CLIMATE COUNCIL

HEATWAVES: HOTTER, LONGER, MORE OFTEN

The Climate Council is an independent, crowd-funded organisation providing quality information on climate change to the Australian public.

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WARNING: This report may contain the images of Aboriginal and Torres Strait Islander people now deceased.

This report is printed on 100% recycled paper.

Preface

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

For the second year in a row, heatwaves and extreme hot weather have plagued much of Australia. Preliminary accounts of the January 2014 heatwave in Victoria point to significant health impacts—203 heat-related deaths, a 20-fold increase in ambulance call-outs, a four-fold increase in calls to nurses-on-call, and a four-fold increase to locum doctors. Severe heat also afflicted areas further north: for the week ending 4 January 2014, average maximum temperatures were 8°C or more above normal in southern inland Queensland. By 9 February Canberra had recorded 16 days above 35°C this summer, compared to the long-term average of 5.2 days. Australia's extreme heat drew international attention when play in the 2014 Australian Open tennis tournament was suspended for the afternoon of 16 January because of the heat. Off-court ambulances treated almost 1000 tennis fans for heat exhaustion in the first few days of the tournament.

This report sets out the facts about heatwaves and hot weather. We explore the observed changes to heatwaves in Australia—their severity, duration and timing—and place this in the context of increasing extreme heat around the world. The contribution of climate change to the Australia-wide and global trends in heatwaves is clear and compelling. The impacts of heatwaves are often under-the-radar compared to other extreme weather events, but they are widespread and serious, damaging human health, infrastructure and natural ecosystems; and decreasing workplace performance and agricultural productivity. The report concludes by outlining what needs to be done to slow, and eventually stabilize, the trend towards more severe and more frequent heatwaves. The report draws directly on the peer-reviewed scientific literature as well as on authoritative assessments, such as those of the Intergovernmental Panel on Climate Change (IPCC). A reference list is provided at the end of the report for those who would like more information.

We are very grateful to our team of expert reviewers and community readers, whose comments and suggestions improved the report. The expert reviewers were: Dr Lisa Alexander (University of New South Wales), Prof Helen Berry (University of Canberra), Prof David Karoly (University of Melbourne), Prof Tord Kjellstrom (Health and Environment International Trust, Mapua, New Zealand), and Dr Sophie Lewis (University of Melbourne). We also thank the Bureau of Meteorology and

CSIRO, which reviewed the accuracy and relevance of the science underpinning the report. Their reviews are not an endorsement of the conclusions drawn. We are also grateful for Ron Collins, Jill Dumsday and Michael Kirkpatrick's feedback as community readers.

We are also grateful to Climate Council staff for their many contributions to the production of this report.

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

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Key findings

1. **Climate change is already increasing the intensity and frequency of heatwaves in Australia. Heatwaves are becoming hotter, lasting longer and occurring more often.**

   - Over the period 1971–2008, both the duration and frequency of heatwaves increased, and the hottest days during heatwaves became even hotter.
   - Hot days have doubled in Australia in the last 50 years. In the last decade, hot weather records have occurred three times more often than cold weather records.
   - Several of our capital cities—Adelaide, Melbourne and Canberra—are experiencing more intense hot weather than expected. The increase in hot weather observed in the 2000–2009 decade has already reached the best estimate projected for 2030.
   - The southeast of Australia, which includes many of our largest population centres, stands out as being at increased risk from many extreme weather events, including heatwaves, drought and bushfires.
   - The trend toward more frequent and more severe heatwaves in Australia is part of a larger global trend. Very severe heatwaves have occurred elsewhere, including Europe in 2003, Russia in 2010 and several regions in the south and central US in 2011 and 2012.

2. **Climate change is making heatwaves worse in terms of their impacts on people, property, communities and the environment. Heatwaves have widespread impacts, ranging from direct impacts on our health to damage to ecosystems, agriculture and infrastructure.**

   - Heatwaves pose a widespread risk for Australians as they affect people in all capital cities and most regional areas. Over the past 100 years, heatwaves have caused more deaths than any other natural hazard. Heatwaves also restrict work capacity and decrease the productivity of exposed workers.
   - Extreme heat can damage infrastructure such as electricity distribution and transport systems, causing flow-on effects. Heatwaves experienced in Melbourne in recent years have disrupted the railway system and electricity grid.
   - Hot, dry conditions have a major influence on bushfires—these conditions are driving up the likelihood of very high fire danger weather. Heatwaves exacerbate drought, which in turn can also increase bushfire risk.

- Heatwaves affect marine ecosystems, particularly vulnerable reefs. The 2011 marine heatwave in Western Australia caused the first-ever reported bleaching of Ningaloo reef. Bleaching events on the Great Barrier Reef have occurred repeatedly since the late 1970s.

- Heatwaves can reduce crop yields, decrease livestock productivity and trigger mass deaths of heat-sensitive species such as flying foxes and birds.

- It is crucial that communities; emergency services; health, medical and social services; and other authorities prepare for the increases that are already occurring in the severity and frequency of hot weather.

3. The climate system has shifted, and is continuing to shift, increasing the likelihood of more extreme hot weather.

- As greenhouse gases continue to accumulate in the atmosphere, primarily from the burning of fossil fuels, more heat is trapped in the lower atmosphere. This increases the likelihood of more frequent and more severe heatwaves.

- Small increases in average temperature lead to much larger increases in the frequency and intensity of extreme heat.

- Since 1950, increases in extreme daily temperatures have been reported over most regions of the globe.

4. Record hot days and heatwaves are expected to increase in the future

- The number of hot days, warm nights and heatwaves are all expected to increase through the 21st century across the globe.

- Record hot days and warm nights are also expected to increase across Australia over the coming decades. For both northern and southern Australia, 1-in-20 year extreme hot days are expected to occur every two to five years by the middle of the century.

- If the current trend in greenhouse gas emissions continues through the rest of this century, today's record-breaking hot weather will become commonplace, occurring almost every summer across the country.

5. Limiting the increase in heatwave activity requires urgent and deep reductions in the emissions of greenhouse gases.

- The choices we make over this decade will largely determine the severity of the extreme heat that our children and grandchildren will experience.

- To stabilize the climate, action on reducing emissions is required now. This is the critical decade.

Introduction

Heatwaves are one of the most important climate-related risks for Australians.

The extreme heat in Melbourne that plagued the 2014 Australian Open Tennis Tournament and the record-breaking heat in large areas of Queensland this summer reminded us of the risks that heatwaves pose. Coming on the heels of a record-breaking summer of 2012/2013, this summer's heat is part of a longer-term trend towards hotter weather (Climate Commission 2013a). The link between climate change and more extreme heatwaves is clear.

This report begins by exploring the long-term observations of hot weather to show how the nature of heatwaves is changing—their length, their frequency, their intensity and when they are occurring. We then describe what these trends mean for Australians—their impacts on our health and well-being, infrastructure, agriculture, biodiversity, and natural ecosystems. But heatwaves don't occur in isolation from other factors and their interactions with events such as droughts can exacerbate the effects of extreme heat. Finally, we take a look at the future—how the risks of extreme heat change as the Earth warms further, and what we need to do to stabilize the climate and avoid the more severe projections for future heatwaves.

1. HEATWAVES ARE BECOMING LONGER AND MORE INTENSE

Hot days, hot nights and extended periods of hot weather—heatwaves—are one of the most direct consequences of climate change.

As greenhouse gases continue to accumulate in the atmosphere from the burning of fossil fuels, more heat is trapped in the lower atmosphere. This increases the likelihood that hot weather will occur and that heatwaves will become longer and more intense. Observations over the past half-century confirm this physical process.

In this section we first describe the observational evidence of how the nature of heatwaves is changing in Australia. We then look at how heatwaves are changing around the rest of the world. Finally, we show the role of climate change in influencing the trends that we are observing.

1.1 The nature of changing heatwaves

Since 1950 the annual number of record hot days across Australia has more than doubled (CSIRO and BoM 2012), and maximum and minimum temperatures have both increased by around 0.9°C (Fawcett et al. 2012).

Over the past decade, the frequency of record hot days has been more than three times the frequency of record cold days (Trewin and Smalley 2013). The hottest ever area-averaged Australian maximum temperature occurred on 7 January 2013, reaching 40.3°C. This means that the maximum temperature averaged over the whole continent on that day was over 40°C. Extreme temperature records were broken in every state and territory throughout the course of the 2012/2013 summer.

While hot weather is a pre-requisite for heatwaves, it is important to remember that heatwaves are more than just stand-alone hot days. At least three excessively hot days must occur in a row for a heatwave to form, according to the Australian definition (BoM 2012; Nairn and Fawcett 2013). Furthermore, heatwaves have several significant characteristics. These include (i) frequency characteristics, such as the number of heatwave days and the annual number of summer heatwave events; (ii) duration characteristics, such as the length of the longest heatwave in a season; (iii) intensity characteristics, such as the average excess temperature expected during a heatwave and the hottest day of a heatwave; and (iv) timing characteristics, including the occurrence of the first heatwave event in a season.

Each heatwave characteristic shows different rates and patterns of change across Australia. Numerous characteristics of heatwaves have increased across many regions of Australia since the middle of the 20th century (Alexander and Arblaster 2009), with trends for some characteristics accelerating in the most recent decades. Over the period 1971–2008, both the

Over the period 1971–2008, both the duration and frequency of heatwaves increased, and in several parts of the country the hottest days during heatwaves became even hotter.

duration and frequency of heatwaves increased, and in several parts of the country the hottest days during heatwaves became even hotter (Perkins and Alexander 2013). This is consistent with trends in heatwaves for other global regions, such as Central Asia and Europe (See section 1.3; Perkins et al. 2012).

Using the heatwave definition of the Australian Bureau of Meteorology (Nairn and Fawcett 2013), Figure 1 depicts changes in five heatwave characteristics across the continent from 1950–2013. Figure 1(A) clearly shows that the number of heatwave days has increased over much of Australia (see also Figure 2), particularly the eastern half. An increase in the number of heatwave days in turn influences the number of heatwave events and/or their duration. Although smaller, the areas of increasing trends in heatwave frequency (Figure 1(B)) and duration of the longest annual event (Figure 1(C)) are consistent with the increase in heatwave days. Increases in the number of heatwave events and in their duration will generally lag behind increases in the number of heatwave days. While an increase in the number of days is required to increase the duration and the frequency, both cannot occur at the same time. That is, for each extra heatwave day, the new heatwave day can contribute to either heatwave duration or heatwave frequency, but not to both characteristics.

Since 1950, despite considerable year-to-year variability, almost all of Australia has experienced a lengthening of the heatwave season (Figure 1(D)), with the first event occurring much earlier (Table 1). The intensity of heatwaves, as measured by the temperature of the hottest day (the peak of the heatwave), is also increasing. Figure 1(E) shows that the temperature of the hottest day of a heatwave has increased over almost all of Australia below the tropics. Such trends are consistent with, and extend, the trends reported by Perkins and Alexander (2013) since they include the latest complete data for Australian summers.

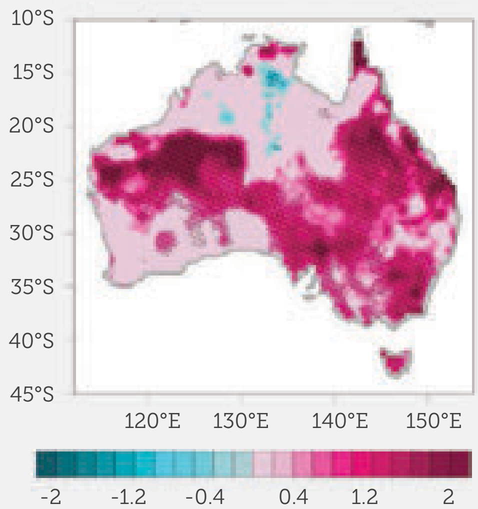
WHAT IS A HEATWAVE?

In Australia, a heatwave is defined operationally 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 2012; Nairn and Fawcett 2013). Two aspects of this definition are important. First, a heatwave is defined relative to the local climate. That is, a heatwave for Hobart will occur at lower temperatures than one for Alice Springs. Second, the concept of excess heat is also important. Excess heat occurs when unusually high overnight temperatures do not provide relief from the daytime heat.

Figure 1: Heatwaves in Australia are becoming hotter, longer, more frequent, and occurring earlier. Figures A through E depict changes in five heatwave characteristics across the continent from 1950–2013. All heatwave metrics are calculated relative to a 1961–1990 base period, using the heatwave definition from the Australian Bureau of Meteorology (Nairn and Fawcett 2013). Source: Modified from Perkins and Alexander (2013) using AWAP (Australian Water Availability Project) data from the Bureau of Meteorology.

How are heatwaves changing in Australia?

A

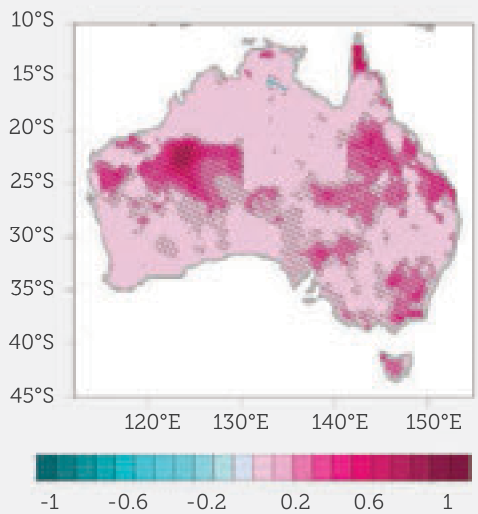


Heatwave days expressed as a percentage of all summer days per summer.

THE NUMBER OF HEATWAVE DAYS IS INCREASING

Red shows an increase in the number of heatwave days. Figure A clearly shows that the number of heatwave days has increased over much of Australia, particularly the eastern half.

B



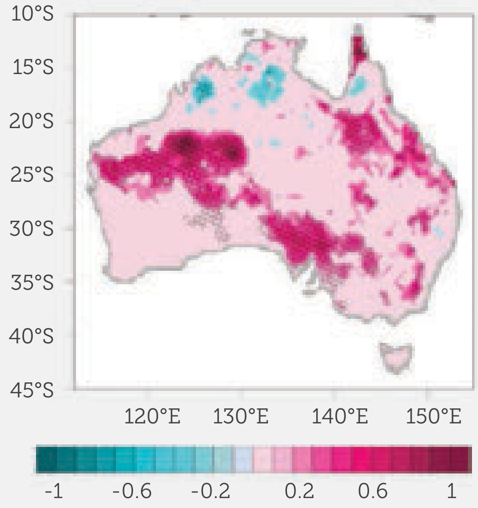
Number of heatwave events per summer

HEATWAVES ARE OCCURING MORE FREQUENTLY

Red indicates an increase in the number of heatwave events per summer.

An increase in the number of heatwave days in turn influences the number of heatwave events and/or their duration, and although smaller, areas of increasing trends in heatwave frequency (Figure B) and duration of the longest yearly event (Figure C) are consistent with that of heatwave days. Note that changes in heatwave events and duration will generally lag behind that of heatwave days—while an increase in the number of days is required to increase the duration and frequency, both cannot occur at the same time. That is, for each extra heatwave day that is gained, the new day can only contribute to heatwave duration or frequency.

C

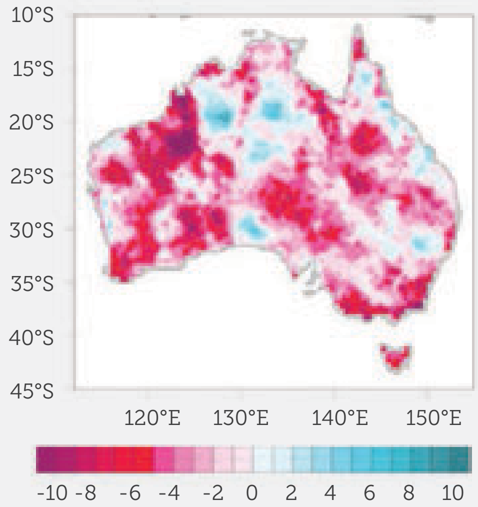


The length in days of the longest event per summer

THE DURATION OF THE LONGEST YEARLY HEATWAVE IS INCREASING

Red indicates an increase in the number of days of the longest heatwave of a summer.

D

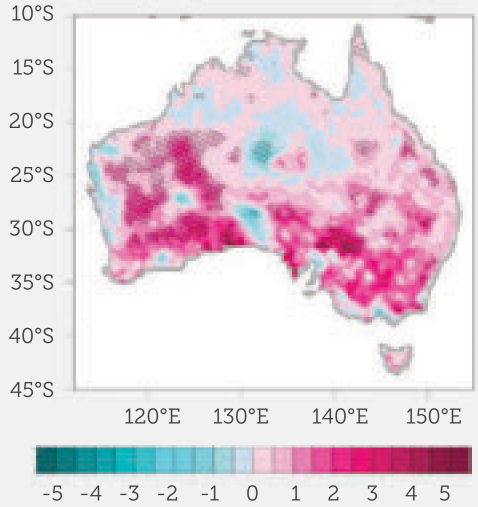


Start day of the first event per summer

THE FIRST HEATWAVE OF THE SEASON IS OCCURING EARLIER

Red indicates a heatwave occurring earlier relative to the long-term average. Since 1950, almost all of Australia has experienced a lengthening of the heatwave season, where the first event is occurring much earlier (Figure D).

E



Extreme Heat Factor units (°C_2)

THE HOTTEST DAY OF A HEATWAVE IS BECOMING HOTTER

Red shows increasing temperatures. Figure E shows that the hottest day of a heatwave, i.e. its peak, has a detectable increase for almost all of Australia below the Tropics. Such trends are consistent with, and continue on from those reported by (Perkins et al. 2012), since they include the latest complete Australian summer data.

