rain, hail or snow) indices (BoM, 2013a):

- Heavy precipitation days: days with daily precipitation greater than or equal to 10 mm
- Very heavy precipitation days: days with daily precipitation greater than or equal to 30 mm
- Very wet day precipitation: daily precipitation greater than 95th percentile
- Extremely wet day precipitation: daily precipitation greater than 99th percentile.

The amount of rainfall in a day is also referred to as rainfall intensity. An extreme rainfall event may also be defined by its 'return period'. A 1-in-20 year event at a site is the daily rainfall total that would be on average expected to occur once in 20 years. The magnitude of such an event would vary from site to site.

What are the consequences of heavy rainfall events?

Flooding is the most prominent impact of very heavy rainfall events. However, the severity of floods is also influenced by several other factors in addition to rainfall, including the condition of catchments, the effectiveness of dams to manage flooding, and the vulnerability of people and infrastructure. Floods cause significant societal disruption including damage to human health, buildings, infrastructure, ecosystems and agricultural land (*Box 8*).

Box 8: Damage from the Queensland 2010/2011 floods

Extreme and extended rainfall over large areas of Queensland 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. The floods also broke river height records at over 100 observation stations.

Thirty-three people died with three remaining missing, and 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 and difficulties in accessing health services and treatments.

Approximately 2.5 million people were affected and 29,000 homes and businesses experienced some form of flooding (*Figure 12*). The economic cost of the flooding was estimated to be in excess of $5 billion.

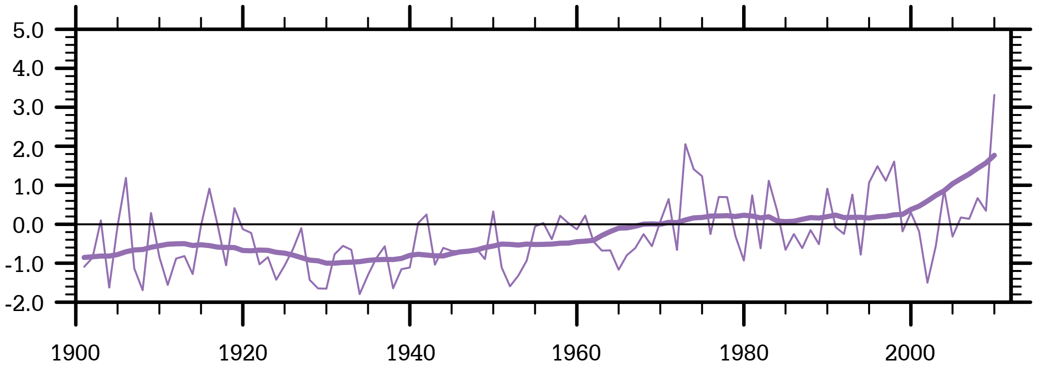
Major damage occurred to infrastructure, including thousands of kilometres of road and rail, as well as to electricity generation and distribution and to other essential infrastructure. Over 3000 km of Queensland Rail track were affected, much of the electrical infrastructure in the Lockyer Valley was destroyed, and around 300,000 homes and businesses lost power in Brisbane and Ipswich at some stage during the floods.

Source: QFCI, 2012

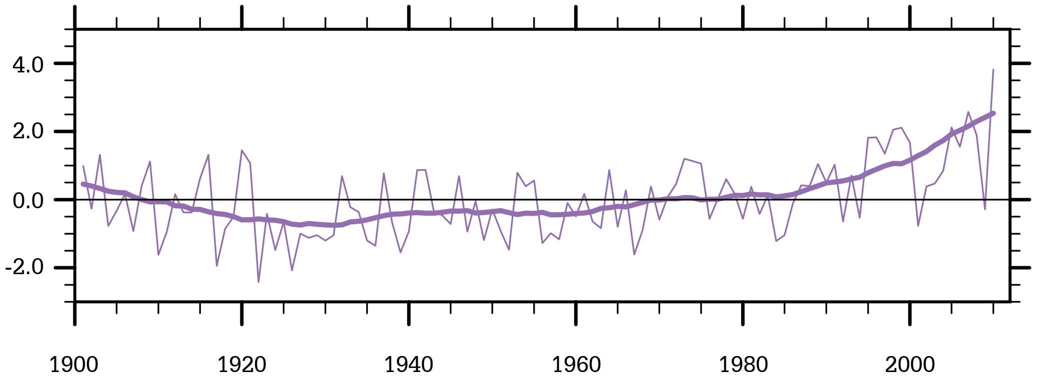
Figure 12: Heavy rainfall caused widespread flooding across many areas of Brisbane including the CBD. The corner of Margaret and Albert Streets in Brisbane is pictured.

Source: Flickr/David Peddler

(a) the number of heavy precipitation days



(b) the contribution from very wet days to the total rainfall, in percentage



(c) a simple rainfall intensity index in mm per day (index defined in Donat et al. 2013).

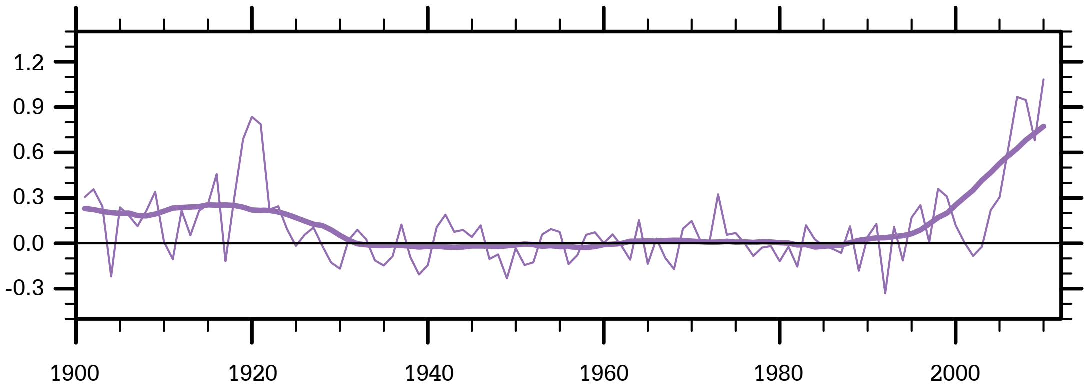


Figure 13: Globally averaged time series from 1901 to 2010 in (a) the number of heavy precipitation days; (b) the contribution from very wet days to the total rainfall, in percentage; and (c) a simple daily rainfall intensity index in mm per day.

Source: Donat et al., 2013a

What changes have been observed in heavy rainfall events?

Heavy rainfall is increasing. There have been statistically significant increases in the number of heavy precipitation events in most regions of the world (IPCC, 2012). A recent global analysis showed that there are more areas around the globe with significant increases in heavy precipitation events than with decreases (Donat et al., 2013a; *Figure 13*). Furthermore, independent measurements show an increase of water vapour in the atmosphere from 1988 to 2004, the period over which reliable measurements are available (IPCC, 2007). Increased water vapour in the atmosphere increases the availability of water to fall as precipitation.

There is considerable variability in rainfall and rainfall extremes across Australia. Northwest Australia has experienced a significant increase in the frequency of heavy rainfall events (Donat et. al, 2013b; IPCC, 2012). In comparison, there is a slight decrease (not statistically significant) in the number of heavy rainfall events in southeast and southwest Australia (Donat et. al., 2013b). These findings are consistent with the changing pattern of average rainfall across Australia, where southeast and southwest Australia are experiencing a decrease and the northwest is experiencing an increase in total annual rainfall (BoM, 2013f). An increasing trend in short duration (sub-daily) rainfall extremes in Australia is stronger than for longer duration events (Westra and Sisson, 2011; Jakob et al., 2011).

The period from 1 January 2010 to 31 December 2011 was exceptional in terms of the heavy rainfall that occurred over much of the continent (*Figure 14*). The total of 1409 mm of rain averaged over the entire continent was a record, eclipsing the previous record set in the 1973-1974 two-year period. The 2010-2011 period was also remarkable in the widespread nature of the heavy rainfall. Every state and territory had sites that either set all-time rainfall records for a two-year period or had rainfall that was very much above average.

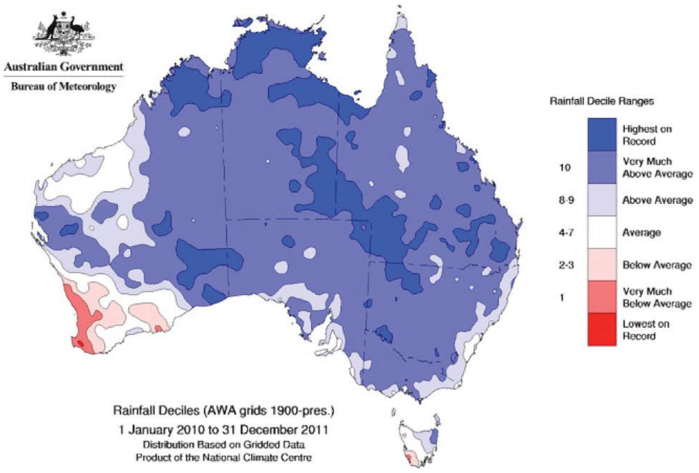


Figure 14: Map of Australia showing rainfall for 1 January 2010 through 31 December 2011

Source: BoM, 2012b

How is climate change influencing heavy rainfall events?

The physical connection between a warming climate and more rainfall is well understood (*Figure 15*), especially for rainfall that is derived from an oceanic source and thus not limited by the amount of water that can be evaporated from the surface (Hardwick-Jones et al., 2010). Higher temperatures in the surface ocean waters lead to more evaporation, and, because the atmosphere is warmer, it can hold more water vapour. This leads to a higher water vapour content in the atmosphere. As a result, precipitation increases in many locations, with a higher proportion of the precipitation coming as heavy falls. The observations described above are consistent with this physical understanding, including the heavy rainfall over from January 2010 to December 2011. The statistical evidence for this connection is beginning to emerge; the Intergovernmental Panel on Climate Change (IPCC) noted that 'there is medium confidence that human influences have contributed to the intensification of extreme precipitation at the global scale' (IPCC, 2012).