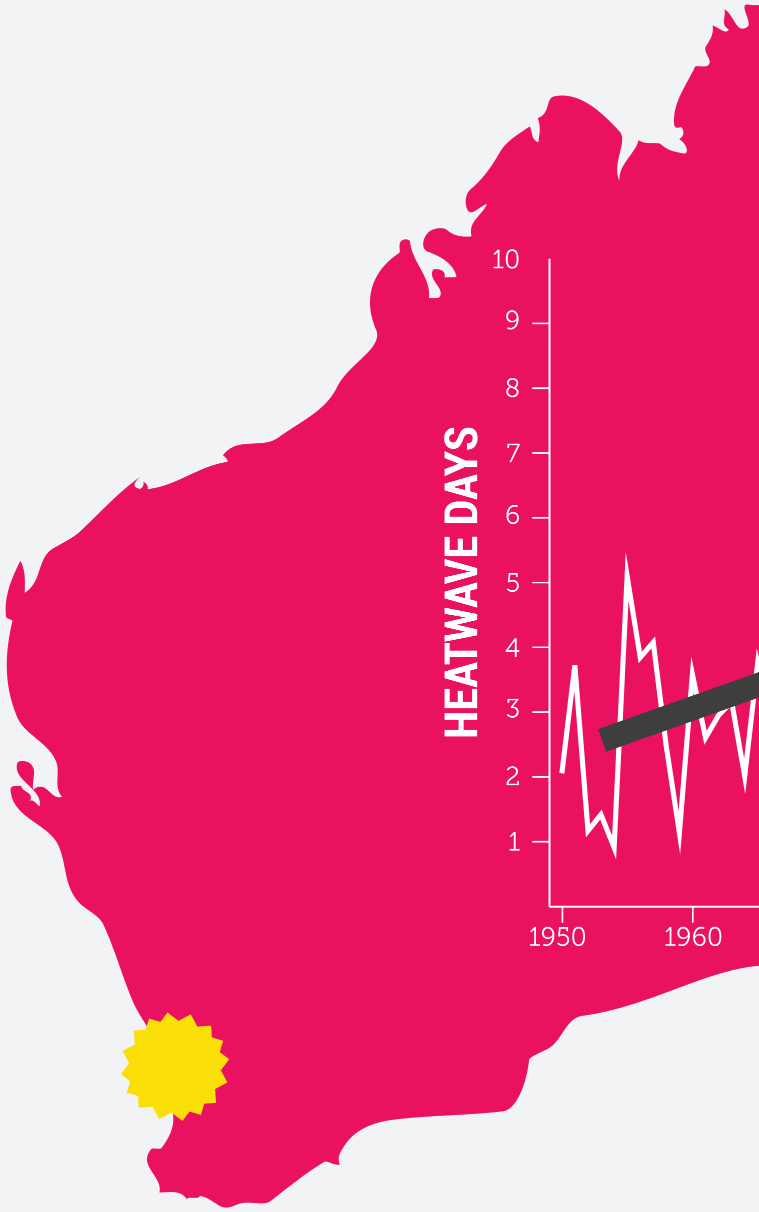
Figure 2: Heatwaves in Australia. The number of heatwave days has been increasing across Australia, and in Australian capital cities, since 1950. Such trends are consistent with, and continue on from those reported by Perkins et al. 2012, since they include the latest complete Australian summer data. Source: Modified from Perkins and Alexander 2013.

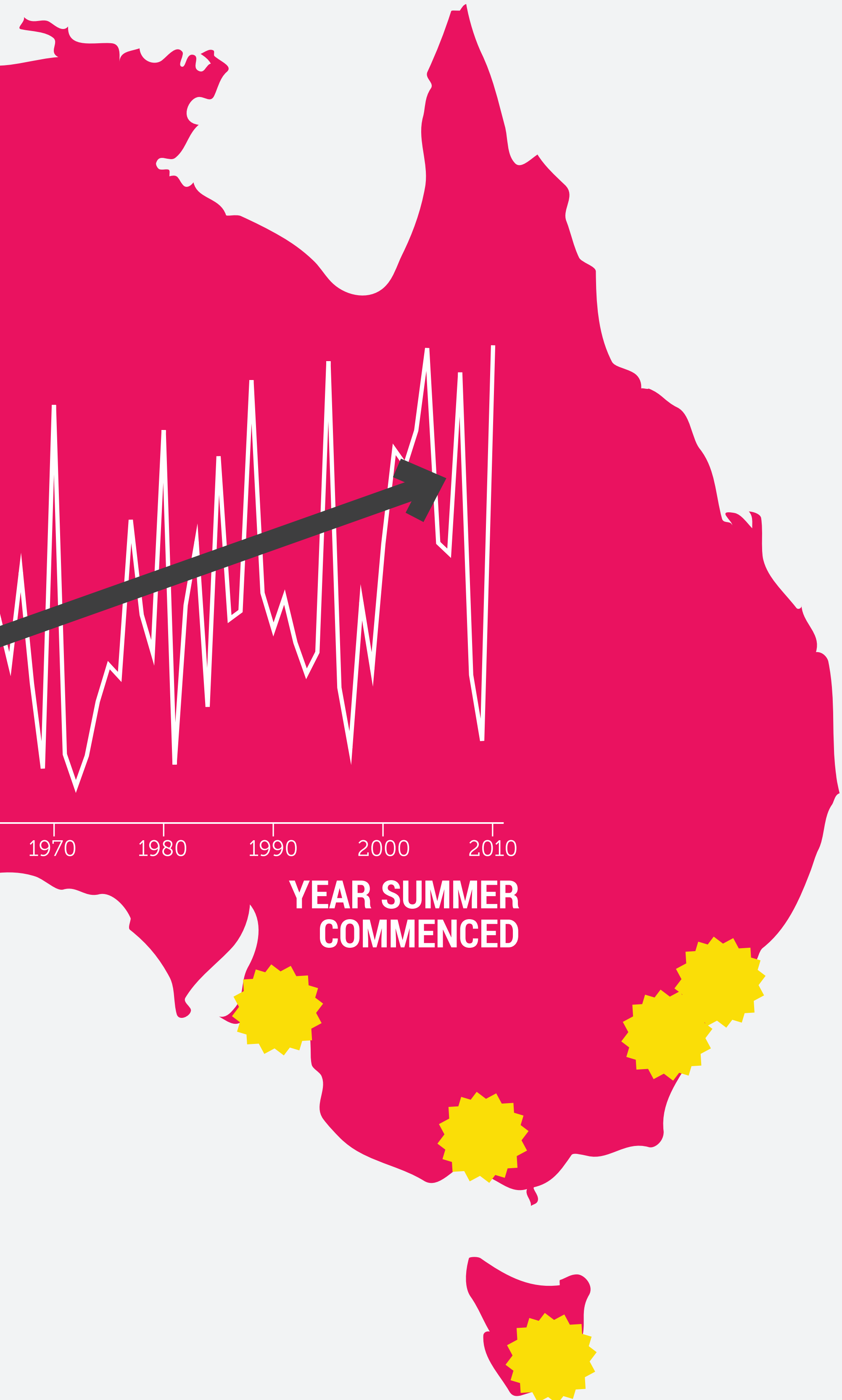
Heatwaves: State of the Nation

The number of heatwave days in Australia is increasing.

In Australia, a heatwave is defined 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, 2012; Nairn and Fawcett, 2013).

The central line graph shows the number of heatwave days for Australia as a whole over the period 1950–2010. The number of heatwave days each year has been increasing in Perth, Adelaide, Melbourne, Sydney, Canberra and Hobart, and across Australia as a whole since 1950.




1970
1980
1990
2000
2010
YEAR SUMMER COMMENCED

Using the definition of a heatwave, Table 1 presents the average number of heatwave days, events, and duration, a well as the average intensity over all heatwaves and the average of the hottest (peak) day for Australia's capital cities, over the period 1950–2011. Note that the frequency, intensity and duration of heatwaves differ across these locations, and that these characteristics are influenced by local factors, such as synoptic conditions (meteorological conditions over a wide area at a given time), rainfall, location, and the overall climate classification.

City	Number of heatwave days		Number of heatwaves (events)		Length of longest event		Changes in average intensity of the heatwave (°C)	Changes in average intensity of the peak day (°C)	Changes in timing of first event (days)
	1950–1980	1981–2011	1950–1980	1981–2011	1950-1980	1981–2011			
Sydney	6	9	1-2	2-3	4	5	1.5	1.5	-19
Melbourne	5	6	1-2	1-2	4	4	1.5	2	-17
Brisbane	10	10	2-3	2-3	6	6	1	1.5	-8
Perth	6	9	1-2	2-3	4	5	1.5	1.5	+3
Adelaide	5	9	1-2	1-2	4	6	2.5	4.3	-2
Hobart	4	5	1	1-2	4	4	-1.5	1.7	-12
Darwin	3	7	1	1-2	4	5	0	1	-7
Canberra	6	13	1-2	2-3	5	7	0	1.5	-3

Table 1: The average number of heatwave days, number of events, length of the longest event, average heatwave intensity, average intensity of the peak heatwave day, and change in the timing of the first summer heatwave for Australia's capital cities (Perkins and Alexander 2013). Statistics were calculated from the high-quality ACORN-SAT temperature dataset for the period 1951-2011 (Trewin 2012), using the Excess Heat Factor heatwave definition (Nairn and Fawcett 2013; Perkins and Alexander 2013). All statistics are rounded to the nearest integer. The first column for each characteristic is for the 1950–1980 period and the second is for the 1981–2011 period. Changes in average intensity and peak intensity are calculated by subtracting the respective average from 1950–1980 and 1981–2011. Changes in timing are calculated by subtracting the average start date during 1981–2011 from that of 1950–1980.

IN DETAIL 1

Variability in heatwave characteristics

The occurrence, duration and intensity of extreme Australian temperatures varies from year to year, due to the influences of climate variability (Kenyon and Hegerl 2008; Alexander et al. 2009). Heatwaves, therefore, are also affected. During El Niño years, for example, much of Australia is prone to below average rainfall and above average temperatures. This increases the chance of stand-alone hot days (Kenyon and Hegerl 2008; Alexander et al. 2009; Arblaster and Alexander 2012; Min et al. 2013), and possibly also the chance of heatwaves. During La Niña years, when much of Australia generally receives higher than average rainfall, average temperatures are lower and therefore heatwaves are less common in many places.

The occurrence of heatwaves is also governed by meteorological conditions (see Engel et al. 2012), which are influenced by climate variability, as described above. The most important weather system for Australian heatwaves is the persistent anticyclone, where a high-pressure system remains stationary adjacent to the area affected for a prolonged time (Hudson et al. 2011; Pezza et al. 2012; Marshall et al. 2013). The high-pressure system brings warm air from the interior of the continent to the area experiencing the heatwave, which sustains excessively hot temperatures for a number of days. For southeastern Australia heatwaves, this high is generally centred over the Tasman Sea and is in line with the subtropical ridge (an east-west zone of high pressure that often lies over the southern part of the continent) (Hudson et al. 2011; Marshall et al. 2013), and for southwestern Australia, it is centred over the Great Australian Bight (Pezza et al. 2012). Other regional features can also influence the occurrence and intensity of Australian hot days and heatwaves, including intra-seasonal drivers of variability (Marshall et al. 2013), rainfall deficits (Nicholls 2004), local sea surface temperatures (Pezza et al. 2012), the Australian monsoon, and tropical cyclones (Parker et al. 2013).

See section 1.3 for the influence of climate change on heatwaves.

While a fine balance of climate variability and synoptic systems governs year-to-year occurrences of Australian heatwaves (see In Detail 1), such conditions cannot explain longer-term changes (Lewis and Karoly 2013). Although highly variable over a small number of years, the number, duration and intensity of heatwaves should not change over decades in a stable climate. The changes in Australian heatwaves as described above are part of a long-term global trend towards more heatwaves and hot weather in many regions, a trend that is very likely influenced by human-driven climate change (IPCC 2013), as explained in more detail in section 1.3.

The trend towards more frequent and more intense heatwaves is reflected in recent observations of individual heatwave events. Over the past decade a remarkably large number of record-breaking and devastating heatwaves have occurred in Australia and in many other parts of the world (Coumou and Rahmstorf 2012). The extent of the heatwave that affected eastern to central Australia in 2004, from 9–22 February, was greater than any other February heatwave on record. All-time records for consecutive days of heat include 17 days over 30°C at Adelaide, 16 days over 35°C at Snowtown, 16 days over 40°C at Wilcannia, seven days over 35°C at Bathurst, and 12 days over 35°C at Wagga Wagga (BoM 2005).

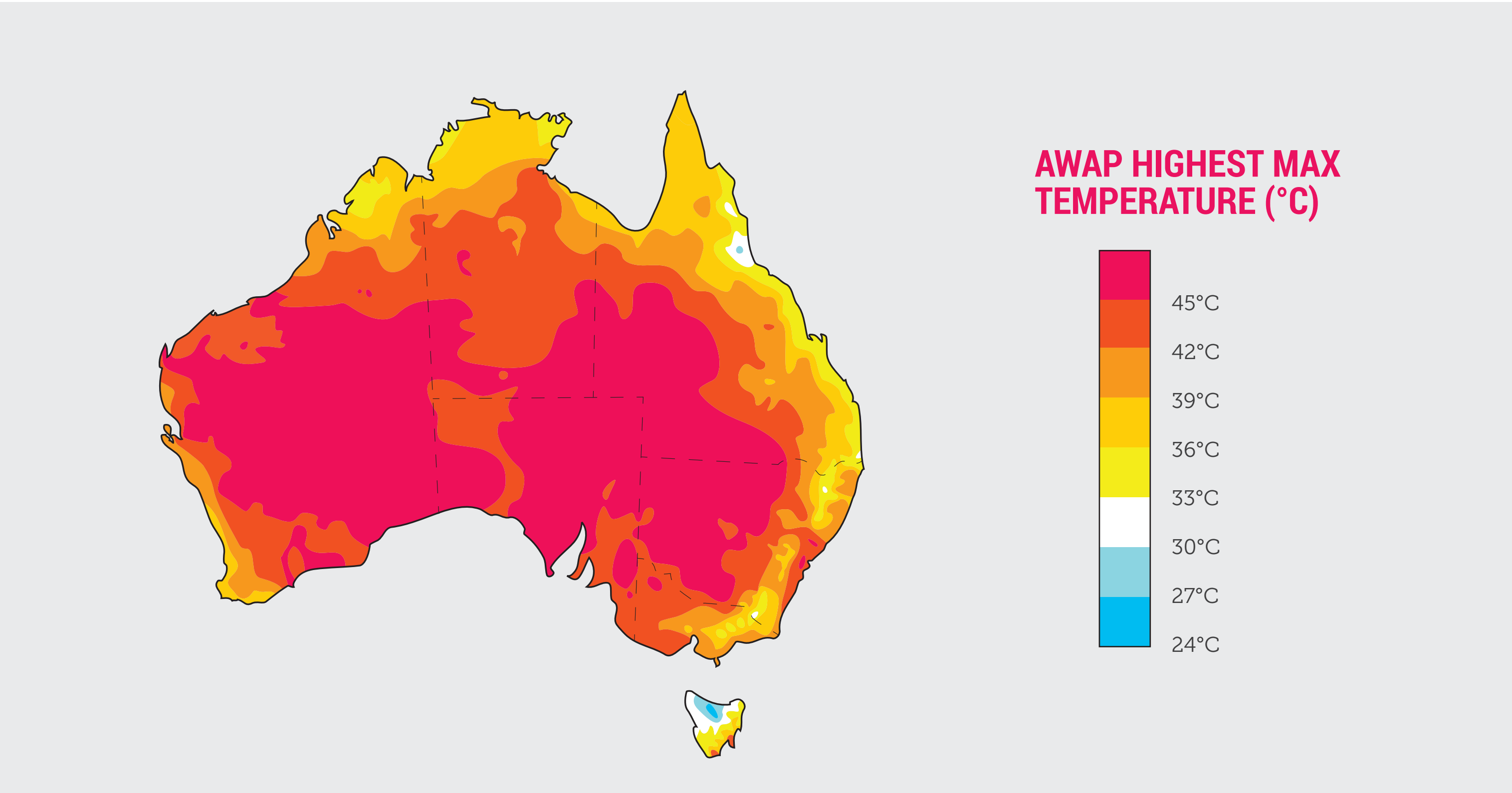


Figure 3: Highest maximum temperature reported in the period 1 January 2013—18 January 2013. Source: (BoM 2013a)

South and southeast Australia experienced an extreme heatwave in 2009, with two significant periods of exceptionally high temperatures, from 28–31 January and 6–8 February (BoM 2009; McEvoy et al. 2012; see section 3.2 for the link to the Black Saturday bushfires). On 30 January, Tasmania experienced its hottest day on record when the temperature soared to 42.2°C. Overnight minimum temperatures were also very high in many places during the heat wave. Adelaide experienced its warmest night on record when the temperature dropped to only 33.9°C on 29 January. The most extreme heat of the whole episode occurred on 7 February with record highs throughout much of Victoria (BoM 2009). An all-time state record was broken at Hopetoun when the temperature reached 48.8°C, which is considered the highest ever recorded in the southern hemisphere so far from the equator. Records stretching over 154 years were broken in Melbourne, where the temperature reached 46.4°C. South Australia also experienced its hottest February day on record (48.2°C) at Renmark (BoM 2009).

The heatwave that occurred during the 2012–2013 summer was unusual for its size and duration. A massive pool of hot air became established over 70% of the continent at the end of December 2012 and persisted until the middle of January (Figure 3). Through the 2–8 January period, the country experienced seven consecutive days of area-averaged maximum temperature over 39 °C. In 102 years of weather records, Australia has experienced only 21 such days, and eight of them occurred in 2013. January 2013 was Australia's hottest January on record. Temperature records were set in every state and territory during the summer, and all-time high maximum temperatures were set at 44 weather stations, including Sydney, Hobart and Newcastle (BoM 2013a; Climate Commission 2013a). Extreme heat played a role in several of the extreme weather events that occurred during the 2012–2013 summer (Figure 4).

Section 1.3 describes the link between climate change and heatwaves and is supported by the observational data of heatwaves in Australia.

RECORD TEMPERATURES ACROSS THE COUNTRY

A major heatwave affected central and eastern Australia in late 2013/early 2014. The most significant records were set on 3 January, when Queensland experienced its area-averaged hottest day on record. For the week ending 4 January, average maximum temperatures were 8°C or more above normal in southern inland Queensland. Overall, record high maximum temperatures occurred over 8.8% of Australia from 1 to 4 January, including 16.8% of New South Wales, 16.8% of the Northern Territory, 15.2% of Queensland and 7.9% of South Australia (BoM 2014).

"Angry Summer" 2012–2013: Events Snapshot

HEAT

- Australia's hottest summer on record.
- January 2013 was the hottest month on record for Australia.
- Hottest day ever recorded for Australia as a whole—40.3°C on 7 January.
- 7 days in a row with a temperature above 39°C for Australia as a whole.
- Heatwave and temperature records were broken across Australia including:
  - 44 weather stations set hottest maximum temperatures.
  - 2 weather stations also set December record maximum temperatures.
  - 13 weather stations also set January record maximum temperatures.
  - 4 weather stations also set February record maximum temperatures.
  - 29 warmest night records (highest minimum temperature) including 7 all-time records.

RAIN

- 26 daily rainfall records across Australia were broken at weather stations with over 80 years of data including 11 all-time daily rainfall records during late January even in eastern Australia.
- There were also 9 December records, 23 January records and 2 February records broken across Australia.
- Gladstone, Queensland set records for its highest 4-day rainfall (819.8mm)—higher than Gladstone's previous record for a whole calendar month.

FLOODS

- 5 river height records broken.
- Major flooding through southeast Queensland and northern New South Wales.

Figure 4: A snapshot of the "angry summer" 2012–2013. Source: Modified from Climate Commission 2013a

DRY

- Much of Australia was drier than normal from mid-2012 with record lowest July to December rainfall across Central South Australia, and below average rainfall across almost all of southeastern Australia.
- Lowest monthly rainfall records were broken at weather stations in Queensland, New South Wales, Victoria, South Australia and the Northern Territory.

TROPICAL CYCLONES

- TROPICAL CYCLONE OSWALD: Former tropical cyclone Oswald caused extremely heavy rainfall to fall over Queensland and northern New South Wales. The low pressure system also caused high waves, storm surges and flooding.
- TROPICAL CYCLONE RUSTY: Near the end of February, tropical cyclone Rusty, a large and slowly moving storm system, threatened the Pilbara coast of north Western Australia with winds of up to 230km/h and heavy rainfall.

BUSHFIRES

- Bushfires in every state and territory with very damaging fires in Tasmania and New South Wales.
- On 4 January, up to 40 bushfires occured across Tasmania. Over 25,000 hectares were burnt and close to 200 properties destroyed.
- "One of the worst fire danger days on record for NSW" — NSW Rural Fire Service Commissioner Shane Fitzsimmons.
- In New South Wales bushfires occured across the state on January 8, with reports of up to 140 incidents.

TORNADOES

- Tornadoes with damaging winds hit Bundaberg and other coastal Queensland townships on Australia Day.

1.2 Severe heatwaves in other parts of the world *(Europe, Russia, USA)*

In the last 10–15 years, many severe heatwaves have occurred in other parts of the world. One of the most severe was the European heatwave of July and August 2003, which occurred during an unusually dry summer (Black et al. 2004).

It was likely the hottest period that Europe has experienced since at least 1500 AD (Stott et al. 2004). From May to August, Europe experienced anticyclonic (high atmospheric pressure) conditions, which contributed to the low rainfall and high temperatures, leading to a reduction in soil moisture (Black et al. 2004). Low soil moisture content has been an important factor in the increasing number of days of extreme heat in many regions of the world (Mueller and Seneviratne 2012; see section 3.1). Average monthly temperatures across Europe were significantly higher than usual, and mean June temperatures over central Europe were 4.2°C hotter than the long-term (1958–2002) average (Black et al. 2004).

While most of Western and much of Eastern Europe sweltered, France and Switzerland were particularly affected, with the mean summer temperature averaged across four weather stations in Switzerland a remarkable 5.1°C higher than the 1864–2000 average (Black et al. 2004). During July and August, nighttime temperatures also climbed dramatically, and were higher even than long-term mean daily temperatures (Black et al. 2004). The 2003 heatwave closely resembled the projections of maximum summer temperatures from regional climate models for the second half of the 21st century (Beniston 2004; Schär et al. 2004), and, under a high greenhouse gas emissions scenario (the IPCC SRES A2 scenario), summers such as this are expected to be common occurrences in Europe by the end of this century (Beniston 2004; Schär et al. 2004).

The 2003 European heatwave was followed in 2010 by an even more intense and widespread heatwave, which scorched enormous areas across Eastern Europe (Barriopedro et al. 2011), including western Russia, Belarus, Estonia, Latvia, and Lithuania (Dole et al. 2011). By May 2010, record high sea surface temperatures had developed in the Indian and Atlantic Oceans, with a number of consequences for weather patterns. One of the most important consequences was the unusually strong and persistent anticyclonic condition that settled over Russia during the summer, and was responsible for the extreme heat. The most intense period of the heatwave occurred from June to mid-August (Trenberth and Fasullo 2012), including the hottest July on record in western Russia since at least 1880 (Dole et al. 2011). During July, temperatures soared to over 40°C, breaking numerous records, and daily maximum temperatures persisted around record levels (Dole et al. 2011). As with the 2003 European heatwave, the 2010 summer in Russia matched climate projections for the latter half of the 21st century, based on a scenario of no emission reductions until mid-century (IPCC SRES A1B; Barriopedro et al. 2011). Rahmstorf and Coumou (2011) calculated with a likelihood of around 80% that the Russian 2010 heatwave would not have occurred without the influence of human-caused climate change (see next section).

hottest and driest summer the state has seen since records began in 1895 (Peterson et al. 2012). 2011 was a La Niña year, an effect that typically brings warmer winters and decreased rainfall to southern parts of the US (Luo and Zhang 2012), and by July, around 75% of Texas was experiencing a drought described as "exceptional" (NOAA 2012). Soil moisture content had been reduced because of decreased rainfall (Mueller and Seneviratne 2012; Winguth and Kelp 2013), predisposing the region to prolonged extreme temperatures (Mueller and Seneviratne 2012, section 3.1) that culminated in a heatwave across the state in July. The June to August three-month average temperature was 2.9°C above the long-term (1981–2010) average, at 30.4°C. While the reduced rainfall has been largely attributed to natural variability

"'Mega-heatwaves' such as the 2003 and 2010 events likely broke the 500-year-long seasonal temperature records over approximately 50% of Europe" Barriopedro et al. 2011

North America has also experienced a number of heatwaves in recent years, with a major heatwave and devastating drought affecting the state of Texas in July 2011 (NOAA 2011; Luo and Zhang 2012; Peterson et al. 2012) and a larger heatwave covering a greater area of the country in 2012 (NOAA 2012). The 2011 summer (June to August) was the 4th hottest summer on record for the US (NOAA 2012), and broke many heat-related records around the country (NOAA 2011). Texas experienced the

(Hoerling et al. 2013), climate models have shown a shift to warmer and drier conditions over the period 1964 to 2008 (Peterson et al. 2012). The circumstances that led up to the Texas 2011 drought, which in turn set the scene for a record heatwave, are much more likely now than they were 40–50 years ago and climate change has increased the likelihood of setting a hot temperature record by 6% in 2011 in comparison to the 1981–2010 period (Peterson et al. 2012).

1.3 The influence of climate change on heatwaves

Human-driven climate change has contributed to the increase in hot days and heatwaves.

The increase in greenhouse gases in the atmosphere, primarily caused by the burning of fossil fuels, is trapping more heat in the lower atmosphere (IPCC 2013), that in turn increases the likelihood of heatwaves and hot days and decreases the likelihood of cold weather.

The influence of climate change on heatwaves is more significant than the increase in global average temperature, about 0.85°C since 1880 (IPCC 2013), might suggest. Figure 5 shows how small changes in average temperature can have a significant influence on extremes (IPCC 2012). The figure shows the distribution of temperatures, say, daily maximum temperature, around the average. On most days, the temperature

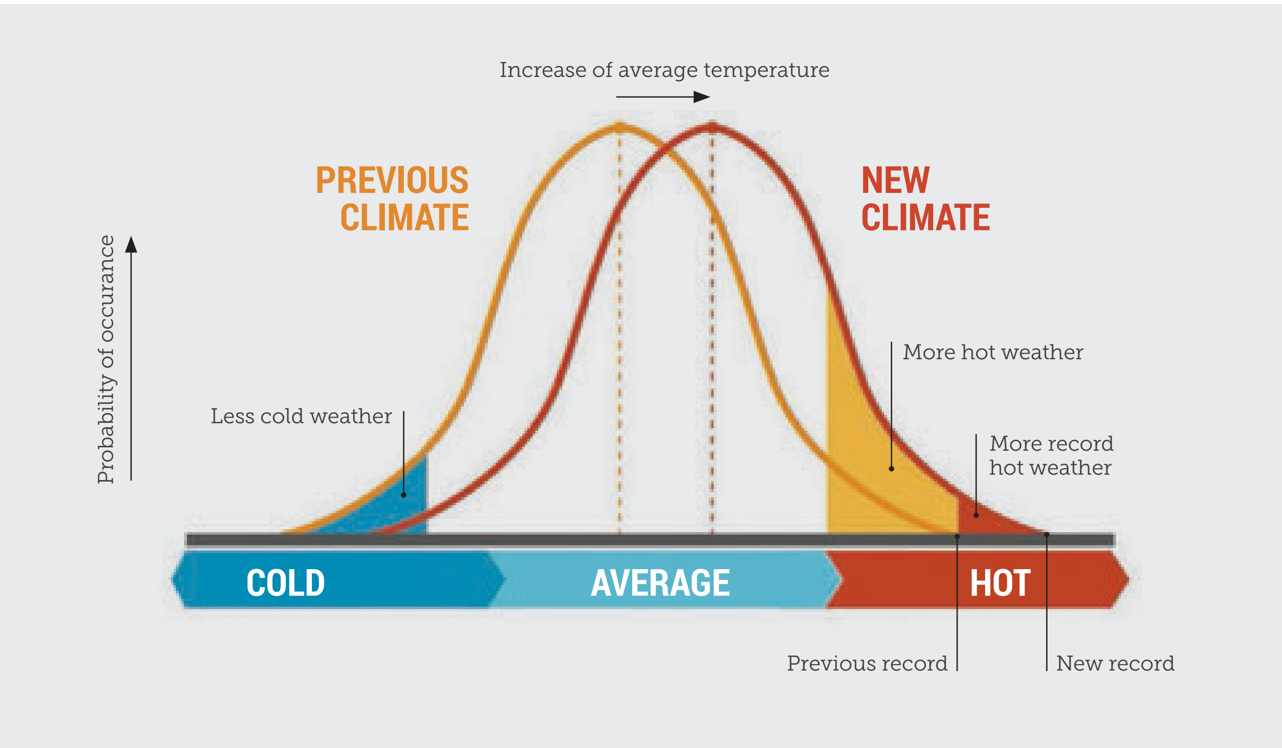


Figure 5: Relationship between average and extremes, showing the connection between a shifting average and the proportion of extreme events. Source: Climate Commission 2013b, modified from IPCC 2007

is not too far from the average, but occasionally some very hot or very cold days can occur. But when the average temperature warms by even a small amount towards a higher level, the temperatures at the "tails"—the ends of the temperature distribution—also shift. The result is a much greater likelihood of very hot weather and a much lower likelihood of very cold weather.

Long-term observations demonstrate the effect of warming on temperature extremes shown in Figure 5. Globally, since 1950 it is very likely (greater than 90% probability) that there has been an overall increase in the number of warm days and nights, and an overall decrease in the number of cold days and nights (IPCC 2013). It is also likely (greater than 66% probability) that there has been an increase in the frequency, intensity and duration of heatwaves and warm spells over that period across many global regions (IPCC 2013; Perkins et al. 2012). An increase in heatwave frequency has been observed in China (Ding et al. 2010), and increases in the frequency, duration and intensity of heatwaves have been observed in the Mediterranean region since the 1960s (Kuglitsch et al. 2009). A doubling in the length of European heatwaves between 1880–2005 has also been found (Della Marta et al. 2007). Other areas of the world, particularly Africa, Antarctica, India, and parts of South America, do not yet have enough high quality data to undertake comprehensive investigations of changes in heatwave activity.

For regions where adequate and consistent data exist, increases in extreme daily temperatures have been reported over most global regions since 1950 (Brown et al. 2008) (see Figure 6 for the Northern Hemisphere). The number of heatwave days has increased each decade between 1950–2010 for much of Northern America, Europe, Central and East Asia, and, consistent with Figure 1 above, eastern and southern Australia (Figure 7; Perkins et al. 2012).

Global changes in warm spells have also been found since 1950 (Alexander et al. 2006; Perkins et al. 2012; Donat et al. 2013). Unlike heatwaves, warm spells

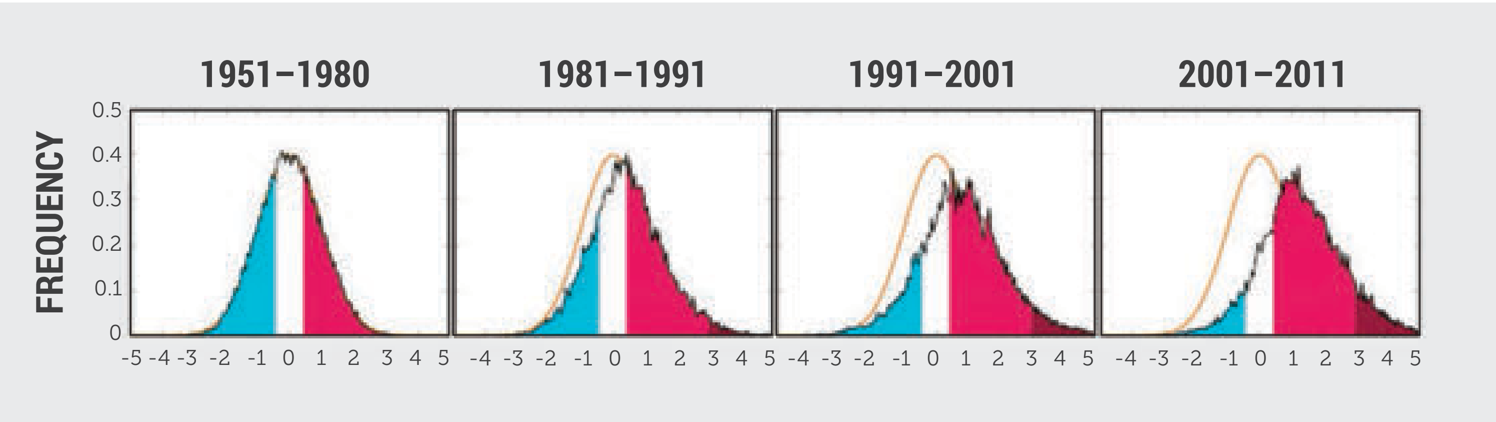


Figure 6: Summer temperature shifts in the Northern Hemisphere over the period 1951–2011. During the 1951–1980 period, the Northern Hemisphere experienced an equal number of hotter-than-average (red) as colder-than-average days (blue). Since that time, average summer temperatures have shifted towards warmer days, and the Northern Hemisphere now experiences many more hotter-than-average days than it does colder-than-average. Source: NASA/GISS 2012