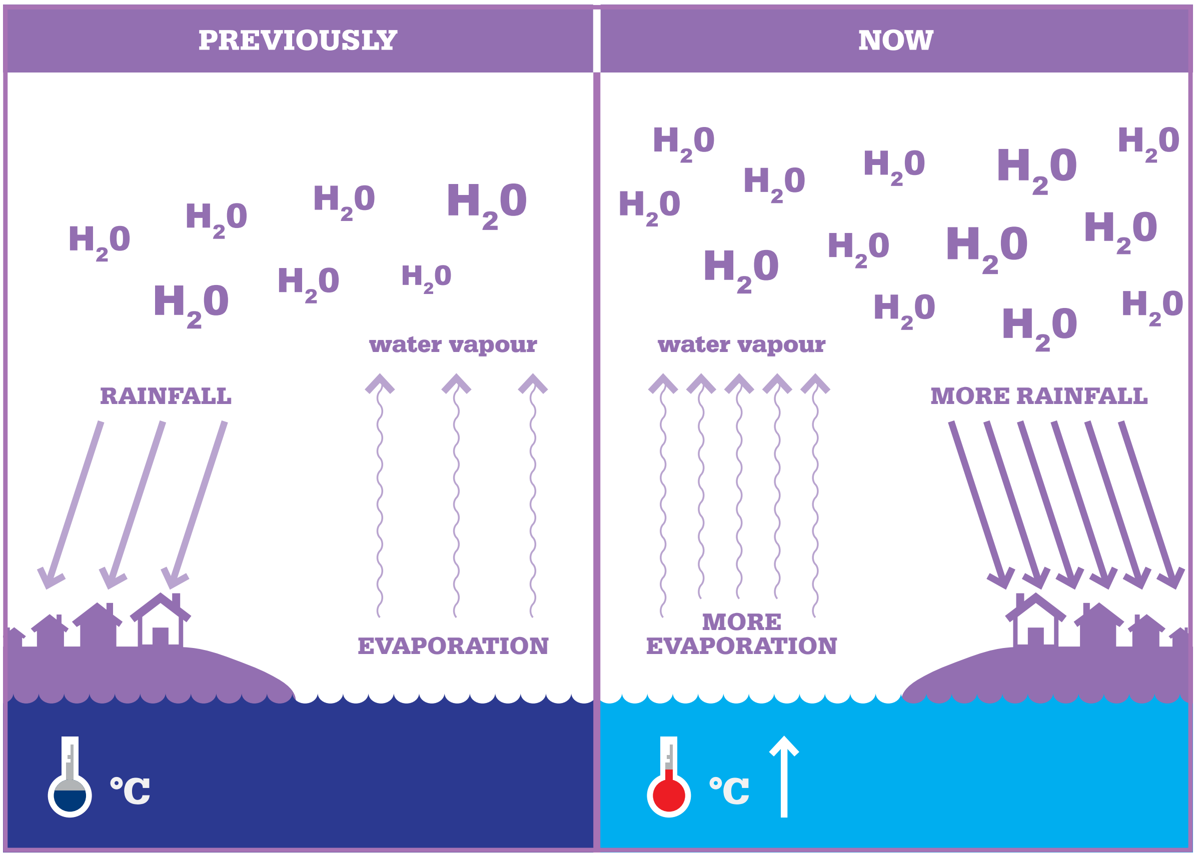
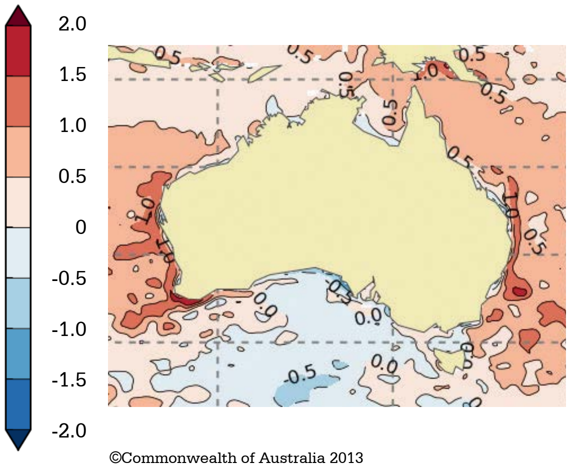


Figure 15: The influence of climate change on the water cycle. LEFT: The pre-climate change water cycle. RIGHT: The water cycle operating under higher surface ocean and air temperatures. The symbol H_2O represents water vapour.

Although the physics of the climate change-heavy rainfall link is understood, it can be difficult to determine the extent of the impact of climate change on individual extreme rainfall events. This is especially so for Australia, where modes of natural variability such as El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) play an important role in influencing rainfall patterns.

A good example is the 2010-2011 period of record-breaking rainfall across much of Australia (*Figure 14*), where climate change exacerbated the intensity of a naturally occurring event (Evans and Boyer-Souchet, 2012). That rainfall occurred during a period of strong La Niña conditions. In Australia, La Niña years are notable for the above-average rainfall they bring to much of the continent. The higher rainfall associated with the La Niña phase of ENSO is due to favourable atmospheric circulation combined with higher-than-average sea surface temperatures (SSTs) in the seas surrounding Australia. These conditions drive increased atmospheric convection, driving moisture from the oceans into the atmosphere in the Australian region.

The 2010-2011 period coincided with unusually high SSTs, even for a La Niña event. In fact, the SSTs during the spring and early summer of 2010-11 were the highest on record at that time (*Figure 16*). Climate change is driving higher temperatures of the surface ocean waters around the world, and so very likely pushed up the already high La Niña SSTs around northern Australia even further. In this way, climate change likely contributed to the exceptionally heavy rainfalls of 2010-2011 (Evans and Boyer-Souchet, 2012).



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Australian Bureau of Meterology, COSPPac COMP
Reynolds SST

Figure 16: Sea surface temperature anomalies (°C) in the Australia region, for the period May 2010 to April 2011

Source: Produced by the Bureau of Meteorology for this report

What are the projections for heavy rainfall events in a changing climate?

It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe (IPCC, 2012). Based on a range of IPCC emissions scenarios, a 1-in-20 year maximum daily rainfall event is likely to become a 1-in-5 to 1-in-15 year event by the end of the 21st century in many regions (IPCC, 2012).

Across Australia, it is more likely than not that heavy rainfall events will become more frequent as the temperature increases. The tendency for 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 (CSIRO and BoM 2007), such as southern Australia (CSIRO and BoM, 2007; Pitman and Perkins, 2008; Moise and Hudson, 2008).

3.2 Drought

What is a drought?

Drought is defined as a period of abnormally long dry weather compared to the normal pattern of rainfall (BoM, 2013f). Drought can be considered as an ‘agricultural drought’, when insufficient soil moisture negatively affects crop production; a ‘hydrological drought’, when stream flow, lake levels or groundwater levels drop to a sufficiently low level; or a ‘meteorological drought’, when there is a period of insufficient rainfall compared to a long-term average (IPCC, 2012). The meteorological definition of drought is most relevant for discussing the relationship between climate change and drought.

The Bureau of Meteorology (2013f) defines meteorological drought as a serious or severe rainfall deficiency of three months or more. A serious rainfall deficiency is defined as rainfall in the lowest 5 to 10% range (where 50% is average rainfall) for the period measured (BoM, 2013f). A severe rainfall deficiency is rainfall in the 0 to 5% range for the period (BoM, 2013f).

Drought is a complex phenomenon because it is also related to other weather features such as temperature, wind and evaporation, as well as to environmental conditions like the amount of soil moisture. Thus drought, as an extreme weather event is actually an accumulation of weather events which may or may not be considered ‘extreme’ individually (IPCC, 2012).

What are the consequences of drought?

Australians have long experienced drought, with some major droughts affecting large parts of the country and having severe economic, environmental and social impacts (*Figure 17*; ABARES, 2012).

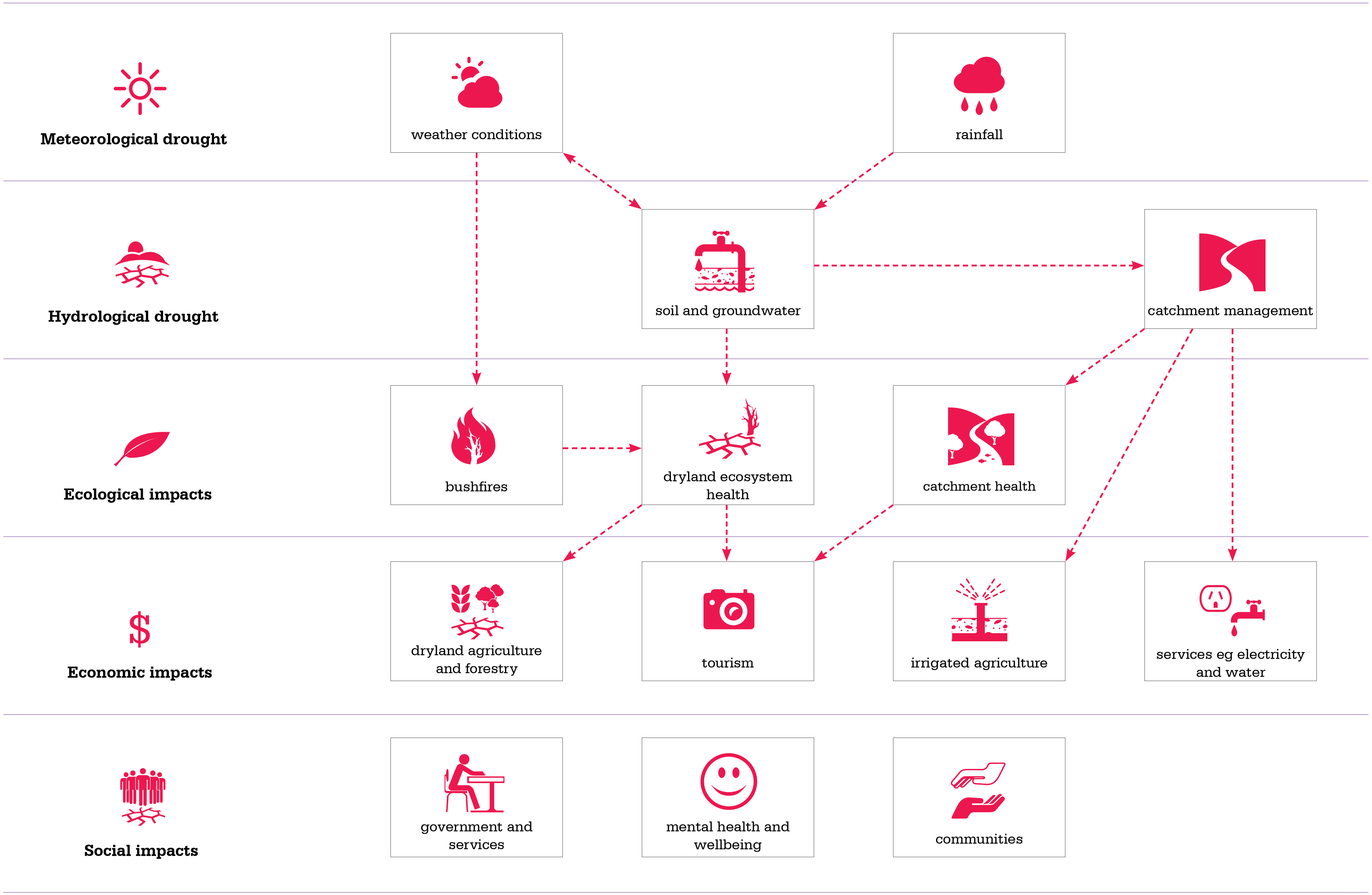

Figure 17: The ecological, economic and social impacts of droughts
Drought has a complex range of impacts not limited to the major impacts displayed in this image. The links between impacts represent key relationships and many other links also exist. In addition, social impacts are recognised to be the combined result of several impacts.

Source: modified from van Dijk et al., 2013.

The impacts of drought on agriculture can be severe (*Figure 18*). For instance, during the 2002-03 financial year, drought is estimated to have reduced Australia's agricultural output by 26% (PMSEIC Independent Working Group, 2007). The Millennium Drought (*Box 9*) led to severe reductions in agricultural production in the southeast. For example, in the Wimmera Southern Mallee region of Victoria, the drought resulted in an 80% reduction in grain production and a 40% reduction in livestock production (BCG, 2008). In the wheat belt of southwest Western Australia, the very dry conditions in recent years have driven sharp decreases in yields; the production of winter wheat crops in the 2010 and 2011 seasons was around 43% lower than for previous seasons (ABARES, 2011).