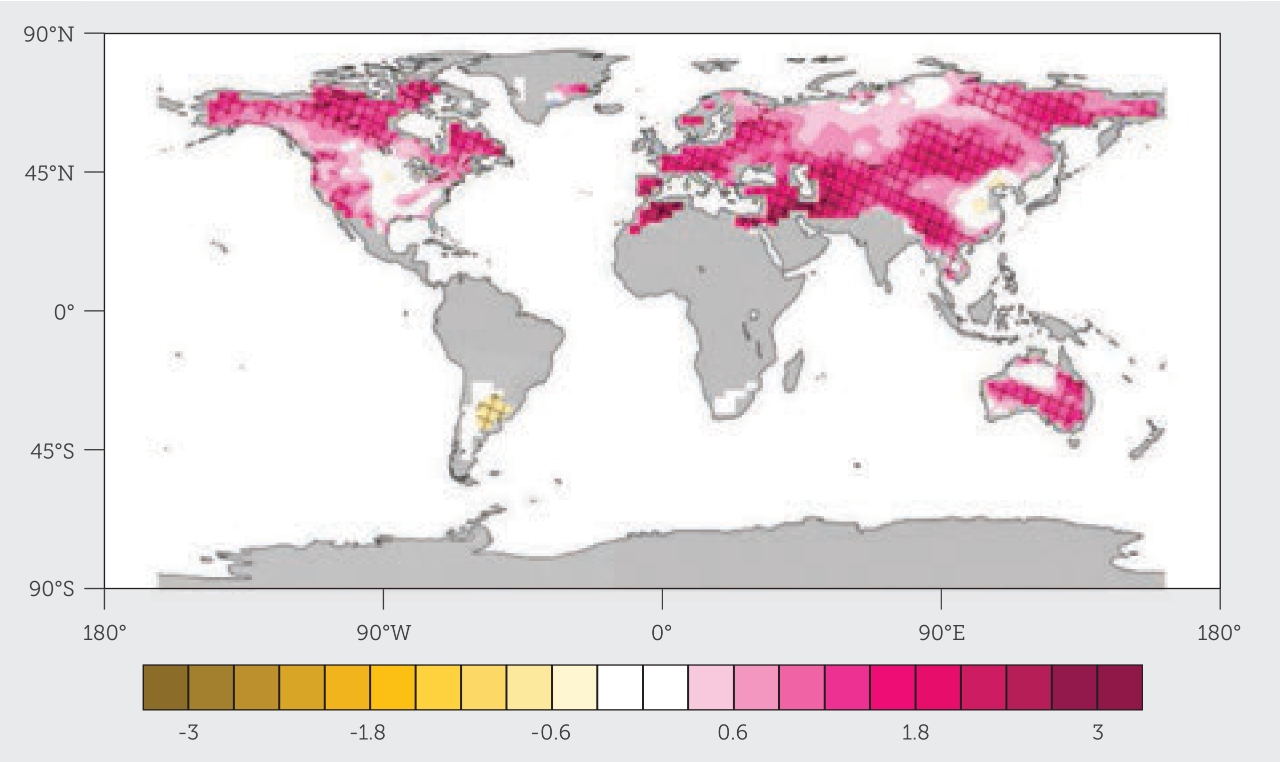
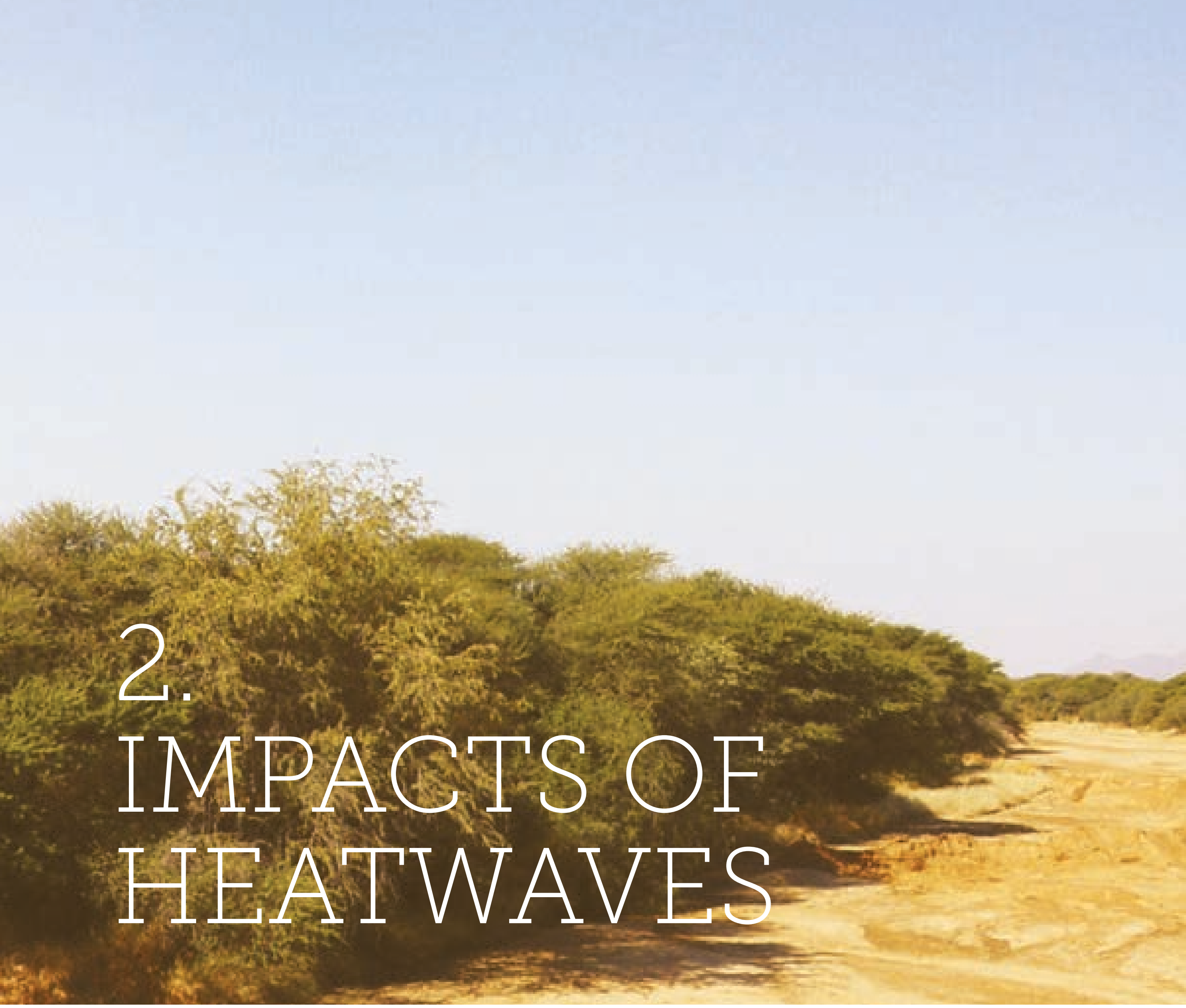


Figure 7: Global trends in the number of heatwave days per decade, from 1950–2011. Hatching represents statistically significant trends at the 5% level, calculated by non-parametric methods. Grey regions did not have adequate data for heatwave calculation. There has been an increase in occurrence of heatwaves over many other regions in addition to Australia, as a results of the long-term rise in global average temperatures. Source: Adapted from Figure 1 of (Perkins et al. 2012), calculated using the Excess Heat Factor index (Perkins et al. 2012, Nairn and Fawcett 2013) from the HadGHCND gridded daily temperature dataset (Caesar et al. 2006)

include excessively warm events (relative to time of year) that occur outside of summer. Trends in these non-summer events are increasing faster than heatwaves during the summer seasons only, as measured by the number of heatwave/warm spell days and events, and their duration and peak intensity (Perkins et al. 2012). There is considerable evidence that nighttime temperature extremes are increasing faster than daytime temperature extremes (IPCC 2013), a trend that is important for the impacts of heatwaves (section 2 below).

Recently scientists have used model-based approaches to estimate the increase in the likelihood that a particular heatwave will occur due to the human-driven increase in atmospheric greenhouse gas concentrations. Using such methods, Lewis and Karoly (2013) concluded that the odds of the Australian 2013 Angry Summer occurring when it did increased more than five times due to the human-driven increase in atmospheric greenhouse gases. Using similar methods, a study by Rahmstorf and Coumou (2011) estimated that there is a likelihood of around 80% that the Russian 2010 heatwave would not have occurred without the influence of human-caused climate change.



2. IMPACTS OF HEATWAVES

Heatwaves have been dubbed "the most under-rated weather hazard in Australia" (BoM, cited in PwC 2011). While heatwaves and hot weather do not result in obvious violent effects on the landscape, unlike the effects of many other weather-related disasters such as high-intensity storms and bushfires, the impacts of heatwaves on health, infrastructure, agriculture, and the environment can nonetheless be serious, costly and long-lasting.

In Australia, heatwaves and hot weather are responsible for the greatest number of deaths from any type of natural disaster, and contribute significantly to morbidity, particularly among the elderly. The economic burden of heatwaves is large, through the decrease in labour productivity during the hottest periods (Kjellstrom and McMichael 2013), the demand placed on emergency services, infrastructure stress and breakdown, and agricultural losses.

2.1 Human health: *Direct impacts on health*

The increasing frequency, intensity and duration of heatwaves are increasing the burden on Australia's people and health services.

Those most at risk include the very old, the very young, Aboriginal and Torres Strait Islander communities, and those who work outdoors or whose physical and mental wellbeing are compromised. Consequently, as Australia's population grows and ages, the proportion and absolute number of people most at risk from heatwaves will continue to rise, increasing the pressure on emergency and health services.

Heatwaves are a particularly important risk for people living in cities because metropolitan areas can be significantly warmer than neighbouring countryside areas (Stone et al. 2010). Dense urban areas, such as inner city environments, may be 1 to 3°C hotter than surrounding areas (Climate Commission 2011; Figure 8). This phenomenon is known as the 'Urban Heat Island' and occurs because of a decreased amount of vegetation and increased areas of dark surfaces in urban environments, in addition to the heat produced from vehicles and generators (Luber and McGeehin 2008; Stone et al. 2010). The Urban Heat Island effect is generally more prominent during the night than the day, so its major impact is to increase the likelihood of extreme high minimum temperatures.

"Heatwaves kill more Australians than any other natural disaster. They have received far less public attention than cyclones, floods or bushfires—they are private, silent deaths which only hit the media when morgues reach capacity or infrastructure fails."

Price-Waterhouse Cooper, "Extreme Heat Events"

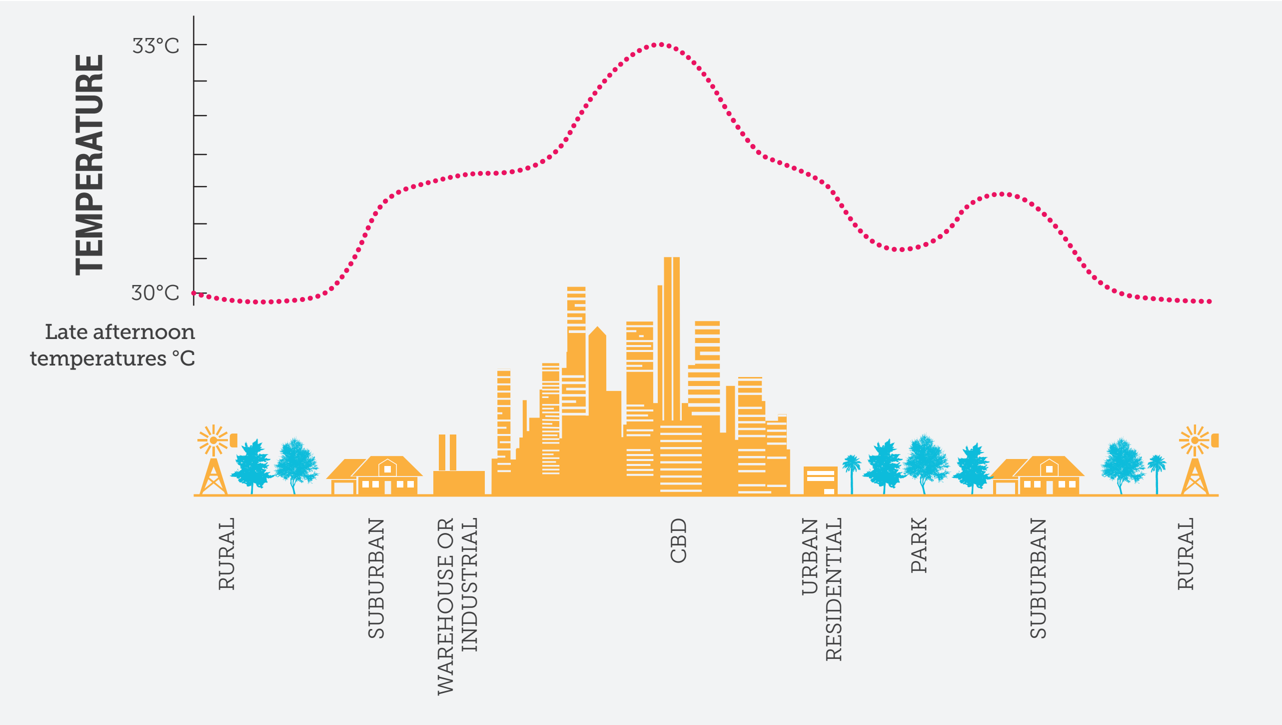


Figure 8: A stylised view of the urban heat island effect. The average annual air temperature in sprawling urban areas, and inner-city environments, is higher than surrounding areas, although the exact temperature profile can vary from city to city. Source: Climate Commission 2011, modified from US EPA 2008 and NASA 1999

As even more Australians move into urban areas, they are increasingly moving into the inner city, and thus into areas where the urban heat island effect is more likely. Similarly, much of our infrastructure—roads, rail, and medical facilities—is concentrated in inner city areas, where a disruption to this infrastructure can affect a large number of people. This was shown by the breakdown of the electricity grid and metropolitan railway system in Melbourne during the 2009 heatwave (see section 2.2 below), when many areas in Melbourne were left without electricity, and thousands of commuters were stranded on the way home from work in the CBD (McEvoy et al. 2012). For most people this would have caused no more than inconvenience. But for those needing medical help it would have been much more serious—an example of the indirect effects heatwaves have on health.

Extreme and prolonged heat can directly affect our health by causing heat stress and, under very severe conditions, even death. Our bodies operate at a core temperature of 37°C and must maintain that temperature within a very narrow range (Parsons 2003; Hanna et al. 2011). As we produce heat during our daily activities (especially if we exert ourselves), we need to release that heat to the air around us to maintain a steady core body temperature. We do this by direct transfer to air when the air around our bodies is at a temperature below 37°C or by sweating, which is a type of evaporative cooling. At very high temperatures—around 37°C or higher—

this cooling can become difficult, especially if humidity is high, and core body temperature can rise.

If core body temperature rises to 38°C for several hours, heat exhaustion occurs, and mental and physical capacity becomes impaired (Parsons 2003; Berry et al. 2010). If core temperature goes above 42°C, even for just a few hours, heat stroke and death can result (Parsons 2003) (see Figure 9).

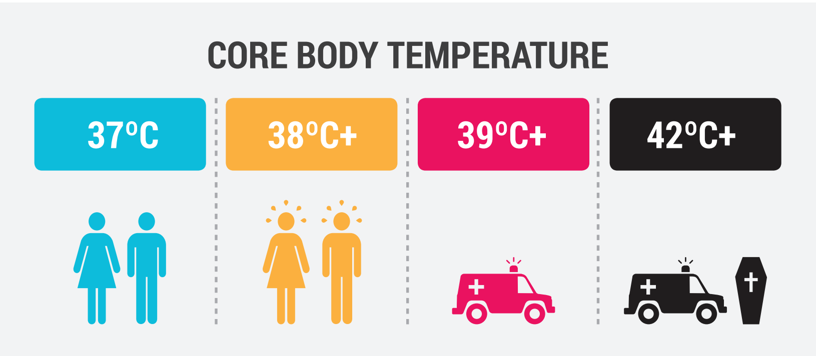


Figure 9: Temperature effects on the human body. Source: Climate Commission 2011

People living in dense urban environments, the very old and the very young, those with pre-existing medical conditions and heat-exposed workers are the most vulnerable when the temperature soars. Even so, most people can survive one extremely hot day. However, heatwaves lasting even a few days, especially if coupled with high nighttime temperatures (e.g. upper 20s or low 30s °C), can cause serious health impacts. The warm nights are particularly important because our bodies don't get the chance to recover (Banwell et al. 2012). It is the cumulative effects over a few days of an intense heatwave that lead to serious health impacts and deaths—and we tend to see these after the worst of the heatwave has passed.

The heatwave in Melbourne in late January 2009 exemplifies such conditions. On 27 January the maximum temperature rose to 36.4°C from a high of 25.5°C the previous day. The maximum temperatures during the next three days were 43.4°C, 44.3°C and 45.1°C, before dropping to 30.5°C on 31 January. Nighttime minimum temperatures were also very much above average. There were 374 excess deaths recorded during this period. The death rate peaked on 30 and 31 January, towards the end of the heatwave, lagging behind the extreme temperatures by a few days (DHS 2009; Figure 10).

Similar impacts have been observed in other parts of Australia. Deaths in Brisbane increased by 23% during the 7–26 February 2004 period (especially during the 21–22 February weekend), when the temperature increased from 26°C to 42°C (Tong et al. 2010). From 1993 to 2006, Adelaide recorded a 7% increase in total hospital admissions during periods of heatwaves compared with non-heatwave periods and the number of people requiring ambulance transport increased 4% during heatwaves (Nitschke et al. 2007). During the heatwave of January 1994, Sydney recorded 110 excess heat-related deaths (Gosling et al. 2007). Mortality during heatwave events also occurs in other countries (Figure 11).

There have been newspaper reports of the health impacts of the January 2014 heatwave in Victoria—203 heat-related deaths, a 20-fold increase in ambulance call-outs, a four-fold increase in calls to nurses-on-call, and a four-fold increase to locum doctors (The Age, 23 January 2014)—but these figures will need to be verified by more thorough, peer-reviewed analyses.

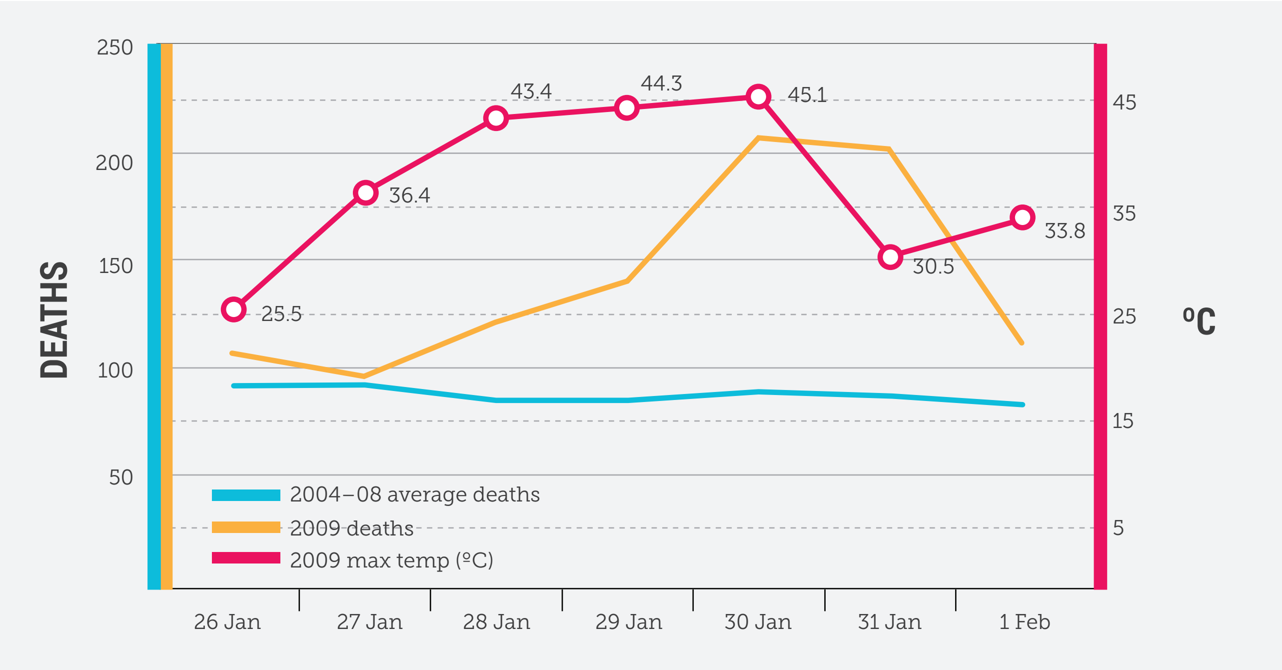


Figure 10: Mortality and temperature during the 2009 Melbourne heatwave. This graph shows the relationship between prolonged periods of higher temperature and death rates over the same period. Source: Climate Commission 2013c, modified from DHS 2009

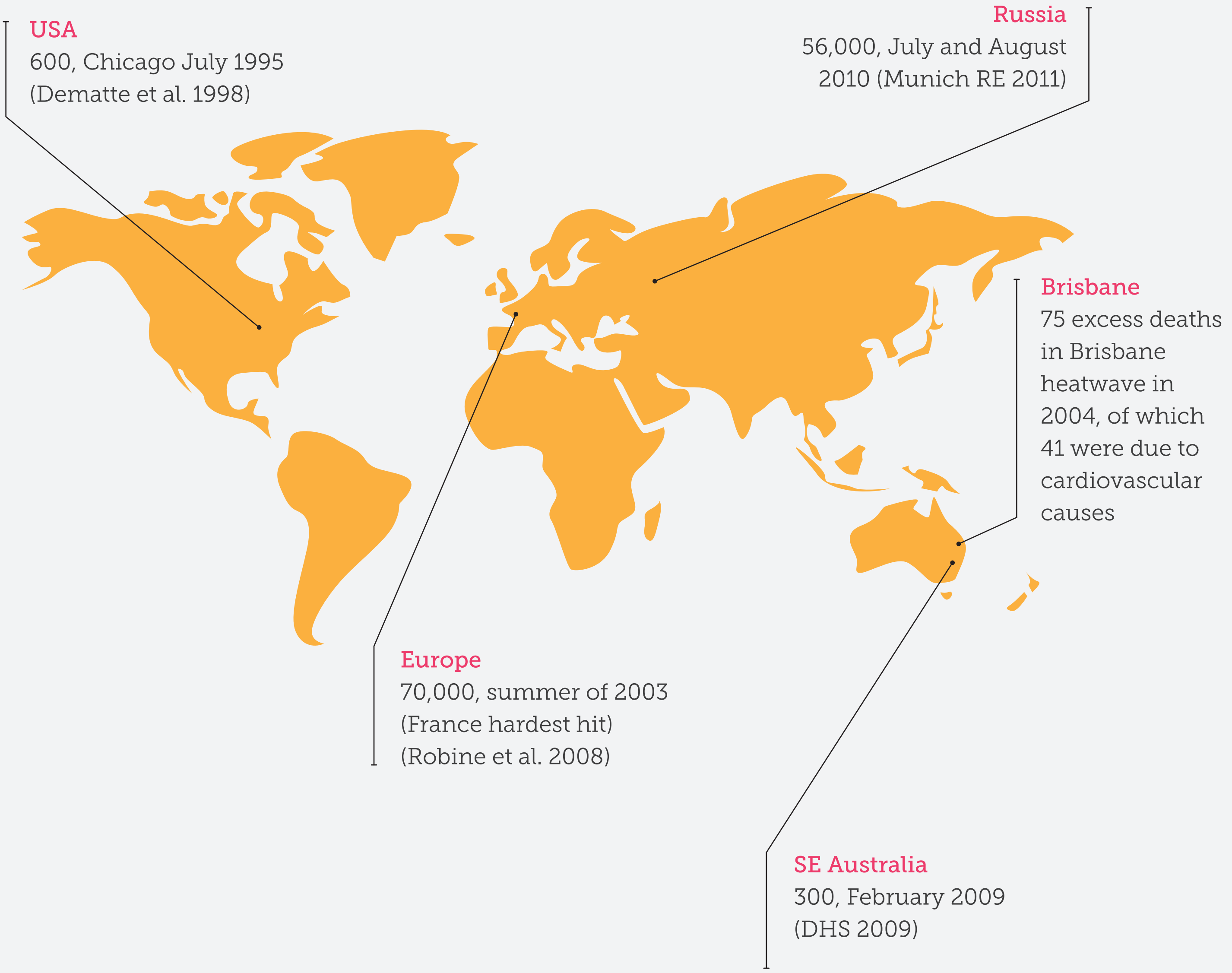
With Australia's population growing and ageing, the proportion and absolute number of older adults is rising. Projections indicate that by 2031 almost one in four Australians will be aged over 65 (Booth and Tickle 2003). These Australians are particularly vulnerable to the effects of heatwaves (van Iersel and Bi 2009), partly because general physical frailty increases with advancing age, as does the incidence of falls, illnesses and disease. In these circumstances, people's ability to do the things they need to do to keep their bodies cool diminishes, for example drinking, and remembering to drink, enough. Dehydration is an important cause of heat-related deaths among older adults (Rikkert et al. 2009).

"Older people who live in big cities that are not prepared for heatwaves or in areas with clear "heat island" effects... have the highest risk of heat-related morbidity."

Rikkert et al. 2009

Figure 11: Global mortality during recent heatwave events.

Impacts (mortality) of recent heatwaves



Despite heat being felt more intensely in urban areas compared to the surrounding countryside, older adults are also at risk of extreme heat in regional Australia, where community and medical services are less accessible. Poor access to services is largely responsible for the relatively poorer health of rural Australians compared to city-dwellers (Smith et al. 2008) and older adults face more challenges than most in reaching services. Older Australians, who rely entirely on income support, particularly where they do not own their own homes, typically live under financial hardship. This means they are likely to struggle to cope with the economic burden associated with hot days and heatwaves, for example, larger electricity bills for air conditioning (if they have it), with consequent risks for their health (Luber and McGeehin 2008).

In any single year, one in five Australians suffer from some type of mental disorder and these illnesses account for by far the largest proportion of Australia's burden of disease (Slade 2009). Because these illnesses are so common and so disabling, mental health is a National Health Priority Area. People experiencing mental health problems are sometimes at increased risk during heatwaves. Nitschke et al. (2007) found that during heatwaves in Adelaide, hospital admissions due to mental health problems increased by 7%. A similar study conducted in Adelaide from 1993 to 2006 found that, once the air temperature climbed above 26.7°C, hospital admission numbers due to mental health and behavioral disorders rose (Hansen et al. 2008). There was an almost 10% increase in admissions due to mood (affective) anxiety, stress-related and somatoform disorders (disorders characterized by symptoms that suggest physical illness or injury), and an increase of around 17% in admissions among people with dementia. A study of heatwaves in New South Wales also found that people with an underlying mental health problem were more vulnerable to extreme heat (Khalaj et al. 2010).

2.1 Human health: *Indirect impacts*

There are a number of indirect effects that extreme heat has on our health. People with pre-existing medical conditions such as cardiac, respiratory or renal disease (also more common in the elderly) are particularly vulnerable.

For example, hospital admissions in Adelaide for acute renal failure and kidney disease rose during heatwave compared to non-heatwave periods (Nitschke et al. 2007; Hansen et al. 2008; Khalaj et al. 2010). The relative increase in kidney-related effects was greater than for any other effect, and was particularly large in middle-aged adults. Hospital admissions for ischemic heart disease among people aged 65–74 also increased during heatwaves (Nitschke et al. 2007). Over the period 1999–2004, hospital admissions in Melbourne for heart attacks rose by 10% on days over 30°C and by 40% during heatwaves (Loughnan et al. 2010).

Heatwaves can also affect health because they can interfere with electricity distribution leading to mass impacts, such as on public transport or hospital air conditioning (see section 2.2 on infrastructure). Extreme heat can lead to power outages, which in turn can lead to a loss of air-conditioning. This removes one major coping strategy for heatwaves, and greatly increases the risks of health impacts for the most vulnerable population groups.

Power outages can also lead to a loss of refrigeration and cooling, affecting homes and food outlets. Cool temperatures slow or prevent the growth of potentially harmful bacteria in food. If cooling systems fail, outbreaks of gastrointestinal infections can occur. Within two hours, many bacterial pathogens can grow to numbers sufficient to cause gastrointestinal illness in food chilled to 5°C, and some can produce harmful poisons that, when ingested, can cause serious illness (Marx et al. 2006).

The consequences of power outages for health were shown by a non-heatwave-related incident in Japan. In 2000, the country suffered its worst case of food poisoning after the operations of a milk products manufacturer were interrupted by a power outage (Wrigley et al. 2006). During the power outage untreated milk was left on a production line for three hours, long enough for the bacterium *Staphylococcus aureus* to proliferate. The derived milk products were contaminated with a bacterial toxin and led to around 13,000 cases of food poisoning (Wrigley et al. 2006).

The impacts of extreme heat and power outages on perishable food can have flow-on effects, for example, on pest control (Beatty et al. 2006). In the northeast US, in August 2003, the intense heat and increased demand on electricity transmission systems led to widespread power outages in New York City that affected around nine million people (White et al. 2003). Large populations were without electricity for periods from a few hours to over two days (Marx et al. 2006). A study that also investigated the 2003 New York Blackout concluded that there was a likely link between people reporting diarrheal symptoms and the consumption of spoilt meat or fish after the power outage (Marx et al. 2006).

2.1 Human health: *Workplace safety and productivity*

Increased mortality and use of health services are the most reported impacts of extreme heat on human health (Kjellstrom and McMichael 2013), but the effect of extreme heat in slowing down daily activities and in reducing work productivity may be of significant economic importance (Kjellstrom et al. 2009a).

Extreme heat can pose serious health risks for outdoor workers and for those working in enclosed indoor spaces without adequate ventilation. Under extreme conditions, heat stress or even death can occur (Kjellstrom et al. 2011; Kjellstrom et al. 2013). Those most at risk include construction workers, farmers, emergency and essential service workers, and those working outside in the mining industry (Singh et al. 2013). Risks increase for those whose work is "externally paced" by machine speed or because they are paid per unit output (Hanna et al. 2011).

As noted above, during physical exertion in periods of extreme heat, the body can have difficulty removing the heat generated and core body temperature can rise to dangerous levels (Parsons 2003), leading to heat stress or death. Extreme heat can also lead to mental health problems in workers, such as aggression, confusion, psychological distress and other behavioural changes (Berry et al. 2010; Tawatsupa et al. 2010) that affect workers and their productivity.

One measure of the risk to workers of extreme heat is the "dangerous day" concept. A dangerous day occurs when sweating cannot cool the body and core body temperature rises by 2.5°C over less than two hours (Maloney and Forbes

> "The reduction in work ability can be considered a form of "disability" that should be taken into account when assessing the "burden of disease or ill health" caused by global warming."

Kjellstrom 2000

2011). Applying this measure to Perth for those workers accustomed to working in hot climates, the number of dangerous days is projected to rise from the current value of one per year to as much as 21 days per year by 2070, depending on the emissions scenario used (Maloney and Forbes 2011). Spatial and temporal analysis of heat stress can be a useful tool for analysing such impacts (Hyatt et al. 2010). This type of analysis uses the Wet Bulb Globe Temperature (WBGT) index, which is a composite meteorological indicator derived from temperature, humidity, direct and diffuse heat radiation, and wind speed and thus can be estimated from weather station data (Lemke and Kjellstrom 2012; Kjellstrom et al. 2009a).

turn delays vessels and disrupts shipping schedules. Labour costs, of course, are significantly increased in such conditions (QUT 2010).

Reduced labor productivity from future heatwaves will not only be costly, but will force changes in the workplace. Measures such as introducing air-conditioning to workplaces to enhance worker productivity may be costly and unreliable. Similarly, workers may need to take more frequent breaks, or work at a slower pace (Kjellstrom et al. 2009a). As a result, to maintain current productivity levels, it will be necessary to either engage greater numbers of workers or to increase working hours for existing workers. Changing working hours to

"Global climate change…may impair health and productivity for millions of working people."

Kjellstrom et al. 2009b

The impacts of extreme heat on worker wellbeing and productivity can also be measured in economic terms (Kjellstrom and McMichael 2013), the underlying cause being a general slowing down of work or the complete stopping of work on very hot days. For example, Fisk (2000) estimated the cost of suboptimal workplace temperatures in the US to be in the billions of dollars. In Australia, workers at the Port of Melbourne are permitted to stop work when the temperature reaches 38°C. During an extended heatwave, this slows the loading and unloading process, which in

night shifts to avoid the heat of the day is also a common, but costly, response, as in the case of the Melbourne 2009 heatwave during which railway repair workers were sent in at night to cool the buckled railways, incurring extra maintenance costs (McEvoy et al. 2012).

The combination of more extreme heat and an increase in absolute humidity is expected to place severe limitations on human activity in tropical and mid-latitude regions, including Northern Australia, during peak months of heat stress. Dunne et al. (2013) estimated that

Figure 12: Temperatures soared during the heatwave in Melbourne in January 2014 and the Australian Open tennis tournament was suspended on 16 January due to increased risk of heat stress for players.

environmental heat stress has already reduced labour capacity by 10% over the past few decades. They project a further 10% reduction during the hottest months by 2050. Under the warmest projections, they project a 60% reduction in labour capacity (compared to 2010) by the end of the century with most tropical and mid-latitude regions experiencing extreme climatological heat stress. Under a high emissions scenario, projections indicate that those countries most affected by declining labor productivity could see GDP fall by up to 20% by 2080 (Kjellstrom et al. 2009b).

Sport is also feeling the heat. During the 2014 Australian Open tennis tournament, play was suspended for the afternoon of 16 January after the temperature exceeded 43°C and the WBGT index exceeded regulation limits (Figure 12). Aside from the general effects of heat stress, playing tennis in extreme heat can also cause muscle twitches, cramps, and painful spasms due to the loss of large amounts of electrolytes through sweating (Bergeron 2003). While players sweltered in extreme temperatures, off-court ambulances treated almost 1000 tennis fans in the first few days of the tournament for heat exhaustion (SMH 16 January 2014).

2.2 Infrastructure

Extreme heat can have significant impacts on infrastructure and essential services, especially electricity transmission and transport systems. Financial losses from the 2009 heatwave in southeast Australia, for example, have been estimated at $800 million, mainly due to power outages and disruptions to the transport system (Chhetri et al. 2012).

Heatwaves place electricity generation and transmission systems under considerable stress, greatly testing their ability to withstand the pressures of increased energy demand (predominately from use of air conditioners). Insulator capacity is reduced, and in coal-fired power stations water kept for cooling the steam turbines warms and is consequently less effective (McEvoy et al. 2012). Electricity transmission is also affected, and transmission lines may become so hot that they expand and can hang dangerously low. If this occurs, the electricity flow is decreased to allow the transmission line to cool, and contract. Ceramic insulators on power lines that are affected by smoke, moisture, or ash from heatwave-associated bushfires, become less effective and lines affected may have their electricity supply stopped (McEvoy et al. 2012). Similarly, transformers—responsible for regulating electricity voltage and current—may also break down. Under these circumstances load shedding (or rolling blackouts) may be instituted. Blackouts further enhance the risk to vulnerable groups and can hinder emergency services.

Increased demand for electricity during the 2009 heatwave in Victoria broke previous records by approximately 7% (QUT 2010). During this heatwave the Basslink electricity cable between Tasmania and Victoria reached maximum operating temperature and was automatically shut down for safety reasons (QUT 2010). This shutdown, combined with faults at a number of transformers, caused widespread blackouts across Melbourne; on the evening of 30 January 2009, an estimated 500,000 residents were without power (QUT, 2010). In January 2014, Victorian electricity consumption topped 10,300 megawatts (MW), with the highest level of electricity use occurring during the heatwave. Installation of 3 GW of solar power in Australia has assisted with meeting the demand—according to the Australian Renewable Energy Agency, solar PV contributed more than 11% of South Australia's power needs on some of the hottest days in the January 2014 event (SMH 18 January 2014).

The 2009 heatwave saw Melbourne's train and tram networks suffering widespread failures caused by faults to air conditioning systems and the buckling of tracks (QUT 2010; Figure 13). The January 2014 heatwave also disrupted some public transport services in Melbourne, with trains operating 10 km per hour slower than normal as a precaution during this event, with flow-on disruptions to rail services (Mullett and McEvoy 2014). Heatwaves can also cause "bleeding" of bitumen on roads and traffic signal failure (QUT 2010).