Figure 18: Cattle near Wagga Wagga during drought in 2006.

Source: Flickr/John Schilling

Rural communities face large economic and social consequences from droughts when incomes decline and people move away. Impacts on health and well-being can be severe. The experience of droughts and their impacts, such as loss of income as well as changes to social roles, are often associated with stress, anxiety and sometimes suicide (McMichael, 2011; Clarke, 2010). One study estimated that the suicide rate would rise by 8% over the long-term average with a severe decrease in annual rainfall of around 300 mm (Nicholls et al., 2006). Health can also suffer from water quality problems caused by drought. For example, a decrease in the volume of water in dams increases the concentration of pollutants, and the growth of toxic blue-green algae increases with higher water temperatures (Kjellstrom and Weaver, 2009).

Drought also places increased pressure on the natural environment, including plants, animals and water resources. One prominent example is the Coorong, an internationally recognised and significant wetland system near the mouth of the Murray River that supports a diverse range of birds, animals and plants. During the drought of 1997-2009 the inflows into the Murray-Darling system were the lowest on record (MDBA River Murray inflow data; CSIRO, 2010). As a result the Coorong reached extreme levels of salinity that threatened the viability of many plants and animals in the wetlands (Leblanc et al., 2012). Drought-related mortality of amphibians in southeast Australia (MacNally et al., 2009), savanna trees in northeast Australia (Fensham et al., 2009; Allen et al., 2010) and eucalypts in sub-alpine regions in Tasmania (Calder and Kirkpatrick, 2008) have been recorded in the past decade.

One of the most serious consequences of drought is the reduction in urban and irrigation water supplies. Perth's water supply has been hit hard by the drying of southwest Western Australia since the mid-1970s (*Box 10*). The water supplies of Australia's two largest cities have also recently been threatened by drought. The annual inflow into Melbourne's dams dropped by almost 40% in the 1997-2011 period compared to the average over the previous 80 years, and inflow in 2006 was the lowest on record (Melbourne Water, 2012). The 1997-2009 drought also affected Sydney's water supply as dam levels dropped below 40%, triggering severe water restrictions and permanent water efficiency rules (Sydney Water, 2012). In regional Australia, dam levels fell to 12% of capacity in Goulburn, on the NSW Southern Tablelands, raising the prospect of having to truck in water to the community (Goulburn Mulwaree Council, 2012).

Box 9: The 'Millennium Drought', 1997-2009

One of Australia's most severe droughts, commonly known as the Millennium Drought, occurred in the period from 1997-2009 and had far-reaching impacts, particularly on agricultural production, urban water supplies and natural ecosystems.

The drought was largely restricted to southern Australia, where annual rainfall during the period was 12% below the long-term average (1900-2010), the lowest rainfall recorded over a 13-year period for the region affected (CSIRO, 2012). In fact, because the rainfall deficits were most prominent in autumn and early winter and thus had a large impact on runoff into catchments, it was the most severe hydrological drought since accurate records began in 1865 (CSIRO, 2012), eclipsing the Federation drought (1895-1902) and the World War II drought (1937-1945) (Kiem et al., 2010).

Recent research through the South Eastern Australian Climate Initiative (SEACI) provides evidence that the Millennium Drought was influenced by climate change (CSIRO, 2012). The research found a strong relationship between the rainfall decline in southeast Australia and the intensity of the subtropical ridge (STR) (CSIRO, 2010), an east-west zone of high pressure that often lies over the southern part of the continent. The STR has intensified with increasing global air temperature (Timbal and Drosdowsky, 2012).

Simulations of the global climate over recent decades found that increasing greenhouse gases in the atmosphere were necessary to replicate the changes in the STR, but the observed changes were much larger than those simulated in the model. The strengthening of the STR is estimated to account for around 80% of the recent rainfall decline in southeast Australia (Murphy and Timbal, 2008; CSIRO, 2010).

The Millennium Drought had major ecological, agricultural, social and economic impacts particularly in southeastern Australia and the Murray-Darling Basin. Ecological impacts included toxicity in the lakes at the end of Murray River and widespread tree deaths in floodplains throughout the Basin (van Dijk et al., 2013). The long drought also placed increased pressure on environments that are already under stress from changing and reduced habitats.

Agricultural impacts were most severe in southeast Australia (van Dijk et al., 2013). For example, irrigated rice and cotton production in the Murray-Darling Basin fell by 99% and 84% between 2002 and 2009, respectively (ABS, 2011). Wheat production also showed a 12% reduction in yield but production increased overall due to a large increase in cropping area (van Dijk et al., 2013).

Estimates of the economic impact of the drought vary and are difficult to quantify due to the many other influences over the 13-year period (van Dijk et al., 2013). In 2006-2007 it is estimated that the drought reduced national gross domestic product by almost 1% (RBA, 2006).

Reports on the social impacts of the drought show that rural communities suffered losses of employment, household income, local businesses, services, recreational opportunities and social cohesion (van Dijk et al., 2013). In 2002 it is estimated that employment was reduced by 3% in the Murray River region and from 2006 to 2009, 6000 jobs were lost (Horridge et al., 2005; Wittwer and Griffith, 2011).

Although the drought ended with the heavy rainfalls of 2010 and 2011, the rain was not nearly enough to wipe out the rainfall deficit that had accumulated over the previous 13 years (*Figure 19*). In fact, only about one-third of the 'rainfall debt' was paid back, and many more years of above-average rainfall will be required to fully eliminate this deficit.

(Box 9 continued)

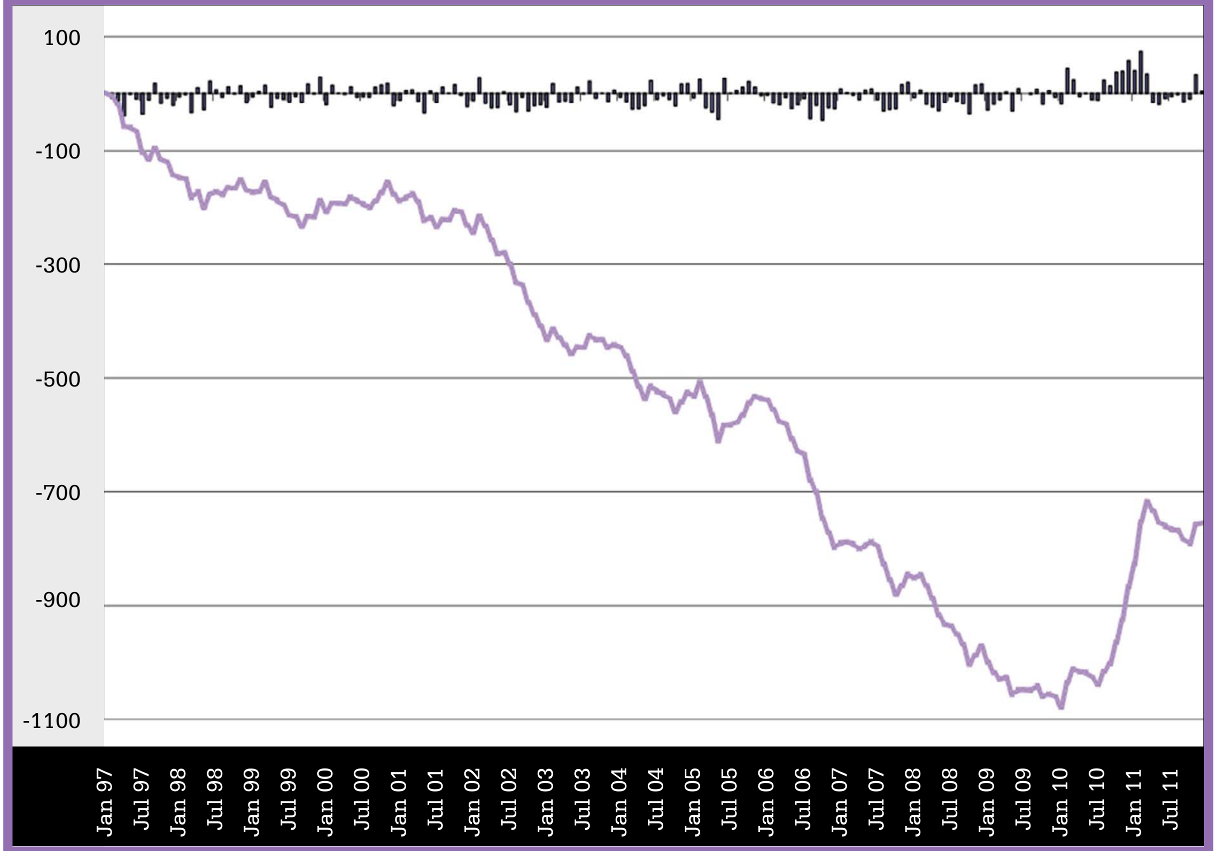

Figure 19: Cumulative rainfall variations (in mm) from the long-term average for southeast Australia for the period January 1997 to December 2011. Individual monthly variations are shown in the columns.

Source: BoM, 2012b

Box 10: Increasing dry conditions in southwest Western Australia

Southwest Western Australia has experienced a significant decline in rainfall since the 1970s. Since the mid-1970s, rainfall has declined by 15% and has necessitated redevelopment of water supply systems and changes in land use (WC, 2012). Lower rainfall has reduced the inflows to Perth dams. From 1911 to 1974 the average stream flow into the dams was 338 gigalitres (GL) per year; from 1975 to 2000 flows almost halved to 177 GL per year (WC, 2012). Inflows more than halved again from 2006 to 2012 to approximately 66 GL per year (WC 2012; *Figures 20 and 21*).

This drying tend is particularly important because most of the state's population and much of its agricultural activity occur in the southwest corner. The growing season in the Western Australian wheat belt has become shorter and drier in the northeastern part of the wheat belt, with consequent declines in yields (Stephens et al., 2009). Following the very dry conditions in 2010, production of wheat and other winter crops in 2010-2011 was around 43% lower than production for the previous season (ABARES, 2011). By 2050, changing rainfall and higher temperatures could result in yield losses of more than 30% compared to 1999 yields (van Gool, 2009).

(Box 10 continued)

There is considerable evidence that climate change is making a significant contribution to the drying trend in southwest Western Australia. The primary reason is a southerly shift of the winter rain-bearing fronts from the Southern Ocean, which means that more of them are missing the southwest corner of Western Australia.

Model-based projections suggest that the drying trend in southwest Western Australia will continue to intensify to the middle and end of this century. Projections of average annual rainfall indicate further decreases of up to 10% by 2030, and possibly up to 20% by 2050 (CSIRO and BoM, 2007). If the current climate trends continue, southwest Western Australia will potentially experience 80% more drought-months by 2070 (Mpelasoka et al., 2008).

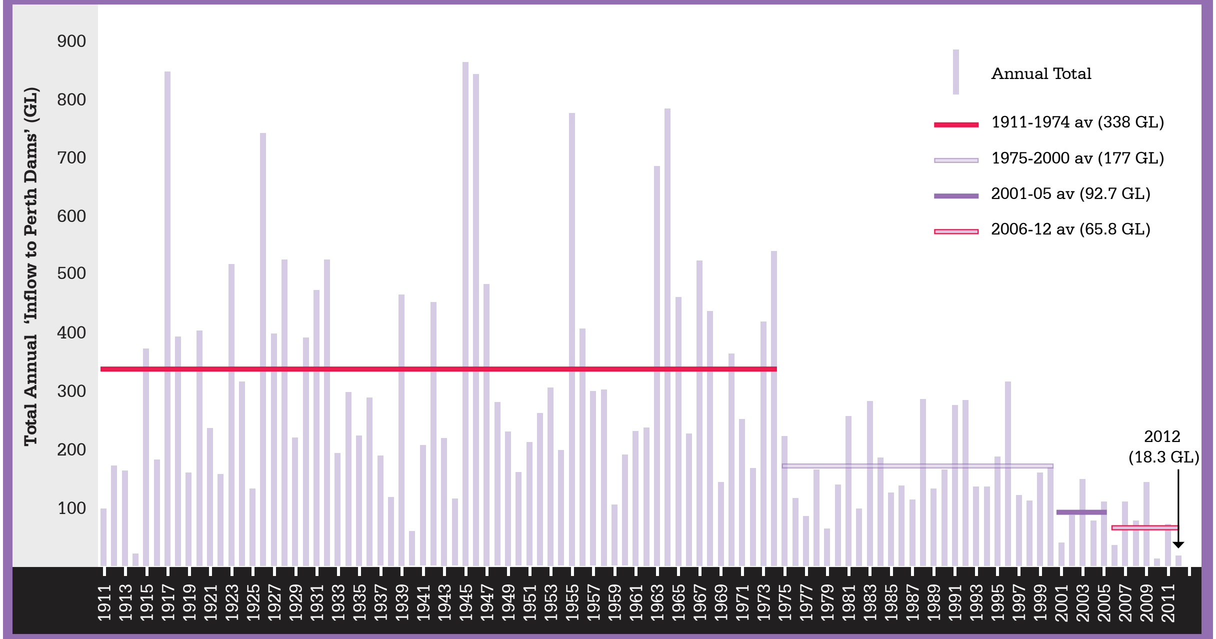

Figure 20: Trend in total annual stream flow into Perth dams 1911-2012

Source: WC, 2012

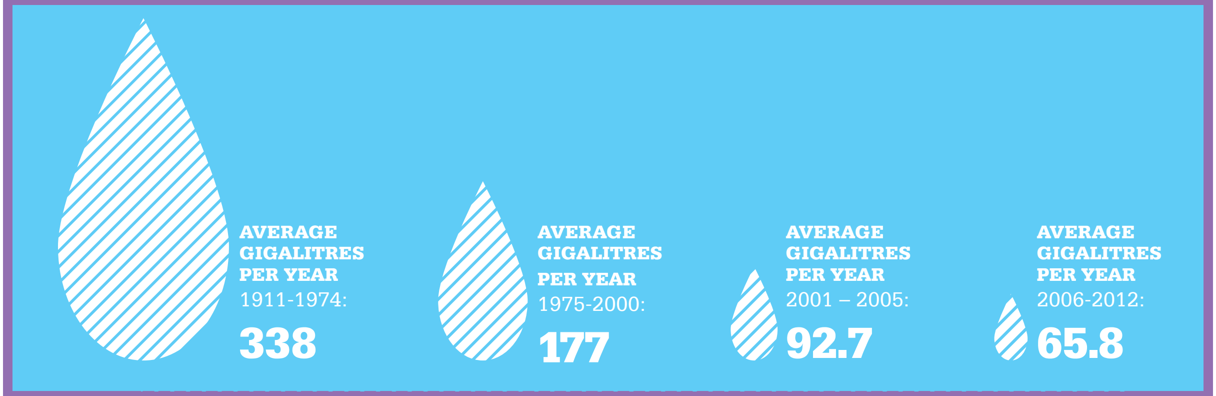

Figure 21: Changes in water inflow into Perth dams

Source: WC, 2012

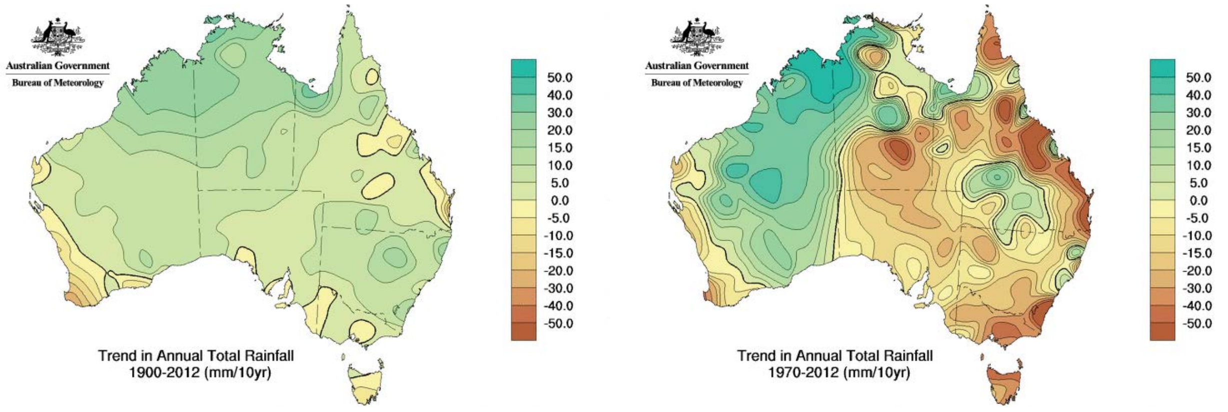

Figure 22: Trends in annual rainfall across Australia for the periods 1900-2012 (left) and 1970-2012 (right).

Source: BoM, 2013g

What changes have been observed in drought conditions?

There are no observed global trends in droughts, although there are some trends at the regional level (IPCC, 2012). Since the 1950s some regions of the world, such as southern Europe and West Africa, have experienced more intense and longer droughts (IPCC, 2012). However, in other regions, such as northwest Australia, droughts have become less frequent, less intense or shorter (IPCC, 2012).

In Australia, rainfall over the continent as a whole has increased since 1900. However, from 1970 to the present, the period during which the trend of rising global average temperature due to human-driven emissions of greenhouse gases has become clear, the trend in rainfall shows a complex pattern (*Figure 22*). At the continental scale, the western part of the country, and especially the northwest, has become wetter, apart from the southwest corner of Western Australia. Much of the eastern part of Australia has become drier, apart from some areas along the east coast and the Gulf of Carpentaria, and southwest Queensland (already a dry area).

When the rainfall trends of the 1997-2012 period, encompassing both the Millennium Drought and the very wet period during the La Niña conditions of 2010-2011 (*Figure 23*), are compared to the pattern for the 1970-2012 period (*Figure 22*), the southwest and southeast stand out as being consistently dry. The southwest has experienced ongoing dry conditions since the mid-1970s, and the southeast has experienced major droughts in 1963-1968, 1972-1973, 1982-1983 and 1997-2009 (BoM, 2013f). In particular, the period of 1997-2009, the Millennium Drought, was unusual in terms of its duration and severity (*Box 9*).

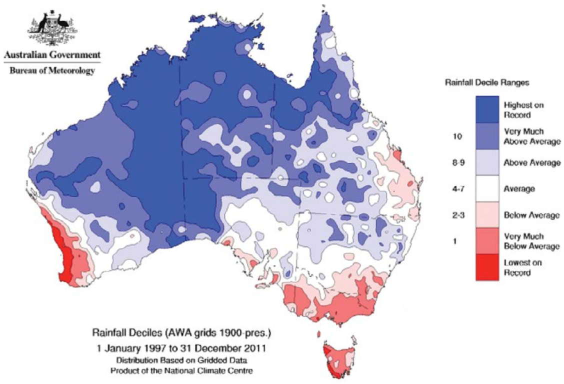

Figure 23: Australian rainfall deciles for the 15 year period January 1997 to December 2011. Deciles represent 10 categories of rainfall across a range above and below the long-term average. During this period, southwest and southeast Australia experienced at least below average rainfall, while the northwest experienced the highest on record.

Source: BoM, 2013b

Just as important as the geographical pattern of rainfall are the changes in its seasonality. The most pronounced trend is in southwest Western Australia and in the far southeast of the continent, where the rainfall declines have occurred primarily in the cooler months of the year. Even during the exceptionally wet conditions of 2011 and 2012 across much of the country, many parts of southern Australia experienced dry conditions during the start of the cooler period, from April to June in 2011.

How is climate change influencing drought conditions?

Climate change is likely influencing the increasing aridity in the southwest and possibly the southeast of the continent. The primary reason for this is the influence of climate change on one of the most important modes of air flow that affect rainfall in these regions – the rain-bearing fronts that sweep off the Southern Ocean across southern Australia in the autumn and winter months. This pattern of air flow has shifted southwards over the past several decades, affecting southwest Australia since the 1970s and the southeast from the mid-1990s. The shift is associated with changes in atmospheric circulation patterns – the poleward expansion of the tropics, a shift of the mid-latitude storm tracks towards the poles, and the strengthening of the sub-tropical high pressure ridge over the continent – that are consistent with a warming planet.

Droughts are invariably associated with hot weather, because of generally clear skies and the lack of evaporative cooling because of the dry landscapes. However, on top of these effects, the long-term trend of rising temperature is likely making droughts even more severe, particularly in environments that are already semi-arid or in marginal agricultural land.

What are the projections for droughts in a changing climate?

Globally, climate model projections indicate increased frequency of extremely hot years and increased variability in rainfall (IPCC, 2007). There is medium confidence that droughts will intensify in the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration (IPCC, 2012). As the climate warms, the water cycle strengthens – that is, more evaporation from water bodies and more rainfall back down onto the Earth's surface (Coumou and Rahmstorf, 2012; Trenberth, 2012; see section 3.1 Heavy rainfall events). As a general rule, this strengthening will lead to regions that are currently dry becoming even drier, and wet regions becoming wetter (Trenberth, 2012).

In Australia, climate model projections for the rest of the century indicate a tendency for reduced rainfall in southern and eastern Australia, with uncertain changes in rainfall in the north (CSIRO and BoM, 2007). The exceptions to this high degree of uncertainty are the areas that are already experiencing increased drought conditions – the southwest and, to a lesser extent, the southeast of the continent – which are likely to see more droughts in the future (Hennessy et al., 2008). For example, the intensity of the sub-tropical ridge over southern Australia (*Box 9*) is projected to increase through the 21st century, leading to decreases in cool season rainfall (Kent et al., 2011). In addition, it is virtually certain that the frequency of very hot days and hot periods will increase (Kirono and Kent, 2010; Kirono et al. 2011), which will likely exacerbate the severity of drought conditions in the drier parts of Australia.

A recent analysis has examined the likelihood of changes in drought conditions around the world by exploring the projected changes in the number of consecutive dry days, where a dry day is defined as one with less than 1 mm of precipitation. For both southwest and southeast Australia, nearly all of the climate models used in the study project a significant increase in drought by the end of the century (IPCC, 2012).

4.
BUSHFIRES

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SUMMARY

Australia has a long history of fire and already faces the regular risk of serious and extreme fire danger conditions. Over the past decade large and uncontrollable fires destroyed 500 houses in Canberra in 2003, bushfires in Victoria in 2009 took 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. Climate change can affect bushfire conditions by increasing the probability of extreme fire weather days. Many parts of Australia, including southern New South Wales, Victoria, Tasmania and parts of South Australia have seen an increase in extreme fire weather over the last 30 years. The projections for the future indicate a significant increase in dangerous fire weather for southeast Australia.