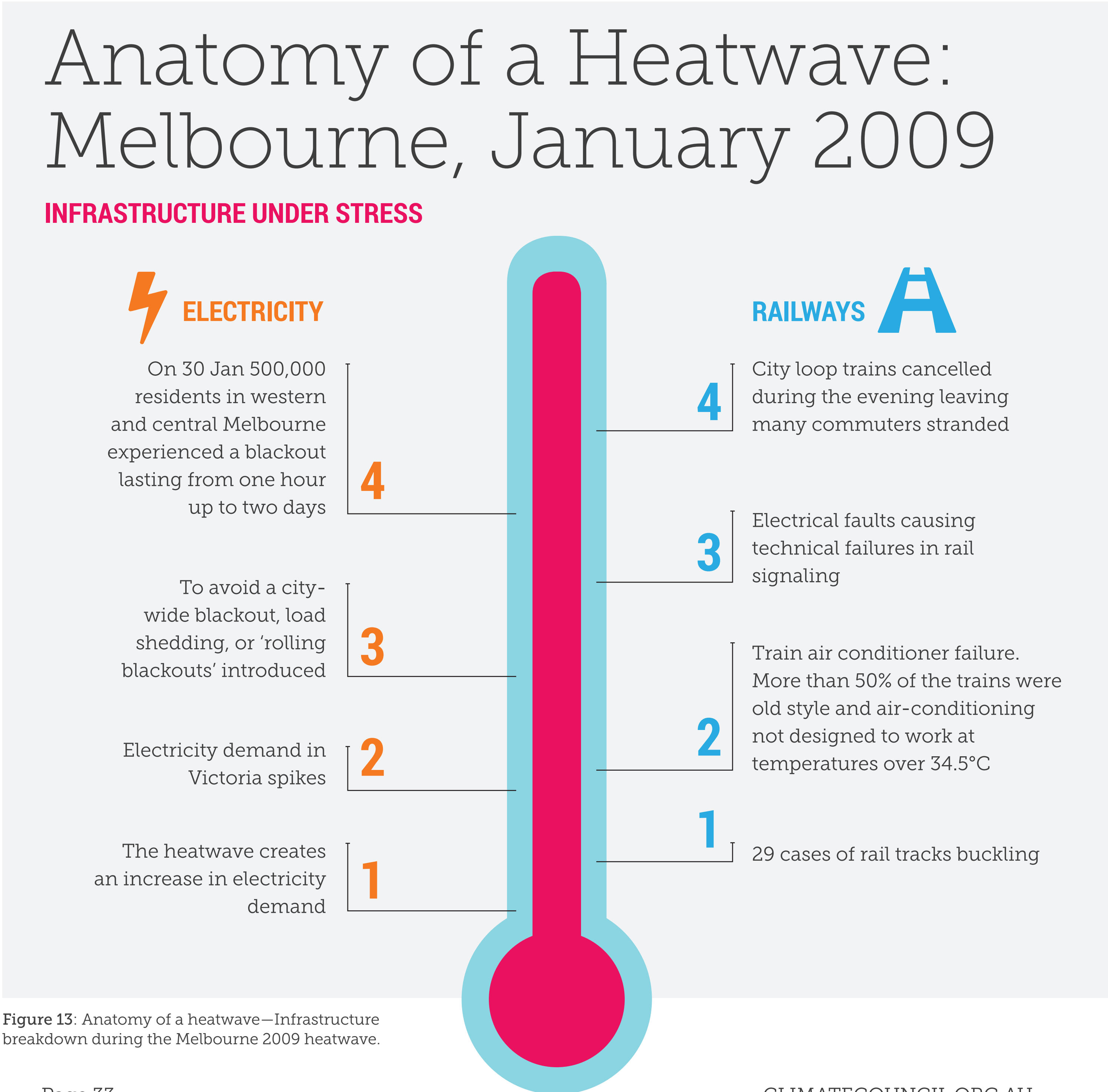


Figure 13: Anatomy of a heatwave—Infrastructure breakdown during the Melbourne 2009 heatwave.

2.3 Agriculture

Despite the complexity of global food supply, there are well-established linkages between growing season temperatures, precipitation and crop performance. Global studies such as those by Lobell and Field (2007) show that 30% or more of year-to-year variations in global average yields for the world's six most widely grown crops can be linked back to these two variables.

For wheat, maize and barley, there is a clear negative response of global yields to increased temperatures. Based on these sensitivities and observed climate trends, the study estimates that the warming since 1981 has resulted in annual combined losses of these three crops of approximately 40 Mt or $5 billion per year, as of 2002.

Heatwaves can have significant impacts on agricultural crops and livestock. High temperatures over several days can reduce the crop yield substantially, through both direct and indirect effects. The direct effect is through damage to the crop's reproductive parts, responsible for producing grain, and thus reducing productive potential. Indirectly, extreme temperatures increase plant water stress, which if not addressed will result in cessation of photosynthesis and possibly death (Schlenker and Roberts 2009).

Extreme heat can also affect yield and quality of crops (van der Velde et al. 2012). The 2009 heatwave in southeast Australia, in conjunction with a shortage of irrigation water, caused significant heat-stress related crop losses in many vineyards (Webb et al. 2010). For example, wine grape production in 2008–09 is estimated to have been 1.7 million tonnes, around 7% (119,000 tonnes) lower than the 2007–08 harvest (Gunning-Trant 2010).

High temperatures, especially when combined with high humidity and low air movement, can exceed the ability of livestock to cope, resulting in a loss of appetite, productivity, reproductive vigor and sometimes death (Lefcourt and Adams 1996). Provision of shade can reduce heat stress, but not completely eliminate risk, especially in feedlots where cattle are crowded (Gaughan et al. 2010). Dairy cattle are particularly susceptible to heat stress, which can reduce appetite, milk production and milk quality (QFF 2008; DEEDI 2010).

Projected increases in heatwaves could result in changes in the types of animals and genotypes that are used, changes in facilities and housing utilized for care and management of livestock, and eventually a potential redistribution of livestock and livestock species in a region (Henry et al. 2012).

There have been relatively few economic estimates of agricultural losses due to heat waves. Losses in the 2003 European severe heat event, during which there were dramatic reductions in maize and wheat production, were estimated at € 4 billion (COPA COGECA 2003; van der Velde et al. 2012). A heatwave in July 2006 was the second most costly event ($492 million insured losses) for Californian agriculture in the period 1993–2007, the event being especially damaging for livestock (Lobell et al. 2011). Crop and livestock losses arising from the 2011 heatwave in Texas were estimated at $5.2 billion (Raloff 2012).

2.4 Natural 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).

The January 2009 heatwave, when air temperatures were above 45°C for several consecutive days, caused the deaths of thousands of birds, mostly zebra finches and budgerigars, in Western Australia (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. 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 (Figure 14). 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. 2008). 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 are also at risk during extended periods of hot weather. The green ringtail possum (Figure 15), 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).

Marine organisms are also affected by the impacts of severe heat. Heatwaves can occur in the surface waters of the ocean, sometimes leading to dramatic impacts on 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 16).

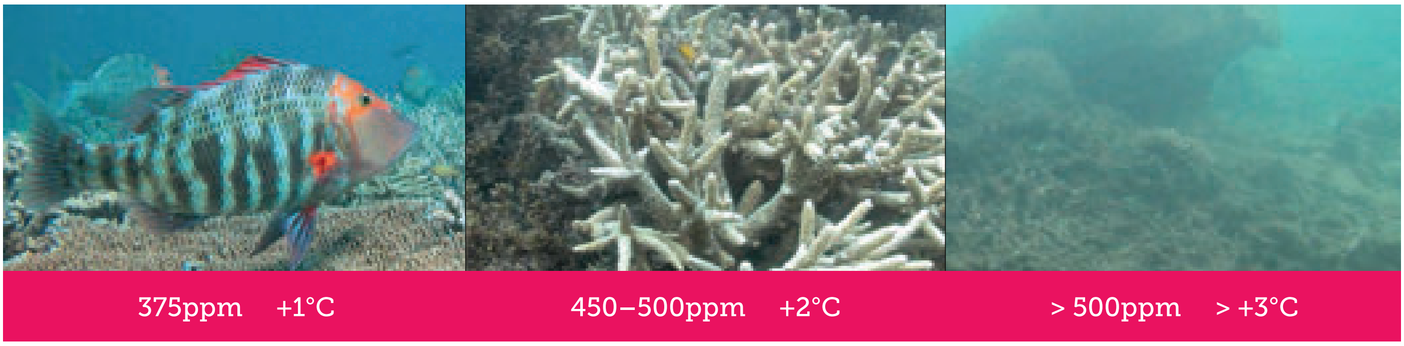
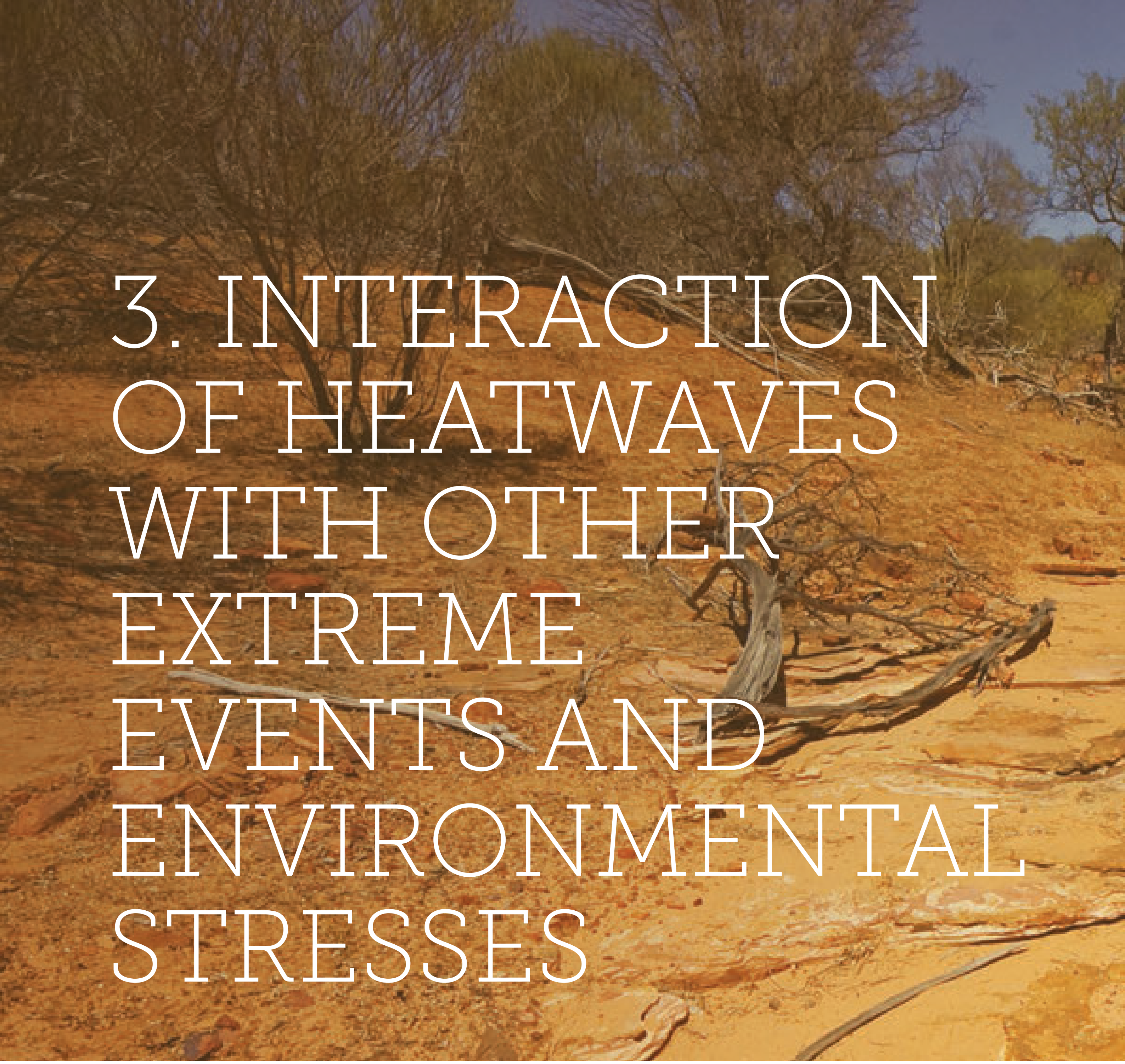


Figure 14: Flying foxes are particularly vulnerable to heatwaves. Since 1994, more than 30,000 flying foxes have died in heatwaves at sites along the east coast of Australia.

Figure 15: The green ringtail possum is unable to control its body temperature when exposed to temperatures above 30°C for long periods, making it at risk during heatwaves.

Figure 16: Anticipated reef states under varying carbon dioxide concentrations.

Bleaching events on the Great Barrier Reef have occurred repeatedly since the late 1970s, and none were observed before the 1970s. Bleaching events have contributed to the decline in coral cover observed from 1985 to 2002 (De'ath et al. 2012). The 2011 marine heat wave in Western Australia caused the first-ever reported bleaching at Ningaloo Reef (Wernberg et al. 2012), with temperatures peaking at 28.7°C off the Houtman Abrolhos Islands, 5°C above the long-term average (Smale and Wernberg 2012). 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 or major bleaching events, that ecosystems may never return to their original state. Mass mortality of the habitat-forming seaweed Scytothelia dorycarpa off the coast of Western Australia in 2011, for example, was followed by a rapid increase in turf-forming algae and declines in cover of sponges and encrusting algae, resulting in a substantial change in the nature of the marine community in the region (Smale and Wernberg 2013).



3. INTERACTION OF HEATWAVES WITH OTHER EXTREME EVENTS AND ENVIRONMENTAL STRESSES

In addition to the direct impacts caused by heatwaves, intense heat often interacts with other stressors to increase the risks for human health, infrastructure, agriculture and ecosystems. Three of the most important interactions are those associated with the combination of heat and drought, the role that heat plays in the risk of bushfires, and the interaction of ocean heatwaves with ocean acidification and other marine stresses. The contribution of human-driven climate change to the increase in hot days and heatwaves is increasing many risks through these interactive effects as well as through the direct effects described earlier.

3.1 Droughts

Drought and heat are interrelated. Drought can exacerbate hot conditions, while hot conditions can exacerbate drought.

In moisture-limited regions, when soil moisture is reduced (i.e. the Earth's surface is dry), the air temperature rises, and this can result in longer and more intense heatwaves (Seneviratne et al. 2010; Mueller and Seneviratne 2012). In fact, in these regions, the level of soil moisture can determine whether an embryonic heatwave grows and intensifies, or whether it collapses. If there is enough water remaining in the soil, cooling associated with its evaporation could slow or dampen the severity of an oncoming heatwave, preventing the occurrence of very extreme heatwaves (Hirschi et al. 2010). If soil moisture is too low, there is no buffering capacity and extreme temperatures can be exacerbated. This effect can even occur in moister climates if the heatwave is preceded by a severe and prolonged dry period that significantly reduces the water content of normally moist soils.

This phenomenon has been observed in heatwaves over the United States (Durre et al. 2009; Hoerling et al. 2013), Europe (Fischer et al. 2007; Hirschi et al. 2010) and Australia (Mueller and Seneviratne 2012). Linkages between drought conditions and extreme heatwaves are also reported for some specific regions, with drought conditions increasing the intensity of the 2003 European and 2009 southeast Australian heatwaves (BoM 2009; Nicholls and Larsen 2011).

On the other hand, extended periods of heat can increase evaporation rates, leading to increased loss of soil moisture and an intensification of droughts. Thus, when droughts occur, the long-term increase in heat in the atmosphere from increasing greenhouse gas concentrations can further intensify the heat that usually co-occurs with drought—one reinforces the other as conditions become hotter and drier. This effect is important for southern Australia, where droughts are projected to occur more frequently with the ongoing increase in greenhouse gas emissions (Hennessey et al. 2008; Kirono et al. 2011).

3.2 Bushfires

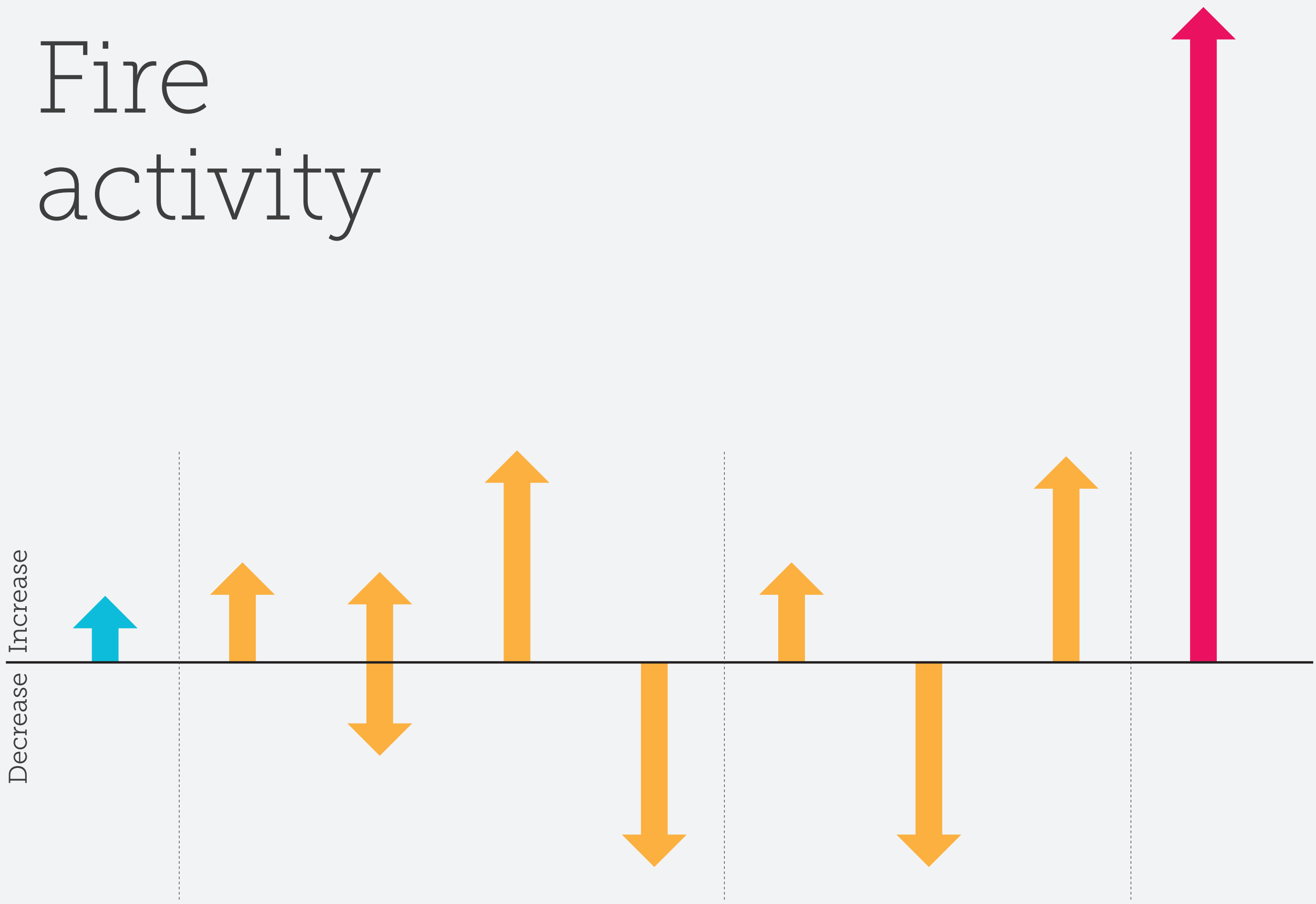
The most direct link between bushfire activity and climate change is the increasing trend in hot days and heatwaves. More hot weather has led to increases in the Forest Fire Danger Index (FFDI), an indicator of extreme fire weather, measured at 16 of 38 weather stations across Australia over the 1973–2010 period; none of the stations recorded a significant decrease (Clarke et al. 2012).

Most of the stations showing an increase are located in the populous regions of southwest and southeast Australia (Figure 17). The effect of extreme heat (see section 1.1 above) was an important factor in the 2009 Black Saturday bushfires in Victoria, with the FFDI ranging from 120 to 190, the highest values ever recorded (Karoly 2009). Increased temperatures can also increase the incidence of lightning, causing more ignitions (Price and Rind 1994). With the projected increase in hot weather and heatwaves, high fire risk weather is also likely to increase further in Australia in future decades (Lucas et al. 2007; Climate Council of Australia 2013).

Heat can also affect bushfires via its impact on fuel availability, but in quite complex ways (Figure 18; Climate Council of Australia 2013). High temperatures and heatwaves in the weeks and months prior to a bushfire can dry out fuel and make it more prone to ignition. However, periods of extreme temperatures can also stunt vegetation growth and thus reduce the amount of fuel available. More moderate temperatures can stimulate growth in temperature-limited ecosystems, such as the high altitude mountain ash forests in the southeast, thus increasing the fuel load.

Overall, increasing heatwaves are likely contributing to greater bushfire activity. Around the world, regions with increasing numbers of heatwave days are also experiencing more bushfire activity. Alaska, Canada, western USA, Spain, Russia and southeast Australia all show increased bushfire activity and have also recorded increases in the number of heatwave days.

Figure 17: Fire fighters protecting property in southern Western Australia in 2011. In addition to the obvious dangers that the bushfires themselves pose, fire fighters are also subject to the impacts on their health and productivity of the extreme heat that often accompanies bushfires (Budd 2001).



Ignitions	Fuel Load				Fuel Condition			Weather
Increased incidence of lightning as climate warms	Increased atmos-pheric CO_2	Increased temperature (either increases or decreases vegetation productivity)	Increased rainfall (impacts on fuel load and fuel condition)	Decreased rainfall (impacts on fuel load and fuel condition)	Increased temperature	Increased rainfall	Decreased rainfall	Temperature increase, more extreme hot days

Figure 18: Potential impacts of atmospheric and climatic change on factors that affect fire. Increased temperatures may increase the incidence of lightning and thus increase the probability of ignitions. Increased temperatures may either increase or decrease vegetation productivity, and thus fuel availability, depending on the region. Changes in rainfall may also have complex impacts via changes in fuel load and fuel condition. Increasing atmospheric CO2 concentration may also increase the fuel load through enhancement of vegetation growth. Increases in extreme hot days will increase the probability that fires, once started, will spread and become more intense. Source: Climate Council of Australia 2013

3.3 Multiple interacting stresses on coral reefs

Ocean heatwaves are a well-known cause of bleaching in corals (section 2.4 above). If there is enough time between extreme heat events, coral reefs can recover.

However, as extreme temperature events become more frequent due to the accumulation of extra heat in the lower atmosphere and upper ocean, the composition and structure of coral reefs may be irreversibly changed. Degree Heating Week (DHW) is a measure of this accumulation of stress; it is defined as the sum of weekly sea-surface temperature (SST) anomalies above the thermal stress threshold accumulated over 12 weeks (Donner 2009). DHW values above eight mean that the risk of bleaching is considered severe. If severe bleaching events occur more often than once every five years, the viability of coral reef ecosystems becomes threatened.

Heatwaves also interact with a wide range of climate and non-climate stressors to threaten the health of coral reef ecosystems (See In Detail 2).

IN DETAIL 2

Multiple interacting stresses on coral reefs

The risk to coral reef ecosystems from ocean heatwaves is increased by the interactions among a number of stressors that simultaneously and synergistically affect the ability of coral reef ecosystems to cope.

Climate-related stressors include:

- Ocean acidity: Increasing dissolution of atmospheric CO_2 into the ocean increases the concentration of carbonic acid in seawater, which in turn reduces the concentration of carbonate ions (Friedrich et al. 2012). The hard shells of corals, and of many other marine organisms, are formed from calcium carbonate. Increasing ocean acidity reduces calcification rates, making it more difficult for corals to recover from other stressors (De'ath et al. 2009). If ocean acidity rises beyond a threshold level, seawater can actually become corrosive to corals.

- Sea-level rise: Coral reef ecosystems also include atolls, which are important nesting sites for many sea turtles. The sea-level rise that has already occurred, 19 cm over the period 1901–2010, and the additional 26–98 cm projected for the end of this century (IPCC 2013), are increasing the risk of inundation of important turtle nesting sites. A high rate of sea-level rise will also pose challenges for many species over corals to keep pace.

- Tropical cyclones: Most tropical cyclones along Australia's east coast cut across the Great Barrier Reef (GBR) in an east-west direction, and thus damage only a relatively small area of the reef. However, an intense, very large cyclone with a large north-south extent can cause extensive physical damage. This situation occurred in 2011 when severe tropical Cyclone Yasi crossed the central GBR. This storm was one of the largest, most intense tropical storms ever recorded in Queensland (Callaghan and Power 2011). Cyclone Yasi stretched for over 1000 km, produced waves over 9 m in height, and sustained wind speeds of over 200 km per hr, with some gusts reaching 285 km per hr (Lukoschek et al. 2013). The cyclone caused extensive damage, with impacts reported over an area of nearly 90,000 km^2 of the Great Barrier Reef Marine Park. An estimated 15% of the total reef area in the park suffered damage, with 6% severely affected (GBRMPA 2011).

In addition to climate-related stressors, there are a number of human-related stressors that also reduce the resilience of coral reefs:

- Sedimentation and eutrophication (algal blooms): Fluxes of sediments and nutrients from adjacent land areas, often from agricultural or mining activities, can damage coral reefs by sediment deposition on the surface of the reef, attenuation of light through the water column, eutrophication of coastal waters and stimulation of algal growth by excess nutrients. These effects, which can reduce the resilience of the reefs, make it more difficult for them to cope with climate-related stressors. Near-shore reefs are most affected by sedimentation and eutrophication.

- Fishing: Overfishing can reduce or remove large fish from reef ecosystems, with potential knock-on effects down the food web and consequent impacts on the structure and functioning of these ecosystems. For example, the combination of a reduction or loss of fish that graze on algae and an increase in nutrients in the water can lead to outbreaks of algae that can smother corals.

- Tourism: Large volumes of tourists can lead to stress on reefs through physical damage as well as impacts on small coral atolls, for example, on seabird breeding areas.

- Shipping: Spillages and shipping accidents can threaten the reef through release of massive amounts of pollutants. Also, the volume of shipping traffic through and near reefs can affect large marine mammals (e.g. whales) that use the same areas.

Many of the human-related stressors can, and are, being managed to improve the resilience of the reef. This is important for reducing the impact of ocean heatwaves when they occur, and will become increasingly important through this century as the GBR struggles to cope with escalating climate-related stressors. A good overall indicator of the integrated effects of these multiple, interacting stressors, is overall coral cover in the GBR. The trend is not encouraging. Despite some significant management improvements, the GBR has lost 50% of its coral cover in the last 30 years (De'arth et al. 2012). Underwater heatwaves have made a contribution to that trend, and are likely to make an increasing contribution in future.

The GBR has lost 50% of its coral cover in the last 30 years

De'ath et al. 2012

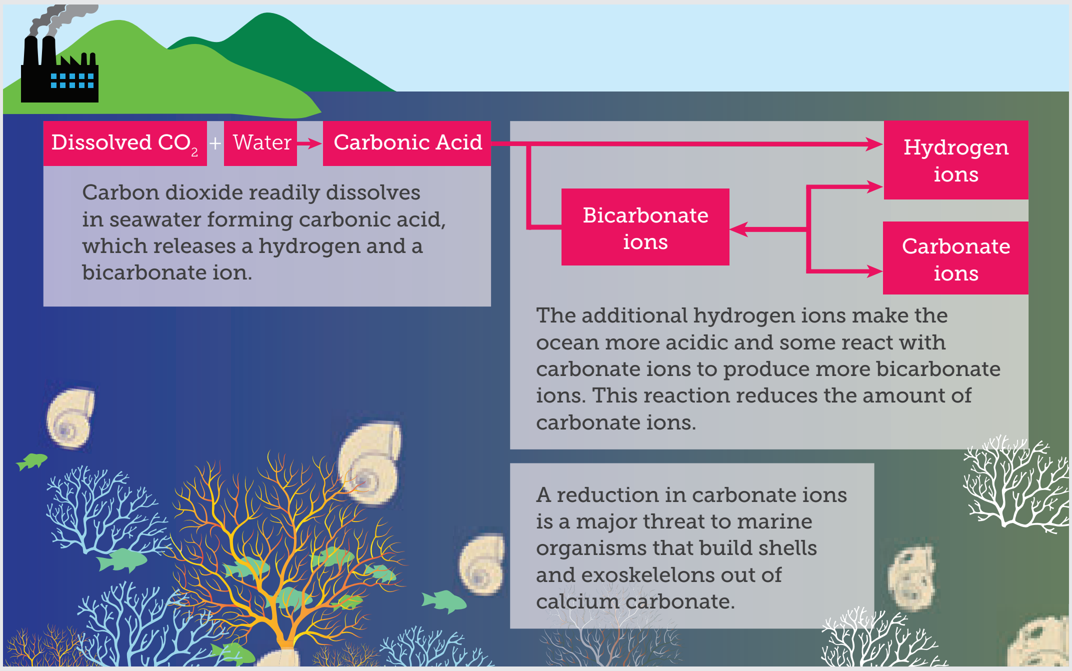


Figure 19: The chemistry of ocean acidification. Source: Climate Commission 2013b

4. HEATWAVES IN THE FUTURE

4.1 Projections for extreme heat globally

With greenhouse gas concentrations in the atmosphere continuing to rise, extreme hot weather will become even more severe.

The IPCC Special Report on Extremes (2012) and the IPCC Fifth Assessment Report (2013) projected that it is virtually certain (greater than 99% probability) that hot extremes will increase and cold extremes will decrease through the century compared to the current climate. It is also very likely (greater than 90% probability) that the length, frequency and/or intensity of heatwaves will increase over most land areas around the globe.

In many regions around the world the time between these very hot days will decrease significantly. By mid century (the 2046–2065 period in the figure) unusually hot days will occur every two-five years in many regions (IPCC 2012). The variation among the three emissions scenarios used in the analysis is not large for this time period, reflecting the fact that the momentum of the climate system means increasing hot weather is already locked in for the next several decades.

By the end of the century, the 2081–2100 period in the figure (see next page), the projections for the three emissions scenarios show more divergence, a reflection that human responses—our ability to reduce greenhouse gas emissions rapidly and deeply—will strongly influence the extent to which extreme hot weather will worsen towards the end of the century (section 4.4). Under a scenario of continuing high emissions—the track that we are currently on—the type of extreme hot weather we now regard as unusual will become a normal pattern in many regions, occurring every year or two.

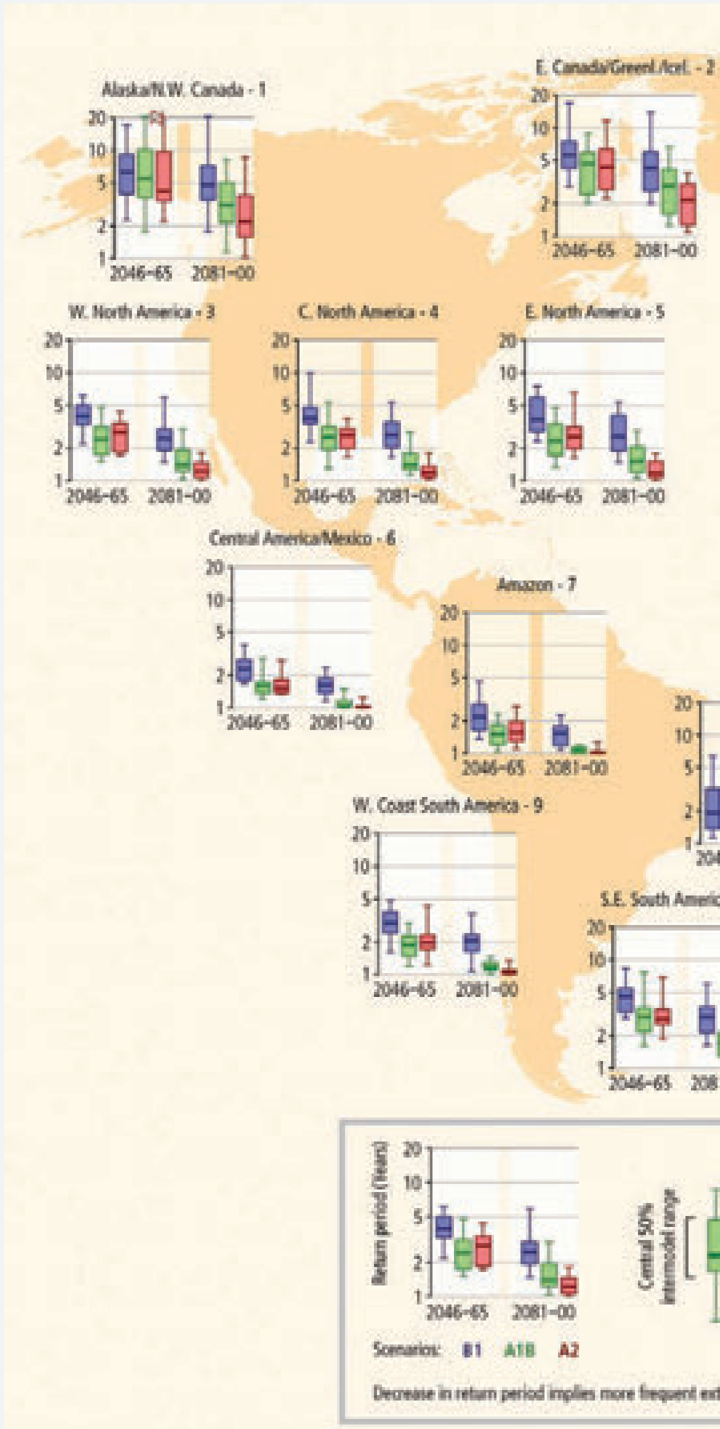
The type of extreme hot weather we now regard as unusual will become a normal pattern in many regions, occurring every year or two.