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What are bushfires and fire weather?

A bushfire is a generic term for an unplanned vegetation fire. The three broad types of bushfire in Australia are forest, grass and savanna fires (AFAC, 2012). Bushfires are common across the continent, but especially in the north where the vast savanna landscapes burn regularly in the dry season. Internationally bushfires are also referred to as 'forest fires', 'wildfires' or 'brushfires', and are common in many other regions of the world including the vast boreal forests of Canada, Alaska and Siberia; Mediterranean ecosystems (e.g., the Mediterranean region, California, southern Africa); large savanna regions (Africa and parts of South America); and the dry forests of the western USA.

Large areas of Australia are very fire-prone, and much of our vegetation is adapted to periodic fires. A key concept in understanding the nature of bushfires in Australia, and in assessing changes in their behaviour, is that of 'fire regimes'. A fire regime describes a recurrent pattern of fires, with the most important characteristics being the frequency, intensity and seasonality of the fire. Significant changes in any of these characteristics of a fire regime can greatly change the level of risk that the fire poses for settlements and ecosystems, and have a very important influence on its impacts (Williams et al., 2009).

All three of these features of fire regimes are influenced by changes in climate and weather. The most commonly used method to assess fire risk is based on a set of indices that relate weather conditions to the likelihood of fire outbreak (*Box 11*).

THE PROJECTIONS FOR THE FUTURE INDICATE A SIGNIFICANT INCREASE IN DANGEROUS FIRE WEATHER FOR SOUTHEAST AUSTRALIA BY 2100.

What are the consequences of bushfires?

Bushfires can be catastrophic, claiming lives and affecting health, causing widespread damage to property, and devastating towns and communities. Direct impacts on humans are particularly important. Burn injuries and death are well-known and obvious impacts, but fires also lead to a higher incidence of respiratory illnesses, such as asthma attacks. Severe fires also cause a higher incidence of trauma and longer-term disruptions to social systems.

Within the past decade alone, there have been several large fires that demonstrate the many consequences that bushfires have for Australians. The Black Saturday bushfires of 2009 (*Box 12*) are still vivid in the memories of many people around the country, especially in Victoria, where the loss of life and property was staggering. In January 2003 four fires in the Brindabella Mountains west of Canberra combined under intense heat and high wind to sweep into the city, destroying about 500 houses and taking three lives. In January 2013 a large fire broke out in Tasmania during a period of record high maximum temperatures in the region. The fire moved into the town of Dunalley, destroying nearly 200 properties, including the local primary school and the RSL club, and forced the evacuation of hundreds of people from the Tasman Peninsula.

Bushfires are also a major driver of change in natural ecosystems. Significant changes in a fire regime, whether driven deliberately by human management or by climate change, can trigger major changes in ecosystems (Williams et al., 2009). An example of the former is the use of fire to control the ratio of trees to grasses in savanna ecosystems, while an example of the latter may be the conversion of moist mountain forests in the southeast into woodlands if the interval between severe fires is reduced due to a hotter and drier climate.

Box 11

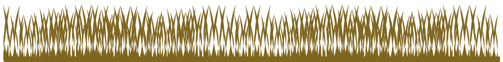
MEASURING BUSHFIRE RISK

Wind + **Humidity** + **Temperature** + **Rainfall** + **Vegetation**

The Bureau of Meteorology assesses the above variables for both

to calculate

FORESTS
Forest fire danger index (FFDI)



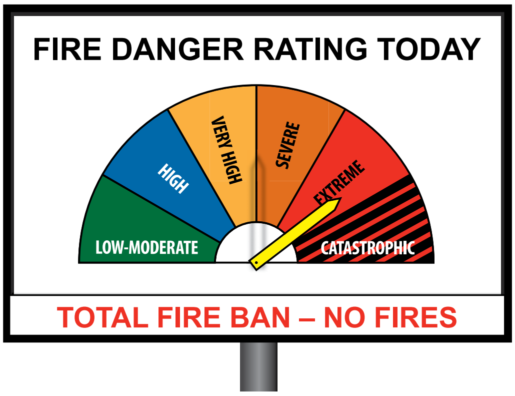
GRASSLANDS
Grasslands fire danger index (GFDI)

FFDI and GFDI are used as the Fire Danger Index depending on the predominent vegetation

FIRE DANGER INDEX (FDI)

When FDI is forecast to exceed critical thresholds, the Bureau of Meteorology issues fire weather warnings. The Bureau publishes fire danger information and provides detailed fire weather forecast warnings to support state fire agencies

State fire agencies then use the FDI and the fire weather forecast warnings to make a Fire Danger Rating



The Fire Danger Rating conveys overall threat level to the general public

Box 12: 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 24* displays the extent of the Black Saturday bushfires.

The extreme heat of early 2009 and the prolonged dry conditions in the months preceding the fires provided the ingredients 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 had been kept. Furthermore, little to no rain had fallen in the previous two months (PoV, 2010). On Saturday 7 February 2009 temperatures across Victoria reached at least 40°C (and over 46°C in Melbourne) accompanied by strong winds, creating extreme bushfire conditions (PoV, 2010).

The bushfire threat across Victoria on 7 February 2009 reached unprecedented levels. The Forest Fire Danger Index, one of the measures of bushfire threat (*Box 11*), ranged from 120 to 190 at a number of sites. 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 severe bushfire conditions are rated, with the introduction of the 'catastrophic' Fire Danger Rating level (CFA, 2009).

Figure 24: Location of the Black Saturday bushfires

Source: PoV, 2009

What changes have been observed in bushfires and bushfire weather?

The intensity and seasonality of large bushfires in southeast Australia vary considerably from year to year, and can be related to prominent modes of climate variability such as ENSO (El Niño-Southern Oscillation) and the IOD (Indian Ocean Dipole) (Cai et al., 2009).

Very high fire danger conditions in Australia are associated with high maximum temperatures, extended periods of low rainfall, low humidity and strong winds. Extreme events that are closely related to temperature, such as bushfires, are also showing changes consistent with what is expected from a warming climate.

Many regions have already experienced an increase in extreme fire weather as indicated by changes in the Forest Fire Danger Index (FFDI) (Clarke et al., 2012). The main contributors to this increase are prolonged periods of low rainfall and the increased frequency and intensity of extreme heat (Lucas et al., 2007).

The FFDI increased significantly at 16 of 38 weather stations across Australia between 1973 and 2010, with none of the stations recording a significant decrease (Clarke et al., 2012). The increase has been most prominent in southeast Australia, and has been manifest as a longer duration fire season, with fire weather extending into November and March.

The opportunity for fuel reduction burning is reducing as fire seasons have become longer (Mathews et al., 2012). Overall, this means that fire prone conditions and vulnerability to fire are increasing.

How is climate change influencing bushfires and bushfire weather?

During the 2012/2013 summer climate change aggravated bushfire conditions across southern Australia.

Daily weather conditions play a strong role in the outbreak of bushfires. Very hot, dry and windy days create very high bushfire risk. Climate change is increasing the frequency of very hot days. Over the past several decades, fire danger ratings have risen at many areas in Australia, especially in the southeast.

Climate change can also influence bushfires through its effects on the amount and condition of the fuel load.

The amount of the fuel load is affected by vegetation growth, which in turn can be affected by rainfall, temperature, the concentration of carbon dioxide in the air and a number of non-climate related ecological factors. The condition of the fuel load is affected by the climatic conditions in the period leading up to the fires. These relationships are very complex, and it is not possible to determine how - or in what direction - a changing climate will affect the amount and condition of the fuel load.

What are the projections for bushfires in a changing climate?

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 the fires and their consequences. Perhaps the most important of these non-climate factors is the role of human management and decision-making, such as fire suppression activities, land-use planning and many others.

However, as dangerous fire weather is sensitive to changes in climatic and weather conditions, such as high temperatures, the duration of heat events, the wind speed, and the condition of vegetation and soils, 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 (Lucas et al., 2007; Clarke et al., 2011).

The projected increases in hot days across the country, and in consecutive dry days and droughts in the southwest and southeast, will very likely lead to increased frequencies of days with extreme fire danger in those regions. An analysis of the impact of climate change on bushfire risk found that in the summer rainfall-dominated tropical northeast of Australia, average and extreme values of the FFDI are projected to decrease or remain close to 20th century levels. On the other hand, the FFDI is projected to increase strongly in regions with uniform rainfall through the year and in winter rainfall regions, which mainly occupy southeast Australia (Clarke et al., 2011).

> THE PROJECTED INCREASES IN HOT DAYS ACROSS THE COUNTRY, AND IN CONSECUTIVE DRY DAYS AND DROUGHTS IN THE SOUTHWEST AND SOUTHEAST, WILL VERY LIKELY LEAD TO INCREASED FREQUENCIES OF DAYS WITH EXTREME FIRE DANGER IN THOSE REGIONS.

5.

SEA-LEVEL RISE AND COASTAL FLOODING

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SUMMARY

Global sea level has risen by 0.21 m from 1880 to 2009 (Church and White, 2011) and is continuing to rise as the oceans become warmer, and glaciers and polar ice sheets melt with increasing temperatures. This increases 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. Sea level is likely to rise by 0.5 – 1.0 m by the end of the century compared to 1990. 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. Even a sea-level rise of 0.5 m could lead to large increases in the frequency of flooding, typically by several hundred times compared to the baseline.

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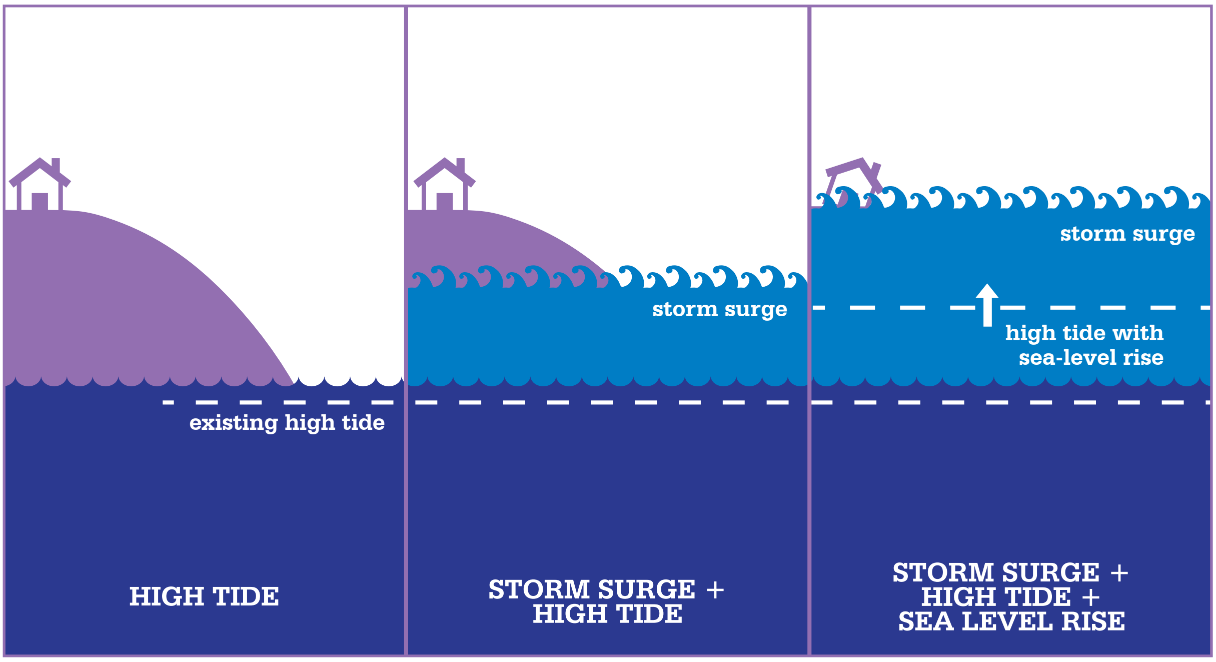

Figure 25: Sea-level rise increases the base sea level and thus exacerbates the effects of a storm surge.