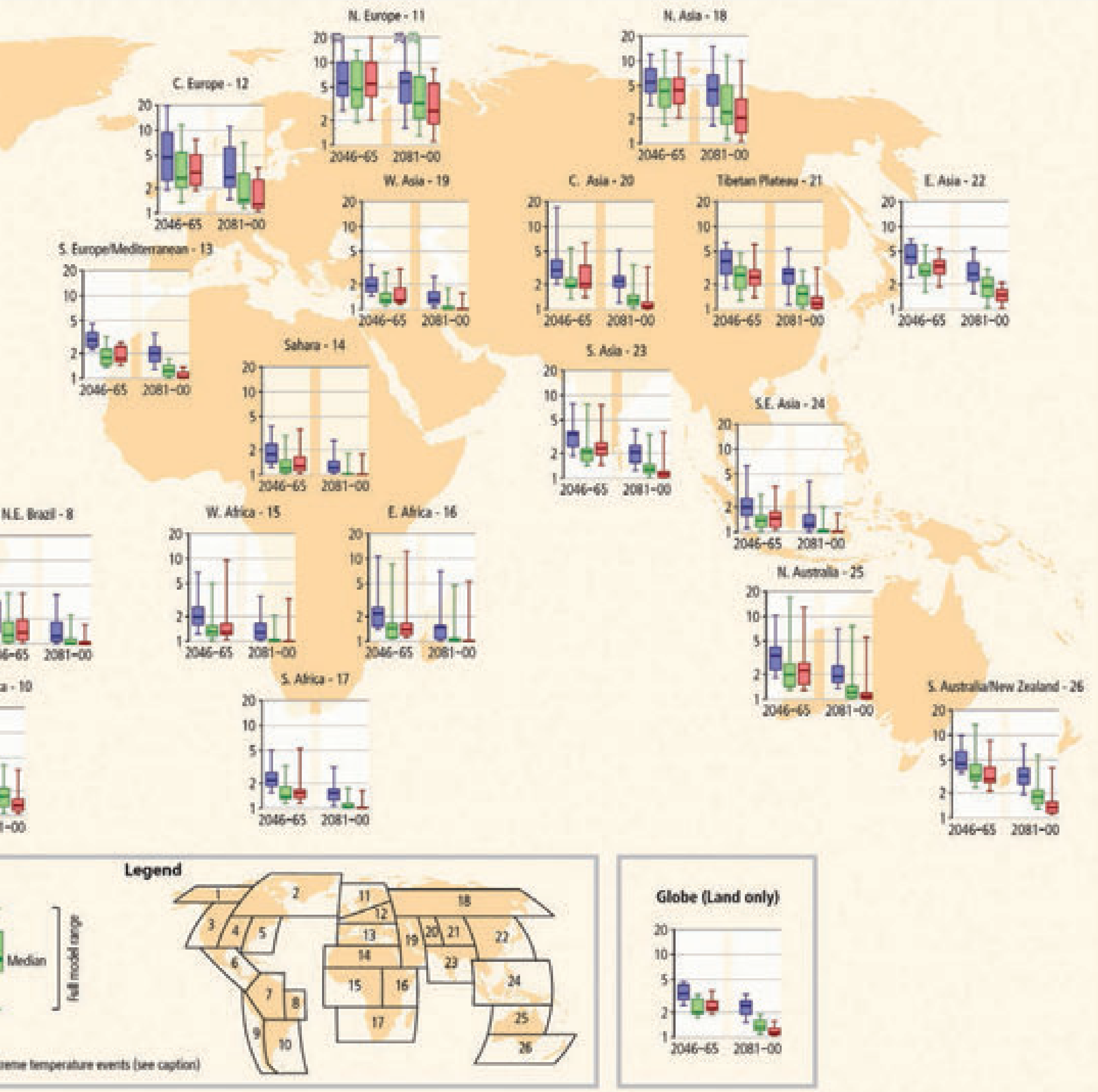
Figure 20 (see next page) shows the projected changes in hot weather through the rest of this century. Climate models consistently project more frequent hot days through the century, particularly towards its end. The projections are expressed as the time interval between "1-in-20 year" hot days, that is, hot days that occurred on average only once in 20 years in the climate of 1981–2000.

Projections for extreme heat globally

Extreme hot weather is projected to become more frequent throughout the century

Figure 20: Projected return periods for the maximum daily temperature that was exceeded on average once during a 20-year period in the late-20th-century (1981–2000). A decrease in return period implies more frequent extreme temperature events (i.e., less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late-20th-century, and for three different SRES emissions scenarios (B1, A1B, A2) (see legend). Results are based on 12 Global Climate Models (GCMs) contributing to the third phase of the Coupled Model Intercomparison Project (CMIP3). The level of agreement among the models is indicated by the size of the colored boxes (in which 50% of the model projections are contained), and the length of the whiskers (indicating the maximum and minimum projections from all models). See legend for defined extent of regions. Values are computed for land points only. The "Globe" inset box displays the values computed using all land grid points. Source: IPCC 2012




N. Europe - 11
C. Europe - 12
N. Asia - 18
W. Asia - 19
C. Asia - 20
Tibetan Plateau - 21
E. Asia - 22
S. Europe/Mediterranean - 13
Sahara - 14
S. Asia - 23
S.E. Asia - 24
N.E. Brazil - 8
W. Africa - 15
E. Africa - 16
N. Australia - 25
S. Africa - 17
S. Australia/New Zealand - 26
2046-65
2081-00
Legend
Median
full model range
Globe (Land only)

4.2 Projections of future hot weather for Australia

The projections for increasing hot days in Australia are consistent with the projected global trends (Figure 20). For both northern and southern Australia, 1-in-20 year extreme hot days are expected to occur every two–five years by the middle of the century (Figure 20; IPCC 2012).

By the end of the century, the frequency of extreme hot weather we experience will depend on our success in reducing global emissions of greenhouse gases in the next one or two decades. With deep emission cuts over that period, the projected frequency of today's unusually hot days (1-in-20 year events) will be stabilized at about one every two years for northern Australia and about one every three–four years for southern Australia (Figure 20, lowest emission scenario). However, if greenhouse gas emissions continue to rise through the rest of this century, today's unusually hot weather will become commonplace, occurring every summer across the country (Figure 20, highest emission scenario).

City	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 2: The long-term annual average number of hot days (above 35°C) compared to the 2000 – 2009 average and the projected average number for 2030 and 2070 for some Australian capital cities. Most cities have experienced an increase in the average number of hot days in the decade 2000–2009 compared to the long-term average, and are on track to reach the 2030 projections. Both 2030 and 2070 projections feature the median and, in brackets, the range of projections for the number of hot days based on the results from 23 climate models. The lowest number in the range is the 10th percentile and the highest number is the 90th percentile. 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

Increasing extreme heat can already be observed in many of Australia's capital cities, as measured by the annual number of hot days (over 35°C), and is expected to continue to increase further through this century, the amount of increase depending on whether or not we can stabilize the climate system (Table 2). For several of our capital cities—Adelaide, Melbourne and Canberra—the increase in hot weather that was observed in the 2000–2009 decade had already reached the level previously projected for 2030. The severe drought that affected these three cities during the 2000–2009 period is likely to have also contributed to the extreme heat observed during the period, as described in section 3.1.

The projections for the future demonstrate the importance of greenhouse gas emission reductions and stabilization of the climate this century. Only one set of projections is given for 2030, as the level of climate change that we experience then is already locked into the system and is thus largely independent of the emission scenario. Hence, adaptation to further increases in heatwaves is necessary. However, the number of hot days we experience towards the end of this century is strongly dependent on the emissions trajectory that actually occurs. A low emissions trajectory, implying deep and ongoing reductions in emissions, could stabilize the climate system this century so that the number of hot days projected for 2070 is not much greater than the number projected for 2030, and indeed for the number already observed in Melbourne, Adelaide and Canberra. However, continuing on the current high emissions trajectory would result in large increases in hot weather in all capital cities by 2070 compared to the current climate or to 2030 projections.

4.3 Implications of more severe heatwaves and hot weather

The prospect of increasing extreme heat events and heatwaves has important implications for our health and health services, our economy, our infrastructure and our environment.

With older adults forming an increasingly large proportion of Australia's growing population in future, population health policy, public health programs and emergency services will need to be sufficiently supported to keep pace. This challenges the capacity of our infrastructure, emergency services, and social planning systems (Luber and McGeehin 2008). Increasing peak electrical demand as people become more reliant on air conditioning will also increase household costs (Saman et al. 2013).

Without adaptation, it has been estimated that heatwaves could cause an additional 6214 deaths (or 402 deaths annually) by 2050 in Victoria alone (Keating and Handmer 2013). This translates to an additional $6.4 billion loss or $218 million per year (based on the CSIRO3.5 climate model, a 5% discount rate and 2011 $AUD) (Keating and Handmer 2013; see also Jones et al. 2013).

The impacts on work capacity, labour productivity and the local economy in places affected by heatwaves will be increasingly important (Kjellstrom et al. 2009a). The reduction of labour productivity globally due to heat is projected to be as large as USD one trillion by 2030 (Kjellstrom and McMichael 2013). Although Australians are better adapted than workers in many northern hemisphere temperate countries to deal with extreme heat, our economy will not be spared the impacts of heat on productivity. Considering that the number of full working days in a year is often estimated at 200, a loss of only four working days due to a heat wave means that 2% of the annual work time is lost. In terms of the consequences for the annual economic output, even small increases of heatwave days can cause significant losses.

Some government agencies and community services are increasing their efforts and resources to manage some of the risks associated with extreme heat. The Bureau of Meteorology, for example, has developed a pilot heatwave forecasting system (www.bom.gov.au/australia/heatwave). Following the 2009 heatwave, the Victorian government developed the Heat Health Alert System to notify local governments, hospitals and community services about conditions that could affect human health (see State of Victoria 2011), and Brisbane also provides heatwave emergency management guidance (www.emergency.qld.gov.au/emq/css/heatwave.asp).

It has been estimated that heatwaves could cause an additional 6214 deaths by 2050 in Victoria alone.

While some adaptation is occurring in human systems, there are barriers and limits to this adaptation (CSIRO 2011). Our biodiversity and natural environment face even more immense challenges. While human management to reduce the impact of other stresses may increase resilience, the rate of climatic change is generally considered to be occurring too quickly for many species to adapt "under their own steam" (Steffen et al. 2009). Loss of species will have flow-on effects to ecological communities and the services that ecosystems provide. Loss of the Great Barrier Reef due to bleaching from heat stress, for example, has been estimated to cost over $37 billion, with more than 50% of tourists who would normally visit the Reef staying away from Queensland if beaching was permanent (Oxford Economics 2009). More importantly, many forms of life, such as coral reefs, ultimately face threats to their very survival.

4.4 This is the critical decade

The choices we make over this decade will largely determine the severity of the extreme heat that our children and grandchildren will experience.

As numerous model projections have made clear, we are already committed to an increasing frequency and intensity of heatwaves over the coming decades owing to the inertia in the climate system. Many other extreme events are expected to become more frequent and more severe in the future (IPCC 2012), with serious consequences for Australia (Climate Commission 2013c). The reason that many extreme events are worsening is well known—the increasing human emission of greenhouse gases (IPCC 2012, 2013).

We cannot wait to make greenhouse gas emission reductions later, when extreme events have already become unmanageable. That will be too late. The climate system is much like a battleship—it has too much momentum to change course quickly and so the ship's wheel must be turned well before the ship needs to complete its turn. To stabilize the climate in a state that humans, our societies and natural ecosystems can cope with, decisive, coherent and significant action is required now. The timing and magnitude of the emission reduction challenge are crystal clear.

Nearly all countries of the world have agreed to limit climate change to a rise in global average temperature of 2°C above pre-industrial levels, the so-called 2°C guardrail. Even a 2°C world will not be easy to cope with, as heatwaves and many other extreme events will become more frequent and intense than today (IPCC 2012), and other climate-related risks, such as coastal flooding, will increase as sea level continues to rise through the century (IPCC 2013). But, on current emission rates, we are heading towards a 4°C world. The risks that a 4°C world would pose for Australia—up to 7°C warmer in summer on average in inland areas; droughts five times more frequent in the south and west; sea-level rise of up to 1.1 m, and more than 7 m in the long term—are so stark (Christoff 2013) that no rational person would consider those risks acceptable. The need to reduce emissions and stabilize the climate has never been more urgent.

Scientists have developed a carbon budget approach to simplify the challenge we face to stabilize the climate at no more than a 2°C rise (Figure 21). The question is simple: How much more carbon dioxide can societies globally emit into the atmosphere to stabilize the climate within the 2°C guardrail?

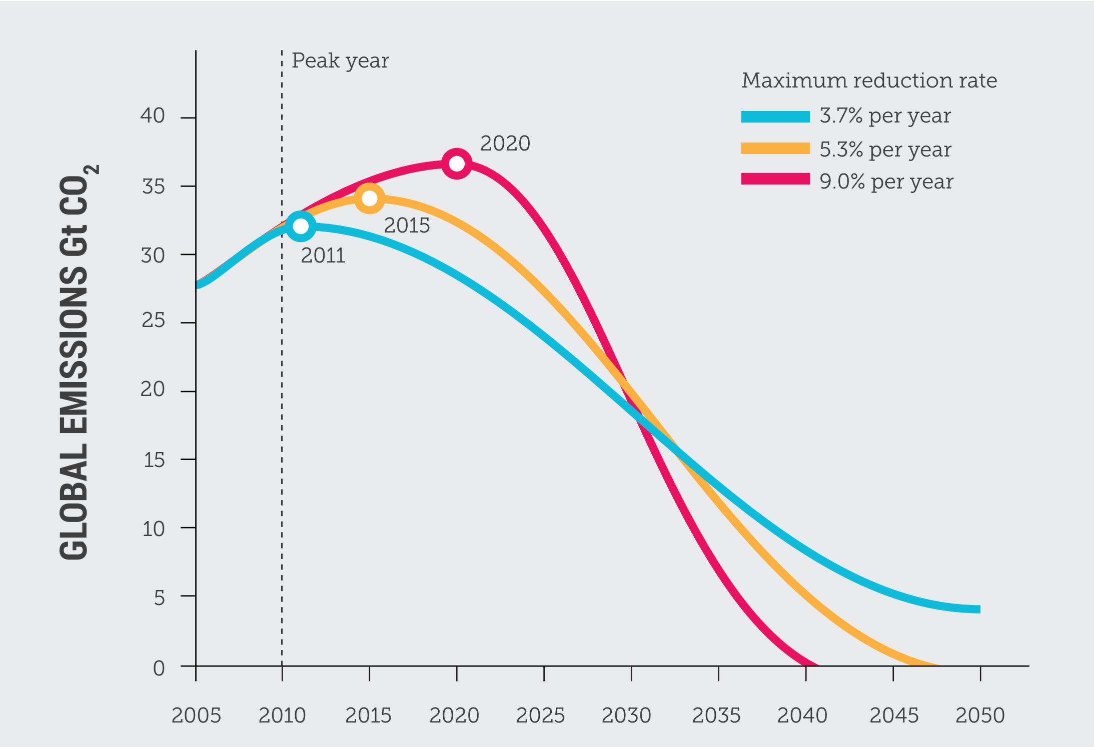


Figure 21: Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2°C guardrail. Source: WBGU 2009; Climate Commission 2013b

To have a two-out-of-three chance (67%) of staying within the 2°C guardrail, humanity can emit no more than 1,000 billion tonnes of CO_2 from 2012 until the world's economies must be completely decarbonized (IPCC 2013). A similar budget approach, but increasing our chances to a three-in-four (75%) chance of staying within the guardrail, calculated a limit of 600–900 billion tonnes of CO_2 emissions, depending on assumptions made about the emissions of other greenhouse gases such as nitrous oxide and methane (Meinshausen et al. 2009; Carbon Tracker and the Grantham Research Institute 2013; Climate Commission 2013b).

Whatever budget approach is used, the bottom line is the same—most of the world's known fossil fuel reserves, currently estimated to be the equivalent of 2,860 billion tonnes of CO_2 if all were burnt (IEA 2012), must be left in the ground. Under even the most optimistic assumptions, only about one-third of the fossil fuel reserves can be exploited to have a reasonable change of meeting the 2°C guardrail.

Turning the global emissions trend sharply downward this decade is an urgent priority if the cost of meeting the 2°C guardrail is to be minimized. The year at which global emissions peak is thus a key indicator. If global emissions can peak in 2015, the maximum rate of emission reductions along the subsequent pathway to decarbonisation is 5.3% per year. If the peak emissions year is delayed just five years to 2020, the subsequent maximum emission reduction rate rises to 9.0%, a much more difficult and costly goal than a 5% reduction rate, itself a daunting enough challenge.

There are some glimmers of hope as the world's two largest emitters, the USA and China, ramp up action to reduce their emissions. Renewable energy technologies, particularly solar and wind, are being deployed at increasing rates in many countries around the world. Technologies and management approaches for achieving energy efficiencies across the economy are multiplying rapidly. The rate of increase of global fossil fuel emissions for 2012 and 2013 (estimated) was lower than the 2003–2012 average but absolute emissions continue to rise at the highest of the IPCC emission trajectories (Global Carbon Project 2013).

This is the critical decade for action. We are now in 2014 and approaching the halfway point in the decade. Global emissions are still rising and Australian emissions have yet to make a decisive turn downwards. Despite the promising developments in low carbon technologies and energy efficiency measures, Australians have not yet reached a consensus on the need to decarbonize our economy and on the development of policies that will turn investment towards a decarbonized future. This challenge must be met if we are to minimize the risk of worsening heatwaves and other extreme events for our children and grandchildren. It's time to get on with the job.

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What to do in a heatwave

IN AN EMERGENCY, CALL TRIPLE ZERO (106 FOR PEOPLE WITH A HEARING OR SPEECH IMPAIRMENT)

- Take care of yourself
- Stay hydrated
- Stay cool
- Keep out of the sun
- Keep in touch with family, friends and neighbours
- Stay informed

AT HOME

- Spend time in cooled, well air-conditioned places. If you do not have air-conditioning at home, spend time in places that do, such as public libraries, cinemas, etc
- Avoid using an indoor fan in indoor areas without air-conditioning where the temperature is higher than 37°C
- The elderly should be reminded to remain in cool environments, and to wear cool, comfortable clothes
- Check with your local council to hear their heatwave response plan

AT THE WORKPLACE

- Limit trips outside air-conditioned buildings; rearrange work meetings if necessary
- Drink plenty of water

FOOD

- Ensure that food is refrigerated properly and immediately
- Dispose of spoilt food, and dispose responsibly

TRANSPORT/INFRASTRUCTURE

- Stay informed and up-to-date about planned blackouts
- Have a backup plan in case electricity or transport (road/rail) infrastructure fails

WILDLIFE

- Leave out shallow containers of water for birds, possums, and other animals, placing small stones in the bottom of the container and ensuring that the water is left in a shady, protected environment (out of view from birds of prey and high enough to be safe from cats)
- If you find injured or heat-stressed wildlife, bring them into cooler environments and lightly mist with water
- If you are concerned about an animal, call a wildlife rescue centre near to you

PETS

- If dogs or cats appear heat stressed, panting or restless, bath in cool water; call your vet if you are concerned about a pet