5.1 High sea-level events

What is a high sea-level event?

A high sea-level event is a coastal flooding or inundation event 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 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. 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. The worst impacts of a storm surge occur when it coincides with a particularly high tide.

Sea-level rise is now exacerbating high sea-level events by increasing the base sea level and thus the effects of a storm surge (*Figure 25*).

BETWEEN 157,000 AND 247,600 INDIVIDUAL BUILDINGS IN AUSTRALIA ARE AT RISK FROM A 1.1 M SEA-LEVEL RISE

What are the consequences of a high sea-level event?

High sea-level events can threaten human physical safety and health, damage settlements and infrastructure in low-lying coastal areas, and erode sandy beaches and other soft coastlines (*Figure 26*). Australia's coastal region is of immense social, economic and environmental importance, with around 85% of Australia's total population living on or near the coast (DCC, 2009). A projected sea-level rise of 1.1 m, considered to be at the upper end of projections for 2100 compared to a 1990 baseline, poses significant risks to residential and commercial buildings and to social building stock such as hospitals, roads and schools (*Figure 27*). It is estimated that between 157,000 and 247,600 individual buildings in Australia are at risk from a 1.1 m sea-level rise (DCC, 2009).

Rising sea level can also have serious consequences for natural ecosystems and biodiversity. 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. 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 expansion of the estuarine wetland system at the expense of present-day freshwater wetlands. There is some evidence that these changes are already occurring, especially in the Mary River system (Mulrennan and Woodroffe, 1998; BMT WBM, 2011). On the Great Barrier Reef, the nesting sites of sea turtles are vulnerable to high sea-level events associated with even modest rises in sea level (Fuentes et al., 2010).

Figure 26: Rising sea level leads to very large increases in the frequency of coastal flooding and greater beach erosion, particularly in vulnerable low-lying areas such as the Swan River and sandy beaches such as Mandurah, Western Australia (pictured).

Source: Don Ward, City of Mandurah

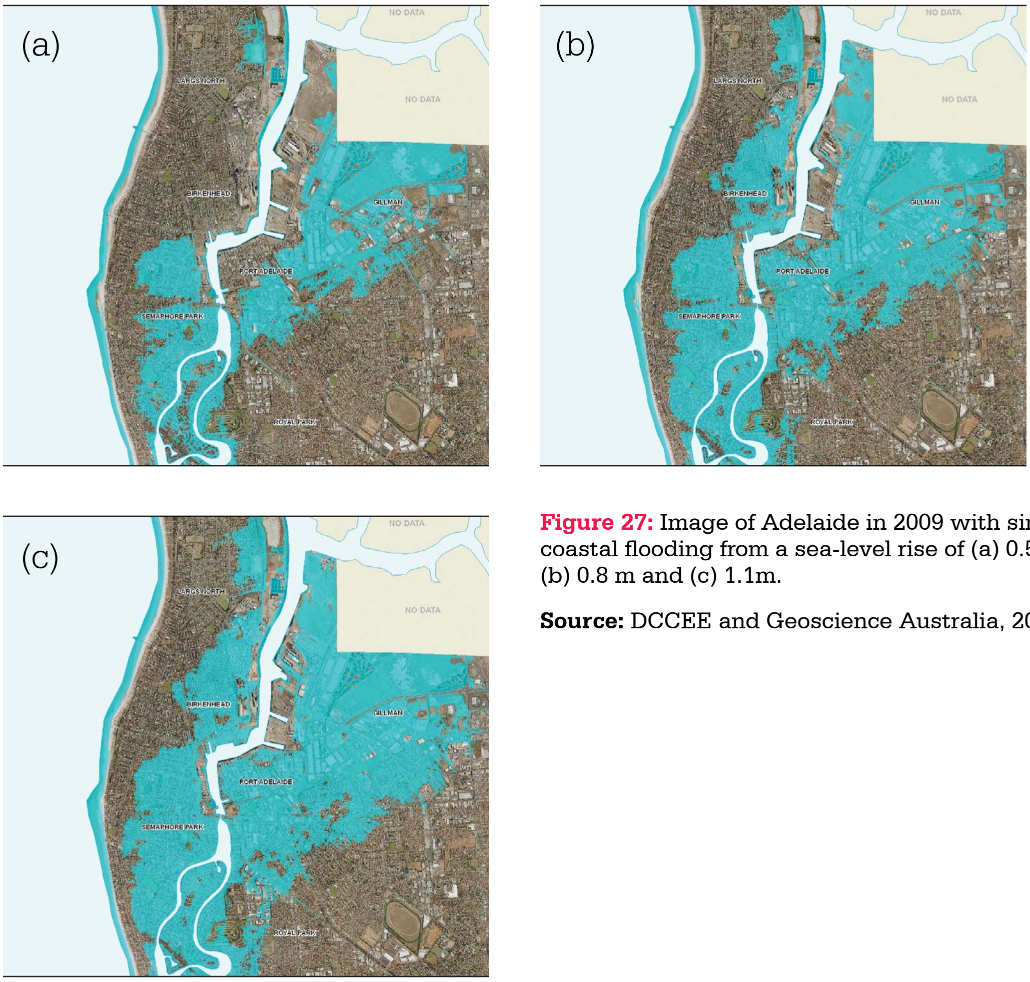

Figure 27: Image of Adelaide in 2009 with simulated coastal flooding from a sea-level rise of (a) 0.5m (b) 0.8 m and (c) 1.1m.

Source: DCCEE and Geoscience Australia, 2012

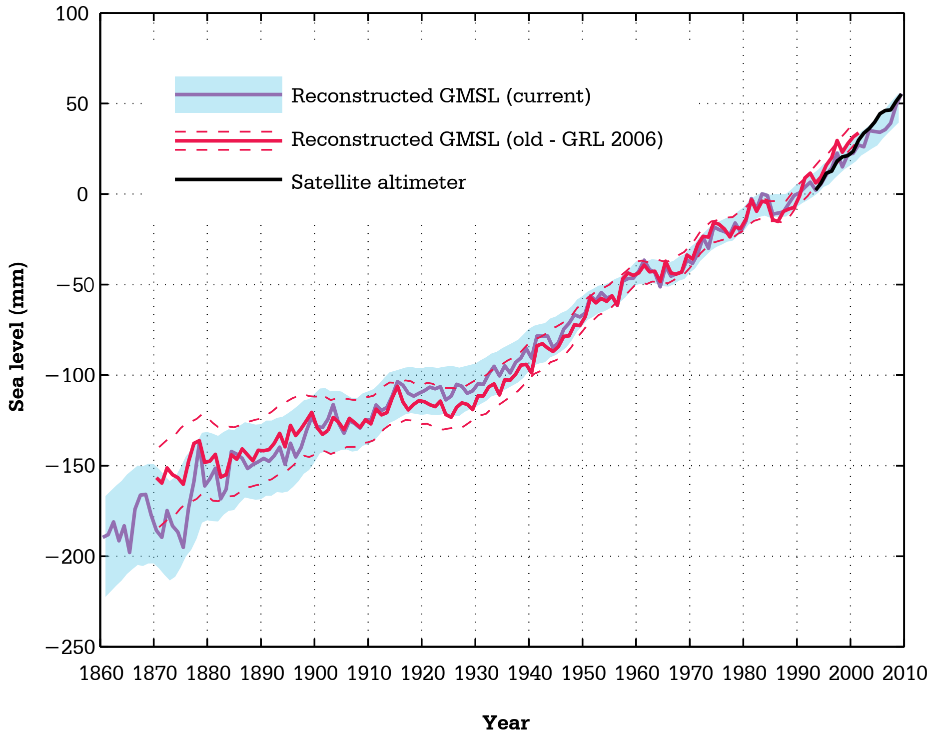

Figure 28: Global average sea level from 1860 to 2009. Earlier estimates for 1870-2001 (Church and White, 2006) are shown by the solid red line. Satellite altimeter data since 1993 is shown in black (Church and White, 2011). Shading and dashed lines are one standard deviation errors.

Source: Church and White, 2011

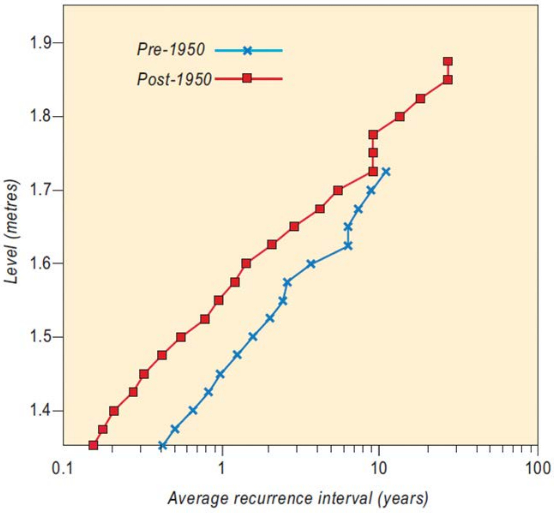

Figure 29: Changes in the average recurrence intervals of extreme sea levels, Fremantle 1897-2007.

Source: Church et al., 2006

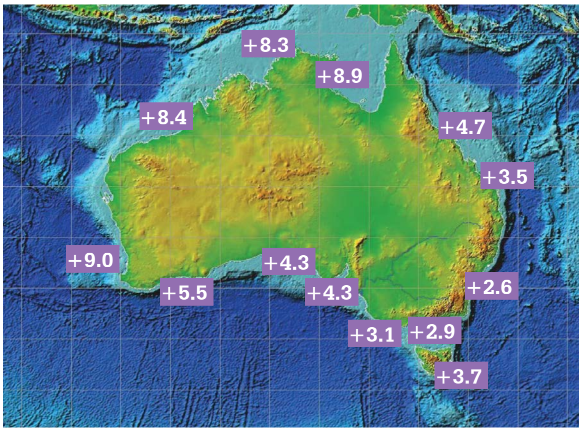

Figure 30: The regional variation of the rate of sea-level rise (mm per year) around Australia from the early 1990s to 2011.

Source: NTC, 2011

What are the observed changes in sea-level rise?

The average rate of global sea-level rise was 1.7 mm per year for the 1900-2009 period (Church and White, 2011). The average rate over the last two decades was about 3 mm per year (Church and White, 2011; *Figure 28*). The observed global sea level is tracking close to the upper range of the Intergovernmental Panel on Climate Change (IPCC) model projections (Rahmstorf et al., 2012).

The observed sea-level rise of about 0.2 m from 1880 to 2000 has already led to an increase in the incidence of extreme sea level events. Such increases have been observed at places with very long records, such as Fremantle, where a 3-fold increase in inundation events has occurred, as shown by comparing the pre-1950 to the post-1950 frequency of flooding (Church et al., 2006; *Figure 29*). The impacts of sea-level rise on the frequency and extent of inundation are also being observed in the Torres Strait Islands, where the impacts have already become serious for local communities (*Box 13*).

Just as for many other climatic parameters, sea-level rise shows strong regional variations (*Figure 30*). However, given the short time period for these observations, the variability shown around Australia could have a temporal as well as a spatial component. For planning purposes, information now becoming available from improved projections of regional sea-level rise should be used (e.g., Church et al., 2011a; Hunter et al., 2013).

Box 13. Flooding in the Torres Strait Islands

Many Torres Strait Islands are already vulnerable to flooding, but rising sea levels are increasing this vulnerability. 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 and community gardens and affected the function of waste treatment facilities (Green, 2006; Green et al., 2008; J. Rainbird, pers comm. 13 September 2012; *Figure 31*). 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).

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 31: Inundation at Saibai Island, Torres Strait in 2010.

How is climate change affecting sea level?

It is likely that climate change has had an influence on the increasing number of high sea-level events due to an increase in average sea level (IPCC, 2012).

Global average sea level is rising for two main reasons - the expansion of the mass of ocean water as it warms and the addition of new water from the melting of glaciers, icecaps and the polar ice sheets of Greenland and Antarctica.

Since the IPCC Fourth Assessment report in 2007, greater agreement has been reached on the ‘sea-level budget’ – the factors that contribute to sea-level rise and their relative importance. Over the period 1972-2008 the largest contributor was the expansion of the mass of ocean water, which increased sea level by 0.8 mm per year. This was followed by the melting of mountain glaciers and ice caps (0.7 mm per year) and then by the contribution of the large polar ice sheets of Greenland and Antarctica (0.4 mm per year) (Church et al., 2011a). However, the higher rate of sea-level rise over the last two decades has been driven primarily by increased contributions from the polar ice sheets (Church et al., 2011b).

What are the projections for sea-level rise through the 21st century?

The IPCC projections for the end of this century, compared to the 1990 baseline, range from about 0.2 m to 0.8 m but higher levels cannot be ruled out (IPCC, 2007; DCC, 2009; *Figure 32*). Taking into account the possibility of higher levels, most experts agree that a rise within the range of 0.5 to 1.0 m is likely by 2100 compared to a 1990 baseline (see *Critical Decade,* 2011 for a more detailed discussion). However, depending on the stability of the large polar ice sheets in Greenland and the Antarctic (*Box 14*), a sea-level rise over 1.0 m is a distinct possibility. 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).

Although there is a strong focus on projections of sea-level rise to 2100, the sea level will continue to rise for many centuries or even millennia beyond the end of the century, owing to the thermal inertia in both the oceans and the large polar ice sheets. Evidence from changes in ice sheet cover, sea level, and global average temperature in the geological past suggests that the current, observed sea-level rise is the beginning of a long process that will eventually equilibrate with at least several metres of sea-level rise above the pre-industrial level.

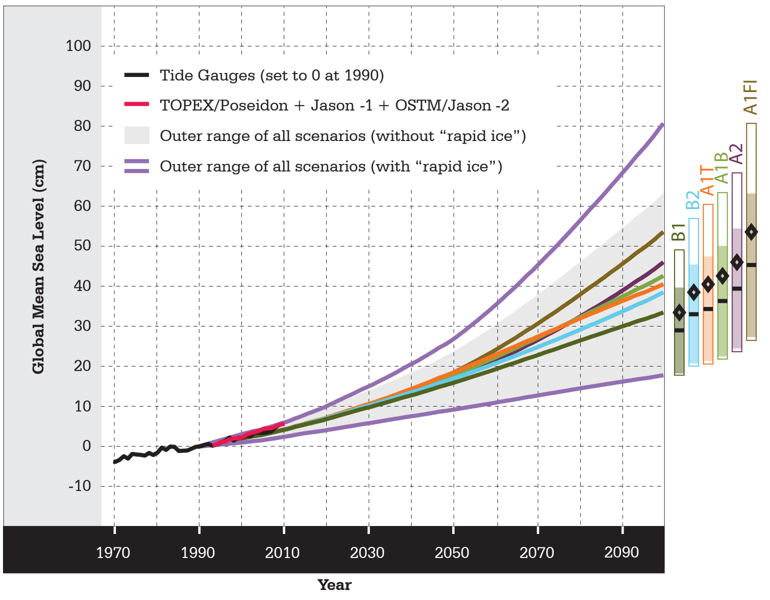

Figure 32: Global averaged projections of sea-level rise in the IPCC Special Report on Emission Scenarios (SRES) to 2100. The shaded region/outer light lines show the full range of projections, not including/including any rapid ice component. The continuous coloured lines from 1990 to 2100 indicate the central value of the projections, including the rapid ice contribution. The bars at right show the range of projections for 2100 for the various SRES scenarios. The horizontal lines/diamonds in the bars are the central values without and with the rapid ice sheet contribution. The observational estimates of global averaged sea level based on tide-gauge measurements and satellite altimeter data are shown in black and red, respectively. The tide-gauge data are set to zero at the start of the projections in 1990, and the altimeter data are set equal to the tide-gauge data at the start of the record in 1993. The projections are based on the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4).

Source: Church et al., 2011a

Box 14: The role of the polar ice sheets in future sea-level rise

The largest uncertainty in the projections of sea-level rise to 2100 and beyond is the melt of large masses of ice on Greenland and Antarctica.

Observations over the past twenty years show an increasing contribution of the Greenland and Antarctic ice sheets to sea-level rise. For example, between 1992 and 2009, Greenland contributed 0.2 to 0.4 mm per year to sea-level rise (ACE CRC, 2012). This rate increased to 0.4 to 0.7 mm per year for the period 2002 to 2009 (ACE CRC, 2012).

The large polar ice sheets lose mass by two processes. One of them is surface melting, which produces liquid water that can run off the ice sheet into the sea and add to the volume of water in the ocean. This process is important in Greenland, where satellite observations have shown dramatic changes in the area of the ice sheet subject to summer melting (*Figure 33*).

The second process is `dynamic' whereby, rather than the ice melting *in situ*, it is transported into the sea to float as solid ice before it eventually melts. Just as the water level in a glass rises if a cube of ice is added, so sea level rises immediately the ice starts to float on the sea; the subsequent melting does not raise sea level further. Ice sheets terminate at the sea either as vertical walls (`tidewater glaciers', e.g. *Figure 34*) or as floating tongues (`ice shelves'). Warming of both the air and the ocean can erode these walls or tongues of ice, leading to accelerated flow of the grounded ice behind them. When the ice sheet is grounded below sea level, as in the case of much of the West Antarctic Ice Sheet, it may be particularly vulnerable to destabilisation by this process.

Observations of the combined change in mass of the two polar ice sheets show a continuing increase in the rate of ice loss for the 1992-2010 period (*Figure 35*) (Shepherd et al., 2012). The causes of the increasing rate of ice release and future dynamic responses for both ice sheets are largely unknown. This leads to great uncertainty for future projections of sea-level rise, especially at the upper end of the projections.

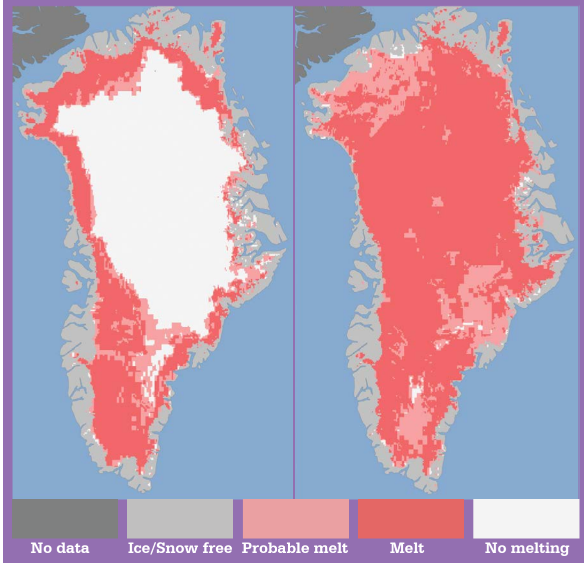

Figure 33: NASA satellite image of the extent of surface melt over Greenland's ice sheet on 8 July (left) 2012 and 12 July 2012 (right)

Source: NASA, 2012

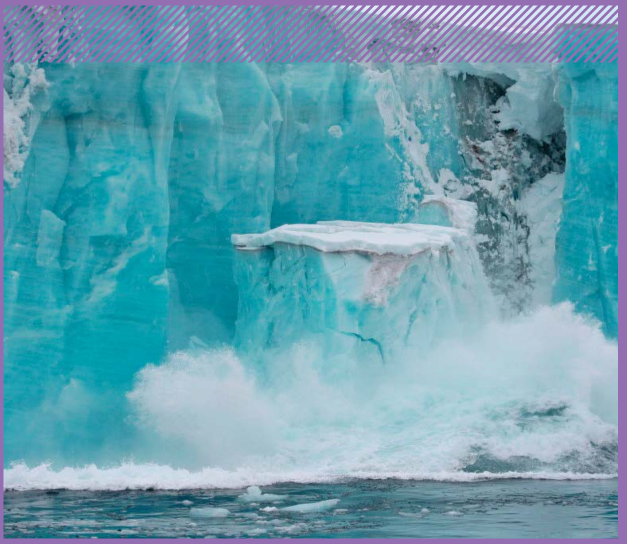

Figure 34: Ice sheets often lose their mass by calving. Ice calving is a sudden breaking away of a mass of ice from the edge of the ice sheet and its loss to the sea. Ice calving in Ausfonna, Norway pictured.

Source: Flickr/Yukon White Light

(Box 14 continued)

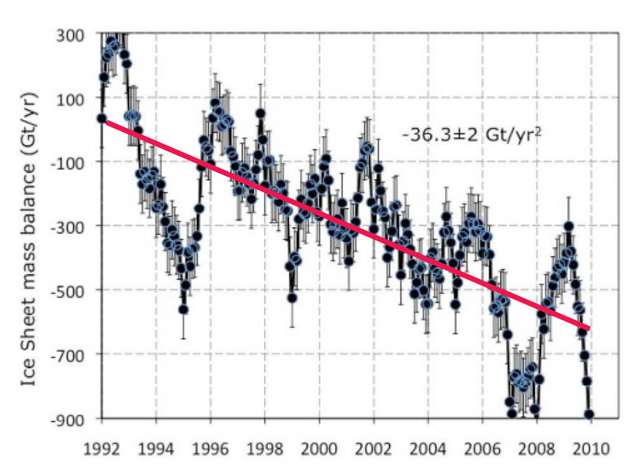

Figure 35: Trend of ice loss from Greenland and Antarctica combined between 1992 and 2010.

Source: Rignot et al., 2011

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OBSERVATIONS ... SHOW A CONTINUING INCREASE IN THE RATE OF ICE LOSS FOR THE 1992-2010 PERIOD.

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Projections have also been made of the increase in coastal flooding from high sea-level events for a given rise in sea level. *Figure 36* 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 the figure, and leads to surprisingly large impacts. For coastal areas around Australia's largest cities, such as Sydney and Melbourne, 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.

5.2 'Double Whammy' coastal flooding

Many coastal flooding events are associated with simultaneous high sea-level events and heavy rainfall events in the catchments inland of the 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 a modest increase in the frequency of heavy rainfall events for southern Australia (IPCC, 2012) suggest that the risk of these 'double whammy' flooding events will increase.

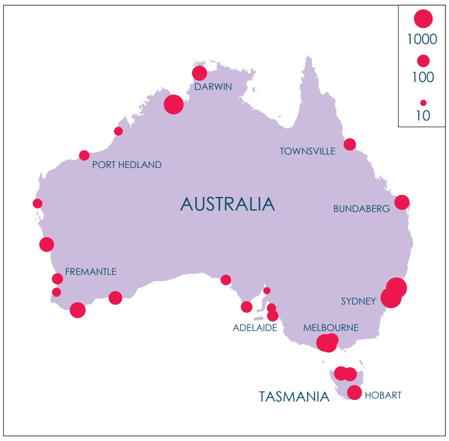

Figure 36: Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m

Source: Hunter, 2012

6.

TROPICAL CYCLONES AND STORMS

SUMMARY

Tropical cyclones and severe storms are naturally occurring extreme weather events that cause significant damage. While some trends have been identified in tropical cyclone data in the past few decades, such as an increase in Atlantic cyclone activity (Kossin et al., 2007), identifying statistically significant signals within these trends is limited by the lack of long-term, consistent observational data. However, in the future it is likely that the proportion of the most severe tropical cyclones, in terms of wind speeds, will increase, while the total number of tropical cyclones will likely decrease, particularly in the southern hemisphere. Increases in rainfall intensity from tropical cyclones, and severe storms in general, are likely to increase as the global average temperature increases. Similarly, increases in coastal flooding due to storm surges associated with tropical cyclones are more likely as sea level rises.

6.1 Tropical cyclones

What is a tropical cyclone?

Tropical cyclones are low pressure systems that form over warm, tropical waters and have gale force winds (sustained winds of 63 kilometres per hour or greater and gusts in excess of 90 kilometres per hour near the centre). Gale force winds can extend hundreds of kilometres from the centre (eye) of the cyclone (BoM, 2013h).

Tropical cyclones can persist for many days and may follow quite erratic paths, but they usually dissipate over land and colder oceans.

Cyclone season in Australia occurs between November and April with, on average, 10 cyclones per year, with about half of these occurring in the waters off the northwest coast and the remainder along the Top End and Queensland's east coast (Geoscience Australia, 2011a).

What are the consequences of tropical cyclones?

Tropical cyclones are dangerous because they produce destructive winds, heavy rainfall, storm surges and enhanced wave action that can cause flooding of low-lying coastal areas.

Cyclones pose risks to human health through injury and death from high winds, and loss of access to health and medical facilities. Coastal property and infrastructure is also vulnerable to damage and destruction from high winds.

Coastal flooding from the storm surge generated by a tropical cyclone is one of the most common and important consequences (Section 5.1) of these storms. Large tropical cyclones have the potential to trigger 'double whammy' coastal floods (section 5.2) through the temporary rise in sea level caused by the storm surge and by heavy rainfall in the catchments adjacent to coastal and settlements and infrastructure.

Agriculture and natural ecosystems can both suffer serious impacts from the high winds of tropical cyclones. For example, tropical cyclone Larry in 2006 destroyed many banana plantations in North Queensland, causing a sharp drop in banana production at the national level for several years. The Great Barrier Reef suffered extensive physical damage to the coral in 2011 when tropical cyclone Yasi passed over large areas of the reef (*Box 15*).

Box 15: Cyclone Yasi, 2 February 2011

Severe tropical cyclone Yasi (*Figure 37*) was one of the most powerful cyclones to have affected Queensland since records began, and was one of Australia's most costly natural disasters. Cyclone Yasi first hit the North Queensland coast on 2 February 2011, creating widespread damage and contributing to flooding across Queensland.

Cyclone Yasi was classified as a category 5 severe tropical cyclone, the highest rating of severity, described as "extremely dangerous causing widespread destruction" (BoM, 2013h).

The cyclone brought extreme winds of up to 285 kilometres per hour, heavy rain of up to 200-300 mm in 24 hours and storm surges (*Figure 38*), including a 5 metre tidal surge at Cardwell (QRA and World Bank, 2011).

Cyclone Yasi caused extensive damage to tourism and agricultural industries and to many towns (*Figure 37*; 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).

Tropical cyclone Yasi also caused extensive damage to the Great Barrier 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 damage spanned a very wide area and the ecological legacy of this severe tropical cyclone is likely to be evident for several decades (GBRMPA, 2011).

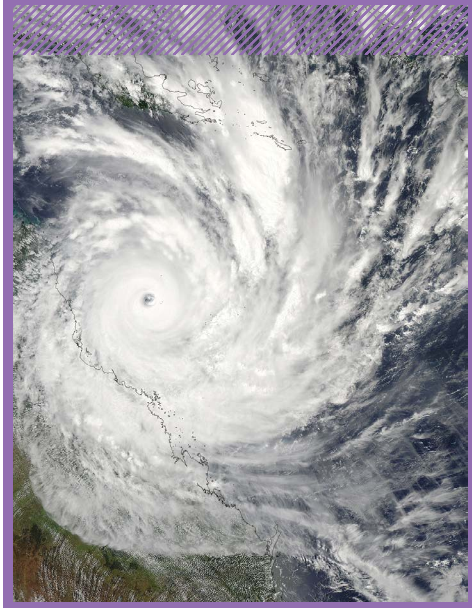

Figure 37: Satellite image of cyclone Yasi approaching the Queensland coast

Source: NSAS Goddard MODIS Rapid Response Team

Figure 38: Cyclone Yasi brought extreme winds and large storm surges to the Queensland coast. The Rock Pool on The Strand, Townsville, pictured.

Source: Flickr/BitKeeper82

What changes have been observed in tropical cyclones?

Large, long-term (decadal) patterns of natural variability, the relatively short period of observations, and questions surrounding the reliability of some observations prevent many changes in cyclone behaviour over the last half century from being unequivocally determined by observational records. With the advent of satellite-measured intensities of tropical cyclones in 1980, some studies have found a possible link between cyclone intensity and higher sea surface temperatures (e.g. Elsner et al., 2008), but questions about data reliability and the short time period over which measurements were taken do not allow the identification of a definitive link between any changes in cyclone intensity to the underlying trend of rising surface sea temperature (Knutson et al., 2010). As for the global-level analysis described above, no clear trends since 1980 in tropical cyclone activity in the seas around Australia can yet be determined.

However, a more recent analysis of tropical cyclone data since 1923 in the North Atlantic region shows that the largest cyclones are being affected by the warmer conditions. The frequency of large storm surge events, which is related to the size of the tropical cyclone, has increased since 1923 (Grinsted, et al., 2012). In addition, the understanding of the physical relationship between warmer surface ocean waters and a warmer atmosphere (see next section) suggests that cyclone behaviour is already being influenced by climate change, although the observational constraints do not yet allow an unequivocal statistical link to be made.

For this reason, there is only low confidence that human influences have contributed to changes in tropical cyclone activity (IPCC, 2012).

How does climate change influence cyclone behaviour?

The relationship between tropical cyclone behaviour and climate change is complex, with some uncertainty in our current understanding, compounded by the lack of long-term, consistent data to monitor cyclone behaviour. However, two aspects of climate change, in particular, are likely to affect cyclone behaviour.

First, the vertical gradient in temperature through the atmosphere, that is, 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. 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 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 of the 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 with the cyclone. This is because the storms draw energy from the surface waters of the ocean (*Figure 39*), 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).

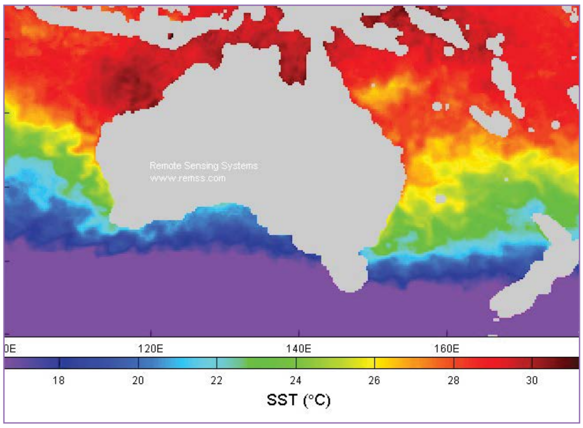

Figure 39: The sea surface temperatures (SSTs) around Australia immediately following the passage of cyclone Yasi across the Queensland coast. The yellow area of cooler water off the North Queensland coast shows the reduction in SST along Yasi's track.

Source: Remote Sensing Systems

In addition, future changes in atmospheric circulation and wind patterns could affect the paths that tropical cyclones take once they are formed.

What are the projections for tropical cyclones in a changing climate?

Tropical cyclones are likely to become more intense; however, they are not likely to increase in number.

Maximum wind speeds and rainfall rates that occur during tropical cyclones are likely to increase, and thus pose a greater risk in terms of their impacts on people, property and ecosystems. The intensity of rainfall events associated with a number of other weather systems is already increasing with the observed temperature rise and will continue to do so, pointing to similar changes in tropical cyclones.

On the other hand, the number of cyclones may decrease or remain unchanged, for the reasons described in the sections above (IPCC, 2012).

TROPICAL CYCLONES ARE LIKELY TO BECOME MORE INTENSE; HOWEVER, THEY ARE NOT LIKELY TO INCREASE IN NUMBER

6.2 Storms

Severe storms range from isolated thunderstorms to large, intense low pressure systems affecting thousands of square kilometres (Geoscience, 2011b). In Australia a severe storm is defined as such if it produces hailstones with a diameter of at least 2 cm, wind gusts of 90 kilometres per hour or greater, very heavy rain leading to flash flooding, or tornadoes (BoM, 2013i). In Australia most severe storms occur between September and March and occur more frequently than any other major natural hazard (Geoscience Australia, 2011c).

Severe storms can cause heavy financial losses, and, on average, account for about one quarter of the annual cost of natural disasters in Australia (BTE, 2001). Australia's most costly storm occurred in Sydney's eastern and city suburbs on 14 April 1999 (*Figure 40*). This storm produced hailstones of at least 9 cm in diameter (BoM, 2013j) and within one hour resulted in insurance losses of around $4.3 billion (normalised to 2011) (Insurance Council of Australia, 2013; Crompton, 2011; Crompton and McAneney, 2008).

Figure 40: Some hailstones in the 1999 Sydney hailstorm were comparable to the size of a cricket ball.

Source: Daniel/Wikicommons

Systematically collected data on thunderstorms, other severe storms and tornadoes are lacking in many parts of the world. For example, changes in reporting practices, incomplete datasets, increased population density and even changes in ambient noise level have led to inconsistencies in the observed record of severe storms (IPCC, 2012). In Australia, an attempt has been made to develop a systematic climatology of severe thunderstorm environments (Allen et al., 2011). However, because many such storms occur on small spatial scales, they cannot easily be simulated in global climate models and reliable projections of future changes in severe storms are not available.

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